Heteroatom Chemistry
Volume 6, Number 3, 1995

Construction of α-Phosphonolactams via Rhodium (II)-Catalyzed Intramolecular C–H Insertion Reactions

Yoshiharu Okada, Toru Minami,* Masahiro Miyamoto, Tsuneyuki Otaguro, Sumiko Sawasaki, and Junji Ichikawa

Department of Applied Chemistry, Kyushu Institute of Technology, Sensui-cho, Tobata, Kitakyushu 804, Japan

Received 30 September 1994

ABSTRACT

The Rh(II)-catalyzed intramolecular C–H insertion reactions of N,N-dialkyl-α-diazo-α-(diethylphosphono)acetamides **2a,f–j** *in $CHCl_3$ or $ClCH_2CH_2Cl$ were found to give monocyclic and bicyclic α-phosphono-β-lactams,* **3a** *and* **3f–j**, *in 43–67% yields via regiospecific α-C–H insertion of the N-alkyl groups. Similar treatment of N-benzyl-N-isopropyl-α-diazo-α-(diethylphosphono)acetamide* (**2b**) *and the corresponding N-isobutyl-N-methylacetamide* **2d** *in $ClCH_2CH_2Cl$ afforded mixtures of β-lactams* **3b** *(35%) and* **3b′** *(16%), β-lactam* **3d** *(47%), and γ-lactam* **4d** *(10%), respectively, each of which is formed by the competitive C–H insertion reaction between benzylic and isopropyl α-C–H bonds and between methyl α-C–H and methine β-C–H bonds, respectively. For the formation of β-lactams, the selectivity in the rhodium-mediated C–H insertion in $ClCH_2CH_2Cl$ follows the order methyl > methine > benzylic α-C–H bond on N-substituents. The N,N-dibutyl-α-diazo homologue* **2c** *and N-[α-diazo-α-(diethylphosphono)acetyl]-2-methylindoline* (**2k**) *exclusively produced γ-lactams* **4c** *(67%) and* **4k** *(81%) via insertion into the methylene β-C–H and methyl β-C–H bonds. tert-Butyl N-[α-diazo-α-(dibenzylphosphono)acetyl]-piperidine-2-carboxylate* (**2m**) *on similar treatment, followed by deprotection of the benzyl ester afforded the 7-phosphono carbacepham* **6** *in 32% overall yield. Similar Rh(II)-catalyzed cyclization of N-methyl-N[4-benzyloxy-α-(diethylphosphono)-phenyl(diethylphosphono)methyl]-α-diazo-acetamide* (**2n**) *led to 1-[4′-benzylphenyl(diethylphosphono)methyl] - 3-(diethylphosphono)azetidin-2-one* (**3n**) *in 78% yield. The phosphono group at C-7 of* **3f** *was converted into the acetylamino group via a four-step reaction. Application of chiral rhodium(II) carboxylates* **12a–c** *to the insertion reactions of* **2b,c** *produced α-phosphono-β- and γ-lactams,* **3b** *and* **4c**, *in 6–24% ee and 25–29% ee, respectively.*

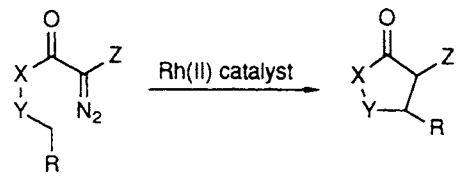
Dedicated to Prof. Shigeru Oae on the occasion of his seventy-fifth birthday.

*To whom correspondence should be addressed.

INTRODUCTION

Recently, the rhodium(II)-catalyzed intramolecular insertion of diazo compounds into a C–H bond has been widely studied and found to be of great synthetic value [1]. For instance, α-diazo compounds of ketones [2], α-diazo β-keto esters [3], β-keto sulfones [4], and β-keto phosphonates [5] smoothly undergo intramolecular C–H insertion in the presence of rhodium(II) catalyst to give ordinarily five-membered ring compounds such as cyclopentanones and γ-lactones with functionality at the α-position (Equation 1). In contrast, a similar reaction of diazoacetamides has been found to produce β-lactams by highly selective intramolecular C–H insertion [6].

1042-7163/95/$5.00 + .25



(1)

Although α-phosphorylated β-lactams are expected to be versatile intermediate reagents for the synthesis of β-lactam antibiotics, as well as functionalized lactams, a convenient synthetic method for the α-phosphonolactams has not, to our knowledge, been reported, except for the cycloaddition reaction of (diethylphosphono)ketenes to imines [7]. As a continuation of the studies on α-phosphorylated lactams [8] and lactones [9], we have become interested in the development of new efficient syntheses of α-phosphonolactams and their synthetic utilization. We now report the synthesis of mono- and bicyclic α-phosphono-β-lactams *via* rhodium(II)-catalyzed C–H insertion and their application in the Wittig–Horner reaction. We also describe the application to phosphorylated carbacephams and to a nocardicin segment.

RESULTS AND DISCUSSION

α-Diazo-α-(diethylphosphono)acetamides **2a–k** were readily prepared from α-(diethylphosphono)-acetamides **1a–k** according to the conventional diazo transfer method by the use of *p*-toluenesulfonyl azide [10].

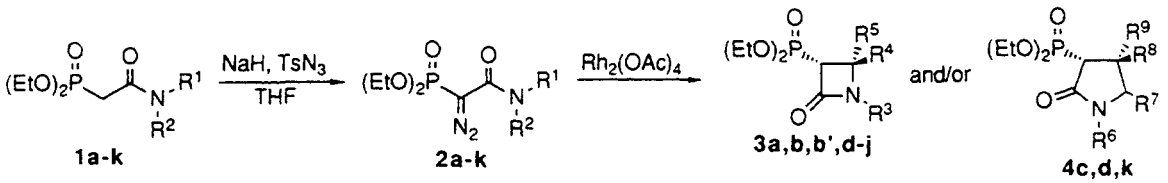
Catalytic decomposition of the α-diazo-α- (diethylphosphono)acetamides **2a–k** was carried out in a refluxing solvent containing $Rh_2(OAc)_4$ to afford α-(diethylphosphono)-β- and/or γ-lactams **3** and/or **4** (Scheme 1 and Table 1). Thus, treatment of *N,N*-diisopropyl-α-diazo-α-(diethylphosphono)-acetamide (**2a**) with rhodium(II) catalyst in refluxing $CHCl_3$ led to a single product, 1-isopropyl-4,4-dimethyl-3-(diethylphosphono)-β-lactam (**3a**) in 42% yield, but the formation of a γ-lactam was not observed (entry 1 of Table 1). Similar treatment of *N*-benzyl-*N*-isopropyl-α-diazo-α-(diethylphosphono)acetamide (**2b**) led to a 3:2 mixture of two types of 3-(diethylphosphono)-β-lactams **3b** and **3b'** in 41% yield (entry 2), which were produced by competitive insertion reactions between benzylic and isopropyl α-C–H bonds. When the same reaction was carried out in $ClCH_2CH_2Cl$ instead of $CHCl_3$, the enhanced yield of **3b'** (39%) and a remarkable change in the isomer ratio (2:3) were observed (entry 3). The stereochemical assignment of **3b** was established as the isomer with a *trans* relationship between phenyl and diethylphosphono substituents on the basis of its ^1H NMR spectrum, which exhibits coupling constants of 2.6 Hz for hydrogens of the β-lactam ring [11].

In contrast, *N,N*-dibutyl-α-diazo-α-(diethylphosphono)acetamide (**2c**) on similar treatment gave 1-butyl-4-ethyl-3-(diethylphosphono)-γ-lactam (**4c**) *via* regioselective β-C–H insertion without contamination of a β-lactam (entry 4). *N*-Isobutyl-*N*-methyl-α-diazo-α-(diethylphosphono)acetamide (**2d**) underwent cyclization to yield both a β-lactam **3d** (47%) and a γ-lactam **4d** (10%), of which formation was attributed to insertion into methyl α-C–H and isobutyl β-C–H bonds, respectively. The

TABLE 1 Rh (II)-Catalyzed C–H Insertion of α-Diazo-α-(diethylphosphono)-acetamides **2**[a]

Entry	*Substrate 2*	*Solvent*	*Time (h)*	**3** *and/or* **4** *(% yield)*[b]
1	**2a**	$CHCl_3$	6	**3a** (42)
2	**2b**	$CHCl_3$	5	**3b** (25) + **3b'** (16)
3	**2b**	$ClCH_2CH_2Cl$	5	**3b** (26) + **3b'** (39)
4	**2c**	$ClCH_2CH_2Cl$	6	**4c** (67)
5	**2d**	$ClCH_2CH_2Cl$	4	**3d** (47) + **4d** (10)
6	**2d**	C_6H_6	4	**3d** (57) + **4d** (19)
7	**2e**	$ClCH_2CH_2Cl$	4	[c]
8	**2f**	$ClCH_2CH_2Cl$	4	**3f** (57)[d]
9	**2g**	$ClCH_2CH_2Cl$	6	**3g** (43)
10	**2h**	$ClCH_2CH_2Cl$	4	**3h** (67)
11	**2i**	$ClCH_2CH_2Cl$	5	**3i** (48)
12	**2j**	$ClCH_2CH_2Cl$	5	**3j** (43)
13	**2k**	C_6H_6	4	**4k** (81)

[a]All reactions of 3 mmol of **2** in 15 mL of solvent were carried out in the presence of 0.017 mmol of $Rh_2(OAc)_4$ at reflux unless otherwise noted.
[b]Isolated yield.
[c]An unidentified complex mixture was obtained.
[d]In the presence of 0.05 mmol of catalyst in 40 mL of solvent.



1a, **2a**: $R^1=R^2={}^i$Pr
1b, **2b**: $R^1={}^i$Pr, $R^2=CH_2Ph$
1c, **2c**: $R^1=R^2={}^n$Bu
1d, **2d**: $R^1={}^t$Bu, R^2=Me
1e, **2e**: R^1 R^2=$-(CH_2)_4-$
1f, **2f**: R^1 R^2=$-(CH_2)_5-$
1g, **2g**: R^1 R^2=$-CH(Me)(CH_2)_3CH(Me)-$
1h, **2h**: R^1 R^2=$-(CH_2)_6-$
1i, **2i**: R^1 R^2=$-(CH_2)_3OCH(Me)-$
1j, **2j**: R^1 R^2=$-(CH_2)_4CH(CO_2{}^t$Bu)$-$
1k, **2k**: R^1 R^2=

3a: $R^3={}^i$Pr, $R^4=R^5$=Me
3b: $R^3={}^i$Pr, R^4=Ph, R^5=H
3b': $R^3=CH_2Ph$, $R^4=R^5$=Me
3d: $R^3={}^t$Bu, $R^4=R^5$=H
3e: R^3 R^4=$-(CH_2)_3-$, R^5=H
3f: R^3 R^4=$-(CH_2)_4-$, R^5=H
3g: R^3 R^4=$-CH(Me)(CH_2)_3-$, R^5=Me
3h: R^3 R^4=$-(CH_2)_5-$, R^5=H
3i: R^3 R^4=$-CH(Me)O(CH_2)_2-$, R^5=H
3j: R^3 R^4=$-CH(CO_2{}^t$Bu)$(CH_2)_3-$, R^5=H

4c: $R^6={}^n$Bu, $R^7=R^9$=H, R^8=Et
4d: R^6=Me, R^7=H, $R^8=R^9$=Me
4k: R^6 R^7= , $R^8=R^9$=H

SCHEME 1

reaction of **2d** in refluxing benzene improved both yields of **3d** (57%) and **4d** (19%) while decreasing the ratio of **3d**/**4d** (β/γ = 3.0) (entries 5 and 6). On the basis of these results, the selectivity in the rhodium-mediated C–H insertion in $ClCH_2CH_2Cl$ for the formation of the β-lactam was found to follow the order methyl > methine > benzylic proton at the α-position on *N*-substituents.

Since the synthesis of various α-phosphono monocyclic lactams was successfully achieved by the rhodium(II)-catalyzed decomposition of α-diazo-α-(phosphono)acetamides, we have further investigated the applicability of this methodology to the synthesis of fused β-lactams. A similar rhodium(II)-catalyzed decomposition of an *N*,*N*-tetramethylenediazoacetamide **2e** did not give the expected 6-phosphonocarbapenam having a cyclopentane-fused β-lactam framework, but instead an unidentified complex mixture was obtained (entry 7). In contrast to **2e**, the use of larger-membered *N*,*N*-polymethylene-diazoacetamides **2f–j** resulted in the formation of the desired 7-phosphonocarbacepham **3f** in 57% yield (entry 8) and the bicyclic β-lactams **3g–j** in 43–67% yields (entries 9 through 12), while the diazo amide **2k** derived from 2-methylindoline produced a γ-lactam **4k** in high yield (81%) (entry 13). These results showed that the five-membered ring-fused β-lactams could not be constructed in this system, but six- and seven-membered ring-fused β-lactams were easily formed.

The stereochemical assignment of the cycloalkane-fused β-lactams **3f–j** was made on the basis of ^{1}H NMR spectroscopy [12] and X-ray crystal analysis. In the ^{1}H NMR spectrum (500 MHz) of **3j**, characteristic resonances of H7, H6, H1α, and H4α protons were observed at δ 3.31 (dd, J_{H7-H6} = 2.1, J_{H7-P} = 5.6 Hz), 3.86–3.92 (m), 1.28 (dddd, $J_{H1\alpha-H2\alpha}$ = 3.2, $J_{H1\alpha-H6}$= 10.9, $J_{H1\alpha-H1\beta}$ = 13.0, $J_{H1\alpha-H2\beta}$ = 13.0 Hz), and 4.47 (d, $J_{H4\alpha-H3\alpha}$ = 6.7 Hz), respectively (see the Experimental Section). The small coupling (2.1 Hz) between H6 and H7 must be a *trans* coupling. The large coupling (10.9 Hz) between H6 and H1α must be an axial-axial coupling, and therefore, H6 must be axial. The medium coupling (6.7 Hz) between H4α and H3α is typical of equatorial-axial coupling for six-membered rings; therefore, H4α must be equatorial. Accordingly, the phosphono and ester groups and H6 all must be situated on the β-face. Furthermore, the stereochemistry of **3j** was also confirmed by X-ray analysis (Figure 1).

In addition, we have taken interest in the development of 7-phosphonocarbacephamcarboxylic acid (7-PCA) (**6**) in connection with biological activities of antibiotics. Thus, 7-(dibenzylphosphono)carbacepham-carboxylic acid *tert*-butyl ester **3m**, which can be considered as a precursor of **6**, was successfully prepared, albeit in rather low yield (32%), by a similar $Rh_2(OAc)_4$-catalyzed insertion reaction of *tert*-butyl *N*-[α-diazo-α-(dibenzylphosphono)acetyl]pyperidine-2-carboxylate (**2m**) (Scheme 2). Treatment of the *tert*-butyl ester **3m** with palladium on charcoal (ethanol, room temperature), followed by thermolysis (benzene, 60°C), furnished the hoped-for 7-PCA **6** in essentially quantitative yield.

It is similarly of interest to develop monocyclic β-lactam nocardicin analogues, since nocardicin A,

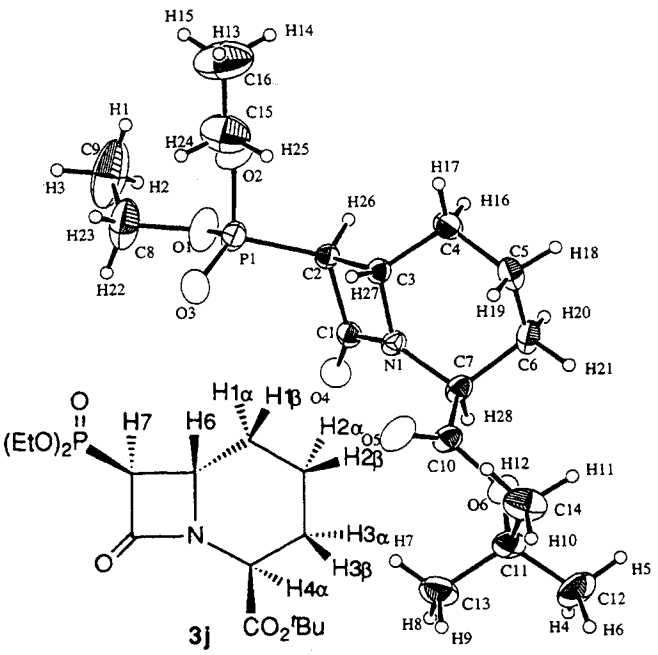
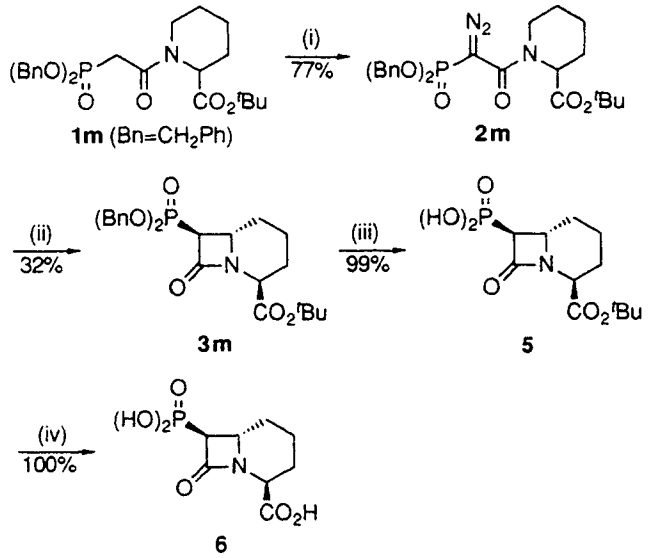


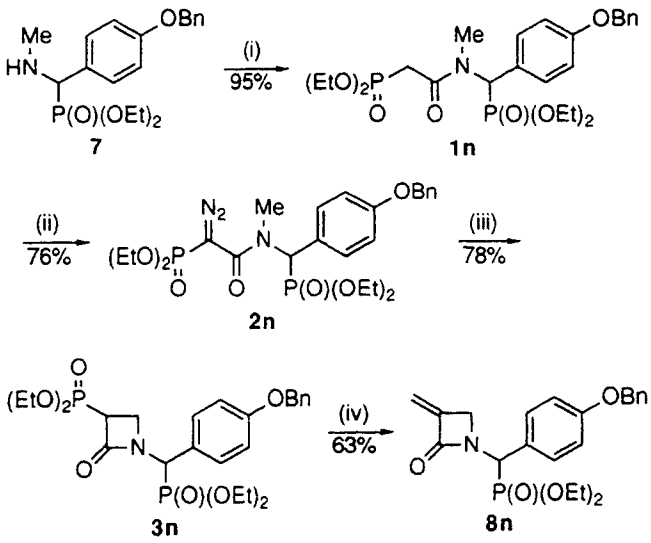
FIGURE 1 Crystal structure of **3J** (ORTEP, ellipsoids at the 20% probability level).

showing antibiotic activity against some Gram-negative species and against Pseudomonas [13], has the monocyclic β-lactam skeleton. We therefore attempted to synthesize the β-lactam containing the phosphonic acid side chain with an aromatic ring, 1 [4'-benzyloxyphenyl(diethylphosphono)methyl]-3-(diethylphosphono)azetidin-2-one (**3n**). As shown



Reagents and Conditions: (i) NaH, TsN_3, THF, r.t. (ii) $Rh_2(OAc)_4$, $ClCH_2CH_2Cl$, reflux. (iii) H_2, Pd/C, EtOH, r.t. (iv) benzene, 60 °C

SCHEME 2



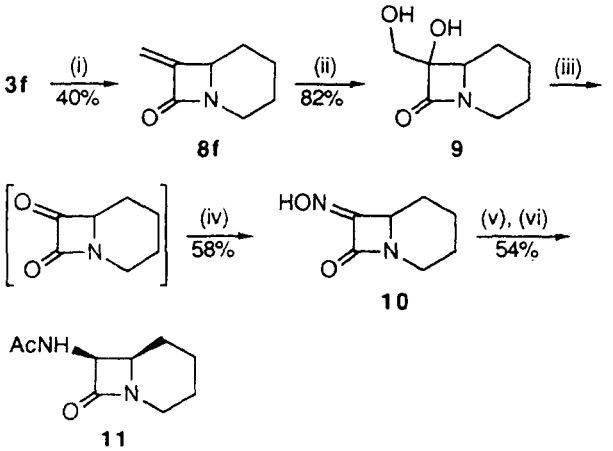
Reagents and Conditions: (i) Im_2CO, $(EtO)_2P(O)CH_2CO_2H$, CH_2Cl2, 0 °C → r.t.(ii) NaH, $TosN_3$, THF, r.t. (iii) $Rh_2(OAc)_4$, $ClCH_2CH_2Cl$, reflux. (iv) NaH, $(HCHO)_n$, THF, r.t.

SCHEME 3

in Scheme 3, the key starting phosphonoacetamide **1n** was prepared by condensation of (diethylphosphono)acetic acid with [4-benzyloxyphenyl-(diethylphosphono)methyl]methylamine (**7**), which was derived from 4-benzyloxybenzaldehyde, methylamine, and diethyl phosphite. Treatment of the diazo amide **2n**, prepared from the phosphonoacetamide **1n** by a similar diazo transfer, with $Rh_2(OAc)_4$, led to the expected β-lactam **3n** in 78% yield. The Wittig–Horner reaction of **3n** with paraformaldehyde afforded the 3-methylene-β-lactam **8n** in 63% yield [14], which would be a useful synthetic equivalent for the corresponding 3-amino-β-lactam [15].

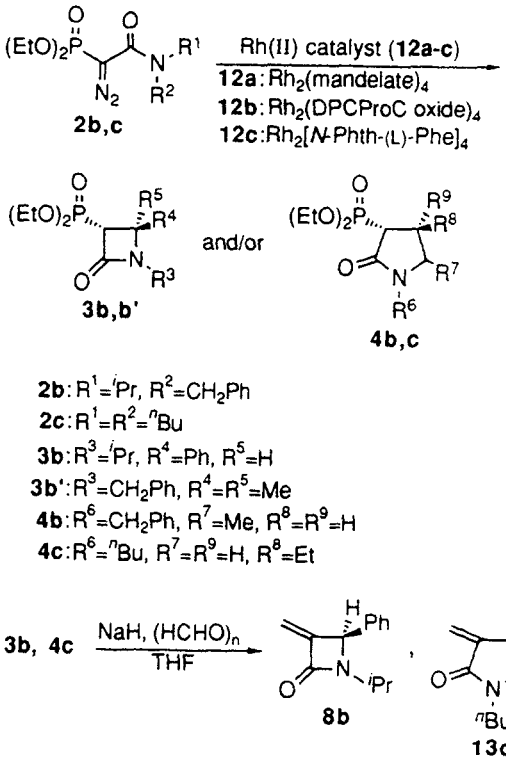
We also studied synthetic utilization of the 3-phosphono substituent of the lactam ring in **3f**. Treatment of **3f** with paraformaldehyde afforded the expected α-methylene-β-lactam **8f** in a moderate yield. Oxidation of **8f** with osmium tetraoxide/*N*-methylmorpholine *N*-oxide was carried out to afford the diol **9** in 82% yield. The oxidative cleavage of **9** with sodium metaperiodate and subsequent treatment with hydroxylamine readily produced the α-hydroxyimino-β-lactam **10** (58%). Treatment of **10** with acetic anhydride containing sodium acetate in ethyl acetate, followed by hydrogenation, gave 7-acetylaminocarbacepham **11** (54%), of which the stereochemical assignment was established as the *cis* isomer on the basis of the coupling constant of 4.5 Hz for hydrogens of the β-lactam ring in its ^1H NMR spectrum (Scheme 4).

Having succeeded in the simple synthesis of α-phosphonolactams as mentioned earlier, we next attempted to apply this synthetic method to the



Reagents and Conditions: (i) NaH, $(HCHO)_n$, THF, r.t. (ii) OsO_4 (0.5 mol%), N-methylpiperidine N-oxide, Me_2CO-H_2O, r.t. (iii) $NaIO_4$, CH_2Cl_2-H_2O, 0 °C. (iv) NH_2OH•HCl, pyridine, CH_2Cl_2, r.t. (v) Ac_2O, AcONa, EtOAc, r.t. (vi) H_2, PtO_2, EtOAc, r.t.

SCHEME 4



SCHEME 5

enantioselective synthesis [16,17] of α-phosphonolactams. The chiral rhodium(II) carboxylates **12a–c** to be used as rhodium catalysts were prepared according to reported procedures using $RhCl_3$ and optically active mandelic acid [18], DPCProC oxide [19], and *N*-phthaloyl-(L)-phenylalanine [*N*-Phth-(L)-Phe] [20], respectively. A similar decomposition of **2b,c** with chiral Rh(II) carboxylates prepared in this manner afforded the desired optically active lactams **3b** or **4c** (Scheme 5 and Table 2). The enantiomeric excess of the asymmetric C–H insertion product **3b** or **4c** was determined by high-performance liquid chromatography (HPLC) analysis of the corresponding α-methylene-β-lactam **8b** or γ-lactam **13c**, derived from **3b** or **4c** and paraformaldehyde.

The insertion reaction of **2b** with rhodium(II) catalyst **12a** produced the optically active **3b** in 24% ee (32% yield), while the use of **12b** or **12c** instead of **12a** as a catalyst decreased the optical yield of **3b** (11 or 6% ee) (entries 1–4 in Table 2). On the other hand, little difference in chiral induction among the catalysts **12a–c** in the reaction with **2c** was observed (entries 5–8).

In conclusion, *N,N*-dialkyl-α-diazo-α-(dialkylphosphono)acetamides undergo an intramolecular rhodium(II)-catalyzed C–H insertion reaction to give α-phosphono mono and bicyclic β- and/or γ-lactams. Applications of this synthetic method have been successfully achieved in some cases to give 7-phosphonocarbacepham and a phosphorylated nocardicin segment. Using chiral rhodium(II) catalysts in this insertion of α-diazo phosphonoacetamides resulted in the formation of optically active α-phosphono-β- and γ-lactams.

EXPERIMENTAL

General

The ^1H and ^{13}C NMR spectra were obtained in $CDCl_3$ on a JEOL JNM-FX-60, or a JEOL JNM-α500 spectrometer, operating ^1H NMR at 60 or 500 MHz, and ^{13}C NMR at 15.0 or 125.65 MHz, with Me_4Si as an internal standard. Two-dimensional proton-proton and proton-carbon correlations were used when necessary, to assign ^1H and ^{13}C NMR spectra. IR spectra were recorded with a Shimadzu IR-408 instrument. High-resolution mass spectra (HRMS) and fast atom bombardment (FAB) mass spectra were recorded on a JEOL DX-300 mass spectrometer. Analytical HPLC was carried out with a Shimadzu HPLC system equipped with a chiral column, Daicel Chemical Industries, Ltd., CHIRALPAK AS Packed Column (4.6 × 250 mm) and E. Merck, ChiraDex Packed Column (4 × 244 mm). Optical rotations were measured with a Horiba SEPA-200 polarimeter. X-Ray analysis was made on a Rigaku AFC7R diffractometer with graphite monochromated Mo K_α radiation (0.71069 Å). Melting points were measured in open capillary tubes and are uncorrected.

Materials

p-Toluenesulfonyl azide was prepared according to the established procedure [10]. (Diethylphos-

TABLE 2 Enantioselective C–H Insertion of α-Diazo-α-(dialkylphosphono)acetamides **2**[a] and Conversion to α-Methylene Lactams **8** or **13**

	Substrate	*Rh(II) Catalyst*			*α-Methylene Lactams* **8** *or* **13**		
Entry	**2**	**12**	*Time (h)*	**3** *and/or* **4** *(Yield %)*[b]	*(Yield %)*[b]	$[\alpha]_D^{24}$ *(c, $CHCl_3$)*	*%ee*[c]
1	**2b**	(−)-**12a**	9	**3b** (32) + **3b′** (43)	(+)-**8b** (67)	3.6 (1.3)	24
2	**2b**	(+)-**12a**	8	**3b** (28) + **3b′** (40)	(−)-**8b** (64)	−3.4 (1.9)	19
3	**2b**	(+)-**12b**	4	**3b** (31) + **3b′** (26)	(−)-**8b** (75)	−2.1 (1.6)	11
4	**2b**	(−)-**12c**	6	**3b** (45) + **3b′** (25) + **4b** (22)	(−)-**8b** (66)	−0.9 (1.7)	6
5	**2c**	(+)-**12a**	6	**4c** (79)	(−)-**13c** (72)	−11.8 (3.2)	25
6	**2c**	(+)-**12a**	17	**4c** (91)[d]	(−)-**13c** (69)	−13.9 (2.1)	29[e]
7	**2c**	(+)-**12b**	12	**4c** (92)	(+)-**13c** (63)	12.1 (1.7)	26[e]
8	**2c**	(−)-**12c**	4	**4c** (88)[f]	(+)-**13c** (68)	13.0 (1.5)	28[e]

[a]All reactions of 3 mmol of **2** in $ClCH_2CH_2Cl$ were carried out in the presence of 0.017 mmol of Rh(II) catalyst at reflux unless otherwise noted.
[b]Isolated yield.
[c]Determined by HPLC analysis with CHIRALPAK AS (Daicel) or ChiraDex (Merck).
[d]The reaction was carried out in the presence of 0.054 mmol of catalyst at room temperature in CH_2Cl_2.
[e]Determined by comparison of the optical rotation value in entry 5.
[f]The reaction was carried out in the presence of 0.03 mmol of catalyst at room temperature in CH_2Cl_2.

phono)acetic acid was obtained by alkali-hydrolysis of triethyl phosphonoacetate.

Preparation of [4-Benzyloxyphenyl(diethylphosphono)methyl]methylamine (7)

To a suspension of 4-benzyloxybenzaldehyde (4.45 g, 20.1 mmol) in 95% ethanol (5 mL) was added methylamine (40 wt% aqueous solution, 2.35 mL, 27.3 mmol). After the mixture became clear, benzene (70 mL) was added. Water was removed by azeotropic distillation for 1 hour, and benzene was distilled off. Diethyl phosphite (2.97 mL, 23.1 mmol) was added to the residual mixture and the mixture was stirred for 1 hour at 100°C. The mixture was allowed to stand overnight at room temperature, and the solid material was filtered off. The crude product was recrystallized from benzene-hexane mixed solvent to give **7** as colorless crystal (6.67 g, 88%). **7**: R_f = 0.38 (AcOEt:$CHCl_3$ = 2:1); mp 76.0–78.0°C; IR (KBr) 1247 cm^{-1}; ^1H NMR (60 MHz) δ 1.16 (t, J = 7.0 Hz, 3H, CH_3), 1.27 (t, J = 7.0 Hz, 3H, CH_3), 1.89 (br, 1H, NH), 2.32 (d, J = 0.7 Hz, 3H, CH_3), 3.50–4.30 (m, 5H, OCH_2 and PCH), 5.05 (s, 2H, OCH_2Ph), 6.70–7.50 (m, 9H, aromatic H). Anal. calcd for $C_{19}H_{26}NO_4P$: C, 62.80; H, 7.21; N, 3.85. Found: C, 62.73; H, 7.28; N, 3.49.

General Procedure for the Synthesis of α-(Dialkylphosphono)acetamides **1a–n**: *Method A*

To a suspension of 2-chloro-1-methylpyridinium iodide (8.43 g, 33.0 mmol) and (diethylphosphono)acetic acid (5.88 g, 30.0 mmol) in CH_2Cl_2 (50 mL) was added a solution of a given secondary amine (36.0 mmol) and triethylamine (9.2 mL, 66.0 mmol) in CH_2Cl_2 (20 mL) at room temperature. After being stirred overnight, the reaction mixture was washed with dilute HCl aq. and H_2O. Solvent was removed *in vacuo*, and the residue was chromatographed on silica gel to give the appropriate α-(diethylphosphono)acetamide. Further purification of α-(diethylphosphono)acetamides was carried out by bulb-to-bulb distillation *in vacuo*.

Method B

To a suspension of *N,N′*-carbonyldiimidazole (1.00 g, 6.17 mmol) in THF (7 mL) was added dropwise (diethylphosphono)acetic acid (1.21 g, 6.17 mmol) at 0°C. After the mixture was stirred for 1 hour at this temperature, a solution of a given secondary amine (5.61 mmol) in THF (10 mL) was added to the mixture. After being stirred for 24 hours at room temperature, the reaction mixture was treated with 10% citric acid aqueous solution. The mixture was extracted with AcOEt, washed with 10% citric acid solution, brine, saturated sodium bicarbonate solution, and brine, then dried over Na_2SO_4, and concentrated. The column chromatography of the residue on silica gel gave the appropriate α-(diethylphosphono)acetamide.

Method C

To a solution of dialkyl phosphite (11.0 mmol) and sodium hydride (60% dispersion in mineral oil, 0.44 g, 11.0 mmol) in THF (20 mL) was added a solution of a given α-chloroacetamide (10.0 mmol) in THF (10 mL) at 0°C. After being stirred overnight at room temperature, the mixture was extracted with AcOEt or CH_2Cl_2 and washed with H_2O. After evaporation of the solvent *in vacuo*, the residue was

chromatographed on silica gel to give the appropriate α-(dialkylphosphono)acetamide.

N,N-Diisopropyl-α-(diethylphosphono)acetamide (**1a**)

Yield 100% (Method A); R_f = 0.43 (AcOEt:$CHCl_3$ = 1:2); bp 80°C/0.6 mmHg; IR (neat) 1640, 1025, 965 cm^{-1}; ^1H NMR (60 MHz) δ 1.22 (d, J = 6.6 Hz, 12H, CH_3), 1.33 (t, J = 7.0 Hz, 6H, CH_3), 3.03 (d, J = 22.1 Hz, 2H, PCH_2), 3.30–3.70 (m, 2H, NCH), 4.17 (dq, J = 7.0 and 7.9 Hz, 4H, OCH_2).

N-Benzyl-N-isopropyl-α-(diethylphosphono)acetamide (**1b**)

Yield 91% (Method A); R_f = 0.58 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1680, 1020, 960 cm^{-1}; ^1H NMR (500 MHz) δ 1.11 (d, J = 6.7 H, 3H, CH_3), 1.17 (d, 6.6 Hz, 3H, CH_3), 1.32 (t, J = 7.0 Hz, 3H, CH_3), 1.34 (t, J = 7.2 Hz, 3H, CH_3), 2.90 (d, J = 22.0 Hz, 1H, PCH_2), 3.20 (d, J = 22.3 Hz, 1H, PCH_2), 4.10–4.24 (m, 4H, OCH_2), 4.36 (quint, J = 6.4 Hz, 0.5H, NCH), 4.55 (s, 1H, CH_2Ph), 4.64 (s, 1H, CH_2Ph), 4.85 (quint, J = 6.7 Hz, 0.5H, NCH), 7.15–7.38 (m, 5H, phenyl H).

N,N-Di-n-butyl-α-(diethylphosphono)acetamide (**1c**)

Yield 90% (Method A); R_f = 0.54 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1680, 1020, 960 cm^{-1}; ^1H NMR (60 MHz) δ 0.60–1.90 (m, 14H, CH_2 and CH_3), 1.34 (t, J = 7.0 Hz, 3H, CH_3), 1.34 (t, J = 7.0 Hz, 3H, CH_3), 3.02 (d, J = 22.1 Hz, 2H, PCH_2), 3.00–3.50 (m, 4H, NCH_2), 3.80–4.50 (m, 4H, OCH_2).

N-Isobutyl-N-methyl-α-(diethylphosphono)acetamide (**1d**)

Yield 86% (Method A); R_f = 0.40 (AcOEt:$CHCl_3$:MeOH = 10:5:1); IR (neat) 1680, 1020, 960 cm^{-1}; ^1H NMR (500 MHz) δ 0.90 (d, J = 6.7 Hz, 3H, CH_3), 0.94 (d, J = 6.7 Hz, 3H, CH_3), 1.34 (t, J = 7.0 Hz, 6H, CH_3), 1.94–1.99 (m, 1H, CH), 3.06 (dd, J = 3.7 and 22,0 Hz, 2H, PCH_2), 3.11 (s, 3H, NCH_3), 3.22 (dd, J = 7.6 and 9.8 Hz, 2H, NCH_2), 4.13–4.21 (m, 4H, OCH_2).

N,N-Tetramethylene-α-(diethylphosphono)acetamide (**1e**)

Yield 40% (Method A); R_f = 0.42 (AcOEt:$CHCl_3$:MeOH = 10:5:1); bp 135°C/1 mmHg; IR (neat) 1620, 1025, 965 cm^{-1}; ^1H NMR (500 MHz) δ 1.34 (t, J = 7.0 Hz, 6H, CH_3), 1.88 (quint, J = 6.8 Hz, 2H, CH_2), 1.97 (quint, J = 6.8 Hz, 2H, CH_2), 2.99 (d, J = 22.0 Hz, 2H, PCH_2), 3.49 (t, J = 6.7 Hz, 2H, NCH_2), 3.60 (t, J = 7.0 Hz, 2H, NCH_2), 4.14–4.23 (m, 4H, OCH_2).

Piperidino-α-(diethylphosphono)acetamide (**1f**)

Yield 99% (Method C); R_f = 0.38 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1640, 1025, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.34 (t, J = 6.9 Hz, 6H, CH_3), 1.64 (br, 6H, CH_2), 3.07 (d, J = 22.0 Hz, 2H, PCH_2), 3.32–3.74 (m, 4H, NCH_2), 4.17 (dq, J = 7.1 and 8.1 Hz, 4H, OCH_2).

2,6-Dimethylpiperidino-α-(diethylphosphono)acetamide (**1g**)

Yield 85% (Method A); R_f = 0.47 (AcOEt:$CHCl_3$ = 1:2); bp 150°C/4 mmHg; IR (neat) 1625, 1020, 960 cm^{-1}; ^1H NMR (500 MHz) δ 1.21 (d, J = 5.5 Hz, 3H, CH_3), 1.29 (d, J = 2.7 Hz, 3H, CH_3), 1.34 (t, J = 6.7 Hz, 6H, CH_3), 1.51 (dq, J = 3.5 and 12.4 Hz, 1H, CH_2), 1.60 (br s, 3H, CH_2), 1.71–1.83 (m, 2H, CH_2), 2.95 (dd, J = 22.6 and 14.7 Hz, 1H, PCH_2), 3.18 (dd, J = 20.0 and 13.9 Hz, 1H, PCH_2), 4.18 (quint, J = 7.3 Hz, 4H, OCH_2), 4.26 (br s, 1H, NCH), 4.77 (br s, 1H, NCH).

N,N-Hexamethylene-α-(diethylphosphono)acetamide (**1h**)

Yield 73% (Method A); R_f = 0.40 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1640, 1030, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.34 (t, J = 7.0 Hz, 6H, CH_3), 1.62 (br, 8H, CH_2), 3.05 (d, J = 22.1 Hz, 2H, PCH_2), 3.30–3.70 (m, 4H, NCH_2), 4.18 (dq, J = 7.0 and 7.9 Hz, 4H, OCH_2).

N-[α-(Diethylphosphono)acetyl]-2-methylperhydro-1,3-oxazine (**1i**)

Yield 90% (Method B); R_f = 0.42 (AcOEt:$CHCl_3$:MeOH = 10:5:1); bp 135°C/1 mmHg; IR (neat) 1640, 1020, 975 cm^{-1}; ^1H NMR (60 MHz) δ 1.34 (t, J = 7.0 Hz, 6H, CH_3), 1.55 (d, J = 6.3 Hz, 3H, CH_3), 1.30–1.90 (m, 2H, CH_2), 3.06 (d, J = 22.0 Hz, 2H, PCH_2), 3.62–4.44 (m, 8H, OCH_2 and NCH_2), 5.68 (q, J = 6.2 Hz, 1H, NCH).

tert-Butyl N-[α-(diethylphosphono)acetyl]-piperidine-2-carboxylate (**1j**)

Yield 90% (Method A); R_f = 0.50 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1735, 1650, 1020, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.20–1.90 (br, 6H, CH_2), 1.34 (t, J = 7.0 Hz, 6H, CH_3), 1.46 (s, 9H, *t*-Bu), 3.00–3.40 (br, 1H, NCH_2), 3.11 (dd, J = 3.0 and 22.0 Hz, 2H, PCH_2), 4.18 (dq, J = 7.0 and 8.0 Hz, 4H, OCH_2), 4.70 (br, 1H, NCH_2), 5.26 (br, 1H, NCH).

N-[α-(Diethylphosphono)acetyl]-2-methylindoline (**1k**)

Yield 90% (Method A); R_f = 0.50 (AcOEt:$CHCl_3$ = 1:1); bp 160°C/0.6 mmHg; IR (neat) 1655, 1600, 1025, 970 cm^{-1}; ^1H NMR (500 MHz) δ 1.31 (d, J = 6.4 Hz, 3H, CH_3), 1.32 (t, J = 7.3 Hz, 3H, CH_3), 1.36

(t, J = 7.0 Hz, 3H, CH_3), 2.66 (d, J = 15.6 Hz, 1H, CH_2), 3.10 (dd, J = 14.5 and 23.0 Hz, 1H, PCH_2), 3.25 (dd, J = 14.5 and 21.4 Hz, 1H, PCH_2), 3.44 (dd, J = 8.7 and 15.6 Hz, 1H, CH_2), 4.13–4.28 (m, 4H, OCH_2), 4.75 (quint, J = 6.9 Hz, 1H, NCH), 7.05 (t, J = 7.5 Hz, 1H, aromatic H), 7.18–7.22 (m, 2H, aromatic H), 8.15 (d, J = 8.2 Hz, 1H, aromatic H).

tert-Butyl N-[α-(dibenzylphosphono)acetyl]-piperidine-2-carboxylate (**1m**)

Yield 62% (Method C); R_f = 0.50 (AcOEt:$CHCl_3$ = 1:1); IR (neat) 1735, 1645, 1020 cm^{-1}; ^1H NMR (500 MHz) δ 1.25–1.40 (m, 2H, CH_2), 1.44 (s, 9H, *t*-Bu), 1.46–1.66 (m, 3H, CH_2), 2.19 (d, J = 13.7 Hz, 1H, CH_2), 2.95–3.33 (m, 3H, NCH_2 and PCH_2), 3.79 (d, J = 12.2 Hz, 1H, NCH_2), 5.03–5.12 (m, 4H, OCH_2), 5.25 (d, J = 4.9 Hz, 1H, NCH), 7.31–7.37 (m, 10H, phenyl H).

N-[4'-Benzyloxyphenyl(diethylphosphono)methyl]-N-methyl-α-(diethylphosphono) acetamide (**1n**)

Yield 90% (Method B); R_f = 0.38 (AcOEt:$CHCl_3$:MeOH = 10:5:1); IR (neat) 1645, 1025, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.17 (t, J = 7.0 Hz, 3H, CH_3), 1.27 (t, J = 7.0 Hz, 3H, CH_3), 1.33 (t, J = 7.0 Hz, 6H, CH_3), 3.09 (d, J = 21.5 Hz, 2H, PCH_2), 3.14 (s, 3H, NCH_3), 3.70–4.40 (m, 8H, OCH_2), 5.05 (s, 2H, $PhCH_2$), 6.35 (d, J = 22.7 Hz, 1H, CH), 6.94 (d, J = 8.8 Hz, 2H, aromatic H), 7.37 (s, 5H, phenyl H), 7.55 (d, J = 8.8 Hz, 2H, aromatic H).

Preparation of α-Diazo-α-(dialkylphosphono)acetamides **2a–n**: *General Procedure*

To a solution of a given α-(dialkylphosphono)-acetamide (10.0 mmol) and sodium hydride (60% dispersion in mineral oil, 0.44 g, 11.0 mmol) in THF (40 mL) was added a solution of *p*-toluenesulfonyl azide (2.37 g, 12.0 mmol) in THF (10 mL) at room temperature. After being stirred overnight at room temperature, the reaction mixture was treated with 2N HCl aq. The mixture was extracted with AcOEt or CH_2Cl_2, washed with H_2O, and dried over Na_2SO_4. The solvent was evaporated *in vacuo*, and the residue was chromatographed on silica gel to give the appropriate α-diazo-α-(dialkylphosphono)acetamide **2a–n**.

N,N-Diisopropyl-α-diazo-α-(diethylphosphono)acetamide (**2a**)

Yield 90%; R_f = 0.49 (AcOEt:hexane = 1:1); IR (neat) 2100, 1620, 1020, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.32 (d, J = 6.6 Hz, 12H, CH_3), 1.37 (t, J = 6.9 Hz, 6H, CH_3), 3.79 (quint, J = 6.6 Hz, 2H, NCH), 3.92–4.44 (m, 4H, OCH_2). Anal. calcd for $C_{12}H_{24}N_3O_4P$: C, 47.21; H, 7.92; N, 13.76. Found: C, 46.93; H, 8.13; N, 13.35.

N-Benzyl-N-isopropyl-α-diazo-α-(diethylphosphono)acetamide (**2b**)

Yield 93%; R_f = 0.58 (AcOEt:$CHCl_3$ = 1:1); IR (neat) 2120, 1620, 1010, 965 cm^{-1}; ^1H NMR (60 MHz) δ 1.20 (d, J = 6.7 Hz, 6H, CH_3), 1.32 (t, J = 7.0 Hz, 6H, CH_3), 3.90–4.42 (m, 5H, OCH_2 and NCH), 4.51 (s, 2H, NCH_2Ph), 7.27 (s, 5H, phenyl H). Anal. calcd for $C_{16}H_{24}N_3O_4P$: C, 54.39; H, 6.85; N, 11.89. Found: C, 54.12; H, 6.91; N, 11.64.

N,N-Di-n-butyl-α-diazo-α-(diethylphosphono)acetamide (**2c**)

Yield 77%; R_f = 0.40 (AcOEt:hexane = 2:1); IR (neat) 1680, 1020, 960 cm^{-1}; ^1H NMR (60 MHz) δ 0.60–1.90 (m, 14H, CH_2 and CH_3), 1.36 (t, J = 7.0 Hz, 3H, CH_3), 1.37 (t, J = 7.0 Hz, 3H, CH_3), 3.00–3.55 (m, 4H, NCH_2), 3.80–4.50 (m, 4H, OCH_2); HRMS (*m/e*) calcd for $C_{14}H_{29}N_3O_4P$: 334.1896. Found: 334.1869 (M^+ + 1).

N-Isobutyl-N-methyl-α-diazo-α-(diethylphosphono)acetamide (**2d**)

Yield 68%; R_f = 0.58 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 2125, 1625, 1020, 970 cm^{-1}; ^1H NMR (60 MHz) δ 0.90 (d, J = 6.4 Hz, 6H, CH_3), 1.36 (t, J = 7.0 Hz, 3H, CH_3), 1.37 (t, J = 7.1 Hz, 3H, CH_3), 1.70–2.24 (m, 1H, CH), 3.02 (s, 3H, NCH_3), 3.22 (d, J = 7.5 Hz, 2H, NCH_2), 4.21 (dq, J = 7.0 and 8.3 Hz, 4H, OCH_2). Anal. calcd for $C_{11}H_{22}N_3O_4P$: C, 45.36; H, 7.61; N, 14.43. Found: C, 45.18; H, 7.65; N, 14.29.

N,N-Tetramethylene-α-diazo-α-(diethylphosphono)acetamide (**2e**)

Yield 52%; R_f = 0.50 (AcOEt:$CHCl_3$:MeOH = 10:5:1); IR (neat) 2130, 1610, 1020, 975 cm^{-1}; ^1H NMR (500 MHz) δ 1.37 (t, J = 7.0 Hz, 6H, CH_3), 1.90–1.94 (m, 4H, CH_2), 3.50–3.53 (m, 4H, NCH_2), 4.18–4.27 (m, 4H, OCH_2).

Piperidino-α-diazo-α-(diethylphosphono)acetamide (**2f**)

Yield 67%; R_f = 0.37 (AcOEt:hexane = 2:1); IR (neat) 2150, 1625, 1020, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.36 (t, J = 7.0 Hz, 3H, CH_3), 1.37 (t, J = 7.1 Hz, 3H, CH_3), 1.61 (br, 6H, CH_2), 3.48 (br, 4H, NCH_2), 4.20 (dq, J = 7.0 and 8.3 Hz, 4H, OCH_2). Anal. calcd for $C_{11}H_{20}N_3O_4P$: C, 45.67; H, 6.97; N, 14.53. Found: C, 45.53; H, 6.86; N, 14.35%.

2,6-Dimethylpiperidino-α-diazo-α-(diethylphosphono)acetamide (**2g**)

Yield 52%; R_f = 0.46 (AcOEt:hexane = 1:1); IR (neat) 2100, 1610, 1015, 970 cm^{-1}; ^1H NMR (60 MHz)

δ 1.29 (d, J = 7.0 Hz, 6H, CH_3), 1.35 (t, J = 7.0 Hz, 3H, CH_3), 1.37 (t, J = 6.9 Hz, 3H, CH_3), 1.50–1.74 (m, 6H, CH_2), 3.82–4.60 (m, 6H, OCH_2 and NCH). Anal. calcd for $C_{13}H_{24}N_3O_4P$: C, 49.21; H, 7.62; N, 13.24. Found: C, 49.13; H, 7.74; N, 12.87.

N,N-Hexamethylene-α-diazo-α-(diethylphosphono)acetamide (**2h**)

Yield 40%; R_f = 0.43 (AcOEt:hexane = 1:1); IR (neat) 2130, 1620, 1020, 975 cm^{-1}; ^1H NMR (60 MHz) δ 1.35 (t, J = 7.0 Hz, 3H, CH_3), 1.37 (t, J = 7.0 Hz, 3H, CH_3), 1.63 (br, 8H, CH_2) 3.30–3.64 (m, 4H, NCH_2), 4.21 (dq, J = 7.0 and 8.2 Hz, 4H, OCH_2). Anal. calcd for $C_{12}H_{22}N_3O_4P$: C, 47.52; H, 7.31; N, 13.85. Found: C, 47.42; H, 7.24; N, 13.66.

N-[α-Diazo-α-(diethylphosphono)acetyl]-2-methylperhydro-1,3-oxazine (**2i**)

Yield 87%; R_f = 0.40 (AcOEt:hexane = 1:1); IR (neat) 2150, 1630, 1020, 975 cm^{-1}; ^1H NMR (60 MHz) δ 1.37 (t, J = 7.3 Hz, 6H, CH_3), 1.55 (d, J = 6.3 Hz, 3H, CH_3), 1.30–1.90 (m, 2H, CH_2), 3.00–3.56 (m, 2H, NCH_2), 3.62–4.44 (m, 8H, OCH_2), 5.68 (q, J = 6.2 Hz, 1H, NCH). Anal. calcd for $C_{11}H_{20}N_3O_5P$: C, 43.28; H, 6.60; N, 13.76. Found: C, 43.21; H, 6.69; N, 13.86.

tert-Butyl N-[α-diazo-α-(diethylphosphono)acetyl]piperidine-2-carboxylate (**2j**)

Yield 76%; R_f = 0.52 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 2130, 1740, 1630, 1015, 970 cm^{-1}; ^1H NMR (500 MHz) δ 1.29–1.43 (m, 1H, H4), 1.37 (t, J = 7.1 Hz, 6H, CH_3), 1.43–1.53 (m, 1H, H5), 1.47 (s, 9H, t-Bu), 1.59–1.77 (m, 3H, H5, H4 and H3), 2.24 (ddd, J = 1.9, 1.9, and 13.7 Hz, 1H, H3), 3.19 (br, 1H, H6), 3.94 (br d, J = 10.8 Hz, 1H, H6), 4.14–4.28 (m, 4H, OCH_2), 4.91 (br, 1H, H2). Anal. calcd for $C_{16}H_{28}N_3O_6P$: C, 49.35; H, 7.25; N, 10.79. Found: C, 49.03; H, 7.39; N, 10.76.

N-[α-Diazo-α-(diethylphosphono)acetyl]-2-methylindoline (**2k**)

Yield 83%; R_f = 0.60 (AcOEt:$CHCl_3$ = 1:2); IR (neat) 2120, 1620, 1590, 1020, 970 cm^{-1}; ^1H NMR (500 MHz) δ 1.35 (d, J = 6.4 Hz, 3H, CH_3), 1.38 (t, J = 7.1 Hz, 3H, CH_3), 1.39 (t, J = 7.0 Hz, 3H, CH_3), 2.64 (dd, J = 1.9 and 15.6 Hz, 1H, CH_2), 3.35 (dd, J = 8.6 and 15.6 Hz, 1H, CH_2), 4.20–4.35 (m, 4H, OCH_2), 4.73 (ddq, J = 2.2, 8.6, and 6.4 Hz, 1H, NCH), 7.03 (dd, J = 7.4 and 7.4 Hz, 1H, aromatic H), 7.21 (d, J = 7.5 Hz, 2H, aromatic H), 7.62 (d, J = 7.9 Hz, 1H, aromatic H); HRMS (m/e) calcd for $C_{15}H_{20}N_3O_4P$: 337.1192, found: 337.1209.

tert-Butyl N-[α-diazo-α-(dibenzylphosphono)acetyl]piperidine-2-carboxylate (**2m**)

Yield 77%; R_f = 0.5 (AcOEt:hexane = 1:1); IR (neat) 2130, 1740, 1630, 1000 cm^{-1}; ^1H NMR (500 MHz) δ 1.25–1.39 (m, 2H, H4 and H5), 1.44 (s, 9H, t-Bu), 1.46–1.60 (m, 2H, H4 and H3), 1.65 (dd, J = 2.4 and 9.0 Hz, 1H, H4), 2.16 (d, J = 13.7 Hz, 1H, H3), 3.11 (br, 1H, H6), 3.81 (br, 1H, H6), 4.85 (br, 1H, H2), 5.13 (d, J = 8.8 Hz, 4H, OCH_2), 7.25–7.40 (m, 10H, phenyl H). Anal. calcd for $C_{26}H_{32}N_3O_6P$: C, 60.82; H, 6.28; N, 8.18. Found: C, 60.70; H, 6.53; N, 7.93.

N-[4'-Benzyloxyphenyl(diethylphosphono)methyl]-N-methyl-α-diazo-α-(diethylphosphono)acetamide (**2n**)

Yield 76%; R_f = 0.40 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 2120, 1615, 1020, 970 cm^{-1}; ^1H NMR (500 MHz) δ 1.17 (t, J = 7.0 Hz, 3H, CH_3), 1.32 (t, J = 7.0 Hz, 3H, CH_3), 1.33 (t, J = 7.0 Hz, 6H, CH_3), 3.09 (s, 3H, NCH_3), 3.90–4.30 (m, 8H, OCH_2), 5.06 (s, 2H, $PhCH_2$), 6.13 (d, J = 22.9 Hz, 1H, CH), 6.96 (d, J = 8.9 Hz, 2H, aromatic H), 7.30–7.45 (m, 5H, phenyl H), 7.57 (d, J = 8.9 Hz, 2H, aromatic H). Anal. calcd for $C_{25}H_{35}N_3O_8P_2$: C, 52.91; H, 6.22; N, 7.40. Found: C, 52.60; H, 6.26; N, 7.20.

Rh(II)-Catalyzed Decomposition of α-Diazo-α-(dialkylphosphono)acetamides **2a–k**

General Procedure. A solution of a given α-diazo-α-(dialkylphosphono)acetamides **2a–k** (1 mmol) and rhodium (II) catalyst (0.005–0.025 mmol) in organic solvents was heated. Then, the solvent was evaporated *in vacuo* and thin-layer chromatography (TLC) of the residue gave the appropriate lactam(s). Reaction conditions were summarized in Table 1. The products had the following properties.

1-Isopropyl-3-(diethylphosphono)-4,4-dimethylazetidin-2-one (**3a**)

R_f = 0.48 (AcOEt:$CHCl_3$ = 1:1); IR (neat) 1740, 1020, 960 cm^{-1}; ^1H NMR (60 MHz) δ 1.34 (d, J = 6.9 Hz, 6H, CH_3), 1.35 (t, J = 7.0 Hz, 6H, CH_3), 1.49 (s, 3H, CH_3), 1.62 (s, 3H, CH_3), 3.26 (d, J = 17.1 Hz, 1H, PCH), 3.54 (quint, J = 6.7 Hz, 1H, NCH), 3.90–4.50 (m, 4H, OCH_2). Anal. calcd for $C_{12}H_{24}NO_4P$: C, 51.98; H, 8.72; N, 5.05. Found: C, 52.13; H, 8.92; N, 4.61.

1-Isopropyl-3-(diethylphosphono)-4-phenylazetidin-2-one (**3b**)

R_f = 0.45 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1760, 1025, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.06 (d, J = 6.7 Hz, 3H, CH_3), 1.31 (d, J = 6.7 Hz, 3H, CH_3), 1.32

(t, J = 7.0 Hz, 3H, CH_3), 1.36 (t, J = 7.0 Hz, 3H, CH_3), 3.37 (dd, J = 2.6 and 14.6 Hz, 1H, PCH), 3.78 (quint, J = 6.7 Hz, 1H, NCH), 3.90–4.50 (m, 4H, OCH_2), 4.76 (dd, J = 2, 6 and 8.9 Hz, 1H, PhCH), 7.38 (s, 5H, phenyl H). Anal. calcd for $C_{16}H_{24}NO_4P$: C, 59.07; H, 7.44; N, 4.31. Found: C, 59.00; H, 7.68; N, 4.11.

1-Benzyl-3-(diethylphosphono)-4,4-dimethylazetidin-2-one (**3b'**)

R_f = 0.50 (AcOEt:$CHCl_3$:eOH = 10:5:1); bp 150°C/0.25 mmHg; IR (neat) 1755, 1025, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.30 (d, J = 1.2 Hz, 3H, CH_3), 1.34 (t, J = 7.0 Hz, 6H, CH_3), 1.45 (s, 3H, CH_3), 3.36 (d, J = 17.3 Hz, 1H, PCH), 3.90–4.50 (m, 4H, OCH_2), 4.32 (s, 2H, NCH_2), 7.30 (s, 5H, phenyl H). Anal. calcd for $C_{16}H_{24}NO_4P$: C, 59.07; H, 7.44; N, 4.31. Found: C, 58.67; H, 7.47; N, 4.15.

1-n-Butyl-3-(diethylphosphono)-4-ethylpyrrolidin-2-one (**4c**)

R_f = 0.50 (AcOEt:hexane = 1:1); bp 120–125°C/0.3 mmHg; IR (neat) 1680, 1025, 970 cm^{-1}; ^1H NMR (500 MHz) δ 0.94 (t, J = 7.3 Hz, 3H, CH_3), 0.94 (t, J = 7.6 Hz, 3H, CH_3), 1.31–1.37 (m, 2H, CH_2), 1.34 (t, J = 7.0 Hz, 3H, CH_3), 1.35 (t, J = 7.0 Hz, 3H, CH_3), 1.44–1.54 (m, 3H, CH_2), 1.63 (sept, J = 7.0 Hz, 1H, CH_2), 2.54–2.60 (m, 1H, CH), 2.64 (dd, J = 4.3 and 22.3 Hz, 1H, PCH), 2.98 (ddd, J = 1.8, 3.3, and 9.5 Hz, 1H, NCH_2), 3.25 (quint, J = 7.0 Hz, 1H, NCH_2), 3.33 (d, quint, J = 1.6 and 7.1 Hz, 1H, NCH_2), 3.65 (dd, J = 7.8 and 9.6 Hz, 1H, NCH_2) 4.13–4.26 (m, 4H, OCH_2). Anal. calcd for $C_{14}H_{28}NO_4P$: C, 55.07; H, 9.24; N, 4.59. Found: C, 54.71; H, 9.07; N, 4.47.

1-Isobutyl-3-(diethylphosphono)azetidin-2-one (**3d**)

R_f = 0.50 (AcOEt:$CHCl_3$:MeOH = 10:5:1); IR (neat) 1750, 1020, 960 cm^{-1}; ^1H NMR (500 MHz) 0.94 (d, J = 6.7 Hz, 3H, CH_3), 0.96 (d, J = 7.0 Hz, 3H, CH_3), 1.35 (t, J = 7.0 Hz, 6H, CH_3), 1.89 (sept, J = 6.7 Hz, 1H, CH), 2.95 (dd, J = 6.4 and 13.7 Hz, 1H, NCH_2), 3.13 (dd, J = 7.5 and 13.9 Hz, 1H, NCH_2), 3.41–3.49 (m, 2H, CH_2), 3.62 (ddd, J = 2.9, 5.3, and 14.8 Hz, 1H, PCH), 4.15–4.30 (m, 4H, OCH_2). Anal. calcd for $C_{11}H_{22}NO_4P$: C, 50.19; H, 8.42; N, 5.32. Found: C, 49.76; H, 8.50; N, 5.21.

3-(Diethylphosphono)-4,4-dimethyl-1-methylpyrrolidin-2-one (**4d**)

R_f = 0.58 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1690, 1025, 970 cm^{-1}; ^1H NMR (60 MHz) δ 0.91 (d, J = 6.4 Hz, 3H, CH_3), 1.35 (t, J = 7.1 Hz, 6H, CH_3), 1.35 (d, J = 1.0 Hz, 3H, CH_3), 2.36–3.40 (m, 6H, CH_2, NCH_3, and PCH), 3.88–4.52 (m, 4H, OCH_2); HRMS (m/e) calcd for $C_{11}H_{22}NO_4P$: 263.1286, found: 263.1258.

7-(Diethylphosphono)-1-azabicyclo[4.2.0]octan-8-one (**3f**)

R_f = 0.50 (AcOEt:$CHCl_3$:MeOH = 10:5:1); bp 130°C/1 mmHg; IR (neat) 1745, 1015, 960 cm^{-1}; ^1H NMR (500 MHz) δ 1.28 (ddddd, J = 1.7, 3.1, 11.8, 11.8, and 12.1 Hz, 1H, H1α), 1.35 and 1.36 (t, J = 7.0 Hz, 6H, CH_3), 1.34–1.48 (m, 2H, H2β and H3α), 1.68 (dd, J = 4.3 and 12.8 Hz, 1H, H3β), 1.91 (d, J = 11.6 Hz, 1H, H2α), 2.17 (d, J = 12.2 Hz, 1H, H1β), 2.74–2.83 (m, 1H, H4β), 3.28 (ddd, 1.8, 1.8, and 15.3 Hz, 1H, H7), 3.56 (dddd, J = 2.4, 4.4, 10.0, and 10.0, 1H, H6), 3.84 (dd, J = 4.1 and 13.6 Hz, 1H, H4α), 4.10–4.30 (m, 4H, OCH_2). Anal. calcd for $C_{11}H_{20}NO_4P$: C, 50.55; H, 7.72; N, 5.36. Found: C, 50.31; H, 7.76; N, 5.32.

7-(Diethylphosphono)-2,6-dimethyl-1-azabicyclo[4.2.0]octan-8-one (**3g**)

R_f = 0.58 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1735, 1015, 960 cm^{-1}; ^1H NMR (500 MHz) δ 1.20 (d, J = 6.7 Hz, 3H, CH_3), 1.36 (t, J = 6.7 Hz, 6H, CH_3), 1.40–1.52 (m, 2H, H1α and H3α), 1.57–1.74 (m, 2H, H3β and H2β), 1.64 (s, 3H, CH_3), 1.76–1.87 (m, 1H, H2α), 2.00–2.32 (m, 1H, H1β), 3.31 (d, J = 18.3 Hz, 1H, H7), 4.08–4.31 (m, 5H, H4α and OCH_2). Anal. calcd for $C_{13}H_{24}NO_4P$: C, 53.97; H, 8.36; N, 4.84. Found: C, 53.70; H, 8.52; N, 4.48.

8-(Diethylphosphono)-1-azabicyclo[5.2.0]nonan-9-one (**3h**)

R_f = 0.45 (AcOEt:$CHCl_3$ = 2:1); bp 130°C/0.5 mmHg; IR (neat) 1750, 1025, 970 cm^{-1}; ^1H NMR (500 MHz) δ 1.35 (t, J = 7.0 Hz, 3H, CH_3), 1.36 (t, J = 7.1 Hz, 3H, CH_3), 1.35–1.52 (m, 3H, H3, H5, and H6), 1.52–1.62 (m, 1H, H4), 1.85–1.98 (m, 3H, H3, H4, and H5), 2.11–2.16 (m, 1H, H6), 3.13 (dd, J = 2.3 and 14.4 Hz, 1H, H8), 3.29–3.43 (m, 2H, H2), 3.88 (dddd, J = 2.4, 2.4, 8.8 and 8.8 Hz, 1H, H7), 4.12–4.31 (m, 4H, OCH_2); HRMS (m/e) calcd for $C_{12}H_{22}NO_4P$: 275.1287, found: 275.1292.

7-(Diethylphosphono)-2-methyl-3-oxa-1-azabicyclo[4.2.0]octan-8-one (**3i**)

R_f = 0.43 (AcOEt:$CHCl_3$ = 2:1); IR (neat) 1760, 1025, 970 cm^{-1}; ^1H NMR (60 MHz) δ 1.35 (t, J = 7.0 Hz, 6H, CH_3), 1.69 (d, J = 6.0 Hz, 3H, CH_3), 1.70–2.20 (m, 2H, H1), 3.33 (dd, J = 2.1 and 16.1 Hz, 1H, H7), 3.40–4.60 (m, 7H, OCH_2, H2, and H6), 5.43 (q, J = 6.0 Hz, 1H, H4). Anal. calcd for $C_{11}H_{20}NO_5P$: C, 47.66; H, 7.27; N, 5.05. Found: C, 47.03; H, 7.42; N, 4.79.

2-tert-Butyloxycarbonyl-7-(diethylphosphono)-1-azabicyclo[4.2.0]octan-8-one (**3j**)

R_f = 0.60 (AcOEt:$CHCl_3$ = 2:1); mp 77.0–78.0°C (from Et_2O); IR (KBr) 1760, 1745, 1020, 970 cm^{-1}; ^1H NMR (500 MHz) δ 1.28 (dddd, J = 3.2, 10.9, 13.0, and 13.0 Hz, 1H, H1α), 1.36 (t, J = 7.0 Hz, 6H, CH_3), 1.48 (s, 9H, *t*-Bu), 1.51 (ddddd, J = 2.9, 2.9, 13.5, 13.5, and 13.5 Hz, 1H, H2β), 1.65 (dddd, J = 3.2, 6.8, 13.6, and 13.6 Hz, 1H, H3α), 1.80 (ddddd, J = 3.4, 3.4, 3.4, 3.4, and 13.9 Hz, 1H, H2α), 2.04 (ddd, J = 3.1, 3.1, and 13.7 Hz, 1H, H3β), 2.20 (dddd, J = 3.4, 3.4, 3.4, and 13.1 Hz, 1H, H1β), 3.31 (dd, J = 2.1 and 15.6 Hz, 1H, H7), 3.86–3.92 (m, 1H, H6), 4.15–4.29 (m, 4H, OCH_2), 4.47 (d, J = 6.7 Hz, 1H, H4α). Anal. calcd for $C_{16}H_{28}NO_6P$: C, 53, 18; H, 7.81; N, 3.88. Found: C, 53.13; H, 7.84; N, 3.87.

Crystal Data. Crystal system: monoclinic; space group: $P2_1/n$; a = 14.377(2) Å, b = 8.928(4) Å, c = 15.554(3) Å, β = 95.81(1)°, V = 1986.4(9) $Å^3$; Z = 6; R = 0.060, R_W = 0.086.

3-(Diethylphosphono)-2-oxocyclopenta[1,5-a]indoline (**4k**)

R_f = 0.40 (AcOEt:$CHCl_3$ = 1:1); bp 160°C/0.6 mmHg; IR (neat) 1695, 1600, 1020, 960 cm^{-1}; ^1H NMR (500 MHz) δ 1.34 and 1.36 (t, J = 7.0 Hz, 5.1H, CH_3), 1.39 (t, J = 7.1 Hz, 0.9H, CH_3), 2.31 (ddd, J = 10.0, 10.0, and 13.0 Hz, 0.3H, CH_2), 2.36 (dddd, J = 9.9, 12.6, 14.3, and 14.3 Hz, 0.7H, CH_2), 2.70 (dddd, J = 1.3, 6.2, 7.5, and 12.5 Hz, 0.3H, CH_2), 2.84 (dddd, J = 0.9, 6.3, 12.9, and 16.6 Hz, 0.7H, CH_2), 2.88 (dd, J = 10.1 and 15.6 Hz, 0.7H, CH_2), 2.95 (dd, J = 10.0 and 15.6 Hz, 0.3H, CH_2), 3.18 (ddd, J = 8.0, 8.0, and 16.0 Hz, 1H, CH_2), 3.23 (ddd, J = 0.9, 9.9, and 22.7 Hz, 0.7H, PCH), 3.44 (ddd, J = 7.5, 12.5, 22.0 Hz, 0.3H, PCH), 4.14–4.39 (m, 4H, OCH_2), 4.60 (dddd, J = 6.1, 8.4, 9.4, and 9.4 Hz, 0.3H, NCH), 4.90 (ddddd, J = 1.3, 6.3, 8.6, 9.9, and 9.9, Hz, 0.7H, NCH), 7.03–7.07 (m, 1H, aromatic H), 7.17–7.24 (m, 2H, aromatic H), 7.48 and 7.61 (d, J = 7.5 and 7.8 Hz, 1H, aromatic H); HRMS (*m/e*) calcd for $C_{15}H_{20}NO_4P$: 309.1130, found: 309.1147.

Synthesis of 2-tert-Butyloxycarbonyl-7-(dibenzylphosphono)-1-azabicyclo[4.2.0]octan-8-one (**3m**)

A mixture of **2m** (0.51 g, 1.0 mmol) and $Rh_2(OAc)_4$ (9.5 mg, 0.02 mmol) in $ClCH_2CH_2Cl$ (10 mL) was refluxed for 5 hours. Removal of the solvent and preparative TLC of the residue gave **3m** (0.42 g, 32%).

3m: R_f = 0.50 (AcOEt:hexane = 2:1); IR (neat) 1765, 1740, 1010 cm^{-1}; ^1H NMR (500 MHz) δ 1.19 (dddd, J = 2.1, 12.4, 12.1, and 12.1 Hz, 1H, H1α), 1.43 (s, 9H, *t*-Bu), 1.43–1.50 (m, 1H, H2β), 1.63 (dddd, J = 13.5, 13.5, 3.2, and 6.7 Hz, 1H, H3α), 1.76 (ddd, J = 14.0, 2.9, and 2.9 Hz, 1H, H2α), 2.00–2.07 (m, 2H, H3β and H1β), 3.31 (d, J = 15.3 Hz, 1H, H7), 3.89–3.94 (m, 1H, H6), 4.47 (d, J = 6.7 Hz, 1H, H4α), 5.06–5.20 (m, 4H, OCH_2), 7.25–7.40 (m, 10H, phenyl H). Anal. calcd for $C_{26}H_{32}NO_6P$: C, 64.32; H, 6.64; N, 2.89. Found: C, 64.01; H, 6.88; N, 2.74.

Hydrogenolysis of **3m**

A suspension of **3m** (0.24 g, 0.5 mmol) and palladium on activated carbon (10 wt%, 200 mg) in ethanol (10 mL) was stirred at room temperature for 5 hours under a hydrogen atmosphere. After the palladium catalyst was filtered off, removal of the solvent *in vacuo* gave 2-*tert*-butyloxycarbonyl-7-phosphono-1-azabicyclo[4.2.0]octan-8-one (**5**) (0.15 g, 99%).

5: IR (neat) 1740, 1730 cm^{-1}; ^1H NMR (500 MHz) δ 1.34 (dd, J = 11.6 and 11.6 Hz, 1H, H1α), 1.40–1.55 (m, 1H, H2β), 1.47 (s, 9H, *t*-Bu), 1.64 (br, 1H, H3α), 1.77 (d, J = 12.2 Hz, 1H, H2α), 2.04 (d, J = 12.8 Hz, 1H, H3β), 2.20 (d, J = 7.0 Hz, 1H, H1β), 3.48 (br, 1H, H6), 3.85 (br, 1H, H7), 4.43 (d, J = 4.6 Hz, 1H, H4α); FAB mass (*m/e*) 304 (M^+ − 1).

Synthesis of 2-Carboxyl-7-phosphono-1-azabicyclo[4.2.0]octan-8-one (**6**)

A solution of **5** (0.15 g, 0.49 mmol) in benzene (10 mL) was refluxed for 5 hours. The precipitate was filtered off, washed with benzene, and dried *in vacuo* to give **6** as a hygroscopic solid (0.12 g, 100%).

6: IR (KBr) 1740, 1720 cm^{-1}; ^1H NMR (500 MHz) δ 1.25–1.39 (m, 1H, H1α), 1.53 (ddd, J = 12.7, 12.7, and 12.7 Hz, 1H, H2β), 1.60–1.70 (m, 1H, H3α), 1.77 (d, J = 12.2 Hz, 1H, H2α), 2.05 (d, J = 12.5 Hz, 1H, H3β), 2.15 (br, 1H, H1β), 3.26 (d, J = 13.7 Hz, 1H, H7), 3.80 (br s, 1H, H6), 4.43 (d, J = 3.1 Hz, 1H, H4α); FAB mass (*m/e*) 248 (M^+ − 1).

Preparation of [4'-Benzyloxyphenyl(diethylphosphono)methyl]-3-(diethylphosphono)azetidin-2-one (**3n**)

A mixture of **2n** (0.57 g, 1.0 mmol) and $Rh_2(OAc)_4$ (4.7 mg, 0.01 mmol) in $ClCH_2CH_2Cl$ (10 mL) was refluxed for 0.5 hours. Removal of the solvent and preparative TLC of the residue gave **3n** (0.42 g, 78%).

3n: R_f = 0.38 (AcOEt:$CHCl_3$:MeOH = 10:5:1); IR (neat) 1760, 1020, 965 cm^{-1}; ^1H NMR (500 MHz) δ 1.11–1.39 (m, 12H, CH_3), 3.50–3.57 (m, 1H, NCH_2), 3.64–3.70 (m, 1H, PCH), 3.83–3.90 (m, 1H, NCH_2), 3.98–4.29 (m, 8H, OCH_2), 5.06 (s, 2H, OCH_2Ph), 5.15 (d, J = 20.4 Hz, 0.5H, NCHP), 5.20 (d, J = 20.8 Hz, 0.5H, NCHP), 6.97 (d, J = 8.9 Hz, 2H, aromatic H), 7.32–7.46 (m, 7H, aromatic H); HRMS (*m/e*) calcd for $C_{25}H_{35}NO_8P_2$: 539.1837, found: 539.1806.

Wittig–Horner Reaction of the Phosphonolactams **3b,f,n** *and* **4c** *with Paraformaldehyde*

General Procedure. To a suspension of sodium hydride (60% dispersion in mineral oil, 0.044 g, 1.1 mmol) in THF (5 mL) was added a solution of the lactam **3b,f,n** or **4c** (1.0 mmol) in THF (5 mL) at room temperature. The reaction mixture became a clear solution in 0.5 hours, then paraformaldehyde (0.090 g, 3.0 mmol) was added. After being stirred at room temperature overnight, the reaction mixture was treated with 2 N HCl aq, extracted with AcOEt, washed with water and brine, and dried over Na_2SO_4. Removal of the solvent and preparative TLC of the residue gave each respective methylene lactam **8b,f,n** or **13c**.

1-Isopropyl-3-methylene-4-phenylazetidin-2-one (**8b**)

R_f = 0.58 (AcOEt:hexane = 1:1); mp 57.0–58.0°C (from hexane); IR (KBr) 1745 cm^{-1}; ^1H NMR (60 MHz) δ 1.03 (d, J = 6.7 Hz, 3H, CH_3), 1.28 (d, J = 6.7 Hz, 3H, CH_3), 3.90 (quint, J = 6.7 Hz, 1H, CH), 4.97 (dd, J = 1.4 and 1.4 Hz, 1H, olefinic H), 4.97 (s, 1H, PhCH), 5.64 (dd, J = 1.6 and 1.6 Hz, 1H, olefinic H), 7.35 (s, 5H, phenyl H). Anal. calcd for $C_{13}H_{15}NO$: C, 77.58; H, 7.51; N, 6.96. Found: C, 77.83; H, 7.39; N, 6.95.

7-Methylene-1-azabicyclo[4.2.0]octan-8-one (**8f**)

R_f = 0.52 (AcOEt:$CHCl_3$ = 1:2); bp 90°C/0.6 mmHg; IR (neat) 1740 cm^{-1}; ^1H NMR (60 MHz) δ 1.00–2.30 (m, 6H, CH_2), 2.50–3.10 (br m, 1H, NCH_2), 3.60–4.10 (m, 2H, NCH and NCH_2), 5.12 (dd, J = 1.2 and 1.2 Hz, 1H, olefinic H), 5.56 (dd, J = 1.4 and 1.4 Hz, 1H, olefinic H); HRMS (m/e) calcd for $C_8H_{11}NO$: 137.0841, found: 137.0848.

1-[4'-Benzyloxyphenyl(diethylphosphono) methyl]-3-methyleneazetidin-2-one (**8n**)

Yield 63%; mp 81.5–82.0°C (from AcOEt/hexane); R_f = 0.54 (AcOEt:$CHCl_3$ = 2:1); IR (KBr) 1745, 1610, 695 cm^{-1}; ^1H NMR (500 MHz) δ 1.12 (t, J = 6.9 Hz, 3H, CH_3), 1.32 (t, J = 7.0 Hz, 3H, CH_3), 3.50–4.40 (m, 6H, OCH_2 and NCH_2), 5.04 (s, 2H, OCH_2Ph), 5.16 (s, 1H, olefinic H), 5.31 (d, J = 17.0 Hz, 1H, NCHP), 5.70 (s, 1H, olefinic H), 6.95 (d, J = 8.6 Hz, 2H, aromatic H), 7.63 (s, 5H, phenyl H), 7.44 (d, J = 9.1 Hz, 2H, aromatic H). Anal. calcd for $C_{22}H_{26}NO_5P$: C, 63.61; H, 6.31; N, 3.37. Found: C, 63.69; H, 6.54; N, 3.35.

1-n-Butyl-4-ethyl-3-methylenepyrrolidin-2-one (**13c**)

R_f = 0.70 (Et_2O); IR 2950, 1690, 1660 cm^{-1}; ^1H NMR (500 MHz) δ 0.94 (t, J = 6.9 Hz, 3H, CH_3), 0.95 (t, J = 7.0 Hz, 3H, CH_3), 1.33 (sext, J = 7.4 Hz, 2H, CH_2), 1.44–1.51 (m, 2H, CH_2), 1.54 (dq, J = 7.3 and 7.3 Hz, 1H, CH_2), 1.65–1.75 (m, 1H, CH_2), 2.80 (br s, 1H, CH), 3.02 (dd, 1H, NCH_2), 3.37 (t, J = 7.3 Hz, 2H, NCH_2), 3.50 (dd, J = 8.2 and 9.8 Hz, 1H, NCH_2), 5.26 (d, J = 2.4 Hz, 1H, olefinic H), 5.99 (d, J = 2.8 Hz, 1H, olefinic H); HRMS (m/e) calcd for $C_{11}H_{19}NO$: 181.1467, found: 181.1471.

Oxidation of **8f** *with Osmium Tetraoxide*

To a solution of **8f** (1.23 g, 9 mmol) and *N*-methylmorpholine *N*-oxide (1.28 g, 9.48 mmol) in aqueous acetone (90%, 6.7 mL) was added an aqueous solution of osmium tetraoxide (2%, 0.43 mL, 0.0086 mmol) at room temperature. After the reaction mixture had been stirred for 13 hours at this temperature, 20% sodium hydrogen sulfite solution was added to the mixture. After being stirred for 20 minutes, *n*-butanol (7 mL) and water (2 mL) were added to the mixture. Then the mixture was acidified with 6 N sulfuric acid (pH ~3), saturated with NaCl, and extracted with *n*-butanol. The extract was washed with a 1:1 mixture of saturated sodium bicarbonate and brine, dried over Na_2SO_4, and evaporated. The residue was chromatographed on silica gel with $CHCl_3$-MeOH (9:1) to give 7 - hydroxy - 7 - hydroxymethyl-1-azabicyclo[4.2.0] clo[4.2.0]octan-8-one (**9**) (1.26 g, 82%).

9: R_f = 0.20 (AcOEt:$CHCl_3$:MeOH = 10:5:1); mp 124.0–128.0°C (from EtOH-Et_2O); IR (KBr) 3300, 1740, 1725 cm^{-1}; ^1H NMR (500 MHz) δ 1.37–1.46 (m, 3H, H1α, H2β, and H3α), 1.64–1.71 (m, 1H, H3β), 1.88–1.95 (m, 2H, H1β and H2α), 2.53 (br s, 1H, OH), 2.82 (ddd, J = 4.4, 11.9, and 13.0 Hz, 1H, H4β), 3.48 (dd, J = 4.4 and 10.5 Hz, 1H, H6), 3.78 (dd, J = 4.0 and 13.1 Hz, 1H, H4α), 3.85 (d, J = 12.2 Hz, 1H, OCH_2), 3.95 (d, J = 11.9 Hz, 1H, OCH_2), 5.34 (br s, 1H, OH). Anal. calcd for $C_8H_{13}NO_3$: C, 56.13; H, 7.65; N, 8.18. Found: C, 56.48; H, 7.41; N, 8.04.

Synthesis of 7-Hydroxyimino-1-azabicyclo[4.2.0]octan-8-one (**10**)

To a solution of **9** (0.86 g, 5 mmol) in CH_2Cl_2 (8 mL) and water (2 mL) was added sodium metaperiodate (1.60 g, 7.5 mmol) in one portion at 0°C. After being stirred for 45 minutes at 0°C, anhydrous sodium sulfate was added to the mixture. After filtration, the mixture was concentrated *in vacuo* under a low temperature (<10°C). To the residual oil dissolved in dry CH_2Cl_2 (10 mL) was added a solution of hydroxylamine hydrochloride (0.69 g, 10 mmol) and pyridine (1.3 mL, 16 mmol) in dry CH_2Cl_2 (5 mL). After the reaction mixture had been stirred for 24 hours at room temperature, the mixture was washed with water, dried, and evaporated. The residue was chromatographed on silica gel with $CHCl_3$-MeOH (9:1) to give **10** (0.45 g, 58%).

10: R_f = 0.60 (AcOEt:$CHCl_3$:MeOH = 10:5:1); mp 126.0–130.0°C; IR (KBr) 3200, 1740 cm^{-1}; ^1H NMR (500 MHz) δ 1.41–1.47 (m, 3H, H1α, H2β, and H3α), 1.71–1.75 (m, 1H, H3β), 1.93 (br, 1H, H2α), 2.19–2.24 (m, 1H, H1β), 2.94 (ddd, J = 4.7, 11.6, and 13.4 Hz, 1H, H4β), 3.98 (dd, J = 4.1 and 13.3 Hz, 1H, H4α), 4.16 (dd, J = 4.6 and 10.5 Hz, 1H, H6), 7.86 (s, 1H, OH). Anal. calcd for $C_7H_{10}N_2O_2$: C, 54.54; H, 6.54; N, 18.17. Found: C, 54.85; H, 6.53; N, 18.10.

Synthesis 7-Acetylamino-1-azabicyclo[4.2.0]octan-8-one (**11**)

A solution of **10** (80 mg, 0.5 mmol), sodium acetate (82 mg, 1.0 mmol), and acetic anhydride (0.8 mL, 8.5 mmol) in ethyl acetate (6 mL) was stirred at room temperature for 18 hours. An additional portion of ethyl acetate (15 mL) and PtO_2 (10 mg) was added to the solution, and the mixture was stirred under 3.5 kg/cm^2 of H_2 for 24 hours. After the catalyst had been filtered off through a celite pad, the filtrate was evaporated under reduced pressure. Silica gel column chromatography of the residue with $CHCl_3$-MeOH (9:1) as eluent gave **11** (49 mg, 54%).

11: R_f = 0.38 (AcOEt:$CHCl_3$:MeOH = 10:5:1); mp 160–164°C; IR (KBr) 3280, 1735, 1685, 1555 cm^{-1}; ^1H NMR (500 MHz) δ 1.23–1.35 (m, 2H, H1α and H2β), 1.40 (tq, J = 2.6 and 13.0 Hz, 1H, H3α), 1.63 (dd, J = 2.7 and 13.0 Hz, 1H, H3β), 1.72 (dd, J = 3.4 and 12.9 Hz, 1H, H2α), 1.87 (dt, J = 3.4 and 13.3 Hz, 1H, H1β), 1.98 (s, 3H, CH_3), 2.70 (dddd, J = 1.5, 4.2, 12.8, and 13.5 Hz, 1H, H4β), 3.57 (dt, J = 4.5 and 10.9 Hz, 1H, H4α), 3.73 (dd, J = 5.0 and 13.4 Hz, 1H, H6), 5.12 (ddd, J = 1.6, 4.5, and 7.4 Hz, 1H, H7), 7.34 (d, J = 7.0 Hz, 1H, NH). Anal. calcd for $C_9H_{14}N_2O_2$: C, 59.32; H, 7.74; N, 15.37. Found: C, 59.03; H, 7.83; N, 15.20.

Preparation of Chiral Rhodium(II) Carboxylates **12a–c**

Dirhodium tetramandelate (**12a**) was prepared according to the reported procedure [17].

Preparation of dirhodium tetra(DPCProC oxide) (**12b**) was as follows. To a solution of $RhCl_3 \cdot 3H_2O$ (0.53 g, 2.0 mmol) in H_2O (10 mL) was added a solution of (+)-DPCProC oxide (2.20 g, 4.4 mmol) in DMF (2 mL). Then the mixture was heated at 80°C for 6 hours while the solution level was maintained by additions of H_2O. At the end of 6 hours of heating, the blue-green precipitate that had formed was filtered off and washed with H_2O. The product was dried *in vacuo* to yield **12b** as a green solid, mp 202–204°C (dec) (1.39 g, 63%).

Preparation of dirhodium tetra[*N*-phthaloyl-(L)-phenylalanine] **12c** was as follows. A mixture of $Rh_2(OAc)_4$ (0.05 g, 0.1 mmol), *N*-phthaloyl-(L)-phenylalanine (0.32 g, 1.1 mmol), and chlorobenzene (20 mL) was refluxed for 3 hours and cooled to room temperature. The mixture was extracted with CH_2Cl_2, washed with five percent aqueous sodium bicarbonate solution and H_2O, dried, and concentrated. The preparative TLC of the residue with Et_2O gave **12c** as a light green solid, mp 212–214°C (dec) (0.12 g, 82%).

Data Collection for X-Ray Diffraction Analysis of **3j**

A colorless prismatic crystal of $C_{16}H_{28}NO_6P$ having approximate dimensions of 0.20 × 0.20 × 0.30 mm was mounted on a glass fiber. All measurements were made on a Rigaku AFC7R diffractometer with graphite monochromated Mo K_α radiation and a 12 kW rotating anode generator.

Cell constants and an orientation matrix for data collection, obtained from a least-squares refinement using the setting angles of 25 carefully centered reflections in the range $35.17 < 2\theta < 40.48°$, corresponded to a primitive monoclinic cell with the following dimensions:

$$a = 14.377(2)\ \text{Å}$$

$$b = 8.928(4)\ \text{Å} \quad \beta = 95.81(1)°$$

$$c = 15.554(3)\ \text{Å}$$

$$V = 1986.4(9)\ \text{Å}^3$$

For Z = 6 and F.W. = 361.37, the calculated density is 1.81 g/cm^3. The systematic absences of

$$h0l: h + l \neq 2n$$

$$0k0: k \neq 2n$$

uniquely determine the space group to be

$$P2_{1/n}\ (\text{no. } 14)$$

The data were collected at a temperature of 20 ± 1°C using the ω-2θ scan technique to a maximum 2θ value of 55.0°. Omega scans of several intense reflections, made prior to data collection, had an average width at half-height of 0.28° with a take-off angle of 6.0°. Scans of (1.73 + 0.30 tanθ)° were made at a speed of 16.0°/min (in omega). The weak reflections ($I < 10.0\sigma(I)$) were rescanned (maximum of three scans) and the counts were accumulated to ensure good counting statistics. Stationary background counts were recorded on each side of the reflection. The ratio of peak counting time to background counting time was 2:1. The diameter of the incident beam collimator was 1.0 mm, the crystal to detector distance was 235 mm, and the computer-controlled detector aperture was set to 9.0 × 13.0 mm (horizontal × vertical).

Data Reduction

Of the 5048 reflections that were collected, 4860 were unique (R_{int} = 0.018). The intensities of three

TABLE 3 Crystal Data, Data Collection, and Refinement Parameters

Crystal Data	
Empirical formula	$C_{16}H_{28}NO_6P$
Formula weight	361.37
Crystal color, habit	colorless, prismatic
Crystal dimensions	0.20 × 0.20 × 0.30 mm
Crystal system	monoclinic
Lattice type	primitive
No. of reflections used for unit cell determination (2θ range)	25 (35.2–40.5°)
Omega scan peak width at half-height	0.28°
Lattice parameters	a = 14.377(2) Å b = 8.928(4) Å c = 15.554(3) Å β = 95.81(1)° V = 1986.4(9) Å^3
Space group	$P2_1/n$ (no. 14)
Z value	6
D_{calcd}	1.812 g/cm^3
F_{000}	1164.00
μ(Mo K_α)	2.49 cm^{-1}
Intensity Measurements	
Diffractometer	Rigaku AFC7R
Radiation	Mo K_α (λ = 0.71069 Å) graphite monochromated
Attenuator	Zr foil (factors = 1.00, 8.92, 8.92, 8.92)
Take-off angle	6.0°
Detector aperture	9.0 mm horizontal 13.0 mm vertical
Crystal-to-detector distance	235 mm
Temperature	20.0°C
Scan type	$\omega - 2\theta$
Scan rate	16.0°/min (in ω)—up to 3 scans
Scan width	(1.73 + 0.30 tan θ)°
$2\theta_{max}$	55.0°
No. of reflections measured	total: 5048 *unique*: 4860 (R_{int} = 0.018)
Corrections	Lorentz-polarization
Structure Solution and Refinement	
Structure solution	direct methods (SAPI91)
Refinement	full-matrix least-squares
Function minimized	$\Sigma w(\|Fo\| - \|Fc\|)^2$
Least-squares weights	$\frac{1}{\sigma^2(Fo)} = \frac{4Fo^2}{\sigma^2(Fo^2)}$
p-Factor	0.06
Anomalous dispersion	all nonhydrogen atoms
No. of observations ($I > 3.00\sigma(I)$)	2613
No. of variables	330
Reflection/Parameter ratio	7.92
Residuals: R; R_w	0.060; 0.086
Goodness of fit indicator	1.99
Max shift/error in final cycle	0.03
Maximum peak in final diffraction map	0.29 e^-/Å^3
Minimum peak in final diffraction map	−0.31 e^-/Å^3

TABLE 4 Bond Lengths (Å)

Atom	*Atom*	*Distance*	*Atom*	*Atom*	*Distance*
P(1)	O(1)	1.569(3)	P(1)	O(2)	1.556(3)
P(1)	O(3)	1.455(2)	P(1)	C(2)	1.775(3)
O(1)	C(8)	1.449(6)	O(2)	C(15)	1.408(7)
O(4)	C(1)	1.202(4)	O(5)	C(10)	1.190(4)
O(6)	C(10)	1.327(4)	O(6)	C(11)	1.486(4)
N(1)	C(1)	1.348(4)	N(1)	C(3)	1.471(4)
N(1)	C(7)	1.449(4)	C(1)	C(2)	1.550(4)
C(2)	C(3)	1.554(4)	C(2)	H(26)	0.97
C(3)	C(4)	1.507(4)	C(3)	H(27)	0.96
C(4)	C(5)	1.526(5)	C(4)	H(16)	0.97
C(4)	H(17)	0.98	C(5)	C(6)	1.508(5)
C(5)	H(18)	0.95	C(5)	H(19)	0.96
C(6)	C(7)	1.546(5)	C(6)	H(20)	0.95
C(6)	H(21)	0.97	C(7)	C(10)	1.517(4)
C(7)	H(28)	0.95	C(8)	C(9)	1.317(8)
C(8)	H(22)	1.00	C(8)	H(23)	0.97
C(9)	H(1)	0.98	C(9)	H(2)	0.95
C(9)	H(3)	0.95	C(11)	C(12)	1.514(6)
C(11)	C(13)	1.493(6)	C(11)	C(14)	1.489(6)
C(12)	H(4)	0.96	C(12)	H(5)	0.99
C(12)	H(6)	0.94	C(13)	H(7)	0.97
C(13)	H(8)	0.96	C(13)	H(9)	0.96
C(14)	H(10)	0.94	C(14)	H(11)	0.99
C(14)	H(12)	0.94	C(15)	C(16)	1.355(9)
C(15)	H(24)	0.94	C(15)	H(25)	0.97
C(16)	H(13)	0.99	C(16)	H(14)	0.98
C(16)	H(15)	0.94			

representative reflection were measured after every 150 reflections. No decay correction was applied.

The linear absorption coefficient, μ, for Mo K_α radiation is 2.5 cm^{-1}. Azimuthal scans of several reflections indicated no need for an absorption correction. The data were corrected for Lorentz and polarization effects.

Structure Solution and Refinement

The structure was solved by direct methods [21] and expanded using Fourier techniques [22]. The nonhydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. The final cycle of full-matrix least-squares refinement [23] was based on 2613 observed reflections ($I > 3.00\sigma(I)$) and 330 variable parameters and converged (largest parameter was 0.03 times its esd) with unweighted and weighted agreement factors of

$$R = \Sigma||Fo| - |Fc||/\Sigma|Fo| = 0.060$$

$$R_w = \sqrt{(\Sigma w(|Fo| - |Fc|)^2/\Sigma wFo^2)}] = 0.086$$

The standard deviation of an observation of unit weight [24] was 1.99. The weighting scheme was based on counting statistics and included a factor (p = 0.059) to downweight the intense reflections.

TABLE 5 Bond Angles (°)

Atom	*Atom*	*Atom*	*Angle*	*Atom*	*Atom*	*Atom*	*Angle*
O(1)	P(1)	O(2)	102.7(2)	O(1)	P(1)	O(3)	117.6(2)
O(1)	P(1)	C(2)	100.2(1)	O(2)	P(1)	O(3)	114.4(2)
O(2)	P(1)	C(2)	104.5(2)	O(3)	P(1)	C(2)	115.4(1)
P(1)	O(1)	C(8)	123.1(3)	P(1)	O(2)	C(15)	122.9(3)
C(10)	O(6)	C(11)	122.0(3)	C(1)	N(1)	C(3)	96.6(2)
C(1)	N(1)	C(7)	132.2(3)	C(3)	N(1)	C(7)	126.7(2)
O(4)	C(1)	N(1)	132.7(3)	O(4)	C(1)	C(2)	136.0(3)
N(1)	C(1)	C(2)	91.3(2)	P(1)	C(2)	C(1)	119.9(2)
P(1)	C(2)	C(3)	118.7(2)	P(1)	C(2)	H(26)	110.2
C(1)	C(2)	C(3)	85.5(2)	C(1)	C(2)	H(26)	110.0
C(3)	C(2)	H(26)	110.4	N(1)	C(3)	C(2)	86.7(2)
N(1)	C(3)	C(4)	112.3(2)	N(1)	C(3)	H(27)	111.8
C(2)	C(3)	C(4)	119.3(2)	C(2)	C(3)	H(27)	111.6
C(4)	C(3)	H(27)	112.5	C(3)	C(4)	C(5)	108.5(3)
C(3)	C(4)	H(16)	111.2	C(3)	C(4)	H(17)	110.9
C(5)	C(4)	H(16)	110.7	C(5)	C(4)	H(17)	110.0
H(16)	C(4)	H(17)	105.5	C(4)	C(5)	C(6)	111.0(3)
C(4)	C(5)	H(18)	111.7	C(4)	C(5)	H(19)	108.9
C(6)	C(5)	H(18)	109.2	C(6)	C(5)	H(19)	107.3
H(18)	C(5)	H(19)	108.7	C(5)	C(6)	C(7)	112.6(3)
C(5)	C(6)	H(20)	108.4	C(5)	C(6)	H(21)	108.7
C(7)	C(6)	H(20)	110.1	C(7)	C(6)	H(21)	109.3
H(20)	C(6)	H(21)	107.6	N(1)	C(7)	C(6)	107.6(2)
N(1)	C(7)	C(10)	110.7(2)	N(1)	C(7)	H(28)	109.2
C(6)	C(7)	C(10)	110.8(3)	C(6)	C(7)	H(28)	109.4
C(10)	C(7)	H(28)	109.1	O(1)	C(8)	C(9)	113.3(5)
O(1)	C(8)	H(22)	108.6	O(1)	C(8)	H(23)	110.2
C(9)	C(8)	H(22)	108.3	C(9)	C(8)	H(23)	112.0
H(22)	C(8)	H(23)	103.9	C(8)	C(9)	H(1)	108.1
C(8)	C(9)	H(2)	111.9	C(8)	C(9)	H(3)	113.4
H(1)	C(9)	H(2)	107.1	H(1)	C(9)	H(3)	106.6
H(2)	C(9)	H(3)	109.4	O(5)	C(10)	O(6)	125.6(3)
O(5)	C(10)	C(7)	124.8(3)	O(6)	C(10)	C(7)	109.6(3)
O(6)	C(11)	C(12)	101.6(3)	O(6)	C(11)	C(13)	110.6(3)
O(6)	C(11)	C(14)	109.2(3)	C(12)	C(11)	C(13)	111.3(4)
C(12)	C(11)	C(14)	111.0(4)	C(13)	C(11)	C(14)	112.6(4)
C(11)	C(12)	H(4)	111.6	C(11)	C(12)	H(5)	110.0
C(11)	C(12)	H(6)	112.6	H(4)	C(12)	H(5)	105.6
H(4)	C(12)	H(6)	109.8	H(5)	C(12)	H(6)	106.8
C(11)	C(13)	H(7)	110.9	C(11)	C(13)	H(8)	111.4
C(11)	C(13)	H(9)	111.8	H(7)	C(13)	H(8)	107.0
H(7)	C(13)	H(9)	107.6	H(8)	C(13)	H(9)	107.9
C(11)	C(14)	H(10)	111.1	C(11)	C(14)	H(11)	109.3
C(11)	C(14)	H(12)	111.2	H(10)	C(14)	H(11)	107.0
H(10)	C(14)	H(12)	110.7	H(11)	C(14)	H(12)	107.3
O(2)	C(15)	C(16)	119.1(6)	O(2)	C(15)	H(24)	107.7
O(2)	C(15)	H(25)	105.8	C(16)	C(15)	H(24)	107.8
C(16)	C(15)	H(25)	107.2	H(24)	C(15)	H(25)	109.0
C(15)	C(16)	H(13)	111.4	C(15)	C(16)	H(14)	112.6
C(15)	C(16)	H(15)	113.4	H(13)	C(16)	H(14)	104.4
H(13)	C(16)	H(15)	106.9	H(14)	C(16)	H(15)	107.7

Plots of $\Sigma w(|Fo| - |Fc|)^2$ vs. $|Fo|$, reflection order in data collection, $\sin\theta/\lambda$, and various classes of indices showed no unusual trends. The maximum and minimum peaks on the final difference Fourier map corresponded to 0.29 and -0.31 $e^-/Å^3$, respectively.

Neutral atom scattering factors were taken from double prime Cromer and Waber [25]. Anomalous dispersion effects were included in F calcd [26], the values for $\Delta f'$ and $\Delta f''$ were those of Creagh and McAuley [27]. The values for the mass attenuation coefficients are those of Creagh and Hubbel [28]. All calculations were performed using the teXsan [29] crystallographic software package of Molecular Structure Corporation.

Crystal data are presented in Table 3, bond lengths are given in Table 4, and bond angles are given in Table 5. Tables of atomic coordinates and B_{iso}/B_{eq}, anisotropic displacement parameters, torsion angles, and nonbonded contacts out to 3.60 Å can be obtained on written request to Prof. Dr. Toru Minami or to William E. McEwen, Editor-in-Chief, *Heteroatom Chemistry*.

ACKNOWLEDGMENTS

We are grateful for the financial support of this work by a Grant-in-Aid for Scientific Research on Priority Areas (06225228) from Japan Ministry of Education, Science and Culture, and by Nagase Science and Technology Foundation. We also thank the Center for Instrumental Analysis KIT for the use of its facilities.

REFERENCES

[1] For reviews of rhodium(II)-catalyzed reactions, see (a) S. D. Burke, P. A. Grieco, *Org. React., 26*, 1979, 361; (b) M. P. Doyle, *Chem. Rev., 86*, 1986, 919; (c) G. Maas, *Topics Curr. Chem., 137*, 1987, 75; (d) J. Adams, D. M. Spero, *Tetrahedron, 47*, 1991, 1765; (e) D. F. Taber: Carbon–Carbon Bond Formation by C–H Insertion, in B. M. Trost, I. Fleming (eds): *Comprehensive Organic Synthesis*, Pergamon Press, Oxford, vol. 3, pp. 1045–1062 (1991).

[2] (a) J. Adams, M.-A. Poupart, L. Grenier, C. Schaller, N. Ouimet, R. Frenette, *Tetrahedron Lett., 30*, 1989, 1749; (b) J. Adams, M.-A. Poupart, L. Grenier, *Tetrahedron Lett., 30*, 1989, 1753; (c) H. R. Sonawane, N. S. Bellur, J. R. Ahuja, D. G. Kulkarni, *J. Org. Chem., 56*, 1991, 1434; (d) P. Padwa, D. J. Austin, S. F. Hornbuckle, M. A. Semones, *J. Am. Chem. Soc., 114*, 1992, 1874.

[3] (a) D. F. Taber, E. H. Petty, *J. Org. Chem., 47*, 1982, 4808; (b) D. F. Taber, J. L. Schuchardt, *J. Am. Chem. Soc., 107*, 1985, 5289; (c) D. F. Taber, R. E. Ruckle, Jr., *Tetrahedron Lett., 26*, 1985, 3059; (d) D. F. Taber, R. E. Ruckle, Jr., *J. Am. Chem. Soc., 108*, 1986, 7686; (e) D. F. Taber, J. L. Schuchardt, *Tetrahedron, 43*, 1987, 5677; (f) E. Lee, K. W. Jung, Y. S. Kim, *Tetrahedron Lett., 31*, 1990, 1023; (g) S. Hashimoto, N. Watanabe, S. Ikegami, *Tetrahedron Lett., 33*, 1992, 2709; (h) M. P. Doyle, L. J. Westrum, W. N. E. Wolthuis, M. M. See, W. P. Boone, V. Bagheri, M. M. Pearson, *J. Am. Chem. Soc., 115*, 1993, 958.

[4] H. J. Monteiro, *Tetrahedron Lett., 28*, 1987, 3459.

[5] (a) B. Corbel, D. Hernot, J.-P. Haelters, G. Sturtz, *Tetrahedron Lett., 28*, 1987, 6605; (b) M. Mikolajczyk, R. Zurawinski, P. Kielbasinski, *Tetrahedron Lett., 30*, 1989, 1143.

[6] (a) M. P. Doyle, M. S. Shanklin, S.-M. Oon, H. Q. Pho, F. R. van der Heide, W. R. Veal, *J. Org. Chem., 53*, 1988, 3384; (b) M. P. Doyle, J. Taunton, H. Q. Pho, *Tetrahedron Lett., 30*, 1989, 5397; (c) M. P. Doyle, R. J. Pieters, J. Taunton, H. Q. Pho, A. Padwa, D. L. Hertzog, L. Precedo, *J. Org. Chem., 56*, 1991, 820.

[7] J. Motoyoshiya, K. Hirata, *Chem. Lett.*, 1988, 211.
[8] T. Minami, M. Kamitamari, T. Utsunomiya, T. Tanaka, J. Ichikawa, *Bull. Chem. Soc. Jpn.*, *66*, 1993, 1496.
[9] (a) T. Minami, Y. Kitajima, T. Chikugo, *Chem. Lett.*, 1986, 1229; (b) T. Minami, K. Hirakawa, S. Koyanagi, S. Nakamura, M. Yamaguchi, *J. Chem. Soc., Perkin Trans.*, *1*, 1990, 2385; (c) T. Minami, Y. Matsumoto, S. Nakamura, S. Koyanagi, M. Yamaguchi, *J. Org. Chem.*, *57*, 1992, 167.
[10] M. Regitz, J. Hocker, A. Liedhegener: *Organic Synthesis, Coll. V*, Wiley, New York, p. 197 (1973).
[11] The *trans* and *cis* coupling constants for hydrogens on β-lactam ring are in the range of 2.2–2.8 and 4.9–5.9 Hz, respectively. See (a) H. B. Kagan, J. J. Basselier, J. L. Luche, *Tetrahedron Lett.*, 1964, 941; (b) K. D. Barrow, T. M. Spotswood, *Tetrahedron Lett.*, 1965, 3325.
[12] (a) J. D. Buynak, M. N. Rao, *J. Org. Chem.*, *51*, 1986, 1571; (b) T. Kametani, S.-D. Chu, A. Itoh, S. Maeda, T. Honda, *J. Org. Chem.*, *53*, 1988, 2683; (c) R. S. Miller, D. W. Hoard, R. A. Johnson, W. D. Luke, *J. Org. Chem.*, *59*, 1994, 3289.
[13] W. Dürckheimer, J. Blumbach, R. Lattrell, K. H. Scheunemann, *Angew. Chem. Int. Ed. Engl.*, *24*, 1985, 180.
[14] For the alternative synthesis of 3-methylene-β-lactams, see (a) T. Minami, M. Ishida, T. Agawa, *J. Chem. Soc., Chem. Commun.*, 1978, 12; (b) S. R. Fletcher, I. T. Kay, *J. Chem. Soc., Chem. Commun.*, 1978, 903; (c) M. Ishida, T. Minami, T. Agawa, *J. Org. Chem.*, *44*, 1979, 2067; (d) M. Mori, K. Chiba, M. Okita, Y. Ban, *J. Chem. Soc., Chem. Commun.*, 1979, 698; (e) R. M. Adlington, A. G. M. Barrett, P. Quayle, A. Walker, M. J. Betts, *J. Chem. Soc., Chem. Commun.*, 1981, 404; (f) R. M. Adlington, A. G. M. Barrett, P. Quayle, A. Walker, M. J. Betts, *J. Chem. Soc., Perkin Trans, 1*, 1983, 605; (g) M. Mori, K. Chiba, M. Okita, I. Kayo, Y. Ban, *Tetrahedron*, *41*, 1985, 375.
[15] Chiba et al. have similarly reported the conversion of the 3-methylene-β-lactam containing the carboxylic acid esters side chain with aromatic ring into 3-amino-β-lactams: K. Chiba, M. Mori, Y. Ban, *Tetrahedron*, *41*, 1985, 387.
[16] For an enantioselective intramolecular C–H insertion with chiral rhodium(II) carboxylates, see (a) S. Hashimoto, N. Watanabe, S. Ikegami, *Tetrahedron Lett.*, *31*, 1990, 5173; (b) H. Brunner, K. Wutz, M. P. Doyle, *Monatsh. Chem.*, *121*, 1990, 755; (c) M. P. Doyle, A. van Oeveren, L. J. Westrum, M. N. Protopopova, T. W. Clayton, Jr., *J. Am. Chem. Soc.*, *113*, 1991, 8982; (d) M. P. Doyle, M. N. Protopopova, W. R. Winchester, K. L. Daniel, *Tetrahedron Lett.*, *33*, 1992, 7819; (e) M. P. Doyle, W. R. Winchester, J. A. A. Hoorn, V. Lynch, S. H. Simonsen, R. Ghosh, *J. Am. Chem. Soc.*, *115*, 1993, 9968. For an enantioselective intramolecular C–H insertion of the chiral substrates with rhodium(II) tetraacetate, see (f) D. F. Taber, E. H. Petty, K. Raman, *J. Am. Chem. Soc.*, *107*, 1985, 196.
[17] For a diastereoselective intramolecular C–H insertion of chiral moiety containing substrates with rhodium(II) tetraacetate, see (a) D. F. Taber, K. Raman, *J. Am. Chem. Soc.*, *105*, 1983, 5935; (b) D. F. Taber, K. Raman, M. D. Gaul, *J. Org. Chem.*, *52*, 1987, 28.
[18] (a) P. A. Agaskar, F. A. Cotton, L. R. Falvello, S. Han, *J. Am. Chem. Soc.*, *108*, 1986, 1214; (b) H. Brunner, H. Kluschanzoff, K. Wutz, *Bull. Soc. Chim. Belg.*, *98*, 1989, 63.
[19] DPCProC oxide is the abbreviation of *trans*-2,3-bis(diphenylphosphinyl)-1-methyl-1-cyclopropanecarboxylic acid: Y. Okada, T. Minami, T. Yamamoto, J. Ichikawa, *Chem. Lett.*, 1992, 547.
[20] (a) H. J. Callot, F. Metz, *Tetrahedron*, *41*, 1985, 4495; (b) G. H. L. Nefkens, G. I. Tesser, R. J. F. Nivard, *Recl. Trav. Chim. Pays-Bas*, *79*, 1960, 688.
[21] *SAPI91*: Fan Hai-Fu: *Structure Analysis Programs with Intelligent Control*, Rigaku Corporation, Tokyo, Japan (1991).
[22] *DIRDIF92*: P. T. Beurskens, G. Admiraal, G. Beurskens, W. P. Bosman, S. Garcia-Granda, R. O. Gould, J. M. M. Smits, C. Smykalla: The DIRDIF program system, Technical Report of the Crystallography Laboratory, University of Nijmegen, Netherlands (1992).
[23] Least-Squares:
Function minimized: $\Sigma w(|Fo| - |Fc|)^2$
where $w = \dfrac{1}{\sigma^2(Fo)} = \dfrac{4Fo^2}{\sigma^2(Fo^2)}$;
$\sigma^2(Fo^2) = \dfrac{S^2(C + R^2 B) + (pFo^2)^2}{Lp^2}$;
S = scan rate;
C = total integrated peak count;
R = ratio of scan time to background counting time;
B = total background count;
Lp = Lorentz-polarization factor; and
p = p-factor.
[24] Standard deviation of an observation of unit weight:
$\sqrt{\Sigma w(|Fo| - |Fc|)^2/(No - Nv)}$
where No = number of observations; and
Nv = number of variables.
[25] D. T. Cromer, J. T. Waber: *International Tables for X-ray Crystallography*, The Kynoch Press, Birmingham, England, vol. IV, Table 2.2 A (1974).
[26] J. A. Ibers, W. C. Hamilton, *Acta Crystallogr.*, *17*, 1964, 781.
[27] D. C. Creagh, W. J. McAuley: in A. J. C. Wilson (ed.): *International Tables for Crystallography*, Kluwer Academic Publishers, Boston, vol. C, pp. 219–222 (1992).
[28] D. C. Creagh, J. H. Hubbell: in A. J. C. Wilson (ed.): *International Tables for Crystallography*, Kluwer Academic Publishers, Boston, vol. C, pp. 200–206 (1992).
[29] *teXsan*: Crystal Structure Analysis Package, Molecular Structure Corporation, The Woodlands, TX, 77381 (1985 and 1992).