アミド基に対する金属ナイトレンの反応性の研究

2019 年

河野　将人

目次

略語表

便宜上、本論文全般において以下に示す略語、および略称を用いた。

Ac	acetyl
AIBN	azobisisobutyronitrile
Ar	aryl
aq.	aqueous
BHT	butylated hydroxytoluene
Bn	benzyl
Boc	*tert*-butoxycarbonyl
brsm	based on recovered starting material
^{n}Bu	normal butyl
^{t}Bu	tertiary butyl
Bz	benzoyl
calcd	calculated
cat.	catalyst
CBZ	benzyloxycarbonyl
conc.	concentration or concentrated
*m*CPBA	*meta*-chloroperoxybenzoic acid
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DCE	1,2-dichloroethane
DFT	density functional theory
DIBALH	diisobutylaluminum hydride
DMAP	4-(dimethylamino)pyridine
DMF	*N,N*-dimethylformamide
DMSO	dimethyl sulfoxide
dr	diastereomeric ratio
EDCI	1-(3-dimethylaminopropyl)-3-ethylcarbodiimide Hydrochloride
ee	enantiomeric excess
eq	equivalent
ESI	electrospray ionization
esp	$\alpha,\alpha,\alpha',\alpha'$-tetramethyl-1,3-benzenedipropanoate
espn	$\alpha,\alpha,\alpha',\alpha'$-tetramethyl-1,3-benzenedipropanamidate
Et	ethyl
EWG	electron withdrawing group

Gly	glycine
h	hour
HOBt	1-hydroxybenzotriazole
HPLC	high performance liquid chromatography
HRMS	high resolution mass spectrometry
IR	infrared
IRC	intrinsic reaction coordinate
J	coupling constant (in NMR)
LAH	lithium aluminum hydride
LG	leaveng group
LHMDS	lithium bis(trimethylsilyl)amide
LiDBB	lithium 4,4'-di-tert-butylbiphenylide
LUMO	lowest unoccupied molecular orbital
M	mol/L
Me	methyl
Min	minute(s)
mp	melting point
Ms	mesyl
MS	mass spectrometry
N	normality
n	normal
NIS	*N*-chlorosuccinimide
NMR	nuclear magnetic resonance
n.r.	no reaction
Nu	nucleophile
oct	octanoate
PG	protecting group
Ph	phenyl
Phe	phenylalanine
Piv	pivaloyl
PMB	*para*-methoxybenzyl
^{i}Pr	isopropyl
quant.	quantitative yield
R	*rectus*
Rf	rate of flow
rt	room temperature

S	*sinister*
solv.	solvent
t	tertiary
TBAF	tetrabutylammonium fluoride
TBDPS	*tert*-butyldiphenylsilyl
TBS	*tert*-butyldimethylsilyl
Tces	2,2,2-trichloroethoxysulfonyl
temp.	temperature
TEMPO	2,2,6,6-tetramethylpiperidinyloxyl
Tf	trifluoromethanesulfonyl
tfam	trifluoroacetamide
THF	tetrahydrofuran
TLC	thin layer chromatography
TMS	tetramethylsilane
tpa	triphenylacetate
TS	transition state
Ts	tosyl
UV	ultraviolet
Z	benzyloxycarbonyl

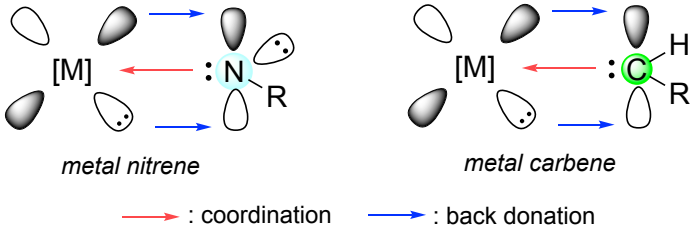
第 1 部　研究背景

第 1 章　金属ナイトレンと金属カルベンについて

1-1. 錯体の構造と一般的な反応性

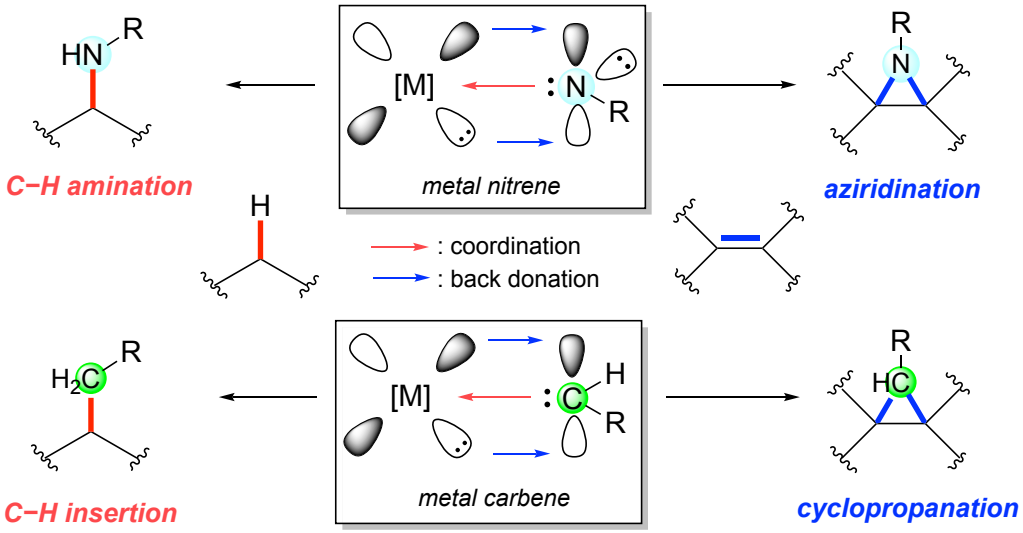
金属ナイトレンと金属カルベンは、原子価殻に 6 つの電子しか持たないナイトレンまたはカルベンが金属と錯体を形成した化学種である [1]。ナイトレン、カルベンが金属に電子対を供与すると同時に、金属からナイトレン、カルベンの空軌道への電子が逆供与され、二重結合を形成している（Figure 1-1）。

Figure 1-1. Metal nitrene and metal carbene complex



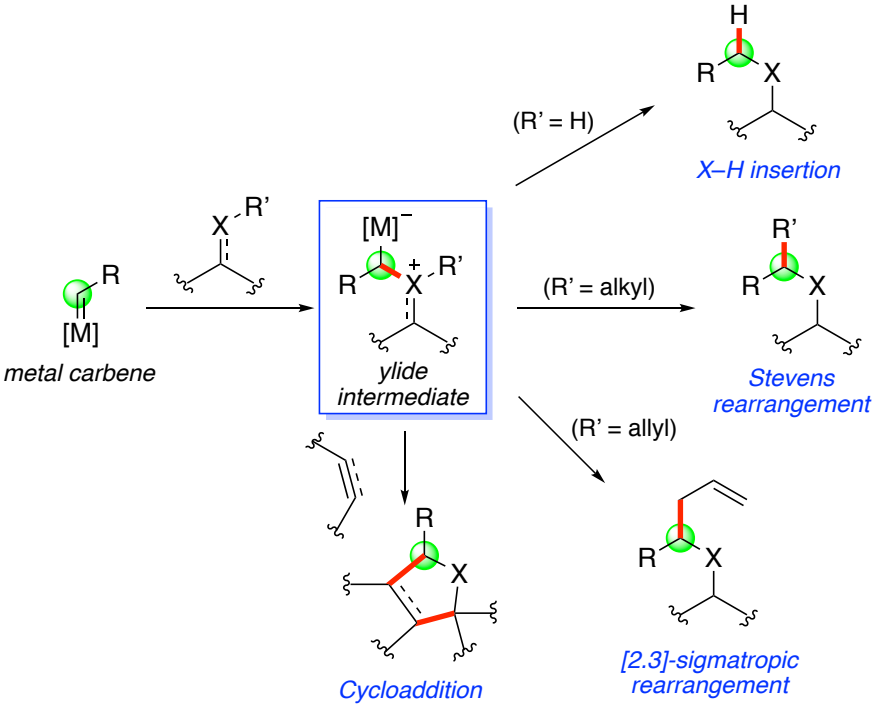
上図のように金属ナイトレンと金属カルベンは類似した電子構造を有するため、同様の反応性を示す [2]。中心窒素、中心炭素でのオクテット則を満たすために、通常は不活性な C–H 結合や二重結合へ挿入し、C–H 官能基化体 [3] や、アジリジン [4] またはシクロプロパン [5] を与える（Scheme 1-1）。

Scheme 1-1. General reactivities of metal nitrene and metal carbene



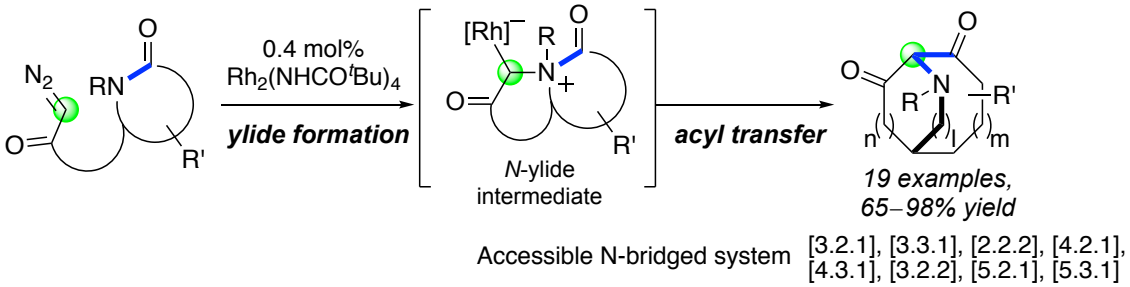
金属カルベンの場合、カルベン炭素へのヘテロ原子の求核攻撃によるイリド形成も、C–H 結合や二重結合への挿入反応と並ぶ重要な反応性である（Scheme 1-2）。イリドは、プロトン移動による X–H 挿入反応(X=N,O,S,Si,P) [6]、アルキル基の Stevens 転位やシグマトロピー転位 [7] などを起こす重要な中間体である。金属カルベンはアミド基の窒素原子や酸素原子のような求核性が低いヘテロ原子ともイリドを形成することが知られている。カルボニル酸素とのイリドは双極子として用いられ、求双極子体との付加環化反応 [8] によって複雑な骨格を与える [9]。

Scheme 1-2. Ylide chemistry of metal carbene



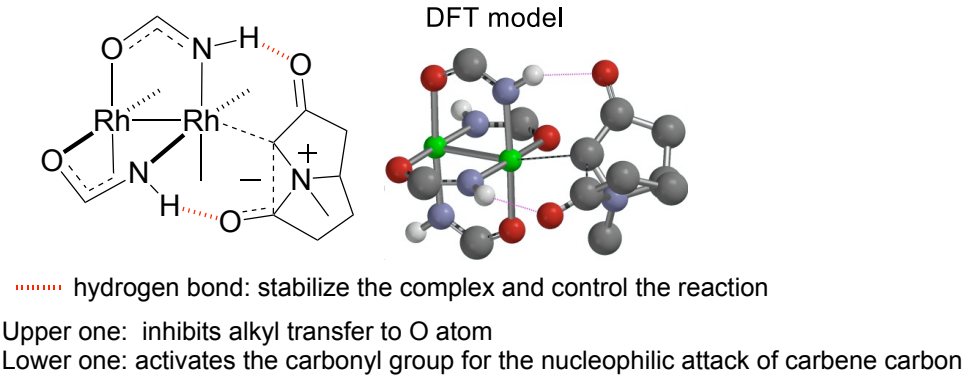
私は以前に、ロジウムカルベンのイリド形成を利用してアミド挿入反応を開発した[10,11]。アミド挿入反応は、ロジウムカルベンとアミド窒素とのイリド形成と、続くアシル基の転移による段階的な機構によって進行する（Scheme 1-3）。

Scheme 1-3. Amide insertion reaction of Rh-carbene



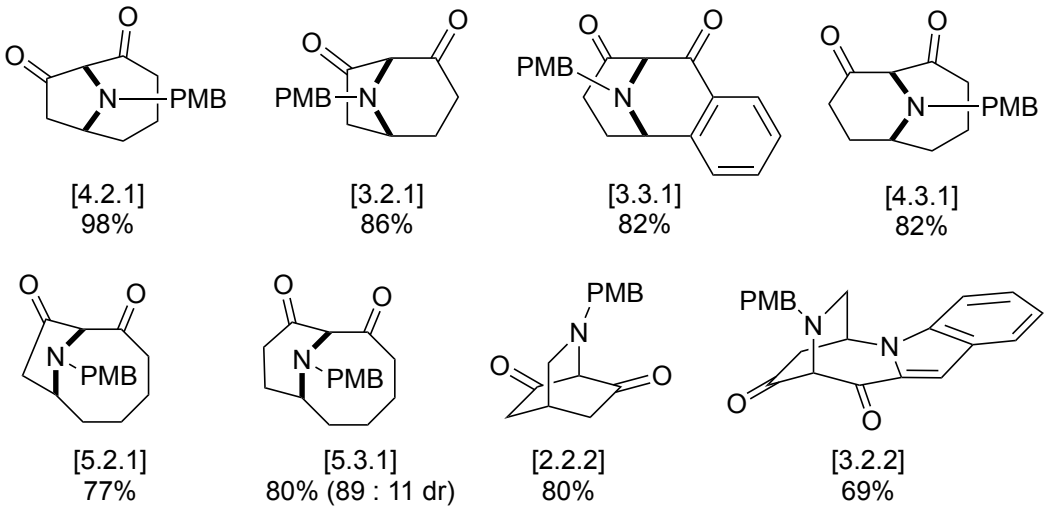
イリド中間体のアシル基の転移反応は例がなかったが、本反応ではアミダート系配位子を持つ $Rh_2(NHCO^tBu)_4$ が水素結合供与体として働くことで反応が円滑に進行している(Figure 1-2)。通常はイリド中間体の形成後に窒素原子上のアルキル基が転移するが、転移先の酸素原子の求核性を水素結合により下げ、同時に転移するカルボニル基の求電子性を水素結合によって向上させることで、アシル基の転移を促進している。また、水素結合には基質と触媒の複合体を安定化させる効果もあり、これにより高収率で反応が進行していると考えられる。

Figure 1-2. Transition state of the amide insertion reaction of Rh-carbene



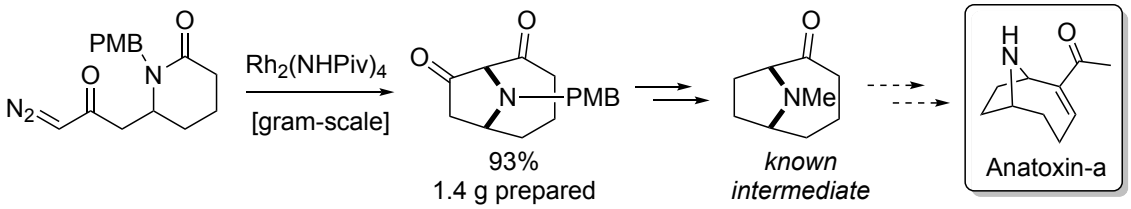
アミド挿入反応の生成物は生物活性物質に頻出する含窒素架橋型骨格であり[12]、従来法よりも多い８種類の骨格の構築に成功した（Figure 1-3）。

Figure 1-3. Synthesis of various azabicyclic compounds



また実際に、ロジウムカルベンのアミド挿入反応を用いて anatoxin-a の形式合成を達成した（Scheme 1-4）[13]。アザビシクロ[4.2.1]ノナン骨格を有する鍵中間体はアミド挿入反応によりグラムスケールで合成された。

Scheme 1-4. Foamal synthesis of anatoxin-a via amide insertion reaction

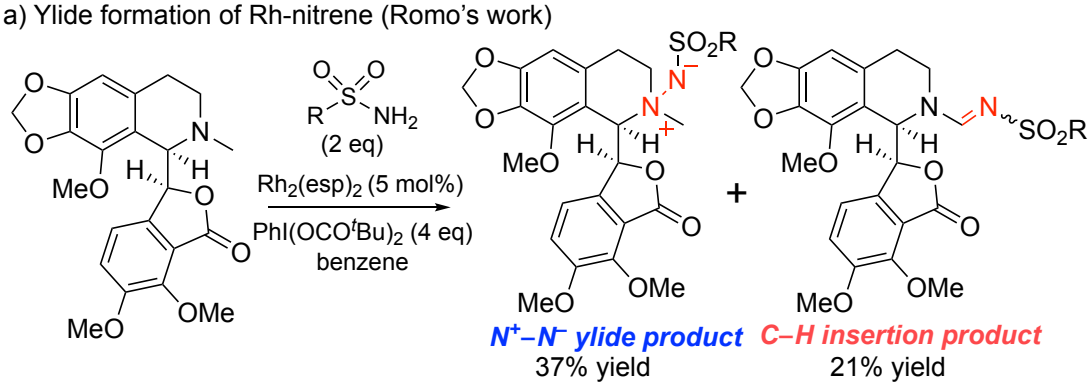


一方で、金属ナイトレンのイリド化学に関する研究は僅かしかない。

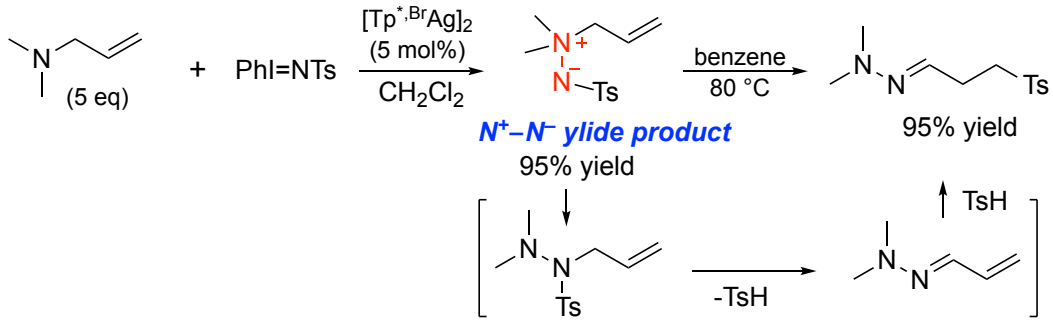
2013 年、Romo らはロジウムナイトレンと求核的な第三級アルキルアミンを用いて N^+–N^- イリド [14] の合成に成功した（Scheme 1-4 (a)）[15]。Pérez らのグループも銀ナイトレンと塩基性アミンを用いる N^+－N^- イリド形成に成功し、N^+–N^- イリドのシグマトロピー転位と続くトシル基の転移を報告している（Scheme 1-5 (b)）[16]。

Scheme 1-5. Ylide formation of metal nitrenes with nucleophilic amines

a) Ylide formation of Rh-nitrene (Romo's work)



b) Ylide formation of Ag-nitrene (Maseras, Díaz-Requejo, Echavarren, and Pérez's work)



金属ナイトレンを用いる N^+－N^- イリド形成の報告は他にも数例あるが [17]、N^+–N^- イリドを有用中間体として利用する構造変換反応の研究は十分になされていない。さらに、求核剤は求核的な sp^2 または sp^3 混成のアミンに限られており、アミド窒素のような求核性が低いヘテロ原子とのイリド形成は報告がない。したがって、金属ナイトレンのイリド化学の発展には更なる研究が必要である。

第 5 章　アミド基に対するロジウムナイトレンの反応性の検証と新規挿入反応の発見

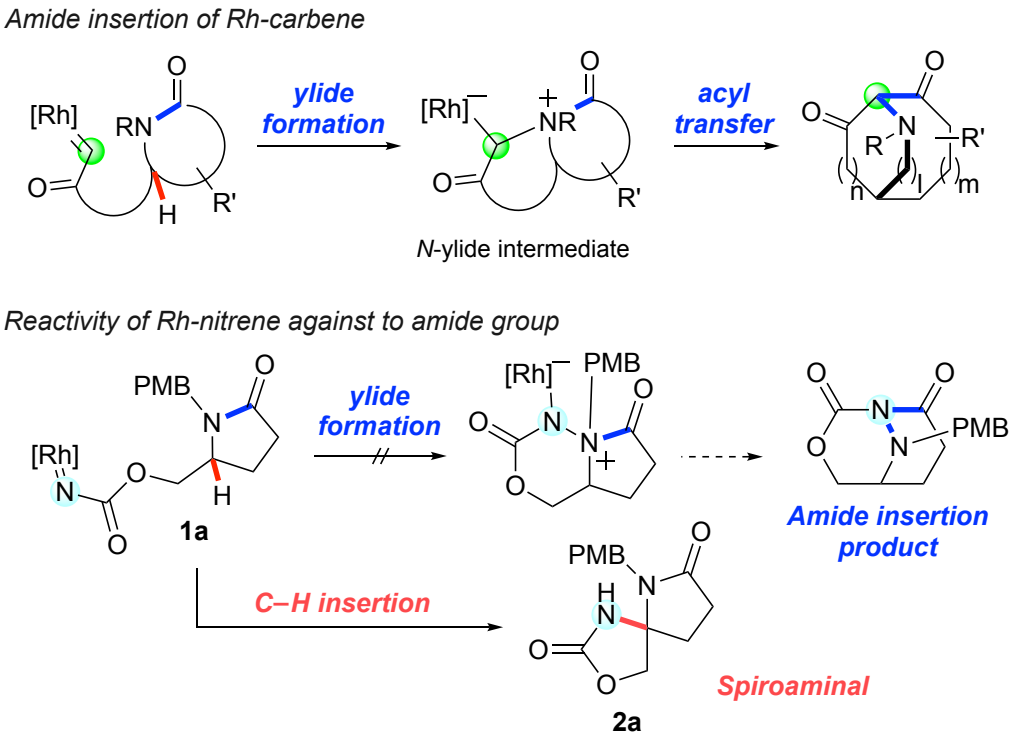
1-5.アミド基に対する金属ナイトレンの反応性の検証

前章で述べた通り、金属ナイトレンがアミド窒素のような求核性の低い原子とイリドを形成した例はない。そこで私は、金属ナイトレンがアミド基に対してどのような反応を示すか興味を抱いた。ロジウムナイトレンがロジウムカルベンと同様にアミド窒素とイリドを形成すれば続くアシル転移によってアミド挿入反応を起こすと考えられるが、アミド窒素とのイリド形成が困難な場合にどのような生成物を与えるか確かめるべく、研究に着手した。

1-5-1. スピロアミナール化反応の発見

ロジウムカルベンのアミド挿入反応の基質に類似した基質 **1a** を用いて、実際にアミド挿入反応を試みた。しかしながら、**1a** からロジウムナイトレンを発生させてもアミド挿入体は得られず、アミド窒素 α 位の C–H 結合への挿入反応によってスピロアミナール化合物 **2a** が得られた（Scheme 1-6）。詳細を第 2 部で述べる。

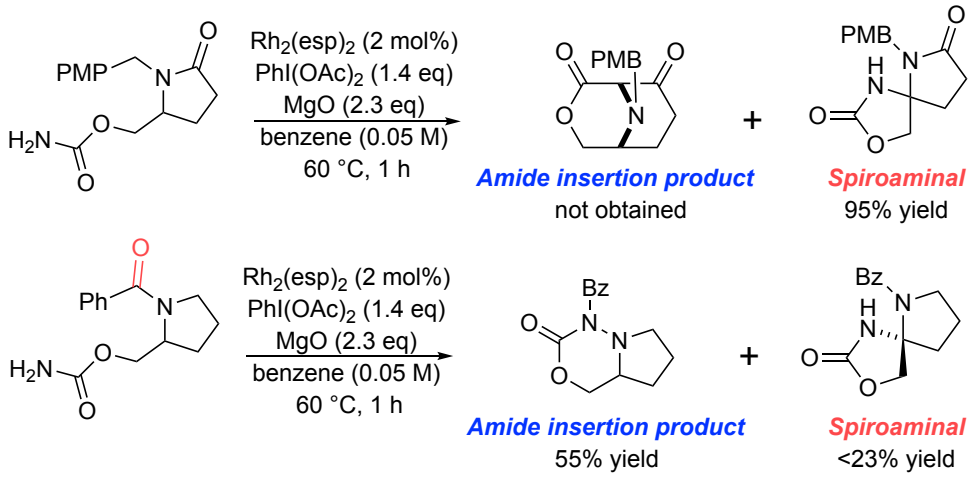
Scheme 1-6. Examination of the amide insertion reaction of metal nitrene



1-5-2. ロジウムナイトレンのアミド挿入反応の発見

スピロアミナール化反応で用いた基質のカルボニル基を環外へと移したところ、予期せずアミド挿入反応が進行した（Scheme 1-7）。前述の通り、金属ナイトレンが求核性の低いヘテロ原子とイリドを形成した例はなく、基礎化学的に興味深い。本反応について、第 3 部で詳細を報告する。

Scheme 1-7. Observation of the amide insertion reaction of Rh-nitrene



1-5-3. 本博士研究の目的

金属ナイトレンとアミド基との反応性を検証する中で見出した 2 つの新規挿入反応について研究を行い、歴史が浅い金属ナイトレンの化学の発展に貢献することを目的とした。また、金属ナイトレンと金属カルベンは C–H 結合や二重結合への挿入という同様の反応性を示すにも関わらず、イリド化学においては異なる反応性を示す原因の解析も目標に定めた。

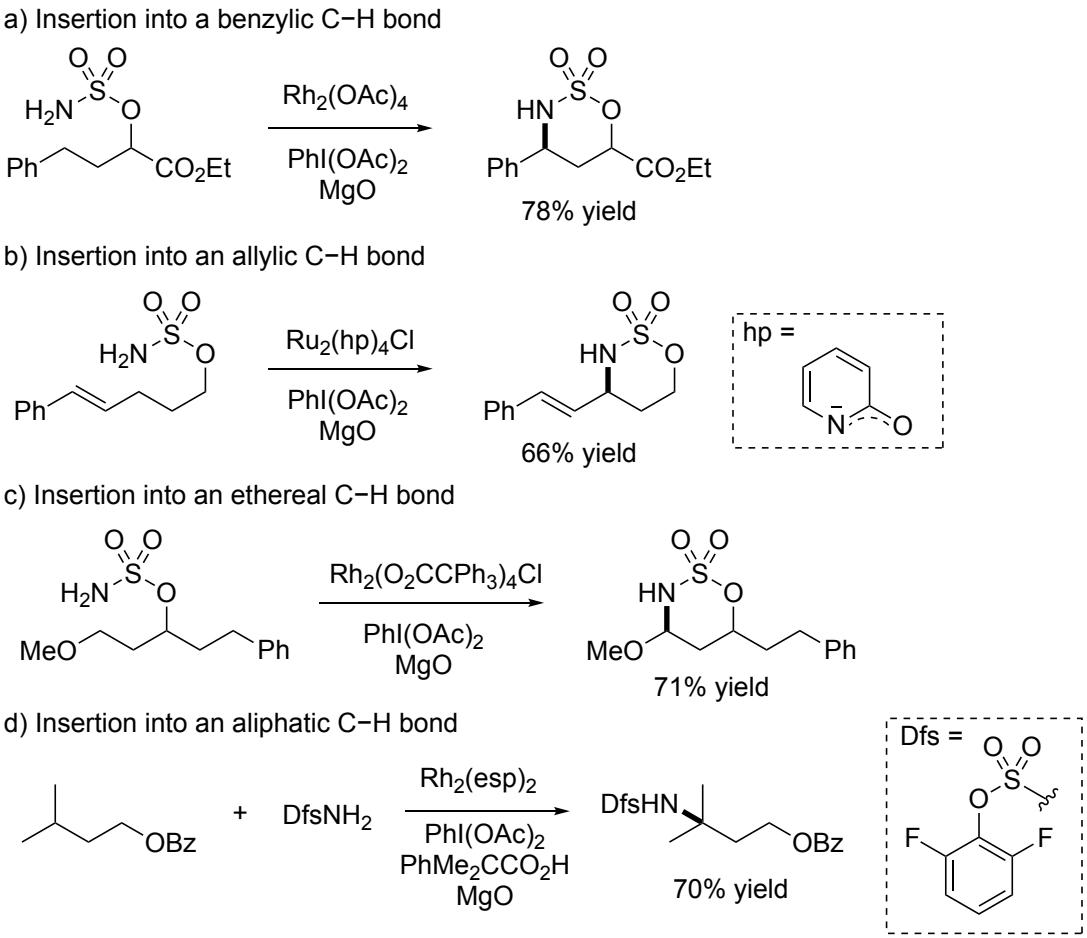
第２部　ロジウムナイトレンの C−H 挿入反応によるスピロアミナール骨格の構築および
ロジウムカルベンとの反応性の比較

第１章　研究背景

2-1-1. 金属ナイトレンの C–H 挿入反応

金属ナイトレンの C–H 挿入反応は不活性な C−H 結合に対して直接的にアミノ基を導入する強力な反応であり、全合成の終盤でもしばしば用いられる [18]。金属ナイトレンの C–H 挿入反応は Müller ら [19] や Du Bois ら [20] の報告を皮切りに今日まで盛んに研究され、ベンジル位 [20b,21]、アリル位 [22]、酸素原子の α 位 [23] での C–H 挿入反応の他、脂肪族 C–H 結合への挿入反応 [24] も開発されている (Scheme 2-1) [25]。反応機構に関する研究も多数報告がある [26]。

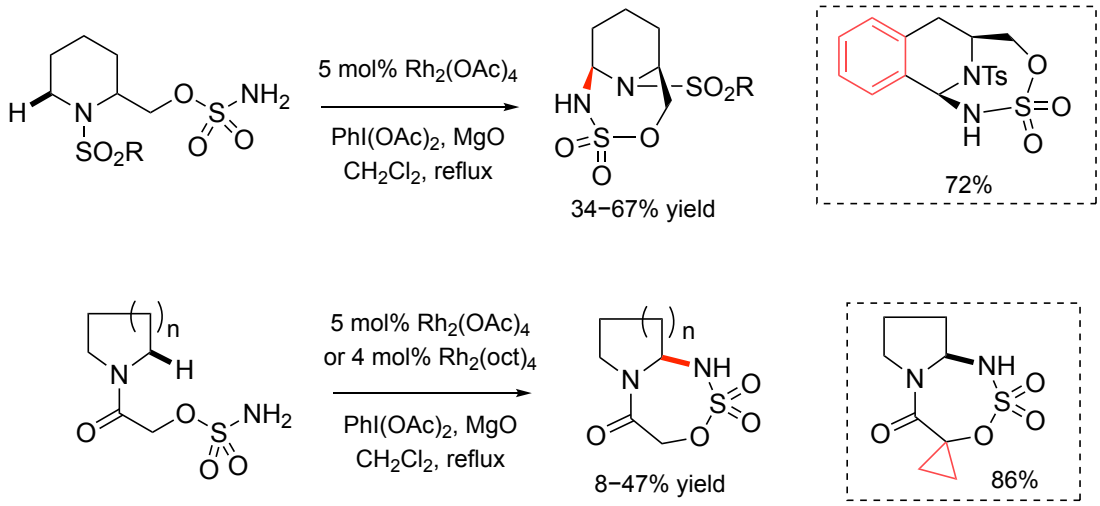
Scheme 2-1. Various C–H insertion reactions of metal nitrene



2-1-2. 窒素原子α位での C–H 挿入反応

前項で述べた C–H 挿入反応に加え、窒素原子α位での金属ナイトレンの C–H 挿入反応も開発されている（Scheme 2-2）。しかしながら、これらの反応の収率は基本的に中程度に留まっており、高収率での変換のためには基質が活性化されている必要がある。すなわち、Scheme 2-2 の上段の反応は窒素原子のα位であると同時にベンジル位であるために収率良く反応が進行し [27]、下段の場合はシクロプロパン環による Thorpe-Ingold 効果により目的物が良好な収率で得られていると考えられる [28]。したがって、窒素原子α位での C–H 挿入反応は未だ研究の余地がある。

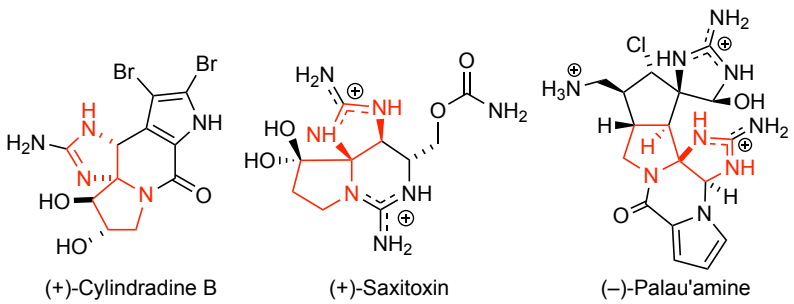
Scheme 2-2. C–H insertion reaction of metal nitrene at α position of nitrogen



2-1-3. スピロアミナール骨格とその合成法

スピロアミナール骨格は(+)-cylindradine B[29]や(+)-saxitoxine[30]、(–)-palau'amine[31]などの海産天然物（Figure 2-1）や材料化学のモノマー[30]によく見られる構造である。

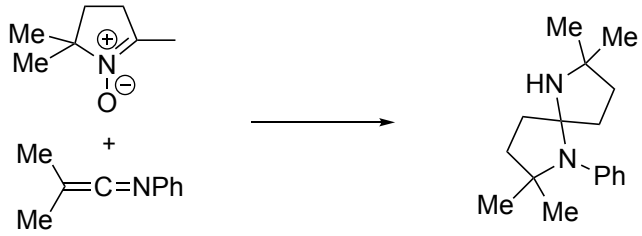
Figure 2-1. Spiroaminals in natural products



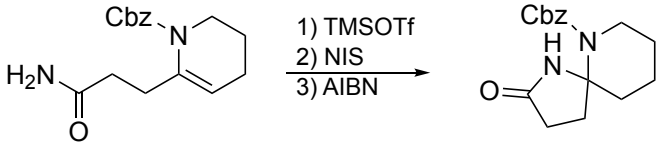
しかしながら、スピロアミナール骨格は有用な骨格であるにも関わらず、その骨格構築に関する研究は僅か数例しかない。Scheme 2-3 に示すように、柘植らによるケテンイミンとニトロンを用いる方法（a）[33]、Bermejo らによるヨードラクタム化反応を経る方法（b）[34]、福山らによるセミピナコールタイプの転位反応[35]（c）、Vassilikogiannakis らによる分子内 S_N2 反応[36]（d）が開発されているが、これらはラセミ反応または他の不斉点を利用したジアステレオ選択的な反応であり、キラルなスピロアミナール骨格を直接的に合成できる方法は未だ開発されていない[37]。

Scheme 2-3. Synthetic method for spiroaminals

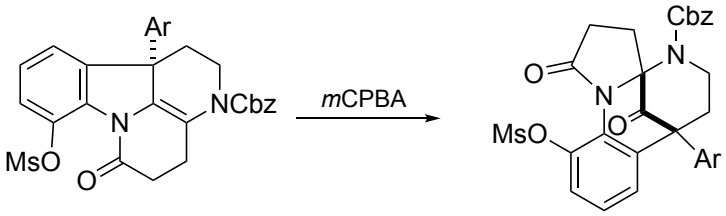
a) Spiroaminal synthesis from ketenimine and nitrone



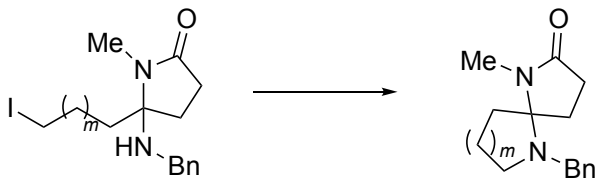
b) Spiroaminal synthesis via iodolactamization



c) Spiroaminal synthesis by semi-pinacol type rearrangement



d) Spiroaminal synthesis by intramolecular S_N2 reaction



2-1-4. 研究目的

第 1 部第 5 章で述べたスピロアミナール化反応は、数少ない窒素原子α位での C–H 挿入反応である点、また、有用なスピロアミール骨格が構築できる点で重要だと考えた。本 C–H 挿入反応が立体化学を保持して進行すれば、従来法では困難であったキラルなスピロアミナール骨格の直接的な構築が可能になる。

また、本反応はロジウムカルベンのアミド挿入反応と同様の反応を試みた際に副反応として起こった反応であり、ロジウムナイトレンとロジウムカルベンが異なる反応性を示す要因についても実験と量子化学計算を用いて解明することとした。

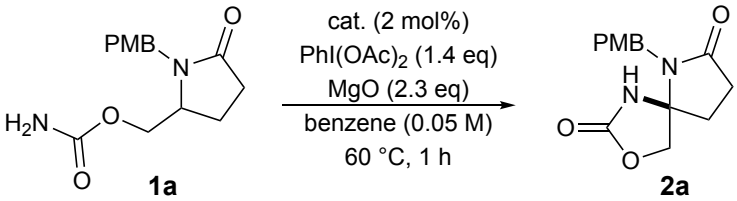
第 2 章　反応条件の最適化

2-2-1. 配位子の検討

カーバメート側鎖を有する 5 員環ラクタム **1a** をナイトレン前駆体とし、触媒の最適化を行った（Table 2-1）。酸化剤である超原子価ヨウ素試薬 $PhI(OAc)_2$ は、第 1 級カーバメートとの反応によりイミノヨージナンを形成し、その後金属との配位子交換によって金属ナイトレンを発生させる役割がある。塩基である MgO はイミノヨージナンの形成に伴って生成する酢酸を補足する目的で加えている。また、塩基によって生じるカルボキシラートアニオンが、酸化されて失活した触媒を活性な触媒種に還元するという報告もある [18a]。

まず、ロジウムカルベンのアミド挿入における最適触媒 $Rh_2(NHCO^tBu)_4$ と $PhI(OAc)_2$ を用いて、ベンゼン中、60 ℃でロジウムナイトレンを発生させたところ、ジアザスピロ[4.4]ノナン骨格を有する化合物 **2a** が 66%収率で得られた（entry 1）。次に、広く用いられている $Rh_2(OAc)_2$ を用いたところ、**2a** の収率が 80%まで向上した（entry 2）。しかしながら、$Rh_2(OCOC_7H_{15})_4$ や $Rh_2(OCOCPh_3)_4$ などの二核ロジウム（II,II）カルボキシラート系触媒や、二核ロジウム（II,III）アミダート触媒である $Rh_2(espn)_2Cl$ を用いると目的物の収率は低下した（entries 3-5）。一方で、金属ナイトレンの C−H 挿入反応の先駆者である Du Bois らによって開発された $Rh_2(esp)_2$[38] を用いると、**2a** の収率は 95%まで向上した（entry 6）。

Table 2-1. Study of catalyst



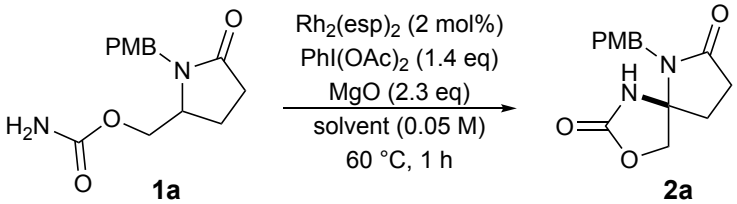
entry	cat.	yield (%)[a]
1	$Rh_2(NHCO^tBu)_4$	66 (SM: 33)
2	$Rh_2(OAc)_4$	80
3	$Rh_2(oct)_4$	76 (SM: 4)
4	$Rh_2(tpa)_4$	71 (SM: 15)
5	$Rh_2(espn)_2Cl$	72
6	$Rh_2(esp)_2$	95[b]

[a] Determined by ^1H NMR analysis of the crude mixture using $CHPh_3$ as an internal standard.
[b] Isolated yield.

2-2-2. 溶媒の検討

最適触媒を $Rh_2(esp)_2$ とし、溶媒の検討を行ったが、ベンゼン中での収率（95%, entry 1）を上回る結果は得られなかった(Table 2-2)。ジクロロメタン、アセトニトリル、1,4-ジオキサン中では途中で反応が止まってしまい、中程度の収率に留まった（entries 2-4）。酢酸イソプロピル中では基質が完全に消費されたものの、収率は 86%であった（entry 5）。

Table 2-2. Study of solvent



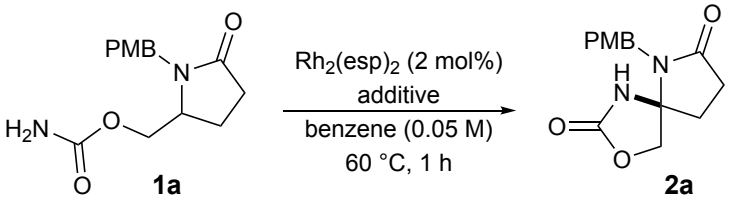
entry	cat.	yield (%)[a]
1	benzene	95[b]
2[c]	CH_2Cl_2	59 (SM: 29)
3	CH_3CN	68 (SM: 19)
4	dioxanae	73 (SM: 15)
5	^{i}PrOAc	86

[a] Determined by ^{1}H NMR analysis of the crude mixture using $CHPh_3$ as an internal standard. [b] Isolated yield. [c] Conducted at 40 °C.

2-2-3. 酸化剤の検討

ナイトレンを発生させるための超原子価ヨウ素試薬についても検討を行ったが、$PhI(OAc)_2$ と共に頻繁に用いられている $PhI(OCO^tBu)_2$ を用いても収率は向上しなかった。

Table 2-3. Study of oxidant



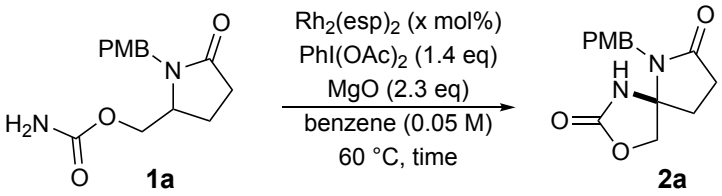
entry	additive	yield (%)[a]
1	$PhI(OAc)_2$ (1.4 eq), MgO (2.3 eq)	95[b]
2	$PhI(OCO^tBu)_2$	74 (SM: 13)

[a] Determined by ^{1}H NMR analysis of the crude mixture using $CHPh_3$ as an internal standard.
[b] Isolated yield.

2-2-4. 触媒量の検討

ロジウム触媒は高価であるため、触媒量を減らすことができるか検討を行った（Table 2-4）。触媒量を 1 mol%、0.5 mol%と減らしたところ、目的物の収率が低下した（entries 2,3）。また、触媒量の低下に伴う触媒濃度の低下を考慮して反応溶液の濃度を濃くしたが、収率の向上には至らなかった（entry 4）。

Table 2-4. Study of catalyst loading



entry	x	time (h)	yield[a]
1	2	1	95[b]
2	1	3	86
3	0.5	3	85
4[c]	0.5	2	79

[a] Determined by ^{1}H NMR analysis of the crude mixture using $CHPh_3$ as an internal standard.
[b] Isolated yield.
[c] conc. = 0.2 M

以上の検討より、Table 2-4 の entry 1 に示す条件を最適条件として定めた。

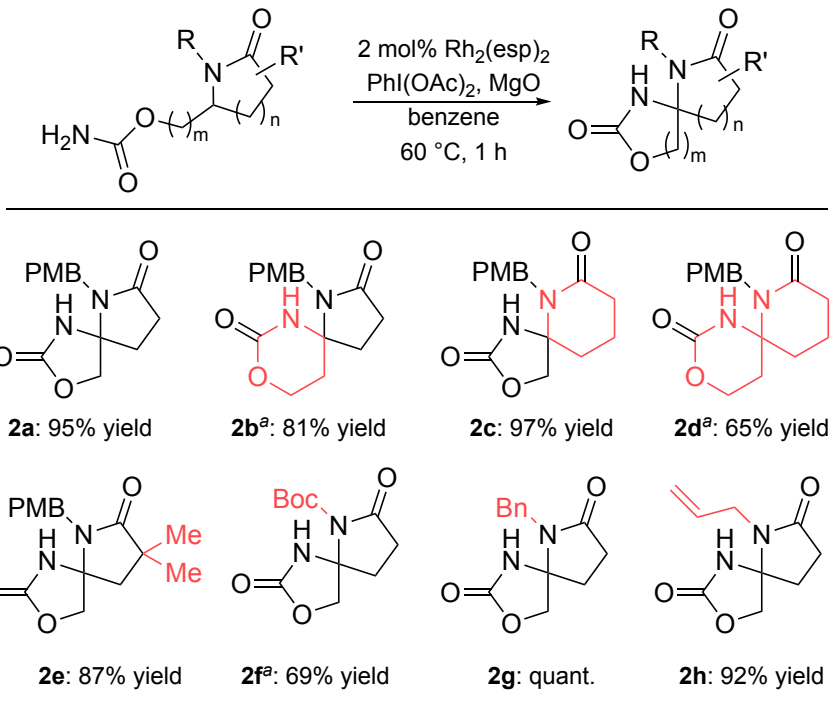
第 3 章　基質一般性の検討

2-3-1. カーバメート基質の検討

最適条件下、他のカーバメート基質について基質一般性を検討した（Table 2-5）。

本スピロアミナール化反応は 1,6-ジアザスピロ[4.4]ノナン骨格（**2a**）以外に、8-オキサ-1,6-ジアザスピロ[4.5]デカン骨格（**2b**）、3-オキサ 1,6-ジアザスピロ[4.5]デカン骨格（**2c**）、1,7-ジアザスピロ[5.5]ウンデカン骨格（**2d**）の構築が可能である。カーバメートから発生した金属ナイトレンは 5 員環形成を好む傾向があるため、6 員環形成反応となる化合物 **2b**、**2d** の合成は最適条件下では良い結果が得られなかった。しかしながら、触媒量を 4 mol%に増やし、溶媒を酢酸イソプロピルへと変換することで、良好な収率でスピロアミナール体が得られた。また、化合物 **2b** と **2d** の合成において 5 員環生成物が観測されなかったことから、ロジウムナイトレンがアミド窒素 α 位の第 3 級 C–H 結合へ高化学選択的に挿入していることがわかる。他にも、アミドカルボニル基の α 位に置換基を有するスピロアミナール（**2e**）や、Boc 基（**2f**）、Bn 基（**2g**）、アリル基（**2h**）を保護基として持つスピロアミナールが合成可能であった。化合物 **2h** にはアジリジン化が起こりうるオレフィン部位があるが、ロジウムナイトレンは高化学選択的に第 3 級 C－H 結合へ挿入した。

Table 2-5. Substrate scope of carbamate type substrates

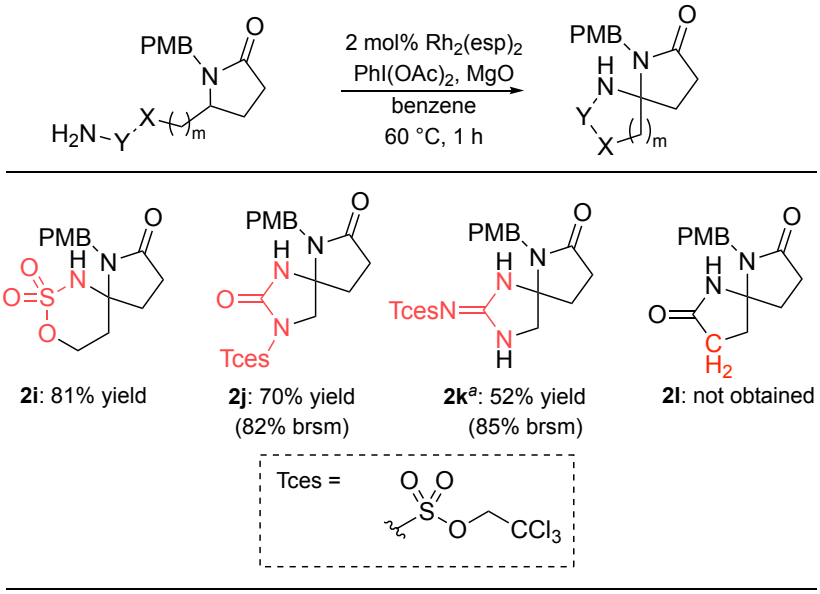


[a] Conducted with 4 mol% $Rh_2(esp)_2$ in ^{i}PrOAc.

2-3-2. 様々な側鎖の検討

側鎖はカーバメート以外に、スルファメート（**2i**）、ウレア（**2j**）、グアニジン（**2k**）を用いることができた。グアニジンを有するスピロアミナール（**2k**）の合成では触媒の失活が早く、6 mol%の触媒を用いた。一方で、側鎖がアミドの基質ではスピロアミナール化は起こらず、**2l** は得られなかった。^{1}H NMR と MS の解析の結果、Hofmann 転位 [39] による生成物の生成が示唆された。

Table 2-6. Substrate scope of other side chain

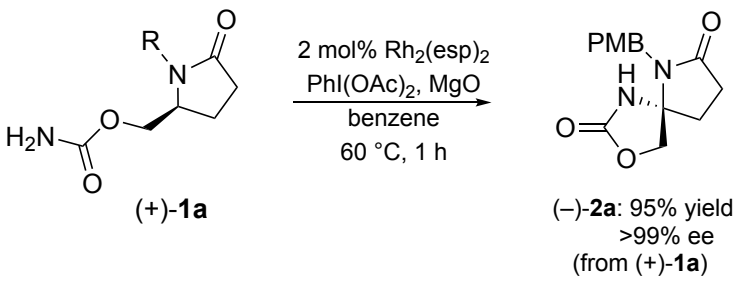


[a] Conducted with 6 mol% $Rh_2(esp)_2$.

2-3-3. 立体化学の保持

キラルな基質を用いた場合はキラルなスピロアミナールが得られた（Scheme 2-4）。この結果より、本反応は一重項状態のロジウムナイトレン [26a,c] による協奏的な機構で進行していると考えられる [40]。

Scheme 2-4. Retention of stereochemistry



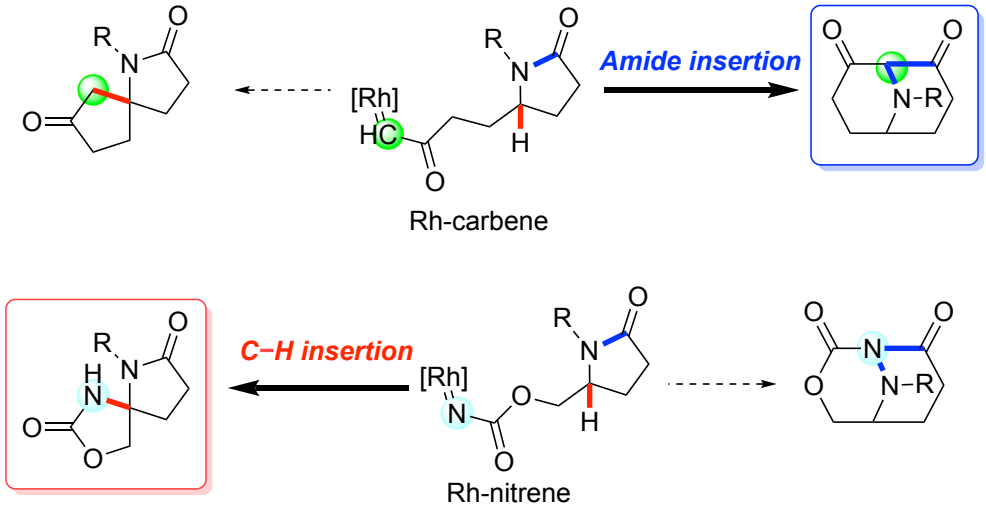
第４章　アミド基に対するロジウムナイトレンとロジウムカルベンの異なる反応性の解析

2-4-1. 金属ナイトレンと金属カルベンの異なる反応性

第一部で述べた通り、金属ナイトレンと金属カルベンは電子的に類似した構造を有するにも関わらず、アミド基に対して異なる反応性を示す。すなわち、類似基質を用いても、ロジウムカルベンはアミド C–N 結合へ挿入する一方でロジウムナイトレンはアミド窒素 α 位への C–H 挿入反応によってスピロアミナールを与える（Scheme 2-5）。

金属カルベンと金属ナイトレンのそれぞれの反応に関する報告は多数あるものの、金属カルベンと金属ナイトレンの反応性の違いに関する研究はない。私はこのような反応性の違いに興味を抱き、その原因を解明するために実験的・計算化学的な解析を行った。

Scheme 2-5. Different reactivity of metal nitrene and metal carbene



2-4-2. 実験的な解析

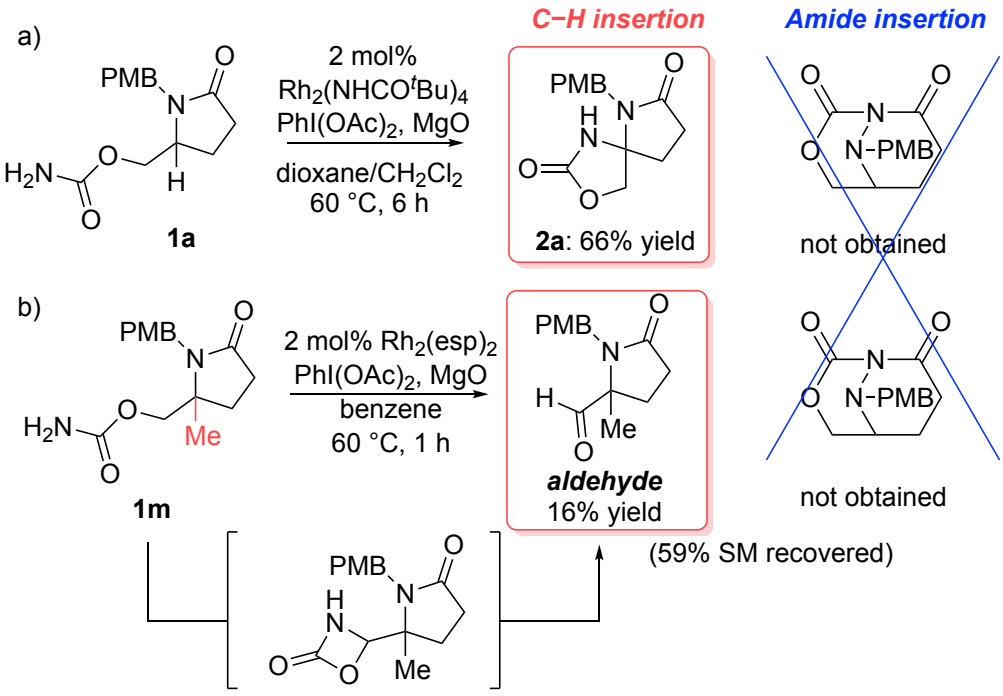
まず、実験的な解析を試みた。すなわち、金属ナイトレンのアミド挿入が進行する条件、または金属カルベンの C–H 挿入反応が進行する条件を見出し、その条件ともう一方の化学種の条件を比較することで異なる反応性の要因を解明できると考えた。

2-4-2-1. ロジウムナイトレンのアミド挿入反応の検討

ロジウムナイトレンのアミド挿入を起こすために、ロジウムカルベンのアミド挿入反応における最適条件下でロジウムナイトレンを発生させた（Scheme 2-6（a））。ロジウムカルベンのアミド挿入反応では 1,4-ジオキサン溶媒中で $Rh_2(NHCO^tBu)_4$ を用いることでアミド挿入反応が促進されたため、ロジウムナイトレンでもアミド挿入反応が起こると期待した。しかしながらアミド挿入体は得られず、スピロアミナール化が進行するのみであった。

そこで、スピロアミナール化を抑制するために第 3 級 C–H 結合を持たない基質 **1m** からロジウムナイトレンを発生させたが、アミド挿入体は得られずにアルデヒド化合物が得られた（Scheme 2-6（b））。アルデヒド化合物は、アミド窒素 β 位への C–H 挿入反応による 4 員環の形成と続く環開裂により生成したと考えられる [41]。

Scheme 2-6. Examination of amide insertion of Rh-nitrene



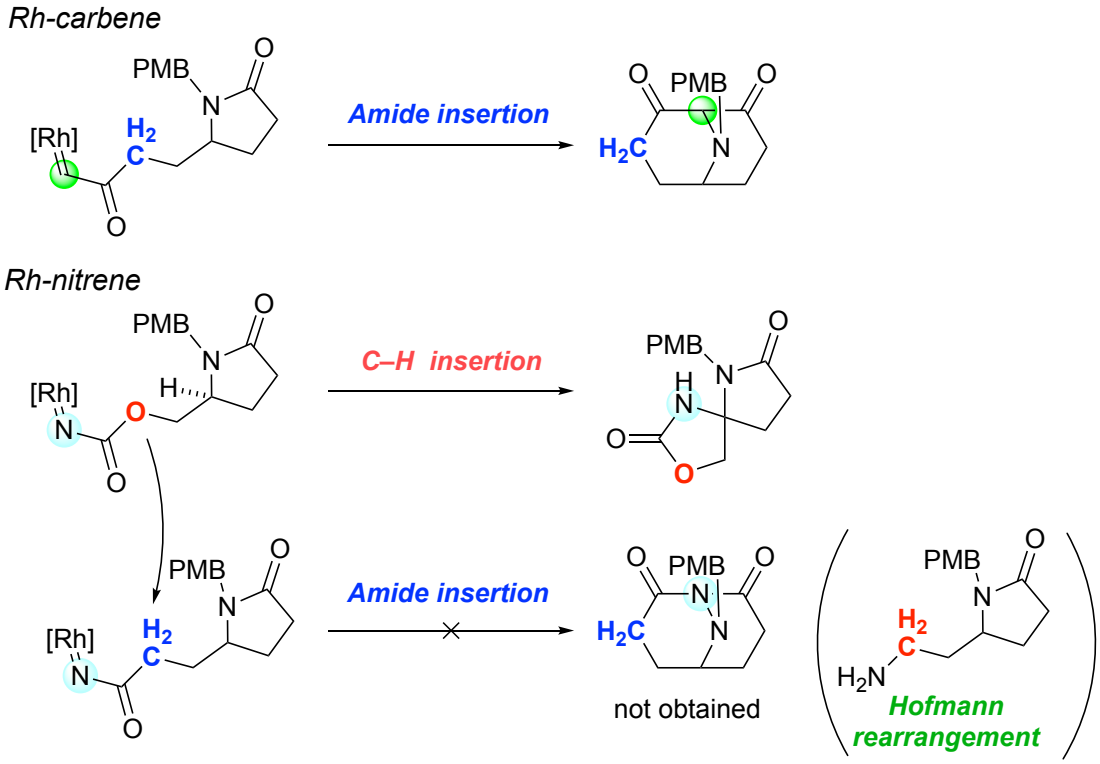
これらの結果より、ロジウムナイトレンが C–H 挿入反応を強く好むこと、またロジウムナイトレンのイリド形成が非常に起こりにくいことがわかった。

2-4-2-2. 側鎖上の酸素原子の効果

ロジウムカルベンのアミド挿入反応の基質は側鎖上に酸素原子を持たないため、側鎖上の酸素原子によって異なる反応性を示している可能性がある（Scheme 2-7）。しかしながら「2-3-2. 様々な側鎖の検討」で述べたように、ロジウムナイトレンの側鎖から酸素原子を除去すると Hofmann 転位が起こるため、酸素原子を取り除いて検討することはできない。

そこで、ロジウムナイトレンのアミド挿入反応を引き起こすことを断念し、ロジウムカルベンの C–H 挿入反応の検討に移った。

Scheme 2-7. Effect of the oxygen atom in a tether

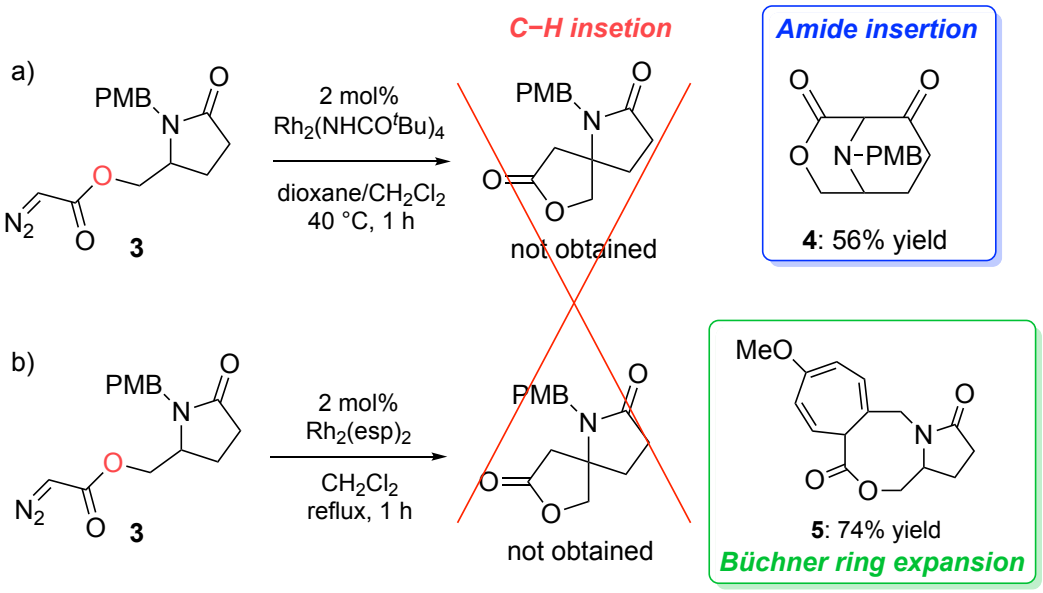


2-4-2-3. ロジウムカルベンの C–H 挿入反応の検討

側鎖の酸素原子の影響を調べるためにジアゾエステル化合物 **3** を合成し、アミド挿入反応の最適条件に付した。その結果、化合物 **3** から発生したロジウムカルベンもアミド C–N 結合へ挿入したため、側鎖上の酸素原子はロジウムカルベンとロジウムナイトレンの異なる反応性の要因ではないと考えられる（Scheme 2-8（a））。

以前の研究により、アミダート系配位子を持つ $Rh_2(NHCO^tBu)_4$ と 1,4-ジオキサン溶媒がアミド挿入反応を促進することが明らかとなっている点、また Wee らがジクロロメタン中でジアゾエステルを基質として用いる C–H 挿入反応を報告している点[42]から、触媒と溶媒による影響を考えた。そこで、ジクロロメタン中でカルボキシラート系ロジウム触媒である $Rh_2(esp)_2$ を用いて C－H 挿入反応を試みたが、C–H 挿入反応によるスピロ化合物の生成は観測されず、ブフナー環拡大反応[43]によるトリエン **5** が得られるのみであった（Scheme 2-8（b））。

Scheme 2-8. Examination of C－H insertion of Rh-carbene



2-4-3. 量子化学計算による解析

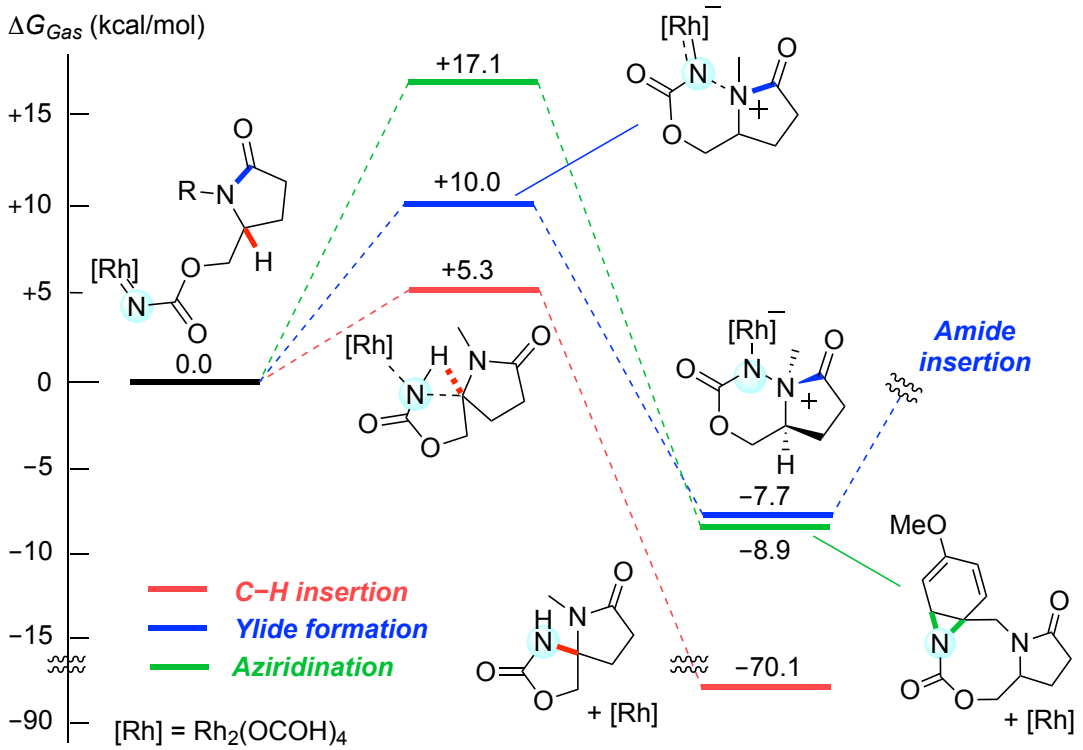
ロジウムナイトレンとロジウムカルベンが異なる反応性を示す要因を実験的に解析することが困難であったため、量子化学計算を用いる解析を行った。

2-4-3-1. ロジウムナイトレンの反応に関する DFT 計算

まず、起こり得るロジウムナイトレンの反応（C–H 挿入反応、イリド形成、アジリジン化）について DFT 計算を行った（Figure 2-2）[44]。汎関数として RB3LYP、基底関数として 6-31G*（C,H,N,O）と LANL2DZ（Rh）を用いている [45]。

DFT 計算の結果、ロジウムナイトレンの C–H 挿入反応は最も低い活性化エネルギー（+5.3kcal/mol）で進行することが示唆された。アミド挿入の第一段階であるイリド形成の活性化エネルギーは+10.0 kcal/mol、芳香環のアジリジン化の活性化エネルギーは+17.1 kcal/mol であり、どちらも C–H 挿入反応よりも高くなっている。活性化エネルギーに 3 kcal/mol 以上の差がある場合、99:1 以上の反応速度で有利な反応が優先的に進行すると考えることができる。したがって、DFT 計算の結果は C–H 挿入反応によるスピロアミナール化のみが進行したという実験結果と合致する。

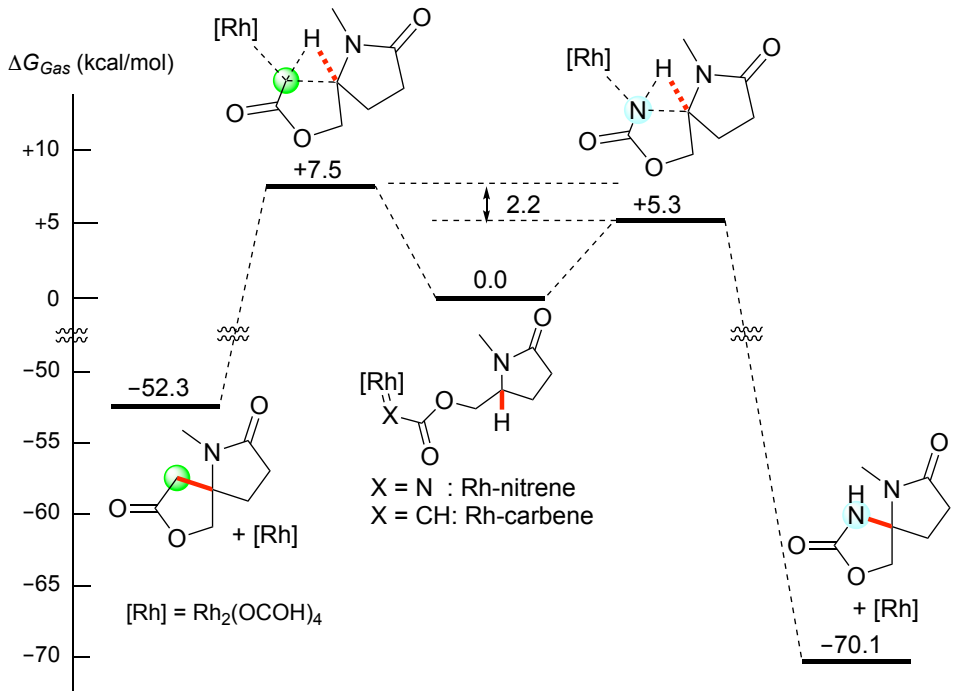
Figure 2-2. Energy profiles of postulated reactions of Rh-nitrene



2-4-3-2. ロジウムカルベンの C–H 挿入反応の計算と Rh ナイトレンとの比較

ロジウムカルベンの C–H 挿入反応についても同様の計算レベルで DFT 計算を行った（Figure 2-3）。その結果、ロジウムカルベンの C–H 挿入反応は+7.5 kcal/mol の活性化エネルギーで進行することが示唆され、ロジウムナイトレンの C–H 挿入反応（+5.3 kcal/mol）よりやや高い値であった。一般的にもロジウムナイトレンの C–H 挿入反応[26a,b]はロジウムカルベンの C–H 挿入反応[45,46]よりも低い活性化エネルギーで進行することがわかっており、本研究でも同様の傾向が見られた。しかしながら、ロジウムカルベンの C–H 挿入反応はロジウムナイトレンよりも不利であるものの、異なる選択性が出るほど差があるとは考えにくい。したがって、C–H 挿入反応自体はロジウムナイトレンとロジウムナイトレンの異なる反応性の要因ではないと考えた。

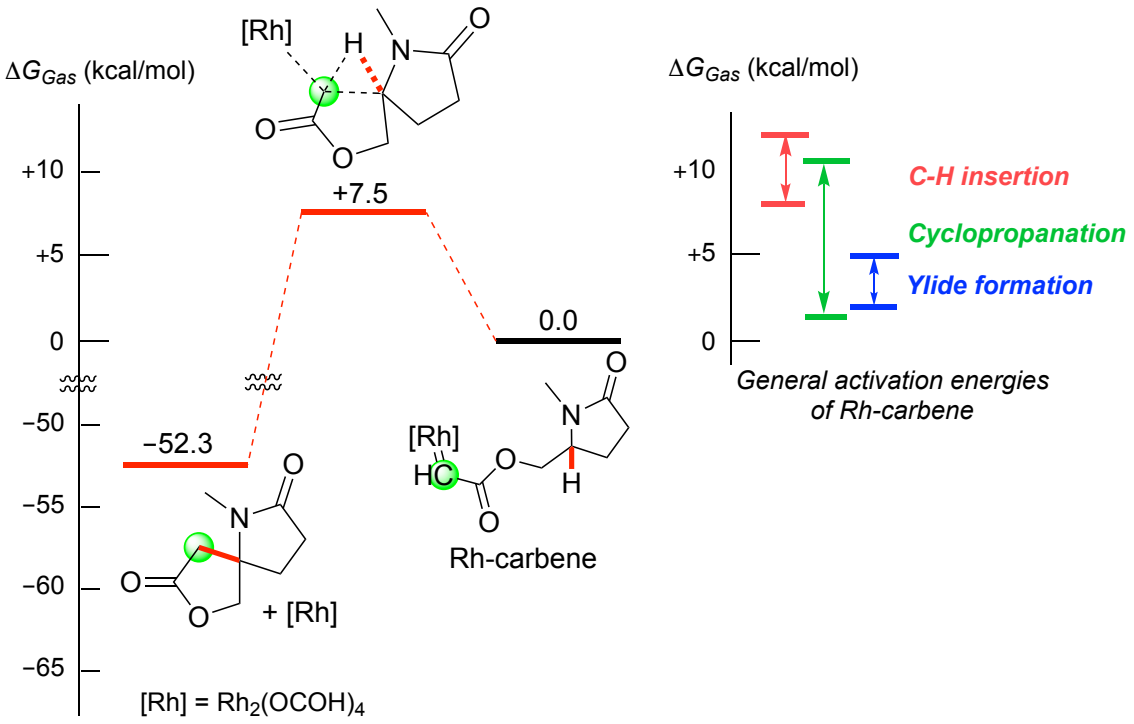
Figure 2-3. Activation energies for C－H insertion reaction of Rh-carbene and Rh-nitrene



2-4-3-3. ロジウムカルベンの他の反応経路の考察

C–H 挿入反応自体は異なる反応性の要因ではないと考えたため、ロジウムカルベンの他の反応経路も含めて考察した。ロジウムカルベンのそれぞれの反応について文献を調査した結果、Rh カルベンのイリド形成[7d,47]とシクロプロパン化[48]は一般的に C–H 挿入反応[26a,b]よりも低い活性化エネルギーで進行することがわかった（Figure 2-4）。

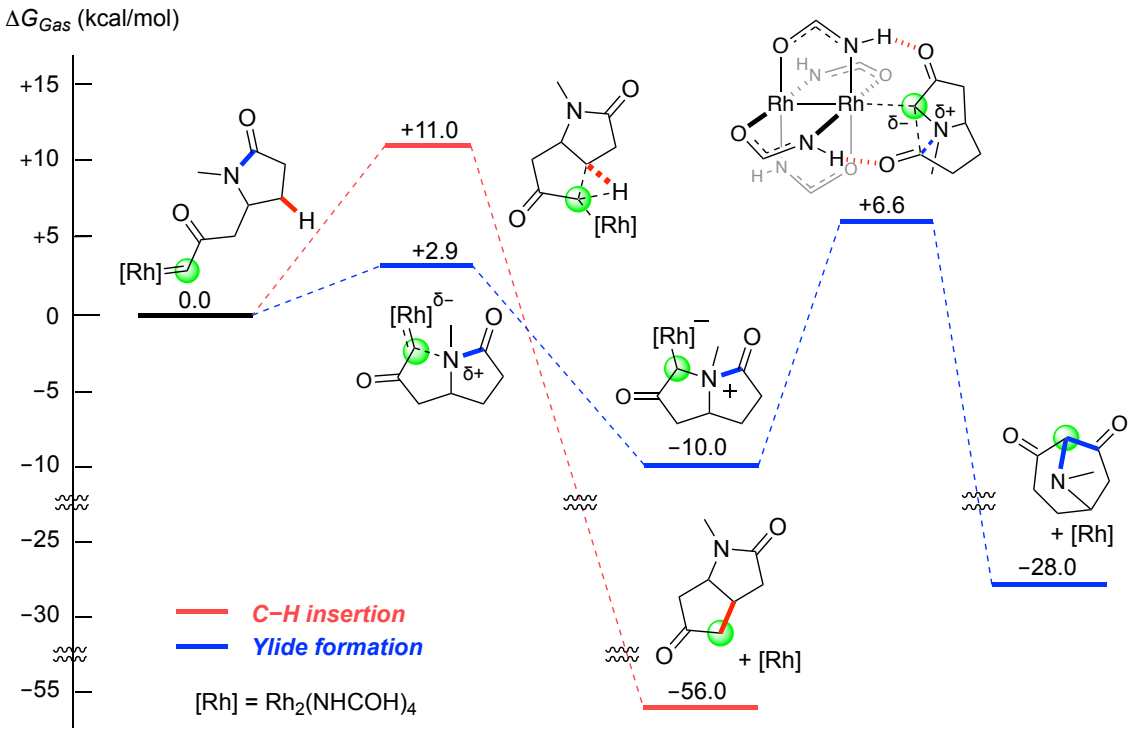
Figure 2-4. General activation energies of other reactions of Rh-carbene



この傾向はロジウムカルベンのアミド挿入反応に関する研究[47]の中でも見られた（Figure 2-5）。すなわち、イリド形成（アミド挿入反応の第一段階）は+2.9 kcal/mol という非常に低い活性化エネルギーで進行している一方で、C–H 挿入反応は約 8 kcal/mol も大きい活性化エネルギーが必要であると算出された。なお、この計算においても汎関数として RB3LYP、基底関数として 6-31G*（C,H,N,O）と LANL2DZ（Rh）を用いた。

したがって、ロジウムナイトレンとロジウムカルベンではイリド形成の活性化エネルギーが大きく異なっており、それが異なる反応性の原因であると考えられる。

Figure 2-5. Previous calculations on the reactions of Rh-carbene

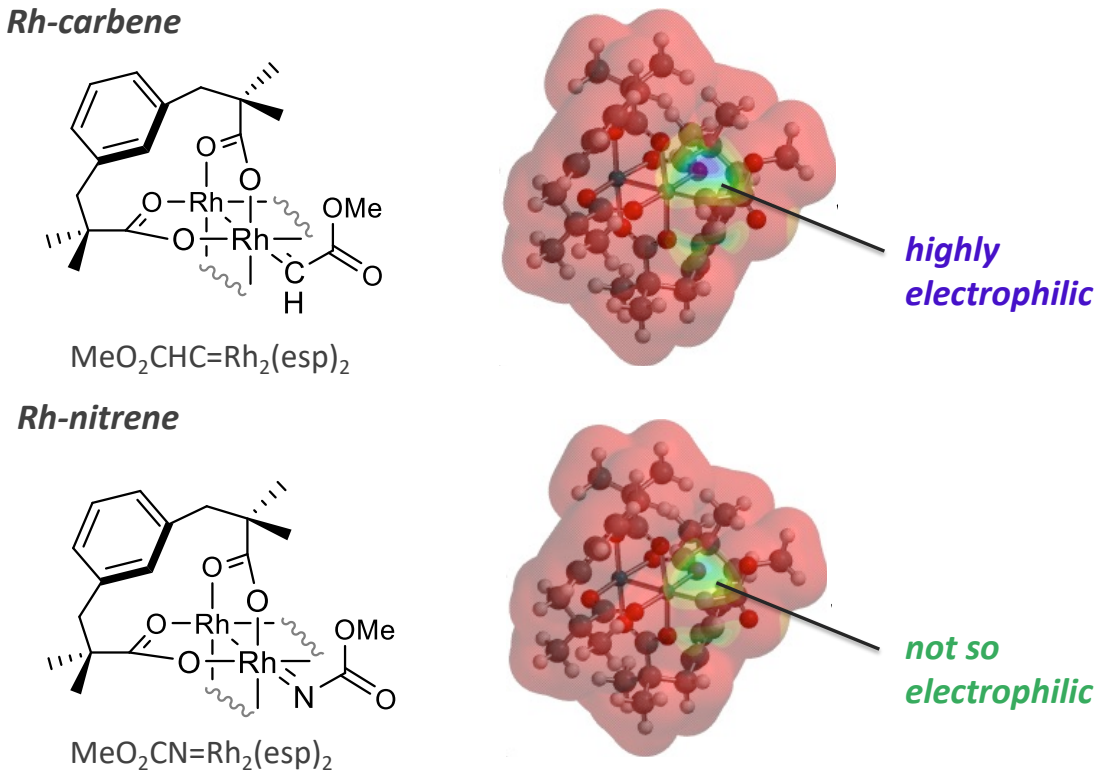


2-4-3-4. LUMO マップによる解析

更なる知見を得るため、LUMO マップを用いる解析を行った[49]。LUMO マップとは電子密度表面を LUMO の大小により彩色した図のことであり、青色が濃ければ濃いほどその部位の求電子性が高いことを示す。本計算では弱い電子的相互作用も厳密に計算するため、汎関数として ωB97X-D を用いている。基底関数は活性化エネルギーの計算と同様に、6-31G*（C,H,N,O）と LANL2DZ（Rh）を用いた。

計算で得られた図（Figure 2-6）から明らかなように、ロジウムカルベンは中心炭素が青く求電子性が高いと見積もられている一方で、ロジウムナイトレンの中心窒素は青くなっておらず求電子性が低い。したがって、ロジウムカルベンはヘテロ原子の求核攻撃によるイリド形成が円滑に進行するが、ロジウムナイトレンはその低い求電子性によってイリド形成を好まず、C–H 挿入反応を起こすと考えられる。

Figure 2-6. LUMO map analysis of Rh-nitrene and Rh-carbene



2-4-4. ロジウムナイトレンとロジウムカルベンが異なる反応性を示す要因

以上の実験的、計算化学的な解析により、ロジウムナイトレンとロジウムカルベンでは反応中心での求電子性が異なり、それによってヘテロ原子の求核攻撃で始まるイリド形成の活性化エネルギーが異なることが明らかとなった。これにより、ロジウムカルベンは求電子性が高いためイリド形成が容易に進行する一方、ロジウムナイトレンは求電子性が低いためヘテロ原子の中心窒素への求核攻撃には大きなエネルギーが必要となる。その結果、それぞれの化学種においてイリド形成と C–H 挿入反応との活性化エネルギーの関係が逆転し、異なる生成物を与えたと結論づけた。

第３部　ロジウムナイトレンのアミド挿入反応の開発

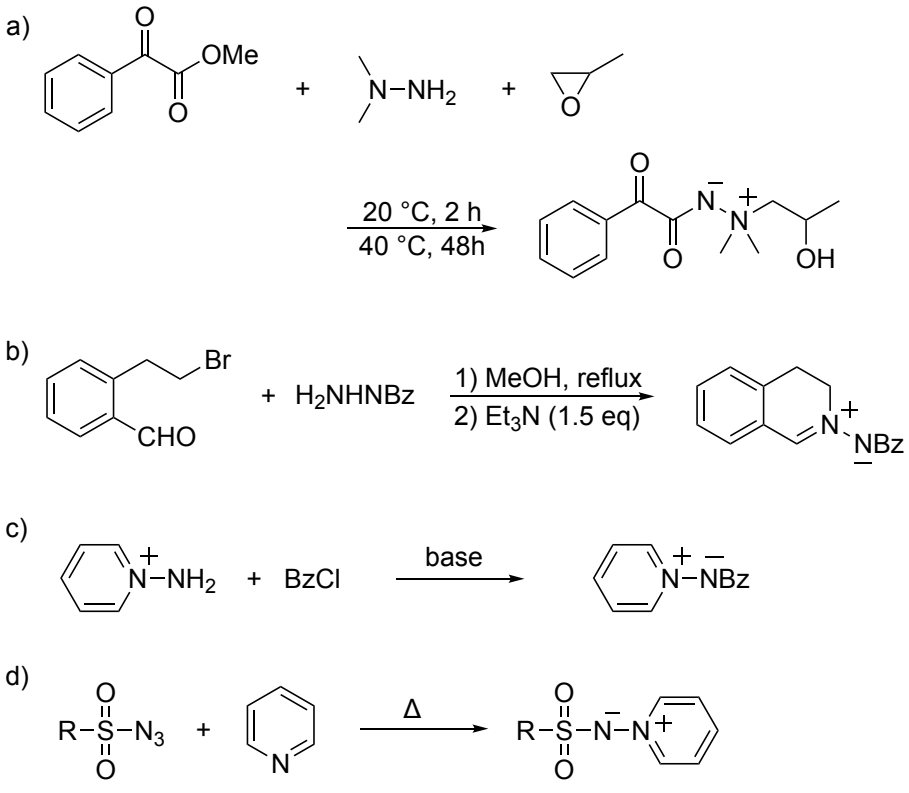
第１章　研究背景

3-1-1. N^+–N^-イリドの化学

金属カルベンと同様に金属ナイトレンと様々なヘテロ原子とのイリド形成が可能になれば、金属ナイトレンを用いる多様な結合形成反応が開発できる。

例えば、窒素原子の求核攻撃を受けると N^+–N^-イリドが生成するが、N^+–N^-イリドは通常の反応では達成できない構造変換のための有用中間体である。従来はヒドラジン誘導体から合成されることが多く（Scheme 3-1）、C–H 官能基化のための配向基や多重結合との環化反応の基質として用いられた[14a,c,50]。

Scheme 3-1. Previous methods for the preparation of N^+–N^- ylide



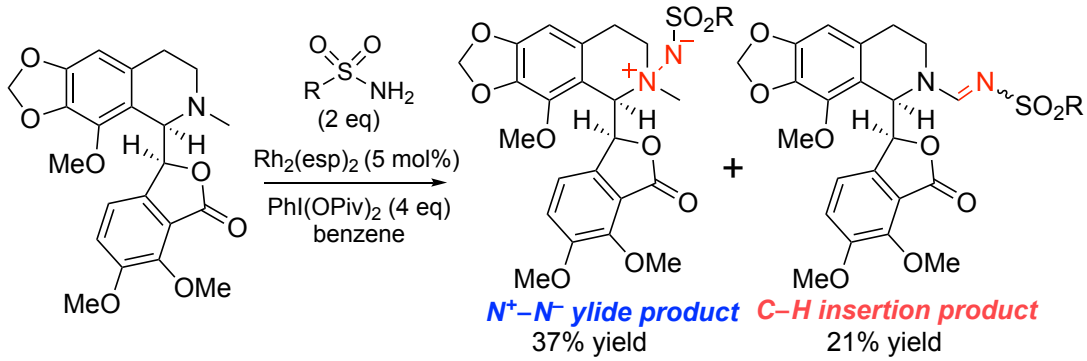
3-1-2. 金属ナイトレンのイリド形成

第 1 部第 4 章で述べた通り、金属ナイトレンのイリド化学に関する研究はほとんどない。また、求核的な窒素原子を用いた例しか報告がない点でも、さらなる研究が必要な分野である。

しかしながら第 2 部で明らかになったように、金属ナイトレンは金属カルベンに比べて反応中心の求電子性が低いためイリドを形成しづらい。これにより求核的なアミンを用いた例しか存在しないものと考えられる。また、金属ナイトレンの C–H 挿入反応の活性化エネルギーが金属カルベンの C－H 挿入反応よりも低い点[22a,51]も、イリド形成を難しくしている。例えば、Romo らは求核性が高い第 3 級アミンを用いているにも関わらず、N^{+}–N^{-} イリドの生成と共に C–H 挿入体が副生している（Scheme 3-2）[15]。

したがって、金属ナイトレンと求核性が低いアミド窒素とのイリド形成を高い選択性で進行させるのは不可能のように思える。

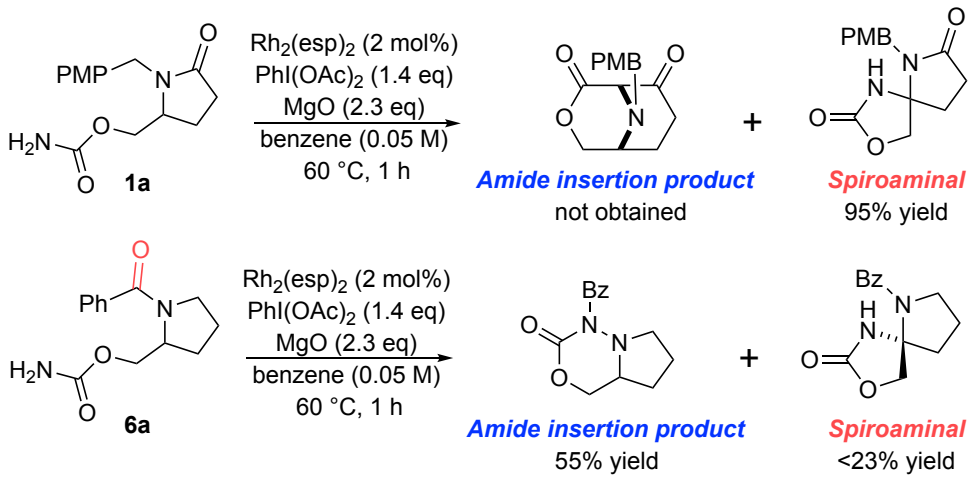
Scheme 3-2. Romo's report on N^{+}–N^{-} ylide formation



3-1-3. ロジウムナイトレンのアミド挿入反応

「1-5-2. ロジウムナイトレンのアミド挿入反応の発見」で述べた通り、スピロアミナール化反応の研究の中でカルボニル基を環外へと移した際に、意図せずロジウムナイトレンのアミド挿入反応を観測した（Scheme 3-3）。

Scheme 3-3. Discovery of amide insertion reaction of Rh-nitrene



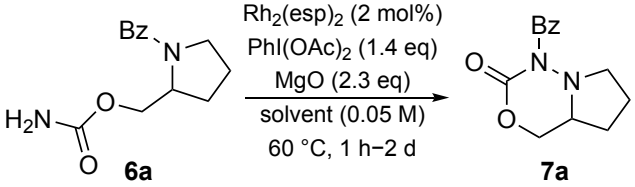
アミド挿入反応は金属ナイトレンの全く新しい反応性であり、その研究により金属ナイトレンの化学の発展に貢献できると考えた。また、本反応はロジウムナイトレンとアミド窒素とのイリド形成と続くアシル基の転移によって進行していると考えられるが、金属ナイトレンがアミド窒素のような求核性の低いヘテロ原子とイリドを形成した例はないため、詳細な反応機構解析も目的に研究に着手した。

第 2 章　反応条件の最適化

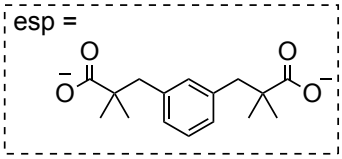
3-2-1. 溶媒の検討

カーバメート化合物 **6a** を用いて溶媒の検討を行った（Table 3-1）。触媒は $Rh_2(esp)_2$ 触媒、イミノヨージナン発生のための酸化剤は $PhI(OAc)_2$、添加剤として MgO を用いた。ヘキサフルオロベンゼンを用いた場合は基質と酸化剤が溶解しなかったために反応が進行しなかったが、他の溶媒中ではいずれも良好な収率で反応が進行した。特にベンゾトリフルオリドを用いた際に最も良い結果が得られたため（entry 7）、ベンゾトリフルオリドを最適溶媒とした。

Table 3-1. Study of solvent



entry	solvent	yield (%)
1	benzene	55
2	CH_2Cl_2	59
3	PhF	66
4	PhCl	66
5	^{i}PrOAc	53
6	C_6F_6	n.r.
7	$PhCF_3$	68

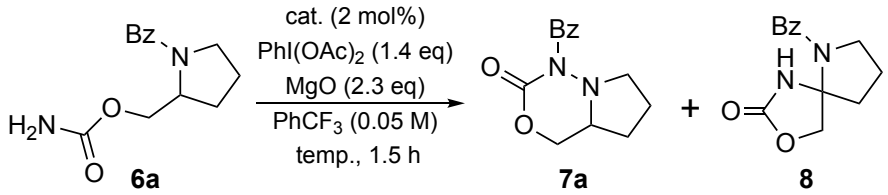


3-2-2. 触媒と反応温度の検討

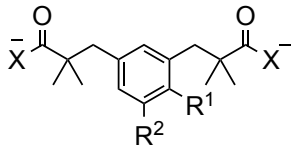
続いて触媒の検討を行った（Table 3-2）。ロジウムカルベンのアミド挿入反応における最適触媒、$Rh_2(NHCO^tBu)_4$ を用いた際はスピロアミナール **8** が主生成物として得られ、アミド挿入体 **7a** は 8%収率に留まった（entry 1）。二座のアミダート系配位子を有する $Rh_2(espn)_2Cl$[52] を用いた場合も同様の結果が得られた（entry 2）。しかしながら。カルボキシラート系ロジウム触媒である $Rh_2(OAc)_4$ を用いると生成物の選択性が逆転し、アミド挿入体 **7a** が主生成物として得られた（entry 3, 17% yield）。さらに、より嵩高い配位子を持つロジウム触媒を使用するに連れて生成物の選択性、収率ともに向上した(entries 4,5)（entry 5 は 0.2 mmol スケールで行っており、0.05 mmol スケールで行った Table 3-1 とは収率が異なっている）。反応温度を 80 ℃まで昇温するとアミド挿入体が単一の生成物として得られた（entry 6）。

酸化剤や反応の濃度についても検討を行ったが収率の改善には至らなかったため、$Rh_2(esp)_2$ の電子的チューニングを行った。その結果、esp 配位子にメトキシ基を導入した $Rh_2(esp\text{-}OMe)_2$ を用いることでアミド挿入体 **7a** の収率が 78%まで改善した（entry 8）。

Table 3-2. Optimization of the reaction conditions



entry	catalyst	temp.	yield (%)[a]	
			7a	**8**
1	$Rh_2(NHPiv)_4$	60 °C	8	38
2	$Rh_2(espn)_2Cl$	↓	9	36
3	$Rh_2(OAc)_4$	↓	17	7
4	$Rh_2(OCO^tBu)_4$	↓	36	6
5	$Rh_2(esp)_2$	↓	62	8
6	$Rh_2(esp)_2$	80 °C	71[b]	0
7	$Rh_2(esp\text{-}NO_2)_2$	↓	62[b]	0
8	$Rh_2(esp\text{-}OMe)_2$	↓	78[b]	0



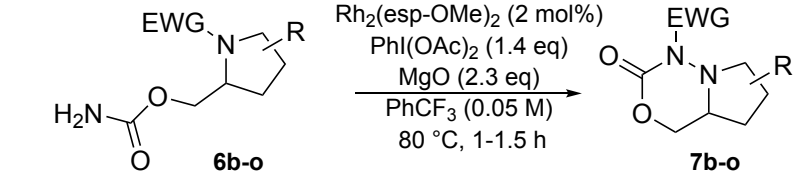
espn: $R^1 = R^2 = H$, X = NH
esp: $R^1 = R^2 = H$, X = O
esp-NO_2: $R^1 = NO_2$, $R^2 = H$, X = O
esp-OMe: $R^1 = H$, $R^2 = OMe$, X = O

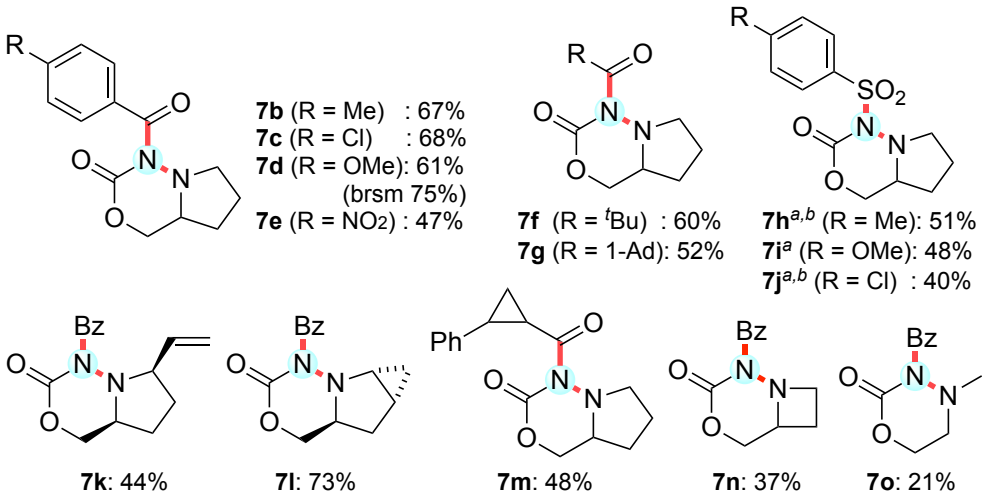
[a] Yield was determined by ^1H NMR analysis of the crude mixture using $CHPh_3$ as an internal standard.
[b] Isolated yield

アミダート系ロジウム触媒とカルボキシラート系ロジウム触媒で反応の選択性が逆転した理由として、活性なロジウム触媒の価数が異なる点が挙げられる。カルボキシラート系ロジウム触媒の 2 つのロジウム原子はどちらも二価であるが(Rh_2(II,II))、$Rh_2(espn)_2Cl$ の片方のロジウム原子は III 価であり（Rh_2(II,III)）、$Rh_2(NHCO^tBu)_4$ は反応開始直後に溶液が鮮やかな赤色となるため系中で酸化されて Rh_2(II,III)となっていると考えられる [18a]。片方のロジウム原子が III 価（Rh_2(II,III)）であるロジウムナイトレンは、非常に低い活性化エネルギーで C–H 挿入反応を起こすことが報告されているため [53]、entries 1,2 と entry3 以後で選択性が逆転したと考えられる。

最適条件下で様々な基質のアミド挿入反応を検討した（Table 3-3）。まず、ベンゾイル基のパラ位にメチル基、クロロ基、メトキシ基、ニトロ基を導入した基質を最適条件に付したところ、それぞれ対応するアミド挿入体に変換された（**7b**－**7e**, 47－68%）。アルキルアミドにも適用可能であった（**7f** (60%), **7g** (52%)）。また、触媒量と添加剤を増やす必要はあったものの、ロジウムナイトレンはスルホンアミドの S–N 結合へも挿入した（**7h**－**7j**, 40－51%）。分子内アジリジン化が進行し得るビニル基を有する基質 **6k** もアミド挿入体 **7k**（44%）に変換され、アミド窒素またはアミドカルボニル基の隣にラジカルクロックとしてシクロプロパンを有する基質でも、環の開裂を伴わずに反応が進行した（**7l**[44,54] (73%), **7m** (48%)）。また、アゼチジン環を持つ基質や鎖状の基質を用いた場合にも低収率ながら目的のアミド挿入体が得られた（**6n** (37%), **7o** (21%)）。

Table 3-3. Substrate scope of the amide insertion reaction of Rh-nitrene

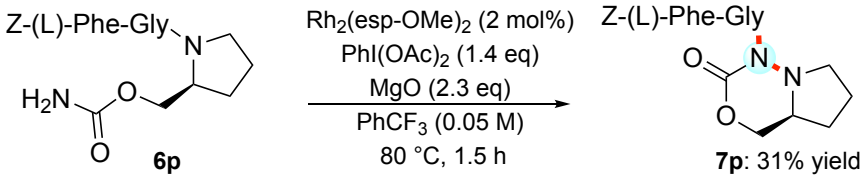




[a] 4 mol% Rh cat., 2.8 equiv. $PhI(OAc)_2$, and 4.6 equiv. MgO were used.　[b] Conducted at 60 °C

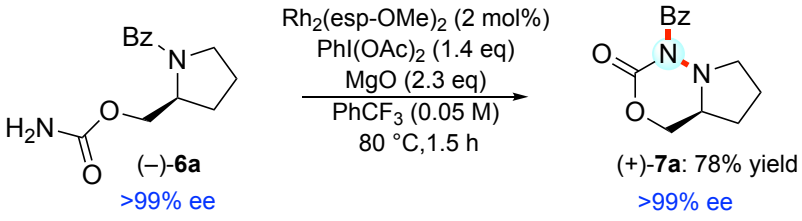
本アミド挿入反応は短いペプチド鎖を基質として用いた場合にも進行し、α-ヒドラジノアミド構造[55]を持つペプチド鎖の合成に成功した（**7p**, 31%）（Scheme 3-4）。α-ヒドラジノアミド構造は、プロテアソーム阻害物質[56]、抗菌物質[57]、生物活性物質[58]の探索研究においてしばしば用いられている。

Scheme 3-4. Application to peptide substrate



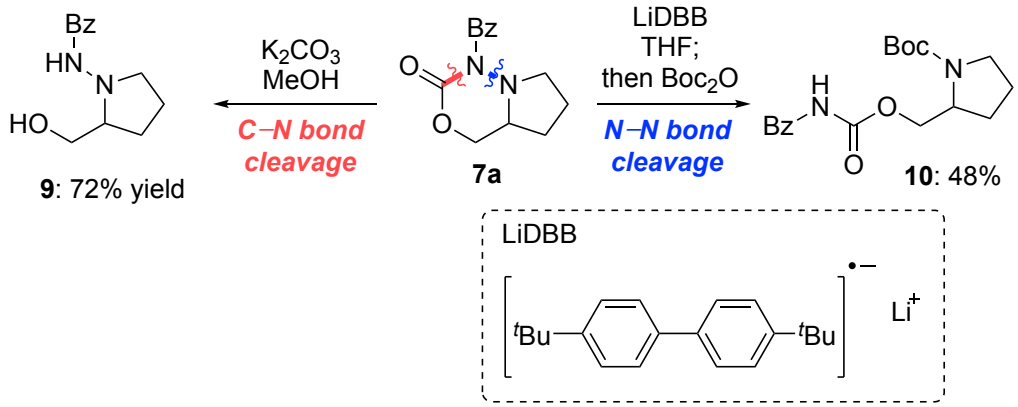
また、キラルな基質を用いた場合はキラルなアミド挿入体(+)-**7a**が得られた（Scheme 3-5）。

Scheme 3-5. Retention of the stereochemistry



アミド挿入体 **7a** には切断可能な結合がいくつかある。アミド挿入反応後の更なる化学選択的な変換を達成するために種々の条件を検討した結果、炭酸カリウムとメタノールで処理するとカーバメート構造の C–N が、一電子還元剤である LiDBB を用いると N–N 結合が選択的に切断できることが明らかとなった（Scheme 3-6）。N–N 結合切断後の化合物は精製のための分液操作中に水層に移行してしまったため、生じた第 2 級アミンを Boc 保護した後に単離している。

Scheme 3-6. Derivatization of amide insertion product

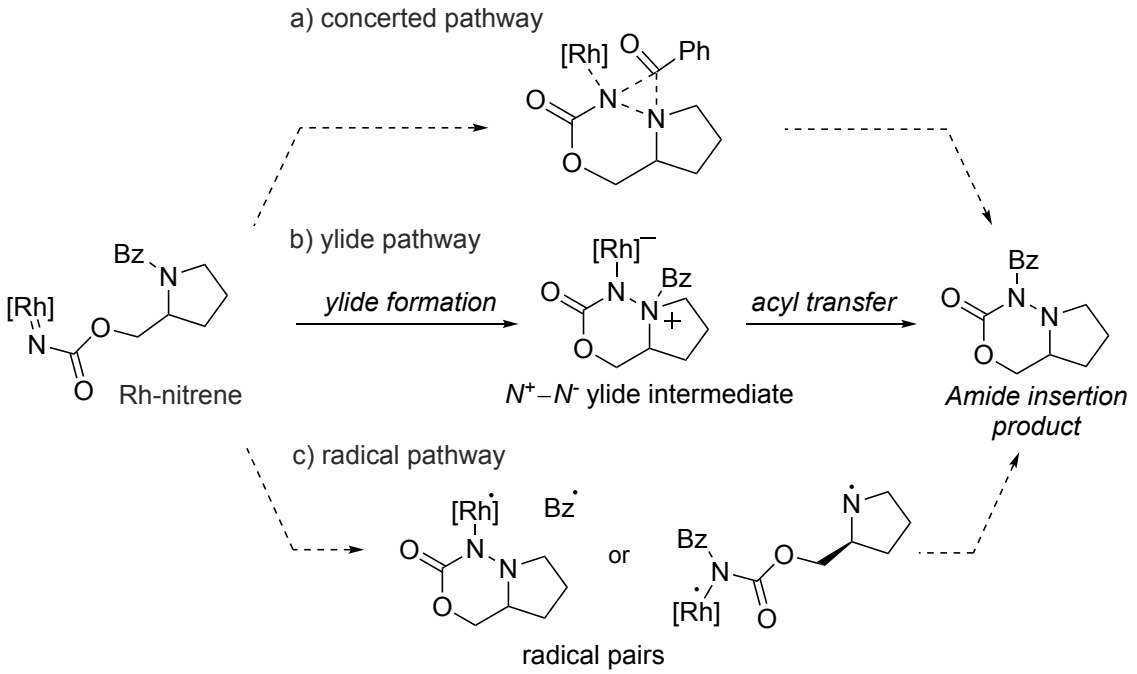


3-5. 考えられる 3 つの反応機構

本反応はロジウムカルベンのアミド挿入反応と同様にイリド中間体を経て進行していると考えられるが、研究背景で述べた通り、金属ナイトレンが求核性の弱いヘテロ原子とイリド形成をした例はない。そこで、他の反応経路で進行している可能性を考慮し、反応機構解析を行った。

考えられる反応機構は 3 つある（Scheme 3-7）。1 つ目は協奏機構であり、アミド C–N 結合の切断と同時に N–C（ナイトレンとアミドカルボニル基）結合と N–N（ナイトレンとアミド窒素）結合が一挙に形成される（a）。2 つ目はこれまでに述べてきたイリド中間体を経る経路であり、ロジウムナイトレンへのアミド窒素の求核攻撃によってイリド中間体が生成し、続くアシル基の転移によってアミド挿入体を与える（b）。3 つ目は三重項状態のロジウムナイトレン [59] からビラジカル中間体を経て進行するラジカル機構である（c）。

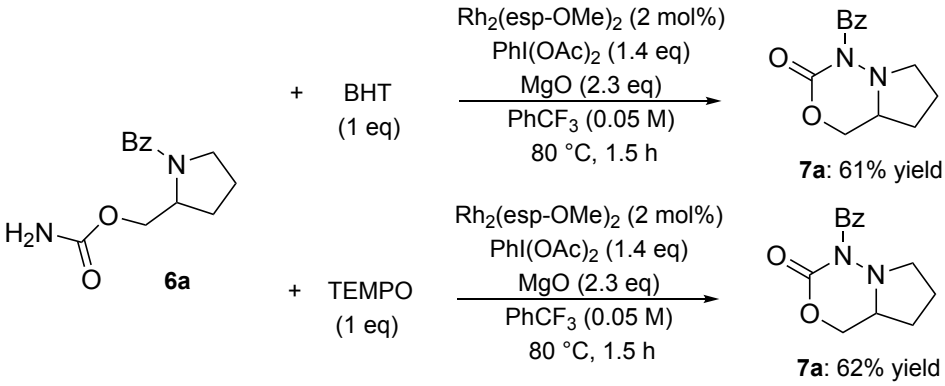
Scheme 3-7. Three possible reaction pathways of the amide insertion of Rh-nitrene



3-5-1. ラジカル機構に関する実験的な解析

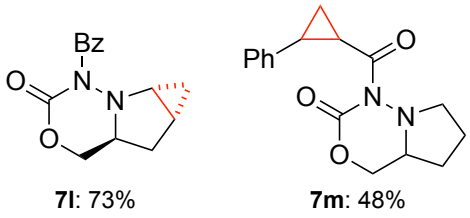
最適条件下、ラジカル捕捉剤として BHT や TEMPO を加えて **6a** のアミド挿入反応を行ったところ、大幅な収率の低下を伴うことなくアミド挿入反応が進行した（Scheme 3-8）。TEMPO と結合形成した副生成物も得られなかった [60]。

Scheme 3-8. Amide insertion reaction with radical trapping reagents



また、基質一般性の検討の中で、ラジカルクロックとしてシクロプロパン環を有する基質が環の開裂を伴わずにアミド挿入体に変換されたことも考慮し、ジラジカル中間体を経て進行している可能性は極めて低いと結論づけた（Figure 3-1）[61]。

Figure 3-1. Amide insertion products with cyclopropane ring



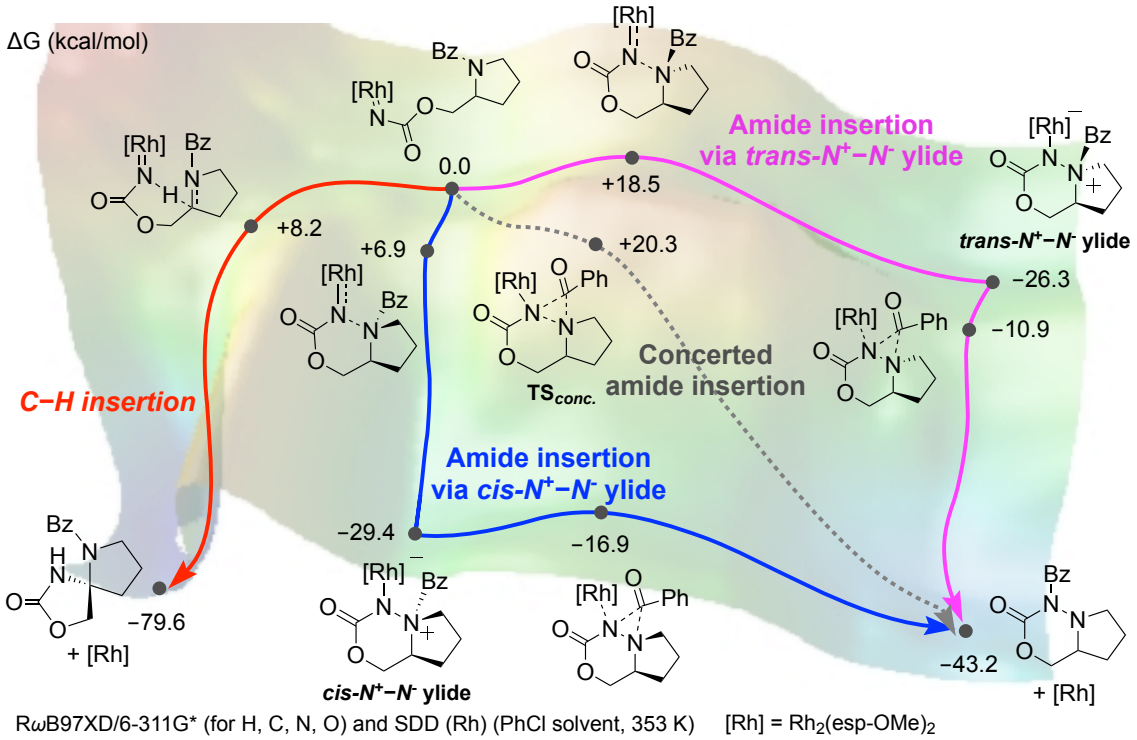
3-5-2. 協奏機構、イリド機構、C–H 挿入反応に関する量子化学計算

協奏機構とイリド機構を実験的に区別することは困難であったため、量子化学計算を用いて解析を行った（Figure 3-2）。

まずイリド機構について計算した。イリド中間体にはピロリジン環と新たに形成した 6 員環がシス縮環の *cis*-N^+–N^- イリドと、トランスに縮環している *trans*-N^+–N^- イリドが存在する。DFT 計算の結果、*cis* 縮環している *cis*-N^+–N^- イリドを中間体とする機構が最も小さい活性化エネルギーで進行することが明らかとなり（+6.9 kcal/mol）、続くアシル転移反応の活性化エネルギーも十分に低い値であった（+12.5 kcal/mol）。一方で *trans*-N^+–N^- イリドの形成には *cis*-N^+–N^- イリドよりも高い活性化エネルギー（+18.5 kcal/mol）が必要であり、続くアシル転移反応の活性化エネルギーも *cis*-N^+–N^- イリドのそれよりも高かった（+15.4 kcal/mol）。

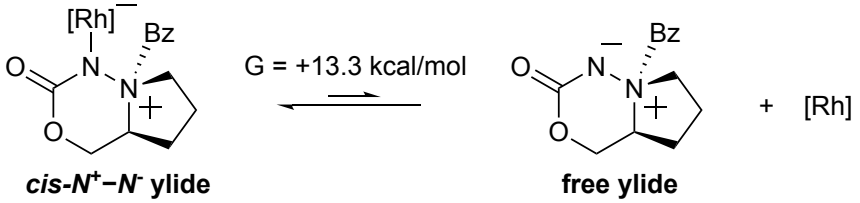
協奏機構の遷移状態の構造は計算によって求められなかったため、仮想の遷移状態構造（$TS_{conc.}$）のエネルギーを計算したところ、*cis*-N^+–N^- イリド形成よりも遥かに高い活性化エネルギーが必要だとわかった（+20.3 kcal/mol）。また、副反応である C–H 挿入反応の活性化エネルギーも *cis*-N^+–N^- イリド形成より大きい（+8.2 kcal/mol）ことを確認した。

Figure 3-2. Potential energy surface for the possible amide insertion reaction and the competing C－H insertion reaction



cis-N^+–N^-イリド形成後、ロジウム触媒が解離してからアシル基が転移する可能性も考えられる。しかしながら、ロジウム触媒との錯体形成が解消されるとエネルギー的に不利なN^+–N^-イリドが生じると算出されたため、アシル基の転移段階においてもロジウム触媒が近傍に位置していると考えられる（Figure 3-3）。

Figure 3-3. Dissociation energy of Rh associated *cis*-N^+–N^- ylide complex



3-5-3. ラジカル機構を否定する計算結果

ラジカル機構は実験的に否定されたものの、短寿命のラジカル中間体（$k_{react.}$ <1.3 x $10^{-8}$$s^{-1}$）を経て進行している可能性があるため、三重項状態のロジウムナイトレンの反応について計算を行った（Figure 3-4）。その結果、アミド挿入反応の 2 つの遷移状態（+62.4 kcal/mol、+54.2 kcal/mol）と C－H 挿入反応の遷移状態（+18.6 kcal/mol）は共に一重項状態よりも遥かに高いエネルギーであることが明らかとなった。

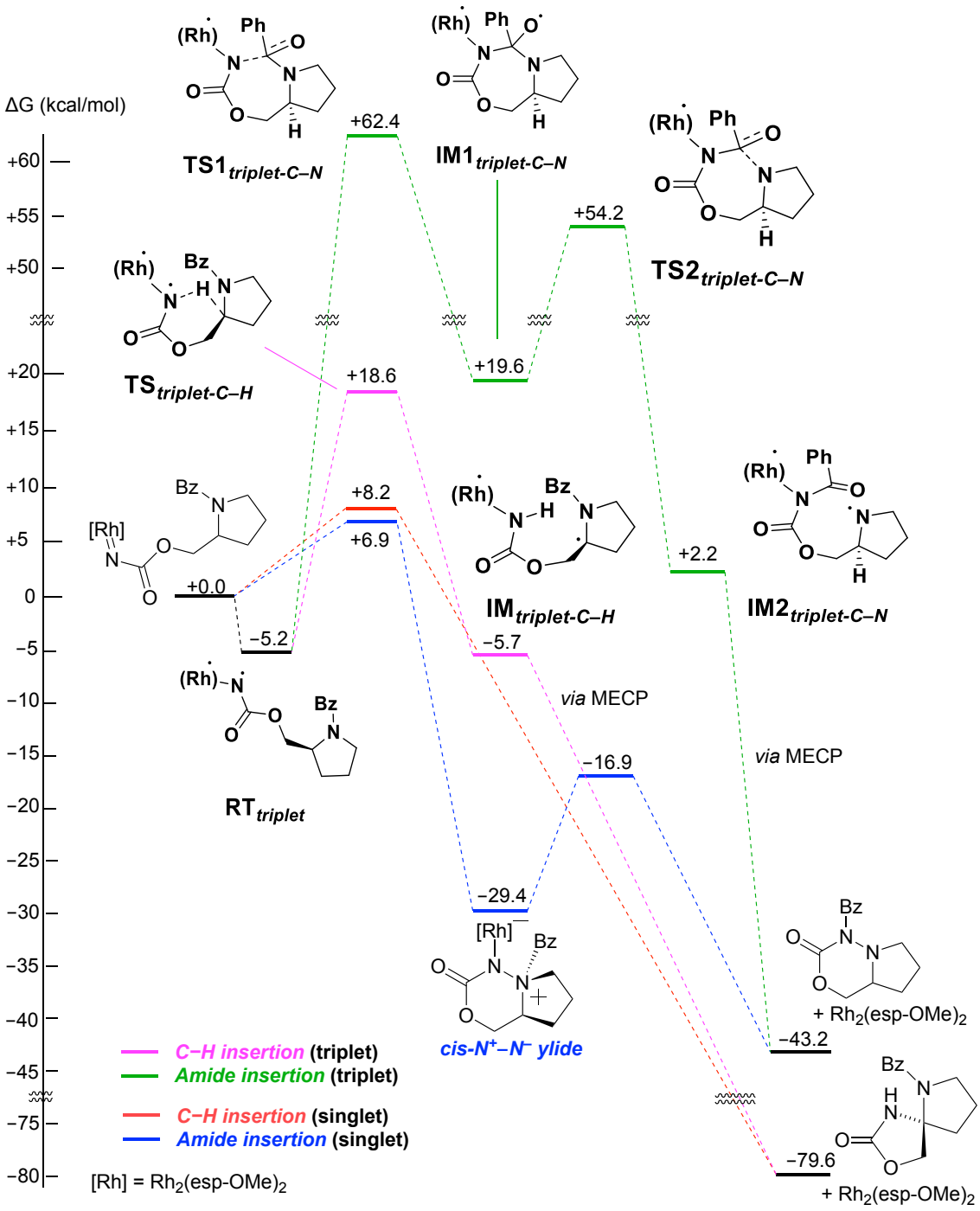
なお、本計算においては汎関数として UωB97XD、基底関数として 6-311+G*（C,H,N,O）と SDD（Rh）を用いている。

この結果より、ラジカル機構は完全に否定された。

3-5-4. 反応機構の決定

以上の実験的、計算化学的な解析により、ロジウムナイトレンのアミド挿入反応は *cis*-N^+–N^-イリド中間体の生成と続くアシル転移反応による段階的な反応機構で進行していると結論づけた。

Figure 3-4. Reaction coordinate diagram of the amide insertion and the C−H insertion reaction of triplet and singlet Rh-nitrene

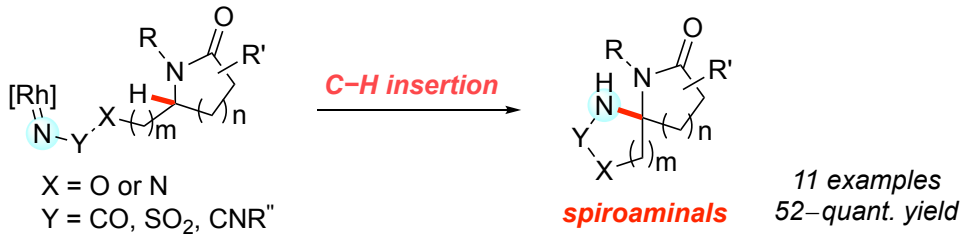


結語

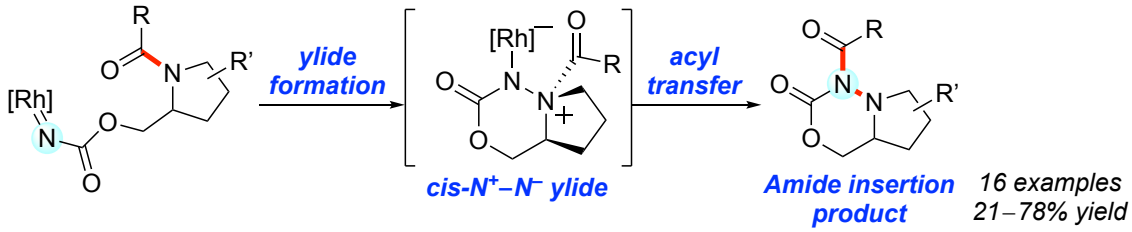
本博士論文は、以下に示す２つのロジウムナイトレンの新規挿入反応について纏めたものである。

まず、ロジウムナイトレンが高化学選択的にアミド窒素α位の C−H 結合へ挿入し、スピロアミナール骨格を与えることを見出した。本反応は基質の立体化学を保持して進行するため、従来法では困難であったキラルなスピロアミナールの直接的な合成が可能である。

また、金属ナイトレンと金属カルベンが異なる反応性を示す要因について実験と量子化学計算によって解析し、それぞれの化学種の反応中心における電子密度の違いによって異なる反応性を示していることを明らかにした。



さらに、上記の研究の中でロジウムナイトレンのアミド挿入を見出し、反応を開発すると共に詳細な反応機構解析を行った。その結果、ロジウムナイトレンのアミド挿入反応は *cis* 縮環している *cis*-$N^{+}-N$ イリド中間体の形成と続くアシル基の転移によって進行していることを明らかにした。本研究は金属ナイトレンと求核性が低いヘテロ原子とイリドを形成した初の例である。



実験の部

1. General information

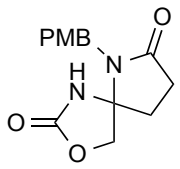
NMR spectra were recorded on a JEOL ecs 400 spectrometer. Chemical shifts in $CDCl_3$, were reported downfield from TMS (= 0 ppm) for ^1H NMR. Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, and br = broad), integration and coupling constants in Hz. For ^{13}C NMR, chemical shifts were reported in the scale relative to the solvent signal [$CHCl_3$ (77.0 ppm)] as an internal reference. ESI mass spectra were measured on JEOL AccuTOF LC-plus JMS-T100LP. Optical rotations were measured on a JASCO P-1020 polarimeter. The enantiomeric excess (ee) was determined by HPLC analysis. HPLC was performed on JASCO HPLC systems consisting of the following: pump, PU-980; detector, UV-970; column DAICEL CHIRALPAK AD-H, DAICEL CHIRALCEL OJ-H; mobile phase, *n*-hexane/*i*-PrOH. Melting points were measured with a SIBATA NEL-270 melting point apparatus. Analytical thin layer chromatography was performed on Kieselgel 60F254, 0.25 mm thickness plates. Column chromatography was performed with silica gel 60 N (spherical, neutral 40-50 mesh). Reactions were conducted in dry solvent. Other reagents were purified by the usual methods.

2. Rh-Catalyzed Stereospecific C－H Amination for the Construction of Spiroaminal Cores: Reactivity Difference between Nitrenoid and Carbenoid Species against Amide Functionality

2-1. Characterization of spiroaminals 2a－2k

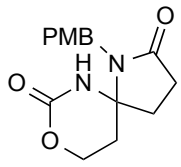
General procedure A for the C－H insertion reaction

A primary carbamate substrate (0.2 mmol), $PhI(OAc)_2$ (0.28 mmol, 1.4 eq, 90.2 mg), MgO (0.46 mmol, 2.3 eq, 18.5 mg), and $Rh_2(esp)_2$ (4 μmol, 2 mol%, 3.0 mg) were suspended in benzene (0.05 M, 4 mL), and the whole was stirred for 1 h at 60 ℃. After complete consumption of the starting material, the reaction mixture was concentrated under reduced pressure. The crude residue was purified by flash chromatography on silica gel to afford a spiroaminal.



6-(4-Methoxybenzyl)-3-oxa-1,6-diazaspiro[4.4]nonane-2,7-dione (2a)

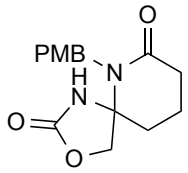
Prepared according to the general procedure A and isolated as white solid in 95% yield (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): mp 134－136 ℃; R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.21-2.38 (m, 2H), 2.44-2.62 (m, 2H), 3.79 (s, 3H), 4.15 (d, J = 10.0 Hz, 1H), 4.22 (d, J = 10.0 Hz, 1H), 4.24 (d, J = 15.2 Hz, 1H), 4.57 (d, J = 15.2 Hz, 1H), 5.87 (s, 1H), 6.84 (d, J = 8.4 Hz, 2H), 7.27 (d, J = 8.4 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 28.6, 32.1, 42.1, 55.3, 73.3, 79.0, 114.2, 129.3, 129.4, 157.4, 159.2, 173.5; IR (ATR) ν 3254, 2925, 1761, 1683, 1513, 1387, 1246, 1033 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{14}H_{16}N_2NaO_4^+$ m/z 299.1002, found m/z 299.0997.



1-(4-Methoxybenzyl)-8-oxa-1,6-diazaspiro[4.5]decane-2,7-dione (2b)

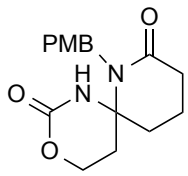
Prepared according to the general procedure A using 4 mol% catalyst in *i*PrOAc for 3 h and isolated as a pale yellow oil in 81% yield (column condition; gradient elution: EtOAc →

EtOAc/MeOH, 10/1): R_f = 0.1 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.72 (d, J = 14.0 Hz, 1H), 2.09 (m, 1H), 2.17-2.27 (m, 2H), 2.48 (ddd, J = 16.8, 8.0, 8.0 Hz, 1H), 2.63 (ddd, J = 16.8, 8.8, 6.4 Hz, 1H), 3.78 (s, 3H), 4.13-4.27 (m, 3H), 4.60 (d, J = 15.2 Hz, 1H), 6.40 (s, 1H), 6.84 (d, J = 8.8 Hz, 2H), 7.21 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 28.3, 31.3, 35.2, 42.0, 55.2, 63.0, 75.8, 114.1, 128.9, 129.9, 153.7, 158.9, 173.8; IR (ATR) ν 3249, 2926, 1679, 1513, 1396, 1287, 1244, 1175 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{15}H_{18}N_2NaO_4^+$ *m/z* 313.1159, found *m/z* 313.1171.



6-(4-Methoxybenzyl)-3-oxa-1,6-diazaspiro[4.5]decane-2,7-dione (2c)

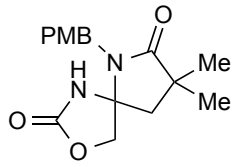
Prepared according to the general procedure A and isolated as a pale yellow oil in 97% yield (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.80 (m, 1H), 1.89 (m, 1H), 2.07-2.15 (m, 2H), 2.54 (d, J = 6.4 Hz, 1H), 2.55 (d, J = 7.2 Hz, 1H), 3.78 (s, 3H), 4.19 (d, J = 10.0 Hz, 1H), 4.34 (d, J = 10.0 Hz, 1H), 4.49 (d, J = 15.2 Hz, 1H), 4.67 (d, J = 15.2 Hz, 1H), 6.04 (s, 1H), 6.83 (d, J = 8.8 Hz, 2H), 7.21 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 16.7, 32.1, 36.8, 44.2, 55.2, 74.0, 75.8, 114.0, 128.4, 130.5, 157.4, 158.7, 170.5; IR (ATR) ν 3245, 2953, 1762, 1633, 1513, 1442, 1388, 1246 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{15}H_{18}N_2NaO_4^+$ *m/z* 313.1159, found *m/z* 313.1156.



7-(4-Methoxybenzyl)-3-oxa-1,7-diazaspiro[5.5]undecane-2,8-dione (2d)

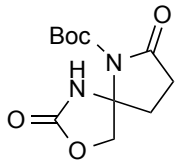
Prepared according to the general procedure A using 4 mol% catalyst in *i*PrOAc for 3 h and isolated as yellow solid in 65% yield (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): mp 181−183 °C; R_f = 0.1 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.72-1.98 (m, 3H), 1.99-2.14 (m, 2H), 2.25 (ddd, J = 14.4, 11.2, 6.0 Hz, 1H), 2.54 (m, 2H), 3.77 (s, 3H), 4.12-4.24 (m, 2H), 4.31 (d, J = 16.0 Hz, 1H), 4.70 (d, J = 16.0 Hz, 1H), 6.71 (s, 1H), 6.82 (d, J = 8.8 Hz, 2H), 7.13 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 15.9, 31.3, 32.2, 36.9, 44.3, 55.2, 63.1, 72.6, 113.9, 128.0, 130.6, 153.9, 158.4, 171.0; IR (ATR) ν

3254, 2954, 1701, 1635, 1512, 1393, 1315, 1245 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{20}N_2NaO_4^+$ *m/z* 327.1315, found *m/z* 327.1308.



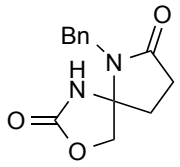
6-(4-Methoxybenzyl)-8,8-dimethyl-3-oxa-1,6-diazaspiro[4.4]nonane-2,7-dione (2e)

Prepared according to the general procedure A and isolated as a yellow oil in 87% yield (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): R_f = 0.5 (EtOAc); ^1H NMR (400 MHz, $CDCl_3$) δ 1.21 (s, 3H), 1.27 (s, 3H), 2.10 (d, J = 13.6 Hz, 1H), 2.22 (d, J = 13.6 Hz, 1H), 3.78 (s, 3H), 4.13 (d, J = 10.0 Hz, 1H), 4.17 (d, J = 10.0 Hz, 1H), 4.24 (d, J = 14.8 Hz, 1H), 4.55 (d, J = 14.8 Hz, 1H), 6.08 (s, 1H), 6.84 (d, J = 8.8 Hz, 2H), 7.25 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 25.6, 26.0, 39.4, 42.2, 47.9, 55.2, 74.1, 76.3, 114.2, 129.3, 129.6, 157.4, 159.2, 178.4; IR (ATR) ν 3249, 2963, 1765, 1675, 1513, 1437, 1388, 1246 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{20}N_2NaO_4^+$ *m/z* 327.1315, found *m/z* 327.1313.



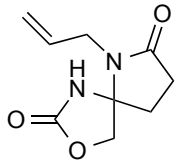
tert-Butyl 2,7-dioxo-3-oxa-1,6-diazaspiro[4.4]nonane-6-carboxylate (2f)

Prepared according to the general procedure A using 4 mol% catalyst in *i*PrOAc for 2.5 h and isolated as a colorless oil in 69% yield (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): R_f = 0.2 (EtOAc); ^1H NMR (400 MHz, $CDCl_3$) δ 1.55 (s, 9H), 2.22 (m, 1H), 2.38-2.51 (m, 2H), 2.72 (ddd, J = 18.4, 10.0, 10.0 Hz, 1H), 4.34 (d, J = 9.6 Hz, 1H), 4.69 (d, J = 9.6 Hz, 1H), 7.14 (br s, 1H); ^{13}C NMR (100MHz, $CDCl_3$) δ 27.9, 30.0, 33.2, 74.7, 78.2, 85.5, 148.8, 157.7, 172.7; IR (ATR) ν 3303, 2982, 1747, 1534, 1397, 1370, 1300 cm^{-1}; HRMS (ESI-TOF) $[2M + Na]^+$ calcd for $C_{22}H_{32}N_4NaO_{10}^+$ *m/z* 535.2011, found *m/z* 535.2012.



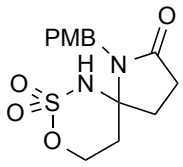
6-Benzyl-3-oxa-1,6-diazaspiro[4.4]nonane-2,7-dione (2g)

Prepared according to the general procedure A and isolated as a colorless oil in quantitative yield (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.23 (ddd, J = 14.0, 9.6, 8.0 Hz, 1H), 2.36 (ddd, J = 14.0, 9.6, 4.4 Hz, 1H), 2.47 (ddd, J = 17.2, 9.6, 4.4 Hz, 1H), 2.61 (ddd, J = 17.2, 9.6, 8.0 Hz, 1H), 4.12 (d, J = 10.0 Hz, 1H), 4.18 (d, J = 10.0 Hz, 1H), 4.21 (d, J = 15.2 Hz, 1H), 4.67 (d, J = 15.2 Hz, 1H), 6.71 (s, 1H), 7.27-7.35 (m, 5H); ^{13}C NMR (100MHz, $CDCl_3$) δ 28.6, 32.1, 42.6, 73.2, 79.0, 127.9 (2C), 128.9, 137.3, 157.4, 173.7; IR (ATR) ν 3244, 2924, 1759, 1679, 1437, 1386, 1234, 1163 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{13}H_{14}N_2NaO_3^+$ *m/z* 269.0897, found *m/z* 269.0896.



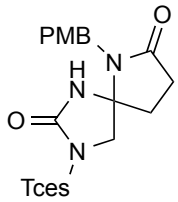
6-Allyl-3-oxa-1,6-diazaspiro[4.4]nonane-2,7-dione (2h)

Prepared according to the general procedure A and isolated as a colorless oil in 92% yield (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): R_f = 0.1 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.26 (ddd, J = 13.6, 10.0, 8.0 Hz, 1H), 2.36-2.47 (m, 2H), 2.59 (ddd, J = 18.0, 10.0, 8.8 Hz, 1H), 3.83 (dd, J = 16.0, 6.4 Hz, 1H), 3.93 (dd, J = 16.0, 5.2 Hz, 1H), 4.27 (d, J = 10.0 Hz, 1H), 4.52 (d, J = 10.0 Hz, 1H), 5.17 (dd, J = 10.0, 1.2 Hz, 1H), 5.25 (dd, J = 17.2, 1.2 Hz, 1H), 5.84 (dddd, J = 17.2, 10.0, 6.4, 5.2 Hz, 1H), 7.18 (s, 1H); ^{13}C NMR (100MHz, $CDCl_3$) δ 28.6, 32.0, 41.8, 73.3, 79.0, 117.9, 132.9, 157.6, 173.5; IR (ATR) ν 3259, 2928, 1759, 1683, 1388, 1234, 1040 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_9H_{12}N_2NaO_3^+$ *m/z* 219.0740, found *m/z* 219.0741.



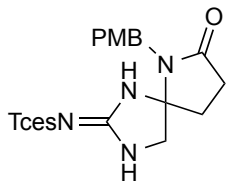
1-(4-Methoxybenzyl)-8-oxa-7-thia-1,6-diazaspiro[4.5]decan-2-one 7,7-dioxide (2i)

Prepared according to the general procedure A and isolated as yellow oil in 81% yield (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.60 (dd, J = 14.8, 2.0 Hz, 1H), 1.93 (ddd, J = 13.2, 9.2, 9.2 Hz, 1H), 2.43-2.55 (m, 2H), 2.68 (ddd, J = 17.6, 9.2, 9.2 Hz, 1H), 3.06 (ddd, J = 13.2, 9.2, 2.8 Hz, 1H), 3.79 (s, 3H), 4.47 (d, J = 15.6 Hz, 1H), 4.51 (ddd, J = 12.4, 5.2, 2.0 Hz, 1H), 4.57 (ddd, J = 12.4, 12.4, 2.0 Hz, 1H), 4.65 (ddd, J = 12.4, 12.4, 2.0 Hz, 1H), 4.93 (s, 1H), 6.76 (d, J = 8.4 Hz, 2H), 7.22 (d, J = 8.4 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 28.2, 30.3, 33.1, 42.0, 55.3, 66.9, 80.5, 114.5, 128.9, 129.0, 159.3, 175.7; IR (ATR) ν 3145, 2938, 1652, 1513, 1439, 1408, 1294, 1247 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{18}N_2NaO_5S^+$ *m/z* 349.0829, found *m/z* 349.0837.



2,2,2-Trichloroethyl 6-(4-methoxybenzyl)-2,7-dioxo-1,3,6-triazaspiro-[4.4]nonane-3-sulfonate (2j)

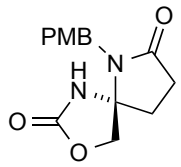
Prepared according to the general procedure A and isolated as a colorless oil in 70% yield (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): R_f = 0.2 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.32 (m, 1H), 2.48-2.58 (m, 2H), 2.70 (m, 1H), 3.80 (s, 3H), 4.11 (d, J = 11.2 Hz, 1H), 4.24 (d, J = 10.8 Hz, 1H), 4.37 (d, J = 10.8 Hz, 1H), 4.65 (d, J = 11.2 Hz, 1H), 4.70 (d, J = 11.2 Hz, 1H), 4.73 (d, J = 11.2 Hz, 1H), 6.86 (d, J = 8.8 Hz, 2H), 7.22 (d, J = 8.8 Hz, 2H), 7.94 (br s, 1H); ^{13}C NMR (100MHz, $CDCl_3$) δ 28.2, 31.2, 42.4, 55.3, 74.6, 78.7, 81.4, 93.6, 114.5, 128.4, 129.2, 159.5, 161.0, 173.4; IR (ATR) ν 3215, 2925, 1697, 1615, 1513, 1352, 1247, 1173 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{16}H_{18}Cl_3N_3NaO_6S^+$ *m/z* 507.9874, found *m/z* 507.9864.



2,2,2-Trichloroethyl (6-(4-methoxybenzyl)-7-oxo-1,3,6-triazaspiro[4.4]-nonan-2-ylidene)sulfamate (2k)

Prepared according to the general procedure A using 6 mol% catalyst in benzene for 24 h and isolated as a colorless oil in 52% yield (column condition; gradient elution: EtOAc →

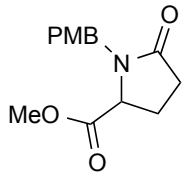
EtOAc/MeOH, 10/1): R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) (major rotamer) δ 2.28 (m, 1H), 2.44-2.55 (m, 2H), 2.69 (m, 1H), 3.51 (d, J = 11.2 Hz, 1H), 3.54 (d, J = 11.2 Hz, 1H), 3.77 (s, 3H), 4.07 (d, J = 15.2 Hz, 1H), 4.62 (s, 2H), 4.68 (d, J = 15.2 Hz, 1H), 6.61 (br s, 1H), 6.83 (d, J = 8.8 Hz, 2H), 7.24 (d, J = 8.8 Hz, 2H), 7.29 (br s, 1H); ^{13}C NMR (100MHz, $CDCl_3$) δ 28.5, 33.0, 42.3, 52.7, 55.3, 77.9, 80.5, 94.0, 114.2, 129.2 (2C), 159.0, 150.3, 173.5; IR (ATR) ν 3235, 2924, 1684, 1607, 1512, 1245, 1166, 1021 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{19}Cl_3N_4NaO_5S^+$ m/z 507.0034, found m/z 507.0017.



(*S*)-6-(4-Methoxybenzyl)-3-oxa-1,6-diazaspiro[4.4]nonane-2,7-dione ((–)-2a)

Prepared according to the general procedure A for the synthesis of **2a** and isolated as white powder: mp 146−148 °C; $[\alpha]^{20}_D$ − 24.2° (c 1, $CHCl_3$). The enantiomeric excess was determined to be >99% by analytical chiral HPLC. Thirteen min, 16 min (AD-H column, 85/15 n-hexane/iPrOH, 1 mL/min, 254 nm).

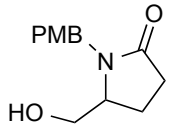
2-2. Synthesis and characterization of substrates



Methyl 1-(4-methoxybenzyl)-5-oxopyrrolidine-2-carboxylate (s1a)

To a stirred solution of methyl 5-oxopyrrolidine-2-carboxylate (20 mmol, 2.3 mL) in DMF (0.3 M, 67 mL) was added NaH (22 mmol, 1.1 eq, 880 mg) at 0 ℃. After being stirred for 30 min at 0 ℃, PMBCl (22 mmol, 1.1 eq, 2.8 mL) and TBAI (2 mmol, 0.1 eq, 738 mg) were added, and the reaction mixture was stirred for 17.5 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with toluene, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 1/1) to afford **s1a** as a colorless oil (3.1 g, 51% yield).

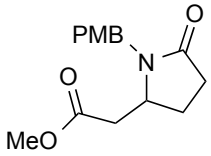
^1H and ^{13}C NMR, IR, and MS were identical to those reported.[62]



5-(Hydroxymethyl)-1-(4-methoxybenzyl)pyrrolidin-2-one (s2a)

To a stirred solution of **s1a** (12 mmol, 3.1 g) in THF (0.2 M, 60 mL) was added $LiBH_4$ (14 mmol, 1.2 eq, 312 mg) at 0 ℃. After being stirred at room temperature for 5 h, the reaction was quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (gradient elution: EtOAc → EtOAc/MeOH, 10/1) to afford **s2a** as a white solid (2.6 g, 91% yield).

^1H and ^{13}C NMR, IR, and MS were identical to those reported.[63]

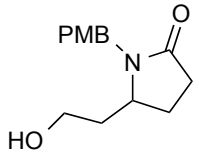


Methyl 2-(1-(4-methoxybenzyl)-5-oxopyrrolidin-2-yl)acetate (s1b)

To a stirred solution of triethyl phosphonoacetate (10.8 mmol, 1.8 eq, 2.1 mL) in THF (0.2 M, 30 mL) was added NaH (12 mmol, 2 eq, 480mg) at 0 ℃, and the stirring was continued

for 30 min. To the stirred suspension was added 5-hydroxy-1-(4-methoxybenzyl)pyrrolidin-2-one[64] (6 mmol, 1.33 g) , and the reaction mixture was stirred for 36 h at room temperature. Then 10% NaOH aq. (8 mL) and MeOH (8 mL) were added and stirred for additional 1 h. The reaction mixture was acidified with 1 N HCl aq. and extracted with Et_2O, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The resulting white powder was washed with Et_2O to give a crude carboxylic acid, which is used in the next step without further purification.

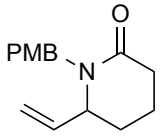
To a suspension of the crude carboxylic acid in CH_2Cl_2 (1 M, 5 mL) was added $(COCl)_2$ (6.5 mmol, 1.3 eq, 0.56 mL) at room temperature, and the reaction mixture was stirred for 15 min before adding MeOH (5 mL). After being stirred at room temperature for 15 min, the reaction mixture was concentrated under reduced pressure. The crude product was purified by flash chromatography on silica gel (gradient elution: *n*-hexane/EtOAc 1/1 → EtOAc) to afford **s1b** as a colorless oil (1.4496 g, 87% yield, 2 steps): R_f = 0.2 (*n*-hexane/EtOAc 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.79 (m, 1H), 2.21 (m, 1H), 2.30-2.45 (m, 2H), 2.51 (m, 1H), 2.65 (dd, J = 15.2, 4.0 Hz, 1H), 3.65 (s, 3H), 3.80 (s, 3H), 3.85 (m, 1H), 4.00 (d, J = 15.2 Hz, 1H), 4.83 (d, J = 15.2 Hz, 1H), 6.85 (d, J = 8.8 Hz, 2H), 7.16 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 24.4, 29.7, 37.9, 43.8, 51.8, 53.9, 55.2, 114.0, 128.5, 129.1, 159.0, 170.9, 174.8; IR (ATR) ν 2951, 1732, 1634, 1511, 1458, 1440 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{15}H_{19}NNaO_4^+$ *m/z* 300.1206, found *m/z* 300.1203.



5-(2-Hydroxyethyl)-1-(4-methoxybenzyl)pyrrolidin-2-one (s2b)

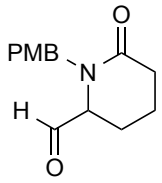
To a stirred solution of **s1b** (2.8 mmol, 785 mg) in THF (0.2 M, 14 mL) was added $LiBH_4$ (8.4 mmol, 3.0 eq, 185 mg) at 0 ℃. After being stirred at room temperature for 47 h, the reaction was quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (gradient elution: EtOAc → EtOAc/MeOH, 10/1) to afford **s2b** as a white solid (651 mg, 92% yield).

^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[65]



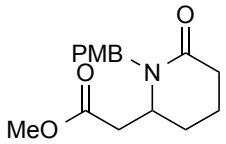
1-(4-Methoxybenzyl)-6-vinylpiperidin-2-one (s3)

To a solution of 6-vinylpiperidin-2-one[66] (1.9 mmol, 234.6 mg) in THF (0.13 M, 14.6 mL) was added NaH (2.5 mmol, 1.3 eq, 100 mg) at 0 ℃, and the stirring was continued for 30 min. To the stirred suspension were added PMBCl (2.3 mmol, 1.2 eq, 0.31 mL) and tetrabutylammonium iodide (0.19 mmol, 0.1 eq, 70.2 mg). After the reaction mixture was stirred for 3 h at 60 ℃, the reaction was cooled to room temperature, quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 2/1) to afford **s3** as a colorless oil (411.8 mg, 90% yield): R_f = 0.3 (*n*-hexane /EtOAc, 2/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.64-1.74 (m, 2H), 1.75-1.92 (m, 2H), 2.38-2.54 (m, 2H), 3.63 (d, J = 14.8 Hz, 1H), 3.79 (s, 3H), 3.86 (m, 1H), 5.12 (d, J = 17.2 Hz, 1H), 5.26 (d, J = 10.8 Hz, 1H), 5.46 (d, J = 14.8 Hz, 1H), 5.74 (ddd, J = 17.2, 10.8, 6.8 Hz, 1H), 6.84 (d, J = 8.8 Hz, 2H), 7.16 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 17.2, 28.7, 32.1, 46.6, 55.2, 57.7, 113.8, 117.0, 129.4, 129.7, 137.4, 158.7, 170.2; IR (ATR) ν 2946, 1632, 1511, 1459, 1413, 1242 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{15}H_{19}NNaO_2^+$ *m/z* 268.1308, found *m/z* 268.1306.



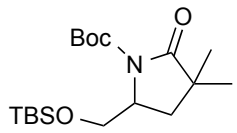
1-(4-Methoxybenzyl)-6-oxopiperidine-2-carbaldehyde (s4)

To a solution of **s3** (1.7 mmol, 412 mg) in THF/H_2O (10/3, 0.1 M, 17 mL) were added OsO_4 (10 wt% in *t*BuOH, 0.1 mmol, 6 mol%, 0.32 mL) and $NaIO_4$ (8.5 mmol, 5 eq, 1.8 g) at 0 ℃. After the reaction mixture was stirred for 46.5 h at 0 ℃, the reaction was quenched with 2 M aqueous NaS_2O_3, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 2/1) to afford **s4** as a colorless oil (172.1 mg, 41% yield): R_f = 0.2 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.64 (m, 1H), 1.75-1.92 (m, 2H), 2.14 (m, 1H), 2.42-2.59 (m, 2H), 3.79 (s, 3H), 3.89-3.95 (m, 2H), 5.30 (d, J = 15.2 Hz, 1H), 6.84 (d, J = 8.8 Hz, 2H), 7.14 (d, J = 8.8 Hz, 2H), 9.48 (d, J = 1.2 Hz, 1H); ^{13}C NMR (100MHz, $CDCl_3$) δ 18.3, 23.5, 31.9, 48.4, 55.2, 64.0, 114.1, 128.2, 129.8, 159.2, 169.9, 199.8; IR (ATR) ν 2949, 1733, 1636, 1512, 1458, 1244, 1174, 1032 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{17}NNaO_3^+$ *m/z* 270.1101, found *m/z* 270.1104.



Methyl 2-(1-(4-methoxybenzyl)-6-oxopiperidin-2-yl)acetate (s1d)

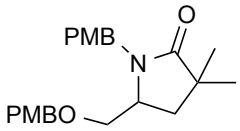
To a stirred solution of 2-(1-(4-methoxybenzyl)-6-oxopiperidin-2-yl)acetic acid[10] (2 mmol, 554.6 mg) in CH_2Cl_2 (1 M, 2 mL) was added $(COCl)_2$ (2.6 mmol, 1.3 eq, 0.22 mL), and the reaction mixture was stirred for 15 min before adding MeOH (3 mL). After being stirred for 15 min at room temperature, the reaction mixture was concentrated under reduced pressure. The crude product was purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 1/1) to afford **s1d** as a colorless oil (567.5 mg, 97% yield): R_f = 0.4 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.73-1.82 (m, 3H), 1.88 (m, 1H), 2.39-2.56 (m,3H), 2.68 (dd, J = 15.6, 4.0 Hz, 1H), 3.67 (s, 3H), 3.79 (s, 3H), 3.84 (m, 1H), 3.93 (d, J = 14.8 Hz, 1H), 5.19 (d, J = 14.8 Hz, 1H), 6.85 (d, J = 8.8 Hz, 2H), 7.18 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, CD_3CN) δ 17.7, 27.9, 32.4, 37.9, 47.6, 52.3, 53.5, 55.8, 114.8, 129.7, 130.9, 159.8, 170.8, 172.5; IR (ATR) ν 2951, 1732, 1634, 1511, 1458, 1440 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{21}NNaO_4^+$ *m/z* 314.1363, found *m/z* 314.1361.



***tert*-Butyl 5-(((*tert*-butyldimethylsilyl)oxy)methyl)-3,3-dimethyl-2-oxopyrrolidine-1-carboxylate (s5)**

To a stirred solution of *tert*-butyl 2-(((*tert*-butyldimethylsilyl)oxy)methyl)- 5-oxopyrrolidine-1-carboxylate[67] (5 mmol, 1.6466 g) in THF (87 mL) was added 1.3 M LHMDS solution in THF (10.5 mmol, 2.1 eq, 8.1 mL) at -78 °C. After being stirred for 20 min at -78 °C, MeI (10 mmol, 2 eq, 0.62 mL) in THF (5 mL) was added, and the reaction mixture was stirred for 15 min at -78 °C and for 4.5 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (*n*-hexane/EtOAc 15/1) to afford **s5** as a colorless oil (1.03 g, 58% yield): R_f = 0.6 (*n*-hexane/EtOAc 3/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.01 (s, 3H), 0.02 (s, 3H), 0.85 (s, 9H), 1.17 (s, 3H), 1,22 (s, 3H), 1.51 (s, 9H), 1.89 (dd, J = 13.2, 8.4 Hz, 1H), 1.94 (dd, J = 13.2, 5.6 Hz, 1H), 3.69 (dd, J = 10.0, 2.8 Hz, 1H), 3.87 (dd, J = 10.0, 4.8 Hz, 1H), 4.03 (dddd, J = 8.4, 5.6, 4.8, 2.8 Hz, 1H); ^{13}C NMR (100MHz, $CDCl_3$) (major rotamer) δ -5.6, 16.0, 18.1, 25.7, 27.0, 27.9, 34.8, 41.0, 55.2, 63.0, 82.5, 150.4, 179.6; IR

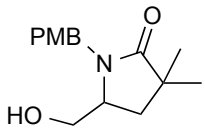
(ATR) ν 2956, 2856, 1791, 1748, 1712, 1472, 1366, 1306, 1252 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{18}H_{35}NNaO_4Si^+$ *m/z* 380.2228, found *m/z* 380.2234.



1-(4-Methoxybenzyl)-5-(((4-methoxybenzyl)oxy)methyl)-3,3-dimethylpyrrolidin-2-one (s6)

To a stirred solution of **s5** (1 mmol, 358.6 mg) in CH_2Cl_2 (2.5 mL) was added trifluoroacetic acid (2.5 mL) at 0 ℃. After being stirred for 3.5 h at room temperature, the reaction mixture was concentrated under reduced pressure to afford the crude product.

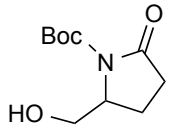
To a solution of the crude residue in DMF (0.2 M, 5 mL) was added NaH (4 eq, 161.8 mg) at 0 ℃. After the reaction mixture was stirred for 30 min 0 ℃, PMBCl (2.2 eq, 0.28 mL) and tetrabutylammonium iodide (0.1 eq, 36.9 mg) were added and the stirring was continued for additional 66.5 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with toluene, washed with water and brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 3/1) to afford **s6** as a colorless oil (111.2 mg, 29% yield, 2 steps): R_f = 0.5 (*n*-hexane/EtOAc 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.10 (s, 3H), 1.22 (s, 3H), 1.64 (dd, *J* = 12.8, 7.6 Hz, 1H), 1.86 (dd, *J* = 12.8, 8.0 Hz, 1H), 3.38 (dd, *J* = 10.0, 5.6 Hz, 1H), 3.43 (dd, *J* = 10.0, 4.0 Hz, 1H), 3.51 (dddd, *J* = 8.0, 7.6, 5.6, 4.0 Hz, 1H), 3.77 (s, 3H), 3.81 (s, 3H), 3.98 (d, *J* = 14.8 Hz, 1H), 4.35 (d, *J* = 11.2 Hz, 1H), 4.39 (d, *J* = 11.2 Hz, 1H), 4.89 (d, *J* = 14.8 Hz, 1H), 6.79 (d, *J* = 8.8 Hz, 2H), 6.89 (d, *J* = 8.8 Hz, 2H), 7.08 (d, *J* = 8.8 Hz, 2H), 7.22 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 25.2, 25.5, 37.2, 40.0, 44.0, 53.2, 55.1, 55.2, 71.1, 72.8, 113.7 (2C), 129.2, 129.3, 129.3, 129.7, 158.7, 159.2, 180.0; IR (ATR) ν 2957, 1681, 1611, 1511, 1457, 1361, 1302, 1246 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{23}H_{29}NNaO_4^+$ *m/z* 406.1989, found *m/z* 406.1991.



5-(Hydroxymethyl)-1-(4-methoxybenzyl)-3,3-dimethylpyrrolidin-2-one (s2e)

To a solution of **s6** (0.13 mmol, 50.5 mg) in CH_2Cl_2 (3 mL) was added trifluoroacetic acid (0.6 mL) at 0 ℃. After the reaction mixture was stirred for 30 min at room temperature, the reaction was quenched with saturated aqueous $NaHCO_3$ at 0 ℃, extracted with CH_2Cl_2,

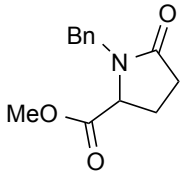
washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (gradient elution: *n*-hexane/EtOAc, 1/1 → EtOAc) to afford **s2e** (32.8mg, 95% yield) as a colorless oil: R_f = 0.2 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.14 (s, 3H), 1.25 (s, 3H), 1.74-1.88 (m, 3H), 3.43-3.52 (m, 2H), 3.73-3.81 (m, 4 H), 4.22 (d, J = 14.8 Hz, 1H), 4.72 (d, J = 14.8 Hz, 1H), 6.85 (d, J = 8.8 Hz, 2H), 7.19 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 25.4, 36.2, 40.2, 44.3, 55.2, 55.6, 62.3, 114.1, 129.1, 129.2, 159.0, 180.9; IR (ATR) ν 3382, 2958, 1657, 1612, 1512, 1466, 1245, 1176 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{15}H_{21}NNaO_3^+$ *m/z* 286.1414, found *m/z* 286.1413.



tert-Butyl 2-(hydroxymethyl)-5-oxopyrrolidine-1-carboxylate (s2f)

To a stirred solution of *tert*-butyl 2-(((*tert*-butyldimethylsilyl)oxy)methyl)- 5-oxopyrrolidine-1-carboxylate (2 mmol, 659.0 mg) in THF (0.1 M, 20 mL) was added TBAF (4 mmol, 2 eq, 1.05 g) at 0 ℃. After being stirred for 40 min at 0 ℃, the reaction mixture was concentrated under reduced pressure, purified by flash chromatography on silica gel (gradient elution: *n*-hexane/EtOAc, 1/1 → EtOAc) to afford **s2f**.

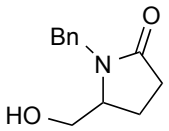
^{1}H and ^{13}C NMR were identical to those reported.[68]



Methyl 1-benzyl-5-oxopyrrolidine-2-carboxylate (s1g)

To a stirred solution of methyl 5-oxopyrrolidine-2-carboxylate (5 mmol, 0.57 mL) in THF (0.3 M, 67 mL) was added NaH (5.5 mmol, 1.1 eq, 220 mg) at 0 ℃. After being stirred for 30 min at 0 ℃, BnBr (5.5 mmol, 1.1 eq, 0.65 mL) was added, and the reaction mixture was stirred for 2.5 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 2/1) to afford **s1g** as a colorless oil (398 mg, 34% yield).

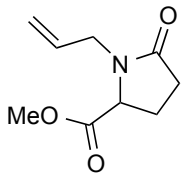
^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[69]



1-Benzyl-5-(hydroxymethyl)pyrrolidin-2-one (s2g)

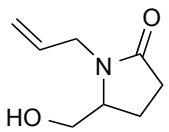
To a stirred solution of **s1g** (1.7 mmol, 398 mg) in THF (0.2 M, 8.6 mL) was added $LiBH_4$ (2.6 mmol, 1.5 eq, 55.8 mg) at 0 °C. After being stirred at room temperature for 18.5 h, the reaction was quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (gradient elution: EtOAc → EtOAc/MeOH, 10/1) to afford **s2g** (328.1 mg, 94% yield).

^1H and ^{13}C NMR, IR, and MS were identical to those reported.[70]



Methyl 1-allyl-5-oxopyrrolidine-2-carboxylate (s1h)

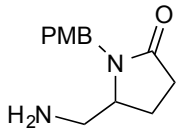
To a stirred solution of methyl 5-oxopyrrolidine-2-carboxylate (7 mmol, 0.8 mL) in THF (0.2 M, 35 mL) was added NaH (8.4 mmol, 1.2 eq, 336 mg) at 0 °C. After being stirred for 30 min at 0 °C, allyl bromide (7.7 mmol, 1.1 eq, 0.65 mL) was added, and the reaction mixture was stirred for 21 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 1/2) to afford **s1h** as a colorless oil (380.4 mg, 30% yield): R_f = 0.5 (EtOAc); ^1H NMR (400 MHz, $CDCl_3$) δ 2.10 (m, 1H), 2.28-2.44 (m, 2H), 2.51 (m, 1H), 3.55 (dd, J = 14.8, 7.2 Hz, 1H), 3.76 (s, 3H), 4.19 (dd, J = 9.2, 3.2 Hz, 1H), 4.35 (dd, J = 14.8, 5.2 Hz, 1H), 5.17 (dd, J = 16.8, 1.2 Hz, 1H), 5.19 (dd, J = 10.0, 1.2 Hz, 1H), 5.71 (dddd, J = 16.8, 10.0, 7.2, 5.2 Hz, 1H); ^{13}C NMR (100MHz, $CDCl_3$) δ 22.8, 29.4, 44.3, 52.3, 58.8, 118.6, 131.9, 172.3, 174.8; IR (ATR) ν 2955, 1739, 1681, 1440, 1409, 1272, 1199, 1172 cm^{-1}; HRMS (ESI-TOF) $[2M + Na]^+$ calcd for $C_{18}H_{26}N_2NaO_6^+$ *m/z* 389.1683, found *m/z* 389.1698.



1-Allyl-5-(hydroxymethyl)pyrrolidin-2-one (s2h)

To a stirred solution of **s1h** (2.1 mmol, 376 mg) in THF (0.2 M, 10 mL) was added $LiBH_4$ (3.0 mmol, 1.5 eq, 67 mg) at 0 °C. After being stirred at room temperature for 12.5 h, the reaction mixture was concentrated under reduced pressure. The crude residue was purified by flash chromatography on silica gel (gradient elution: EtOAc → EtOAc/MeOH, 10/1) to afford **s2h** (263 mg, 83% yield).

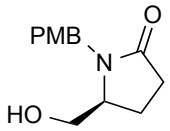
^1H and ^{13}C NMR, IR, and MS were identical to those reported.[71]



5-(Aminomethyl)-1-(4-methoxybenzyl)pyrrolidin-2-one (s7)

To a solution of **s2a** (1 mmol, 235.5 mg) and Et_3N (1.1 mmol, 1.1 eq, 0.15 mL) in CH_2Cl_2 (0.5 M, 2 mL) was added MsCl (1.1 mmol, 1.1 eq, 0.085 mL) at 0 °C. After the reaction mixture was stirred for 1 h at 0 °C, the reaction was quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure to give crude compound that was used for the next step without further purification.

A solution of the crude residue and NaN_3 (1 mmol, 65.1 mg) in DMF (0.1 M, 10 mL) was stirred for 15 h at 60 °C. The reaction was quenched with H_2O, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure to give crude azide. The residue was dissolved in THF (0.1 M, 10 mL), and PPh_3 (3 eq, 787.2 mg) was added to the solution. After being stirred for 20.5 h at room temperature, 5 drops of H_2O was added, and the reaction mixture was stirred for additional 11 h. The solution was concentrated under reduced pressure, and the crude mixture was purified by flash chromatography on silica gel (gradient elution: EtOAc → EtOAc/MeOH, 10/1) to afford **s7** as a pale yellow oil (97 mg, 41% yield, 3 steps): R_f = 0.1 (EtOAc/MeOH, 5/1); ^1H NMR (400 MHz, $CDCl_3$) δ 1.25 (br s, 2H), 1.87 (m, 1H), 2.06 (m, 1H), 2.40 (ddd, J = 16.8, 10.0, 6.0 Hz, 1H), 2.54 (ddd, J = 16.8, 10.0, 7.2 Hz, 1H), 2.73 (dd, J = 13.2, 2.8 Hz, 1H), 2.84 (dd, J = 13.2, 5,6 Hz, 1H), 3.49 (m, 1H), 3.79 (s, 3H), 4.07 (d, J = 14.8 Hz, 1H), 4.78 (d, J = 14.8 Hz, 1H), 6.85 (d, J = 8.8 Hz, 2H), 7.19 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 21.3, 30.3, 43.1, 43.9, 55.1, 58.8, 113.9, 128.8, 129.1, 158.9, 175.6; IR (ATR) ν 3371, 3297, 2935, 1659, 1511, 1417, 1242, 1175 cm^{-1}; HRMS (ESI-TOF) $[2M + Na]^+$ calcd for $C_{26}H_{36}N_4NaO_4^+$ m/z 491.2629, found m/z 491.2619.

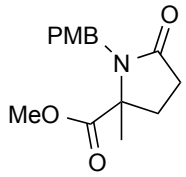


(*S*)-5-(Hydroxymethyl)-1-(4-methoxybenzyl)pyrrolidin-2-one ((*S*)-s2a)

To a stirred solution of (*S*)-5-(((*tert*-butyldimethylsilyl)oxy)methyl)pyrrolidin-2-one[72] (3 mmol, 688 mg) in DMF (0.3 M, 10 mL) was added NaH (3.3 mmol, 1.1 eq, 132 mg) at 0 ℃. After the reaction mixture was stirred for 30 min at 0 ℃, PMBCl (3.3 mmol, 1.1 eq, 0.41 mL) and tetrabutylammonium iodide (0.3 mmol, 0.1 eq, 110.8 mg) was added, and the reaction mixture was stirred for 13 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with toluene, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure to afford crude residue.

A solution of the crude residue in THF (24 mL) was added TBAF (1 M solution in THF) (6 mmol, 2 eq, 6 mL) at 0 ℃. The reaction mixture was stirred for 1 h at 0 ℃, concentrated under reduced pressure, and purified by flash chromatography on silica gel (gradient elution: EtOAc → EtOAc/MeOH, 10/1) to afford (*S*)-**s2a** (511.8 mg, 73% yield (2 steps)).

^1H and ^{13}C NMR were identical to those reported.[73]



Methyl 1-(4-methoxybenzyl)-2-methyl-5-oxopyrrolidine-2-carboxylate (s1m)

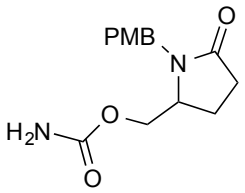
To a stirred solution of **s1a** (0.5 mmol, 132 mg) in THF (0.2 M, 2.5 mL) was added LHMDS (1.3 M solution in THF) (0.53 mmol, 1.05 eq, 0.4 mL) at -78 ℃. After the reaction mixture was stirred for 1 h at -78 ℃, MeI (0.6 mmol, 1.2 eq, 0.037 mL) was added, and the stirring was continued for additional 16 h at -78 ℃. The reaction was quenched with saturated aqueous NH_4Cl, extracted with Et_2O, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure, and purified by flash chromatography on silica gel (gradient elution: *n*-hexane/EtOAc, 1/1 → EtOAc) to afford **s1m** (62.5 mg, 45% yield).

^1H and ^{13}C NMR were identical to those reported.[74]

General procedure B for carbamoylation of alcohol substrate

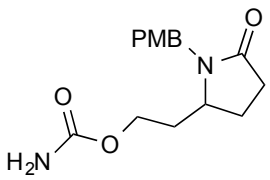
To a stirred solution of alcohol substrate in CH_2Cl_2 (0.1 M) was added $Cl_3CCONCO$ (1.2 eq) at 0 ℃. After being stirred for 10 min, the reaction mixture was concentrated under reduced pressure, and used for the next step without further purification.

The solution of the crude residue and K_2CO_3 (0.2 eq) in MeOH (0.1 M) was stirred at room temperature for 2 h, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (conditions given below) to afford primary carbamate **1**.



(1-(4-Methoxybenzyl)-5-oxopyrrolidin-2-yl)methyl carbamate (1a)

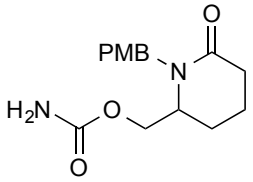
Prepared according to the general procedure B using **s2a**, and isolated as white solid (220.4 mg, 99% yield, two steps) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): mp 134−136 ℃; R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.89 (m, 1H), 2.08 (m, 1H), 2.39 (ddd, J = 16.8, 10.0, 4.8 Hz, 1H), 2.54 (ddd, J = 16.8, 8.8, 8.8 Hz, 1H), 3.63 (m, 1H), 3.79 (s, 3H), 3.95 (d, J = 14.8 Hz, 1H), 4.01 (d, J = 11.6, 4 Hz, 1H), 4.21 (dd, J = 11.6, 4.0 Hz, 1H), 4.97 (d, J = 14.8 Hz, 1H), 5.14 (br s, 2H), 6.85 (d, J = 8.8 Hz, 2H), 7.17 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 21.4, 30.1, 43.7, 55.2, 55.6, 64.2, 114.0, 128.3, 129.2, 156.5, 158.9, 175.3; IR (ATR) ν 3351, 3197, 2951, 1716, 1666, 1611, 1512, 1450 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{14}H_{18}N_2NaO_4^+$ m/z 301.1159, found m/z 301.1168.



2-(1-(4-Methoxybenzyl)-5-oxopyrrolidin-2-yl)ethyl carbamate (1b)

Prepared according to the general procedure B using **s2b**, and isolated as white solid (147.3 mg, quant., two steps) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): mp 134−135 ℃; R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.65 (m, 1H), 1.75 (m, 1H), 2.01-2.18 (m, 2H), 2.39 (ddd, J = 16.4, 10.0, 6.4 Hz, 1H), 2.49 (ddd, J = 16.4, 9.6, 6.8 Hz, 1H), 3.50 (m, 1H), 3.79 (s, 3H), 3.92 (d, J = 14.8 Hz, 1H), 4.01-4.13 (m, 2H), 4.86 (br

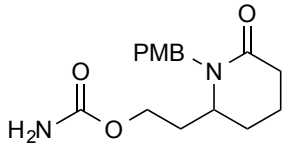
s, 2H), 4.92 (d, J = 14.8 Hz, 1H), 6.85 (d, J = 8.8 Hz, 2H), 7.16 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 23.9, 30.1, 31.8, 43.5, 54.3, 55.2, 61.2, 114.0, 128.5, 129.2, 156.6, 158.9, 174.9; IR (ATR) ν 3352, 3197, 2956, 1714, 1660, 1611, 1512, 1417 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{15}H_{20}N_2NAO_4^+$ *m/z* 315.1315, found *m/z* 315.1315.



(1-(4-Methoxybenzyl)-6-oxopiperidin-2-yl)methyl carbamate (1c)

To a solution of **s2c** in MeOH (0.2 M) was added $NaBH_4$ (1.2 eq) at 0 ℃. After being stirred for 1.5 h at room temperature, the reaction was quenched with saturated aqueous NH_4Cl, and the solvent was removed under reduced pressure. The reaction mixture was extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The residue was used for the next reaction without further purification.

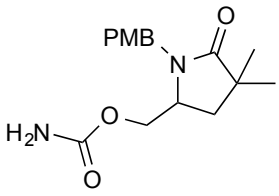
The crude alcohol was converted to carbamate according to the general procedure B, and isolated as a colorless oil (77% yield, three steps) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.70-1.80 (m, 2H), 1.84-1.96 (m, 2H), 2.40-2.55 (m, 2H), 3.55 (m, 1H), 3.79 (s, 3H), 3.95 (d, J = 14.8 Hz, 1H), 4.11 (dd, J = 11,6, 7.2 Hz, 1H), 4.19 (dd, J = 11.6, 3.6 Hz, 1H), 4.71 (br s, 2H), 5.36 (d, J = 14.8Hz, 1H), 6.85 (d, J = 8.8 Hz, 2H), 7.20 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 17.2, 25.2, 31.9, 47.1, 53.6, 55.2, 63.9, 113.9, 129.3, 129.4, 156.1, 158.9, 170.5; IR (ATR) ν 3360, 3197, 2951, 1716, 1612, 1511, 1401, 1329 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{15}H_{20}N_2NaO_8^+$ *m/z* 315.1315, found *m/z* 315.1316.



2-(1-(4-Methoxybenzyl)-6-oxopiperidin-2-yl)ethyl carbamate (1d)

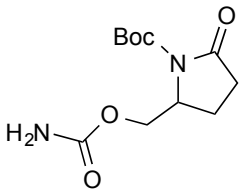
To a stirred solution of **s2d** (1mmol, 263mg) in THF (0.2 M, 5 mL) was added $LiBH_4$ (2.4 eq, 52.3 mg) at 0 ℃. After being stirred for 67 h at room temperature, the reaction was quenched with saturated aqueous NH_4Cl, and the solvent was removed under reduced pressure. The reaction mixture was extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The residue was used for the next reaction without further purification.

The crude alcohol was converted to carbamate according to the general procedure B, and isolated as white solid (73% yield, three steps) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): mp 94－95 °C; R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.67-1.92 (m, 5H), 2.05 (m, 1H), 2.43-2.50 (m, 2H), 3.41 (m, 1H), 3.79 (s, 3H), 3.81 (d, J = 15.2 Hz, 1H), 4.00 (ddd, J = 10.8, 8.4, 5.6 Hz, 1H), 4.09 (ddd, J = 11.2, 5.6, 5.6 Hz, 1H), 4.91 (br s, 2H), 5.36 (d, J = 15.2 Hz, 1H), 6.84 (d, J = 8.8 Hz, 2H), 7.17 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 16.9, 26.2, 31.2, 31.7, 46.7, 52.0, 55.2, 61.8, 113.9, 129.1, 129.4, 156.6, 158.7, 170.1; IR (ATR) ν 3354, 3192, 2951, 1713, 1609, 1511, 1465, 1414 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{16}H_{22}N_2NaO_4^+$ *m/z* 329.1472, found *m/z* 329.1465.



(1-(4-Methoxybenzyl)-4,4-dimethyl-5-oxopyrrolidin-2-yl)methyl carbamate (1e)

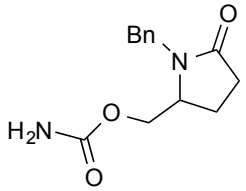
Prepared according to the general procedure B using **s2e**, and isolated as a colorless oil (35.1 mg, 92% yield, two steps) (column condition; EtOAc): R_f = 0.2 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.14 (s, 3H), 1.25 (s, 3H), 1.68 (dd, J = 12.8, 7.6 Hz, 1H), 1.92 (dd, J = 12.8, 8.0 Hz, 1H), 3.54 (dddd, J = 8.0, 7.6, 4.4, 4.0 Hz, 1H), 3.79 (s, 3H), 3.92 (d, J = 14.8 Hz, 1H), 4.01 (dd, J = 11.6, 4.4 Hz, 1H), 4.21 (dd, J = 11.6, 4.0 Hz, 1H), 4.84 (br s, 2H), 5.01 (d, J = 14.8 Hz, 1H), 6.84 (d, J = 8.8 Hz, 2H), 7.14 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 25.3, 25.4, 36.7, 40.0, 43.8, 52.3, 55.2, 64.3, 114.0, 128.5, 129.1, 156.3, 158.9, 180.1; IR (ATR) ν 3348, 3200, 2960, 1718, 1670, 1612, 1513, 1416 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{16}H_{22}N_2NaO_4^+$ *m/z* 329.1472, found *m/z* 329.1474.



***tert*-Butyl 2-((carbamoyloxy)methyl)-5-oxopyrrolidine-1-carboxylate (1f)**

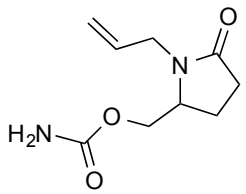
Prepared according to the general procedure B using **s2f**, and isolated as white solid (207.4 mg, 41% yield, two steps) (column condition; gradient elution: *n*-hexane/EtOAc, 1/1 → EtOAc): mp 117－118 °C; R_f = 0.1 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.53 (s, 9H), 1.99 (m, 1H), 2.19 (m, 1H), 2.42 (m, 1H), 2.73 (m, 1H), 4.19 (m, 1H), 4.32-4.42 (m, 2H), 5.30 (br s, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 20.7, 27.8, 31.6, 56.5, 65.1,

83.1, 149.3, 156.6, 174.7; IR (ATR) ν 3355, 3197, 2978, 1776, 1711, 1604, 1397, 1367 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{11}H_{18}N_2NaO_5^+$ *m/z* 281.1108, found *m/z* 281.1100.



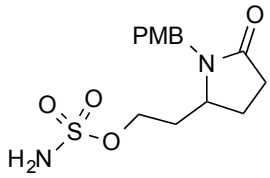
(1-Benzyl-5-oxopyrrolidin-2-yl)methyl carbamate (1g)

Prepared according to the general procedure B using **s2g**, and isolated as a colorless oil (236.2 mg, 93% yield, two steps) (column condition; EtOAc): R_f = 0.3 (EtOAc); ^1H NMR (400 MHz, $CDCl_3$) δ 1.89 (m, 1H), 2.10 (m, 1H), 2.40 (ddd, *J* = 16.8, 10.0, 4.8 Hz, 1H), 2.56 (ddd, *J* = 16.8, 8.4, 8.4 Hz, 1H), 3.64 (m, 1H), 4.00 (dd, *J* = 12.0, 3.6 Hz, 1H), 4.03 (d, *J* = 15.2 Hz, 1H), 4.21 (dd, *J* = 12.0, 3.6 Hz, 1H), 5.01 (d, *J* = 15.2 Hz, 1H), 5.14 (br s, 2H), 7.21-7.35 (m, 5H); ^{13}C NMR (100MHz, $CDCl_3$) δ 21.4, 30.0, 44.3, 55.8, 64.2, 127.5, 127.8, 128.6, 136.3, 156.5, 175.4; IR (ATR) ν 3348, 3192, 2951, 1713, 1665, 1444, 1418, 1402 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{13}H_{16}N_2NaO_3^+$ *m/z* 271.1053, found *m/z* 271.1055.



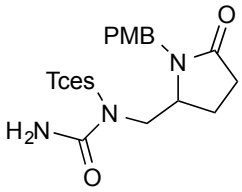
(1-Allyl-5-oxopyrrolidin-2-yl)methyl carbamate (1h)

Prepared according to the general procedure B using **s2h**, and isolated as white solid (178.9 mg, 90%, two steps) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): mp 68−70 °C; R_f = 0.2 (EtOAc); ^1H NMR (400 MHz, $CDCl_3$) δ 1.92 (m, 1H), 2.18 (m, 1H), 2.36 (ddd, *J* = 16.8, 10.0, 4.8 Hz, 1H), 2.51 (ddd, *J* = 16.8, 8.8, 8.8 Hz, 1H), 3.59 (dd, *J* = 15.6, 7.2 Hz, 1H), 3.83 (m, 1H), 4.08, (dd, *J* = 12.0, 3.6 Hz, 1H), 4.22 (dd, *J* = 12.0, 3.6 Hz, 1H), 4.32 (m, 1H), 5.10-5.25 (m, 4H), 5.73 (m, 1H); ^{13}C NMR (100MHz, $CDCl_3$) δ 21.4, 30.0, 43.4, 56.2, 64.4, 118.0, 132.4, 156.5, 175.1; IR (ATR) ν 3352, 3202, 2951, 1707, 1659, 1455, 1403, 1328 cm^{-1}; HRMS (ESI-TOF) $[2M + Na]^+$ calcd for $C_{18}H_{28}N_4NaO_6^+$ *m/z* 419.1901, found *m/z* 419.1904.



2-(1-(4-Methoxybenzyl)-5-oxopyrrolidin-2-yl)ethyl sulfamate (1i)

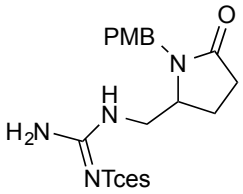
To stirred chlorosulfonyl isocyanate (3 mmol, 3 eq, 0.28 mL) was added formic acid (3mmol, 3 eq, 0.11 mL) at 0 ℃. After the reaction mixture was stirred for 5 min at 0 ℃, CH_3CN (0.77 mL) was added and the stirring was continued for additional 8 h at 0 ℃ to room temperature gradually. A solution of **s2b** (1mmol, 247 mg) in DMA (0.38 mL) was added at 0 ℃, and the reaction mixture was stirred for 14.5 h at room temperature. The reaction was quenched with water, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (EtOAc) to afford **1i** as white solid (149.4 mg, 46% yield): mp 102－104 ℃; R_f = 0.4 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.72-1.87 (m, 2H), 2.08-2.23 (m, 2H), 2.42 (ddd, J = 17.2, 10.0, 6.0 Hz, 1H), 2.53 (ddd, J = 17.2, 9.2, 6.8 Hz, 1H), 3.62 (m, 1H), 3.80 (s, 3H), 3.96 (d, J = 14.8 Hz, 1H), 4.15-4.25 (m, 2H), 4.88 (d, J = 14.8 Hz, 1H), 5.07 (br s, 2H), 6.85 (d, J = 8.8 Hz, 2H), 7.16 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 23.7, 30.1, 31.7, 43.8, 54.3, 55.3, 67.0, 114.1, 128.3, 129.3, 159.1, 175.2; IR (ATR) ν 3198, 3090, 2939, 1659, 1513, 1461, 1414, 1364 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{14}H_{20}N_2NaO_5S^+$ *m/z* 351.0985, found *m/z* 351.0984.



2,2,2-Trichloroethyl-carbamoyl((1-(4-methoxybenzyl)-5-oxopyrrolidin-2-yl)methyl)-sulfamate (1j)

To a stirred solution of **s2a** (0.5 mmol, 117.6 mg), PPh_3 (0.65 mmol, 1.3 eq, 170.5 mg), and $TcesNHCONH_2$ (0.67 mmol, 1.33 eq, 180.5 mg) in THF (0.3 M, 1.7 mL) was added diethyl azodicarboxylate (0.65 mmol, 1.3 eq, 0.1 mL). After being stirred for 39 h at room temperature, the reaction mixture was concentrated under reduced pressure and purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 1/1) to afford **1j** as a colorless oil (118.2 mg, 48% yield): R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) (major rotamer) δ 1.91 (m, 1H), 2.17 (m, 1H), 2.41 (m, 1H), 2.60 (m, 1H), 3.72 (m, 1H), 3.80 (s, 3H), 4.05 (d, J = 14.8 Hz, 1H), 4.18 (dd, J = 11.6, 3.6 Hz, 1H), 4.29 (dd, J = 11.6, 3.2 Hz, 1H), 4.63 (s, 2H), 4.82

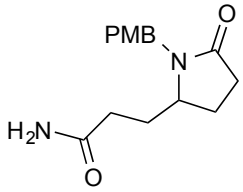
(d, J = 14.8 Hz, 1H), 6.81 (br s, 1H), 6.86 (d, J = 8.8 Hz, 2H), 6.98 (br s, 1H), 7.15 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 21.4, 30.0, 44.2, 55.3, 55.6, 67.8, 78.4, 93.6, 114.2, 127.8, 129.1, 159.2, 160.3, 175.4; IR (ATR) ν 3427, 3319, 2953, 1642, 1558, 1513, 1440, 1334 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{16}H_{20}Cl_3N_3NaO_6S^+$ m/z 510.0031, found m/z 510.0038.



2,2,2-Trichloroethyl (amino(((1-(4-methoxybenzyl)-5-oxopyrrolidin-2-yl)methyl)amino)-methylene)sulfamate (1k)

Prepared according to Du Bois's method[75].

A solution of *S*-methyl-*N*-(2,2,2-trichloroethoxysulfonyl)isothiourea (0.49mmol, 1 eq, 147.8 mg) and **s7** (0.49 mmol, 114.3 mg) in H_2O (1 M, 0.49 mL) in was stirred for 3.5 h at 100 ℃. The reaction mixture was cooled down to room temperature, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (gradient elution: EtOAc → EtOAc/MeOH, 10/1) to afford **1k** as colorless gum (87 mg, 37% yield): R_f = 0.4 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) (major rotamer) δ 1.99 (m, 1H), 2.13 (m, 1H), 2.40-2.50 (m, 2H), 3.36 (m, 1H), 3.69 (m, 1H), 3.75-3.88 (m, 5H), 4.62 (s, 2H), 4.96 (d, J = 14.4 Hz, 1H), 6.68 (br s, 1H), 6.70 (br s, 1H), 6.73 (br s, 1H), 6.88 (d, J = 8.4 Hz, 2H), 7.11 (d, J = 8.4 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 20.6, 30.9, 40.8, 43.6, 55.3, 56.1, 78.0, 94.3, 114.5, 126.4, 129.2, 158.2, 159.6, 176.6; IR (ATR) ν 3447, 3342, 2938, 1665, 1550, 1513, 1419, 1246 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{16}H_{21}Cl_3N_4NaO_5S^+$ m/z 509.0190, found m/z 509.0182.



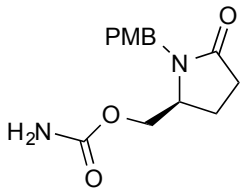
3-(1-(4-Methoxybenzyl)-5-oxopyrrolidin-2-yl)propanamide (1l)

To a stirred solution of 5-(3-diazo-2-oxopropyl)-1-(4-methoxybenzyl) pyrrolidin-2-one[11] (1.7 mmol, 498.3 mg) in dioxane (15.6 mL) and H_2O (1.7 mL) was added CF_3COOAg (0.52 mmol, 30 mol%, 115 mg), and the reaction mixture was stirred for 46 h at room temperature. The reaction was acidified with 1N aqueous HCl, extracted with EtOAc, washed with brine,

dried over Na_2SO_4, and concentrated under reduced pressure to afford carboxylic acid, which was used for the next step without further purification.

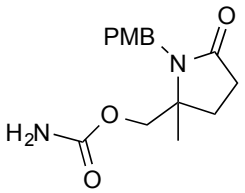
To a stirred solution of the carboxylic acid in CH_2Cl_2 (1.6 mL) was added $(COCl)_2$ (2.1 mmol, 0.18 mL) at room temperature, and the mixture was stirred for 10 min. The reaction mixture was concentrated under reduced pressure to give crude acid chloride.

The residue was dissolved in CH_2Cl_2 (8.1 mL), and saturated aqueous NH_3 (1.9 mL) was added to the solution at 0 ℃. After being stirred for 30 min at 0 ℃, the reaction was quenched with H_2O, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (gradient elution: EtOAc/MeOH, 10/1 → 5/1) to afford **1l** as yellow solid (254 mg, 53% yield (3steps)): mp 103－105 ℃; R_f = 0.1 (EtOAc/MeOH, 10/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.63-1.77 (m, 2H), 2.03-2.19 (m, 4H), 2.34-2.52 (m, 2H), 3.52 (m, 1H), 3.79 (s, 3H), 3.98 (d, J = 15.2 Hz, 1H), 4.88 (d, J = 15.2 Hz, 1H), 5.27 (br s, 2H), 6.85 (d, J = 8.4 Hz, 2H), 7.20 (d, J = 8.4 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 23.3, 28.0, 30.1, 30.2, 43.6, 55.2, 56.1, 114.0, 128.7, 129.4, 159.0, 174.0, 174.9; IR (ATR) ν 3329, 3192, 2929, 1660, 1607, 1511, 1450, 1416 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{15}H_{20}N_2NaO_3^+$ m/z 299.1366, found m/z 299.1363.



(*S*)-(1-(4-Methoxybenzyl)-5-oxopyrrolidin-2-yl)methyl carbamate ((+)-1a)

Prepared according to the same procedure B for the synthesis of **1a** using (*S*)-**s2a** and isolated as white solid: (220.4 mg, 99% yield, two steps): mp 138－140 ℃; $[\alpha]^{20}_D$ + 80.8° (*c* 1, $CHCl_3$). The enantiomeric excess was determined to be 99% by analytical chiral HPLC. Eleven min, 12 min (AD-H column, 85/15 n-hexane/iPrOH, 1 mL/min, 254 nm).

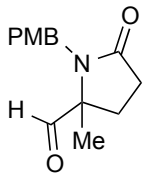


(1-(4-Methoxybenzyl)-2-methyl-5-oxopyrrolidin-2-yl)methyl carbamate (1m)

To a stirred solution of **s1m** (0.2 mmol, 56.0 mg) in THF (0.2 M, 1 mL) was added $LiBH_4$ (0.24 mmol, 1.2 eq, 5.2 mg) at 0 ℃. After being stirred for 3 h at room temperature, the

reaction was quenched with saturated aqueous NH_4Cl, and the solvent was removed under reduced pressure. The reaction mixture was extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The residue was used for the next reaction without further purification.

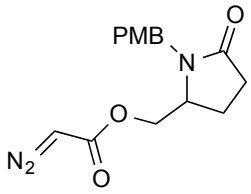
The crude residue was converted to carbamate according to the general procedure B, and isolated as white solid (53.2 mg, 80% yield (three steps)) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): mp 138－140 ℃; R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.13 (s, 3H), 1.79 (ddd, J = 12.8, 10.0, 8.4 Hz, 1H), 2.12 (ddd, J = 12.8, 8.8, 4.4 Hz, 1H), 2.42 (ddd, J = 17.2, 10.0, 4.4 Hz, 1H), 2.57 (ddd, J = 17.2, 8.8, 8.4 Hz, 1H), 3.77 (s, 3H), 3.84 (d, J = 11.2 Hz, 1H), 3.92 (d, J = 11.2 Hz, 1H), 4.30 (d, J = 15.6 Hz, 1H), 4.48 (d, J = 15.6 Hz, 1H), 5.04 (br s, 2H), 6.81 (d, J = 8.8 Hz, 2H), 7.11 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 23.0, 29.8, 30.3, 42.4, 55.2, 62.7, 68.2, 113.8, 128.9, 130.4, 156.3, 158.7, 175.6; IR (ATR) ν 3352, 3197, 2965, 1715, 1666, 1611, 1512, 1466 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{15}H_{20}N_2NaO_4^+$ m/z 315.1315, found m/z 315.1307.



1-(4-Methoxybenzyl)-2-methyl-5-oxopyrrolidine-2-carbaldehyde

Primary carbamate **1m** (0.05 mmol, 14.6 mg), $PhI(OAc)_2$ (0.07 mmol, 1.4 eq, 22.5 mg), MgO (0.12 mmol, 2.3 eq, 4.6 mg), and $Rh_2(esp)_2$ (1 μmol, 2 mol%, 0.8 mg) were suspended in benzene (0.05 M, 1 mL), and the whole was stirred for 2 h at 60 ℃. The reaction mixture was concentrated under reduced pressure, and purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 1/1) to afford the aldehyde (2 mg, 16% yield).

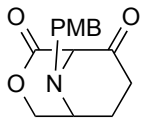
^{1}H and ^{13}C NMR were identical to those reported.[76]



(1-(4-Methoxybenzyl)-5-oxopyrrolidin-2-yl)methyl 2-diazoacetate (3)

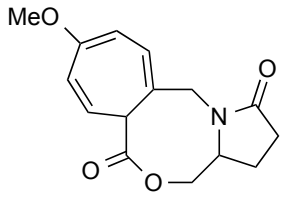
To a stirred solution of 2-(2-tosylhydrazono)acetyl chloride (3.0 mmol, 2 eq, 755.2 mg) in CH_2Cl_2 (0.1 M, 15 mL) were added **s2a** (1.5 mmol, 350.6 mg) and $PhNMe_2$ (2.25 mmol, 1.5 eq, 0.26 mL) at 0 ℃. After the reaction mixture was stirred for 30 min at 0 ℃, DIPEA (1.3

mL) was added and the stirring was continued for 1 h at 0 ℃. The reaction was quenched with aqueous critic acid, extracted with CH_2Cl_2, washed with saturated aqueous $NaHCO_3$ and brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc) to afford **3** as a pale yellow oil (417 mg, 92% yield): R_f = 0.4 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.88 (m, 1H), 2.10 (m, 1H), 2.39 (ddd, J = 16.8, 10.0, 5.2 Hz, 1H), 2.50 (ddd, J = 16.8, 8.8, 8.8 Hz, 1H), 3.65 (m, 1H), 3.79 (s, 3H), 3.98 (d, J = 15.2 Hz, 1H), 4.08 (dd, J = 12.0, 3.6 Hz, 1H), 4.32 (dd, J = 12.0, 3.6 Hz, 1H), 4.77 (br s, 1H), 4.93 (d, J = 15.2 Hz, 1H), 6.85 (d, J = 8.8 Hz, 2H), 7.17 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 21.4, 30.0, 43.9, 46.2, 55.2, 55.5, 64.0, 114.0, 128.3, 129.2, 159.0, 166.4, 175.0; IR (ATR) ν 2956, 2111, 1682,1513, 1396, 1352, 1244, 1176 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{15}H_{17}N_3NaO_4^+$ *m/z* 326.1111, found *m/z* 326.1110.



9-(4-Methoxybenzyl)-3-oxa-9-azabicyclo[3.3.1]nonane-2,8-dione (4)

To a stirred solution of $Rh_2(NHCO\textit{t}Bu)_4$ (0.16 μmol, 0.8 mol%, 1.0 mg) in dioxine (5 mL) and CH_2Cl_2 (3 mL) was added a solution of **3** (0.2 mmol, 60.7 mg) in CH_2Cl_2 (2 mL). The reaction mixture was stirred for 1 h at 40 ℃, concentrated under reduced pressure, and purified by flash chromatography on silica gel (*n*-hexane/EtOAc, 1:1) to afford **4** as a pale yellow oil (30.7 mg, 56% yield): R_f = 0.7 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.14 (m, 1H), 2.47-2.65 (m, 2H), 2.73 (m, 1H), 3.14 (m, 1H), 3.76 (d, J = 13.2 Hz, 1H), 3.80 (s, 3H), 3.81 (d, J = 13.2 Hz, 1H), 3.88 (s, 1H), 4.50 (d, J = 11.6 Hz, 1H), 4.92 (dd, J = 11.6, 5.2 Hz, 1H), 6.87 (d, J = 8.8 Hz, 2H), 7.22 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100MHz, $CDCl_3$) δ 28.2, 35.9, 47.2, 55.3, 56.0, 71.4, 72.8, 114.1, 127.6, 129.9, 159.4, 164.4, 201.1; IR (ATR) ν 2961, 1745, 1712, 1612, 1513, 1455, 1298, 1244 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{15}H_{17}NNaO_4^+$ *m/z* 298.1050, found *m/z* 298.1041.

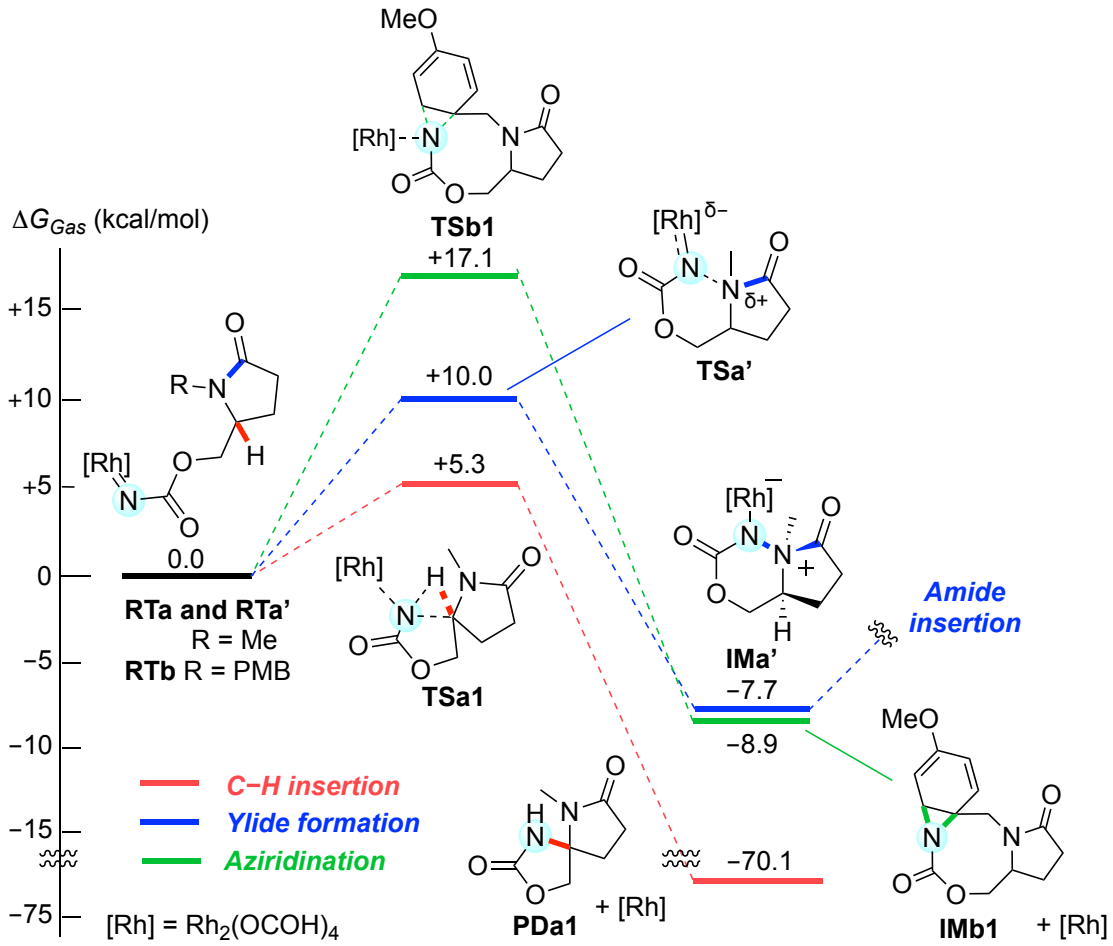


9-Methoxy-2,3,3a,4,6a,12-hexahydro-1H,6H-cyclohepta[f]pyrrolo[2,1-c][1,4]oxazocine-1,6-dione (5)

To a stirred solution of $Rh_2(esp)_2$ (1 μmol, 2 mol%, 0.8 mg) in CH_2Cl_2 (0.5 mL) was added a solution of **3** (0.05 mmol, 15.2 mg) in CH_2Cl_2 (0.5 mL). The reaction mixture was refluxed for 1 h, concentrated under reduced pressure, and purified by flash chromatography on silica gel (gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc) to afford **5** as a coorless oil (10.1 mg, 74% yield): R_f = (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) (mixture of diastereomers) δ 1.60-1.69 (m, 2H), 2.01-2.22 (m, 2H), 2.25-2.45 (m, 3H), 2.51 (m, 1H), 3.06 (d, J = 14.0 Hz, 1H), 3.30 (d, J = 14.0 Hz, 1H), 3.49 (dd, J = 11.6, 8.4 Hz, 1H), 3.55 (dd, J = 12.0, 2.8 Hz, 1H), 3.62-3.73 (m, 8H), 4.02-4.11 (m, 2H), 4.37 (dd, J = 11.2, 4.0 Hz, 1H), 4.42 (dd, J = 12.0, 11.6 Hz, 1H), 5.12 (d, J = 14.0 Hz, 1H), 5.26 (d, J = 14.0 Hz, 1H), 5.33 (d, J = 6.0 Hz, 1H), 5.37 (d, J = 6.0 Hz, 1H), 5.73 (dd, J = 8.8, 8.4 Hz, 1H), 5.82 (dd, J = 8.8, 8.8 Hz, 1H), 6.23 (d, J = 8.8 Hz, 1H), 6.33 (d, J = 8.8 Hz, 1H), 6.36 (d, J = 6.0 Hz, 1H), 6.59 (d, J = 6.0 Hz, 1H); ^{13}C NMR (100MHz, $CDCl_3$) (mixture of diastereomers) δ 2.2, 23.5, 29.4, 30.0, 47.9, 49.3, 49.6, 50.9, 56.0, 56.51, 56.53, 59.9, 65.3, 67.8, 95.1, 96.0, 119.6, 121.7, 128.2, 129.3, 130.3, 130.9, 135.0, 136.7, 155.0, 157.0, 170.1, 171.9, 175.1, 176.5; IR (ATR) ν 2948, 1727, 1673, 1617, 1542, 1440, 1365, 1324 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{15}H_{17}NNaO_4^+$ m/z 298.1050, found m/z 298.1052.

2-3. Computational details

Calculations were performed with the Spartan'16 packages[77] except for the ylide formation calculated with Gaussian 16 program[78] using the hybrid density functional method based on Becke's three-parameter exchange function and the Lee-Yang-Parr nonlocal correlation functional (B3LYP)[79] and ωB97X-D[80]. We used the LANL2DZ basis set for Rh and the 6-31G(d) basis set for the C, H, N, and O. Geometry optimization and frequency calculations at the same level of theory have been performed to identify all of the stationary points as minima (zero imaginary frequencies) or transition states (one imaginary frequency) and to provide free energies at 298.15 K.



RTa

Energy (RB3LYP) : -1583.70605 A.U.
Gibbs Free Energy : -1583.49280 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
Rh	2.8759101	-1.0365513	0.0464139
O	2.6338820	2.0238730	-0.6323071
C	3.8204112	1.5800769	-0.7359050
C	2.4785304	0.3850147	2.5133861
C	0.2111087	-1.9246407	0.7465841
H	-0.5511334	-2.6480229	1.0682128
C	1.6367776	-0.8157810	-2.5190807
O	3.1851118	-0.5392289	2.0301731
O	1.3850396	-2.3632398	0.6247640
O	0.9161190	0.1154682	-2.0420329
H	1.4500852	-1.0516316	-3.5756305
H	4.5685238	2.3218448	-1.0471926
O	-0.2191750	-0.7428273	0.5424565
O	2.5258749	-1.4919932	-1.9351209
O	1.5818694	1.0702011	1.9258475
O	4.2425387	0.4083052	-0.5279850
C	-4.8089153	-1.9274427	0.4731614
H	-4.4012804	-1.8252872	1.4870553
C	-3.8946583	-1.3117526	-0.5983689
H	-2.8344808	-1.3071800	-0.3330221
H	-3.9988393	-1.8565835	-1.5421061
C	-4.4346738	0.1282749	-0.7803923
C	-6.0997303	-1.1115342	0.3872645
O	-7.1837815	-1.3902889	0.8699511
N	-5.8182540	0.0282135	-0.3369457
C	-1.4544045	1.9362928	0.1989694
O	-1.6396875	2.5220668	1.2651096
C	-6.8269387	1.0277425	-0.6269988
H	-6.6141729	1.9845643	-0.1338483
H	-6.9007011	1.2012113	-1.7080418
H	-4.3922902	0.4456846	-1.8304747
H	-7.7786956	0.6444076	-0.2537617
H	2.6434171	0.6427808	3.5677339
H	-5.0263722	-2.9873136	0.3198363
Rh	1.1539329	0.7024072	-0.0527028
N	-0.2005135	2.0725666	-0.2917870
C	-3.6749778	1.1612667	0.0593647
H	-4.1489629	2.1466676	0.0248831
H	-3.5952798	0.8477765	1.1041994
O	-2.3461106	1.2635386	-0.5173084

TSa1

Energy (RB3LYP) : -1583.48435 A.U.
Gibbs Free Energy : -1583.70095 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	-2.2217100	-0.2695714	0.1289937
H	-1.3044450	-0.2208447	-0.5361879
Rh	3.9226075	0.6907470	-0.0301450
O	4.5770291	-0.9663310	1.0234545
C	3.7678100	-1.9227384	1.1744705
O	2.5738052	-2.0194318	0.7497892
O	4.6101550	-0.1535936	-1.7784859
O	2.6256646	-1.2269082	-2.0921598
O	1.1583482	0.4340046	1.4158788
O	3.1507717	1.4876619	1.7244361
C	3.8145693	-0.9097433	-2.4019579
C	1.9764821	1.1810065	2.0471307
O	3.1348451	2.2818883	-1.1109786
O	1.1451266	1.2110671	-1.4150035
C	1.9585455	2.1792370	-1.5535081
H	4.1883422	-1.3554327	-3.3337985
H	4.1304447	-2.7882148	1.7455595
H	1.5945894	1.6059665	2.9860159
H	1.5766597	3.0318083	-2.1323669
N	0.0815338	-1.4390559	-0.7395700
Rh	1.7862498	-0.4597225	-0.3590717
C	-1.7700130	-1.0980678	1.3326645
H	-2.5999593	-1.2894751	2.0175922
H	-0.9482659	-0.6155966	1.8674886
C	-3.3947938	-0.8809613	-0.6688872
H	-3.0450593	-1.5782516	-1.4332294
H	-4.0388830	-1.4394643	0.0209308
N	-2.6706729	1.0571186	0.4551665
C	-0.3543613	-2.4947576	-0.0153166
O	-1.3421687	-2.4053417	0.8929552
O	0.1572279	-3.5697585	-0.3084610
C	-4.1378354	0.3356289	-1.2381519
H	-5.2257831	0.2303166	-1.2499345
H	-3.8232878	0.5758828	-2.2614073
C	-3.7288651	1.4935109	-0.3365702
O	-4.2030903	2.6130041	-0.2982301
C	-1.9175320	1.9909312	1.2745241
H	-0.8829604	2.0610612	0.9208165
H	-1.9108175	1.6813651	2.3256162
H	-2.4103039	2.9610565	1.1899385

TSa2

Energy (RB3LYP) : -1583.67689 A.U.
Gibbs Free Energy : -1583.45916 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	-2.8841874	1.4114493	0.9581340
H	-2.7731318	1.6285388	-0.1095798
C	-1.9539641	2.2989568	1.8030599
H	-1.8523652	3.3208753	1.4252392
H	-2.3026647	2.3477176	2.8430370
C	-0.6396149	1.5058035	1.6930602
C	-2.3795773	-0.0053060	1.2550781
O	-3.0194058	-1.0319677	1.1879016
N	-1.0650611	0.0876820	1.7700788
C	2.0594425	0.3875570	1.4371983
O	3.2271565	0.0446590	1.2403921
C	-0.7911705	-0.8080541	2.9027409
H	-1.2949475	-0.4696051	3.8195921
H	-1.1861318	-1.7860233	2.6258913
H	-0.2645607	1.6724759	0.6764065
H	0.2772179	-0.9091968	3.0805638
H	-3.9442529	1.4750751	1.2131083
C	0.4747872	1.8726173	2.6431016
H	0.5610126	2.9605307	2.6974043
H	0.3043835	1.4907883	3.6545693
O	1.7907468	1.4361592	2.2253600
N	1.1967619	-0.4712625	0.8596849
Rh	0.8523471	-1.2835893	-3.5031016
O	2.7932107	-1.7758765	-1.1616579
C	3.2143661	-2.2772071	-2.2471562
O	2.6639446	-2.2571835	-3.3831108
O	1.9322193	1.0111540	-1.6261080
O	1.8508319	0.5122211	-3.8504195
O	-0.1347304	-3.0271316	-2.9768345
O	0.0236112	-2.5650230	-0.7490726
C	2.1522828	1.2305348	-2.8590768
C	-0.3161904	-3.2669123	-1.7495399
O	-0.8467783	0.1970247	-1.3388357
O	-0.9635724	-0.2883708	-3.5573938
C	-1.3974922	0.2054376	-2.4864180
H	2.6723486	2.1736504	-3.0791095
H	4.1824943	-2.7915104	-2.1773808
H	-0.8363740	-4.2045268	-1.5092483
H	-2.3720299	0.7116796	-2.5373354
Rh	0.9890380	-0.7638408	-1.1102227

PDa1

Energy (RB3LYP) : -607.976560 A.U.

Gibbs Free Energy : -607.835756 A.U.

Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	-0.0511663	-0.5458795	0.1929124
C	-2.2301405	0.0717988	-0.4694320
O	-3.1383910	0.4887936	-1.1402385
O	-2.2472451	0.0338695	0.9030277
C	-1.0528403	-0.6010879	1.3703852
H	-1.2794153	-1.6420267	1.6282579
H	-0.6901234	-0.0764964	2.2566772
N	0.8745691	0.5820158	0.2405423
C	0.8992143	-1.7650384	0.1214871
H	0.4440271	-2.5694775	-0.4604627
H	1.0661317	-2.1389677	1.1383060
C	2.2098409	-1.2216178	-0.4599039
H	2.2792808	-1.3570579	-1.5463508
H	3.1095770	-1.6619371	-0.0234517
C	2.1595677	0.2770277	-0.1683828
O	3.0690308	1.0776892	-0.2882849
C	0.4488763	1.9576201	0.4401695
H	-0.2888527	2.2610877	-0.3119863
H	1.3379071	2.5834486	0.3443730
H	0.0122083	2.1000104	1.4345902
N	-1.0204980	-0.4523955	-0.8943015
H	-0.7365085	-0.2456812	-1.8430865

IMa2
Energy (RB3LYP) : -1583.72883 A.U.
Gibbs Free Energy : -1583.50744 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	3.1002695	0.7301339	-1.1796213
H	2.3581767	1.3992471	-1.6155738
C	4.5282222	1.3029762	-1.1835543
H	5.0144862	1.1287881	-2.1466519
C	2.2374489	-1.7045037	0.2063929
O	1.8352201	-2.7702293	0.5900754
C	5.2437286	0.5885450	-0.0265991
H	5.6954425	-0.3583775	-0.3432704
H	6.0230377	1.1770564	0.4654753
C	4.1685797	0.2392196	0.9715434
O	4.2191286	-0.1575905	2.0861554
C	2.3145441	1.8447505	0.9389602
H	1.4107765	2.1792756	0.4361115
H	4.5110894	2.3856682	-1.0206366
H	2.1077945	1.6212484	1.9836346
N	2.7634647	0.5632770	0.2987446
N	1.7894461	-0.4662777	0.6192821
H	3.1100992	2.5879594	0.8411951
Rh	-2.7815880	0.2020962	-0.2422650
O	-0.9292456	-1.6047711	1.4961006
C	-2.1544885	-1.8961392	1.6181024
C	-1.4234841	-1.6335676	-2.0180268
C	-1.7830305	1.7495522	1.9887957
H	-1.8643271	2.4480202	2.8348323
C	-1.0543484	2.0517161	-1.6787094
O	-2.5709628	-1.1566339	-1.8000257
O	-2.8510364	1.5206505	1.3567676
O	-0.0382311	1.5042232	-1.1393975
H	-0.8344578	2.8770118	-2.3731158
H	-2.3752626	-2.7201548	2.3108557
O	-0.6221651	1.2833290	1.7758383
O	-2.2681423	1.7704930	-1.5187346
O	-0.3387668	-1.3911384	-1.4037546
O	-3.1525883	-1.3638014	1.0490743
H	-1.3450159	-2.3502794	-2.8482251
Rh	-0.3938539	-0.0852112	0.2134318
C	2.9899875	-0.6842581	-1.7720541
H	1.9877189	-0.8589709	-2.1735050
H	3.7247825	-0.8340785	-2.5673675
O	3.2787391	-1.6535040	-0.7550776

RTb

Energy (RB3LYP) : -1929.28015 A.U.
Gibbs Free Energy : -1928.96175 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	-0.1070451	-1.1812652	5.5567685
C	-0.4025262	-2.5245237	3.5623030
C	1.1648765	-0.6654338	3.5431769
C	0.5338897	-1.7406693	2.8982600
C	0.8288771	-0.4018588	4.8743658
C	-0.7284279	-2.2504579	4.8979724
H	-0.8941973	-3.3561031	3.0671075
H	1.3043391	0.4309792	5.3873512
H	-0.3379325	-0.9506981	6.5906208
H	0.7709930	-1.9645758	1.8601556
N	-1.1091910	-0.1556481	-2.3676750
C	-0.1195061	-0.0324137	-1.4527509
O	-1.6538871	-3.0791512	5.4637103
C	-2.0250586	-2.8505278	6.8134434
H	-1.1664996	-2.9476841	7.4912893
H	-2.7628871	-3.6180698	7.0547600
H	-2.4779539	-1.8589318	6.9465748
C	2.1584686	0.2168525	2.8145766
H	2.9548346	0.5477670	3.4865560
H	2.6220317	-0.3385273	1.9904257
Rh	-0.5437231	-0.2842783	-6.7104411
O	1.2393313	-0.6219793	-4.1205486
C	1.9038514	-0.7162891	-5.2028297
O	1.4857267	-0.6324502	-6.3885214
O	-0.4458478	1.7344831	-4.3827541
O	-0.2097798	1.7504167	-6.6464869
O	-0.8811864	-2.3231209	-6.7148798
O	-1.0890092	-2.3472897	-4.4517595
C	-0.2327726	2.2864138	-5.5068627
C	-1.0758013	-2.8844337	-5.6042252
O	-2.8308263	0.0008773	-4.5815651
O	-2.5845003	0.0452121	-6.8498937
C	-3.2469969	0.1095168	-5.7766429
H	-0.0460270	3.3682658	-5.4632361
H	2.9802295	-0.8943486	-5.0716275
H	-1.2550957	-3.9677510	-5.6154250
H	-4.3273262	0.2816236	-5.8803711
Rh	-0.8024900	-0.3161860	-4.2717913
O	0.1424618	-1.0752757	-0.8516797
O	0.3992066	1.1745513	-1.2507646

C	1.3444353	1.2894864	-0.1509625
H	1.9364430	2.1750122	-0.3924934
H	1.9923498	0.4100342	-0.1443052
N	1.5614536	1.4457803	2.2856601
C	1.7362696	2.6680345	2.8942034
O	2.4531131	2.8816914	3.8592187
C	0.6049054	1.4529645	1.1860197
H	-0.0970447	0.6185437	1.2962806
C	0.8874014	3.6851042	2.1277485
H	0.4132719	4.3787639	2.8265835
H	1.5477211	4.2781955	1.4820705
C	-0.1055276	2.8219844	1.3314390
H	-0.3780655	3.2401732	0.3585213
H	-1.0293490	2.6872145	1.9033299

TSb1

Energy (RB3LYP) : -1929.25831 A.U.
Gibbs Free Energy : -1929.93439 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	-0.2730959	3.4151395	1.1582832
C	-1.7771197	1.6070929	1.8522380
C	0.6020199	1.1486830	1.5618714
C	-0.7226138	0.7392805	1.9334005
C	0.7836509	2.5300578	1.2374241
C	-1.5702615	2.9461373	1.4361615
H	-2.7862630	1.3014337	2.1036420
H	1.7905663	2.8810126	1.0290469
H	-0.0975245	4.4422602	0.8635391
H	-0.8585136	-0.2757842	2.2859499
N	0.3882260	0.9673212	-0.6383971
C	1.5951857	0.9571572	-1.2398027
O	-2.6783620	3.6961713	1.3642038
C	-2.5852260	5.0490375	0.9132608
H	-1.9784604	5.6521092	1.5982702
H	-3.6087663	5.4243910	0.9050462
H	-2.1658177	5.0942722	-0.0975613
C	1.7791623	0.3902581	2.1839946
H	2.6719240	1.0157474	2.1304496
H	1.5261356	0.2527349	3.2439833
Rh	-2.6629433	-1.9882546	-2.4814020
O	0.4478248	-1.7120114	-2.1656250

C	0.1082548	-2.7116680	-2.8714697
O	-1.0526459	-3.0970601	-3.1782869
O	-1.1237139	0.6105344	-3.1970214
O	-2.5927953	-0.8272587	-4.1877938
O	-2.6602444	-3.0968155	-0.7204542
O	-1.1590426	-1.6886000	0.2504009
C	-1.8460479	0.1958183	-4.1478414
C	-1.9201539	-2.7052527	0.2238943
O	-2.7030301	0.6378741	-0.7762253
O	-4.1889542	-0.8005008	-1.7393767
C	-3.8630155	0.2280332	-1.0823334
H	-1.8213692	0.8074597	-5.0611763
H	0.9385630	-3.3182381	-3.2619742
H	-1.9218911	-3.3097902	1.1415649
H	-4.6943487	0.8529803	-0.7236278
Rh	-1.0569296	-0.4700715	-1.4167208
O	1.6735289	1.1469375	-2.4451964
O	2.7258894	0.7603773	-0.4658740
C	3.2100177	-0.5976023	-0.5436716
H	4.1812752	-0.5961242	-1.0526159
H	2.5083237	-1.2065075	-1.1214112
N	2.1329182	-0.9186211	1.6606693
C	1.4971320	-2.0675329	2.0580868
O	0.5495348	-2.1212192	2.8300989
C	3.3503137	-1.1357256	0.8777061
H	4.1817623	-0.6092920	1.3666170
C	2.1783957	-3.2321298	1.3447737
H	2.2285584	-4.1078153	1.9959489
H	1.5585779	-3.4933778	0.4780694
C	3.5509642	-2.6737529	0.9299646
H	3.9065837	-3.0678522	-0.0273799
H	4.3038614	-2.9214537	1.6846788

IMb1
Energy (RB3LYP) : -953.453114 A.U.
Gibbs Free Energy : -953.207171 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	-1.3422326	2.7427655	-0.1269201
C	-2.8209662	1.0666579	0.8960310
C	-1.8555667	0.1336693	0.9909803
C	-2.5680142	2.3877925	0.3323581
H	-3.8154684	0.8934629	1.2966345
H	-1.1080802	3.7536588	-0.4384165
H	-2.0234143	-0.8151477	1.4920204
C	0.5703318	-0.0518553	-1.7350508
O	-3.6588439	3.1989213	0.4089299
C	-3.5253955	4.5263877	-0.0740641
H	-2.7916087	5.0928180	0.5147574
H	-4.5091244	4.9872541	0.0300529
H	-3.2229497	4.5346936	-1.1294243
C	0.6558546	-0.3556385	1.1319291
H	1.5097359	0.3138818	1.2426475
H	0.2969781	-0.6175020	2.1336680
O	0.4371066	-0.8283949	-2.6484198
O	1.8061080	0.3115572	-1.2373444
C	2.7601757	-0.7524913	-1.2498287
H	3.7386727	-0.2819955	-1.1335514
H	2.7161247	-1.2605694	-2.2157030
N	1.1291190	-1.5880459	0.4979104
C	0.5474930	-2.7887212	0.8521876
O	-0.4925383	-2.8936393	1.4833024
C	2.4748851	-1.7415732	-0.0764977
H	3.2195893	-1.5673222	0.7156937
C	1.4617845	-3.9169207	0.3907081
H	1.9180078	-4.3578433	1.2863083
H	0.8869667	-4.7054463	-0.1014975
C	2.4906588	-3.2275305	-0.5162453
H	2.1653690	-3.2911934	-1.5596963
H	3.4927614	-3.6600662	-0.4502946
N	-0.5126502	0.5514102	-1.0754507
C	-0.5066622	0.3737074	0.4290584
C	-0.2732511	1.7324061	-0.1842933
H	0.7490440	2.1008524	-0.1724796

RTa'

Energy (RB3LYP) : -1583.674179 A.U.

Gibbs Free Energy : -1583.457427 A.U.

Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
Rh	2.85772600	-1.05209500	-0.04621200
O	2.55904800	1.96646300	-0.85814000
C	3.70385000	1.48726600	-1.12798700
C	2.87323900	0.53217000	2.35288900
C	0.31093800	-1.82717100	1.11426700
H	-0.40192000	-2.51243500	1.59417700
C	1.23504400	-0.97823500	-2.38847900
O	3.48646300	-0.43047800	1.82059100
O	1.45008600	-2.29420500	0.85225000
O	0.61261500	-0.00076000	-1.86908800
H	0.87842600	-1.27913500	-3.38325000
H	4.40590500	2.19225000	-1.59435000
O	-0.13390800	-0.65367300	0.89484200
O	2.19653900	-1.63507000	-1.90790200
O	1.89401400	1.18962300	1.87744100
O	4.13304400	0.31620900	-0.93046400
C	-4.83231600	-1.85659400	0.66902000
H	-4.51304200	-1.64381400	1.69714400
C	-3.83389300	-1.33967400	-0.37983400
H	-2.79985000	-1.29468500	-0.02857600
H	-3.85633900	-1.97777300	-1.26899200
C	-4.36372700	0.06790300	-0.75181100
C	-6.11591700	-1.07294400	0.39075000
O	-7.23685000	-1.31958400	0.80175600
N	-5.77859500	-0.00387000	-0.41379900
C	-1.45563400	1.95093400	0.28045700
O	-1.68411500	2.54530100	1.33396500
C	-6.76470400	0.94637200	-0.88829600
H	-6.59245700	1.95380100	-0.48898900
H	-6.75696500	0.99971800	-1.98445400
H	-4.23773900	0.27749500	-1.82205300
H	-7.74101700	0.59551800	-0.54775800
H	3.21128100	0.85397000	3.34678000
H	-5.02875600	-2.92981700	0.60866600
Rh	1.16006700	0.71361300	0.01622500
N	-0.18490100	2.09957800	-0.15874600
C	-3.67516000	1.18986000	0.03479200
H	-4.15807600	2.15842800	-0.12676400
H	-3.66202300	0.97885700	1.10758700
O	-2.31368100	1.26492600	-0.46357000

TSa'

Energy (RB3LYP) : -1583.662856 A.U.

Gibbs Free Energy : -1583.441487 A.U.

Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	4.01934100	1.53907500	-0.58557400
H	3.51113500	1.23194400	-1.50415900
H	4.84618000	2.21325800	-0.83181900
C	4.57135900	0.30926800	0.14789700
H	5.21411900	0.65038500	0.96951900
N	3.52131200	-0.55014700	0.68868300
O	3.11599100	2.31284600	0.22353100
C	1.77857300	2.25470500	-0.03714400
O	1.07470500	3.24700500	0.08466000
N	1.30594300	1.08661600	-0.51333800
Rh	-0.41969300	0.26762900	-0.11265700
Rh	-2.74229000	-0.49447900	0.06069800
O	-3.39158600	1.11834600	-1.03079500
O	-1.23543200	1.80520400	-1.27159800
O	-0.26120600	-0.89945300	-1.82688800
O	0.07196200	-1.34007900	1.05800100
O	-0.72547100	1.34177100	1.62890600
O	-2.05835700	-2.11510800	1.14803500
O	-2.43774700	-1.56779700	-1.68441000
O	-2.88751300	0.63330300	1.79625800
C	-0.82437200	-2.17533600	1.39559600
C	-1.87099100	1.27988800	2.17398000
C	5.33318400	-0.60402900	-0.85004400
H	6.19743200	-1.05332600	-0.35037200
H	5.70701000	-0.04684200	-1.71513000
C	4.30685800	-1.68891500	-1.21384800
H	3.68713100	-1.40762500	-2.07414500
H	4.74461700	-2.66681000	-1.42503900
C	-1.29093500	-1.53304400	-2.21310800
H	-1.16024100	-2.12672100	-3.12873900
C	-2.48663300	1.89409300	-1.44723900
H	-2.81357300	2.75883400	-2.04054600
H	-0.46536000	-3.03871000	1.97006800
H	-1.98069700	1.86888200	3.09510800
C	3.41945800	-1.76981600	0.02700000
O	2.75432900	-2.71851700	0.39724300
C	3.05325700	-0.39978900	2.05989200
H	2.60350100	0.58301700	2.21115200
H	2.30735100	-1.17225800	2.24057600
H	3.88784000	-0.51781900	2.76627500

IMa'

Energy (RB3LYP) : -1583.695699 A.U.
Gibbs Free Energy : -1583.469716 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
C	4.47174800	1.21004100	-0.60467500
H	4.14807200	1.22389500	-1.65390600
H	5.51835900	1.52373100	-0.56189000
C	4.31661800	-0.19374500	-0.02244800
H	5.00837900	-0.34069800	0.80970600
N	2.90926000	-0.30272700	0.58966700
O	3.71392900	2.13629500	0.15003800
C	2.33241000	1.92265300	-0.02657800
O	1.61202900	2.87391200	-0.19455700
N	1.93413800	0.60584600	-0.04036000
Rh	-0.29982200	0.19237500	0.00415800
Rh	-2.70646300	-0.21841500	-0.08097000
O	-2.76935800	0.90092400	-1.81820500
O	-0.51612300	1.24740200	-1.76735500
O	-0.05817600	-1.54684100	-1.14500500
O	-0.27445600	-0.90199200	1.78594800
O	-0.73565700	1.85248700	1.16462400
O	-2.51138900	-1.31710800	1.67376100
O	-2.30322000	-1.93011800	-1.19516400
O	-2.98406300	1.50030700	1.02645100
C	-1.36845200	-1.39622300	2.19973800
C	-1.94830400	2.12743300	1.39619500
C	4.43845500	-1.32889000	-1.07626900
H	5.13536100	-2.09683500	-0.72818500
H	4.81957200	-0.94027700	-2.02468300
C	3.02358200	-1.92188400	-1.22479900
H	2.39932400	-1.33829300	-1.90651500
H	3.00064000	-2.97214800	-1.51713900
C	-1.10250500	-2.19493900	-1.46713100
H	-0.93081600	-3.10462900	-2.06260100
C	-1.67765500	1.36794500	-2.25529100
H	-1.74250000	1.95454000	-3.18337500
H	-1.30477500	-1.96674100	3.13824300
H	-2.12185100	3.03009700	1.99971800
C	2.48681300	-1.75451500	0.16191300
O	2.02586700	-2.50707800	0.95348700
C	2.89323600	-0.16776000	2.08263800
H	3.22307200	0.84268200	2.32156900
H	1.86912500	-0.34204900	2.40933600
H	3.56637000	-0.90955600	2.51914100

$Rh_2(OAc)_4$
Energy (RB3LYP) : -975.831671 A.U.
Gibbs Free Energy : -975.768726 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
Rh	0.0000000	0.0000000	1.2001539
Rh	0.0000000	0.0000000	-1.2001539
O	2.0675328	0.0000000	-1.1385282
C	2.6233150	0.0000000	0.0000000
O	2.0675328	0.0000000	1.1385282
O	0.0000000	-2.0675328	-1.1385282
O	0.0000000	-2.0675328	1.1385282
O	0.0000000	2.0675328	1.1385282
O	0.0000000	2.0675328	-1.1385282
C	0.0000000	-2.6233150	0.0000000
C	0.0000000	2.6233150	0.0000000
O	-2.0675328	0.0000000	-1.1385282
O	-2.0675328	0.0000000	1.1385282
C	-2.6233150	0.0000000	0.0000000
H	0.0000000	-3.7214802	0.0000000
H	3.7214802	0.0000000	0.0000000
H	0.0000000	3.7214802	0.0000000
H	-3.7214802	0.0000000	0.0000000

$MeO_2CN{=}Rh_2(esp)_2$ (Figure 3)
Energy (ωB97X-D) : -2347.06298 A.U.
Gibbs Free Energy : -2346.40475 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
Rh	1.2770063	-1.0964029	0.3444286
O	2.5956654	0.1034486	-0.6710577
C	2.1865807	1.2130012	-1.0955678
O	0.9996200	1.6575160	-0.9526954
O	1.7345830	-0.1065860	2.0984995
O	0.1529002	1.4648459	1.7580458
O	-0.9527217	-0.3843932	-1.7217131
O	0.6528757	-1.9391506	-1.4407788
C	1.0987354	0.9389909	2.4213686
C	-0.3032023	-1.4257447	-2.0736398
O	-0.0775568	-2.2548252	1.3579929

O	-1.6720111	-0.7029712	1.0298811
C	-1.2399933	-1.7961725	1.5151652
N	-1.8431136	1.8667380	-0.2406409
Rh	-0.4402121	0.5864066	0.0043434
C	-4.3043548	1.0772188	-2.7072132
H	-4.6205327	2.0889244	-2.9694370
H	-3.6620774	0.6765879	-3.4948011
C	-2.5338854	1.8439610	-1.4130610
O	-3.6084275	1.0760106	-1.4545162
O	-2.1103817	2.5787136	-2.2908271
H	-5.1676770	0.4318897	-2.5547649
C	-2.2448095	-2.6021844	2.3353804
C	-1.5487404	-3.7144148	3.1260895
H	-0.9863315	-4.3756589	2.4625687
H	-2.3057391	-4.3077611	3.6503627
C	-3.2192957	-3.2283494	1.3156464
H	-2.6880233	-3.9101646	0.6426736
H	-3.7100760	-2.4568898	0.7148318
H	-3.9883755	-3.8031480	1.8425663
C	-3.0452514	-1.6618363	3.2602993
H	-3.7681576	-2.2842415	3.8036007
H	-3.6348462	-0.9881697	2.6275129
C	1.5018778	1.6156063	3.7334362
C	3.0218724	1.8459597	3.6957130
H	3.5621322	0.9028553	3.5829171
H	3.3449112	2.3293670	4.6240254
H	3.2961088	2.5016779	2.8617515
C	1.1754843	0.6391938	4.9026042
H	1.7297583	-0.2906672	4.7345437
H	1.5718347	1.0920889	5.8192688
C	3.1552166	2.1459419	-1.8178977
C	3.2984926	3.4132769	-0.9550415
H	3.9764833	4.1187803	-1.4473832
H	3.7192160	3.1709935	0.0272861
H	2.3311998	3.9009356	-0.8075570
C	2.5412424	2.5419835	-3.1911387
H	3.2689179	3.1906301	-3.6936177
H	1.6433224	3.1397512	-3.0065312
C	-0.7806764	-2.0785770	-3.3701739
C	-0.7550118	-1.0107883	-4.5010904
H	-1.4949471	-0.2397619	-4.2624603
H	-1.0842653	-1.5065745	-5.4224164
C	-2.2352517	-2.5309219	-3.1482445
H	-2.2931469	-3.2901941	-2.3606104
H	-2.6321129	-2.9691152	-4.0705485
H	-2.8677693	-1.6878287	-2.8566463

C	-0.9216435	-0.5693551	4.2197430
C	-2.4340806	0.7652593	6.1095231
C	-2.2955796	-0.7965729	4.2589270
C	-0.2961832	0.3444942	5.0727691
C	-1.0653610	1.0081320	6.0250895
C	-3.0420881	-0.1205313	5.2301372
H	-0.5951585	1.7205238	6.6982591
H	-4.1157100	-0.2855060	5.2875512
H	-3.0304214	1.2790708	6.8579609
C	0.7715757	2.9483020	3.9116065
H	1.0714533	3.4022390	4.8631754
H	-0.3122662	2.8166368	3.9151084
H	1.0239128	3.6419167	3.1043135
C	0.5911674	-0.3585833	-4.7091915
C	3.1185463	0.8137569	-4.9586009
C	0.9260948	0.7842807	-3.9812600
C	1.5352079	-0.8939957	-5.5872905
C	2.7887960	-0.3050068	-5.7169637
C	2.1912066	1.3667142	-4.0731400
H	0.1854821	1.2289704	-3.3228413
H	1.2852311	-1.7733901	-6.1758975
H	3.5133163	-0.7211836	-6.4109580
H	4.1026099	1.2651900	-5.0579813
H	-0.2919728	-1.0975712	3.5126549
H	-0.8566400	-3.3149275	3.8714524
C	0.0956396	-3.2820545	-3.7217574
H	1.1418470	-2.9938282	-3.8460719
H	-0.2581025	-3.7299261	-4.6574260
H	0.0489129	-4.0410167	-2.9362464
C	4.5170583	1.4695744	-1.9886250
H	4.9568819	1.2266495	-1.0176795
H	5.1963533	2.1491844	-2.5155904
H	4.4368513	0.5427518	-2.5614807

$MeO_2CHC=Rh_2(esp)_2$ (Figure 3)
Energy (ωB97X-D) : -2330.37753 A.U.
Gibbs Free Energy : -2331.04790 A.U.
Cartesian Coordinates (Angstroms)

Atom	X	Y	Z
Rh	-0.9317073	-1.5091693	-0.2196314
O	0.5611170	-2.2216307	-1.4464176
C	1.6115286	-1.5495350	-1.5829983

O	1.8556206	-0.4279085	-1.0235981
O	0.0223720	-2.3535702	1.4228786
O	1.3224829	-0.5434788	1.7769843
O	-0.4531622	1.3700639	-1.3848141
O	-1.7336267	-0.4384252	-1.8077884
C	0.9211422	-1.7220020	2.0421323
C	-1.3431631	0.7304603	-2.0423031
O	-2.3529701	-0.7028855	1.0403473
O	-1.0709899	1.1137496	1.4097156
C	-2.1031467	0.3931808	1.6031060
C	1.5324290	2.0171006	0.5317256
H	2.2649249	2.0636801	1.3450927
Rh	0.4664447	0.4558511	0.2033660
C	0.4121824	5.0947890	-1.1264245
H	1.3220485	5.6986695	-1.1382739
H	0.2392664	4.6717691	-2.1181710
C	1.4995327	3.1790148	-0.3692113
O	0.5208527	4.0415468	-0.1589255
O	2.3337854	3.2257744	-1.2472386
H	-0.4419502	5.6899515	-0.8089228
C	-3.1161697	0.9503246	2.6045596
C	-4.1364649	-0.1165798	3.0144225
H	-4.6547273	-0.5193792	2.1411231
H	-4.8779283	0.3337983	3.6837095
C	-3.8432457	2.1024249	1.8806271
H	-4.3861596	1.7260498	1.0068913
H	-3.1349938	2.8668968	1.5471648
H	-4.5687026	2.5677794	2.5568001
C	-2.3832002	1.5320996	3.8306827
H	-3.1501350	1.9398415	4.5023988
H	-1.7873462	2.3877624	3.4919293
C	1.5737887	-2.4343960	3.2308504
C	2.0451168	-3.8165600	2.7500225
H	1.2095448	-4.4046746	2.3632693
H	2.5074736	-4.3608812	3.5807112
H	2.7921486	-3.7178443	1.9543520
C	0.4870800	-2.6319625	4.3291485
H	-0.3283895	-3.2213257	3.8962013
H	0.9380077	-3.2365741	5.1252631
C	2.7322160	-2.0953572	-2.4687051
C	3.9482317	-2.3618117	-1.5633317
H	4.7807117	-2.7435722	-2.1644838
H	3.7097614	-3.1127861	-0.8018225
H	4.2713605	-1.4471802	-1.0588739
C	3.1165839	-1.0138154	-3.5181028
H	3.9114310	-1.4383182	-4.1436289

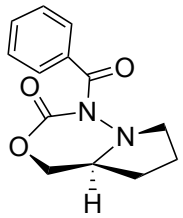
H	3.5414705	-0.1558451	-2.9880570
C	-1.9771954	1.5084645	-3.1970642
C	-0.8486738	2.0045728	-4.1450170
H	-0.2340730	2.7271959	-3.5980206
H	-1.3307185	2.5437428	-4.9699818
C	-2.6883849	2.7315569	-2.5909888
H	-3.4975567	2.4202115	-1.9212338
H	-3.1251719	3.3424522	-3.3887754
H	-1.9894563	3.3463126	-2.0169188
C	-1.0051858	-0.6102448	4.1962335
C	-0.0495150	0.3835090	6.5922146
C	-1.4594767	0.6321516	4.6341122
C	-0.0523241	-1.3449759	4.9080299
C	0.4199200	-0.8383300	6.1164006
C	-0.9726167	1.1129709	5.8546121
H	1.1587903	-1.3978609	6.6846646
H	-1.3184758	2.0758399	6.2244759
H	0.3141226	0.7719609	7.5393208
C	2.7600872	-1.6344759	3.7728139
H	3.2024048	-2.1671130	4.6227613
H	2.4559328	-0.6409232	4.1089597
H	3.5310099	-1.5131109	3.0058329
C	0.0389401	0.9084471	-4.6857029
C	1.6450073	-1.2021535	-5.5756389
C	1.1673922	0.5128991	-3.9658124
C	-0.2620145	0.2438398	-5.8760822
C	0.5419966	-0.8003771	-6.3219372
C	1.9651465	-0.5544429	-4.3809732
H	1.4257905	1.0409603	-3.0527866
H	-1.1288196	0.5478315	-6.4579378
H	0.3058588	-1.3054003	-7.2541375
H	2.2647888	-2.0249313	-5.9234323
H	-1.3801944	-1.0433401	3.2755773
H	-3.6675000	-0.9509619	3.5417021
C	-2.9843789	0.6340382	-3.9460382
H	-2.5120415	-0.2636495	-4.3512695
H	-3.4210318	1.2049378	-4.7737741
H	-3.7922863	0.3144147	-3.2825180
C	2.2904609	-3.3954330	-3.1440921
H	2.0554277	-4.1603383	-2.3992752
H	3.1003297	-3.7690683	-3.7814244
H	1.4012067	-3.2462895	-3.7606302

3. Chemoselective Intramolecular Formal Insertion Reaction of Rh-Nitrenes into an Amide Bond over C－H Insertion

3-1. Characterization of amide insertion products 7a－7p and 8

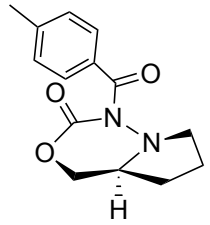
General procedure A for amide insertion reaction

To a pre-dried test tube were added carbamate substrate (0.2 mmol), $PhI(OAc)_2$ (0.28 mmol, 1.4 eq, 90.2 mg), MgO (0.46 mmol, 2.3 eq, 18.5 mg), and $Rh_2(esp\text{-}OMe)_2(acetone)_2$ (4 μmol, 2 mol%, 3.7 mg), and the tube was filled with argon gas. Then $PhCF_3$ (0.05 M, 4 mL) was added *via* a syringe at room temperature, and the reaction mixture was stirred for 1－1.5 h at 80 ℃. After complete consumption of the starting material, the reaction mixture was concentrated under reduced pressure. The obtained crude mixture was purified by flash chromatography on silica gel (*n*-hexane/EtOAc) to afford amide insertion product.



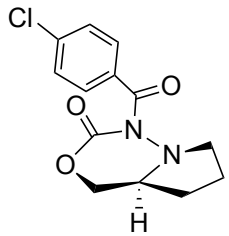
(*S*)-1-Benzoyltetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7a)

Prepared according to the general procedure A using **6a** (48.8 mg, 0.2 mmol), and isolated as white solid in 78% yield (37.7 mg): mp 120－122 ℃; R_f = 0.3 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.84-2.01 (m, 3H), 2.17 (m, 1H), 2.75 (m, 1H), 3.78 (m, 1H), 3.99 (m, 1H), 4.34 (dd, J = 11.6, 2.4 Hz, 1H), 4.46 (dd, J = 11.6, 4.8 Hz, 1H), 7.42 (dd, J = 7.6, 7.2 Hz, 2H), 7.53 (dd, J = 7.6, 7.6 Hz, 1H), 7.62 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.5, 28.0, 56.3, 57.6, 69.1, 128.2, 128.3, 132.1, 134.0, 154.1, 170.0; IR (ATR) ν 2975, 1755, 1697, 1666, 1466, 1448, 1383, 1359 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{13}H_{14}N_2NaO_3^+$ m/z 269.0897, found m/z 269.0902; $[\alpha]^{20}_D$ + 152.1° (*c* 1, $CHCl_3$). The enantiomeric excess was determined to be >99% by analytical chiral HPLC. 59 min, 80 min (OJ-H column, 80/20 n-hexane/iPrOH, 1 mL/min, 254 nm).



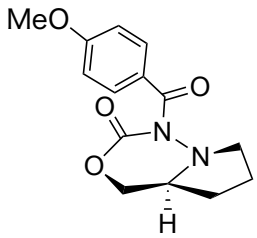
1-(4-Methylbenzoyl)tetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7b)

Prepared according to the general procedure A using **6b** (52.5 mg, 0.2 mmol), and isolated as pale brown solid in 67% yield (34.7 mg): mp 146－148 ℃; R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.78-2.00 (m, 3H), 2.13 (m, 1H), 2.38 (s, 3 H), 2.75 (m, 1H), 3.73 (dd, J = 7.6, 7.2 Hz, 1H), 3.92 (m, 1H), 4.28 (d, J = 11.6, 1H), 4.41 (dd, J = 11.6, 4.8 Hz, 1H), 7.19 (d, J = 8.0 Hz, 2H), 7.52 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.5, 22.4, 28.0, 56.1, 57.5, 69.0, 128.4, 128.9, 131.2, 142.8, 153.9, 169.9; IR (ATR) ν 2973, 1755, 1693, 1608, 1460, 1407, 1382, 1359 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{16}N_2NaO_3^+$ m/z 283.1053, found m/z 283.1051.



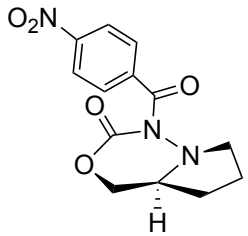
1-(4-Chlorobenzoyl)tetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7c)

Prepared according to the general procedure A using **6c** (56.7 mg, 0.2 mmol), and isolated as white solid in 68% yield (38.5 mg): mp 145－147 ℃; R_f = 0.4 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.83-2.04 (m, 3H), 2.18 (m, 1H), 2.74 (m, 1H), 3.75 (dd, J = 8.0, 7.2 Hz, 1H), 3.97 (m, 1H), 4.35 (dd, J = 11.6, 2.8 Hz, 1H), 4.44 (dd, J = 11.6, 4.8 Hz, 1H), 7.40 (d, J = 8.8 Hz, 2H), 7.56 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.4, 27.8, 56.1, 57.3, 69.0, 128.6, 129.6, 132.2, 138.4, 153.8, 169.0; IR (ATR) ν 2973, 1757, 1698, 1591, 1487, 1406, 1382, 1287 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{13}H_{13}ClN_2NaO_3^+$ m/z 303.0507, found m/z 303.0513.



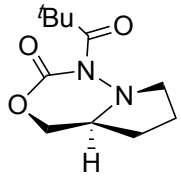
1-(4-Methoxybenzoyl)tetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7d)

Prepared according to the general procedure A using **6d** (55.7 mg, 0.2 mmol), and isolated as white solid in 61% yield (34.0 mg): mp 99－101 ℃; R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.82-2.02 (m, 3H), 2.17 (m, 1H), 2.75 (ddd, J = 10.4, 9.2, 2.0 Hz, 1H), 3.78 (dd, J = 8.8, 6.4 Hz, 1H), 3.85 (s, 3H), 3.97 (m, 1H), 4.31 (dd, J = 11.6, 2.4 Hz, 1H), 4.44 (dd, J = 11.6, 4.8 Hz, 1H), 6.91 (d, J = 8.8 Hz, 2H), 7.63 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.5, 28.0, 55.4, 56.3, 57.5, 69.1, 113.6, 125.9, 130.7, 154.5, 163.0, 160.3; IR (ATR) ν 2968, 1754, 1692, 1604, 1577, 1510, 1461, 1418 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{16}N_2NaO_4^+$ m/z 299.1002, found m/z 299.0996.



1-(4-Nitrobenzoyl)tetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7e)

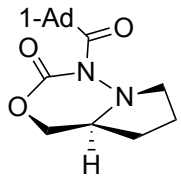
Prepared according to the general procedure A using **6e** (58.7 mg, 0.2 mmol), and isolated as pale yellow solid in 47% yield (27.5 mg): mp 156－158 ℃; R_f = 0.3 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.83-1.95 (m, 2H), 2.00 (m, 1H), 2.20 (m, 1H), 2.77 (ddd, J = 9.2, 9.2, 6.4 Hz, 1H), 3.74 (dd, J = 8.4, 7.2 Hz, 1H), 3.97 (m, 1H), 4.38 (dd, J = 11.6, 3.2 Hz, 1H), 4.45 (dd, J = 11.6, 4.4 Hz, 1H), 7.74 (d, J = 8.4 Hz, 2H), 8.28 (d, J = 8.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.3, 27.6, 55.9, 57.1, 69.1, 123.6, 128.8, 140.0, 149.5, 153.0, 168.2; IR (ATR) ν 2967, 1788, 1759, 1703, 1653, 1604, 1523, 1472 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{13}H_{13}N_3NaO_5^+$ m/z 314.0747, found m/z 314.0742.



1-Pivaloyltetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7f)

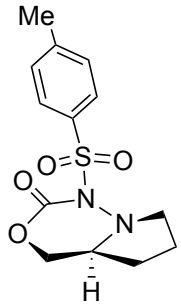
Prepared according to the general procedure A using **6f** (45.9 mg, 0.2 mmol) and isolated as pale yellow solid in 60% yield (27.5 mg): mp 48－50 ℃; R_f = 0.5 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.35 (s, 9H), 1.74 (m, 1H), 1.87-1.99 (m, 2H), 2.14 (m, 1H), 2.75 (ddd, J = 11.6, 9.2, 5.6 Hz, 1H), 3.49 (dd, J = 9.2, 8.4 Hz, 1H), 3.82 (m, 1H), 4.12-4.20 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.4, 27.3, 28.4, 41.0, 56.6, 58.0, 69.0, 153.1, 179.4;

IR (ATR) ν 2972, 1782, 1682, 1481, 1461, 1392, 1366, 1287 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{11}H_{18}N_2NaO_3^+$ m/z 249.1210, found m/z 249.1206.



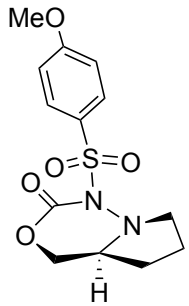
1-((3*r*,5*r*,7*r*)-Adamantane-1-carbonyl)tetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7g)

Prepared according to the general procedure A using **6g** (61.3 mg, 0.2 mmol) and isolated as pale orange solid in 52% yield (31.7 mg): mp 138－140 ℃; R_f = 0.5 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.64-1.80 (m, 7H), 1.84-2.07 (m, 8H), 2.08-2.20 (m, 4H), 2.73 (m, 1H), 3.52 (dd, *J* = 8.4, 7.2 Hz, 1H), 3.83 (m, 1H), 4.10-4.20 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.4, 28.1, 28.3, 36.4, 38.1, 43.9, 56.6, 58.0, 68.9, 153.5, 179.4; IR (ATR) ν 2903, 2849, 1779, 1677, 145, 1277, 1255, 1186, 1165 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{17}H_{24}N_2NaO_3^+$ m/z 327.1679, found m/z 327.1671.



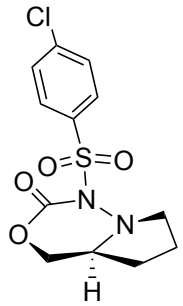
1-Tosyltetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7h)

Prepared according to the general procedure A using **6h** (59.7mg, 0.2 mmol), $PhI(OAc)_2$ (0.56 mmol, 2.8 eq, 180.4 mg), MgO (0.92 mmol, 4.6 eq, 37.1 mg), and $Rh_2(esp\text{-}OMe)_2(acetone)_2$ (8 μ mol, 4 mol%, 7.5 mg) at 60 ℃, and isolated as white solid in 51% yield (30.5 mg): mp 118－120 ℃; R_f = 0.4 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.61 (m, 1H), 1.86-1.96 (m, 2H), 2.11 (m, 1H), 2.44 (s, 3H), 2.84 (ddd, *J* = 9.2, 9.2, 8.8 Hz, 1H), 3.45 (m, 1H), 3.57 (m, 1H), 4.11 (dd, *J* = 11.6, 8.8 Hz, 1H), 4.23 (dd, *J* = 11.6, 8.0 Hz, 1H), 7.33 (d, *J* = 8.4 Hz, 2H), 7.96 (d, *J* = 8.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.6, 21.7, 25.0, 54.5, 55.3, 68.4, 128.7, 129.6, 134.6, 145.2, 148.7; IR (ATR) ν 2954, 1726, 1596, 1494, 1465, 1402, 1368, 1307 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{13}H_{16}N_2NaO_4S^+$ m/z 319.0723, found m/z 319.0727.



1-((4-Methoxyphenyl)sulfonyl)tetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7i)

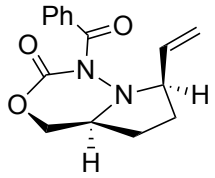
Prepared according to the general procedure A using **6i** (62.9mg, 0.2 mmol), $PhI(OAc)_2$ (0.56 mmol, 2.8 eq, 180.4 mg), MgO (0.92 mmol, 4.6 eq, 37.1 mg), and $Rh_2(esp\text{-}OMe)_2(acetone)_2$ (8 μmol, 4 mol%, 7.5 mg), and isolated as pale yellow solid in 48% yield (30.2 mg): mp 138－140 ℃; R_f = 0.4 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.61 (m, 1H), 1.87-1.96 (m, 2H), 2.12 (m, 1H), 2.84 (ddd, J = 9.2, 9.2, 9.2 Hz, 1H), 3.45 (m, 1H), 3.58 (m, 1H), 3.88 (s, 3H), 4.11 (d, J = 11.6, 4.8 Hz, 1H), 4.23 (d, J = 11.6, 8.0 Hz, 1H), 6.99 (d, 8.8 Hz, 2H), 8.01 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.5, 24.9, 54.4, 55.2, 55.7, 68.3, 114.1, 128.8, 131.0, 148.7, 164.0; IR (ATR) ν 2954, 1731, 1593, 1577, 1496, 1464, 1443, 1402 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{13}H_{16}N_2NaO_5S^+$ m/z 335.0672, found m/z 335.0670.



1-((4-Chlorophenyl)sulfonyl)tetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7j)

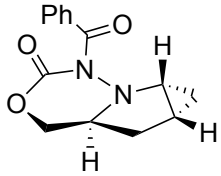
Prepared according to the general procedure A using **6j** (63.8 mg, 0.2 mmol), $PhI(OAc)_2$ (0.56 mmol, 2.8 eq, 180.4 mg), MgO (0.92 mmol, 4.6 eq, 37.1 mg), and $Rh_2(esp\text{-}OMe)_2(acetone)_2$ (8 μmol, 4 mol%, 7.5 mg), and isolated as pale brown solid in 48% yield (25.1 mg): mp 129－131 ℃; R_f = 0.3 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.62 (m, 1H), 1.87-1.98 (m, 2H), 2.33 (m, 1H), 2.86 (ddd, J = 9.2, 9.2, 9.2 Hz, 1H), 3.47 (m, 1H), 3.60 (m, 1H), 4.14 (dd, J = 11.6, 4.8 Hz, 1H), 4.25 (dd, J = 11.6, 8.4 Hz, 1H), 7.52 (d, J = 8.8 Hz, 2H), 8.03 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.5, 24.7, 54.4, 55.3, 68.4, 129.3, 130.1, 135.8, 140.9, 148.4; IR (ATR) ν 2957, 1733, 1583, 1475, 1396, 1374,

1181, 1172 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{12}H_{13}ClN_2NaO_4S^+$ m/z 339.0177, found m/z 339.0179.



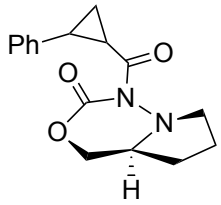
***rac*-(4a*S*,7*R*)-1-Benzoyl-7-vinyltetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7k)**

Prepared according to the general procedure A using **6k** (50.4 mg, 0.18 mmol), and isolated as pale yellow oil in 44% yield (22.0 mg): R_f = 0.6 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.70 (m, 1H), 1.85-2.03 (m, 2H), 2.21 (m, 1H), 3.47 (ddd, J = 10.4, 8.4, 6.0 Hz, 1H), 4.02 (m, 1H), 4.32 (dd, J = 11.6, 2.8 Hz, 1H), 4.41 (dd, J = 11.6, 4.8 Hz, 1H), 5.07 (d, J = 10.0 Hz, 1H), 5.18 (d, J = 17.2 Hz, 1H), 5.60 (ddd, J = 17.2, 10.0, 8.4 Hz, 1H), 7.39 (dd, J = 8.0, 7.2 Hz, 2H), 7.49 (dd, J = 8.0, 8.0 Hz, 1H), 7.55 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 27.0, 28.9, 57.3, 69.4, 71.7, 119.0, 127.9, 128.2, 131.5, 134.4, 137.0, 152.7, 169.8; IR (ATR) ν 2972, 1780, 1704, 1601, 1447, 1381, 1289, 1259 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{15}H_{16}N_2NaO_3^+$ m/z 295.1053, found m/z 295.1050.



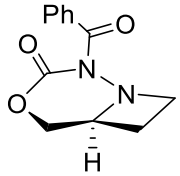
***rac*-(4a*S*,5a*R*,6a*R*)-1-Benzoylhexahydrocyclopropa[4,5]pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (7l)**

Prepared according to the general procedure A using **6l** (52.1 mg, 0.2 mmol), and isolated as pale brown solid in 73% yield (31.9 mg): mp 144−146 °C; R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.50 (ddd, J = 7.2, 4.8, 2.8 Hz, 1H), 0.85 (ddd, J = 8.0, 8.0, 7.2 Hz, 1H), 1.62 (m, 1H), 2.02 (dd, J = 12.8, 8.0 Hz, 1H), 2.29 (m, 1H), 3.31 (ddd, J = 8.0, 5.6, 2.8 Hz, 1H), 3.86 (dd, J = 8.4, 7.6 Hz, 1H), 4.27 (d, J = 11.6 Hz, 1H), 4.49 (dd, J = 11.6, 2.8 Hz, 1H), 7.40 (dd, J = 7.6, 7.6 Hz, 2H), 7.49 (dd, J = 7.6, 7.6 Hz, 1H), 7.57 (d, J = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.6, 16.1, 30.9, 48.5, 61.1, 67.3, 128.0, 128.2, 131.8, 134.1, 153.6, 169.2; IR (ATR) ν 2948, 1748, 1687, 1601, 1557, 1541, 1507, 1490 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{14}H_{14}N_2NaO_3^+$ m/z 281.0897, found m/z 281.0898.



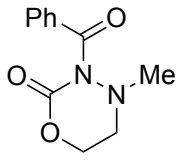
1-(2-Phenylcyclopropane-1-carbonyl)tetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-2(1*H*)-one (2m)

Prepared according to the general procedure A using **1m** (57.7 mg, 0.2 mmol), and isolated as colorless oil in 48% yield (27.4 mg): R_f = 0.6 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.36 (ddd, J = 8.0, 6.8, 4.0 Hz, 1H), 1.75 (ddd, J = 9.6, 4.8, 4.4 Hz, 1H), 1.79-1.91 (m, 2H), 1.96 (m, 1H), 2.13 (m, 1H), 2.67 (ddd, J = 9.6, 6.8, 4.0 Hz, 1H), 2.73 (m, 1H), 2.86 (ddd, J = 8.8, 4.8, 4.0 Hz, 1H), 3.54 (dd, J = 8.8, 7.2 Hz, 1H), 3.84 (m, 1H), 4.22 (dd, J = 11.6, 2.8 Hz, 1H), 4.26 (dd, J = 11.6, 4.0 Hz, 1H), 7.16-7.24 (m 3H), 7.26-7.32 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 18.8, 22.2, 23.8, 27.8, 28.2, 56.0, 56.9, 68.8, 126.5, 126.6, 128.4, 140.0, 152.8, 173.3; IR (ATR) ν 2952, 1782, 1755, 1704, 1604, 1497, 1458, 1400 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{18}N_2NaO_3^+$ m/z 309.1210, found m/z 309.1207.



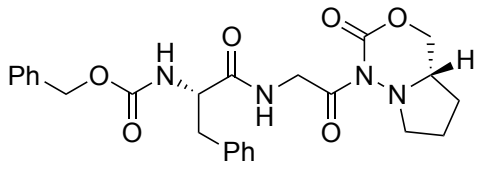
2-Benzoyl-4-oxa-1,2-diazabicyclo[4.2.0]octan-3-one (7n)

Prepared according to the general procedure A using **6n** (46.9 mg, 0.2 mmol), and isolated as white solid in 37% yield (17.3 mg): mp 121－123 ℃; R_f = 0.4 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.32 (m, 1H), 2.52 (m, 1H), 3.66 (ddd, J = 10.4, 9.2, 9.2 Hz, 1H), 4.19 (ddd, J = 9.2, 9.2, 5.6 Hz, 1H), 4.42 (ddd, J = 8.0, 4.4, 4.0 Hz, 1H), 4.50 (d, J = 12.0 Hz, 1H), 4.55 (dd, 12.0, 4.0 Hz, 1H), 7.40 (dd, J = 8.0, 7.2 Hz, 2H), 7.51 (dd, J = 7.2, 7.2 Hz, 1H), 7.59 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.1, 60.0, 63.3, 69.3, 128.2, 128.5, 132.4, 133.6, 154.2, 169.9; IR (ATR) ν 2961, 1778, 1753, 1704, 1448, 1381, 1291, 1268 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{12}H_{12}N_2NaO_3^+$ m/z 255.0746, found m/z 255.0744.



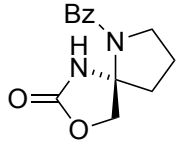
3-Benzoyl-4-methyl-1,3,4-oxadiazinan-2-one (2o)

Prepared according to the general procedure A using **1o** (44.4 mg, 0.2 mmol), and isolated as white solid in 21% yield (9.3 mg): mp 129－131 ℃; R_f = 0.4 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.94 (s, 3H), 3.47 (t, J = 6.0 Hz, 2H), 4.70 (t, J = 6.0 Hz, 2H), 7.42 (dd, J = 8.0, 7.6 Hz, 2H), 7.52 (dd, J = 7.6, 7.6 Hz, 1H), 7.61 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 43.0, 49.5, 64.5, 128.12, 128.13, 132.1, 134.4, 149.2, 170.3; IR (ATR) ν 2923, 1766, 1732, 1694, 1447, 1397, 1249, 1202 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{11}H_{12}N_2NaO_3^+$ m/z 243.0740, found m/z 243.0746.



Benzyl ((*S*)-1-oxo-1-((2-oxo-2-((*S*)-2-oxotetrahydro-4*H*-pyrrolo[1,2-*d*][1,3,4]oxadiazin-1(2*H*)-yl) ethyl)amino)-3-phenylpropan-2-yl)carbamate (7p)

Prepared according to the general procedure A using **6p** (94.2 mg, 0.2 mmol), and isolated as colorless oil in 31% yield (29.0 mg): R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.70-2.00 (m, 3H), 2.13 (m, 1H), 2.70 (m, 1H), 3.04 (dd, J = 14.0, 7.6 Hz, 1H), 3.16 (dd, J = 14.0, 6.4 Hz, 1H), 3.50 (m, 1H), 3.78 (m, 1H), 4.20 (dd, J = 12.0, 4.4 Hz, 1H), 4.25 (dd, J = 12.0, 4.4 Hz, 1H), 4.34 (dd, J = 19.2, 5.6 Hz, 1H), 4.45 (dd, J = 19.2, 4.4 Hz, 1H), 4.55 (m, 1H), 5.01 (d, J = 12.4, 1H), 5.07 (d, J = 12.4 Hz, 1H), 5.52 (d, J = 8.0 Hz, 1H), 6.84 (br s, 1H), 7.16-7.36 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.8, 27.2, 38.4, 43.7, 55.1, 56.0, 56.2, 66.9, 68.7, 126.9, 127.9, 128.1, 128.4, 128.6, 129.2, 136.1, 136.4, 150.9, 156.0, 169.6, 171.4; IR (ATR) ν 3304, 2948, 1791, 1715, 1661, 1521, 1455, 1382 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{25}H_{28}N_4NaO_6^+$ m/z 503.1901, found m/z 503.1898.

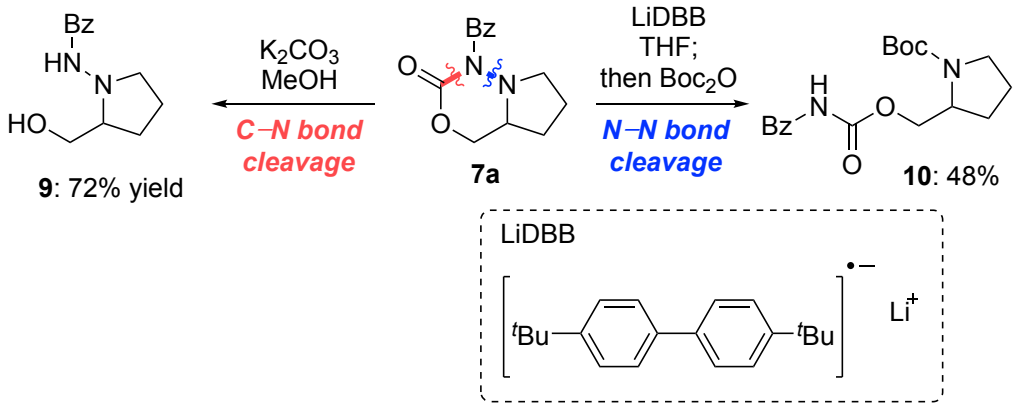


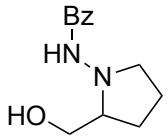
6-Benzoyl-3-oxa-1,6-diazaspiro[4.4]nonan-2-one (8)

Prepared according to the general procedure A using $Rh_2(NHCO^tBu)_4$ instead of Rh_2(esp-OMe)$_2$, and isolated as white powder: mp 153－155 ℃; R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.86 (m, 1H), 1.97 (m, 1H), 2.13 (ddd, J = 12.8, 9.6, 6.4 Hz, 1H), 2.33 (ddd, J = 12.8, 5.6, 5.6 Hz, 1H), 3.47 (m, 1H), 3.56 (m, 1H), 4.35 (d, J = 8.8 Hz, 1H), 4.80 (d, J = 8.8 Hz, 1H), 6.90 (br s, 1H), 7.32-7.43 (m, 3H), 7.49 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.1, 40.1, 50.4, 73.2, 78.5 127.0, 128.3, 130.2, 136.6, 155.7, 170.4; IR

(ATR) ν 3259, 2955, 1749, 1633, 1577, 1446, 1392, 1287 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{13}H_{14}N_2NaO_3^+$ m/z 269.0897, found m/z 269.0892.

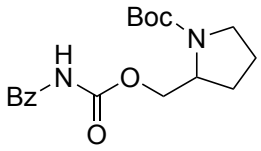
3-2. Derivatization of the amide insertion product 7a





***N*-(2-(Hydroxymethyl)pyrrolidin-1-yl)benzamide (9)**

A mixture of **7a** (0.2 mmol, 49.4 mg) and K_2CO_3 (0.04 mmol, 0.2 eq, 5.5 mg) in MeOH (0.2 M, 1 mL) was stirred for 1.5 h at room temperature and then concentrated under reduced pressure. The crude residue was purified by flash chromatography on silica gel (EtOAc) to afford **9** as white solid in 72% yield (31.9 mg): mp 158－160 ℃; R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, CD_3OD) δ 1.63-1.81 (m, 3H), 1.90 (m, 1H), 2.79 (m, 1H), 2,89 (m, 1H), 3.20 (m, 1H), 3.39 (dd, J = 12.0, 4.4 Hz, 1H), 3.46 (dd, J = 12.0, 4.8 Hz, 1H), 7.36 (dd, J = 8.0, 7.2 Hz, 2H), 7.45 (dd, J = 7.2, 7.2 Hz, 1H), 7.69 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, CD_3OD) δ 22.6, 26.6, 56.4, 63.6, 68.2, 128.4, 129.6, 133.0, 134.4, 170.1; IR (ATR) ν 3321, 3207, 2934, 1650, 1536, 1309, 1281, 1042 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{12}H_{16}N_2NaO_2^+$ m/z 243.1110, found m/z 243.1105.



***tert*-Butyl 2-(((benzoylcarbamoyl)oxy)methyl)pyrrolidine-1-carboxylate (10)**

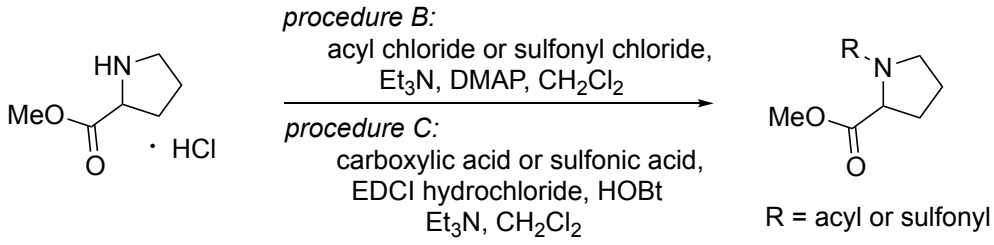
To a stirred solution of **7a** (0.2 mmol, 49.1 mg) in THF (2.9 mL) was added LiDBB in THF (prepared by stirring Li (5.3 mmol, 37 mg) and 4,4′ -Di-*tert*-butylbiphenyl (5.1 mmol, 1.4 g) in THF (17 mL)) at -78 ℃ until the dark green color persisted. The reaction mixture was stirred for 10 min at the -78 ℃, and Boc_2O (0.22 mmol, 1.1 eq, 48.0 mg) was added. After being stirred for 17 h at room temperature, the reaction mixture was concentrated

under reduced pressure and purified by flash chromatography on silica gel (EtOAc) to afford **10** as pale yellow oil in 48% yield (33.1 mg): R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.46 (s, 9H), 1.84 (m, 1H), 1.88-2.03 (m, 2H), 2.10 (m, 1H), 3.53 (m, 1H), 3.67 (m, 1H), 4.05 (dd, J = 10.0, 4.8 Hz, 1H), 4.32-4.16 (m, 2H), 7.43 (dd, J = 7.6, 7.2 Hz, 2H), 7.53 (dd, J = 7.6, 7.6 Hz, 1H), 7.89 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.4, 27.7, 28.4, 47.4, 56.6, 68.0, 82.9, 127.8, 128.5, 132.3, 133.8, 152.2, 153.0, 165.6; IR (ATR) ν 3239, 2977, 1735, 1651, 1476, 1394, 1370, 1271, 1251 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{18}H_{24}N_2NaO_5^+$ m/z 371.1583, found m/z 371.1573.

3-3. Synthesis and characterization of substrates and catalysts

3-3-1. General procedures

General procedures B and C for acylation and sulfonylation of methyl prolinate hydrochloride



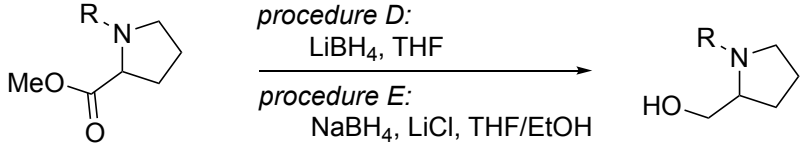
General procedure B

To a stirred solution of methyl prolinate hydrochloride, Et_3N (3 eq), and DMAP (10 mol%) in CH_2Cl_2 (0.2 M) was added acyl chloride or sulfonyl chloride (1 eq) at 0 °C, and the reaction mixture was stirred at room temperature (reaction time is given below). The reaction was quenched with saturated aqueous NH_4Cl, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (conditions are given below).

General procedure C

To a stirred solution of carboxylic acid, methyl prolinate hydrochloride (1.2 eq), and Et_3N (1.5 eq) in CH_2Cl_2 (0.2 M) were added EDCI hydrochloride (1.5 eq) and HOBt (1.3 eq) at 0 °C. Et_3N (1.2 eq) was added dropwise, and the stirring was continued for 2 h at 0 °C. After being stirred at room temperature (reaction time is given below), the reaction was quenched with H_2O, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (conditions are given below).

General procedure D and E for reduction of esters



General procedure D

To a stirred solution of ester substrate in THF (0.2 M) was added $LiBH_4$ (2 eq) at 0 °C. After being stirred at room temperature (reaction time is given below), the reaction was quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4,

and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (conditions are given below).

General procedure E

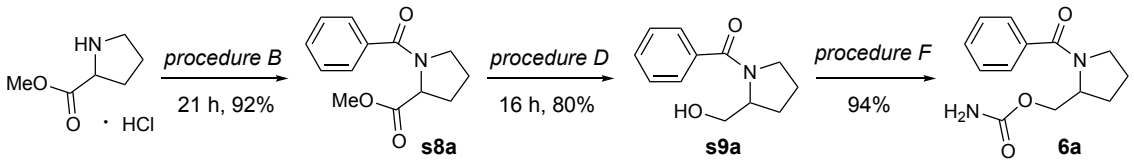
To a stirred solution of ester substrate in THF (1 M) were added LiCl (2 eq) and $NaBH_4$ (2 eq) at 0 ℃. EtOH (0.33 M) was added dropwise over 30 min at 0 ℃, and the reaction mixture was stirred at 0 ℃ for 1 h. Then the reaction mixture was stirred at room temperature (reaction time is given below), quenched with saturated aqueous NH_4Cl, and THF and EtOH was removed under reduced pressure. The reaction mixture was extracted with EtOAc, washed with H_2O and brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (conditions are given below).

General procedure F for carbamoylation of alcohols

To a stirred solution of alcohol substrate in CH_2Cl_2 (0.1 M) was added $Cl_3CCONCO$ (1.2 eq) at 0 ℃. After being stirred for 10 min, the reaction mixture was concentrated under reduced pressure, and used for the next step without further purification.

The solution of the crude residue and K_2CO_3 (0.2 eq) in MeOH (0.1 M) was stirred at room temperature for 2 h, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (conditions are given below) to afford carbamate compound.

3-3-2. Synthesis and characterization of 6a－6j, 6n



Methyl benzoylprolinate (s8a)

Prepared according to the general procedure B (reaction time 21 h) using L-methyl prolinate hydrochloride (828.1 mg, 5 mmol) and benzoyl chloride (0.79 mL, 1 eq, 5 mmol) in 92% yield (1.1 g) (column condition; *n*-hexane/EtOAc, 1/1).

^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[81]

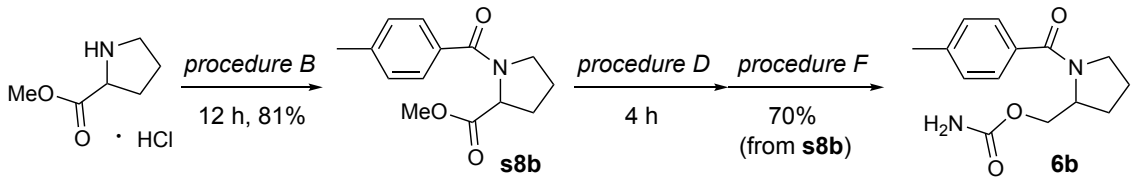
(2-(Hydroxymethyl)pyrrolidin-1-yl)(phenyl)methanone (s9a)

Prepared according to the general procedure D (reaction time 16 h) using **s8a** (1.1 g, 4.6 mmol) in 80% yield (750.5 mg) (column condition; EtOAc).

^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[82]

(1-Benzoylpyrrolidin-2-yl)methyl carbamate (6a)

Prepared according to the general procedure F using **s9a** (750.5 mg, 3.7 mmol), and isolated as colorless gum in 94% yield (2 steps, 853.9 mg) (column condition; EtOAc): R_f = 0.5 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.72-2.01 (m, 3H), 2.06 (m, 1H), 3.47 (br s, 2H), 4.26 (br s, 2H), 4.53 (br s, 1H), 4.86 (br s, 2H), 7.33-7.42 (m, 3H), 7.44-7.51 (m, 2H); ^{13}C NMR (100 MHz, CD_3OD) (major rotamer) δ 25.7, 28.3, 51.6, 57.6, 64.9, 128.1, 129.4, 131.2, 138.0, 159.5, 172.1; IR (ATR) ν 3346, 3196, 2971, 1713, 1600, 1575, 1496, 1397 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{13}H_{16}N_2NaO_3^+$ m/z 271.1053, found m/z 271.1049; $[\alpha]^{20}_D$ – 154.1° (c 1, $CHCl_3$). The enantiomeric excess was determined to be >99% by analytical chiral HPLC. 13 min, 18 min (AD-H column, 85/15 n-hexane/iPrOH, 1 mL/min, 254 nm).



Methyl (4-methylbenzoyl)prolinate (s8b)

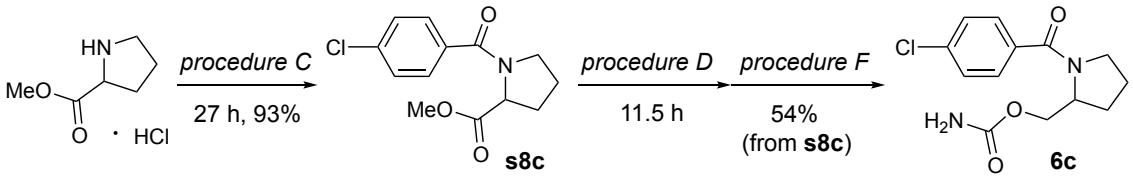
Prepared according to the general procedure B (reaction time 12 h) using methyl prolinate hydrochloride (828.4 mg, 5 mmol) and 4-methylbenzoyl chloride (0.66 mL, 1 eq, 5 mmol) in

81% yield (1.0 g, 4.1 mmol) as colorless oil (column condition; *n*-hexane/EtOAc, 1/1): R_f = 0.3 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) (mixture of rotamers) δ 1.88 (br s, 1H), 1.94-2.07 (m, 2H), 2.27 (m, 1H), 2.36 (s, 3H), 3.45-3.87 (m, 5H), 4.66 (br s, 1H), 7.18 (d, J = 8.0 Hz, 2H), 7.45 (br s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) (major rotamer) δ 21.3, 25.3, 29.2, 49.8, 52.1, 59.1, 127.3, 128.7, 133.1, 140.3, 169.6, 172.7; IR (ATR) ν 2952, 1740, 1625, 1412, 1362, 1281, 1198, 1173 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{17}NNaO_3^+$ m/z 270.1106, found m/z 270.1095.

(1-(4-Methylbenzoyl)pyrrolidin-2-yl)methyl carbamate (6b)

Compound **s8b** (670.7 mg, 2.7 mmol) was reduced to alcohol substrate according to the general procedure D (reaction time 4 h), which was used for the next step without purification by column chromatography.

The crude alcohol was converted to **6b** according to the general procedure F, and isolated as white powder in 70% yield (3 steps, 559.4 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): mp 149－151 °C; R_f = 0.2 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.72-1.98 (m, 3H), 2.05 (m, 1H), 2.36 (s, 3H), 3.49 (br s, 2H), 4.23 (br s, 2H), 4.52 (br s, 1H), 4.77 (br s, 2H), 7.18 (d, J = 8.0 Hz, 2H), 7.39 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, CD_3OD) δ 21.4, 25.8, 28.4, 51.7, 57.8, 65.0, 128.3, 130.0, 135.2, 141.8, 159.7, 172.5; IR (ATR) ν 3351, 3203, 2969, 1714, 1609, 1568, 1514, 1415 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{18}N_2NaO_3^+$ m/z 285.1210, found m/z 285.1208.



Methyl (4-chlorobenzoyl)prolinate (s8c)

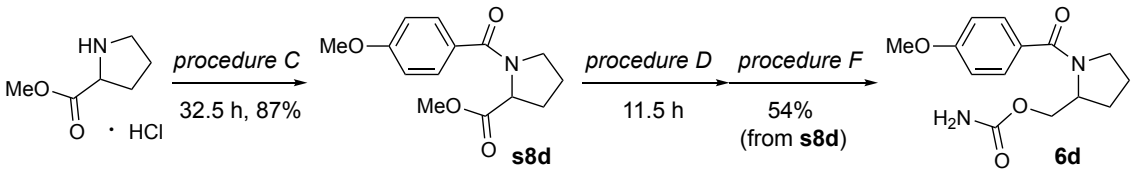
Prepared according to the general procedure C (reaction time, 27 h) using 4-chlorobenzoic acid (782.9 mg, 5.0 mmol) and methyl prolinate hydrochloride (993.7 mg, 1.2 eq, 6.0 mmol) in 93% yield (1.3 g) (column condition; *n*-hexane/EtOAc, 1/1).

^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[83]

(1-(4-Chlorobenzoyl)pyrrolidin-2-yl)methyl carbamate (6c)

Compound **s8c** (863.1 mg, 3.0 mmol) was reduced to the corresponding alcohol according to the general procedure D (reaction time 11.5 h), which was used for the next step without purification by column chromatography.

The crude alcohol was converted to **6c** according to the general procedure F, and isolated as white powder in 54% yield (3 steps, 491.8 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): mp 143－145 ℃; R_f = 0.2 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.75-2.00 (m, 3H), 2.07 (m, 1H), 3.47 (br s, 2H), 4.25 (br s, 2H), 4.52 (br s, 1H), 4.74 (br s, 2H), 7.36 (d, J = 8.0 Hz, 2H), 7.44 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, CD_3OD) δ 25.8, 28.3, 51.6, 57.9, 64.9, 129.7, 129.9, 136.7, 137.3, 159.7, 171.2; IR (ATR) ν 3351, 3199, 2970, 1715, 1612, 1425, 1331, 1090 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{13}H_{15}ClN_2NaO_3^+$ m/z 305.0663, found m/z 305.0668.



Methyl (4-methoxybenzoyl)prolinate (s8d)

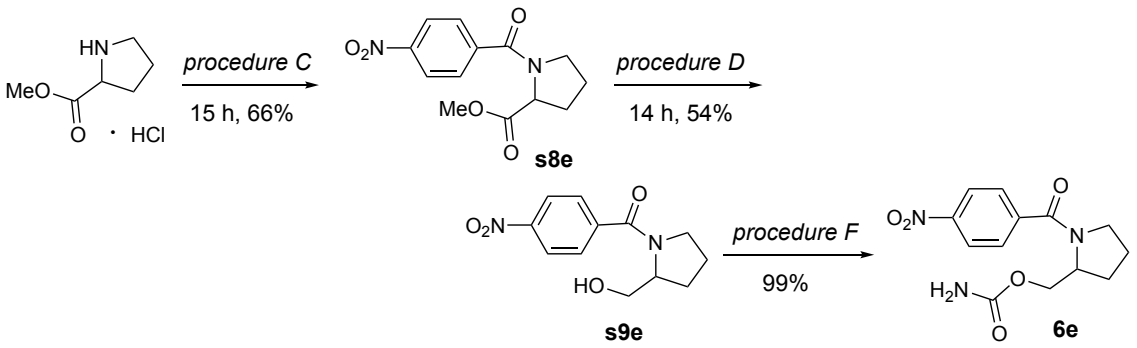
Prepared according to the general procedure C (reaction time 32.5 h) using 4-methoxybenzoic acid (609.4 mg, 4.0 mmol) and methyl prolinate hydrochloride (794.6 mg, 1.2 eq, 4.8 mmol) in 87% yield (921.2 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/1 → EtOAc).

^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[84]

(1-(4-Methoxybenzoyl)pyrrolidin-2-yl)methyl carbamate (6d)

Compound **s8d** (921.1 mg, 3.5 mmol) was reduced to alcohol substrate according to the general procedure D (reaction time 11.5 h), which was used for the next step without purification by column chromatography.

The crude alcohol was converted to **6d** according to the general procedure F, and isolated as white solid in quantitative yield (3 steps, 974.1 mg) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): mp 144－146 ℃; R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.74-1.89 (m, 2H), 1.93 (m, 1H), 2.06 (m, 1H), 3.52 (dd, J = 6.4, 6.0 Hz, 2H), 3.82 (s, 3H), 4.22 (br s, 2H), 4.53 (br s, 1H), 4.77 (br s, 2H), 6.89 (d, J = 8.8 Hz, 2H), 7.48 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, CD_3OD) δ 25.9 28.3, 51.9, 55.9, 57.8, 65.2, 114.7, 130.0, 130.3, 159.7, 162.8, 172.3; IR (ATR) ν 3341, 2965, 1713, 1606, 1572, 1514, 1421, 1402 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{18}N_2NaO_4^+$ m/z 301.1159, found m/z 301.1154.



Methyl (4-nitrobenzoyl)prolinate (s8e)

Prepared according to the general procedure C (reaction time, 15 h) using 4-nitrobenzoic acid (668.5 mg, 4.0 mmol) and methyl prolinate hydrochloride (797.3 mg, 1.2 eq, 4.8 mmol) in 66% yield (731.5 mg) after recrystallization from EtOAc instead of column chromatography.

^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[85]

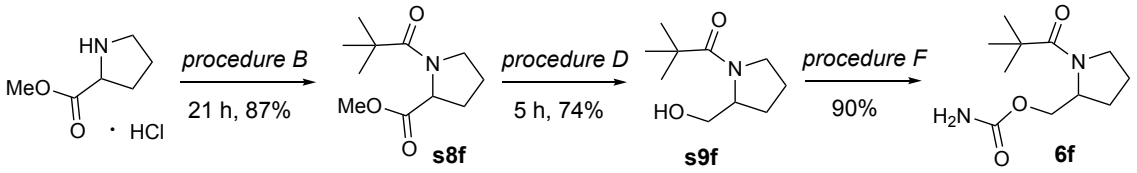
(2-(Hydroxymethyl)pyrrolidin-1-yl)(4-nitrophenyl)methanone (s9e)

Prepared according to the general procedure D (reaction time 14 h) using **s8e** (556.5 mg, 2.0 mmol) in 54% yield (270.3 mg) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1).

^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[86]

(1-(4-Nitrobenzoyl)pyrrolidin-2-yl)methyl carbamate (6e)

Prepared according to the general procedure F using **s9e** (270.3 mg, 1.1 mmol), and isolated as pale yellow solid in 99% yield (2 steps, 314.2 mg) (column condition; EtOAc → EtOAc/MeOH, 10/1): R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.78-2.04 (m, 3H), 2.10 (m, 1H), 3.33 (br s, 1H), 3.46 (br s, 1H), 4.00-4.45 (m, 2H), 4.54 (br s, 1H), 4.79 (br s, 2H), 7.66 (d, J = 8.8 Hz, 2H), 8.25 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, CD_3OD) (major rotamer) δ 25.7, 28.3, 51.4, 58.1, 64.8, 124.8, 129.4, 144.2, 150.0, 159.7, 170.1; IR (ATR) ν 3346, 3196, 2971, 1715, 1621, 1596, 1520, 1429 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{13}H_{15}N_3NaO_5^+$ m/z 316.0904, found m/z 319.0912.



Methyl pivaloylprolinate (s8f)

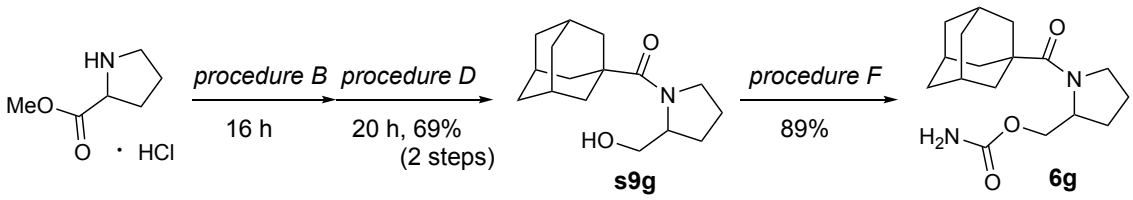
Prepared according to the general procedure B (reaction time 21 h) using methyl prolinate hydrochloride (827.4 mg, 5.0 mmol) and pivaloyl chloride (0.62 mL, 1 eq, 5.0 mmol) in 87% yield (929.3 mg) (column condition; *n*-hexane/EtOAc, 1/1).
^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[87]

1-(2-(Hydroxymethyl)pyrrolidin-1-yl)-2,2-dimethylpropan-1-one (s9f)

Prepared according to the general procedure D (reaction time 5 h) using **s8f** (861.1 mg, 4.0 mmol), and isolated as white solid in 74% yield (552.7 mg) (column condition; *n*-hexane/EtOAc, 1/2): mp 71−73 °C; R_f = 0.2 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.28 (s, 9H), 1.47 (m, 1H), 1.78 (m, 1H), 1.93 (m, 1H), 2.03 (m, 1H), 3.46 (m, 1H), 3.54-3.72 (m, 2H), 3.87 (m, 1H), 4.33 (m, 1H), 5.08 (br s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.4, 27.4, 27.6, 39.2, 48.5, 62.4, 67.8, 179.2; IR (ATR) ν 3405, 2967, 1596, 1479, 1411, 1363, 1213, 1172 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{10}H_{19}NNaO_2^+$ m/z 208.1308, found m/z 208.1304.

(1-Pivaloylpyrrolidin-2-yl)methyl carbamate (6f)

Prepared according to the general procedure F using **s9f** (519.0 mg, 2.8 mmol), and isolated as white powder in 90% yield (2 steps, 579.0 mg) (column condition; *n*-hexane/EtOAc, 1/2): R_f =0.4 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.25 (s, 9H), 1.74-1.94 (m, 3H), 2.00 (m, 1H), 3.55 (m, 1H), 3.69 (m, 1H), 4.12 (dd, J = 10.4, 6.4 Hz, 1H), 4.17 (d, J = 10.4, 3.6 Hz, 1H), 4.41 (m, 1H), 4.64 (br s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.2, 26.2, 27.5, 39.2, 48.0, 57.4, 64.5, 156.9, 176.8; IR (ATR) ν 3350, 3207, 2969, 1714, 1603, 1479, 1406, 1362 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{11}H_{20}N_2NaO_3^+$ m/z 251.1366, found m/z 251.1364.



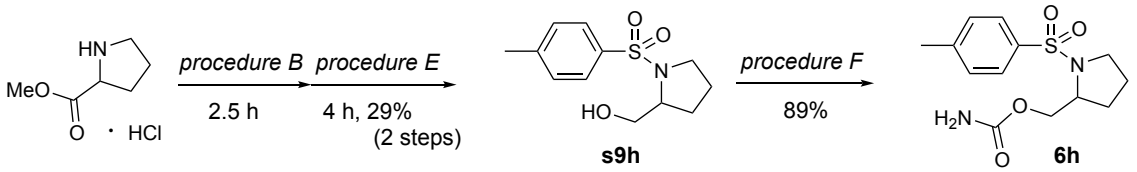
((3*r*,5*r*,7*r*)-Adamantan-1-yl)(2-(hydroxymethyl)pyrrolidin-1-yl)methanone (s9g)

Methyl ((3*r*,5*r*,7*r*)-adamantane-1-carbonyl)prolinate was prepared according to the general procedure B (reaction time, 16 h) using methyl prolinate hydrochloride (492.1 mg, 3.0 mmol) and (3*r*,5*r*,7*r*)-adamantane-1-carbonyl chloride (596.1 mg, 1 eq, 3.0 mmol), which was used for the next step without purification by column chromatography.
The crude ester was reduced to **s9g** according to the general procedure D, and isolated as white solid in 69% yield (2 steps, 547.0 mg) (column condition; *n*-hexane/EtOAc, 1/1): mp

93−95 °C; R_f = 0.2 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.45 (m, 1H), 1.67-1.82 (m, 7H), 1.92 (m, 1H), 1.97-2.08 (m, 10H), 3.49 (ddd, J = 10.4, 8.4, 2.4 Hz, 1H), 3.56 (dd, J = 11.2, 7.6 Hz, 1H), 3.63 (dd, J = 11.2, 2.8 Hz, 1H), 4.01 (ddd, J = 10.4, 6.8, 4.0 Hz, 1H), 4.35 (m, 1H), 5.08 (br s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.5, 27.0, 28.2, 36.5, 38.0, 41.9, 48.3, 62.5, 67.9, 178.6; IR (ATR) ν 3402, 2901, 2849, 1591, 1449, 1397, 1342, 1312, 1179 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{25}NNaO_2^+$ m/z 286.1778, found m/z 286.1779.

(1-((3*r*,5*r*,7*r*)-Adamantane-1-carbonyl)pyrrolidin-2-yl)methyl carbamate (6g)

Prepared according to the general procedure F using **s9g** (263.4 mg, 1.0 mmol), and isolated as white solid in 89% yield (2 steps, 273.4 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/1 → 1/2): R_f = 0.1 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.66-2.06 (m, 19H), 3.59 (m, 1H), 3.79 (m, 1H), 4.07-4.18 (m, 2H), 4.45 (m, 1H), 4.59 (br s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.3, 26.0, 28.4, 36.6, 38.2, 42.0, 48.0, 57.5, 64.7, 156.8, 176.3; IR (ATR) ν 3337, 3199, 2903, 2849, 1716, 1601, 1454, 1395, 1329 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{17}H_{26}N_2NaO_3^+$ m/z 329.1836, found m/z 329.1842.



(1-Tosylpyrrolidin-2-yl)methanol (s9h)

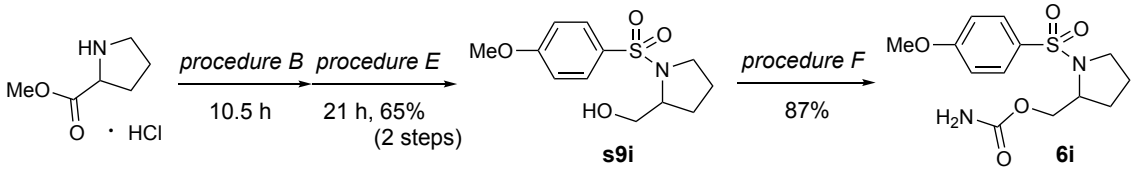
Methyl tosylprolinate was prepared according to the general procedure B (reaction time, 2.5 h) using methyl prolinate hydrochloride (3.3 g, 20 mmol) and tosyl chloride (3.8 g, 1 eq, 20 mmol), which was used for the next step without purification by column chromatography.

The crude ester was reduced to s3a according to the general procedure E, and isolated as white solid in 29% yield (2 steps, 1.5 g) (column condition; *n*-hexane/EtOAc, 1/1). ^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[88]

(1-Tosylpyrrolidin-2-yl)methyl carbamate (6h)

Prepared according to the general procedure F using **s9h** (1.5 g, 6.3 mmol), and isolated as white powder in 60% yield (2 steps, 1.1 g) (column condition; gradient elution: *n*-hexane/EtOAc, 2/1 → 1/1): R_f = 0.2 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.52-1.64 (m, 2H), 1.76 (m, 1H), 1.84 (m, 1H), 2.43 (s, 3H), 3.15 (ddd, J = 10.4, 8.4, 6.8 Hz, 1H), 3.44 (ddd, J = 10.4, 7.6, 4.0 Hz, 1H), 3.86 (ddd, J = 7.2, 4.4, 1.2 Hz, 1H), 4.10 (dd, J = 10.8, 7.2 Hz, 1H), 4.24 (dd, J = 10.8, 4.4 Hz, 1H), 4.89 (br s, 2H), 7.33 (d, J = 8.4 Hz,

2H), 7.74 (d, J = 8.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.5, 23.9, 28.4, 49.1, 58.2, 66.6, 127.5, 129.7, 134.2, 143.6, 156.6; IR (ATR) ν 3472, 3370, 2959, 1714, 1598, 1453, 1402, 1335 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{13}H_{18}N_2NaO_4S^+$ m/z 321.0879, found m/z 321.0874.



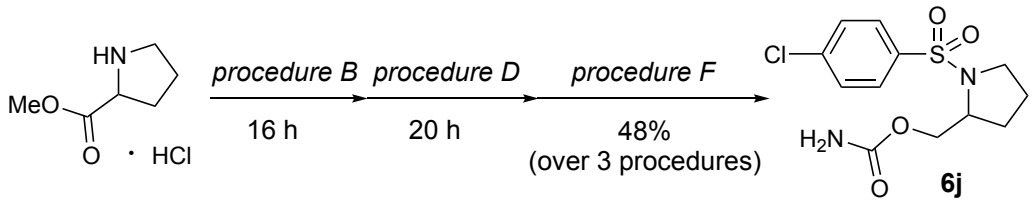
(1-((4-Methoxyphenyl)sulfonyl)pyrrolidin-2-yl)methanol (s9i)

Methyl ((4-methoxyphenyl)sulfonyl)prolinate was prepared according to the general procedure B (reaction time, 10.5 h) using methyl prolinate hydrochloride (832.3 mg, 5.0 mmol) and 4-methoxybenzenesulfonyl chloride (1.0 g, 1 eq, 5.0 mmol), which was used for the next step without purification by column chromatography.

The crude ester was reduced to **s9i** according to the general procedure E, and isolated as white solid in 65% yield (2 steps, 886.9 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/1 → 1/2): mp 50−52 °C; R_f = 0.4 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.46 (m, 1H), 1.65-1.74 (m, 2H), 1.79 (m, 1H), 2.90 (br s, 1H), 3.25 (ddd, J = 10.4, 7.2, 6.8 Hz, 1H), 3.46 (ddd, J = 10.4, 6.4, 6.0 Hz, 1H), 3.59-3.74 (m, 3H), 3.88 (s, 3H), 7.01 (d, J = 9.2 Hz, 2H), 7.80 (d, J = 9.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 24.2, 28.8, 50.0, 55.6, 61.7, 65.8, 114.3, 128.4, 129.6, 163.1; IR (ATR) ν 3519, 2950, 1595, 1577, 1496, 1461, 1443, 1414 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{12}H_{17}NNaO_4S^+$ m/z 294.0770, found m/z 294.0769.

(1-((4-Methoxyphenyl)sulfonyl)pyrrolidin-2-yl)methyl carbamate (6i)

Prepared according to the general procedure F using **s9i** (270.3 mg, 1.0 mmol), and isolated as white solid in 87% yield (2 steps, 272.1 mg) (column condition; *n*-hexane/EtOAc, 1/2): mp 91−93 °C; R_f = 0.2 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.53-1.66 (m, 2H), 1.69-1.91 (m, 2H), 3.15 (ddd, J = 10.4, 8.0, 6.8 Hz, 1H), 3.43 (ddd, J = 10.4, 6.8, 4.4 Hz, 1H), 3.85 (m, 1H), 3.88 (s, 3H), 4.10 (dd, J = 10.8, 7.2 Hz, 1H), 4.23 (dd, J = 10.8, 4.8 Hz, 1H), 4.87 (br s, 2H), 7.00 (d, J = 8.8 Hz, 2H), 7.79 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 24.0, 28.4, 49.2, 55.6, 58.2, 66.6, 114.2, 128.9, 129.6, 156.6, 163.0; IR (ATR) ν 3464, 3372, 2954, 1715, 1595, 1577, 1541, 1497 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{13}H_{18}N_2NaO_5S^+$ m/z 337.0829, found m/z 337.0822.

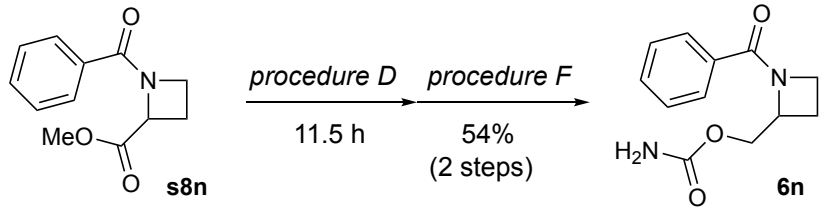


(1-((4-Chlorophenyl)sulfonyl)pyrrolidin-2-yl)methyl carbamate (6j)

Methyl ((4-chlorophenyl)sulfonyl)prolinate was prepared according to the general procedure B (reaction time 16 h) using methyl prolinate hydrochloride (499.2 mg, 3.0 mmol) and 4-chlorobenzenesulfonyl chloride (634.8 mg, 1 eq, 3.0 mmol), which was used for the next step without purification by column chromatography.

The crude ester was reduced to the corresponding alcohol according to the general procedure D (reaction time, 20 h), which was used for the next step without purification by column chromatography.

The crude alcohol was converted to **6j** according to the general procedure F, and isolated as white solid in 48% yield (4 steps, 456.9 mg) (column condition; *n*-hexane/EtOAc, 1/1): mp 120－122 ℃; R_f = 0.3 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.57-1.69 (m, 2H), 1.79 (m, 1H), 1.88 (m, 1H), 3.15 (m, 1H), 3.46 (ddd, J = 10.4, 6.8, 3.6 Hz, 1H), 3.86 (m, 1H), 4.09 (dd, J = 11.2, 3.6 Hz, 1H), 4.24 (dd, J = 11.2, 4.4 Hz, 1H), 5.83 (br s, 2H), 7.52 (d, J = 8.0 Hz, 2H), 7.80 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.9, 28.4, 49.2, 58.3, 66.3, 128.8, 129.4, 135.7, 139.3, 156.7; IR (ATR) ν 3484, 3370, 2957, 1715, 1587, 1476, 1397, 1339 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{12}H_{15}ClN_2NaO_4S^+$ m/z 341.0333, found m/z 341.0333.



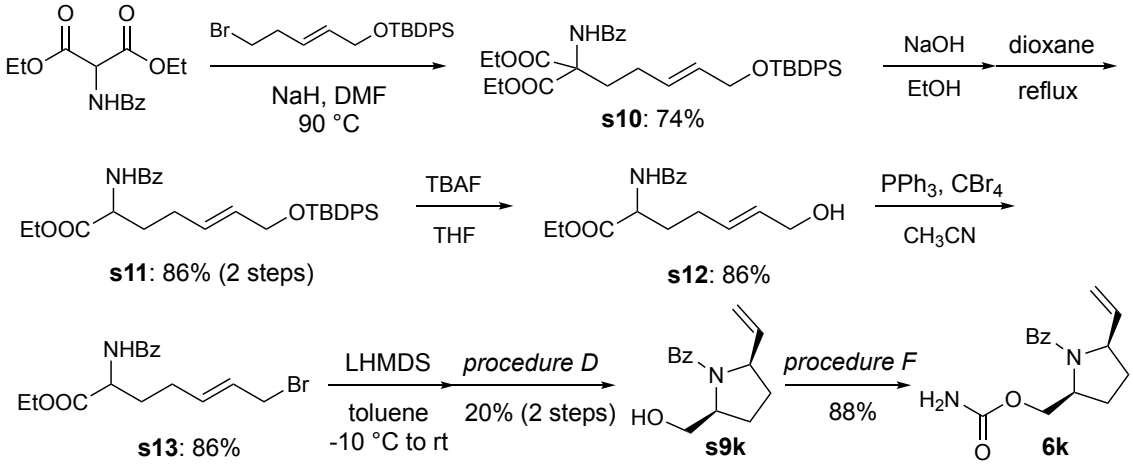
(1-Benzoylazetidin-2-yl)methyl carbamate (6n)

Methyl 1-benzoylazetidine-2-carboxylate[89] (102.6 mg, 0.47 mmol) was reduced to alcohol substrate according to the general procedure D (reaction time 12 h), which was used for the next step without purification by column chromatography.

The crude alcohol was converted to **6n** according to the general procedure F, and isolated as white powder in 54% yield (2 steps, 59.0 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): mp 87－89 ℃; R_f = 0.2 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.17 (m, 1H), 2.45 (m, 1H), 4.04 (ddd, J = 9.2, 9.2, 5.6 Hz, 1H), 4.16-

4.88 (m, 6H), 7.36-7.47 (m, 3H), 7.61 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 19.4, 50.8, 60.7, 65.4, 127.8, 128.4, 130.9, 133.8, 156.6, 170.9; IR (ATR) ν 3357, 3195, 2958, 1715, 1614, 1574, 1450, 1403 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{12}H_{14}N_2NaO_3^+$ m/z 257.0902, found m/z 257.0898.

3-3-3. Synthesis and characterization of 6k－6m and 6o－6p



Diethyl (*E*)-2-benzamido-2-(5-((*tert*-butyldiphenylsilyl)oxy)pent-3-en-1-yl)malonate (s10)

To a stirred solution of NaH (86.6 mg, 2.2 mmol) in DMF (4.0 mL) was added diethyl 2-benzamidomalonate (669.2 mg, 1.7 mmol) in DMF (1.7 mL) dropwise over 10 min at 0 °C. After the reaction mixture was stirred for 5 min at room temperature, (*E*)-((5-bromopent-2-en-1-yl)oxy)(*tert*-butyl)diphenylsilane[90] in DMF (1 mL) was added, and the mixture was stirred for additional 2 h at 90 °C. The reaction was cooled to 0 °C, quenched with saturated aqueous NH_4Cl, extracted with Et_2O, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 1/1 → 1/2) to afford **s10** as yellow oil in 74% yield (2 steps, based on bromide, 739.1 mg): R_f = 0.4 (*n*-hexane/EtOAc, 3/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.04 (s, 9H), 1.26 (t, J = 6.8 Hz, 6H), 1.91-2.01 (m, 2H), 2.52-2.59 (m, 2H), 4.09 (d, J = 4.8 Hz, 2H), 4.25-4.33 (m, 4H), 5.50-5.67 (m, 2H), 7.34-7.48 (m, 8H), 7.49-7.55 (m, 2H), 7.63-7.68 (m, 4H), 7.83 (d, J = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.0, 19.2, 26.6, 26.8, 31.6, 62.6, 64.2, 66.4, 127.1, 127.6, 128.6, 128.8, 129.5, 129.9, 131.9, 133.4, 133.7, 135.5, 165.9, 168.1; IR (ATR) ν 3419, 2931, 1735, 1669, 1507, 1476, 1428, 1369 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{35}H_{43}NNaO_6Si^+$ m/z 624.2752, found m/z 624.2756.

Ethyl (*E*)-2-benzamido-7-((*tert*-butyldiphenylsilyl)oxy)hept-5-enoate (s11)

To a stirred solution of **s10** (739.1 mg, 1.2 mmol) in EtOH (9.4 mL, 0.13 M) was added 6 N NaOH aq. (0.24 mL, 1.2 eq, 1.4 mmol), and the reaction mixture was stirred for 4 h at room temperature. The reaction was cooled to 0 °C, neutralized with 6 N HCl aq. (0.24 mL), and EtOH was removed under reduced pressure. The water layer was acidified with 1 N HCl aq.,

extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was used for the next step without further purification. A solution of the crude carboxylic acid in dioxane (6.0 mL, 0.2 M) was refluxed for 2 h, concentrated under reduced pressure, and purified by flash chromatography on silica gel (column condition; *n*-hexane/EtOAc, 3/1) to afford **s11** as colorless oil in 86% yield (2 steps, 562.2 mg): R_f = 0.3 (*n*-hexane/EtOAc, 3/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.05 (s, 9H), 1.31 (t, J = 7.2 Hz, 3H), 1.87 (m, 1H), 2.00-2.24 (m, 3H), 4.14 (d, J = 4.0 Hz, 2H), 4.25 (q, J = 7.2 Hz, 2H), 4.83 (ddd, J = 7.2, 7.2, 4.8 Hz, 1H), 5.54-5.72 (m, 2H), 6.71 (d, J = 4.8 Hz, 1H), 7.34-7.46 (m, 8H), 7.51 (dd, J = 7.2, 7.2 Hz, 1H), 7.66 (d, J = 7.6 Hz, 4H), 7.81 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.2, 19.2, 26.8, 28.0, 32.2, 52.3, 61.6, 64.3, 127.0, 127.6, 128.6, 129.0, 129.6, 130.1, 131.7, 133.7, 134.0, 135.5, 166.9, 172.5; IR (ATR) ☒ 3324, 2931, 1735, 1669, 1507, 1476, 1428, 1369 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{32}H_{39}NNaO_4Si^+$ m/z 552.2541, found m/z 552.2534.

Ethyl (*E*)-2-benzamido-7-hydroxyhept-5-enoate (s12)

To a stirred solution of **s11** (562.2 mg, 1.1 mmol) in THF (3.5 mL, 0.3 M) was added TBAF (1 M in THF) (2.1 mL, 2 eq, 2.1 mmol) at 0 °C, and the reaction mixture was stirred for 2.5 h at room temperature. The reaction was quenched with brine, concentrated under reduced pressure to remove THF, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 1/1 → 1/2) to afford **s12** as colorless oil in 91% yield (2 steps, 280.8 mg): R_f = 0.3 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.31 (t, J = 7.2 H, 3H), 1.83-2.00 (m, 2H), 2.03-2.25 (m, 3H), 4.07 (br s, 2H), 4.24 (q, J = 7.2 Hz, 2H), 4.84 (m, 1H), 5.62-5.73 (m, 2H), 6.81 (d, J = 8.0 Hz, 1H), 7.45 (dd, J = 8.0, 6.8 Hz, 2H), 7.52 (dd, J = 6.8, 6.8 Hz, 1H), 7.81 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 28.0, 31.9, 52.0, 61.6, 63.4, 127.0, 128.6, 130.6, 130.7, 131.8, 133.8, 167.0, 172.6; IR (ATR) ν 3327, 2929, 1732, 1640, 1603, 1578, 1533, 1489 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{21}NNaO_4^+$ m/z 314.1363, found m/z 314.1363.

Ethyl (*E*)-2-benzamido-7-bromohept-5-enoate (s13)

To a stirred solution of **s12** (280.8 mg, 0.96 mmol) in CH_3CN (4.8 mL, 0.2 M) were added PPh_3 (377.7 mg, 1.5 eq, 1.4 mmol) and CBr_4 (477.5 mg, 1.5 eq, 1.4 mmol) at 0 °C, and the reaction mixture was stirred for 5 min at the same temperature. After being stirred for 45 min at room temperature, the reaction was quenched with saturated aqueous $NaHCO_3$, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure.

The crude mixture was purified by flash chromatography on silica gel (column condition; *n*-hexane/EtOAc, 5/1) to afford **s13** as pale pink oil in 68% yield (232.8 mg): R_f = 0.6 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.32 (t, J = 6.8 Hz, 3H), 1.89 (m, 1H), 2.04-2.28 (m, 3H), 3.97 (d, J = 6.4 Hz, 2H), 4.25 (q, J = 6.8 Hz, 2H), 4.83 (m, 1H), 5.69-5.82 (m, 2H), 6.75 (d, J = 8.0 Hz, 1H), 7.45 (dd, J = 6.8, 6.8 Hz, 2H), 7.52 (dd, J = 6.8, 6.8 Hz, 1H), 7.81 (d, J = 6.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.2, 27.9, 31.8, 32.9, 52.1, 61.7, 127.0, 127.5, 128.6, 131.8, 133.8, 134.3, 166.9, 172.4; IR (ATR) ν 3326, 2981, 2934, 1737, 1643, 1578, 1531, 1489 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{20}BrNNaO_3^+$ m/z 376.0519, found m/z 376.0502.

rac-((2*S*,5*R*)-2-(Hydroxymethyl)-5-vinylpyrrolidin-1-yl)(phenyl)methanone (s9k)

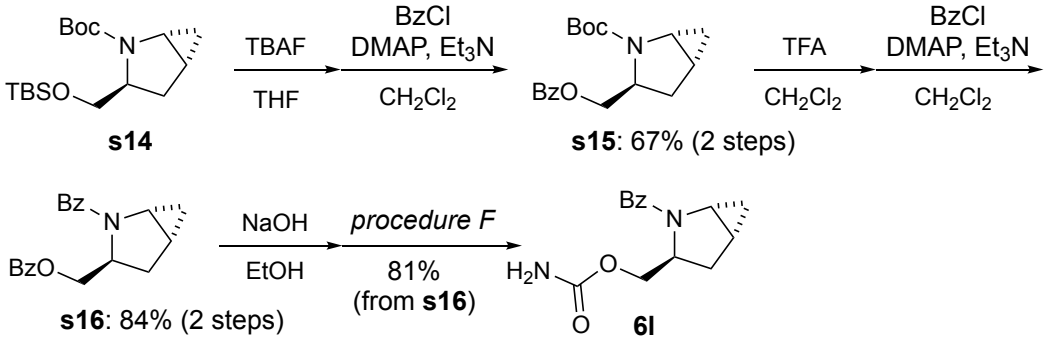
To a stirred solution of **s13** (232.8 mg, 0.66 mmol) in toluene (13.2 mL, 0.05 M) was added LHMDS (1.3 M in THF) (0.76 mL, 1.5 eq, 0.99 mmol) at -10 °C. The reaction mixture was gradually warmed up to room temperature, and stirred for 26 h. The reaction was quenched with saturated aqueous $NaHCO_3$, extracted with EtOAc, washed with brine, dried over Na_2SO_4, concentrated under reduced pressure, and filtered through short pad of silica gel (eluent; *n*-hexane/EtOAc, 3/1) to afford crude cyclized product, which is used for the next step without further purification.

The crude product was reduced to **s9k** according to general procedure D (reaction time 13 h), and isolated as colorless oil in 20% yield (2 steps, 30.6 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/1 → 1/2): R_f = 0.2 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) (major rotamer) δ 1.66 (m, 1H), 1.80 (m, 1H), 2.04-2.30 (m, 2H), 3.75 (d, J = 9.2 Hz, 1H), 3.84 (dd, J = 11.6, 6.4 Hz, 1H), 4.34 (br s, 1H), 4.42-4.54 (m, 2H), 4.60 (d, J = 17.6 Hz, 1H), 4.81 (d, J = 10.4 Hz, 1H), 5.45 (ddd, J = 17.6, 10.4, 6.4 Hz, 1H), 7.29-7.43 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.7, 30.8, 60.8, 62.9, 66.0, 115.1, 126.8, 128.0, 129.6, 137.37, 137.42, 173.1; IR (ATR) ν 3391, 2952, 1599, 1576, 1541, 1496, 1446, 1407 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{14}H_{17}NNaO_2^+$ m/z 254.1151, found m/z 254.1155.

rac-((2*S*,5*R*)-1-Benzoyl-5-vinylpyrrolidin-2-yl)methyl carbamate (6k)

Prepared according to the general procedure F using **s9k** (51.2 mg, 0.22 mmol), and isolated as white solid in 83% yield (2 steps, 50.4 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): mp 108－110 °C; R_f = 0.2 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.71 (m, 1H), 1.89 (dd, J = 12.8, 6.8 Hz, 1H), 2.08 (m, 1H), 2.26 (m, 1H), 4.18-4.93 (m, 8H), 5.48 (br s, 1H), 7.29-7.54 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 24.7, 30.6, 56.1, 62.0, 64.4, 115.1, 127.0, 128.0, 129.6, 137.67, 137.71, 156.8, 171.8; IR (ATR)

ν 3340, 3196, 2956, 1716, 1614, 1577, 1496, 1447 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{15}H_{18}N_2NaO_3^+$ m/z 297.1210, found m/z 297.1218.



***rac-tert*-Butyl (1*R*,3*S*,5*R*)-3-((benzoyloxy)methyl)-2-azabicyclo[3.1.0]hexane-2-carboxylate (s15)**

To a stirred solution of **s14**[91] (561.7 mg, 1.7 mmol) in THF (5.7 mL, 0.3 M) was added TBAF (1 M in THF) (3.4 mL, 2 eq, 3.4 mmol) at 0 °C, and the reaction mixture was stirred for 30 min at room temperature. The reaction was quenched with brine, concentrated under reduced pressure to remove THF, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure to afford crude alcohol which was used for the next step without further purification.

To a stirred solution of crude alcohol, Et_3N (0.59 mL, 2.5 eq, 4.3 mmol), and DMAP (20.8 mg, 10 mol%, 0.17 mmol) in CH_2Cl_2 (8.5 mL, 0.2 M) was added benzoyl chloride (0.3 mL, 1.5 eq, 2.6 mmol) at 0 °C, and the reaction mixture was stirred for 3 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 10/1 → 1/1) to afford **s15** as colorless oil in 67% yield (2 steps, 280.8 mg): R_f = 0.4 (*n*-hexane/EtOAc, 3/1); ^1H NMR (400 MHz, $CDCl_3$) δ 0.42 (m, 1H), 0.91 (m, 1H), 1.45 (s, 9H), 1.55-1.73 (m, 2H), 2.06-2.20 (m, 2H), 3.25 (br s, 1H), 4.15 (br s, 1H), 4.73 (d, J = 4.8 Hz, 2H), 7.44 (dd, J = 7.6, 7.2 Hz, 2H), 7.57 (dd, J = 7.2, 7.2 Hz, 1H), 8.05 (d, J = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.5, 18.8, 28.5, 31.6, 37.4, 60.3, 66.2, 79.8, 128.3, 129.7, 130.4, 132.9, 155.8, 166.4; IR (ATR) ν 2975, 1719, 1693, 1602, 1476, 1453, 1389, 1365 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{18}H_{23}NNaO_4^+$ m/z 340.1519, found m/z 340.1512.

***rac*-((1*R*,3*S*,5*R*)-2-Benzoyl-2-azabicyclo[3.1.0]hexan-3-yl)methyl benzoate (s16)**

To a stirred solution of **s15** (364.4 mg, 1.1 mmol) in CH_2Cl_2 (10 mL) was added trifluoroacetic acid (1 mL) at 0 °C. After being stirred for 1.5 h at room temperature, the reaction mixture

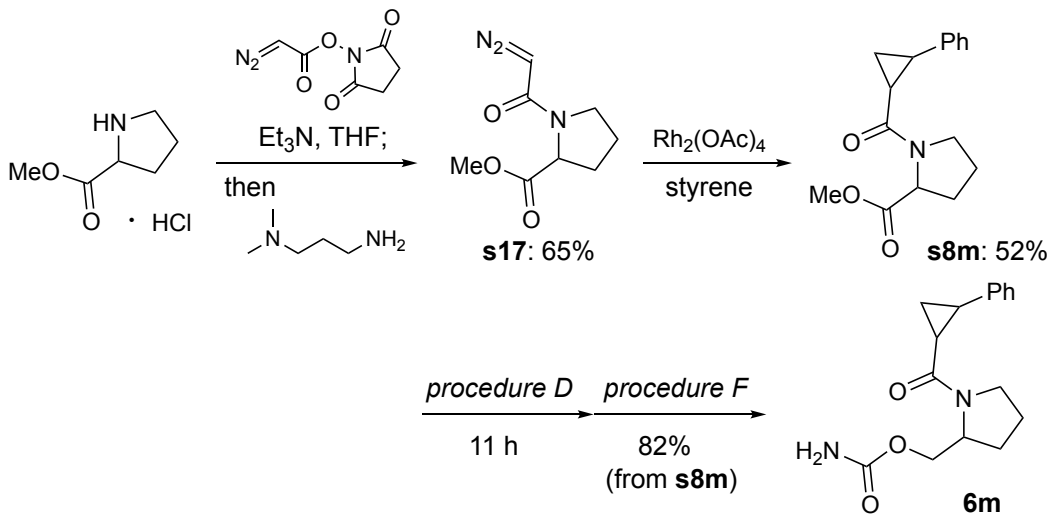
was concentrated under reduced pressure to afford crude product which is used for the next step without further purification.

To a stirred solution of the crude product, Et_3N (0.46 mL, 3 eq, 3.3 mmol), and DMAP (13.4 mg, 10 mol%, 0.11 mmol) in CH_2Cl_2 (5.5 mL, 0.2 M) was added benzoyl chloride (0.13 mL, 1 eq, 1.1 mmol) at 0 °C, and the reaction mixture was stirred for 7 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 3/1 → 1/1) to afford **s16** as pale yellow oil in 84% yield (2 steps, 309.2 mg): R_f = 0.4 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.60 (m, 1H), 0.93 (br s, 1H), 1.81 (m, 1H), 2.13 (dd, J = 13.2, 8.4 Hz, 1H), 2.24 (ddd, J = 13.2, 6.8, 2.4 Hz, 1H), 3.23 (br s, 1H), 4.52 (d, J = 8.4 Hz, 1H), 4.62 (br s, 1H), 4.75 (br s, 1H), 7.36-7.46 (m, 5H), 7.55 (dd, J = 7.2, 6.8 Hz, 1H), 7.65 (d, J = 5.2 Hz, 2H), 8.06 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 18.5, 21.5, 30.8, 39.2, 61.8, 65.3, 127.2, 128.1, 128.3, 129.6, 129.7, 130.2, 132.9, 137.1, 166.4, 170.9; IR (ATR) ν 2951, 1716, 1628, 1576, 1541, 1495, 1448, 1410 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{20}H_{19}NNaO_3^+$ m/z 344.1257, found m/z 344.1249.

rac-((1*R*,3*S*,5*R*)-2-Benzoyl-2-azabicyclo[3.1.0]hexan-3-yl)methyl carbamate (6l)

A solution of **s16** (300.2 mg, 0.93 mmol) in MeOH (2.3 mL) and 1 N LiOH aq. (2.3 mL) was stirred for 30 min at room temperature. The reaction was quenched with saturated aqueous $NaHCO_3$, extracted with EtOAc, washed with brine, dried over Na_2SO_4, concentrated under reduced pressure to afford crude alcohol which was used for the next step without further purification.

The crude alcohol was converted to **6l** according to the general procedure F, and isolated as white solid in 81% yield (3 steps, 197.3 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 1/2 → EtOAc): mp 93−95 °C; R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.51 (ddd, J = 5.2, 5.2, 2.8 Hz, 1H), 0.86 (m, 1H), 1.72 (m, 1H), 1.99 (ddd, J = 13.2, 8.4, 1.6 Hz, 1H), 2.12 (ddd, J = 13.2, 7.2, 2.8 Hz, 1H), 3.17 (m, 1H), 4.27 (d, J = 5.2 Hz, 2H), 4.53 (m, 1H), 5.02 (br s, 2H), 7.34-7.42 (m, 3H), 7.61 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 18.3, 21.5, 30.5, 38.9, 61.9, 65.1, 127.1, 128.0, 129.7, 137.1, 156.9, 171.1; IR (ATR) ν 3346, 3196, 2951, 1714, 1613, 1574, 1542, 1496, 1446 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{16}N_2NaO_3^+$ m/z 283.1053, found m/z 283.1045.



Methyl (2-diazoacetyl)prolinate (s17)

To a stirred solution of methyl prolinate hydrochloride (829.2 mg, 5.0 mmol) in THF (10 mL, 0.5 M) were added Et_3N (2.1 mL, 3 eq, 15 mmol) and 2,5-dioxopyrrolidin-1-yl 2-diazoacetate[92] at room temperature, and the reaction mixture was stirred for 35 h at room temperature. The reaction was quenched with *N,N*-dimethyl-1,3-propane-diamine (2 eq), and stirred for 2 h. The reaction mixture was filtered through celite, concentrated under reduced pressure, and purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 1/1 → 1/2) to afford **s17** in 65% yield (643.7 mg).
^1H and ^{13}C NMR, IR, and MS were identical to those reported.[93]

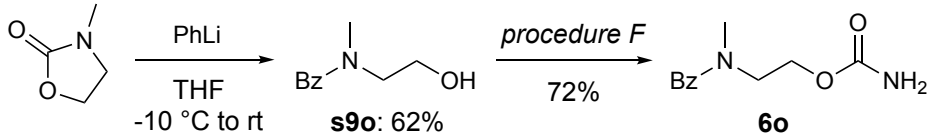
Methyl (2-phenylcyclopropane-1-carbonyl)prolinate (s8m)

A solution of **s17** and $Rh_2(OAc)_4$ (30.1 mg, 4 mol%, 0.070 mmol) in styrene (6.1 mL, 20 eq, 34 mmol) was stirred for 31 h at room temperature. The reaction mixture was concentrated under reduced pressure, and purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 3/1 → 2/1) to afford **s8m** (mixture of diastereomers) as colorless oil in 37% yield (172.7 mg): R_f = 0.4 (*n*-hexane/EtOAc, 1/1); ^1H NMR (400 MHz, $CDCl_3$) (mixture of diastereomers) δ 1.19-1.35 (m, 1H), 1.59-1.78 (m, 1H), 1.87-2.36 (m, 5H), 2.36-2.59 (1H), 3,23 (s, 0.5H), 3.54-3.87 (m, 4.5H), 4.49-4.59 (m, 1H), 7.09-7.15 (m, 2H), 7.16-7.24 (m, 1H), 7.25-7.29 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) (major diastereomer) δ 16.6, 24.4, 24.6, 25.8, 29.2, 47.0, 52.2, 58.8, 125.95, 126.03, 128.4, 140.8, 170.8, 172.9; IR (ATR) ν 2952, 1742, 1636, 1442, 1425, 1375, 1279, 1196 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{16}H_{19}NNaO_3^+$ m/z 296.1257, found m/z 296.1255.

(1-(2-Phenylcyclopropane-1-carbonyl)pyrrolidin-2-yl)methyl carbamate (6m)

Compound **s8m** (136.7 mg, 0.5 mmol) was reduced to the corresponding alcohol according to the general procedure D, which was used for the next step without purification by column chromatography.

The crude alcohol was converted to **6m** according to the general procedure F, and isolated as colorless oil in 82% yield (3 steps, 125.6 mg) (column condition; gradient elution: *n*-hexane/EtOAc, 2/1 → 1/2 → EtOAc → EtOAc/MeOH 10/1): R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) (mixture of diastereomers) δ 1.21-1.33 (m, 1H), 1.58-1.71 (m,1 H), 1.81-2.23 (m, 5H), 2.44-2.59 (m, 1H), 3.51 (m, 1H), 3.64 (m, 1H), 3.82-4.00 (m, 1H), 4.06-4.23 (m, 1H), 4.24-4.44 (m, 1H), 4.84-5.14 (m, 2H), 7.08-7.16 (m, 2H), 7.19 (m, 1H), 7.24-7.31 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) (major rotamer of major diastereomer) δ 16.3, 22.0, 24.7, 25.6, 27.3, 47.2, 56.1, 64.7, 126.1, 126.2, 128.4, 141.1, 156.8, 171.0; IR (ATR) ν 3347, 3196, 2959, 1714, 1603, 1444, 1400, 1377 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{16}H_{20}N_2NaO_3^+$ m/z 311.1366, found m/z 311.1367.



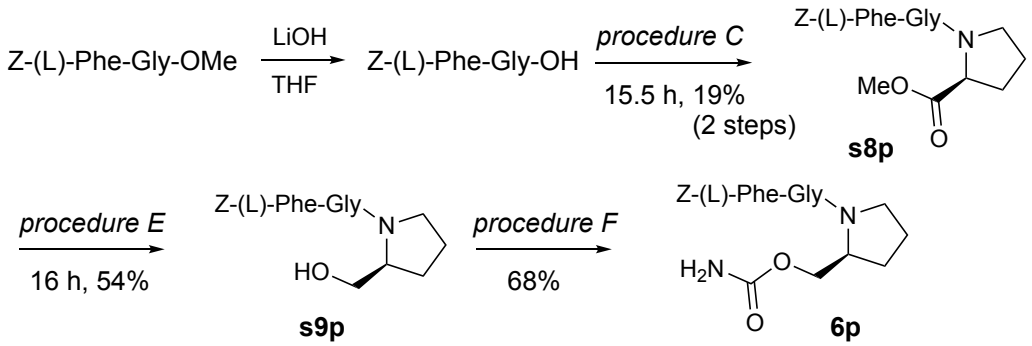
N-(2-Hydroxyethyl)-*N*-methylbenzamide (s9o)

To a stirred solution of 3-methyloxazolidin-2-one (0.43 mL, 5.0 mmol) in THF (25 mL, 0.2 M) was added PhLi (2 M in dibutyl ether) (2.5 mL, 1 eq, 5 mmol) at -78 °C. After being stirred for 1.5 h, the reaction was quenched with saturated aqueous NH_4Cl, extracted with EtOAc, washed with brine, dried over Na_2SO_4, concentrated under reduced pressure, and purified by flash chromatography on silica gel (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1) to afford **s9o** in 62% yield (558.5 mg).

^{1}H and ^{13}C NMR, IR, and MS were identical to those reported.[82]

2-(*N*-Methylbenzamido)ethyl carbamate (6o)

Prepared according to the general procedure F using **s9o** (358.4 mg, 2.0 mmol), and isolated as colorless oil in 72% yield (2 steps, 318.6 mg) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): R_f = 0.4 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.04 (s, 3H), 3.71 (br s, 2H), 4.28 (br s, 2H), 4.81 (br s, 2H), 7.38 (s, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) (major rotamer) δ 38.5, 46.9, 62.0, 126.7, 128.3, 129.5, 136.1, 156.9, 171.7; IR (ATR) ν 3348, 3198, 2957, 1712, 1614, 1577, 1400, 1327, 1070 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{11}H_{14}N_2NaO_3^+$ m/z 245.0897, found m/z 245.0901.



Methyl ((benzyloxy)carbonyl)-*L*-phenylalanylglycyl-*L*-prolinate (s8p)

A solution of Z-(L)-Phe-Gly-OMe (2.2 g, 5.8 mmol) in THF (24.5 mL) and 1 N LiOH aq. (24.5 mL) was stirred for 4 h at room temperature. The reaction mixture was concentrated under reduced pressure to remove THF, and washed with CH_2Cl_2. The water layer was acidified with 1 N HCl aq., and extracted with EtOAc. Combined EtOAc extracts were washed with H_2O and brine, dried over Na_2SO_4, and concentrated under reduced pressure to afford crude carboxylic acid which was used for the next step without further purification.

The crude carboxylic acid was converted to **s8p** according to the general procedure C (reaction time, 15.5 h) using methyl prolinate hydrochloride (1.2 g, 1.2 eq, 7.0 mmol), and isolated as white solid in 19% yield (2 steps, 516.3 mg) (column condition, EtOAc): mp 71−73 °C; R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) (mixture of rotamers) δ 1.78-2.24 (m, 4H), 2.94-3.07 (m, 1H), 3.07-3.17 (m, 1H), 3.38-3.48 (m, 1H), 3.49-3.64 (m, 1H), 3.65-3.77 (m, 3H), 3.90-4.07 (m, 2H), 4.35-4.55 (m, 2H), 5.02 (d, J = 12.0 Hz, 1H), 5.08 (d, J = 12.0 Hz, 1H), 5.23-5.40 (m, 1H), 6.81 (br s, 1H), 7.11-7.35 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 24.6, 29.0, 38.7, 42.0, 45.9, 52.2, 56.2, 58.9, 67.0, 126.9, 127.9, 128.0, 128.5, 128.6, 129.3, 136.4, 136.5, 155.8, 166.6, 170.9, 172.1; IR (ATR) ν 3299, 2953, 1717, 1635, 1525, 1497, 1453, 1435 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{25}H_{29}N_3NaO_6^+$ m/z 490.1949, found m/z 490.1958.

Benzyl ((*S*)-1-((2-((*S*)-2-(hydroxymethyl)pyrrolidin-1-yl)-2-oxoethyl)amino)-1-oxo-3-phenylpropan-2-yl)carbamate (s9p)

Prepared according to the general procedure E (reaction time 16 h) using **s8p** (471.9 mg, 1.0 mmol), and isolated as colorless oil in 54% yield (238.2 mg) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) (mixture of rotamers) δ 1.65-1.99 (m, 4H), 2.98 (dd, J = 12.8, 8.4 Hz, 1H), 3.15 (dd, J = 14.0, 5.6 Hz, 1H), 3.30-3.49 (m, 2H), 3.50-3.67 (m, 2H), 3.74-4.05 (m, 2H), 4.11 (m, 1H), 4.19 (m, 1H), 4.59 (br s, 1H), 4.98 (d, J = 12.8 Hz, 1H), 5.04 (d, J = 12.8 Hz; 1H), 5.84 (br s, 1H), 7.12-7.38 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) (major rotamer) δ 24.0, 27.5, 38.6,

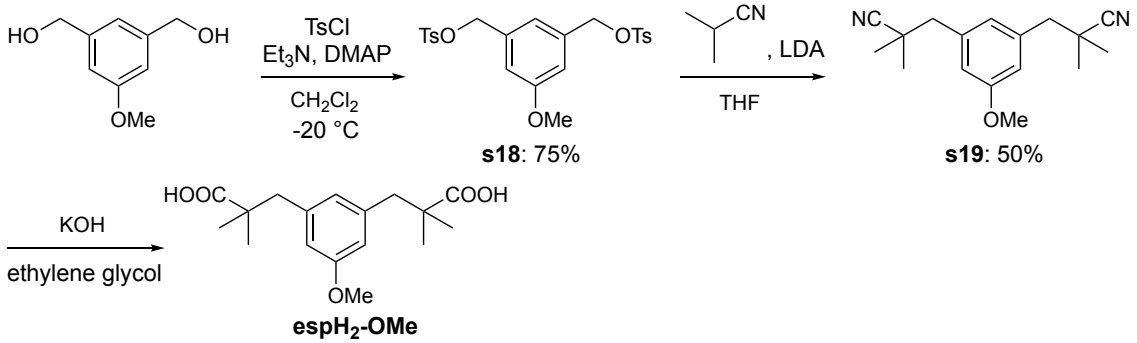
42.1, 46.6, 55.9, 60.8, 64.8, 66.7, 126.6, 127.6, 127.8, 128.2, 128.3, 129.1, 136.3, 155.9, 168.0, 171.3; IR (ATR) ν 3292, 2949, 1710, 1627, 1523, 1454, 1326, 1246 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{24}H_{29}N_3NaO_5^+$ m/z 462.1999, found m/z 462.1999.

Benzyl ((*S*)-1-((2-((*S*)-2-((carbamoyloxy)methyl)pyrrolidin-1-yl)-2-oxoethyl)amino)- 1-oxo-3-phenylpropan-2-yl)carbamate (6p)

Prepared according to the general procedure F using **s9p** (237.3 mg, 0.54 mmol), and isolated as colorless oil in 68% yield (2 steps, 178.6 mg) (column condition; gradient elution: EtOAc → EtOAc/MeOH, 10/1): R_f = 0.2 (EtOAc); ^{1}H NMR (400 MHz, CD_3OD) (mixture of rotamers) δ 1.67-2.01 (m, 4H), 2.79 (m,1H), 3.06-3.19 (m, 1H), 3.20-3.49 (m, 2H), 3.70-4.28 (m, 5H), 4.43 (dd, J = 9.6, 4.8 Hz, 1H), 4.78 (s, 2H), 4.82-4.96 (m, 2H), 7.05-7.24 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) (major rotamer) δ 23.9, 27.0, 38.6, 42.1, 45.9, 56.0, 56.3, 64.1, 66.7, 126.7, 127.7, 127.8, 128.29, 128.33, 129.2, 136.4, 136.7, 155.8, 156.9, 166.8, 171.3; IR (ATR) ν 3296, 2961, 1710, 1635, 1517, 1453, 1401, 1325 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{25}H_{30}N_4NaO_6^+$ m/z 505.2058, found m/z 505.2066.

3-3-4. Synthesis and characterization of $Rh_2(esp\text{-}OMe)_2$ and $Rh_2(esp\text{-}NO_2)_2$

Synthesis and characterization of $espH_2\text{-}OMe$ and $espH_2\text{-}NO_2$



(5-Methoxy-1,3-phenylene)bis(methylene) bis(4-methylbenzenesulfonate) (s18)

To a stirred solution of (5-methoxy-1,3-phenylene)dimethanol (1.0 g, 6.0 mmol) in CH_2Cl_2 (18.2 mL, 0.33 M) were added TsCl (2.5 g, 2.2 eq, 13.2 mmol), Et_3N (1.8 mL, 2.2 eq, 13.2 mmol), and DMAP (73.3 mg, 10 mol%, 0.6 mmol) at -20 °C. After being stirred for 2 h at -20 °C, the reaction was quenched with H_2O, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 2/1 → 1/1) to afford **s18** as colorless oil in 75% yield (2.2 g): R_f = 0.6 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.44 (s, 6H), 3.72 (s, 3H), 4.95 (s, 4H), 6.67 (s, 1H), 6.71 (s, 2H), 7.33 (d, J = 8.4 Hz, 4H), 7.77 (d, J = 8.4 Hz, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.6, 55.3, 71.1, 114.3, 120.2, 127.9, 129.9, 132.9, 135.2, 145.0, 159.9; IR (ATR) ν 2958, 1600, 1469, 1356, 1303, 1189, 1173, 1096 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{23}H_{24}NaO_7S_2^+$ m/z 499.0856, found m/z 499.0850.

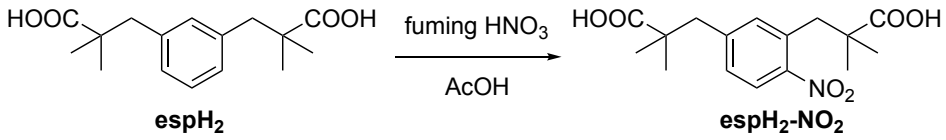
3,3'-(5-Methoxy-1,3-phenylene)bis(2,2-dimethylpropanenitrile) (s19)

To a stirred solution of ^{i}Pr$_2$NH (1.6 mL, 2.5 eq, 11.3 mmol) in THF (10 mL) was added *n*-BuLi (1.6 M in *n*-hexane) (7.0 mL, 2.5 eq, 11.3 mmol) at 0 °C, and the mixture was stirred for 30 min at 0 °C. Then isobutyronitrile (1.0 mL, 2.5 eq, 11.3 mmol) was added, and the stirring was continued for an additional 1 h at 0 °C before adding the solution of **s18** (2.2 g, 4.5 mmol) in THF (15 mL). After being stirred for 14.5 h at room temperature, the reaction was quenched with H_2O, extracted with EtOAc, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 5/1 → 1/1) to afford **s19** as pale brown powder in 86% yield (1.1 g): mp 142−144 °C; R_f = 0.3 (*n*-hexane/EtOAc, 3/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.36 (s, 12H), 2.78 (s, 4H), 3.82 (s,

3H), 6.71 (s, 1H), 6.81 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 26.6, 33.5, 46.6, 55.3, 114.7, 124.5, 124.8, 137.1, 159.4; IR (ATR) ν 2977, 2232, 1595, 1462, 1391, 1339, 1292, 1194 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{17}H_{22}N_2NaO^+$ m/z 293.1624, found m/z 293.1624.

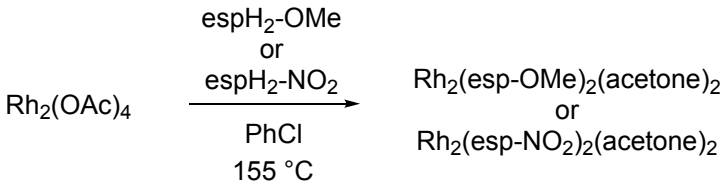
3,3'-(5-Methoxy-1,3-phenylene)bis(2,2-dimethylpropanoic acid) (espH$_2$-OMe)

A solution of **s19** (1.1 g, 3.9 mmol) and KOH (1.2 g, 5.6 eq, 21.8 mmol) in ethylene glycol (7.8 mL, 0.5 M) was stirred for 15 h at 180 °C. After the reaction mixture was cooled down to room temperature, small amount of water was added, and washed with $CHCl_3$. The water layer was acidified with 1 N HCl aq., and extracted with EtOAc. Combined EtOAc extracts were washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure to afford crude espH$_2$-OMe which was used for the synthesis of Rh$_2$(esp-OMe)$_2$ without further purification.



3,3'-(4-Nitro-1,3-phenylene)bis(2,2-dimethylpropanoic acid) (espH$_2$-NO$_2$)

To a stirred solution of espH$_2$[37a] (146.4 mg, 0.53 mmol) in AcOH (5.4 mL) was added fuming HNO_3 (2.6 mL). After being stirred for 29 h at room temperature, the reaction was quenched with crashed ice, extracted with EtOAc, washed with saturated aqueous $NaHCO_3$ and brine, dried over Na_2SO_4, and concentrated under reduced pressure to afford crude espH$_2$-NO$_2$ which was washed with *n*-hexane/Et_2O (1/1) and used for the synthesis of Rh$_2$(esp-NO$_2$)$_2$ without further purification.



Rh$_2$(esp-OMe)$_2$(acetone)$_2$

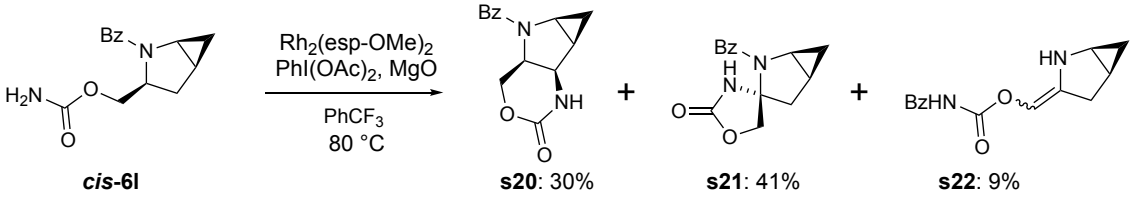
The mixture of Rh$_2$(OAc)$_4$ (89.2 mg, 0.2 mmol) and espH$_2$-OMe (258.1 mg, 4 eq, 0.8 mmol) in chlorobenzene (30 mL) was refluxed for 12 h, and then the solvent was distilled off by heating at a rate that ~10 mL of the solvent was removed per hour. After 3 h, chlorobenzene (30 mL) was added to the mixture, and the solvent was distilled off at the same rate for 3 h. This process was repeated one additional time, and the residue was purified by flash chromatography on silica gel (CH_2Cl_2/ acetone, 19/1) to afford Rh$_2$(esp-OMe)$_2$(acetone)$_2$ as

green powder in 52% yield (96.6 mg): mp >300 °C; R_f = 0.4 (*n*-hexane/EtOAc, 3/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.01 (s, 24H), 2.26 (s, 12H), 2.61 (s, 8H), 3.73 (s, 6H), 6.40 (s, 4H), 6.58 (s, 2H); ^{13}C NMR (100 MHz, DMF-d_7) δ 26.0, 30.6, 45.8, 47.2, 55.2, 113.9, 124.2, 140.1, 159.1, 195.9, 206.6; IR (ATR) ν 2923, 1684, 1573, 1475, 1460, 1408, 1375, 1361 cm^{-1}; HRMS (ESI-TOF) [M (Rh_2(esp-OMe)$_2$) + Na]$^+$ calcd for $C_{34}H_{44}NaO_{10}Rh_2^+$ m/z 841.0937, found m/z 841.0934.

Rh_2(esp-NO_2)$_2$(acetone)$_2$

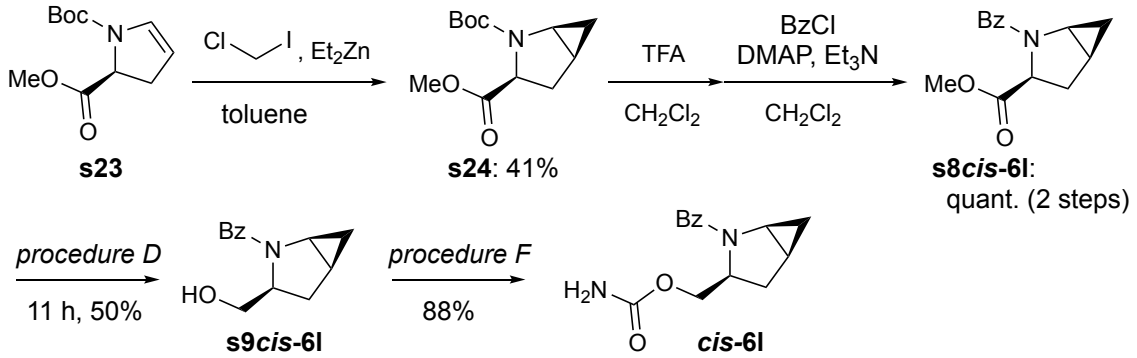
The mixture of $Rh_2(OAc)_4$ (14.6 mg, 0.033 mmol) and espH_2-NO_2 (41.0 mg, 4 eq, 0.13 mmol) in chlorobenzene (6.6 mL) was refluxed for 12 h, and then the solvent was distilled off by heating at a rate that ~3.3 mL of the solvent was removed per hour. After 2 h, chlorobenzene (6.6 mL) was added to the mixture, and the solvent was distilled off at the same rate for 2 h. This process was repeated one additional time, and the residue was purified by flash chromatography on silica gel (CH_2Cl_2/acetone, 19/1) to afford Rh_2(esp-NO_2)$_2$(acetone)$_2$ as green powder in 98% yield (31.3 mg): mp >300 °C; R_f = 0.3 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, DMF-d_7) δ 0.97 (s, 12H), 1.03 (s, 12H), 2.28 (s, 12H), 2.71 (s, 4H), 3.24 (s, 4H), 6.96 (dd, J = 8.0, 2.0 Hz, 2H), 7.07 (d, J = 2.0 Hz, 2H), 7.67 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, DMF-d_7) δ 25.4, 25.7, 30.6, 41.4, 45.9, 46.5, 46.7, 124.3, 130.1, 132.7, 134.1, 144.7, 149.7, 195.7, 195.9, 206.6; IR (ATR) ν 2927, 1682, 1573, 1520, 1475, 1408, 1348, 1245 cm^{-1}; HRMS (ESI-TOF) [M (Rh_2(esp-NO_2)$_2$) + Na]$^+$ calcd for $C_{32}H_{38}N_2NaO_{12}Rh_2^+$ m/z 871.0427, found m/z 871.0416.

3-4. Reaction of *cis*-isomer of 6l



Scheme S2. Nitrene reaction of *cis*-6l

Synthesis and characterization of *cis*-6l, and s20－s22



rac-2-(*tert*-Butyl) 3-methyl (1*S*,3*S*,5*S*)-2-azabicyclo[3.1.0]hexane-2,3-dicarboxylate (s24)

To a stirred solution of **s23**[94] (362.1 mg, 1.6 mmol) in toluene (3 mL) was added Et_2Zn (1.1 M in *n*-hexane) (3.1 mL, 2 eq, 3.2 mmol) dropwise at -20 ℃. Then chloroiodomethane (0.47 mL, 4 eq, 6.4 mmol) in toluene (1 mL) was added dropwise at -20 ℃, and the stirring was continued for 2 h while the reaction was gradually heated up to room temperature. The reaction was quenched with half saturated aqueous $NaHCO_3$, filtered through Celite, extracted with toluene, washed with H_2O, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 10/1 → 5/1) to afford **s24** as pale yellow oil in 41% yield (157.1 mg): R_f = 0.4 (*n*-hexane/EtOAc, 3/1); ^{1}H NMR (400 MHz, $CDCl_3$) (mixture of rotamers) δ 0.65-0.79 (m, 1H), 0.83-0.94 (m, 1H), 1.36-1.58 (m, 10H), 2.00-2.06 (m, 1H), 2.50-2.67 (m, 1H), 3.44-3.57 (m, 1H), 3.71 (s, 3H), 4.50-4.65 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) (major rotamer) δ 13.0, 14.4, 28.2, 31.6, 37.2, 52.0, 59.8, 80.0, 154.1, 174.0; IR (ATR) ν 2975, 1749, 1695, 1404, 1365, 1353, 1317, 1295 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{12}H_{19}NNaO_4^+$ m/z 264.1206, found m/z 264.1213.

rac-Methyl (1*S*,3*S*,5*S*)-2-benzoyl-2-azabicyclo[3.1.0]hexane-3-carboxylate (s8*cis*-6l)

To a stirred solution of **s24** (157.1 mg, 0.65 mmol) in CH_2Cl_2 (6.0 mL) was added trifluoroacetic acid (0.5 mL) at 0 ℃. After being stirred for 1.5 h at room temperature, the reaction mixture was concentrated under reduced pressure to afford crude product which was used for the next step without further purification.

To a stirred solution of the crude product, Et_3N (0.67 mL, 7.4 eq, 4.8 mmol), and DMAP (19.5 mg, 25 mol%, 0.16 mmol) in CH_2Cl_2 (5.5 mL, 0.2 M) was added benzoyl chloride (0.25 mL, 1.7 eq, 1.6 mmol) at 0 ℃, and the reaction mixture was stirred for 24 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl, extracted with CH_2Cl_2, washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The crude mixture was purified by flash chromatography on silica gel (column condition; gradient elution: *n*-hexane/EtOAc, 3/1 → 1/1) to afford **s8*cis*-6l** as pale yellow oil in quantitative yield (2 steps, 159.6 mg): R_f = 0.4 (*n*-hexane/EtOAc, 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.88 (ddd, J = 8.8, 6.0, 6.0 Hz, 1H), 1.12 (ddd, J = 5.2, 5.2, 2.4 Hz, 1H), 1.73 (m, 1H), 2.14 (dd, J = 13.6, 3.6 Hz, 1H), 2.64 (ddd, J = 12.4, 12.4, 6.0 Hz, 1H), 3.35 (ddd, J = 6.0, 6.0, 2.4 Hz, 1H), 3.75 (s, 3H), 5.10 (dd, J = 11.2, 3.6 Hz, 1H), 7.39-7.50 (m, 3H), 7.80 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.0, 18.2, 29.9, 40.0, 52.3, 60.1, 127.8, 128.0, 130.3, 135.6, 168.7, 173.0; IR (ATR) ν 2952, 1745, 1627, 1574, 1496, 1448, 1416, 1353 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{14}H_{15}NNaO_3^+$ m/z 268.0944, found m/z 268.0941.

rac-((1*S*,3*S*,5*S*)-3-(Hydroxymethyl)-2-azabicyclo[3.1.0]hexan-2-yl)(phenyl)methanone (s9*cis*-6l)

Prepared according to the general procedure D (reaction time 11 h) using **s8*cis*-6l** (196.5 mg, 0.8 mmol) as colorless oil in 50% yield (87.0 mg) (column condition; *n*-hexane/EtOAc, 1/2): R_f = 0.4 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.74 (ddd, J = 6.0, 5.2, 2.8 Hz, 1H), 0.93 (dd, J = 8.4, 6.4, 6.0 Hz, 1H), 1.65 (m, 1H), 1.74 (dd, J = 13.6, 5.2 Hz, 1H), 2.52 (ddd, J = 13.6, 11.2, 2.8 Hz, 1H), 3.28 (ddd, J = 6.4, 6.4, 2.8 Hz, 1H), 3.54-3.70 (m, 2H), 4.72-4.85 (m, 2H), 7.39-7.48 (m, 3H), 7.72 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 16.8, 17.7, 29.9, 42.1, 64.1, 68.4, 127.6, 128.1, 130.4, 136.0, 171.1; IR (ATR) ν 3373, 2946, 1602, 1573, 1496, 1448, 1417, 1341 cm^{-1}; HRMS (ESI-TOF) $[M + Na]^+$ calcd for $C_{13}H_{15}NNaO_2^+$ m/z 240.0995, found m/z 240.1003.

rac-((1*S*,3*S*,5*S*)-2-Benzoyl-2-azabicyclo[3.1.0]hexan-3-yl)methyl carbamate (*cis*-6l)

Prepared according to the general procedure F using **s9*cis*-6l** (87.0 mg, 0.4 mmol), and isolated as colorless gum in 88% yield (2 steps, 92.1 mg) (column condition; *n*-hexane/EtOAc,

1/2): R_f = 0.2 (*n*-hexane/EtOAc, 1/2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.83-0.94 (m, 2H), 1.65 (m, 1H), 1.98 (dd, J = 14.0, 3.6 Hz, 1H), 2.42 (ddd, J = 14.0, 11.2, 7.2 Hz, 1H), 3.26 (ddd, J = 6.0, 6.0, 3.2 Hz, 1H), 4.12-4.24 (m, 2H), 4.87 (m, 1H), 5.07 (br s, 2H), 7.38-7.48 (m, 3H), 7.74 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.4, 18.0, 28.5, 41.3, 58.7, 65.7, 128.00, 128.048, 130.4, 136.2, 156.7, 169.2; IR (ATR) ν 3345, 3200, 2952, 1713, 1611, 1574, 1495, 1448 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{16}N_2NaO_3^+$ m/z 283.1053, found m/z 283.1060.

rac-(4a*S*,5a*S*,6a*S*,6b*R*)-5-Benzoyloctahydro-2*H*-cyclopropa[4,5]pyrrolo[3,2-*d*][1,3]oxazin-2-one (s20)

Prepared according to the general procedure A using *cis*-**6l** (50.8 mg, 0.2 mmol), and isolated as colorless oil in 30% yield (15.3 mg): R_f = 0.1 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.03 (ddd, J = 9.2, 6.4, 6.0 Hz, 1H), 1.29 (m, 1H), 2.09 (m, 1H), 3.44 (ddd, J = 6.4, 6.0, 2.8 Hz, 1H), 4.32 (dd, J = 12.0, 4.0 Hz, 1H), 4.40 (dd, J = 12.0, 4.0 Hz, 1H), 4.53 (ddd, J = 10.0, 6.8, 2.4 Hz, 1H), 5.03 (ddd, J = 10.0, 4.0, 4.0 Hz, 1H), 5.81 (br s, 1H), 7.42-7.53 (m, 3H), 7.77 (d, J = 6.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.0, 25.2, 42.0, 52.2, 58.6, 66.7, 128.1, 128.3, 131.1, 134.9, 157.2, 169.9; IR (ATR) ν 3272, 2924, 1715, 1625, 1575, 1449, 1415, 1359 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{14}N_2NaO_3^+$ m/z 281.0897, found m/z 281.0902.

rac-(1*S*,3*S*,5*S*)-2-Benzoyl-2-azaspiro[bicyclo[3.1.0]hexane-3,4'-oxazolidin]-2'-one (s21)

Prepared according to the general procedure A using *cis*-**6l** (50.8 mg, 0.2 mmol), and isolated as colorless oil in 41% yield (20.7 mg): R_f = 0.3 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.50 (ddd, J = 5.6, 5.2, 2.4 Hz, 1H), 1.00 (ddd, J = 8.8, 5.6, 5.6 Hz, 1H), 1.77 (m, 1H), 2.26 (dd, J = 14.8, 2.0 Hz, 1H), 2.76 (dd, J = 14.8, 7.2 Hz, 1H), 3.30 (ddd, J = 7.2, 5.6, 2.4 Hz, 1H), 4.24 (d, J = 8.8 Hz, 1H), 4.65 (d, J = 8.8 Hz, 1H), 7.19 (br s, 1H), 7.35-7.46 (m, 3H), 7.70 (d, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.3, 20.4, 40.3, 44.0, 74.5, 83.8, 127.7, 128.1, 130.5, 136.3, 158.8, 170.5; IR (ATR) ν 3261, 2959, 1748, 1635, 1577, 1446, 1396, 1350 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{14}N_2NaO_3^+$ m/z 281.0897, found m/z 281.0896.

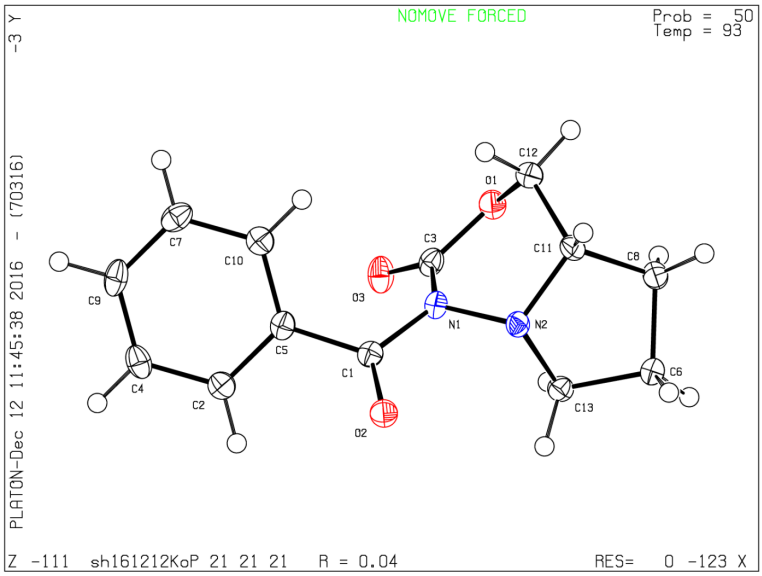
rac-((1*S*,5*S*)-2-Azabicyclo[3.1.0]hexan-3-ylidene)methyl benzoylcarbamate (s22)

Prepared according to the general procedure A using *cis*-**6l** (50.8 mg, 0.2 mmol), and isolated as colorless oil in 9% yield (4.4 mg): R_f = 0.4 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.43 (dd, J = 9.2, 4.4 Hz, 1H), 1.12-1.21 (m, 2H), 2.00 (m, 1H), 2.71 (d, J = 15.2 Hz, 1H), 3.06 (m, 1H), 6.48 (br s, 1H), 6.54 (dd, J = 2.0, 1.2 Hz, 1H), 7.47 (dd, J = 8.4, 6.8 Hz, 2H), 7.56

(dd, J = 8.4, 8.4 Hz, 1H), 7.82 (d, J = 6.8 Hz, 2H), 9.52 (br s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 10.0, 17.1, 21.4, 28.7, 123.5, 125.7, 127.1, 128.8, 132.5, 132.7, 156.6, 170.3; IR (ATR) ν 3253, 3062, 2926, 1741, 1639, 1531, 1489, 1296 cm^{-1}; HRMS (ESI-TOF) [M + Na]$^+$ calcd for $C_{14}H_{14}N_2NaO_3^+$ m/z 281.0897, found m/z 281.0898.

3-5. X-ray Crystallographic Analysis

ORTEP of **7a**, CCDC No. 1852134



EXPERIMENTAL DETAILS

A. Crystal Data

Empirical Formula	$C_{13}H_{14}N_2O_3$
Formula Weight	246.27
Crystal Color, Habit	colorless, block
Crystal Dimensions	0.400 X 0.300 X 0.300 mm
Crystal System	orthorhombic
Lattice Type	Primitive
Lattice Parameters	a = 7.03405(13) Å
	b = 8.84024(16) Å
	c = 18.3533(3) Å
	V = 1141.26(4) Å^3
Space Group	$P2_12_12_1$ (#19)
Z value	4
D_{calc}	1.433 g/cm^3
F000	520.00
μ(CuKα)	8.556 cm^{-1}

B. Intensity Measurements

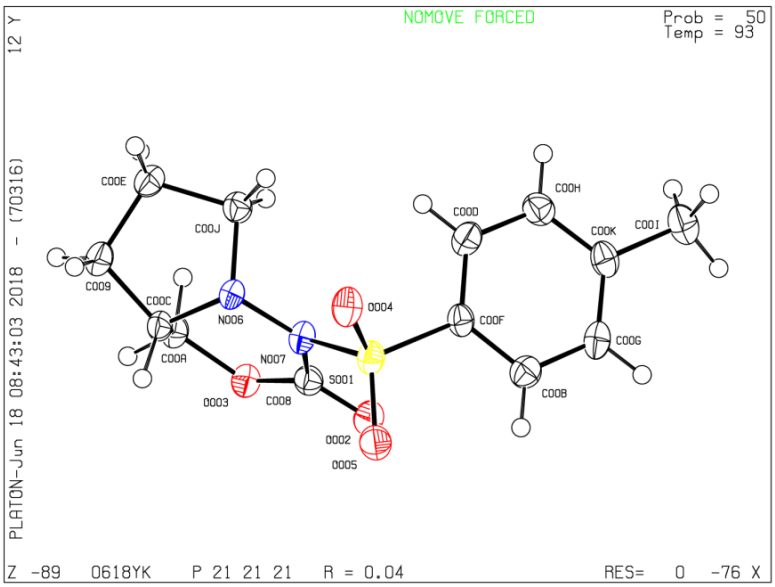
Diffractometer	R-AXIS RAPID
Radiation	CuKα (λ = 1.54187 Å)
Voltage, Current	40kV, 30mA
Temperature	-180.0°C

Detector Aperture	460.0 x 256.0 mm
Data Images	30 exposures
ω oscillation Range (χ=54.0, ϕ=0.0)	80.0 - 260.0°
Exposure Rate	28.0 sec./°
ω oscillation Range (χ=54.0, ϕ=90.0)	80.0 - 260.0°
Exposure Rate	28.0 sec./o
ω oscillation Range (χ=54.0, ϕ=180.0)	80.0 - 260.0°
Exposure Rate	28.0 sec./o
ω oscillation Range (χ=54.0, ϕ=270.0)	80.0 - 260.0°
Exposure Rate	28.0 sec./°
ω oscillation Range (χ=0.0, ϕ=0.0)	80.0 - 260.0°
Exposure Rate	28.0 sec./°
Detector Position	127.40 mm
Pixel Size	0.100 mm
$^{2\theta}$max	136.4°
No. of Reflections Measured	Total: 12061
	Unique: 2087 (R_{int} = 0.0374)
	Friedel pairs: 852
Corrections	Lorentz-polarization
	Absorption
	(trans. factors: 0.687 - 0.774)

C. Structure Solution and Refinement

Structure Solution	Direct Methods (SIR2008)
Refinement	Full-matrix least-squares on F^2
Function Minimized	Σ w $(Fo^2 - Fc^2)^2$
Least Squares Weights	$w = 1/ [\sigma^2(Fo^2) + (0.0543 . P)^2 + 0.1226 . P]$
	where $P = (Max(Fo^2,0) + 2Fc^2)/3$
$2\theta_{max}$ cutoff	136.5°
Anomalous Dispersion	All non-hydrogen atoms
No. Observations (All reflections)	2087
No. Variables	163
Reflection/Parameter Ratio	12.80
Residuals: R1 (I>2.00σ(I))	0.0362
Residuals: R (All reflections)	0.0380
Residuals: wR2 (All reflections)	0.0827
Goodness of Fit Indicator	1.059
Flack Parameter (Friedel pairs = 852)	-0.1(2)
Max Shift/Error in Final Cycle	0.000
Maximum peak in Final Diff. Map	0.14 $e^-/Å^3$
Minimum peak in Final Diff. Map	-0.27 $e^-/Å^3$

ORTEP of **7h**, CCDC No. 1852135



EXPERIMENTAL DETAILS

A. Crystal Data

Empirical Formula	$C_{13}H_{16}N_2O_4S$
Formula Weight	296.34
Crystal Color, Habit	colorless, block
Crystal Dimensions	0.300 X 0.250 X 0.100 mm
Crystal System	orthorhombic
Lattice Type	Primitive
Lattice Parameters	a = 6.1889(3) Å
	b = 9.1001(4) Å
	c = 23.4628(9) Å
	V = 1321.42(10) Å^3
Space Group	$P2_12_12_1$ (#19)
Z value	4
D_{calc}	1.489 g/cm^3
F000	624.00
μ(CuKα)	23.352 cm^{-1}

B. Intensity Measurements

Diffractometer	R-AXIS RAPID
Radiation	CuKα (λ = 1.54187 Å)
Voltage, Current	40kV, 30mA
Temperature	-180.0°C

Detector Aperture	460.0 x 256.0 mm
Data Images	30 exposures
ω oscillation Range (χ=54.0, ϕ=0.0)	80.0 - 260.0°
Exposure Rate	20.0 sec./°
ω oscillation Range (χ=54.0, ϕ=90.0)	80.0 - 260.0°
Exposure Rate	20.0 sec./°
ω oscillation Range (χ=54.0, ϕ=180.0)	80.0 - 260.0°
Exposure Rate	20.0 sec./°
ω oscillation Range (χ=54.0, ϕ=270.0)	80.0 - 260.0°
Exposure Rate	20.0 sec./°
ω oscillation Range (χ=0.0, ϕ=0.0)	80.0 - 260.0°
Exposure Rate	20.0 sec./°
Detector Position	127.40 mm
Pixel Size	0.100 mm
$^{2\theta}$max	136.3°
No. of Reflections Measured	Total: 14180
	Unique: 2411 (R_{int} = 0.0794)
	Friedel pairs: 979
Corrections	Lorentz-polarization
	Absorption
	(trans. factors: 0.606 - 0.792)

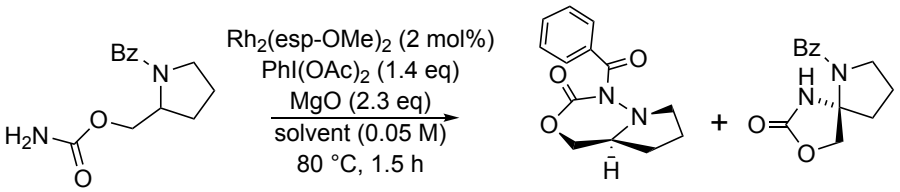
C. Structure Solution and Refinement

Structure Solution	Direct Methods (SIR2008)
Refinement	Full-matrix least-squares on F^2
Function Minimized	Σ w $(Fo^2 - Fc^2)^2$
Least Squares Weights	$w = 1/ [\sigma^2(Fo^2) + (0.0708 . P)^2 + 0.6844 . P]$
	where $P = (Max(Fo^2,0) + 2Fc^2)/3$
$2\theta_{max}$ cutoff	136.3°
Anomalous Dispersion	All non-hydrogen atoms
No. Observations (All reflections)	2411
No. Variables	181
Reflection/Parameter Ratio	13.32
Residuals: R1 (I>2.00σ(I))	0.0361
Residuals: R (All reflections)	0.0511
Residuals: wR2 (All reflections)	0.0965
Goodness of Fit Indicator	1.011
Flack Parameter (Friedel pairs = 979)	0.98(3)
Max Shift/Error in Final Cycle	0.000
Maximum peak in Final Diff. Map	0.29 $e^-/Å^3$
Minimum peak in Final Diff. Map	-0.28 $e^-/Å^3$

3-6. Computational details

All DFT calculations were performed with Gaussian 16 program.[78] The molecular structure optimizations were carried out using the hybrid density functional method based on Becke's three-parameter exchange function and the Lee-Yang-Parr nonlocal correlation functional (B3LYP)[79] and the LANL2DZ basis set for Rh, and the 6-31G* basis set for H, C, N, and O. The vibrational frequencies were computed at the same level to check whether each optimized structure is an energy minimum (no imaginary frequency) or a transition state (one imaginary frequency) and to evaluate its zero-point vibrational energy (ZPVE) and thermal corrections at 353 K. The intrinsic reaction coordinate (IRC) method was used to track minimum energy paths from transition structures to the corresponding local minima.[95] Single point energies were calculated at the RωB97XD[80] level using SDD basis set[96] for Rh and 6-311G* basis set for H, C, N, and O in chlorobenzene solvent. Since similar chemoselectivity and the yield of **2a** were observed between the reaction in $PhCF_3$ and PhCl solvent, we conducted our calculations using chlorobenzene solvent (Table S1).

Table S1. Solvent effect

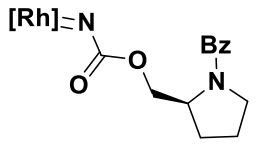


entry	solvent	yield (%)	
		7a	**8**
1	$PhCF_3$	78	0
2	PhCl	71	0

Table S2[a]

	E(R*w*B97XD) (A.U.)	Thermal Correction to Free Energy (A.U.)	Sum of Electronic and Thermal Free Energies (A.U.)
RT	-3134.521619	0.867402	-3133.654217
$TS1_{cis\text{-C-N}}$	-3134.515621	0.872441	-3133.64318
$IM_{cis\text{-C-N}}$	-3134.576525	0.875509	-3133.701016
$TS2_{cis\text{-C-N}}$	-3134.5556	0.874436	-3133.681164
$PD_{C\text{-N}}$	-838.91744	0.206358	-838.711082
[Rh]	-2295.654618	0.642582	-2295.012036
$TS1_{trans\text{-C-N}}$	-3134.497878	0.87308	-3133.624798
$IM_{trans\text{-C-N}}$	-3134.572881	0.876676	-3133.696205
$TS2_{trans\text{-C-N}}$	-3134.54677	0.875261	-3133.671509
PT_{conc}	-3134.492201	0.870275	-3133.621926
$TS_{C\text{-H}}$	-3134.511519	0.87043	-3133.641089
$PD_{C\text{-H}}$	-838.974855	0.205751	-838.769104
$IM_{free\text{-ylide}}$	-838.873814	0.206065	-838.667749

[a] RωB97XD/6-311G*/SDD.



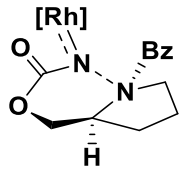
RT

Cartesian Coordinates

Atom	X	Y	Z
C	-3.52701100	-0.98268700	-2.79742700
H	-3.94158000	0.02234400	-2.67722200
H	-3.21633200	-1.11625800	-3.83629700
C	-4.55099300	-2.05763600	-2.41051100
H	-4.10697700	-3.04426200	-2.55120500
N	-5.03691500	-1.91928900	-1.02906000
C	-5.04380900	-2.91489400	-0.06723100
O	-5.82156800	-2.86766600	0.88491800
C	-6.13851900	-0.93116600	-0.98804400
H	-5.78714300	0.01385800	-0.56014100
H	-6.91385200	-1.32526900	-0.32911400
O	-2.36381800	-1.04733100	-1.94272800
C	-1.16302300	-1.11930400	-2.53808500
O	-0.93394300	-1.05631700	-3.74382200
N	-0.10674300	-1.36950900	-1.72900200
Rh	0.68041800	-0.06015800	-0.54989300
Rh	1.50533600	1.42230900	1.18592800
O	0.41295100	2.93195900	0.27036100
O	-0.35803000	1.54610900	-1.34413500
O	-0.87462600	-0.43889100	0.79761700
O	1.77782500	-1.57573100	0.35634900
O	2.31188300	0.52919500	-1.65919400
O	2.53633300	-0.18355700	1.97300600
O	-0.09906000	0.97447300	2.37744500
O	3.10951500	1.86425100	-0.02971300
C	2.46282100	-1.31469500	1.40464400
C	-0.94692700	0.14516000	1.93347600
C	3.18022500	1.33890500	-1.17790700
C	-0.27094700	2.68710800	-0.76546500
C	-5.83877900	-1.85799300	-3.23970700
H	-6.40186000	-2.79731300	-3.24528500
H	-5.64144700	-1.58223800	-4.28127800
C	-6.60340500	-0.76774500	-2.45828300
H	-6.35462900	0.22921400	-2.83720400
H	-7.68693100	-0.88293500	-2.55337600
C	-4.09044200	-4.07421900	-0.18712800
C	-4.60359800	-5.34940800	0.09659000
C	-2.72199900	-3.93126400	-0.45523300

C	-3.77202100	-6.46665800	0.06634700
H	-5.65508800	-5.44729600	0.34754900
C	-1.88620400	-5.05082800	-0.46334100
H	-2.30540000	-2.94709300	-0.63086300
C	-2.41017600	-6.32009800	-0.21473700
H	-4.18317900	-7.45133400	0.27252600
H	-0.82583800	-4.92194000	-0.66298200
H	-1.76037000	-7.19118900	-0.22994100
C	-2.14992000	-0.22677500	2.81935200
C	-3.48031400	0.01773800	2.03100900
H	-3.50539200	-0.67620200	1.18630000
H	-4.30196200	-0.26432000	2.69967200
C	-2.04527000	-1.73671700	3.13875900
H	-1.12508200	-1.95704200	3.69299400
H	-2.89425600	-2.03996900	3.76129800
H	-2.05425300	-2.34089500	2.22776700
C	-2.11936900	0.58373900	4.12511100
H	-1.20063700	0.39089700	4.68656000
H	-2.17893000	1.65857000	3.93791300
H	-2.97145700	0.29274400	4.75067100
C	3.23553700	-2.49436900	2.02436200
C	4.04382600	-2.02767800	3.24535600
H	3.38881100	-1.60018600	4.00987700
H	4.56930200	-2.88475500	3.68343000
H	4.78330600	-1.26987300	2.97590900
C	2.19687700	-3.55459900	2.45834600
H	1.59352600	-3.88931800	1.60998800
H	2.71095500	-4.42258400	2.88717600
H	1.52189700	-3.15355500	3.22347300
C	4.16862900	-3.13377500	0.94164700
H	4.70317500	-3.95683200	1.43197600
H	3.53329300	-3.57636900	0.16748500
C	4.36139400	1.69909400	-2.09398100
C	5.31330100	2.67004300	-1.37744300
H	5.73272200	2.22937900	-0.46996500
H	6.13806100	2.93299000	-2.05075900
H	4.79585300	3.59143600	-1.09481200
C	5.10539400	0.38981900	-2.52460800
H	4.42252200	-0.19583300	-3.14881400
H	5.94101900	0.69981900	-3.16481800
C	3.78343200	2.37007000	-3.36181500
H	3.25676500	3.29814700	-3.10999900
H	4.59861100	2.62389800	-4.04912600
H	3.08462200	1.70668500	-3.87882700
C	-1.05059700	3.84280500	-1.42052900
C	-0.86219100	5.14007200	-0.61838000

H	-1.40674900	5.95511300	-1.11050600
H	-1.23458500	5.04069300	0.40387900
H	0.19418300	5.41847500	-0.56437200
C	-0.49938100	4.02754500	-2.85330200
H	-0.59982900	3.10979700	-3.43935600
H	-1.04758900	4.82974200	-3.36088300
H	0.56029900	4.30799600	-2.83296700
C	-2.56528200	3.45877400	-1.52090700
H	-3.07680400	4.31136400	-1.98555500
H	-2.65050900	2.61623400	-2.21555500
C	5.61039400	-0.47628600	-1.38793300
C	4.75925000	-1.42263600	-0.81460500
C	6.91236300	-0.32877400	-0.88328600
C	5.15738200	-2.18554700	0.29410300
H	3.76577200	-1.56318300	-1.22494600
C	7.33425300	-1.11354700	0.19552700
H	7.58237400	0.38938300	-1.34308800
C	6.45273000	-2.03066400	0.78688700
H	6.81044100	-2.61673100	1.62845900
C	-3.23557800	3.09754800	-0.20997700
C	-3.15107600	1.78785300	0.26740400
C	-3.91842200	4.06146800	0.54862300
C	-3.68132900	1.42924400	1.51742300
H	-2.65190100	1.03296600	-0.32856500
C	-4.48795300	3.70553500	1.77666500
H	-4.00269300	5.07429000	0.17011300
C	-4.35958000	2.39505000	2.26089700
H	-4.80662700	2.15645700	3.22144800
O	8.58287400	-1.06027800	0.74911900
O	-5.18637100	4.56149500	2.58111300
C	9.52031600	-0.14554800	0.20862700
H	9.73760800	-0.36285800	-0.84597100
H	10.43239500	-0.26833200	0.79602600
H	9.17084500	0.89212900	0.29616300
C	-5.33722700	5.90706700	2.16356800
H	-5.88537200	5.97852000	1.21425500
H	-4.36630900	6.40917600	2.05549500
H	-5.91253000	6.40199200	2.94843000



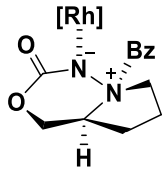
TS1*cis-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	1.49912800	3.68028800	-0.32476700
H	1.62042700	2.75329700	0.24544500
H	2.48569300	4.11674800	-0.50265600
C	0.63110200	4.68053400	0.45119300
H	0.48742900	5.57609900	-0.15406300
N	-0.67358200	4.09743900	0.80111900
C	-1.92037600	4.65429200	0.51067600
O	-2.90214600	4.35550100	1.18514700
C	-0.52893900	3.44416100	2.11830300
H	-0.04896000	2.46940900	1.99661400
H	-1.51862600	3.29714300	2.54545800
O	0.99251700	3.38508900	-1.64352500
C	0.16723100	2.33274900	-1.83285200
O	-0.11809900	1.95371800	-2.96499100
N	-0.44562600	1.72618100	-0.79715400
Rh	0.02202400	-0.06371800	-0.15599800
Rh	0.40180100	-2.39635800	0.39583500
O	1.85440700	-2.42996800	-1.08375100
O	1.52784500	-0.24427300	-1.56682300
O	1.44545600	0.39814000	1.29474100
O	-1.43250300	-0.03277700	1.32487300
O	-1.33877900	-0.81442100	-1.53625700
O	-1.07954600	-2.21146300	1.82590800
O	1.80944100	-1.77519900	1.77187300
O	-0.99700100	-2.97651800	-0.98452400
C	-1.67650900	-1.10371800	1.98157200
C	2.04126300	-0.54471600	1.93174800
C	-1.56467500	-2.06521600	-1.65774900
C	2.10643000	-1.37396000	-1.73503600
C	1.31785400	4.99679100	1.81930700
H	1.48158700	6.07156000	1.93810400
H	2.30247100	4.51610100	1.87267800
C	0.36103300	4.42817000	2.89362600
H	0.89376700	3.95131100	3.72237000
H	-0.25909500	5.22797500	3.31321800
C	-2.07943800	5.65617600	-0.60417500

C	-3.03244100	6.66375700	-0.37448500
C	-1.42808500	5.61235900	-1.84552600
C	-3.30013900	7.62490200	-1.34502500
H	-3.56219300	6.66935100	0.57201000
C	-1.71376400	6.56677800	-2.82497400
H	-0.71289700	4.83216300	-2.07020100
C	-2.64030100	7.57903400	-2.57633300
H	-4.03116700	8.40385600	-1.14568200
H	-1.21151500	6.50911000	-3.78671200
H	-2.85496600	8.32251700	-3.33944000
C	3.08555600	-0.12557800	2.98296900
C	4.18385100	0.76902500	2.31671900
H	3.71141700	1.70413800	1.99550700
H	4.90034900	1.02790500	3.10607700
C	2.35864200	0.71272000	4.05945200
H	1.57775500	0.12490100	4.55551600
H	3.07433200	1.03345500	4.82505900
H	1.89303000	1.60194800	3.62491300
C	3.71274200	-1.36889700	3.63449600
H	2.95047300	-1.98418600	4.12068600
H	4.22926200	-1.99218300	2.90107700
H	4.43757000	-1.05454900	4.39488200
C	-2.77051100	-1.00756500	3.06185000
C	-2.96754800	-2.36673000	3.75158600
H	-2.04106100	-2.70619500	4.22403900
H	-3.73506200	-2.27242200	4.52917600
H	-3.28505300	-3.13678400	3.04482800
C	-2.31225000	0.04254300	4.09989200
H	-2.15718400	1.01868800	3.63249900
H	-3.07389100	0.14789900	4.88096700
H	-1.37693700	-0.26421600	4.58368100
C	-4.10364000	-0.50485800	2.41129700
H	-4.84788300	-0.45589600	3.21591000
H	-3.94301900	0.51835000	2.05636100
C	-2.58953800	-2.46522700	-2.73364800
C	-2.78471700	-3.98956200	-2.74528400
H	-3.16812700	-4.35594400	-1.78993200
H	-3.49875800	-4.25792800	-3.53335900
H	-1.84165800	-4.50521000	-2.94843600
C	-3.94157300	-1.72129900	-2.46692100
H	-3.77147700	-0.65040900	-2.61710600
H	-4.64014500	-2.05007700	-3.24683400
C	-2.03583800	-1.99389400	-4.09879100
H	-1.09516300	-2.50432900	-4.33746200
H	-2.75556800	-2.23178400	-4.89070500
H	-1.85307000	-0.91591900	-4.10144200

C	3.16965400	-1.42834900	-2.84741200
C	3.80655800	-2.82506800	-2.91661400
H	4.53948000	-2.85159500	-3.73220600
H	4.31424300	-3.08559600	-1.98451000
H	3.05102900	-3.59155300	-3.11085600
C	2.45646100	-1.10486900	-4.18155900
H	1.95219200	-0.13566800	-4.13640500
H	3.18784500	-1.08703100	-4.99809300
H	1.70800900	-1.86984600	-4.41942700
C	4.25348300	-0.32760500	-2.59175000
H	4.99414000	-0.42086900	-3.39593500
H	3.77402100	0.64956700	-2.70979400
C	-4.54634200	-1.94388200	-1.09518300
C	-4.15743700	-1.12722800	-0.03149700
C	-5.47353700	-2.97346500	-0.86689000
C	-4.62659800	-1.35476400	1.27130300
H	-3.47239000	-0.30689200	-0.21316700
C	-5.98033700	-3.18210300	0.42028300
H	-5.79436300	-3.59294900	-1.69721500
C	-5.54713200	-2.38024400	1.48632700
H	-5.95389500	-2.57597700	2.47426800
C	4.94031400	-0.38771200	-1.24185200
C	4.35210000	0.24144900	-0.14296900
C	6.14727100	-1.08232400	-1.06525500
C	4.90878100	0.14607900	1.14071500
H	3.43426600	0.79913300	-0.28476500
C	6.73394100	-1.15146800	0.20361000
H	6.61791700	-1.55422500	-1.92066600
C	6.10863500	-0.54561000	1.30382800
H	6.58728500	-0.62685200	2.27539200
O	-6.89785500	-4.14319200	0.74428800
O	7.91207400	-1.78660300	0.47703700
C	-7.37139900	-4.99419200	-0.28441700
H	-7.88481100	-4.42935800	-1.07440600
H	-8.08181200	-5.67355500	0.19098400
H	-6.55746100	-5.57912600	-0.73399200
C	8.58960500	-2.43688900	-0.58490000
H	8.88164100	-1.72953700	-1.37275700
H	7.97772400	-3.23444900	-1.02718000
H	9.48730300	-2.87460500	-0.14403900



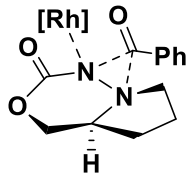
IM*cis-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	0.90242800	4.92077300	-1.14816100
H	1.76586700	4.59643700	-0.55124000
H	1.09451200	5.93566400	-1.50739500
C	-0.38214700	4.89263600	-0.34223900
H	-1.20583200	5.14302200	-1.01441800
N	-0.57288700	3.43440700	0.10059300
C	-2.10324900	3.25048200	0.36164100
O	-2.45554700	3.31814800	1.50979400
C	0.18545800	3.35267700	1.42532900
H	1.19829000	3.07841200	1.14160400
H	-0.23775500	2.53212500	1.99749100
O	0.73105100	4.10440000	-2.28859100
C	0.32789000	2.79163800	-2.06433900
O	0.38298700	2.03077400	-3.00825200
N	-0.11002100	2.41218300	-0.81998800
Rh	0.22383600	0.23452500	-0.11090000
Rh	0.58657500	-2.06459200	0.56412400
O	2.00213900	-2.23542100	-0.92742200
O	1.69727100	-0.07621600	-1.52999300
O	1.71269900	0.75811200	1.28602800
O	-1.21095500	0.37429700	1.41587400
O	-1.21911700	-0.48951700	-1.42775100
O	-0.85985700	-1.77615600	2.02169700
O	2.04415400	-1.40020400	1.87206700
O	-0.86616700	-2.62955300	-0.78414400
C	-1.44211600	-0.65856800	2.13650600
C	2.30114500	-0.16338900	1.94832300
C	-1.44500400	-1.74404700	-1.48357800
C	2.25369000	-1.21566400	-1.64242800
C	-0.38173200	5.70392800	0.95855000
H	-1.38595600	6.08317000	1.16599300
H	0.27437100	6.57442600	0.85634300
C	0.08173400	4.73506100	2.07923100
H	1.05247900	5.02828600	2.48916600
H	-0.63868000	4.72673600	2.89872300
C	-3.03235300	3.19159100	-0.79460400

C	-4.24882500	3.87643200	-0.57981700
C	-2.82511500	2.51637500	-2.01230500
C	-5.21624800	3.92752000	-1.57599900
H	-4.41540100	4.36998400	0.37195500
C	-3.81046400	2.56992700	-2.99971100
H	-1.94005600	1.91880200	-2.17654900
C	-4.99545600	3.27682900	-2.79347600
H	-6.14135400	4.46939100	-1.40243400
H	-3.64471200	2.04223900	-3.93413100
H	-5.75123600	3.31238000	-3.57336100
C	3.39307800	0.28199100	2.94475400
C	4.46533200	1.15098100	2.20801100
H	3.97595900	2.06691400	1.85836100
H	5.20591200	1.44974800	2.96087200
C	2.71393000	1.15825600	4.02179000
H	1.94720000	0.59153900	4.56310500
H	3.45729700	1.49890100	4.75222600
H	2.23878400	2.03811300	3.57709200
C	4.04484800	-0.93840100	3.61443600
H	3.30157800	-1.53355000	4.15232100
H	4.52699300	-1.58926600	2.88155100
H	4.80343700	-0.60245700	4.33219300
C	-2.50392700	-0.51423000	3.24678000
C	-2.64621900	-1.82927300	4.02965800
H	-1.69624000	-2.11758800	4.48912200
H	-3.38978200	-1.70302600	4.82627500
H	-2.96644900	-2.64999800	3.38383900
C	-2.04574200	0.61120300	4.20185500
H	-1.96282300	1.56660800	3.67637000
H	-2.77160900	0.72743400	5.01544300
H	-1.07450400	0.37358900	4.65254000
C	-3.87338500	-0.08986800	2.61773600
H	-4.59274200	-0.02052800	3.44373800
H	-3.75792200	0.91873600	2.20761400
C	-2.49956900	-2.21538500	-2.50508100
C	-2.64908900	-3.74449900	-2.46338000
H	-2.98432700	-4.09077700	-1.48276300
H	-3.38235500	-4.06164200	-3.21563700
H	-1.69776900	-4.23730100	-2.68320300
C	-3.86714200	-1.51569800	-2.20598100
H	-3.74863000	-0.44556900	-2.40383400
H	-4.58793500	-1.90036200	-2.93931800
C	-2.02390000	-1.77525400	-3.90815700
H	-1.08477100	-2.27332000	-4.17581800
H	-2.77407500	-2.04731300	-4.66066600
H	-1.85517300	-0.69574500	-3.94920300

C	3.29389600	-1.35321200	-2.77084400
C	3.94240500	-2.74568200	-2.74967900
H	4.65831800	-2.83002500	-3.57697500
H	4.47230200	-2.93158400	-1.81187000
H	3.18898600	-3.52967500	-2.86749200
C	2.54555700	-1.13618800	-4.10714900
H	2.03762300	-0.16788300	-4.11839000
H	3.25443300	-1.17834300	-4.94311200
H	1.79589400	-1.92106700	-4.26448000
C	4.37077600	-0.22605500	-2.63078700
H	5.08316700	-0.36189100	-3.45475300
H	3.86938200	0.73347000	-2.79208500
C	-4.40747600	-1.70005600	-0.80172600
C	-3.98914500	-0.83845100	0.21376900
C	-5.31115700	-2.73007600	-0.49555100
C	-4.41238600	-1.00884800	1.54013900
H	-3.30747000	-0.03121500	-0.02517300
C	-5.76552200	-2.89079000	0.81796400
H	-5.65301900	-3.38872400	-1.28645100
C	-5.31057200	-2.03526000	1.83202900
H	-5.68057100	-2.19216100	2.84116800
C	5.10982500	-0.18930100	-1.30799400
C	4.54930000	0.49002400	-0.22435100
C	6.33972900	-0.84564200	-1.14045400
C	5.15810500	0.47975200	1.03911300
H	3.60995300	1.01279700	-0.35849200
C	6.97621600	-0.82905900	0.10536300
H	6.78674200	-1.35716500	-1.98587500
C	6.37999700	-0.17507300	1.19337800
H	6.89596700	-0.19172700	2.14913300
O	-6.65527100	-3.85116000	1.21637300
O	8.18090600	-1.42323500	0.36688500
C	-7.13065200	-4.76878900	0.24799700
H	-7.68516500	-4.26272600	-0.55426200
H	-7.80480800	-5.44397600	0.77909500
H	-6.31164400	-5.35073200	-0.19596300
C	8.82419600	-2.12552200	-0.68156000
H	9.06971200	-1.46373500	-1.52342800
H	8.20932500	-2.95816600	-1.04918900
H	9.74816400	-2.52172200	-0.25522500



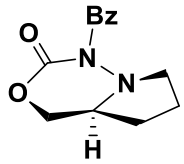
TS2*cis-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	2.03960500	3.88367400	0.50136800
H	2.41155700	2.95707700	0.95630100
H	2.84098100	4.62616400	0.50057300
C	0.81214000	4.39590900	1.23956500
H	0.42257100	5.27301400	0.71836800
N	-0.21082500	3.30515800	1.15378600
C	-1.70387400	3.34852900	0.39370200
O	-2.57549800	2.69130900	0.90511700
C	-0.21483000	2.57850900	2.45131400
H	0.60989100	1.86236200	2.45497100
H	-1.15539700	2.03433000	2.52858800
O	1.70412900	3.66096300	-0.86857200
C	0.58379000	2.93508300	-1.14735500
O	0.30934000	2.68126100	-2.29459400
N	-0.21520300	2.47326000	-0.07209000
Rh	0.03726100	0.09186200	0.05975600
Rh	0.27549500	-2.30976800	-0.02776100
O	1.67675300	-2.06729700	-1.52843200
O	1.47824700	0.18114400	-1.42814900
O	1.56890400	0.10088000	1.51181100
O	-1.35346300	-0.20652000	1.59339400
O	-1.42998500	-0.09622700	-1.37894000
O	-1.14410000	-2.45396100	1.46396600
O	1.77080500	-2.14828800	1.39808600
O	-1.21470200	-2.34666600	-1.45145500
C	-1.65360600	-1.39588100	1.94427600
C	2.10196100	-1.01346600	1.84850200
C	-1.74149800	-1.25116200	-1.81990300
C	1.97791100	-0.89235600	-1.90139100
C	1.02182800	4.62701900	2.75322500
H	0.91116500	5.68202500	3.01705700
H	2.03723200	4.32420400	3.03524100
C	-0.01975700	3.72084900	3.44579100
H	0.31744800	3.35970500	4.42103500
H	-0.96357300	4.25713200	3.59669500
C	-1.91051600	4.58719500	-0.42324500

C	-2.11183500	5.80451300	0.24406000
C	-2.07986400	4.51530500	-1.81061500
C	-2.44506100	6.95080300	-0.47684600
H	-2.02577100	5.84959900	1.32699900
C	-2.41758700	5.66606000	-2.52481900
H	-1.93011000	3.57143800	-2.32071400
C	-2.59523900	6.88271900	-1.86399800
H	-2.59661200	7.89166300	0.04492100
H	-2.54158100	5.60785200	-3.60233400
H	-2.85602300	7.77504800	-2.42638200
C	3.22123400	-0.96279400	2.90985300
C	4.34454400	0.02547500	2.45233500
H	3.91398300	1.03276800	2.41726900
H	5.10572100	0.03074400	3.24275200
C	2.60304600	-0.42364100	4.22002100
H	1.79942800	-1.07948100	4.57453100
H	3.36843900	-0.37706600	5.00361300
H	2.18915300	0.58027900	4.08297200
C	3.79699700	-2.36665100	3.15584500
H	3.01955100	-3.05390200	3.50093800
H	4.23480700	-2.78653400	2.24741100
H	4.57741900	-2.31402300	3.92488600
C	-2.70640000	-1.54411800	3.06101800
C	-2.98907400	-3.02736500	3.34721100
H	-2.07872800	-3.54718800	3.65998500
H	-3.72785500	-3.11108500	4.15376800
H	-3.38058900	-3.54019500	2.46587400
C	-2.14074300	-0.87270600	4.33315800
H	-1.93211400	0.18754900	4.16268400
H	-2.86504400	-0.95480400	5.15207700
H	-1.21285700	-1.35992700	4.65621500
C	-4.01430400	-0.78865600	2.64824600
H	-4.72643300	-0.91154400	3.47440300
H	-3.77927800	0.27808300	2.57416800
C	-2.83237900	-1.29718700	-2.90611100
C	-3.12990300	-2.74763400	-3.31718700
H	-3.49594700	-3.33940400	-2.47474500
H	-3.89224000	-2.75559000	-4.10624400
H	-2.23161700	-3.23727400	-3.70426600
C	-4.12199700	-0.58519800	-2.37552300
H	-3.88517000	0.47381900	-2.23133900
H	-4.86978000	-0.64414200	-3.17708900
C	-2.30680400	-0.50497000	-4.12541900
H	-1.41592800	-0.98402700	-4.54853000
H	-3.07401800	-0.47285500	-4.90836500
H	-2.04242100	0.51885200	-3.84714900

C	3.00459100	-0.72437400	-3.03712600
C	3.56824900	-2.08720000	-3.46768800
H	4.27650600	-1.94668000	-4.29375700
H	4.08727800	-2.58881500	-2.64689800
H	2.76907900	-2.75012700	-3.81116300
C	2.26899400	-0.05655600	-4.22289900
H	1.82368400	0.89609500	-3.92333100
H	2.97288700	0.12131200	-5.04492600
H	1.47065200	-0.70638200	-4.60080400
C	4.14834400	0.23791100	-2.57191200
H	4.84857100	0.32863900	-3.41215100
H	3.70719100	1.22696100	-2.41195500
C	-4.69178400	-1.14678500	-1.08826800
C	-4.20348300	-0.68977400	0.13755200
C	-5.68590600	-2.13860900	-1.10542000
C	-4.64286900	-1.24708200	1.34802400
H	-3.46673400	0.10507300	0.15707100
C	-6.16111900	-2.67009000	0.09799200
H	-6.08080800	-2.47784300	-2.05689200
C	-5.63125300	-2.23110000	1.31970400
H	-6.01547300	-2.67279100	2.23474300
C	4.89215800	-0.18678900	-1.32130100
C	4.37764000	0.14880000	-0.06746900
C	6.07991900	-0.93170000	-1.39405800
C	4.98862400	-0.28873700	1.11672700
H	3.47055700	0.73815000	-0.01310600
C	6.71980100	-1.34228000	-0.21930700
H	6.49254900	-1.17751300	-2.36637400
C	6.16854300	-1.02744500	1.03161200
H	6.68637100	-1.37072300	1.92261200
O	-7.13817500	-3.62480500	0.19058300
O	7.88555100	-2.05630000	-0.18248800
C	-7.70030100	-4.12683100	-1.00804000
H	-8.19822200	-3.33632700	-1.58630200
H	-8.44083400	-4.87003300	-0.70493600
H	-6.94296300	-4.60887300	-1.64128000
C	8.48234200	-2.43244400	-1.41132600
H	8.76684300	-1.55619200	-2.00966400
H	7.81611500	-3.07128900	-2.00655700
H	9.38057700	-2.99505800	-1.14895200



PD_{C-N}

Cartesian Coordinates

Atom	X	Y	Z
C	-2.04373500	1.82751000	-0.66670100
H	-2.79858000	2.61694300	-0.67860000
H	-1.25138300	2.08707800	-1.37772300
C	-2.63887500	0.45699600	-0.97637400
H	-2.73574100	0.35747000	-2.06667100
N	-1.72993000	-0.60543500	-0.46680300
C	0.62557900	-0.99939000	-0.20059700
O	0.41567300	-2.18051000	-0.40290200
C	-2.42314000	-1.39432700	0.57725800
H	-2.27613000	-0.95801100	1.57903900
H	-2.02576600	-2.41124100	0.57934900
O	-1.49354100	1.83301600	0.66627500
C	-0.47278900	0.96062100	0.87980900
O	0.30612800	1.10680500	1.78554800
N	-0.46580200	-0.09680000	-0.06329000
C	-3.98962900	0.18218800	-0.28239500
H	-4.83838800	0.38693700	-0.94182800
H	-4.08628700	0.82475200	0.60139600
C	-3.88861900	-1.28729900	0.15829700
H	-4.57567500	-1.53898100	0.97130700
H	-4.09328000	-1.96047100	-0.68195400
C	2.00656600	-0.43354100	-0.16141400
C	3.04261000	-1.29852400	0.21793900
C	2.31458900	0.86940800	-0.57543300
C	4.36326700	-0.85802900	0.21139400
H	2.79284600	-2.31212700	0.51346900
C	3.63813100	1.30354100	-0.59660800
H	1.52542900	1.53968500	-0.90074100
C	4.66335800	0.44412700	-0.19599400
H	5.15914600	-1.53038400	0.51937100
H	3.86950900	2.31257900	-0.92604400
H	5.69445900	0.78723000	-0.20617100

[Rh]

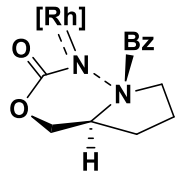
Rh_2(esp-OMe)$_2$

Cartesian Coordinates

Atom	X	Y	Z
Rh	0.00008200	0.08873100	-1.36671200
Rh	0.00010700	0.01395500	1.01521200
O	1.45561000	-1.44632800	0.91088200
O	1.44711600	-1.39276100	-1.34878800
O	1.44668100	1.56575100	-1.25657600
O	-1.44643000	1.56601200	-1.25645300
O	-1.44707900	-1.39271900	-1.34847600
O	-1.45443200	1.47622700	1.00186500
O	1.45471000	1.47625200	1.00173200
O	-1.45537400	-1.44622400	0.91117500
C	-1.86692600	1.93664600	-0.10934900
C	1.86716000	1.93659300	-0.10947000
C	-1.86783300	-1.83419000	-0.22717200
C	1.86796200	-1.83425500	-0.22751900
C	2.93732800	3.04240100	-0.08156400
C	4.17134300	2.59547600	-0.93582800
H	3.84944000	2.52224900	-1.97997300
H	4.90538700	3.40897100	-0.88027100
C	2.32391400	4.30059600	-0.73852900
H	1.45805300	4.65838600	-0.16901800
H	3.06622600	5.10687600	-0.76113700
H	2.00038800	4.09473900	-1.76268500
C	3.35338700	3.36107200	1.36315300
H	2.49522400	3.69263600	1.95489500
H	3.78696700	2.49038300	1.86068700
H	4.09904200	4.16522400	1.35960400
C	-2.93730700	3.04228800	-0.08111800
C	-3.35344400	3.36053600	1.36366100
H	-2.49534000	3.69206400	1.95550100
H	-4.09919900	4.16459300	1.36024300
H	-3.78694300	2.48967300	1.86095500
C	-2.32397500	4.30075600	-0.73770100
H	-2.00043300	4.09524200	-1.76192000
H	-3.06634100	5.10699400	-0.76005500
H	-1.45814600	4.65842300	-0.16806300
C	-4.17125600	2.59553600	-0.93553700
H	-4.90528200	3.40903700	-0.87990100
H	-3.84933200	2.52244300	-1.97969100
C	-2.94026200	-2.93758400	-0.27057700
C	-3.35757700	-3.34672200	1.15075600
H	-3.78671600	-2.50733400	1.70306200

H	-4.10595900	-4.14678800	1.09596200
H	-2.50075100	-3.71871600	1.71993800
C	-4.17160200	-2.43248100	-1.09575000
H	-3.84682700	-2.29256500	-2.13201100
H	-4.90750800	-3.24669400	-1.09615100
C	-2.32982100	-4.15279100	-1.00622500
H	-1.46555100	-4.54891500	-0.46013900
H	-3.07418500	-4.95403300	-1.08183500
H	-2.00448300	-3.88212100	-2.01456400
C	2.94027800	-2.93774200	-0.27098400
C	3.35738400	-3.34726300	1.15029300
H	4.10569700	-4.14737900	1.09534100
H	3.78651100	-2.50806400	1.70288300
H	2.50045100	-3.71934400	1.71926000
C	2.32989700	-4.15276600	-1.00700800
H	2.00463500	-3.88185200	-2.01530800
H	3.07427600	-4.95397500	-1.08275000
H	1.46557100	-4.54902000	-0.46110300
C	4.17174100	-2.43252000	-1.09593000
H	4.90767200	-3.24671300	-1.09632500
H	3.84711100	-2.29252000	-2.13222800
C	-4.81103000	-1.15198500	-0.59694000
C	-4.30470100	0.07898500	-1.01785000
C	-5.89111000	-1.17816300	0.29974900
C	-4.81294000	1.28772000	-0.51855100
H	-3.49044000	0.10152700	-1.73273100
C	-6.43261300	0.02180300	0.77380300
H	-6.30040700	-2.13315400	0.61050100
C	-5.88605900	1.24946000	0.37140800
H	-6.32574000	2.16106200	0.76557700
C	4.81104800	-1.15202800	-0.59695200
C	4.30481200	0.07892500	-1.01801000
C	5.89093100	-1.17818000	0.29998000
C	4.81292900	1.28768900	-0.51863900
H	3.49065200	0.10145200	-1.73301100
C	6.43229500	0.02180000	0.77414200
H	6.30020000	-2.13315800	0.61081000
C	5.88583200	1.24945100	0.37158000
H	6.32545300	2.16105400	0.76581300
O	-7.49220400	0.10560100	1.63364200
O	7.49171900	0.10564000	1.63417300
C	-8.08478400	-1.09765800	2.09026700
H	-8.49842900	-1.68664600	1.26041400
H	-8.89550200	-0.79860400	2.75762300
H	-7.36815000	-1.71680700	2.64671800
C	8.08381200	-1.09760800	2.09146000

H	8.49787500	-1.68687200	1.26200900
H	7.36672300	-1.71649300	2.64761400
H	8.89417300	-0.79852800	2.75923700



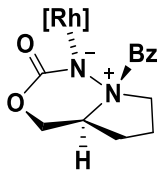
TS1*trans-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	-0.69896900	4.42464900	2.55442300
H	-1.13059000	5.19516900	1.91605900
H	-0.33495200	4.90025200	3.47343800
C	-1.69012000	3.35488600	2.95117200
H	-1.12748600	2.62217500	3.53960300
N	-2.29912200	2.54077500	1.86539700
C	-2.93739400	3.07602200	0.72512700
O	-4.01030100	2.62124800	0.34538400
C	-3.13448400	1.59352100	2.64045000
H	-3.86210300	1.12370400	1.98514800
H	-2.46307900	0.83295200	3.04657800
O	0.45654400	3.92852000	1.85070300
C	0.86721300	2.63113300	1.83719000
O	2.05726300	2.37123300	2.00030700
N	0.00967400	1.60719700	1.66883500
C	-2.90462600	3.76171000	3.80383200
H	-2.61413200	4.04474400	4.82044500
H	-3.42627200	4.61533400	3.35450100
C	-3.77772400	2.47244800	3.75511700
H	-4.81592500	2.70976400	3.50793300
H	-3.77680500	1.94826900	4.71562300
C	-2.31510000	4.20032800	-0.05229300
C	-3.09005600	5.35811100	-0.23060900
C	-1.08197600	4.08537100	-0.70700600
C	-2.61200500	6.41256200	-1.00569800
H	-4.06759300	5.42110900	0.23875500
C	-0.62035800	5.13635500	-1.50289700
H	-0.49943300	3.17635500	-0.61972500
C	-1.37288700	6.30306400	-1.64301500
H	-3.21093600	7.31136400	-1.12411400

H	0.33244100	5.03888600	-2.01514400
H	-1.00174200	7.12017200	-2.25568100
Rh	0.20360100	0.08996100	0.39198600
Rh	0.70771000	-1.86498500	-0.95361300
H	-3.58385600	-1.61566600	2.48158500
C	-3.60974800	-2.58847500	1.97954800
C	-2.17017100	-3.19969900	2.04191200
H	-4.25685300	-3.24081400	2.57991600
C	-4.19088000	-2.41414300	0.59024900
C	-1.21631300	-2.35010300	1.17904400
C	-2.17556600	-4.65954700	1.56055100
C	-1.67472700	-3.13467300	3.50405900
C	-3.90705300	-1.25471400	-0.13300500
C	-5.00164500	-3.40247900	0.00952900
O	-0.61050300	-2.92721000	0.22754200
O	-1.09535100	-1.11728300	1.49873300
H	-2.84112300	-5.25206000	2.20039900
H	-2.52137600	-4.74213700	0.52761100
H	-1.17342600	-5.09478400	1.61317600
H	-1.63215500	-2.10259100	3.86289500
H	-2.35081700	-3.70420200	4.15259100
H	-0.67323600	-3.57046500	3.59908900
C	-4.37590300	-1.07406500	-1.44310700
H	-3.30175100	-0.47891300	0.31963200
C	-5.49902100	-3.22156900	-1.28576200
H	-5.24156700	-4.29471600	0.57743200
C	-3.98857100	0.17829700	-2.20280900
C	-5.17988900	-2.06271600	-2.00932700
O	-6.30610000	-4.11420000	-1.93533300
C	-2.61794400	0.11184700	-2.95822400
H	-3.96428100	1.02542500	-1.51032800
H	-4.74890600	0.40492600	-2.96070800
H	-5.58350000	-1.95634800	-3.01207600
C	-6.65283800	-5.31551200	-1.26968800
C	-1.49624000	-0.26704800	-1.97493300
C	-2.30568700	1.51611300	-3.52293000
C	-2.67779100	-0.90699400	-4.10861500
H	-7.21744500	-5.12071900	-0.34761500
H	-5.76513600	-5.91484900	-1.02593300
H	-7.28314800	-5.87320600	-1.96530200
O	-1.29210800	0.51764400	-0.98073200
O	-0.82824000	-1.31644200	-2.20623200
H	-1.35471100	1.51767900	-4.06927200
H	-3.09416100	1.81374500	-4.22369700
H	-2.24930700	2.26453200	-2.72881800
H	-1.72826200	-0.94761400	-4.65056500

H	-2.90056400	-1.91351000	-3.74695200
H	-3.46308600	-0.60983300	-4.81394900
O	2.00309300	-0.68521800	-2.04858100
C	2.12839600	0.54280400	-1.76511100
O	1.50569600	1.15353200	-0.82746000
C	3.09340600	1.39037600	-2.61606300
C	3.71310900	0.53782600	-3.73471900
C	2.28857300	2.55510700	-3.23442300
C	4.20236700	1.99722400	-1.69072600
H	2.93969200	0.12703600	-4.39066300
H	4.38134300	1.16165500	-4.34062200
H	4.28975600	-0.29790500	-3.33248500
H	1.83086800	3.17210600	-2.45631100
H	2.95255900	3.18707200	-3.83553400
H	1.49386700	2.18261400	-3.89162000
H	4.87213600	2.57557000	-2.33978800
H	3.72143200	2.70394600	-1.00632100
C	4.99651700	0.99177000	-0.88243300
C	4.51135700	0.58568400	0.36972400
C	6.18767000	0.44317700	-1.35758000
C	5.16981600	-0.39367500	1.11563200
H	3.61447800	1.04483300	0.77017000
C	6.87945000	-0.51375600	-0.60082400
H	6.61038800	0.74738300	-2.31085800
C	4.56201600	-0.85624900	2.42451800
C	6.36844900	-0.94056200	0.62962100
O	8.04561900	-0.96857400	-1.15450700
C	3.54145900	-2.03895300	2.31184600
H	4.04676500	-0.01245000	2.89416700
H	5.34942000	-1.18465100	3.11541000
H	6.89281400	-1.68317700	1.22111200
C	8.78642100	-1.94733500	-0.44853400
C	2.42374700	-1.65193200	1.32544100
C	4.23545600	-3.33133100	1.85322600
C	2.89537000	-2.25576200	3.69901400
H	9.11911000	-1.57732900	0.53100100
H	9.66065000	-2.16572300	-1.06537100
H	8.20677000	-2.86930000	-0.30401000
O	1.74907300	-0.60899500	1.61455500
O	2.23227400	-2.38885400	0.31144600
H	4.69767000	-3.21439300	0.87038700
H	5.01504700	-3.60180200	2.57599000
H	3.52371900	-4.16002100	1.79186800
H	2.17433800	-3.08165000	3.67287700
H	3.66931500	-2.51041400	4.43253900
H	2.37595400	-1.35502700	4.03715800



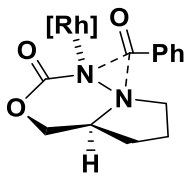
IM*trans-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	-0.19496400	3.50876400	-3.69382400
H	0.06075600	4.50289400	-4.06371700
H	-0.63709700	2.92613100	-4.51082300
C	1.02367800	2.78250800	-3.12814400
H	0.86258000	1.70268500	-3.17198300
N	0.99399400	3.00651100	-1.61556500
C	0.97995300	4.52028600	-1.23979400
O	1.36402500	5.28687400	-2.08758500
C	2.34319100	2.45370100	-1.20048700
H	2.57293100	2.76718500	-0.18282100
H	2.22553300	1.37251800	-1.22838500
O	-1.17005800	3.70845600	-2.66291800
C	-1.30571100	2.74615500	-1.64000000
O	-2.42263200	2.44165700	-1.28735400
N	-0.14341000	2.29813500	-1.06788400
C	2.45274000	3.09793800	-3.58545400
H	2.76260700	2.38298500	-4.35299000
H	2.53323200	4.10398600	-3.99957400
C	3.30730600	2.95939900	-2.28732000
H	3.73744500	3.92626000	-2.01427300
H	4.13357600	2.25258400	-2.40133500
C	0.59839300	4.91224100	0.13549700
C	0.52671000	6.30564000	0.34467400
C	0.37498800	4.03774700	1.21688500
C	0.23014000	6.81557400	1.60228700
H	0.70445800	6.96983800	-0.49366800
C	0.09523400	4.56315200	2.47749000
H	0.39882100	2.96521300	1.08220600
C	0.01591500	5.94324700	2.67369500
H	0.16660200	7.88982300	1.74831700
H	-0.07450900	3.88257400	3.30599800
H	-0.21567400	6.33947600	3.65867900
Rh	-0.09310800	0.16967100	-0.20400600
Rh	-0.23704800	-2.07039200	0.70821400
H	3.97268500	-0.49864100	-2.48326100
C	4.13210000	-1.54233100	-2.18809500

C	2.79431000	-2.31818800	-2.43017700
H	4.87142600	-1.95746400	-2.88505600
C	4.67716500	-1.57658100	-0.77336200
C	1.71531400	-1.81044300	-1.44976000
C	3.00897500	-3.83067200	-2.25772600
C	2.31639700	-2.02335000	-3.86894700
C	4.22863800	-0.63995600	0.15767200
C	5.62334900	-2.53336700	-0.37367300
O	1.22736500	-2.64723500	-0.63904200
O	1.38175400	-0.57617200	-1.53405400
H	3.76087800	-4.17941800	-2.97668800
H	3.34935900	-4.07612400	-1.24925800
H	2.08116400	-4.38105000	-2.43805200
H	2.13902500	-0.95407900	-4.01677700
H	3.07105400	-2.35524200	-4.59188200
H	1.38376900	-2.55547000	-4.08897600
C	4.66750000	-0.65136300	1.48908400
H	3.50378100	0.10382000	-0.14522900
C	6.08820000	-2.54349300	0.94674100
H	5.99095000	-3.25254600	-1.09727000
C	4.10349700	0.36362600	2.46311300
C	5.60776000	-1.60578400	1.87406100
O	7.01488900	-3.42258400	1.43181200
C	2.75272300	-0.02536700	3.15160000
H	3.95292000	1.31451200	1.93918800
H	4.82696400	0.55423500	3.26566600
H	5.99273200	-1.64352900	2.88890500
C	7.52068700	-4.41860200	0.55966200
C	1.69486700	-0.35741200	2.07652700
C	2.25386100	1.19394600	3.95788600
C	2.95513500	-1.22142500	4.09604000
H	8.05440600	-3.97807900	-0.29348800
H	6.72141300	-5.07170000	0.18455300
H	8.22000300	-5.01018400	1.15369700
O	1.37578100	0.57590400	1.26066400
O	1.21095300	-1.52628000	2.08255100
H	1.31037800	0.96565200	4.46767100
H	2.99093600	1.46494100	4.72309200
H	2.09169100	2.05969500	3.30945700
H	2.01842300	-1.49247300	4.59147500
H	3.31392500	-2.10263400	3.55949700
H	3.68957200	-0.95941500	4.86767900
O	-1.68686900	-1.39656600	2.00232900
C	-2.00851300	-0.16848800	1.98184100
O	-1.51319900	0.71347600	1.20541900
C	-3.07440800	0.31475400	2.98499000

C	-3.52986600	-0.84132800	3.88932800
C	-2.44628200	1.43337600	3.84595600
C	-4.28424800	0.92551600	2.20007500
H	-2.68740700	-1.25826100	4.44962500
H	-4.27238000	-0.47311900	4.60802500
H	-3.97974800	-1.65139300	3.31109100
H	-2.10631000	2.26353700	3.22047900
H	-3.18599800	1.81415200	4.56016700
H	-1.59096200	1.05526100	4.41971700
H	-5.02518400	1.23297500	2.94945700
H	-3.93405200	1.83110100	1.69420800
C	-4.92343400	0.00941900	1.17703300
C	-4.40511700	-0.02122800	-0.12634600
C	-6.00096600	-0.81625200	1.49857300
C	-4.91534300	-0.90059800	-1.08301900
H	-3.60292600	0.65669000	-0.39704500
C	-6.54578300	-1.67763500	0.53565500
H	-6.44694000	-0.80522700	2.48911500
C	-4.27228500	-0.95093700	-2.45431500
C	-6.00011200	-1.72883900	-0.75121200
O	-7.61305400	-2.42800500	0.95502900
C	-3.07000000	-1.94480800	-2.59736800
H	-3.91224300	0.05042500	-2.71109800
H	-5.01317000	-1.23850700	-3.21215700
H	-6.41114100	-2.39414100	-1.50285200
C	-8.20006600	-3.32878100	0.03491700
C	-2.00241500	-1.59867900	-1.54136700
C	-3.53254500	-3.40199700	-2.44144100
C	-2.44229100	-1.74524300	-3.99497600
H	-8.60833500	-2.80717100	-0.84187900
H	-9.01497400	-3.81951400	0.57158500
H	-7.48260700	-4.08842500	-0.30494200
O	-1.50803900	-0.42429000	-1.59678800
O	-1.67932300	-2.49524700	-0.70302900
H	-3.97721000	-3.57966300	-1.45974300
H	-4.27974800	-3.63362800	-3.21081200
H	-2.69429800	-4.09561400	-2.55867800
H	-1.59207800	-2.42178600	-4.14562500
H	-3.18450000	-1.96235100	-4.77234500
H	-2.09261700	-0.71732800	-4.12519600



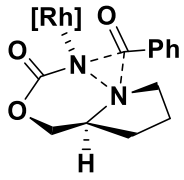
TS2*trans-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	0.11631300	3.09466300	-4.07754700
H	-0.02979900	4.17513400	-4.08944500
H	0.19208200	2.71624900	-5.09941700
C	1.32821900	2.68660800	-3.27254700
H	1.42778500	1.59403300	-3.34643900
N	1.10398500	2.94396600	-1.82801200
C	0.20650500	4.19927500	-1.16122900
O	-0.34750200	4.94975200	-1.93894000
C	2.37532900	2.52221800	-1.19414800
H	2.41964200	2.86529100	-0.16305400
H	2.40163300	1.43228700	-1.20974200
O	-1.05250500	2.47025200	-3.51959700
C	-1.26530800	2.44395100	-2.17835600
O	-2.38415500	2.35780200	-1.74581100
N	-0.16642300	2.47951200	-1.25245900
C	2.68651400	3.35450900	-3.50219600
H	3.21741600	2.90030500	-4.34285600
H	2.55427300	4.41887000	-3.72230100
C	3.42385000	3.15234800	-2.13908900
H	3.77643500	4.10950700	-1.74514400
H	4.29226600	2.49515100	-2.23305400
C	0.66106700	4.59024600	0.20842200
C	1.36270500	5.80222900	0.30941800
C	0.30892700	3.88484200	1.36369400
C	1.73959700	6.28896400	1.55897900
H	1.58930800	6.36320500	-0.59239200
C	0.67007400	4.39363900	2.61411500
H	-0.25694700	2.96405400	1.28449800
C	1.39102900	5.58476500	2.71491600
H	2.28924800	7.22332100	1.63178200
H	0.37942900	3.85526500	3.51140500
H	1.67145300	5.97038900	3.69142900
Rh	-0.11317800	0.23350000	-0.17545800
Rh	-0.31642700	-1.97898800	0.76797000
H	3.85794300	-0.59967000	-2.55107800
C	3.99133100	-1.64484000	-2.24909500

C	2.62084800	-2.37714600	-2.43590300
H	4.69156000	-2.09364600	-2.96521500
C	4.58125400	-1.68332600	-0.85268500
C	1.59125600	-1.81675200	-1.43212400
C	2.78870800	-3.89344700	-2.24512400
C	2.10604700	-2.08876800	-3.86345500
C	4.18508500	-0.72966400	0.08462800
C	5.51614900	-2.66024800	-0.47585700
O	1.08717400	-2.62915300	-0.60348600
O	1.30830300	-0.57078900	-1.51418000
H	3.50567100	-4.27818600	-2.98105600
H	3.15276800	-4.13518500	-1.24400000
H	1.83790200	-4.41463500	-2.38839700
H	1.96255500	-1.01650400	-4.02573600
H	2.82449600	-2.46033400	-4.60365900
H	1.14822900	-2.58995800	-4.04413700
C	4.66535600	-0.74241300	1.40137900
H	3.47151500	0.03130600	-0.20150900
C	6.02264600	-2.67197800	0.82925100
H	5.84322400	-3.39327400	-1.20504100
C	4.15530000	0.29281300	2.38344600
C	5.59414100	-1.71665700	1.76408400
O	6.94301000	-3.56977700	1.29162000
C	2.81421300	-0.05761600	3.10968100
H	4.01591600	1.24501900	1.85934700
H	4.90401900	0.46658500	3.16634400
H	6.00995500	-1.75671000	2.76661000
C	7.40049700	-4.58099000	0.41034800
C	1.71093000	-0.34336900	2.06753500
C	2.38181700	1.16998500	3.94047100
C	3.00570000	-1.26825800	4.03808700
H	7.91666000	-4.15646000	-0.46149000
H	6.57650100	-5.21910700	0.06396300
H	8.10524400	-5.18407500	0.98610400
O	1.39913700	0.59613700	1.25873700
O	1.17916900	-1.49388000	2.09638000
H	1.44829200	0.96746300	4.47914000
H	3.15176700	1.40795600	4.68400600
H	2.22766500	2.04540000	3.30452900
H	2.07789400	-1.50950100	4.56469800
H	3.31542400	-2.15765600	3.48471200
H	3.77488600	-1.03738300	4.78533000
O	-1.70766700	-1.22715100	2.08525300
C	-2.00297000	0.00637300	2.04425900
O	-1.50194400	0.85620000	1.23252900
C	-3.03494800	0.53504800	3.05838000

C	-3.50595000	-0.59577400	3.98689100
C	-2.36024300	1.64569200	3.89459500
C	-4.24239600	1.16761500	2.28687400
H	-2.66570700	-1.02730800	4.53923800
H	-4.22536500	-0.19672000	4.71227000
H	-3.98797900	-1.40120500	3.42845800
H	-2.01861800	2.46771900	3.25931000
H	-3.07387100	2.04616700	4.62404900
H	-1.49944100	1.25295900	4.44962200
H	-4.96113700	1.50296800	3.04547000
H	-3.87987900	2.05990600	1.76595400
C	-4.92336800	0.25554800	1.28730900
C	-4.43126400	0.19066500	-0.02489300
C	-6.01532300	-0.53709800	1.64138500
C	-4.97969500	-0.69087700	-0.95853200
H	-3.61625500	0.84046100	-0.32345200
C	-6.59967000	-1.39922100	0.70246500
H	-6.44244400	-0.49899700	2.63945400
C	-4.36261500	-0.78076800	-2.33961200
C	-6.07876300	-1.48509000	-0.59290700
O	-7.67699900	-2.11474500	1.15303700
C	-3.19579800	-1.81657000	-2.48970400
H	-3.97514600	0.20404100	-2.61844100
H	-5.12533200	-1.05646900	-3.07973800
H	-6.52041000	-2.15135000	-1.32598300
C	-8.30649900	-3.01256900	0.25771400
C	-2.10566100	-1.49834300	-1.45072600
C	-3.70279100	-3.25680500	-2.31627800
C	-2.57910300	-1.64343500	-3.89624500
H	-8.71700000	-2.49237000	-0.61869900
H	-9.12388600	-3.47229300	0.81737900
H	-7.61674300	-3.79665000	-0.08372100
O	-1.56185200	-0.34779900	-1.53186900
O	-1.80811600	-2.38725000	-0.59444700
H	-4.14226600	-3.41316800	-1.32849800
H	-4.46523900	-3.47008500	-3.07567600
H	-2.88870400	-3.97813200	-2.43763300
H	-1.75437200	-2.34935200	-4.05441900
H	-3.33901900	-1.84072800	-4.66156200
H	-2.19884300	-0.62794400	-4.03612500



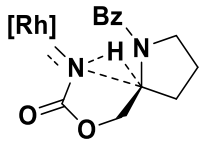
PT_{conc}

Cartesian Coordinates

Atom	X	Y	Z
C	0.07139200	3.17783000	-2.95596200
H	0.60191900	2.21924600	-2.91223200
H	0.04464200	3.53533900	-3.98860400
C	0.74790200	4.19948500	-2.04365500
H	0.14774200	5.11514100	-2.04423900
N	0.79210000	3.65558700	-0.67763000
C	-0.41618300	3.83752500	1.00277400
O	0.15792800	3.50106000	1.97652600
C	2.12351900	3.11908900	-0.40600200
H	2.22708200	2.12457900	-0.84966000
H	2.26725900	3.03343900	0.67285300
O	-1.29399700	3.00419300	-2.58033700
C	-1.58254800	2.49845700	-1.35308300
O	-2.73067600	2.19574200	-1.09402100
N	-0.57607100	2.31965400	-0.40267900
C	2.23723600	4.45107100	-2.41254600
H	2.39692800	5.46925600	-2.77756500
H	2.54164900	3.76516500	-3.21242600
C	3.02076600	4.14422000	-1.11605400
H	4.02316600	3.74993500	-1.30638300
H	3.12452900	5.04681500	-0.50341800
C	-1.45790900	4.85423900	0.74328500
C	-2.80307900	4.53793100	0.96996600
C	-1.07753400	6.15726600	0.39596000
C	-3.76808100	5.53571500	0.83542500
H	-3.08188000	3.52136800	1.22029400
C	-2.05170400	7.14615600	0.26651500
H	-0.02805900	6.39262900	0.24743300
C	-3.39635300	6.83495200	0.48353900
H	-4.81334100	5.29257300	1.00080500
H	-1.76012300	8.15820500	0.00075000
H	-4.15435500	7.60600000	0.37777800
Rh	0.00872700	0.16672900	-0.05080700
Rh	0.28091300	-2.20395800	0.36518900
O	1.78294500	-2.21529200	-1.05660500
O	1.54731400	-0.00741600	-1.49086400

O	1.42351400	0.49126700	1.46263400
O	-1.46826000	0.13631300	1.40759200
O	-1.32236100	-0.36853000	-1.55183500
O	-1.22652800	-2.08471900	1.76139000
O	1.64071600	-1.72970400	1.83967400
O	-1.10678200	-2.57635500	-1.12165600
C	-1.76928600	-0.96013800	1.98680400
C	1.91381500	-0.51434100	2.07752400
C	-1.60514800	-1.59643200	-1.75336100
C	2.09306500	-1.15230600	-1.66724100
C	2.91268000	-0.22069300	3.21602800
C	4.15848200	0.53383900	2.64230700
H	3.83137600	1.53101400	2.32759300
H	4.85628800	0.67574000	3.47704500
C	2.21199800	0.70767100	4.23307200
H	1.35197500	0.20505300	4.69110100
H	2.90870900	0.97722900	5.03593100
H	1.85416300	1.62194500	3.75216400
C	3.34423800	-1.52414300	3.90704800
H	2.48034100	-2.05514400	4.31713800
H	3.85191600	-2.19992400	3.21467400
H	4.02841500	-1.29181400	4.73252300
C	-2.87298300	-0.89355800	3.06033900
C	-3.10388900	-2.27860900	3.68522600
H	-2.18771200	-2.65813800	4.14718200
H	-3.87565100	-2.20574100	4.46141500
H	-3.42946500	-3.00822200	2.94028400
C	-2.41380000	0.10064800	4.15065000
H	-2.21317300	1.08841800	3.72676400
H	-3.19131100	0.19808000	4.91772100
H	-1.49982000	-0.25195100	4.64325400
C	-4.19060200	-0.34410400	2.41699800
H	-4.95186300	-0.34016500	3.20766700
H	-4.01533000	0.69828600	2.13038000
C	-2.62601500	-1.88747500	-2.86954600
C	-2.83455800	-3.40134000	-3.02999800
H	-3.21837400	-3.85425600	-2.11301400
H	-3.55137000	-3.58893400	-3.83918700
H	-1.89528600	-3.90306800	-3.28191500
C	-3.97332300	-1.16039300	-2.53553000
H	-3.79064900	-0.08193100	-2.57353800
H	-4.67314600	-1.40435300	-3.34575000
C	-2.07345800	-1.29324700	-4.18489100
H	-1.12536700	-1.76909600	-4.46412000
H	-2.78650100	-1.46453700	-5.00006700
H	-1.90577100	-0.21696800	-4.08918200

C	3.21670400	-1.24439900	-2.72166400
C	3.69408000	-2.69802200	-2.87281900
H	4.47531200	-2.74941400	-3.64152900
H	4.09948500	-3.08730400	-1.93625600
H	2.87125200	-3.35171400	-3.17628700
C	2.65775300	-0.74025700	-4.07016100
H	2.29914800	0.29014800	-3.99139400
H	3.43878100	-0.77930800	-4.83879400
H	1.82308600	-1.36545400	-4.40775500
C	4.40605600	-0.31637100	-2.30397700
H	5.18808700	-0.44085900	-3.06416100
H	4.06159000	0.72186900	-2.37248600
C	-4.58582800	-1.50648900	-1.19318400
C	-4.21045500	-0.77611400	-0.06394100
C	-5.50904600	-2.55617600	-1.05802900
C	-4.69429600	-1.10934000	1.21021600
H	-3.53525200	0.06461800	-0.17604300
C	-6.02665400	-2.87032500	0.20291300
H	-5.81892700	-3.10793800	-1.93888600
C	-5.61124900	-2.15336700	1.33414000
H	-6.02790600	-2.42886400	2.29877100
C	4.98325100	-0.55291500	-0.92164600
C	4.39989300	0.07312200	0.17969000
C	6.09149100	-1.39103200	-0.72113800
C	4.86683200	-0.14063900	1.48449100
H	3.54953600	0.72528000	0.03093000
C	6.58235000	-1.59690900	0.57352600
H	6.56198300	-1.86513700	-1.57552000
C	5.96827000	-0.97468700	1.67145200
H	6.37850600	-1.15657200	2.66051800
O	-6.94346100	-3.86016800	0.43895300
O	7.66038000	-2.38210100	0.87424500
C	-7.39003800	-4.63470700	-0.65850500
H	-7.89940600	-4.01781900	-1.41174900
H	-8.09851900	-5.35763000	-0.24842600
H	-6.56209700	-5.17332700	-1.13958200
C	8.31056600	-3.06645100	-0.18216100
H	8.73785500	-2.36918800	-0.91582700
H	7.62898700	-3.75608900	-0.69808500
H	9.11716800	-3.63762200	0.28178900



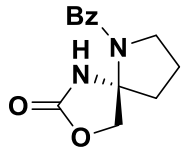
TS_{C-H}

Cartesian Coordinates

Atom	X	Y	Z
C	0.08425100	4.14072900	-2.38507000
H	1.16139000	4.26692000	-2.51976400
H	-0.43867300	4.98683500	-2.84037800
C	-0.28318700	4.00290700	-0.89876000
H	0.17099000	2.98694000	-0.64292600
N	0.19571700	5.06046900	-0.03557200
C	1.47829600	5.57699700	0.12738800
O	1.63177600	6.61481000	0.76555800
C	-0.90922700	5.73390800	0.68322600
H	-0.70634000	6.80433200	0.72690800
H	-0.95877800	5.36134400	1.71546800
O	-0.35836700	2.98678800	-3.10643700
C	0.06439100	1.73944900	-2.72950600
O	0.15603800	0.85230600	-3.56687200
N	0.41701600	1.52679000	-1.44266800
Rh	-0.13114900	-0.02657200	-0.30796900
Rh	-0.50903900	-2.11754100	0.86050600
O	0.84124800	-3.07718900	-0.34734200
O	1.19423000	-1.14389900	-1.46042100
O	1.37591000	0.38578500	1.07793500
O	-1.48755300	0.84247200	1.00917800
O	-1.67999700	-0.55535600	-1.56949500
O	-1.86144200	-1.11979500	2.05537200
O	1.01575800	-1.57488900	2.14854900
O	-2.00089300	-2.53045200	-0.51192700
C	-2.06640500	0.11693800	1.89441100
C	1.62774500	-0.47648300	1.99030500
C	-2.26710000	-1.68042700	-1.41424800
C	1.40131200	-2.38447000	-1.24981500
C	-1.80270000	3.94446000	-0.63707900
H	-2.00042500	3.19197000	0.13105500
H	-2.35077500	3.65052800	-1.53628300
C	-2.14858300	5.35011000	-0.12536800
H	-2.28227700	6.04678000	-0.96164200
H	-3.06302900	5.37061000	0.47439900
C	2.66661900	4.88845500	-0.47905700

C	3.63540200	5.71726900	-1.06883300
C	2.90297700	3.50938000	-0.38938800
C	4.79922700	5.17145400	-1.60379100
H	3.46246800	6.78841700	-1.09384100
C	4.08096800	2.96893700	-0.91154300
H	2.19335600	2.84712100	0.09331700
C	5.02355500	3.79383500	-1.52693900
H	5.53464000	5.81986200	-2.07210300
H	4.25803100	1.90007600	-0.83610100
H	5.93366400	3.36600900	-1.93858200
C	2.75220700	-0.12522800	2.98373900
C	4.07674500	0.16324600	2.20091700
H	3.92822900	1.06934500	1.60445900
H	4.84150400	0.39782800	2.95164600
C	2.33619200	1.16585700	3.72578600
H	1.41035000	1.01185100	4.29275700
H	3.11921000	1.45477100	4.43622900
H	2.17940000	1.99322900	3.02802500
C	2.95194100	-1.26381300	3.99678100
H	2.03395900	-1.45494000	4.55992600
H	3.24348800	-2.19508300	3.50552100
H	3.73943900	-0.98541100	4.70740000
C	-3.05996700	0.81994000	2.83765300
C	-3.63808900	-0.18523100	3.84732700
H	-2.84455400	-0.64311300	4.44476400
H	-4.32340400	0.33518000	4.52701900
H	-4.18734900	-0.98718700	3.34893700
C	-2.29337900	1.93057400	3.59162500
H	-1.85245200	2.65320800	2.89883200
H	-2.97680800	2.46337100	4.26275400
H	-1.48709500	1.50727900	4.20173800
C	-4.20504100	1.48650700	2.00293400
H	-4.89685400	1.93851200	2.72454300
H	-3.77063000	2.30747900	1.42205700
C	-3.36820100	-2.01578500	-2.43652700
C	-4.00220100	-3.37946300	-2.12051700
H	-4.47449700	-3.38851300	-1.13504000
H	-4.76399100	-3.61116100	-2.87498600
H	-3.25116900	-4.17435900	-2.13805300
C	-4.44590100	-0.87958400	-2.43083100
H	-3.97582900	0.03058900	-2.81714300
H	-5.21877700	-1.17328500	-3.15233100
C	-2.70696100	-2.05146900	-3.83431800
H	-1.97361500	-2.86397900	-3.89758800
H	-3.47007200	-2.22894200	-4.60134300
H	-2.19317100	-1.11184300	-4.05444700

C	2.39562600	-3.07295100	-2.20156600
C	2.59131800	-4.54429500	-1.80456200
H	3.28072300	-5.02322500	-2.51060100
H	3.00376600	-4.64081300	-0.79710500
H	1.64246600	-5.08760800	-1.83155800
C	1.80307000	-2.98224200	-3.62760400
H	1.60396700	-1.94418900	-3.90759800
H	2.50508600	-3.41716400	-4.34876300
H	0.86343400	-3.54324600	-3.69556800
C	3.75487900	-2.29602700	-2.18430600
H	4.42925800	-2.82584400	-2.86896300
H	3.57795200	-1.30350600	-2.61079900
C	-5.07560600	-0.58369800	-1.08406800
C	-4.45519800	0.31851700	-0.21757100
C	-6.26143500	-1.21588800	-0.67761400
C	-4.95956800	0.56238300	1.06850800
H	-3.55383000	0.82595400	-0.54088100
C	-6.79458300	-0.95260300	0.58916500
H	-6.75750300	-1.90022500	-1.35697000
C	-6.13775400	-0.07171700	1.46142500
H	-6.57582300	0.10432900	2.43958100
C	4.40759700	-2.14803300	-0.82384100
C	4.03924100	-1.08740500	0.00715600
C	5.36387000	-3.07103700	-0.37175900
C	4.56335900	-0.95692200	1.30292600
H	3.31638200	-0.36308300	-0.34967200
C	5.92041800	-2.93078400	0.90449900
H	5.66710500	-3.88306000	-1.02347400
C	5.51210900	-1.88067000	1.74023700
H	5.95928800	-1.80628300	2.72727700
O	-7.94839600	-1.50270400	1.07220900
O	6.86693300	-3.76438300	1.43105100
C	-8.65437300	-2.41663400	0.25043000
H	-8.99217200	-1.94559200	-0.68255900
H	-9.52464500	-2.73050900	0.83010700
H	-8.04459200	-3.29717800	0.00747400
C	7.31430600	-4.85608200	0.64604800
H	7.78928600	-4.51847200	-0.28507400
H	6.49263600	-5.54245700	0.40085700
H	8.05204600	-5.38150800	1.25569700



PD$_{C-H}$

Cartesian Coordinates

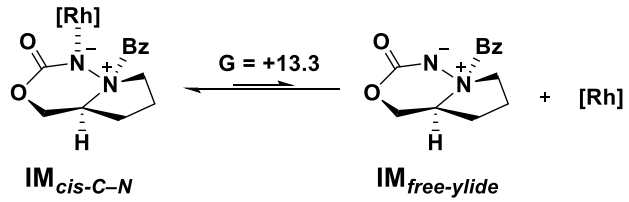
Atom	X	Y	Z
C	-0.66143700	0.84632800	1.53369900
H	0.04331500	0.08732800	1.87506200
H	-1.30211000	1.14858700	2.36846500
C	-1.53162900	0.36470000	0.33157500
H	-1.61991500	1.48706300	-1.52982100
N	-1.21219000	-0.96243100	-0.25794700
C	-0.02414700	-1.68102000	-0.26456100
O	-0.06131100	-2.90299400	-0.38573100
C	-2.43406100	-1.76649400	-0.48846700
H	-2.50200000	-2.56375500	0.26169300
H	-2.38344400	-2.25051400	-1.46713600
O	0.07143200	1.99134500	1.09010800
C	-0.33405500	2.35928100	-0.16334100
O	0.11740200	3.29857900	-0.76944200
N	-1.31723200	1.48388300	-0.56701700
C	-3.01953900	0.19145300	0.71510500
H	-3.51741700	1.16253100	0.77538200
H	-3.07733000	-0.28666700	1.70203700
C	-3.57342300	-0.75702400	-0.34726100
H	-4.51535200	-1.23021000	-0.05670600
H	-3.74583400	-0.22456800	-1.29108300
C	1.30140800	-0.98454100	-0.16398500
C	2.26967700	-1.55536800	0.67736200
C	1.64902700	0.11060900	-0.96343300
C	3.54588700	-1.00472200	0.75443900
H	2.00880500	-2.43563300	1.25687300
C	2.93496700	0.64957400	-0.89912600
H	0.92684000	0.53101500	-1.65431600
C	3.88032900	0.10111000	-0.03312400
H	4.28415400	-1.44310200	1.42039700
H	3.19011300	1.50102200	-1.52288800
H	4.87792500	0.52799000	0.02400400

3-7. Additional calculations

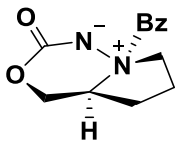
3-7-1. Generation of free ylide intermediate

Generation of Rh-free ylide ($IM_{free\text{-}ylide}$) from $IM_{cis\text{-}C\text{-}N}$ was found to be thermodynamically 13.3 kcal/mol unfavorable.

Dissociation of the Metal Complex



$IM_{cis\text{-}C\text{-}N}$ $IM_{free\text{-}ylide}$



$IM_{free\text{-}ylide}$

Cartesian Coordinates

Atom	X	Y	Z
C	1.99379400	1.00614600	1.43297700
H	3.02253700	0.95621500	1.04479400
H	2.05101900	1.12741200	2.51934600
C	1.22778500	-0.26411100	1.09784200
H	0.21846100	-0.17891200	1.50131000
N	1.11504900	-0.29183400	-0.42420100
C	-0.18946000	-0.95241000	-0.91643600
O	-0.09186300	-1.89072500	-1.66464900
C	2.31337700	-1.09887400	-0.86845700
H	3.14889200	-0.39791400	-0.83922400
H	2.14892800	-1.41882400	-1.89408000
O	1.30898700	2.12641400	0.92155700
C	1.02315400	2.11909000	-0.45515500
O	0.73557700	3.19258100	-0.95190800
N	1.05794100	0.96411200	-1.17417500
C	1.94619900	-1.57353400	1.48812500
H	1.27987000	-2.24042100	2.04173900
H	2.78980200	-1.34416700	2.14888500
C	2.42852800	-2.21797600	0.16125200

H	3.45295600	-2.59383800	0.22839200
H	1.78535700	-3.05497500	-0.12284300
C	-1.48486300	-0.45798200	-0.36965800
C	-2.36739800	-1.47490700	0.04358200
C	-1.89300800	0.88438900	-0.29612800
C	-3.61525000	-1.15480000	0.56908700
H	-2.06237400	-2.51243700	-0.05079400
C	-3.15212700	1.19110400	0.22113500
H	-1.26760900	1.67825700	-0.68202500
C	-4.00868400	0.18223500	0.66305100
H	-4.28204600	-1.94762000	0.89593400
H	-3.46497200	2.23019900	0.26370000
H	-4.98563000	0.43470600	1.06620200

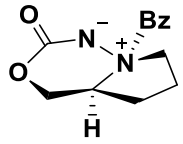
3-7-2. Calculations on the open-shell triplet pathway

Calculations with an open-shell triplet pathway were also performed using the hybrid density functional method based on UB3LYP and the LANL2DZ basis set for Rh, and the 6-31G* basis set for H, C, N, and O (Table S3). The vibrational frequencies were computed at the same level to check whether each optimized structure is an energy minimum (no imaginary frequency) or a transition state (one imaginary frequency) and to evaluate its ZPVE and thermal corrections at 353 K. The IRC method was used to track minimum energy paths from transition structures to the corresponding local minima. Single point energies were calculated at the UωB97XD/6-311+G* (for H, C, N, O) and SDD (Rh) in chlorobenzene solvent.

Table S3[a]

	E(U*w*B97XD) (A.U.)	Thermal Correction to Free Energy (A.U.)	Sum of Electronic and Thermal Free Energies (A.U.)
RT[b]	-3134.557772	0.864072	-3133.6937
$RT_{triplet}$	-3134.566026	0.864072	-3133.701954
$TS1_{triplet\text{-}C\text{-}N}$	-3134.494881	0.900576	-3133.594305
$IM1_{triplet\text{-}C\text{-}N}$	-3134.533938	0.871466	-3133.662472
$TS2_{triplet\text{-}C\text{-}N}$	-3134.475458	0.868168	-3133.60729
$IM2_{triplet\text{-}C\text{-}N}$	-3134.554405	0.864168	-3133.690237
$PD_{C\text{-}N}$[b]	-838.930829	0.206358	-838.724471
(Rh)[b]	-2295.675716	0.642582	-2295.033134
$TS_{triplet\text{-}C\text{-}H}$	-3134.52849	0.86446	-3133.66403
$IM_{triplet\text{-}C\text{-}H}$	-3134.568025	0.865203	-3133.702822
$PD_{C\text{-}H}$[b]	-838.99033	0.205751	-838.784579

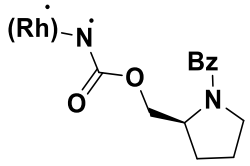
[a] UωB97XD/6-311+G*/SDD. [b] RωB97XD/6-311+G*/SDD.



IM*free-ylide*

Cartesian Coordinates

Atom	X	Y	Z
C	1.99379400	1.00614600	1.43297700
H	3.02253700	0.95621500	1.04479400
H	2.05101900	1.12741200	2.51934600
C	1.22778500	-0.26411100	1.09784200
H	0.21846100	-0.17891200	1.50131000
N	1.11504900	-0.29183400	-0.42420100
C	-0.18946000	-0.95241000	-0.91643600
O	-0.09186300	-1.89072500	-1.66464900
C	2.31337700	-1.09887400	-0.86845700
H	3.14889200	-0.39791400	-0.83922400
H	2.14892800	-1.41882400	-1.89408000
O	1.30898700	2.12641400	0.92155700
C	1.02315400	2.11909000	-0.45515500
O	0.73557700	3.19258100	-0.95190800
N	1.05794100	0.96411200	-1.17417500
C	1.94619900	-1.57353400	1.48812500
H	1.27987000	-2.24042100	2.04173900
H	2.78980200	-1.34416700	2.14888500
C	2.42852800	-2.21797600	0.16125200
H	3.45295600	-2.59383800	0.22839200
H	1.78535700	-3.05497500	-0.12284300
C	-1.48486300	-0.45798200	-0.36965800
C	-2.36739800	-1.47490700	0.04358200
C	-1.89300800	0.88438900	-0.29612800
C	-3.61525000	-1.15480000	0.56908700
H	-2.06237400	-2.51243700	-0.05079400
C	-3.15212700	1.19110400	0.22113500
H	-1.26760900	1.67825700	-0.68202500
C	-4.00868400	0.18223500	0.66305100
H	-4.28204600	-1.94762000	0.89593400
H	-3.46497200	2.23019900	0.26370000
H	-4.98563000	0.43470600	1.06620200



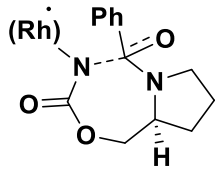
RT*triplet*

Cartesian Coordinates

Atom	X	Y	Z
C	4.09037300	-1.31081200	1.44696100
H	4.14290400	-1.55690000	0.38389500
H	4.70216500	-0.42992800	1.65171700
C	4.54854800	-2.51287300	2.29485300
H	3.92472800	-3.36797800	2.03353600
N	5.97728700	-2.79385700	2.05035900
C	6.58516900	-3.22543100	0.89563900
O	7.80779900	-3.16113900	0.76907300
C	6.83850300	-2.30494300	3.14662600
H	7.63114000	-1.66771900	2.74639900
H	7.32671000	-3.15922900	3.63254300
O	2.74407800	-0.89962200	1.77877900
C	1.73919000	-1.61966800	1.23526000
O	1.87671300	-2.59697700	0.51967600
N	0.50037700	-1.13903500	1.62610800
Rh	-0.74833000	0.04059100	0.61410700
Rh	-1.95327900	1.51223800	-0.88317600
O	-2.69073800	-0.16045800	-1.84146600
O	-1.56281900	-1.54268200	-0.45140400
O	-2.38148400	0.08553200	1.86669700
O	-0.04829600	1.75308800	1.56591200
O	0.78185600	0.14570500	-0.79894700
O	-1.16244400	3.11656900	0.14609300
O	-3.51118100	1.44153800	0.46192900
O	-0.35311100	1.52873700	-2.17723700
C	-0.39206200	2.90483800	1.13161900
C	-3.41280400	0.76397200	1.52948500
C	0.66687000	0.84492700	-1.86205900
C	-2.34883900	-1.31175700	-1.43149900
C	4.51388200	-2.23315800	3.80820500
H	4.43255800	-3.18391700	4.34780200
H	3.65863000	-1.61295900	4.08986500
C	5.87426500	-1.57455300	4.09217400
H	5.83937500	-0.50557800	3.85170100
H	6.17651200	-1.66173500	5.13975000
C	5.74208600	-3.78729300	-0.21873800

C	6.04507700	-3.37718500	-1.52569800
C	4.76272000	-4.76941900	-0.02137000
C	5.34704300	-3.90403400	-2.61033700
H	6.83951700	-2.65245300	-1.67486300
C	4.07801100	-5.31132300	-1.11013300
H	4.55241400	-5.13616100	0.97873400
C	4.35953300	-4.87165600	-2.40418000
H	5.58122900	-3.57012800	-3.61772400
H	3.32465700	-6.07634000	-0.94507200
H	3.81905800	-5.28803500	-3.25001800
C	-4.59272400	0.76335500	2.51510000
C	-5.04465600	-0.71165400	2.78638600
H	-4.22985000	-1.22373800	3.30897900
H	-5.89136700	-0.65791300	3.48183700
C	-4.08902400	1.37014800	3.84540900
H	-3.76744400	2.40906300	3.70673000
H	-4.89945100	1.36602000	4.58327300
H	-3.24704800	0.80006400	4.24782200
C	-5.75402800	1.60583000	1.96399600
H	-5.44254000	2.64030200	1.79234500
H	-6.13047900	1.20721000	1.01904500
H	-6.57582900	1.61100400	2.68986800
C	0.16875500	4.11928500	1.89415100
C	-0.33678000	5.42947200	1.26998300
H	-1.42937500	5.47900100	1.29239200
H	0.05675000	6.28006900	1.83934300
H	-0.01829300	5.53215600	0.23008700
C	-0.31273700	4.01669600	3.35969000
H	0.01371700	3.07974400	3.81926100
H	0.09162100	4.85280400	3.94186300
H	-1.40649100	4.06660000	3.41820400
C	1.73405500	4.05779600	1.88618500
H	2.08697000	4.94632200	2.42437800
H	2.03933400	3.18319200	2.47010300
C	1.86450000	0.81769000	-2.82752700
C	1.58736800	1.70391700	-4.05205700
H	1.43057400	2.74762900	-3.76927300
H	2.44089300	1.65276700	-4.73888300
H	0.69646300	1.36498400	-4.58861300
C	3.15159700	1.28858700	-2.06906600
H	3.38961700	0.53296600	-1.31339300
H	3.96916800	1.27912800	-2.80091600
C	2.07264200	-0.64867000	-3.27330000
H	1.20155300	-1.01627500	-3.82846600
H	2.94324800	-0.71294800	-3.93628900
H	2.23610600	-1.30759100	-2.41616100

C	-2.89346500	-2.54517400	-2.17448000
C	-3.84767200	-2.11893500	-3.30122200
H	-4.20633000	-3.00969100	-3.83127100
H	-4.71205400	-1.57336900	-2.91502200
H	-3.33954900	-1.47322700	-4.02322400
C	-1.68272000	-3.30154200	-2.76910200
H	-0.97155600	-3.58635600	-1.98897200
H	-2.02742900	-4.20822100	-3.27992900
H	-1.15656900	-2.68230100	-3.50522300
C	-3.61086600	-3.49130200	-1.15325900
H	-3.99203600	-4.34473500	-1.72831900
H	-2.85274200	-3.87918600	-0.46530900
C	3.06017700	2.64718300	-1.40329700
C	2.55435900	2.74543700	-0.10529800
C	3.45399000	3.81456200	-2.07673400
C	2.37506700	3.99169400	0.51483700
H	2.28449900	1.84249000	0.43083600
C	3.31852800	5.05912700	-1.45185700
H	3.86900000	3.73730100	-3.07562600
C	2.77033400	5.14432200	-0.16342100
H	2.67123900	6.12720000	0.28799600
C	-4.73213000	-2.85752300	-0.35416100
C	-4.43510300	-2.18232700	0.83137000
C	-6.06409600	-2.91530700	-0.79451900
C	-5.42982700	-1.50980000	1.55732100
H	-3.41250700	-2.16616900	1.19052700
C	-7.07085800	-2.28328300	-0.05628400
H	-6.30001900	-3.45900400	-1.70270600
C	-6.74937800	-1.57400700	1.11049100
H	-7.55441600	-1.08794700	1.65397500
O	3.68721100	6.24989900	-2.01180300
O	-8.39664400	-2.29454400	-0.38852600
C	4.23610800	6.23845000	-3.31835400
H	5.16758000	5.65796800	-3.36182200
H	4.45050900	7.28066600	-3.56274600
H	3.52642900	5.83343400	-4.05233900
C	-8.79051700	-2.98266600	-1.56301400
H	-8.55107800	-4.05313800	-1.50555400
H	-8.31892700	-2.55742100	-2.45925500
H	-9.87306300	-2.85993700	-1.63383900



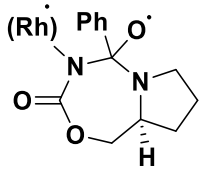
TS1*triplet-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	-0.92491700	3.32427800	2.64571500
H	-1.34405700	2.32586000	2.48480500
H	-1.10360400	3.63308600	3.67894300
C	-1.53312300	4.36292900	1.69072600
H	-0.92121900	5.26890300	1.77486900
N	-1.59792100	3.91901600	0.29149100
C	-0.50986400	3.56312600	-0.51515700
O	-0.75823700	3.08736600	-1.67841900
C	-2.94454200	3.48750400	-0.11267300
H	-2.90842800	2.47554500	-0.52629100
H	-3.32053200	4.14756600	-0.90620000
O	0.51323900	3.27798000	2.54771400
C	1.08583900	2.67044400	1.48358200
O	2.29222300	2.56360200	1.41533700
N	0.22931400	2.20561600	0.48004800
C	-3.01656400	4.64498200	2.00754300
H	-3.27078600	5.65740800	1.67359200
H	-3.23374200	4.58586800	3.07866100
C	-3.77694800	3.59978500	1.17169600
H	-3.79937700	2.63669300	1.69323600
H	-4.81230600	3.88891400	0.97096700
C	0.62821100	4.58885200	-0.68113300
C	1.88592000	4.16467700	-1.13358400
C	0.35022700	5.95549700	-0.55455500
C	2.87844900	5.10702200	-1.38895900
H	2.07662100	3.10562700	-1.26391300
C	1.35144900	6.89245900	-0.81340200
H	-0.64246100	6.28173700	-0.26345000
C	2.61682600	6.47066500	-1.22596700
H	3.85898200	4.77538500	-1.71810200
H	1.13837100	7.95153300	-0.69680700
H	3.39488700	7.20192200	-1.42711700
Rh	0.04864200	0.15469200	0.13411900
Rh	0.04730100	-2.24485700	-0.22001800
O	1.55549200	-1.99399000	-1.60260700
O	1.54540500	0.24610500	-1.30117200

O	1.41654600	-0.20480700	1.65412900
O	-1.47280400	-0.15670500	1.55008100
O	-1.37030200	0.29476800	-1.37007200
O	-1.45752900	-2.38911100	1.18550600
O	1.44685900	-2.43337100	1.28376500
O	-1.34373700	-1.93803500	-1.71299800
C	-1.88661700	-1.34942800	1.76500000
C	1.82890900	-1.38924800	1.89364800
C	-1.75245900	-0.76678900	-1.97215200
C	1.97855700	-0.82446100	-1.84710500
C	2.85653100	-1.53525600	3.03082500
C	4.10413800	-0.64044200	2.71776400
H	3.78141400	0.40529500	2.73623400
H	4.80958800	-0.78229500	3.54636600
C	2.20051900	-1.00866000	4.32795000
H	1.31727500	-1.60311500	4.59157900
H	2.91199900	-1.08041000	5.15886000
H	1.89563400	0.03581800	4.21961600
C	3.25672200	-3.00783600	3.21105100
H	2.38559500	-3.62522400	3.45010600
H	3.71747000	-3.41502500	2.30814700
H	3.97465100	-3.09296600	4.03583500
C	-2.98803800	-1.52904100	2.82957400
C	-3.34151200	-3.01640300	2.99190100
H	-2.46420300	-3.59823700	3.28855500
H	-4.10695300	-3.12713200	3.76964500
H	-3.72655100	-3.44325100	2.06304300
C	-2.45343900	-0.97338600	4.16854200
H	-2.17559300	0.08080700	4.08050500
H	-3.22124900	-1.06829000	4.94531200
H	-1.57026600	-1.53146800	4.50025200
C	-4.25343000	-0.70366800	2.42174800
H	-5.01589800	-0.89111600	3.18806900
H	-3.99540400	0.35968500	2.48236300
C	-2.77638000	-0.59150000	-3.10849800
C	-3.09992000	-1.94741300	-3.75568200
H	-3.54389000	-2.64214400	-3.03836900
H	-3.80641400	-1.79835800	-4.58155500
H	-2.19721900	-2.41573700	-4.15840700
C	-4.07480100	0.07765800	-2.54522200
H	-3.82486900	1.10557700	-2.26303700
H	-4.78421500	0.14157400	-3.38009900
C	-2.15685600	0.36237400	-4.15534700
H	-1.25936400	-0.08036500	-4.60326600
H	-2.87631800	0.54795700	-4.96183200
H	-1.87710500	1.31673400	-3.70151000

C	3.08907700	-0.65541700	-2.90075500
C	3.50785600	-2.02211300	-3.46565500
H	4.28322400	-1.87971800	-4.22854100
H	3.90328700	-2.67731700	-2.68601000
H	2.65898700	-2.53098500	-3.93158800
C	2.52876500	0.22959800	-4.03769600
H	2.19058600	1.19769700	-3.65826000
H	3.30482100	0.39970500	-4.79334500
H	1.68084100	-0.25836200	-4.53280400
C	4.30908500	0.08345500	-2.25424300
H	5.07841500	0.16423500	-3.03311900
H	3.99341600	1.10242900	-2.00727500
C	-4.72463500	-0.61963200	-1.36589500
C	-4.27958500	-0.34363500	-0.07191700
C	-5.76448100	-1.54541400	-1.54581200
C	-4.81703000	-0.99831900	1.04592800
H	-3.48394200	0.37682300	0.07280500
C	-6.32792400	-2.18636100	-0.43641900
H	-6.12704900	-1.74823800	-2.54753100
C	-5.85027500	-1.91478800	0.85472900
H	-6.31059700	-2.43137100	1.69195400
C	4.88524000	-0.57128600	-1.01468300
C	4.34033900	-0.27424700	0.23617000
C	5.94280600	-1.49091300	-1.10459600
C	4.78900700	-0.92424400	1.39647600
H	3.55632300	0.47033600	0.31713900
C	6.42545200	-2.11192200	0.05214900
H	6.38090900	-1.70399600	-2.07359600
C	5.84072000	-1.83516400	1.29623500
H	6.23446700	-2.34185700	2.17264900
O	7.46150200	-3.00609900	0.07581900
O	-7.35036000	-3.09074000	-0.50353700
C	8.08487100	-3.34305700	-1.15003400
H	8.54119100	-2.46577500	-1.62890000
H	8.86697000	-4.06359100	-0.90176300
H	7.37737800	-3.80537300	-1.85194000
C	-7.86452800	-3.43243300	-1.77919400
H	-8.64982300	-4.16907100	-1.59849700
H	-8.29715800	-2.56095600	-2.28914400
H	-7.09210400	-3.87663200	-2.42123500



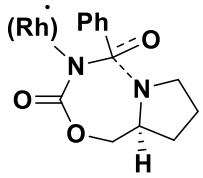
IM1 ***triplet-C–N***

Cartesian Coordinates

Atom	X	Y	Z
C	-0.96587900	3.17951800	2.76751700
H	-1.40380300	2.20139900	2.54548400
H	-1.20338000	3.46732800	3.79475300
C	-1.46394100	4.26302600	1.79820800
H	-0.85017700	5.15705200	1.97494800
N	-1.39452500	3.88117000	0.38405100
C	-0.18294400	3.41613600	-0.26571600
O	-0.37779500	3.09176900	-1.55498400
C	-2.69959600	3.46458700	-0.15858500
H	-2.63456200	2.46446100	-0.59622900
H	-2.99685400	4.15317200	-0.96116000
O	0.47272300	3.08111100	2.76699200
C	1.11139900	2.61711400	1.67236000
O	2.31306200	2.48684900	1.67522900
N	0.31113200	2.28568800	0.55612200
C	-2.96705800	4.55624500	1.98153200
H	-3.17760500	5.58226500	1.65924900
H	-3.28585000	4.46487900	3.02468200
C	-3.65240800	3.54706000	1.04273900
H	-3.73522900	2.56903200	1.52837000
H	-4.66052100	3.85584000	0.75216000
C	0.86254600	4.52673800	-0.53766800
C	2.17322600	4.15790500	-0.88817600
C	0.47697800	5.87565300	-0.55691100
C	3.10842600	5.14695900	-1.17941000
H	2.44304900	3.10862300	-0.91010500
C	1.42014400	6.85691500	-0.84844500
H	-0.55120500	6.13877700	-0.33294600
C	2.73642600	6.49458800	-1.15672200
H	4.12730800	4.86643400	-1.42951700
H	1.13080100	7.90403500	-0.83978000
H	3.46921500	7.26321000	-1.38682300
Rh	0.04105300	0.16569800	0.15785300
Rh	-0.01458700	-2.21202400	-0.29977200
O	1.49441700	-1.94253300	-1.67815900
O	1.54505300	0.28067200	-1.27050700

O	1.39754100	-0.27226100	1.66238100
O	-1.48624200	-0.16208100	1.56268600
O	-1.39299900	0.38983900	-1.35321600
O	-1.51624100	-2.37707300	1.10806000
O	1.38525200	-2.48279500	1.19467100
O	-1.40476300	-1.83201000	-1.77717500
C	-1.92244100	-1.35418200	1.73190500
C	1.78484800	-1.47445600	1.85084100
C	-1.79411600	-0.64484100	-1.98728700
C	1.94874100	-0.77377300	-1.86566000
C	2.80643400	-1.69117000	2.98248700
C	4.07554200	-0.81431100	2.70744500
H	3.77728400	0.23703000	2.76921200
H	4.77653300	-1.00677000	3.52963500
C	2.16138800	-1.20202000	4.29947300
H	1.26480400	-1.78672000	4.53887600
H	2.86998200	-1.32261600	5.12730000
H	1.87971600	-0.14764900	4.23234600
C	3.17229600	-3.17863200	3.10322500
H	2.28645500	-3.78487500	3.31527300
H	3.62550100	-3.55925000	2.18501400
H	3.88600400	-3.31427900	3.92500600
C	-3.02326800	-1.55774200	2.79303200
C	-3.39660900	-3.04511100	2.90231400
H	-2.52641500	-3.64896000	3.17502100
H	-4.16170600	-3.17409800	3.67766600
H	-3.78919700	-3.43262600	1.95949400
C	-2.47892800	-1.05851300	4.15000600
H	-2.18780300	-0.00541600	4.10035600
H	-3.24582800	-1.17241300	4.92520100
H	-1.60181500	-1.63915000	4.45818700
C	-4.27905300	-0.70210500	2.41934800
H	-5.04106900	-0.90536200	3.18213800
H	-4.00690800	0.35515500	2.51562800
C	-2.82492900	-0.41989800	-3.11160100
C	-3.16932600	-1.74950900	-3.80170200
H	-3.61652600	-2.46218000	-3.10438200
H	-3.87961100	-1.56508600	-4.61730700
H	-2.27494300	-2.21504200	-4.22543400
C	-4.11417000	0.24269200	-2.52095300
H	-3.85607700	1.25935600	-2.20671200
H	-4.82711800	0.34023600	-3.34964200
C	-2.20203800	0.55808400	-4.13333400
H	-1.31320600	0.11871300	-4.60117100
H	-2.92436700	0.77891900	-4.92838300
H	-1.90511200	1.49477200	-3.65406100

C	3.06488500	-0.58556700	-2.91058200
C	3.45608800	-1.93542500	-3.53247600
H	4.23517100	-1.77783700	-4.28870600
H	3.83668100	-2.63086400	-2.78068600
H	2.59713300	-2.40661100	-4.01896000
C	2.52502900	0.35937900	-4.00847100
H	2.20203000	1.31451900	-3.58533400
H	3.30627400	0.54972000	-4.75405900
H	1.67019300	-0.09097900	-4.52681700
C	4.29965800	0.09942200	-2.23388400
H	5.07255600	0.19428100	-3.00771400
H	4.00562700	1.11489600	-1.94840800
C	-4.76671700	-0.48487800	-1.36137900
C	-4.30931300	-0.26079400	-0.06169300
C	-5.82338900	-1.38609200	-1.56591100
C	-4.85290700	-0.94207600	1.03707700
H	-3.49906600	0.43888600	0.10184200
C	-6.39172400	-2.05415100	-0.47518400
H	-6.19476700	-1.54903100	-2.57168500
C	-5.90323500	-1.83339900	0.82148300
H	-6.36827000	-2.36918600	1.64390300
C	4.86034400	-0.61474300	-1.02012000
C	4.32037000	-0.35733000	0.24158900
C	5.90038700	-1.55013600	-1.14554800
C	4.75584000	-1.05970300	1.37609000
H	3.54668700	0.39409600	0.35174200
C	6.36989100	-2.22516000	-0.01395300
H	6.33492500	-1.73365200	-2.12217300
C	5.79021200	-1.98569600	1.24018600
H	6.17341000	-2.53382200	2.09610500
O	7.38841900	-3.13970700	-0.02546600
O	-7.42988200	-2.93857400	-0.56648200
C	8.00265300	-3.44377300	-1.26436000
H	8.47735400	-2.55925600	-1.71106400
H	8.76929300	-4.18989000	-1.04503900
H	7.28432300	-3.86387400	-1.98161200
C	-7.95435200	-3.23095300	-1.85006400
H	-8.75046000	-3.96069100	-1.68968000
H	-8.37529900	-2.33693400	-2.32997200
H	-7.19159400	-3.66623700	-2.50953100



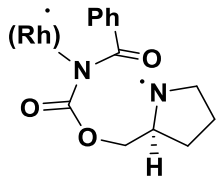
TS2*triplet-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	-1.06974800	3.03298900	2.76744300
H	-1.46611000	2.08613200	2.39234200
H	-1.36380500	3.16712500	3.81190600
C	-1.59595700	4.24005900	1.95732900
H	-1.01459200	5.11421200	2.27761100
N	-1.45781400	4.08496900	0.50701400
C	0.07984500	3.30887000	-0.31580800
O	-0.32228000	3.06847000	-1.53357000
C	-2.71331100	3.57744000	-0.05538300
H	-2.53750500	2.62179400	-0.56264400
H	-3.03191700	4.28427300	-0.83591000
O	0.36074200	2.98946800	2.81818000
C	1.07028900	2.63538800	1.71792800
O	2.27528700	2.57648300	1.78322000
N	0.31466400	2.31677000	0.56940400
C	-3.11670400	4.42459600	2.16466000
H	-3.38666200	5.46824900	1.96717500
H	-3.43315100	4.18881200	3.18597300
C	-3.72869800	3.49636200	1.10023300
H	-3.80253900	2.47080400	1.47485000
H	-4.73253600	3.80416200	0.79432800
C	1.03290200	4.47594700	-0.56015000
C	2.37716600	4.15028800	-0.83112000
C	0.59393500	5.80724600	-0.64140300
C	3.28747100	5.16870300	-1.09063300
H	2.68708800	3.11238600	-0.80157400
C	1.51356600	6.81704800	-0.90417200
H	-0.45343900	6.02847200	-0.47473100
C	2.85940700	6.50062400	-1.12601700
H	4.33044700	4.92540600	-1.26974500
H	1.18402900	7.85133900	-0.94254100
H	3.57291800	7.29265000	-1.33650100
Rh	0.03623700	0.13439700	0.15909200
Rh	-0.01482800	-2.23472100	-0.32985000
O	1.50531100	-1.93164300	-1.69354200
O	1.54888800	0.28734100	-1.25725300

O	1.39391900	-0.30865800	1.65771600
O	-1.49973400	-0.20616500	1.55277900
O	-1.38417800	0.39365800	-1.35371300
O	-1.52869200	-2.41513000	1.06545900
O	1.37778600	-2.51611100	1.17134600
O	-1.40304600	-1.82210400	-1.80717800
C	-1.94028400	-1.39921300	1.69805000
C	1.77801800	-1.51277400	1.83636400
C	-1.78825800	-0.63132400	-2.00269800
C	1.95858600	-0.75924300	-1.86178200
C	2.79541500	-1.74177900	2.96969400
C	4.05773000	-0.84786700	2.72059400
H	3.74781800	0.19929600	2.79565800
H	4.75345100	-1.04550800	3.54604900
C	2.13612400	-1.28260900	4.29060200
H	1.24348800	-1.88017800	4.51227500
H	2.83958600	-1.41117200	5.12169800
H	1.84444700	-0.23001100	4.23971200
C	3.17461200	-3.22756200	3.06627200
H	2.29313700	-3.84539300	3.26211900
H	3.63636400	-3.58771300	2.14399100
H	3.88501200	-3.37163000	3.88957100
C	-3.05423700	-1.61617600	2.74314700
C	-3.45930400	-3.09793100	2.80150000
H	-2.60401700	-3.72815700	3.06090700
H	-4.23367100	-3.23621600	3.56607900
H	-3.85185200	-3.44645600	1.84343500
C	-2.50768200	-1.17292500	4.11883900
H	-2.19303900	-0.12548400	4.10406600
H	-3.28122300	-1.29486000	4.88629100
H	-1.64515400	-1.78237300	4.41217300
C	-4.28927400	-0.72256100	2.39189100
H	-5.05686700	-0.92787600	3.14855400
H	-3.99256600	0.32498300	2.51671700
C	-2.81679200	-0.38661100	-3.12489400
C	-3.19303200	-1.70889700	-3.81206500
H	-3.65217600	-2.41095700	-3.11176600
H	-3.90317700	-1.51065100	-4.62461700
H	-2.31065100	-2.19385800	-4.23900700
C	-4.08778600	0.30812600	-2.53277100
H	-3.79932400	1.31228600	-2.20442800
H	-4.79413800	0.43747200	-3.36282300
C	-2.17270100	0.57391700	-4.15023500
H	-1.29213100	0.11462800	-4.61450800
H	-2.88895900	0.80633000	-4.94750300
H	-1.85801700	1.50671400	-3.67452300

C	3.08268100	-0.55858700	-2.89684400
C	3.48739400	-1.90167500	-3.52462500
H	4.27206900	-1.73491800	-4.27319500
H	3.86545600	-2.59986600	-2.77411800
H	2.63522600	-2.37461400	-4.02114600
C	2.54588200	0.38956600	-3.99340600
H	2.21703700	1.34144500	-3.56720800
H	3.33032400	0.58703000	-4.73386800
H	1.69552600	-0.06130300	-4.51863400
C	4.30835900	0.12985800	-2.20780500
H	5.08477100	0.23841600	-2.97639600
H	4.00427000	1.14038900	-1.91511000
C	-4.76718800	-0.41418200	-1.38530100
C	-4.30082800	-0.23172100	-0.08222400
C	-5.85685400	-1.27119900	-1.60593200
C	-4.86917500	-0.91323100	1.00420100
H	-3.46334100	0.43237800	0.09190800
C	-6.44923000	-1.93819500	-0.52748800
H	-6.23363800	-1.40183000	-2.61443800
C	-5.95202800	-1.76058000	0.77238900
H	-6.43559400	-2.29494800	1.58501100
C	4.86917600	-0.59060000	-0.99781300
C	4.31747200	-0.35511800	0.26303700
C	5.92152000	-1.51168200	-1.12691200
C	4.75263700	-1.06634300	1.39212300
H	3.53203200	0.38334800	0.37704600
C	6.39108400	-2.19462600	-0.00015200
H	6.36460000	-1.67860400	-2.10269200
C	5.79938000	-1.97777300	1.25244900
H	6.18228100	-2.53244300	2.10427400
O	7.42078500	-3.09675800	-0.01540000
O	-7.51971000	-2.78164900	-0.63444000
C	8.04522700	-3.38051200	-1.25389000
H	8.51284600	-2.48610700	-1.68830400
H	8.81873400	-4.12065600	-1.03837900
H	7.33559500	-3.80042900	-1.97987200
C	-8.05501800	-3.02973400	-1.92274200
H	-8.87804900	-3.73188700	-1.77553500
H	-8.44206800	-2.11157700	-2.38537800
H	-7.30938600	-3.48085700	-2.59112000



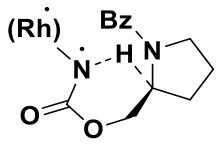
IM2*triplet-C–N*

Cartesian Coordinates

Atom	X	Y	Z
C	-2.56043700	3.33010300	0.44165400
H	-1.95992900	2.92906000	-0.37777500
H	-3.58110700	2.94902600	0.36492300
C	-2.56445000	4.86803000	0.44646500
H	-3.16107000	5.17337900	1.32026400
N	-1.20710900	5.35634900	0.65561100
C	0.80138100	3.08547700	0.02689200
O	0.41386600	3.45149600	-1.07065500
C	-0.92852300	6.33011400	-0.38343400
H	0.13969100	6.32507700	-0.62456500
H	-1.15845800	7.33139100	0.02696500
O	-2.07530900	2.85023700	1.71324700
C	-0.79016400	2.54282000	1.89828800
O	-0.30841800	2.45433900	3.00361900
N	-0.03395800	2.16745400	0.74925700
C	-3.11574000	5.47358700	-0.87474100
H	-3.81018100	6.29089500	-0.65000500
H	-3.66188800	4.74261800	-1.48155900
C	-1.85073200	6.00568500	-1.57409800
H	-1.38728900	5.22380400	-2.18437500
H	-2.04523400	6.87046900	-2.21632000
C	2.11107700	3.46514300	0.60815100
C	2.56656600	2.97255800	1.84084600
C	2.91490900	4.34838500	-0.13409200
C	3.81181100	3.37391500	2.32560700
H	1.94874000	2.29044500	2.41183500
C	4.15631100	4.74022700	0.35464900
H	2.54762200	4.71073000	-1.08853900
C	4.60563000	4.25362600	1.58739900
H	4.16168100	2.99742300	3.28258900
H	4.77534600	5.42291000	-0.22072700
H	5.57575900	4.56012900	1.96955800
Rh	-0.03890700	0.11674400	0.20223600
Rh	-0.06620500	-2.22183200	-0.39781400
O	1.34050400	-1.79017700	-1.85173000
O	1.38102200	0.39957200	-1.28591000

O	1.44972500	-0.37140100	1.56738800
O	-1.45552000	-0.32118700	1.64933700
O	-1.53853000	0.37503400	-1.22433700
O	-1.47441600	-2.51193000	1.09132400
O	1.42907500	-2.55078300	0.97657100
O	-1.56794400	-1.82118200	-1.75112000
C	-1.86598900	-1.52501100	1.78351900
C	1.86301400	-1.57759200	1.66249200
C	-1.98248200	-0.63096800	-1.87625000
C	1.75978100	-0.60115300	-1.98502000
C	2.95654900	-1.85547200	2.71013400
C	4.21011100	-0.96706400	2.40709400
H	3.93160300	0.07908500	2.57173200
H	4.96666500	-1.22262400	3.15961100
C	2.39658600	-1.45220100	4.09352900
H	1.52700200	-2.06520300	4.35802400
H	3.16178400	-1.60720500	4.86314500
H	2.09069100	-0.40255900	4.10910300
C	3.32991200	-3.34652900	2.71467200
H	2.45906200	-3.96860000	2.94090400
H	3.72815300	-3.66682600	1.74909600
H	4.09123300	-3.52920700	3.48268600
C	-2.90033200	-1.77230300	2.89666400
C	-3.32617600	-3.24838300	2.92253300
H	-2.46570300	-3.90201700	3.09221000
H	-4.04394700	-3.40728200	3.73638500
H	-3.79586100	-3.55086900	1.98340900
C	-2.23484600	-1.39148100	4.23993400
H	-1.89681600	-0.35154200	4.23386500
H	-2.95077200	-1.52441300	5.05945800
H	-1.36998600	-2.03398200	4.44373400
C	-4.13518900	-0.83378400	2.68037600
H	-4.84206700	-1.04938000	3.49117300
H	-3.79816300	0.19981500	2.81090900
C	-3.09094900	-0.35306800	-2.90907800
C	-3.53867700	-1.65938900	-3.58382200
H	-3.94883500	-2.36752100	-2.85983700
H	-4.31046100	-1.43843000	-4.33142800
H	-2.70079500	-2.14666400	-4.09035300
C	-4.29716900	0.35495400	-2.20674800
H	-3.95785200	1.34133200	-1.87295400
H	-5.05857500	0.52344300	-2.97905400
C	-2.51025200	0.61078700	-3.96936800
H	-1.66956600	0.14844700	-4.49975300
H	-3.27964200	0.85653900	-4.71081100
H	-2.15544600	1.53815600	-3.51097600

C	2.79392200	-0.31202800	-3.08912400
C	3.14330400	-1.59894400	-3.85289600
H	3.86249400	-1.36803800	-4.64843100
H	3.58243700	-2.35244100	-3.19471900
H	2.25270000	-2.03631700	-4.31350900
C	2.17015300	0.72036000	-4.05621600
H	1.88043000	1.63237700	-3.52715000
H	2.89219800	0.98035000	-4.83934600
H	1.27900300	0.30974800	-4.54573700
C	4.07273100	0.32597300	-2.44860000
H	4.78675000	0.49107400	-3.26573600
H	3.79741900	1.31113700	-2.05804900
C	-4.90377100	-0.38844000	-1.03248700
C	-4.34564300	-0.24310600	0.23873800
C	-6.00886600	-1.23792000	-1.20137000
C	-4.82906900	-0.96695100	1.33954400
H	-3.50543000	0.42551200	0.37922500
C	-6.52285300	-1.93823300	-0.10423500
H	-6.45767400	-1.33728700	-2.18363700
C	-5.92708800	-1.80724200	1.15929400
H	-6.34824100	-2.37133800	1.98640700
C	4.72222500	-0.48168400	-1.34262900
C	4.27324500	-0.33019600	-0.02966300
C	5.75356400	-1.39536100	-1.61265300
C	4.79109000	-1.11024600	1.01500000
H	3.49996000	0.39759400	0.18563000
C	6.30397100	-2.15216300	-0.57233500
H	6.11929900	-1.49887900	-2.62836100
C	5.81593600	-2.01399000	0.73549200
H	6.26200000	-2.62226100	1.51701100
O	7.32007500	-3.05458600	-0.72628000
O	-7.60158400	-2.77617900	-0.15890900
C	7.84428500	-3.26148500	-2.02593500
H	8.28536700	-2.34317400	-2.43710000
H	8.62476800	-4.01741800	-1.91814400
H	7.07620700	-3.63092000	-2.71885600
C	-8.23962600	-2.97163100	-1.40870300
H	-9.05516900	-3.67335000	-1.22285700
H	-8.65309100	-2.03397700	-1.80452900
H	-7.55394700	-3.40229700	-2.15089900



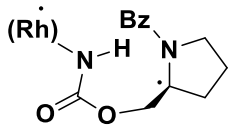
TS*triplet-C–H*

Cartesian Coordinates

Atom	X	Y	Z
C	-0.06779900	4.20558900	-2.51145100
H	1.01004700	4.37988500	-2.52379300
H	-0.56452300	5.03386300	-3.02936100
C	-0.60126500	4.05547700	-1.08411900
H	-0.20865500	2.86046600	-0.90909100
N	-0.17078900	5.01066600	-0.10808400
C	1.09604000	5.51898900	0.17560200
O	1.20418700	6.48368900	0.92734600
C	-1.31567200	5.57852600	0.64327200
H	-1.12048000	6.63177000	0.84425000
H	-1.41145200	5.06324300	1.60828400
O	-0.36941700	3.04286800	-3.29355500
C	-0.13250000	1.77331900	-2.81582800
O	-0.12372700	0.84780000	-3.60609700
N	0.03252500	1.63666900	-1.45206600
Rh	-0.07813300	-0.05233800	-0.35437100
Rh	-0.38296500	-2.09536200	0.91424400
O	0.99209000	-3.00211800	-0.32716700
O	1.28110700	-1.09518800	-1.50629200
O	1.41864000	0.46201800	0.99940100
O	-1.46273300	0.83665200	0.94918300
O	-1.61524000	-0.74385400	-1.55862000
O	-1.74717400	-1.09249800	2.09453500
O	1.13771900	-1.45716100	2.15462100
O	-1.88051900	-2.65462500	-0.38205700
C	-1.99682800	0.12851300	1.87265500
C	1.71044900	-0.34704800	1.94925300
C	-2.17285000	-1.87034200	-1.33465100
C	1.52464200	-2.32459500	-1.25685300
C	-2.13171900	3.98683600	-0.95475300
H	-2.40159500	3.13564000	-0.31982200
H	-2.60958200	3.83571100	-1.92722500
C	-2.51067100	5.31076700	-0.27205600
H	-2.60195300	6.11409300	-1.01268700
H	-3.45441600	5.25250700	0.27772200
C	2.32101900	4.90910200	-0.43993000
C	3.28560700	5.79931500	-0.93815300
C	2.58622500	3.53210200	-0.44159500

C	4.47537500	5.31821100	-1.47952700
H	3.08918200	6.86574600	-0.89095300
C	3.78930700	3.05632500	-0.97001900
H	1.88186000	2.82581700	-0.01570800
C	4.72813200	3.94384100	-1.49895800
H	5.20804700	6.01446300	-1.87820000
H	3.99140800	1.98948600	-0.96497500
H	5.65769700	3.56629300	-1.91608600
C	2.82608800	0.08664800	2.91751600
C	4.13872800	0.37874000	2.11607400
H	3.96468100	1.25858900	1.48819900
H	4.90062600	0.66003400	2.85348100
C	2.37270000	1.39746700	3.60089500
H	1.45420400	1.24168400	4.17904200
H	3.14929800	1.74250200	4.29302300
H	2.18841900	2.18680900	2.86681400
C	3.06458700	-0.99781000	3.98055200
H	2.15462700	-1.19288500	4.55521800
H	3.38550100	-1.94049100	3.53098300
H	3.84407700	-0.66148600	4.67463000
C	-3.00984400	0.83442800	2.79583000
C	-3.53229600	-0.13960600	3.86434400
H	-2.71256200	-0.53158400	4.47318000
H	-4.23135400	0.38577100	4.52620200
H	-4.05187600	-0.98939900	3.41590800
C	-2.28613000	2.01645800	3.47934200
H	-1.88207000	2.71541900	2.74116500
H	-2.98526600	2.55728200	4.12766400
H	-1.45696700	1.66247300	4.10292300
C	-4.19247400	1.40523900	1.94301400
H	-4.89626600	1.86463100	2.64831600
H	-3.79968700	2.21209400	1.31465700
C	-3.27006700	-2.29380100	-2.32730500
C	-3.84936300	-3.66293200	-1.93845000
H	-4.31010700	-3.64195100	-0.94778600
H	-4.61004600	-3.95827500	-2.67148100
H	-3.06947000	-4.42980800	-1.92779000
C	-4.38801600	-1.19740500	-2.36051800
H	-3.95509300	-0.29133200	-2.79673100
H	-5.15836700	-1.55289100	-3.05650900
C	-2.62434800	-2.37078100	-3.73035900
H	-1.86048700	-3.15658300	-3.76513300
H	-3.38886500	-2.61446300	-4.47754000
H	-2.15165800	-1.42295400	-4.00135000
C	2.53239000	-3.01946000	-2.18964500
C	2.75884900	-4.47495300	-1.75229900

H	3.45832700	-4.95905200	-2.44481900
H	3.17260800	-4.53465800	-0.74256600
H	1.82154200	-5.03846300	-1.76361700
C	1.94150200	-2.98205200	-3.61844500
H	1.72291100	-1.95701300	-3.92985600
H	2.65269300	-3.42443000	-4.32596500
H	1.01231500	-3.56157400	-3.67147200
C	3.87656200	-2.21662300	-2.19232600
H	4.56288300	-2.75192200	-2.86062300
H	3.68198700	-1.23999500	-2.64726400
C	-5.01193900	-0.85818600	-1.02131600
C	-4.41716800	0.11067600	-0.21064400
C	-6.16738000	-1.51391200	-0.56729300
C	-4.91683900	0.40245200	1.06750500
H	-3.53933500	0.63410400	-0.57152200
C	-6.69568500	-1.20624500	0.69136400
H	-6.64414300	-2.25083000	-1.20415300
C	-6.06459000	-0.25587200	1.50781400
H	-6.49840400	-0.04596000	2.48117400
C	4.52364400	-2.01680000	-0.83572200
C	4.12789900	-0.94370200	-0.03433900
C	5.50328000	-2.90138300	-0.35787900
C	4.65010200	-0.75961000	1.25539300
H	3.38308400	-0.25210900	-0.40984800
C	6.05597400	-2.70973700	0.91353100
H	5.82738400	-3.72385600	-0.98600000
C	5.62254300	-1.64541000	1.71834400
H	6.06970900	-1.52972700	2.70139800
O	-7.82130200	-1.77511500	1.21774800
O	7.02302900	-3.50349400	1.46345600
C	-8.49839100	-2.75893800	0.45465600
H	-8.86621000	-2.35203900	-0.49701900
H	-9.34824000	-3.07693900	1.06177500
H	-7.85563200	-3.62558400	0.24959800
C	7.49613500	-4.60760500	0.71145400
H	7.96281700	-4.28713000	-0.22984800
H	6.69093300	-5.32036300	0.48798700
H	8.24625400	-5.09655500	1.33613100



$IM_{triplet\text{-}C\text{–}H}$

Cartesian Coordinates

Atom	X	Y	Z
C	-1.73346500	3.65583000	-2.55738100
H	-0.81825400	4.03715500	-2.09728700
H	-2.04380300	4.38699300	-3.31973900
C	-2.84905100	3.43593000	-1.55962300
H	-1.18952700	2.00129900	-0.90181200
N	-3.36583400	4.49346300	-0.79117800
C	-2.75631400	5.61367100	-0.23090800
O	-3.44727600	6.54583100	0.17852600
C	-4.83837300	4.37045500	-0.62202800
H	-5.29318900	5.35389000	-0.74205200
H	-5.05295200	4.02425100	0.39691800
O	-1.43987000	2.47378600	-3.31377800
C	-0.69286400	1.44664300	-2.78357400
O	-0.24460200	0.61265400	-3.54497900
N	-0.51118100	1.43491000	-1.41676100
Rh	0.23661700	-0.11025600	-0.33747300
Rh	0.75719500	-2.09820100	0.93722900
O	2.26159400	-2.48186000	-0.42295400
O	1.79165400	-0.60398200	-1.59077900
O	1.54241700	0.92908700	0.90814800
O	-1.26920200	0.28020100	1.05291800
O	-1.02154500	-1.34366500	-1.42901700
O	-0.78707900	-1.59473600	2.22191900
O	2.04763600	-0.94953700	2.04937000
O	-0.54356100	-3.18888100	-0.21989000
C	-1.46284100	-0.54434900	2.01402300
C	2.17790800	0.28929700	1.81759300
C	-1.15091900	-2.58292100	-1.15448700
C	2.46293700	-1.66874700	-1.37718600
C	-3.98058700	2.47853700	-1.85802100
H	-3.99293700	1.64326000	-1.14111200
H	-3.88730000	2.03736000	-2.85410500
C	-5.24492500	3.34673200	-1.68568200
H	-5.47691200	3.85785900	-2.62698800
H	-6.12594800	2.76995900	-1.39053700
C	-1.26472800	5.66061100	-0.10262000
C	-0.62521800	6.88578500	-0.34141800
C	-0.50767900	4.56658300	0.33763600

C	0.75625800	6.99754400	-0.19604300
H	-1.22530100	7.73960100	-0.63966100
C	0.87482300	4.67983800	0.48695500
H	-0.99762400	3.62658600	0.57302900
C	1.51004900	5.89287000	0.21079600
H	1.24565900	7.94604600	-0.39958100
H	1.44689200	3.81236700	0.80073500
H	2.58801300	5.97875900	0.31768400
C	3.14810800	1.09252700	2.70255700
C	4.18067900	1.84834400	1.80050300
H	3.63586500	2.58507800	1.20041200
H	4.83942200	2.40772100	2.47625400
C	2.31847600	2.13407000	3.48884400
H	1.58317800	1.64101700	4.13548300
H	2.98175600	2.72686700	4.12904500
H	1.78399000	2.81569800	2.82203200
C	3.86514500	0.15994400	3.69289700
H	3.14758300	-0.35107500	4.34102600
H	4.45493600	-0.60161300	3.17790300
H	4.53871000	0.75080100	4.32504400
C	-2.59966100	-0.20355800	2.99588100
C	-2.72539000	-1.29172600	4.07392200
H	-1.79518300	-1.39244900	4.64036300
H	-3.52580000	-1.02172900	4.77319600
H	-2.96000600	-2.26606300	3.63919200
C	-2.25886600	1.15071500	3.65920800
H	-2.15171000	1.94429200	2.91419400
H	-3.05554000	1.43385600	4.35663900
H	-1.32400900	1.08536500	4.22804600
C	-3.94101600	-0.04152300	2.20471300
H	-4.71674600	0.19600000	2.94317900
H	-3.84211200	0.83210500	1.55109900
C	-2.10543900	-3.38192400	-2.05801600
C	-2.18953800	-4.84423800	-1.59366200
H	-2.57902800	-4.92491600	-0.57572400
H	-2.85269600	-5.40206400	-2.26600500
H	-1.20463000	-5.31943400	-1.61374600
C	-3.51713200	-2.70386500	-2.04929600
H	-3.42056300	-1.72462800	-2.52916300
H	-4.16365300	-3.31445500	-2.69211100
C	-1.54309200	-3.31311000	-3.49741600
H	-0.56831600	-3.81112500	-3.55909500
H	-2.22481300	-3.82578600	-4.18614600
H	-1.41944500	-2.27733100	-3.82518700
C	3.57910400	-1.97827300	-2.38933700
C	4.34784900	-3.24363900	-1.97869300

H	5.11896400	-3.46070600	-2.72790700
H	4.83269700	-3.12603800	-1.00628200
H	3.67875800	-4.10663800	-1.91719000
C	2.90229400	-2.19201100	-3.76409200
H	2.30330100	-1.32289000	-4.04924300
H	3.66716000	-2.36446900	-4.53039800
H	2.24550200	-3.06969600	-3.74323700
C	4.53684800	-0.74406300	-2.50045300
H	5.31379200	-1.01280200	-3.22728900
H	3.96618900	0.08498200	-2.93078200
C	-4.15460300	-2.53180500	-0.68445500
C	-3.85343500	-1.40293200	0.08082700
C	-5.03020600	-3.49709000	-0.16270300
C	-4.36235200	-1.24062100	1.37851900
H	-3.19474500	-0.64678500	-0.32987600
C	-5.57380100	-3.32843200	1.11583900
H	-5.28259200	-4.36420800	-0.76302100
C	-5.23160900	-2.20617600	1.88514400
H	-5.66585900	-2.11133200	2.87616100
C	5.17411400	-0.29258900	-1.20101600
C	4.48734500	0.59169500	-0.36604900
C	6.43625000	-0.76492200	-0.80712500
C	5.00487400	0.96720500	0.88284900
H	3.52782800	0.98266200	-0.68360100
C	6.98162000	-0.36295400	0.41719100
H	6.98075500	-1.43424400	-1.46407300
C	6.26013400	0.49269800	1.26271400
H	6.70826400	0.77545600	2.21087200
O	-6.44520100	-4.19923100	1.70643900
O	8.20666300	-0.75088400	0.88309900
C	-6.82017100	-5.36533900	0.99309000
H	-7.33547800	-5.11862100	0.05500400
H	-7.50466400	-5.90940700	1.64677200
H	-5.95203900	-5.99981800	0.76954800
C	8.98366800	-1.62704500	0.08497800
H	9.23015600	-1.17896000	-0.88710300
H	8.47216800	-2.58473400	-0.08109300
H	9.90511700	-1.80362700	0.64331800

参考文献

1. Y. Wang, M. E. Muratore, A. M. Echavarren, Gold Carbene or Carbenoid: Is There a Difference? *Chem. – Eur. J.* **2015**, *21*, 7332.
2. "Synthetic Carbene and Nitrene Chemistry": M. P. Doyle in Reactive Intermediate Chemistry (Eds.: R. A. Moss, M. S. Platz, M. Jones, Jr.), Wiley Interscience, New York, **2004**, chap. 12, pp. 561.
3. a) H. M. L. Davies, J. R. Manning, Catalytic C–H Functionalization by Metal Carbenoid and Nitrenoid insertion. *Nature* **2008**, *451*, 417 and references cited therein; b) M. P. Doyle, R. Duffy, M. Ratnikov, L. Zhou, Catalytic Carbene Insertion into C−H Bonds. *Chem. Rev.* **2010**, *110*, 704; c) J. Egger, E. M. Carreira, Efficient Synthesis Strategies by Application of Transition Metal-Catalyzed Carbene/Nitrene Insertions into C–H Bonds. *Nat. Prod. Rep.* **2014**, *31*, 449.
4. a) P. Müller, C. Fruit, Enantioselective Catalytic Aziridinations and Asymmetric Nitrene Insertions into C–H Bonds. *Chem. Rev.* 2003, *103*, 2905; b) T. Uchida, T. Katsuki, Asymmetric Nitrene Transfer Reactions: Sulfimidation, Aziridination and C–H Amination Using Azide Compounds as Nitrene Precursors. *Chem. Rec.* **2014**, *14*, 117.
5. H. Lebel, J.-F. Marcoux, C. Molinaro, A. B. Charette, Stereoselective Cyclopropanation Reactions. *Chem. Rev.* **2003**, *103*, 977.
6. D. Gillingham, N. Fei, Catalytic X–H Insertion Reactions Based on Carbenoids, *Chem. Soc. Rev.* **2013**, *42*, 4918.
7. a) F. G. West, B. N. Naidu, New Route to Substituted Piperidines via the Stevens [1,2]-Shift of Ammonium Ylides. *J. Am. Chem. Soc.* **1993**, *115*, 1177; (b) J. S. Clark, P. B. Hodgson, An Enantioselective Synthesis of the CE Ring System of the Alkaloids Manzamine A, E and F, and Ircinal A. *Tetrahedron Lett.* **1995**, *36*, 2519; (c) A. Padwa, T. Hasegawa, A. B. Liu, Z. Zhang, Rhodium(II)-Catalyzed Cyclization of Amido Diazo Carbonyl Compounds. *J. Org. Chem.* **2000**, *65*, 7124; (d) A. Padwa, J. P. Snyder, E. A. Curtis, S. M. Sheehan, K. J. Worsencroft, C. O. Kappe, Rhodium(II)-Catalyzed Equilibration of Push-Pull Carbonyl and Ammonium Ylides. A Computationally Based Understanding of the Reaction Pathway. *J. Am. Chem. Soc.* **2000**, *122*, 8155; (e) A. Padwa, L. S. Beall, C. K. Eidell, K. J. Worsencroft, An Approach toward Isoindolobenzazepines Using the Ammonium Ylide/Stevens [1,2]-Rearrangement Sequence. *J. Org. Chem.* **2001**, ***66***, 2414; (f) J. A. Vanecko, H. Wan, F. G. West, Recent Advances in the Stevens Rearrangement of Ammonium

Ylides. Application to the Synthesis of Alkaloid Natural Products. *Tetrahedron* **2006**, *62*, 1043.

8. a) D. L. Hertzog, D. J. Austin, W. R. Nadler, A. Padwa, Intramolecular Cycloaddition of Isomünchnones Derived from the Rhodium(II) Catalyzed Cyclization of Diazoimides. *Tetrahedron Lett.* **1992**, *33*, 4731; b) E. A. Curtis, K. J. Worsencroft, A. Padwa, Cyclization of Rhodium Carbenoids using Ester and Amido Carbonyl Groups. *Tetrahedron Lett.* **1997**, *38*, 3319.
9. A. Padwa, Domino Reactions of Rhodium(II) Carbenoids for Alkaloid Synthesis. *Chem. Soc. Rev.* **2009**, *38*, 3072.
10. S. Harada, M. Kono, T. Nozaki, Y. Menjo, T. Nemoto, Y. Hamada, General Approach to Nitrogen-Bridged Bicyclic Frameworks by Rh-Catalyzed Formal Carbenoid Insertion into an Amide C–N Bond. *J. Org. Chem.* **2015**, *80*, 10317.
11. Amide insertion of Cu-carbenoid, see: S. Harada, R. Kato, T. Nemoto, Construction of Functionalized Azapolycyclic Architectures *via*Formal Amide Insertion at a Low Catalyst Loading of Copper Trifluoroacetylacetonate. *Adv. Synth. Catal.* **2016**, *358*, 3123.
12. a) G. A. Cordell, M. Lou Quinn Beattie, N. R. Farnsworth, The Potential of Alkaloids in Drug Discovery. *Phytother. Res.* **2001**, *15*, 183; b) S. Wonnacott, T. Gallagher, The Chemistry and Pharmacology of Anatoxin-a and Related Homotropanes with respect to Nicotinic Acetylcholine Receptors. *Mar. Drugs* **2006**, *4*, 228; c) K. Zaima, I. Koga, N. Iwasawa, T. Hosoya, Y. Hirasawa, T. Kaneda, I. S. Ismail, N. H. Lajis, H. Morita, Vasorelaxant Activity of Indole Alkaloids from *Tabernaemontana Dichotoma*. *J. Nat. Med.* **2012**, *67*, 9; d) C. R. Edwankar, R. V. Edwankar, J. R. Deschamps, J. M. Cook, Nature-Inspired Stereospecific Total Synthesis of *P*-(+)-Dispegatrine and Four Other Monomeric *Sarpagine* Indole Alkaloids. *Angew. Chem. Int. Ed.* **2012**, *51*, 11762; e) A. Jadhav, W. Liang, P. C. Papageorgiou, A. Shoker, S. C. Kanthan, J. Balsevich, A. S. Levy, S. Heximer, P. H. Backx, V. Gopalakrishnan, Catharanthine Dilates Small Mesenteric Arteries and Decreases Heart Rate and Cardiac Contractility by Inhibition of Voltage-Operated Calcium Channels on Vascular Smooth Muscle Cells and Cardiomyocytes. *J. Pharmacol. Exp. Ther.* **2013**, *345*, 383; f) J. W. Beatty, C. R. J. Stephenson, Synthesis of (–)-Pseudotabersonine, (–)-Pseudovincadifformine, and (+)-Coronaridine Enabled by Photoredox Catalysis in Flow. *J. Am. Chem. Soc.* **2014**, *136*, 10270; g) R. V. Edwankar, C. R. Edwankar, J. R. Deschamps, J. M. Cook, General Strategy for Synthesis of C-19 Methyl-Substituted *Sarpagine*/*Macroline*/*Ajmaline* Indole Alkaloids Including Total Synthesis of

19(*S*),20(*R*)-Dihydroperaksine, 19(*S*),20(*R*)-Dihydroperaksine-17-al, and Peraksine. *J. Org. Chem.* **2014**, *79*, 10030; h) Z.-J. Zhang, J. Yang, J. He, X.-D. Wu, L.-D. Shao, Y. Li, S.-X. Huang, R.-T. Li, Q.-S. Zhao, Vincamajorines A and B, Monoterpenoid Indole Alkaloids with New Carbon Skeletons from *Vinca Major*. *Tetrahedron Lett.* **2014**, *55*, 6490.

13. M. Kono, S. Harada, Y. Hamada, T. Nemoto, Formal Amide Insertion Strategy for the Synthesis of Anatoxin-a using Rhodium Catalysis. *Tetrahedron* **2016**, *72*, 1395.
14. a) W. J. McKillip, E. A. Sedor, B. M. Culbertson, S. Wawzonek, Chemistry of Aminimides. *Chem. Rev.* **1973**, *73*, 255; b) P. Rademacher, *Science of Synthesis* **2008**, *40b*, 1133; c) G. Qiu, Y. Kuang, J. Wu, *N*-Imide Ylide-Based Reactions: C□H Functionalization, Nucleophilic Addition and Cycloaddition. *Adv. Synth. Catal.* **2014**, *356*, 3483.
15. J. Li, J. S. Cisar, C.-Y. Zhou, B. Vera, H. Williams, A. D. Rodríguez, B. F. Cravatt, D. Romo, Simultaneous Structure–Activity Studies and Arming of Natural Products by C–H Amination Reveal Cellular Targets of Eupalmerin Acetate. *Nature Chem.* **2013**, *5*, 510.
16. L. Maestre, R. Dorel, O. Pablo, I. Escofet, W. M. C. Sameera, E. Álvarez, F. Maseras, M. M. Díaz-Requejo, A. M. Echavarren, P. J. Pérez, Functional-Group-Tolerant, Silver-Catalyzed N–N Bond Formation by Nitrene Transfer to Amines. *J. Am. Chem. Soc.* **2017**, *139*, 2216.
17. a) M. Ito, A. Tanaka, K. Higuchi, S. Sugiyama, Rhodium(II)-Catalyzed Synthesis of *N*-Aryl-*N*′-tosyldiazenes from Primary Aromatic Amines Using (Tosylimino)aryliodinane: A Potent Stable Surrogate for Diazonium Salts. *Eur. J. Org. Chem.* **2017**, 1272; b) S. A. Pujari, L. Guénée, J. Lacour, Efficient Synthesis of Imino-methano Tröger Bases by Nitrene Insertions into C–N Bonds. *Org. Lett.* **2013**, *15*, 3930; c) S. L. Jain, V. B. Sharma, B. Sain, Copper-Catalyzed Imination of Pyridines using PhI=NTs as Nitrene Precursor. *Tetrahedron Lett.* **2003**, *44*, 4385.
18. a) J. L. Roizen, M. E. Harvey, J. Du Bois, Metal-Catalyzed Nitrogen-Atom Transfer Methods for the Oxidation of Aliphatic C–H Bonds. *Acc. Chem. Res.* **2012**, *45*, 911; b) J. L. Jeffrey, R. Sarpong, Intramolecular C(sp^3)–H Amination. *Chem. Sci.* **2013**, *4*, 4092. (c) B. Darses, R. Rodrigues, L. Neuville, M. Mazurais, P. Dauban, Transition Metal-Catalyzed Iodine(III)-Mediated Nitrene Transfer Reactions: Efficient Tools for Challenging Syntheses. *Chem. Commun.* **2017**, *53*, 493.
19. I. Nägeli, C. Baud, G. Bernardinelli, Y. Jacquier, M. Moran, P. Müller, Rhodium(II)-Catalyzed C–H Insertions with {[(4-Nitrophenyl)sulfonyl]imino}phenyl-λ^3-iodane. *Helv. Chim. Acta* **1997**, *80*, 1087.

20. a) C. G. Espino, J. Du Bois, A Rh-Catalyzed C−H Insertion Reaction for the Oxidative Conversion of Carbamates to Oxazolidinones. *Angew. Chem. Int. Ed.* **2001**, *40*, 598; b) C. G. Espino, P. M. Wehn, J. Chow, J. Du Bois, Synthesis of 1,3-Difunctionalized Amine Derivatives through Selective C−H Bond Oxidation. *J. Am. Chem. Soc.* **2001**, *123*, 6935.

21. a) P. M. Wehn, J. Lee, J. Du Bois, Stereochemical Models for Rh-Catalyzed Amination Reactions of Chiral Sulfamates. *Org. Lett.* **2003**, *5*, 4823; b) R. P. Reddy, H. M. L. Davies, Dirhodium Tetracarboxylates Derived from Adamantylglycine as Chiral Catalysts for Enantioselective C−H Aminations. *Org. Lett.* **2006**, *8*, 5013; c) K. W. Fiori, J. Du Bois, Catalytic Intermolecular Amination of C−H Bonds: Method Development and Mechanistic Insights. *J. Am. Chem. Soc.* **2007**, *129*, 562.

22. a) M. E. Harvey, D. G. Musaev, J. Du Bois, A Diruthenium Catalyst for Selective, Intramolecular Allylic C–H Amination: Reaction Development and Mechanistic Insight Gained through Experiment and Theory. *J. Am. Chem. Soc.* **2011**, *133*, 17207; b) C. Liang, F. Collet, F. Robert-Peillard, P. Müller, R. H. Dodd, P. Dauban, Toward a Synthetically Useful Stereoselective C−H Amination of Hydrocarbons. *J. Am. Chem. Soc.* **2008**, *130*, 343.

23. K. W. Fiori, J. J. Fleming, J. Du Bois, Rh-Catalyzed Amination of Ethereal C^{α}–H Bonds: A Versatile Strategy for the Synthesis of Complex Amines. *Angew. Chem. Int. Ed.* **2004**, *43*, 4349.

24. J. L. Roizen, D. N. Zalatan, J. Du Bois, Selective Intermolecular Amination of C−H Bonds at Tertiary Carbon Centers. *Angew. Chem. Int. Ed.* **2013**, *52*, 11343.

25. G. Dequirez, V. Pons, P. Dauban, Nitrene Chemistry in Organic Synthesis: Still in Its Infancy? *Angew. Chem. Int. Ed.* **2012**, *51*, 7384.

26. a) X, Lin, C. Zhao, C.-M. Che, Z. Ke, D. L. Phillips, A DFT Study on the Mechanism of $Rh_2^{II,II}$-Catalyzed Intramolecular Amidation of Carbamates. *Chem. - Asian J.* **2007**, *2*, 1101; b) X. Zhang, H. Xu, C. Zhao, Mechanistic Investigation of Dirhodium-Catalyzed Intramolecular Allylic C–H Amination versus Alkene Aziridination. *J. Org. Chem.* **2014**, *79*, 9799; c) K. W. Fiori, C. G. Espino, B. H. Brodsky, J. Du Bois, A Mechanistic Analysis of the Rh-Catalyzed Intramolecular C–H Amination Reaction. *Tetrahedron* **2009**, *65*, 3042; d) V. Bagchi, P. Paraskevopoulou, P. Das, L. Chi, Q. Wang, A. Choudhury, J. S. Mathieson, L. Cronin, D. B. Pardue, T. R. Cundari, G. Mitrikas, Y. Sanakis, P. Stavropoulos, A Versatile Tripodal Cu(I) Reagent for C–N Bond Construction via Nitrene-Transfer Chemistry: Catalytic Perspectives and Mechanistic Insights on C–H Aminations/Amidinations and Olefin Aziridinations. *J. Am. Chem. Soc.* **2014**, *136*, 11362; e) M. M. Díaz-Requejo,

T. R. Belderrain, M. C. Nicasio, S. Trofimenko, P. J. Pérez, Cyclohexane and Benzene Amination by Catalytic Nitrene Insertion into C–H Bonds with the Copper-Homoscorpionate Catalyst $Tp^{Br3}Cu(NCMe)$. *J. Am. Chem. Soc.* **2003**, *125*, 12078; f) M. J. B. Aguila, Y. M. Badiei, T. H. Warren, Mechanistic Insights into C–H Amination via Dicopper Nitrenes. *J. Am. Chem. Soc.* **2013**, *135*, 9399.

27. S. Toumieux, P. Compain, O. R. Martin, M. Selkti, New Aspects of Catalytic Intramolecular C–H Amination: Unexpected Formation of a Seven-Membered Ring in Nitrogen-Containing Systems. *Org. Lett.* **2006**, *8*, 4493.
28. M. S. T. Morin, S. Toumieux, P. Compain, S. Peyrat, J. Kalinowska-Tluscik, Intramolecular Rhodium-Catalyzed Activation of α-Amino C–H Bonds: Decisive Influence of Conformational Factors in the Synthesis of Bicyclic Aminals from *N*-Sulfamoyloxyacetyl Azacycloalkanes. *Tetrahedron Lett.* **2007**, *48*, 8531.
29. a) M. Kuramoto, N. Miyake, Y. Ishimaru, N. Ono, H. Uno, Cylindradines A and B: Novel Bromopyrrole Alkaloids from the Marine Sponge *Axinella cylindratus*. *Org. Lett.* **2008**, *10*, 5465; b) M. Iwata, Y. Kamijoh, E. Yamamoto, M. Yamanaka, K. Nagasawa, Total Synthesis of Pyrrole–Imidazole Alkaloid (+)-Cylindradine B. *Org. Lett.* **2017**, *19*, 420.
30. a) J. Bordner, W. E. Thiessen, H. A. Bates, H. Rapoport, Structure of a Crystalline Derivative of Saxitoxin. Structure of Saxitoxin. *J. Am. Chem. Soc.* **1975**, *97*, 6008; b) A. P. Thottumkara, W. H. Parsons, J. Du Bois, Saxitoxin. *Angew. Chem. Int. Ed.* **2014**, *53*, 5760.
31. a) R. B. Kinnel, H. P. Gehrken, P. J. Scheuer, Palau'amine: A Cytotoxic and Immunosuppressive Hexacyclic Bisguanidine Antibiotic from the Sponge Stylotella agminate. *J. Am. Chem. Soc.* **1993**, *115*, 3376; b) I. B. Seiple, S. Su, I. S. Young, C. A. Lewis, J. Yamaguchi, P. S. Baran, Total Synthesis of Palau'amine. *Angew. Chem. Int. Ed.* **2010**, *49*, 1095.
32. H. Zhou, E. Bucio, S. R. Venumbaka, J. W. Fitch, P. Cassidy, New Spirodilactam Polymers. *Polymer* **2006**, *47*, 6927 and references cited therein.
33. O. Tsuge, H. Watanabe, K. Masuda, M. M. Yousif, Reactions of Ketenimines with Nitrones. *J. Org. Chem.* **1979**, *44*, 4543.
34. M. J. Martín-López, F. Bermejo, Synthesis of Azaspiro[4.5]decane Systems by Oxidative Cyclization of Olefinic Precursors. *Tetrahedron* **1998**, *54*, 12379.
35. K. Matsumoto, H. Tokuyama, T. Fukuyama, Synthetic Studies on Haplophytine: Protective-Group-Controlled Rearrangement. *Synlett* **2007**, *2007*, 3137.

36. D. Kalaitzakis, E. Antonatou, G. Vassilikogiannakis, One-Pot Synthesis of 1-Azaspiro Frameworks Initiated by Photooxidation of Simple Furans. *Chem. Commun.* **2013**, *50*, 400.
37. Enantioselective synthesis of spiroacetals has been studied; I. Čorić, B. List, Asymmetric Spiroacetalization Catalysed by Confined Brønsted Acids. *Nature* **2012**, *483*, 315.
38. a) C. G. Espino, K. W. Fiori, M. Kim, J. Du Bois, Expanding the Scope of C−H Amination through Catalyst Design. *J. Am. Chem. Soc.* **2004**, *126*, 15378; b) D. N. Zalatan, J. Du Bois, Understanding the Differential Performance of $Rh_2(esp)_2$ as a Catalyst for C−H Amination. *J. Am. Chem. Soc.* **2009**, *131*, 7558.
39. A. W. Hofmann, Ueber die Einwirkung des Broms in Alkalischer Lösung auf Amide. *Ber. Dtsch. Chem. Ges.* **1881**, *14*, 2725.
40. A short-lived radical pathway via a triplet nitrenoid cannot, however, be fully excluded.
41. a) S. Sato, M. Shibuya, N. Kanoh, Y. Iwabuchi, Highly Enantioselective Intramolecular Aza-Spiroannulation onto Indoles using Chiral Rhodium Catalysis: Asymmetric Entry to the Spiro-ß-Lactam Core of Chartellines
Chem. Commun. **2009**, 6264; b) R. Gupta, K. M. Sogi, S. E. Bernard, J. D. Decatur, C. M. Rojas, Protecting Group and Solvent Control of Stereo- and Chemoselectivity in Glucal 3-Carbamate Amidoglycosylation. *Org. Lett.* **2009**, *11*, 1527.
42. A. G. H. Wee, G.-J. Fan, H. M. Bayirinoba, Nonracemic Bicyclic Lactam Lactones via Regio- and *cis*-Diastereocontrolled C−H Insertion. Asymmetric Synthesis of (8*S*,8a*S*)-Octahydroindolizidin-8-ol and (1*S*,8a*S*)-Octahydroindolizidin-1-ol. *J. Org. Chem.* **2009**, *74*, 8261.
43. E. Büchner, Ueber Pseudophenylessigsäure. *Ber. Dtsch. Chem. Ges.* **1896**, *29*, 106.
44. See the experimental section for details.
45. This level of theory was previously used in Rh-catalyzed C−H insertions: E. Nakamura, N. Yoshikai, M. Yamanaka, Mechanism of C−H Bond Activation/C−C Bond Formation Reaction between Diazo Compound and Alkane Catalyzed by Dirhodium Tetracarboxylate. *J. Am. Chem. Soc.* **2002**, *124*, 7181.
46. J. Hansen, J. Autschbach, H. M. L. Davies, Computational Study on the Selectivity of Donor/Acceptor-Substituted Rhodium Carbenoids. *J. Org. Chem.* **2009**, *74*, 6555.
47. M. Kono, S. Harada, T. Nemoto, 金属カルベノイドの新規反応性の開拓と有機合成への応用. *有機合成化学協会誌* **2019**, *77*, 49.
48. a) D. T. Nowlan, T. M. Gregg, H. M. L. Davies, D. A. Singleton, Isotope Effects and the Nature of Selectivity in Rhodium-Catalyzed Cyclopropanations. *J. Am. Chem.*

Soc. **2003**, *125*, 15902; b) H. T. Bonge, T. Hansen, Computational Study of Cyclopropanation Reactions with Halodiazoacetates. *J. Org. Chem.* **2010**, *75*, 2309; c) Y.-S. Xue, Y.-P. Cai, Z.-X. Chen, Mechanism and Stereoselectivity of the Rh(II)-Catalyzed Cyclopropanation of Diazooxindole: A Density Functional Theory Study. *RSC Adv.* **2015**, *5*, 57781; d) H. Li, X. Ma, M. Lei, Substituent Effects and Chemoselectivity of the Intramolecular Buchner Reaction of Diazoacetamide Derivatives Catalyzed by the di-Rh(II)-Complex. *Dalton Trans.* **2016**, *45*, 8506.

49. The absolute value of the Kohn-Sham LUMO is mapped onto an electron density surface.

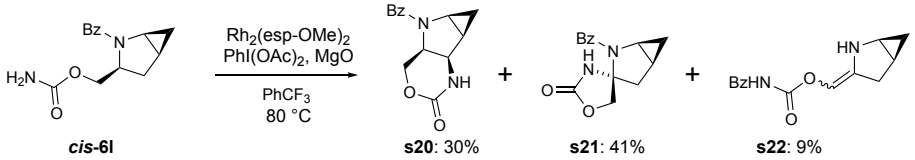
50. a) B. Illien, M. Berthelot, D. G. Morris, C. Laurence, $R_3N^+N^-$: A Substituent with Extreme Electronic Effects. *J. Phys. Org. Chem.* **2000**, *13*, 293; b) B. Capuano, I. T. Crosby, E. J. Lloyd, J. E. Neve, D. A. Taylor, Aminimides as Potential CNS-Acting Agents. III. Design, Synthesis, and Receptor Binding of Aminimide Analogues of Dopamine, Serotonin, Morphine, and Nicotine. *Aust. J. Chem.* **2008**, *61*, 422; c) M. Kirino, I. Tomita, Aminimides Derived from Benzoylformic Acid Esters as Thermally Latent Base Catalysts. *Macromolecules* **2010**, *43*, 8821

51. The reaction control of metal-nitrenes is difficult. a) E. N. Bess, R. J. DeLuca, D. J. Tindall, M. S. Oderinde, J. L. Roizen, J. Du Bois, M. S. Sigman, Analyzing Site Selectivity in $Rh_2(esp)_2$-Catalyzed Intermolecular C–H Amination Reactions. *J. Am. Chem. Soc.* **2014**, *136*, 5783; b) N. S. Dolan, R. J. Scamp, T. Yang, J. F. Berry, J. M. Schomaker, Catalyst-Controlled and Tunable, Chemoselective Silver-Catalyzed Intermolecular Nitrene Transfer: Experimental and Computational Studies. *J. Am. Chem. Soc.* **2016**, *138*, 14658; c) M. Huang, T. Yang, J. D. Paretsky, J. F. Berry, J. M. Schomaker, Inverting Steric Effects: Using "Attractive" Noncovalent Interactions To Direct Silver-Catalyzed Nitrene Transfer. *J. Am. Chem. Soc.* **2017**, *139*, 17376.

52. K. P. Kornecki, J. F. Berry, Introducing a Mixed-Valent Dirhodium(II,III) Catalyst with Increased Stability in C–H Amination. *Chem. Commun.* **2012**, *48*, 12097.

53. a) A. Varela-Álvarez, T. Yang, H. Jennings, K. P. Kornecki, S. N. Macmillan, K. M. Lancaster, J. B. C. Mack, J. Du Bois, J. F. Berry, D. G. Musaev, Rh_2(II,III) Catalysts with Chelating Carboxylate and Carboxamidate Supports: Electronic Structure and Nitrene Transfer Reactivity. *J. Am. Chem. Soc.* **2016**, *138*, 2327; b) X. C. Wang, C. Weigl, M. P. Doyle, Solvent Enhancement of Reaction Selectivity: A Unique Property of Cationic Chiral Dirhodium Carboxamidates. *J. Am. Chem. Soc.* **2011**, *133*, 9572.

54. When the *cis*-isomer of **6l** was used, a variety of side products were generated. No ring-opened compounds were detected.



cis-**6l** **s20**: 30% **s21**: 41% **s22**: 9%

55. These foldamers display the inimitable hydrazino turn, and the hydrazidic bond is stable against proteases, G. Lelais, D. Seebach, Synthesis, CD Spectra, and Enzymatic Stability of *β*²-Oligoazapeptides Prepared from (*S*)-2-Hydrazino Carboxylic Acids Carrying the Side Chains of Val, Ala, and Leu. *Helv. Chim. Acta* **2003**, *86*, 4152.

56. A. Bordessa, M. Keita, X. Marechal, L. Formicola, N. Lagarde, J. Rodrigo, G. Bernadat, C. Bauvais, J. L. Soulier, L. Dufau, T. Milcent, B. Crousse, M. Reboud-Ravaux, S. Ongeri, α- and ß-Hydrazino Acid-Based Pseudopeptides Inhibit the Chymotrypsin-Like Activity of the Eukaryotic 20S Proteasome. *Eur. J. Med. Chem.* **2013**, *70*, 505.

57. M. Laurencin, M. Amor, Y. Fleury, M. Baudy-Floc'h, *De Novo* Cyclic Pseudopeptides Containing Aza-ß³-amino Acids Exhibiting Antimicrobial Activities. *J. Med. Chem.* **2012**, *55*, 10885.

58. J. Suc, L. M. Tumir, L. Glavas-Obrovac, M. Jukic, I. Piantanida, I. Jeric, The Impact of α-Hydrazino Acids Embedded in Short Fluorescent Peptides on Peptide Interactions with DNA and RNA. *Org. Biomol. Chem.* **2016**, *14*, 4865.

59. a) J. G. Harrison, O. Gutierrez, N. Jana, T. G. Driver, D. J. Tantillo, Mechanism of Rh_2(II)-Catalyzed Indole Formation: The Catalyst Does Not Control Product Selectivity. *J. Am. Chem. Soc.* **2016**, *138*, 487; b) J. Wang, K. Zheng, B. Lin, Y. Wenig, A Comparative Study of Inter- and Intramolecular C–H Aminations: Mechanism and Site Selectivity. *RSC Adv.* **2017**, *7*, 34783.

60. K. Matcha, A. P. Antonchick, Metal-Free Cross-Dehydrogenative Coupling of Heterocycles with Aldehydes. *Angew. Chem., Int. Ed.* **2013**, *52*, 2082.

61. a) Y. Maeda, K. U. Ingold, Kinetic Applications of Electron Paramagnetic Resonance Spectroscopy. 35. The Search for a Dialkylaminyl Rearrangement. Ring Opening of N-Cyclobutyl-N-n-propylaminyl. *J. Am. Chem. Soc.* **1980**, *102*, 328; b) N. Takasu, K. Oisaki, M. Kanai, Iron-Catalyzed Oxidative C(3)–H Functionalization of Amines. *Org. Lett.* **2013**, *15*, 1918.

62. H. McAlonan, J. P. Murphy, P. J. Stevenson, A. B. Treacy, Oxidation of N-(4-Methoxybenzyl)-2-pyrrolidinones to N-(4-Methoxybenzoyl)-2-pyrrolidinones. Rapid Entry to Optically Active Aniracetam Analogues. *Tetrahedron* **1996**, *52*, 12521.

63. T. Katoh, Y. Nagata, Y. Kobayashi, K. Arai, J. Minami, S. Terashima, Enantioselective Synthesis of 5-Substituted- and 3,5-Disubstituted-2-formylpyrrolidine Derivatives, the Key D-Ring Fragments of (−)-Quinocarcin and (−)-10-Decarboxyquinocarcin. *Tetrahedron Lett.* **1993**, *34*, 5743.

64. R. Akué-Gédu, S. Al Akoum Ebrik, A. Witczak-Legrand, D. Fasseur, S. El Ghammarti, D. Couturier, B. Decroix, M. Othman, M. Debacker, B. Rigo, Studies on Pyrrolidinones. On the Decarboxylation of Pyroglutamic Acids and *N*-Acyl Prolines in Acidic Media. *Tetrahedron* **2002**, *58*, 9239.

65. S. A. Feutran, H. McAlonan, P. J. Stevenson, A. D. Walker, Palladium-Mediated Reductive Coupling, A Stereoselective Approach to the 8-Dehydropumiliotoxin Skeleton. *Tetrahedron Lett.* **2009**, *50*, 3669.

66. C. E. Neipp, S. F. Martin, A Ring-Closing Olefin Metathesis Approach to Bridged Azabicyclic Structures. *Tetrahedron Lett.* **2002**, *43*, 1779.

67. G. Rassu, F. Zanardi, L. Battistini, E. Gaetani, G. Casiraghi, Expeditious Syntheses of Sugar-Modified Nucleosides and Collections Thereof Exploiting Furan-, Pyrrole-, and Thiophene-Based Siloxy Dienes. *J. Med. Chem.* **1997**, *40*, 168.

68. L. Bunch, P.-O. Norrby, K. Frydenvang, P. Krogsgaard-Larsen, U. Madsen, Unprecedented Migration of *N*-Alkoxycarbonyl Groups in Protected Pyroglutaminol. *Org. Lett.* **2001**, *3*, 433.

69. F. Effenberger, W. Müller, R. Keller, W. Wild, T. Ziegler, Amino Acids. 8. A Novel Synthesis of γ-Carboxy-L-glutamic Acid from L-5-Oxoproline Esters. *J. Org. Chem.* **1990**, *55*, 3064.

70. G. L. Olson, H.-C. Cheung, E. Chiang, V. S. Madison, J. Sepinwall, G. P. Vincent, A. Winokur, K. A. Gary, Peptide Mimetics of Thyrotropin-Releasing Hormone Based on a Cyclohexane Framework: Design, Synthesis, and Cognition-Enhancing Properties. *J. Med. Chem.* **2002**, *38*, 2866.

71. P. F. Keusenkothen, M. B. Smith, Asymmetric Radical Cyclizations: The Synthesis of 6-Alkyl Pyrrolizidin-2-ones. *Tetrahedron* **1992**, *48*, 2977.

72. K. Shimamoto, M. Ishida, H. Shinozaki, Y. Ohfune, Synthesis of Four Diastereomeric L-2-(Carboxycyclopropyl)glycines. Conformationally Constrained L-Glutamate Analogs. *J. Org. Chem.* **1991**, *56*, 4167.

73. T. Katoh, Y. Nagata, Y. Kobayashi, K. Arai, J. Minami, S. Terashima, Synthetic Studies on Quinocarcin and Its Related Compounds. 3. : Synthesis of 5-Substituted-

and 3,5-Disubstituted-2-formyl-pyrrolidine Derivatives, the Key D-Ring Fragments of Enantiomeric Pairs of Quinocarcin and 1. *Tetrahedron* **1994**, *50*, 6221.

74. C. B. Gilley, Y. Kobayashi, 2-Nitrophenyl Isocyanide as a Versatile Convertible Isocyanide: Rapid Access to a Fused γ-Lactam ß-Lactone Bicycle. *J. Org. Chem.* **2008**, *73*, 4198.
75. M. Kim, J. V. Mulcahy, C. G. Espino, J. Du Bois, Expanding the Substrate Scope for C−H Amination Reactions: Oxidative Cyclization of Urea and Guanidine Derivatives. *Org. Lett.* **2006**, *8*, 1073.
76. M. J. Buller, C. B. Gilley, B. Nguyen, L. Olshansky, B. Fraga, Y. Kobayashi, Synthesis of Functionalized Pyroglutamic Acids, Part 1: The Synthetic Utility of *N*-Acylindole and the Ugi Reaction with a Chiral Levulinic Acid. *Synlett* **2008**, 2244.
77. Spartan '16; Wavefunction, Inc.: Irvine (CA), USA, 2013.
78. Gaussian 16, Revision A.03, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. V. Marenich, J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. J. Bearpark, J. J. Heyd, E. N. Brothers, K. N. Kudin, V. N. Staroverov, T. A. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. P. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma, O. Farkas, J. B. Foresman, and D. J. Fox, Gaussian, Inc., Wallingford CT, 2016.
79. a) A. D. Beche, Density-Functional Exchange-Energy Approximation with Correct Asymptotic Behavior. *Phys. Rev.* **1988**, *A38*, 3098. (b) A. D. Beche, A New Mixing of Hartree–Fock and Local Density-Functional Theories. *J. Chem. Phys.* **1993**, *98*. 1372. (c) A. D. Beche, Density-Functional Thermochemistry. III. The Role of Exact Exchange. *J. Chem. Phys.* **1993**, *98*, 5648. (d) C. Lee, W. Yang, R. G. Parr, Development of the Colle-Salvetti Correlation-Energy Formula into a Functional of the Electron Density. *Phys. Rev.* **1988**, *B37*, 785.
80. a) J.-D. Chai, M. H.-Gordon, Optimal Operators for Hartree–Fock Exchange from Long-Range Corrected Hybrid Density Functionals. *Chem. Phys. Lett.* **2008**, *467,*

176; (b) J.-D. Chai, M. H.-Gordon, Long-Range Corrected Double-Hybrid Density Functionals. *J. Chem. Phys.* **2009**, *131*, 174105 /1–174105/13.

81. S. C. Ghosh, J. S. Y. Ngiam, A. M. Seayad, D. T. Tuan, C. W. Johannes, A. Chen, Tandem Oxidative Amidation of Benzyl Alcohols with Amine Hydrochloride Salts Catalysed by Iron Nitrate. *Tetrahedron Lett.* **2013**, *54*, 4922.
82. Y. Nishii, T. Hirai, S. Fernandez, P. Knochel, K. Mashima, Zinc-Catalyzed Esterification of *N*-β-Hydroxyethylamides: Removal of Directing Groups under Mild Conditions. *Eur. J. Org. Chem.* **2017**, 5010.
83. M. Tsuji, E. Kuwano, T. Saito, M. Eto, Root Growth-Promoting Activities of N-Acyl-L-proline Derivatives. *Biosci. Biotech. Biochem.* **1992**, *56*, 778.
84. S. Das, Y. Li, C. Bornschein, S. Pisiewicz, K. Kiersch, D. Michalik, F. Gallou, K. Junge, M. Beller, Selective Rhodium-Catalyzed Reduction of Tertiary Amides in Amino Acid Esters and Peptides. *Angew. Chem. Int. Ed.* **2015**, *54*, 12389.
85. M. Kocevar, P. Mihorko, S. Polanc, An Efficient and Simple Thallium(III)-Induced Cleavage of the Hydrazino Moiety. *J. Org. Chem.* **1995**, *60*, 1466.
86. X.-Y. Qin,; G. Xiong, Y.-G. Sun, M.-Y. Guo, Y. Ma, Q.-F. Wang, P. Liu, P. Gao, X.-L. Sun, Preparation and Characterization of New Chiral Pyrrolyl α-Nitronyl Nitroxide Radicals in which the Imidazolyl Framework was Directly Bound to Chiral Center. *J. Mol. Struct.* **2011**, *989*, 10.
87. D. N. Reddy, R. Thirupathi, S. Tumminakatti, E. N. Prabhakaran, A Method for Stabilizing the *cis* Prolyl Peptide Bond: Influence of an Unusual n→π* Interaction in 1,3-Oxazine and 1,3-Thiazine Containing Peptidomimetics. *Tetrahedron Lett.* **2012**, *53*, 4413.
88. S. Chaudhuri, A. Parida, S. Ghosh, A. Bisai, Highly Stereoselective Syntheses of Proline-Derived Vicinal Amino Alcohols through Grignard Addition onto *N*-Tosylprolinal. *Synlett* **2015**, *27*, 215.
89. Y. Futamura, M. Kurokawa, R. Obata, S. Nishiyama, T. Sugai, Efficient Route to (*S*)-Azetidine-2-carboxylic Acid. *Biosci. Biotech. Biochem.* **2005**, *69*, 1892.
90. L. Banfi, A. Basso, G. Guanti, R. Riva, A new convergent and stereoselective synthesis of 2,5-disubstituted *N*-acylpyrrolidines. *Tetrahedron* **2006**, *62*, 4331.
91. M. Asano, K. Hashimoto, B. Saito, Z. Shiokawa, H. Sumi, M. Yabuki, M. Yoshimatsu K. Aoyama, T. Hamada, N. Morishita, D. R. Dougan, C. D. Mol, S. Yoshida, T. Ishikawa, Design, Stereoselective Synthesis, and Biological Evaluation of Novel tri-Cyclic Compounds as Inhibitor of Apoptosis Proteins (IAP) Antagonists. *Bioorg. Med. Chem.* **2013**, *21*, 5725.

92. W. Zhou, P.-H. Hsieh, Y. Xu, T. R. O'Leary, X. Huang, J. Liu, Design and Synthesis of Active Heparan Sulfate-Based Probes. *Chem. Commun.* **2015**, *51*, 11019.

93. S. P. Bew, P.-A. Ashford, D. U. Bachera, Synthesis of Structure and Function Diverse α-D-Diazoacetates, α-D-Diazoacetamides, α-D-Diazoketones, and the Antibiotic α-D-Azaserine. *Synthesis* **2013**, *45*, 903.

94. V. S. Kubyshkin, P. K. Mykhailiuk, S. Afonin, A. S. Ulrich, I. V. Komarov, Incorporation of *cis*- and *trans*-4,5-Difluoromethanoprolines into Polypeptides. *Org. Lett.* **2012**, *14*, 5254.

95. a) K. Fukui, The Path of Chemical Reactions - The IRC Approach. *Acc. Chem. Res.* **1981**, *14*, 363; b) K. Ishida, K. Morokuma, A. Komornicki, The Intrinsic Reaction Coordinate. An *ab initio* Calculation for HNC→HCN and $H^- + CH_4 \rightarrow CH_4 + H^-$. *J. Chem. Phys.* **1977**, *66*, 2153; c) C. Gonzalez, H. B. Schlegel *J. Chem. Phys.* **1989**, *90*, 2154; d) C. Gonzalez, H. B. Schlegel, Reaction path following in mass-weighted internal coordinates. *J. Phys. Chem.* **1990**, *94*, 5523.

96. D. Andrae, U. Haeussermann, M. Dolg, H. Stoll, H. Preuss, Energy-Adjusted *ab initio* Pseudopotentials for the Second and Third Row Transition Elements. *Theor. Chim. Acta* **1990**, *77*, 123.

主論文目録

本学位論文内容は下記の発表論文による。

1. M. Kono, S. Harada, T. Nemoto Rh-Catalyzed Stereospecific C－H Amination for the Construction of Spiroaminal Cores: Reactivity Difference between Nitrenoid and Carbenoid Species against Amide Functionality *Chemistry – A European Journal* **2016**, *23*, 7428–7432.

2. M. Kono, S. Harada, T. Nemoto Chemoselective Intramolecular Formal Insertion Reaction of Rh-Nitrenes into an Amide Bond over C－H Insertion *Chemistry–A European Journal* **2019**, in press.

謝辞

本研究を行うにあたり、終始御懇篤なるご指導とご鞭撻を賜りました千葉大学大学院薬学研究院　根本哲宏教授に深甚なる感謝の意を表します。

本研究を行うにあたり、時には厳しくも温かいご指導と多大なる御助言、御討論を賜りました千葉大学大学院薬学研究院　原田慎吾助教に深謝致します。

本研究、発表を行う上で貴重なご助言を賜りました千葉大学大学院薬学研究院　中島誠也助教に感謝致します。

学部から修士課程にかけて、研究の基礎をご教授下さった濱田康正先生に深く感謝致します。

まだ科学者として未熟な私を受け入れ、アメリカでの研究生活という貴重な機会を与えて下さったシカゴ大学化学科 Scott A. Snyder 教授に心より御礼申し上げます。

日々の研究生活をご支援いただきました公益社団法人日本薬学会長井記念薬学研究奨励金、公益財団法人戸部眞紀財団、公益財団法人東京生化学研究会に深謝致します。

シカゴ大学への短期留学は千葉大学国際交流事業、公益財団法人吉田科学技術財団のご支援を受けて遂行したものであり、厚く御礼申し上げます。

研究生活を送るにあたり、数々のご協力をいただいた千葉大学大学院薬学研究院の教員、職員、学生の皆様に感謝致します。

最後に、永きに亘る学生生活を支え、応援してくれた家族に心より御礼申し上げます。

2019 年 3 月　河野　将人

本学位論文の審査は千葉大学大学院薬学研究院で指名された下記の審査委員により行われた。

主査　千葉大学大学院教授（薬学研究院）　薬学博士　西田篤司
副査　千葉大学大学院教授（薬学研究院）　薬学博士　高山廣光
副査　千葉大学大学院教授（薬学研究院）　理学博士　石橋正己