

Figure 2. Distribution of the isotopically labeled propene molecules produced upon passage of mixtures of 90% ^{13}C CO + 10% ^{12}C CO, H_2 , and $^{12}\text{CH}_2\text{N}_2$ over a cobalt catalyst. The experimentally observed distribution is given by the points joined via the dotted line. The distributions predicted by the Pichler-Schultz mechanism are given by the symbol \diamond , that predicted by the Anderson-Emmett mechanism by the symbol \square , and that predicted by the Fischer-Tropsch scheme are given by the symbol \triangle .

should be a mixture of ^{13}C - ^{13}C - ^{13}C and ^{12}C - ^{12}C - ^{12}C molecules. In each case the relative amount of the various isotopically labeled carbon molecules would depend on the relative amounts of ^{13}C CO converted and $^{12}\text{CH}_2\text{N}_2$ added. In actual practice we have used a mixture of 90% ^{13}C CO and 10% ^{12}C CO instead of pure ^{13}C CO; varying amounts of $^{12}\text{CH}_2\text{N}_2$ were added to the feedstream and the distribution of isotopic molecules in the propene product was determined by mass spectrometric methods.¹⁰ The total percentage of ^{13}C atoms in the product was determined, and the relative distribution of the various isotopically labeled molecules which would lead to this percentage of ^{13}C , as predicted by the three mechanisms, then calculated.¹¹ In Figure 2 we have indicated for four different experiments, with varying amounts of CH_2N_2 added, the distribution of molecules leading to the observed percentages of ^{13}C in the propene as predicted by the three mechanisms, together with the experimentally observed distribution. The total number of molecules have been arbitrarily normalized to eight. It should be noted that in the Pichler-Schultz theory there can be no less than 60% of ^{13}C in the product no matter how much $^{12}\text{CH}_2$ is deposited on the surface; the other two schemes allow for less than this if sufficient $^{12}\text{CH}_2$ is added.¹²

In Figure 2a,b the data are shown for experiments where 65.4% and 60.1% ^{13}C were found in the propene product and obviously only that distribution as predicted by the Fischer-Tropsch scheme even closely approximates the experimentally observed distribution.¹³ Addition of relatively more $^{12}\text{CH}_2$ produced propene samples containing 54.9% and 30.0% ^{13}C (Figure 2c,d) and this is incompatible with the Pichler-Schultz scheme; of the two mechanisms still tenable the Fischer-Tropsch scheme again accurately predicts the experimentally observed distribution, while the Anderson-Emmett scheme deviates widely.

Of the three proposed mechanisms being evaluated we conclude that only the sequence of steps outlined in eq 1 remains to be

(10) The reactant gases (8 parts of 90% ^{13}C CO, 6 parts of H_2 , and 100 parts of N_2 , total flow rate 114 mL/min) were passed up an ebullating bed of catalyst consisting of 178 mg of 10% cobalt on 120-140 mesh Cabosil at 250 $^\circ\text{C}$; the catalyst had previously been reduced with H_2 at 400 $^\circ\text{C}$. Varying amounts of CH_2N_2 were introduced to the feedstream, via the N_2 flow line, and the propene in the product analyzed by GCMS methods.

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(12) If pure ^{13}C CO were used this value would be 66%.

(13) The methane component of the product mixture, in that sample in which there was found 60.1% ^{13}C in the propene component, was found to contain approximately 40% ^{13}C . The Pichler scheme predicts this value should be less than 1%, while the Anderson-Emmett and Fischer-Tropsch mechanisms predict 50% and 60%, respectively; the discrepancy with either of the latter two schemes is attributed to the presence of O_2 giving rise to a superficially high value for the mass of 16 (i.e., $^{12}\text{CH}_4$).

considered as the primary mechanism of the Fischer-Tropsch reaction.

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A Novel Synthesis of β -Lactams¹

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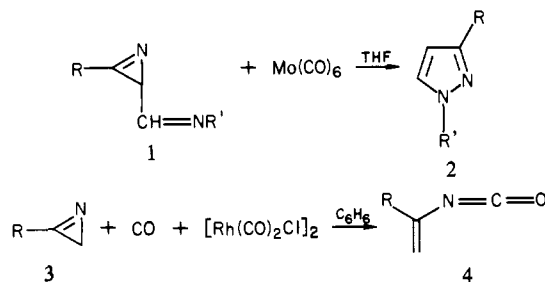
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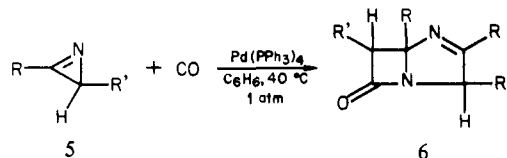
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Investigations during the past five years have uncovered some fascinating metal complex induced ring-opening reactions of azirines.³⁻¹⁶ Examples include the intramolecular cycloaddition of azirines in the presence of group 6 metal carbonyls ($1 \rightarrow 2$)⁸ and the carbonylation of the heterocycles to vinyl isocyanates ($3 \rightarrow 4$) in the presence of chlorodicarbonylrhodium(I) dimer.¹⁶ This communication describes the remarkable palladium(0)-catalyzed carbonylation of azirines.



When carbon monoxide was bubbled through a benzene solution of 2-(*p*-tolyl)azirine (**5**, $\text{R} = p\text{-CH}_3\text{C}_6\text{H}_4$, $\text{R}' = \text{H}$) in the presence



of catalytic amounts of tetrakis(triphenylphosphine)palladium for 1 day at 40 $^\circ\text{C}$, the bicyclic β -lactam **6** ($\text{R} = p\text{-CH}_3\text{C}_6\text{H}_4$; $\text{R}' = \text{H}$) was obtained in 50% (yields are of analytically pure

(1) Issued as N.R.C.C. No. 19132.

(2) E.W.R. Steacie Fellow, 1980-82.

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Table I. Pertinent Spectral Data for 6

6, R, R'	mp, °C ^a	ν_{CO} , cm ⁻¹ ^b	MS m/e	¹ H NMR, δ ^c
<i>p</i> -CH ₃ C ₆ H ₄ , H ^d	109–111	1780	290	2.35 (s, 6 H, methyl protons), 3.55 (s, 2 H, CH ₂), 3.95, 5.00 (d each, 2 H, CH ₂ , <i>J</i> = 16 Hz), 7.05–7.90 (m, 8 H, aromatic protons)
Ph, H ^e	144–146	1780	262	3.59 (s, 2 H, CH ₂), 4.00, 5.10 (d, each, 2 H, CH ₂ , <i>J</i> = 16 Hz), 7.20–7.90 (m, 10 H, aromatic protons)
<i>p</i> -ClC ₆ H ₄ , H	40–42	1780		3.53 (s, 2 H, CH ₂), 3.93, 5.30 (d each, 2 H, CH ₂ , <i>J</i> = 16 Hz), 7.20–7.90 (m, 8 H, aromatic protons)
<i>p</i> -BrC ₆ H ₄ , H	145.5–147.0	1783	420	3.53 (s, 2 H, CH ₂), 3.92, 4.98 (d each, 2 H, CH ₂ , <i>J</i> = 16 Hz), 7.30–7.80 (m, 8 H, aromatic protons)
Ph, CH ₃	oil	1763	290	1.35, 1.62 (dd each, 6 H, methyl protons), 3.78 (m, 1 H, CH), 4.63 (m, 1 H, CH), 7.08–7.78 (m, 10 H, aromatic protons)

^a Satisfactory analytical data (C, H, N) were obtained for all products. ^b CHCl₃ solution. ^c CDCl₃ with Me₄Si as internal standard. ^d ¹³C NMR data δ 21.11 (CH₃), 21.54 (CH₃), 53.23 (CH₂), 55.97 (CH₂), 92.66 (\geq C–N), 125.53, 128.34, 128.78, 129.17, 129.48, 136.90, 137.96, 142.42 (aromatic carbons), 170.19 (CO), 179.37 (CN). ^e ¹³C NMR data δ 53.46 (CH₂), 56.09 (CH₂), 92.91 (\geq C–N), 125.57, 128.40, 128.59, 131.44, 131.98, 139.68 (aromatic carbons), 170.50 (CO), 179.21 (CN).

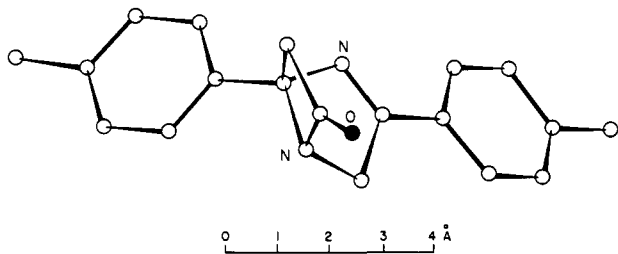
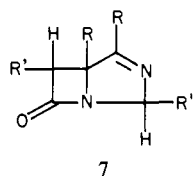


Figure 1. Molecular structure of 6, R = *p*-CH₃C₆H₄, R' = H, as determined by X-ray crystallography; *R* = 0.10. Further refinement of the data is in progress and will be published later. Pertinent X-ray data for 6, R = *p*-CH₃C₆H₄, R' = H—monoclinic; *P*2₁/*a*; *a* = 19.176 (1), *b* = 5.745 (1), *c* = 15.144 (1) Å; β = 109.82 (1)°, *Z* = 4; *D*_c = 1.229 g/cm³.

materials—crude yields were much higher). The ratio of azirine/Pd(PPh₃)₄ used was 10:1. Structure elucidation of 6 was made on the basis of analytical and spectral data (Table I) as well as an X-ray analysis. The infrared spectrum (CHCl₃) of 6 (R = *p*-CH₃C₆H₄, R' = H) showed a carbonyl stretching band at 1780 cm⁻¹, characteristic of a β -lactam unit. While the methylene protons of the β -lactam ring occurred as a singlet in the proton magnetic resonance spectrum at δ 3.55, those of the imidazoline ring were nonequivalent (δ 3.95, 5.00). In the carbon magnetic resonance spectrum, the pair of methyl and methylene carbons were each nonequivalent (the methyl groups occurred as a singlet in the ¹H NMR spectrum), and the carbonyl and unsaturated carbon of the five-membered ring gave signals at δ 170.19 and 179.37, respectively.¹⁷ A molecular ion peak was observed in the mass spectrum, with loss of carbon monoxide being an important fragmentation.

Although structure 6 could be assigned on the basis of the spectral data, isomers such as 7 could not be ruled out. Con-

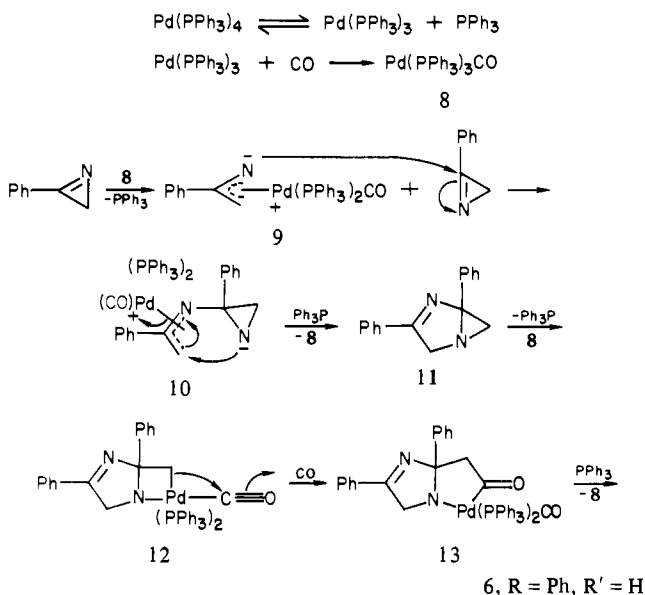


sequently, an X-ray analysis of 6 (R = *p*-CH₃C₆H₄, R' = H) was undertaken to unambiguously establish the structure. The structure, given in Figure 1, shows the interesting geometry of the β -lactam with respect to the five-membered ring.

The palladium(0)-catalyzed carbonylation reactions of 2-phenylazirine, 2-(*p*-chlorophenyl)azirine, 2-(*p*-bromophenyl)azirine, and 2-phenyl-3-methylazirine were effected in the manner described for 2-(*p*-tolyl)azirine to give 6 (R = Ph, R' = H; R = *p*-ClC₆H₄, R' = H; R = *p*-BrC₆H₄, R' = H; R = Ph, R' = CH₃)

(17) The carbonyl carbon signal appeared at a similar chemical shift to the analogous carbon in related penam systems (Hamlet, B.; Durst, T., unpublished results).

Scheme I



in yields of 63, 37, 55, and 25%, respectively (yields were not optimized). Pertinent spectral data are given in Table I.

A possible pathway to account for the formation of 6 from 5 is outlined in Scheme I (illustrated for 2-phenylazirine). Formal ligand substitution of a phosphine ligand of the catalyst by carbon monoxide would give 8. The latter may then effect carbon–nitrogen bond cleavage of the azirine affording the azaallyl complex 9. π -Allyl complexes have been invoked as intermediates in a number of important palladium-catalyzed reactions.^{18,19} Reaction of 9 with another molecule of 2-phenylazirine would produce 10, which on cyclization and decomplexation forms the bicyclic system 11. Insertion of palladium into a carbon–nitrogen bond of 11 would give 12 which on ligand migration (13) and reductive elimination would afford the β -lactam and regenerate the catalyst. It must be emphasized that the scheme, at present, is a working hypothesis and a detailed investigation of the reaction mechanism needs to be done.

The following general procedure was used: a mixture of azirine (10 mmol) and Pd(PPh₃)₄ (1.0 mmol) in dry benzene (50 mL) was stirred at 40 °C while a slow stream of carbon monoxide was passed through the solution. Stirring was continued until thin layer chromatographic analysis indicated that the azirine was consumed (usually overnight). The reaction mixture was concentrated (rotary evaporation) and then chromatographed on silica gel. Elution with benzene–chloroform gave the pure β -lactam.

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In conclusion, the palladium-catalyzed carbonylation of azirines to fused β -lactams is a mild process of genuine novelty. β -Lactams are an important class of antibiotics, and there has been great interest in recent years in the synthesis of hetero (e.g., aza,²⁰ oxa²¹) as well as carbon (e.g., thienamycin)²² analogues of penicillin. We are actively investigating the application of the above described reaction to the synthesis of appropriately functionalized aza analogues of penicillin.

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Cyclen Phosphonium and Homologous Cations. Dimerization in Strained PN_4^+ Systems

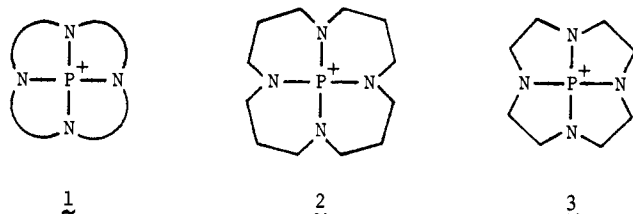
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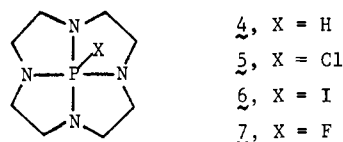
We wish to report the synthesis of the series of polycyclic tetrakis(substituted-amino)phosphonium ions (**1**) and the evidence that aminophosphonium ions can dimerize if the phosphorus is constrained from a tetrahedral geometry.¹



(Curved lines in **1** and **10** represent ethylene and/or trimethylene bridges.)

Models indicate that the four trimethylene bridges of **2** can easily accommodate a tetrahedral phosphonium center. However, the phosphorus in cyclen phosphonium ion (**3**) is constrained to a distorted tetrahedral geometry.²

We have found that cyclen phosphorane (**4**) is oxidized by



carbon tetrachloride producing chloroform and a hygroscopic crystalline solid. The mass spectrum of this solid at high temperature exhibits the molecular ions of cyclen chlorophosphorane (**5**). The analogous reaction of **4** with trifluoromethyl iodide produces a crystalline iodide that analyzes correctly for **6**.

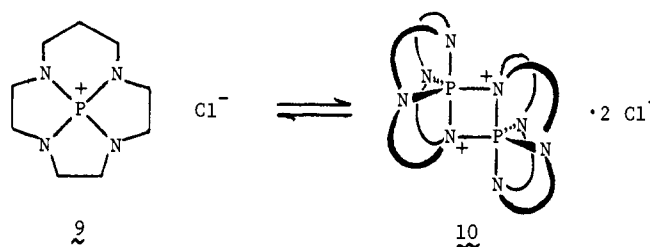
(1) For analogous dimerizations in strained tris(substituted-amino)boranes, see: Richman, J. E.; Yang, N.-C.; Andersen, L. L. *J. Am. Chem. Soc.* **1980**, *102*, 5790.

(2) The X-ray structures of two pentavalent derivatives of **3**, dicyclenphosphorane and **7**, suggest that the geometry of PN_4^+ in **3** will be constrained to resemble that of SF_4 . (a) Richman, J. E. *Tetrahedron Lett.* **1977**, 559. (b) Richman, J. E.; Day, R. O.; Holmes, R. R. *J. Am. Chem. Soc.* **1980**, *102*, 3955.

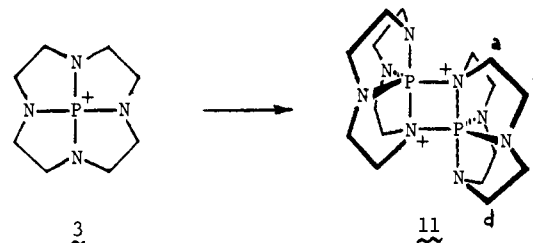
Other physical and spectroscopic properties of these solids are not consistent with covalent structures **5** and **6** but rather suggest ionic structures. Unlike the fluoro derivative **7**, which is known to be covalent,^{2a} the chloro and iodo derivatives are insoluble in nonpolar solvents, nonvolatile, and high melting ($>200^\circ\text{C}$). The iodo compound in nitromethane has a conductance similar to that of tetrakis(dimethylamino)phosphonium iodide, $(\text{Me}_2\text{N})_4\text{P}^+\text{I}^-$ (**8**).³ However, the ^{31}P NMR spectra of these nitromethane solutions are very different: both **5** and **6** show unusually high-field singlets at -9.6 ppm, while **8** appears as a singlet at $+43.3$ ppm.⁴

We originally assigned structure **3** to the common cation of the chloride and iodide salts. However, when we prepared the homologous series of cations represented by structure **1**,⁵ we found that the chemical shift of the ion to which we had assigned structure **3** does not fit the trends in ^{31}P shifts for this series. Cation **2** shows a singlet at $+15$ ppm and the lower homologues of **2** exhibit singlets at progressively lower field. In dilute solution in CDCl_3 homocyclen phosphonium chloride (**9**) appears at $+65$ ppm.⁶

In addition to this low-field singlet ($+65$ ppm) more concentrated solutions of **9** also exhibit four higher field ^{31}P NMR signals from -23 to -30 ppm. We attribute these high-field signals to structures **10** which are formed by dimerization of **9**.⁷



Cyclen phosphonium ion (**3**) is expected to be more strained than **9** and the phosphonium center in **3** should show even greater tendency to dimerize.¹ On the basis of this comparison, it is



reasonable that the singlet at -9.6 ppm originally assigned to cyclen phosphonium ion (**3**) actually arises from the dimeric cation (**11**). The ^{31}P shift of this cation is downfield from that for **10** by about the same difference in shift as that affected by a ring contraction in the monomeric cations (**1**).

The ^{13}C NMR spectrum of cation **11** supports the symmetry of this cation. Four singlets are observed in the decoupled spectrum.⁸ One of these four signals is broadened considerably more than the other three, as is expected for carbon a with two unresolved $^2J_{\text{PC}}$ couplings rather than one.

(3) The specific conductivities at 25°C of 0.01 M solutions (based on monomeric structures) in nitromethane for **6** and **8** are 7.3 and 9.7 S/cm ($\times 10^2$).

(4) Phosphorus and carbon chemical shifts are reported with positive values downfield from external 85% H_3PO_4 and Me_4Si .

(5) Oxidation of the homologues of **4** (Atkins, T. J.; Richman, J. E. *Tetrahedron Lett.* **1978**, 5149) with carbon tetrachloride in each case gives the phosphonium chloride salt with acceptable C, H, N analyses in good yield. Unpublished results (T. J. Atkins, DuPont) indicate that 2-Cl can also be prepared by oxidation with *tert*-butyl hypochlorite.

(6) The phosphonium salt with a periphery of 15 atoms appears at $+25.4$ ppm, while the symmetrical and unsymmetrical salts with peripheries of 14 atoms appear at $+31.4$ and $+43.2$ ppm.

(7) The six isomers of **10** differ in location of the unique trimethylene bridges. Only four signals are expected for these six compounds because two of the isomers have chemically nonequivalent (broadened) phosphorus atoms.

(8) The four ^{13}C signals (in CDCl_3) are at -23.1 , -26.4 , -26.9 , and -29.6 ppm.