

temperature) of tetrols that were extracted into ethyl acetate and chromatographed by high pressure liquid chromatography (LC). The ratio of liberated tetrols corresponding to trans and cis addition of water to the diol epoxides at C-10 were 44:56 from **1** and 70:30 from **2**. In a control incubation in the absence of enzyme, the phosphate esters were essentially stable. In contrast, they slowly hydrolyzed ( $t_{1/2} > 1$  day) in the concentrated phosphate solvolysis solutions.

- (13) Products were analyzed by LC on a Du Pont Zorbax-ODS column (6.2 mm X 25 cm). The material assumed to be phosphate ester was not retained by the column (0–100% linear gradient of methanol–water, 1%/min, 1.2-mL/min flow rate) and displayed a 7,8,9,10-tetrahydrobenzo[*a*]pyrene fluorophore identical with that of the tetrols that eluted much later.
- (14) Kinetic solvent deuterium isotope effects  $k_{H_2PO_4^-}/k_{D_2PO_4^-}$  for the phosphate catalyzed reactions of **1** and **2** in 10% dioxane–water were also measured and found to be  $2.0 \pm 0.2$  and  $1.9 \pm 0.1$  for **1** and **2**, respectively.
- (15) The ratio of cis:trans addition of water to **2** in 0.02 M  $\text{NaH}_2\text{PO}_4$  (pH 7.45) was also 2:98. At this same pH in the absence of phosphate, the spontaneous hydrolysis ( $k_0$ ) of **2** predominates and gives >50% cis addition of solvent.
- (16) Reaction of **1** and **2** in 0.4 M phenol (pH 9.23) yielded mainly phenol adducts, with cis addition of phenol favored over trans addition. LC analysis<sup>13</sup> of the products from **1** indicated the formation of 57% material cochromatographic with cis adduct (retention time, 29.5 min),<sup>3</sup> 17% material assumed to be trans adduct (retention time, 29.0 min), ~2% tetrols, and 24% several unidentified materials. Analysis of the products from **2** indicated the formation of 70% material cochromatographic with cis adduct (retention time, 28.0 min),<sup>3</sup> 17% material assumed to be trans adduct (27.5 min), ~2% tetrols, and ~11% several unidentified materials.
- (17) P. Y. Bruice and T. C. Bruice, *J. Am. Chem. Soc.*, **98**, 2023 (1976).
- (18) D. L. Whalen, *J. Am. Chem. Soc.*, **95**, 3432 (1973).
- (19) D. L. Whalen and A. M. Ross, *J. Am. Chem. Soc.*, **96**, 3678 (1974).
- (20) The kinetic solvent deuterium isotope effects ( $k_{H_2O}/k_{D_2O}$ ) for hydrolysis of **1** and **2** by the spontaneous mechanism in 0.1 M  $\text{NaClO}_4$  solutions were measured and found to be  $2.4 \pm 0.1$  and  $1.7 \pm 0.2$ , respectively.
- (21) General acid catalyzed opening of an epoxide by water would generate a carbonium ion–hydroxide ion pair that need not yield the same product distribution as the cation generated in the hydronium ion catalyzed route.
- (22) (a) P. Y. Bruice, T. C. Bruice, H. Yagi, and D. M. Jerina, *J. Am. Chem. Soc.*, **98**, 2973 (1976); (b) A. R. Becker, J. M. Janusz, D. Z. Rogers, and T. C. Bruice, *ibid.*, **100**, 3244 (1978).

Dale L. Whalen,\* Angela M. Ross  
Jean A. Montemarano

Laboratory for Chemical Dynamics  
Department of Chemistry  
University of Maryland Baltimore County  
Catonsville, Maryland 21228

Dhiren R. Thakker, Harukiko Yagi  
Donald M. Jerina\*

Laboratory of Bioorganic Chemistry  
National Institute of Arthritis, Metabolism, and  
Digestive Diseases, National Institutes of Health  
Bethesda, Maryland 20014

Received March 6, 1979

## Reactivity of Cyclopropylchlorocarbene: an Interactive Experimental and Theoretical Analysis

Sir:

The geometries, energies, and electronic distributions of isolated singlet and triplet carbenes have been calculated.<sup>1</sup> Related techniques have defined energetically probable reaction pathways for simple carbenic abstraction, addition, or insertion reactions.<sup>1</sup> Rarely, however, have experimental and theoretical approaches been simultaneously focussed on a specific problem of intermolecular carbenic reactivity.<sup>2</sup> In this communication we present an interactive experimental and calculational analysis of the olefinic selectivity of cyclopropylchlorocarbene, illustrating this combined approach's potential for detailed elucidation of carbenic reaction mechanisms.

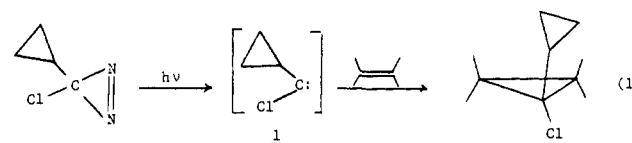
Cyclopropylchlorocarbene (**1**)<sup>3</sup> was photolytically generated ( $\lambda > 300$  nm, 25 °C) from the diazirene<sup>4</sup> in large excesses of

Table I. Relative Reactivities of Cycloalkylchlorocarbenes<sup>a</sup>

olefin	$k_{rel}$ for <i>c</i> -C <sub>3</sub> H <sub>5</sub> CCl ( <b>1</b> )	$k_{rel}$ for <i>c</i> -C <sub>4</sub> H <sub>7</sub> CCl ( <b>2</b> )
Me <sub>2</sub> C=CMe <sub>2</sub>	2.41 ± 0.02	1.49 ± 0.02
Me <sub>2</sub> C=CHMe <sup>b</sup>	1.75 ± 0.01	1.75 ± 0.02
Me <sub>2</sub> C=CH <sub>2</sub> <sup>c</sup>	1.00	1.00
<i>c</i> -MeCH=CHMe <sup>b</sup>	0.67 ± 0.02	0.96 ± 0.02
<i>t</i> -MeCH=CHMe	0.46 <sup>d</sup>	0.46 <sup>e</sup>

<sup>a</sup> Errors are average deviations of two experiments. <sup>b</sup> The reactivity is the sum of *syn*-Cl and *anti*-Cl carbenic additions to this alkene.<sup>9b</sup> <sup>c</sup> Standard alkene. <sup>d</sup> This value was obtained indirectly from the competitions: *t*-MeCH=CHMe/*c*-MeCH=CHMe ( $k_{rel} = 0.68 \pm 0.01$ ) and *c*-MeCH=CHMe/Me<sub>2</sub>C=CH<sub>2</sub> (cf. table for  $k_{rel}$ ). <sup>e</sup> This value was obtained as in *d*, with  $k_{rel} = 0.48 \pm 0.01$  for *t*-MeCH=CHMe/*c*-MeCH=CHMe.

selected binary alkene mixtures (eq 1). Quantitative GC analysis (calibrated to detector) of the known<sup>3</sup> product chlo-



robicyclopopyls, coupled with standard competition reaction analysis,<sup>5</sup> gave the relative reactivities in Table I. Satisfactory cross-check competitions<sup>5</sup> linked the reactivities of the substrate triads Me<sub>2</sub>C=CMe<sub>2</sub>, Me<sub>2</sub>C=CHMe, Me<sub>2</sub>C=CH<sub>2</sub> and Me<sub>2</sub>C=CMe<sub>2</sub>, Me<sub>2</sub>C=CH<sub>2</sub>, *c*-MeCH=CHMe. Least-squares correlation of log ( $k_i/k_0$ ) for carbene **1** with comparable data for CCl<sub>2</sub><sup>6</sup> afforded the relation shown in Figure 1; the slope of the regression line,  $m_1^{obsd}$ , was 0.41.<sup>7</sup>

Carbene selectivity indices ( $m_{CXY}$ ) can be estimated from the empirically based equation (2),<sup>8</sup> in which the  $\Sigma$  terms represent the sums of the appropriate  $\sigma$  constants<sup>9a</sup> for the substituents of CXY.

$$m_{CXY} = -1.10 \sum_{X,Y} \sigma^+ + 0.53 \sum_{X,Y} \sigma_j - 0.31 \quad (2)$$

From the rate constants, and derived values of  $\sigma_p^+$  and  $\sigma_m$ , for solvolyses of *p*- and *m*-cyclopropyl-*tert*-cumyl chlorides in 90% aqueous acetone,<sup>10</sup> we calculate<sup>11</sup>  $\sigma_R^+ = -0.38$  for cyclopropyl. Using this value, and taking  $\sigma_j = \sigma_m = -0.04$ <sup>10</sup> (eq 2), provides  $m_1^{calcd} = 0.73$ .<sup>11</sup> The discrepancy between  $m_1^{obsd}$  (Figure 1) and  $m_1^{calcd}$  (eq 2),  $\Delta m = 0.32$ , is more than three times the standard deviation in  $\Delta m$  expected from eq 2<sup>8</sup> and must be regarded as significant.

Why is **1** so much less selective than predicted by eq 2?<sup>12</sup> A priori, **1** should prefer *bisected* conformation, **1b**, in which



the "bent" cyclopropyl  $\sigma$  bonds can favorably interact with the vacant carbenic p orbital.<sup>3,13</sup> Studies of molecular models, however, indicate that bisected **1** would encounter substantial steric hindrance in electrophilic addition to alkenes: for the vacant p orbital to adequately overlap with the olefinic  $\pi$  orbital, a cyclopropyl carbon and its pair of H atoms must project down and onto the substrate's olefinic carbon atoms or their substituents. *Twisting* the cyclopropyl ring about the  $\sigma$  bond to the carbenic center relieves these adverse steric interactions. Accordingly, **1** should add to alkenes via a twisted conformation (in the limit **1t**), which is largely unstabilized by cyclo-

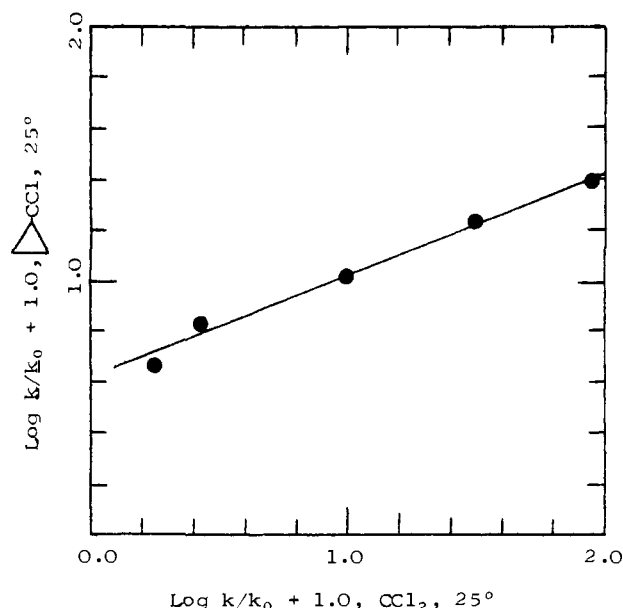


Figure 1.  $\log(k_i/k_0)_1$  vs.  $\log(k_i/k_0)_{\text{CCl}_2}$  at 25 °C. The slope of the regression line is 0.41,  $r = 0.992$ .

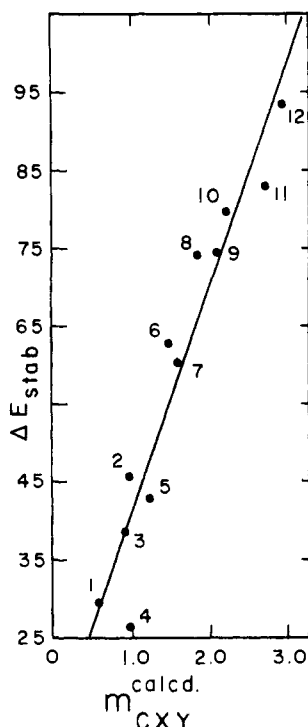
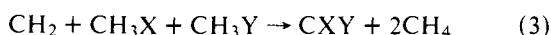


Figure 2. Calculated stabilization energies ( $\Delta E_{\text{stab}}$ ) for CXY vs.  $m_{\text{CXY}}^{\text{calcd}}$ ; see eq 2 and 3 and text. See ref 17 for the numbering of the carbenes.

propyl "conjugation", and should be much less selective than **1b**. This hypothesis immediately explains the discrepancy between  $m_1^{\text{obsd}}$  and  $m_1^{\text{calcd}}$ , because the latter is based on  $\sigma_p^+$  for a "bisected" *p*-cyclopropyl-*tert*-cumyl cation;<sup>14</sup>  $\sigma_R^+$  (and  $m_1^{\text{calcd}}$ ) would be substantially reduced for a "twisted" *p*-cyclopropyl-*tert*-cumyl cation.<sup>14</sup>

Ab initio calculations support the hypothesis of "twisted" cyclopropylchlorocarbene addition. The stabilization of CXY, relative to the corresponding substituted methane, was calculated according to the isodesmic reaction:<sup>15</sup>



The negatives of the 4-31G energies<sup>16a</sup> of twelve such reactions were defined as "carbene stabilization energies",  $\Delta E_{\text{stab}}$ , and

correlated excellently ( $r = 0.96$ , significant at the 99.9% confidence level) with  $m_{\text{CXY}}^{\text{calcd}}$ , calculated from eq 2; cf. Figure 2.<sup>15,17</sup> Next,  $\Delta E_{\text{stab}}$  was calculated<sup>16a</sup> for **1**, held in conformations **1b** or **1t**, affording  $\Delta E_{\text{stab}}^{\text{1b}} = 35.9$  and  $\Delta E_{\text{stab}}^{\text{1t}} = 26.4$  kcal/mol.<sup>16b</sup>

These results not only confirm expectations<sup>13</sup> that bisected **1b** is more stable (by  $\sim 9.5$  kcal/mol) than twisted **1t**, but, using the correlation of Figure 2,<sup>18</sup> they generate  $m_{\text{1b}}^{\text{calcd}} = 0.81$  and  $m_{\text{1t}}^{\text{calcd}} = 0.48$ . Clearly,  $m_1^{\text{calcd}}$  from eq 2, 0.73, is perfectly appropriate to bisected carbene **1b**, whereas  $m_1^{\text{obsd}}$  from Figure 1 (0.41) is equally appropriate to twisted carbene **1t**. The conflict between  $m_1^{\text{obsd}}$  and  $m_1^{\text{calcd}}$  is thus resolved. Moreover, the correspondence between  $m_1^{\text{obsd}}$  and  $m_{\text{1t}}^{\text{calcd}}$  strongly supports the hypothesis of twisted cyclopropylchlorocarbene addition.

Further (experimental) evidence comes from selectivity comparisons of **1** with cyclobutylchlorocarbene (**2**).<sup>19</sup> Relative reactivities of **2** were determined similarly to those of **1**. Excepting an apparent steric problem in the addition of **2** to  $\text{Me}_2\text{C}=\text{CMe}_2$ , Table I reveals a near congruity between olefinic selectivities of carbenes **2** and **1**. Because cyclopropyl is ordinarily considerably more effective than cyclobutyl at electronic stabilization of adjacent cations,<sup>10</sup> one would expect **1** to be significantly more discriminating than **2**. The similar selectivities are understandable, however, if **1** (and **2**) attacks alkenes via twisted conformations, in which the resonance-based electronic differences between cyclopropyl and cyclobutyl groups have been leveled.

The power of a combined experimental and calculational approach to problems of carbenic selectivity is now readily apparent; other applications will be reported in due course.

**Acknowledgments.** We gratefully acknowledge support of this research at Rutgers University by the National Science Foundation (CHE 75-22810) and the Public Health Service (Research Grant CA-14912 from the National Cancer Institute) and at Louisiana State University by the National Science Foundation (CHE 76-11839).

## References and Notes

- Reviews: Gaspar, P. P.; Hammond, G. S. In "Carbenes," Moss, R. A., Jones, M., Jr., Ed.; Wiley: New York, 1975; Vol. II, pp 207 ff. Houk, K. N. In "Reactive Intermediates," Jones, M., Jr., Moss, R. A., Ed.; Wiley: New York, 1978; Vol. 1, p 286 ff.
- A fortuitous example is the study of stereoselectivity in the cyclopropanation of *cis*-butene by CFCI: Fueno, T.; Nagase, S.; Tatsumi, K.; Yamaguchi, K. *Theoret. Chim. Acta*, **1972**, *26*, 43. Moss, R. A.; Gerstl, R. *Tetrahedron* **1967**, *23*, 2549.
- Moss, R. A.; Fantina, M. E. *J. Am. Chem. Soc.* **1978**, *100*, 6788.
- Graham, W. H. *J. Am. Chem. Soc.* **1965**, *87*, 4396.
- Moss, R. A. In "Carbenes," Jones, M., Jr., Moss, R. A., Ed.; Wiley: New York, 1973; Vol. I, p 153 ff.
- Reference 5, p 221.
- The correlation coefficient ( $r$ ) was 0.992, significant at the 99.9% confidence level.
- Moss, R. A.; Mallon, C. B.; Ho, C.-T. *J. Am. Chem. Soc.* **1977**, *99*, 4105.
- (a) Ehrenson, S.; Brownlee, R. T. C.; Taft, R. W. *Prog. Phys. Org. Chem.* **1973**, *10*, 1. (b) Cyclopropylchlorocarbene adds to *cis*-butene affording an 8:1 isomer distribution,<sup>3</sup> in which the *syn*-Cl,*anti*-cyclopropyl isomer dominates: Moss, R. A.; Munjal, R. C., unpublished work. Addition in this mode is favorable because the cyclopropyl ring is opposed only by olefinic H atoms and need not twist (cf. below) as much to relieve steric problems as is necessary in the *syn*-cyclopropyl,*anti*-Cl addition mode.
- Hahn, R. C.; Corbin, T. F.; Shechter, H. *J. Am. Chem. Soc.* **1968**, *90*, 3404.
- Reference 9a, p 31.  $\sigma_R^+$  and  $\sigma_I$  values for Cl are also taken from ref 9a.
- Carbene **1** is also less selective than PhCCl ( $m^{\text{obsd}} = 0.83$ ) and  $\text{CH}_3\text{CCl}$  ( $m^{\text{obsd}} = 0.50$ ), both of which are well-behaved with regard to eq 2.<sup>8</sup>
- Hoffmann, R.; Zeiss, G. D.; Van Dine, G. W. *J. Am. Chem. Soc.* **1968**, *90*, 1485. See also the calculations described below.
- Cf. Brown, H. C.; Cleveland, J. D. *J. Org. Chem.* **1976**, *41*, 1792.
- Rondan, N. G.; Houk, K. N.; Moss, R. A., unpublished work.
- (a) Carbene geometries were optimized by ab initio calculations at the STO-3G level. For carbene **1**, the orientation of the cyclopropyl ring was fixed as in either **1b** or **1t** (the cyclopropyl ring was twisted  $90^\circ$  from the bisected orientation of **1b**) and all cyclopropyl bond lengths and bond angles were taken from Lathan, W. A.; Radom, L.; Hariharan, P. C.; Hehre, W. J.; Pople, J. A. *Fortschr. Chem. Forsch.* **1973**, *40*, 1. Then,  $r_{\text{C-C}}$ ,  $r_{\text{C-Cl}}$ , and  $\angle\text{C-C-Cl}$  at the carbenic center were optimized by calculation. After

geometric optimization, carbene energies were calculated with the split-valence 4-31G basis set.<sup>15</sup> (b) Rotation of the cyclopropyl group of **1b** about the  $\sigma$  bond to the carbenic center by 180° produces a new "bisected" conformer which is calculated to be 2.5 kcal/mol more energetic than **1b**.

- (17) The carbenes were 1, ClCCH<sub>3</sub>; 2, FCPH; 3, ClCSCH<sub>3</sub>; 4, CCl<sub>2</sub>; 5, FCl; 6, CF<sub>2</sub>; 7, ClCOCH<sub>3</sub>; 8, FCOCH<sub>3</sub>; 9, FCOH; 10, C(OCH<sub>3</sub>)<sub>2</sub>; 11, C(OH)<sub>2</sub>; 12, CH<sub>3</sub>OCN(CH<sub>3</sub>)<sub>2</sub>.

(18) The analytical form of Figure 2 is  $\Delta E_{\text{stab}} = 28.6m_{\text{CXY}} + 12.8$ .

- (19) Moss, R. A.; Fantina, M. E.; Munjal, R. C. *Tetrahedron Lett.* **1979**, 1277.

Robert A. Moss,\* Margherita Vezza  
Wenjeng Guo, Ramesh C. Munjal

Department of Chemistry, Rutgers  
The State University of New Jersey  
New Brunswick, New Jersey 08903

K. N. Houk, Nelson G. Rondan

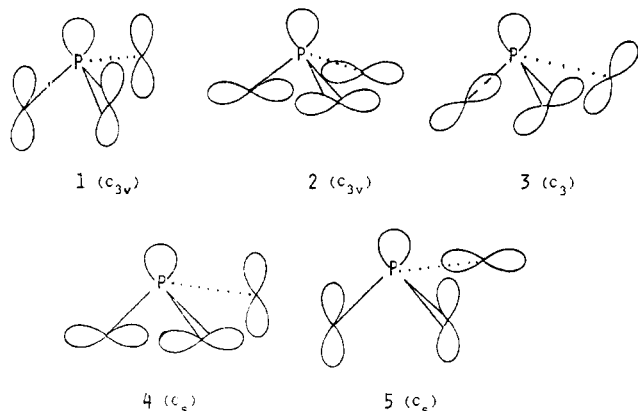
Department of Chemistry, Louisiana State University  
Baton Rouge, Louisiana 70803

Received May 29, 1979

### Conformation of Ligated Tris(dimethylamino)phosphine

Sir:

The electronic and molecular structures of tris(dialkylamino)phosphines have attracted attention recently. Several symmetrical conformations, such as **1-5**, can be considered for



this class of molecule.<sup>1</sup> In an electron diffraction study, Vilkov and co-workers<sup>2</sup> concluded that the geometry of (Me<sub>2</sub>N)<sub>3</sub>P is **3**. In 1973 the ultraviolet photoelectron spectrum (UV PES)

of (Me<sub>2</sub>N)<sub>3</sub>P was measured and interpreted according to structure **4**.<sup>3</sup> In subsequent UV PES work Lappert and co-workers<sup>4</sup> concluded that the structure of (Me<sub>2</sub>N)<sub>3</sub>P could be C<sub>3v</sub> (**1**) and suggested that the pattern of low ionization peaks may be due to Jahn-Teller splitting of the <sup>2</sup>E state of the radical cation rather than to the adoption of the C<sub>s</sub> ground-state geometry, **4**. In 1977 UV PES work on tris(dialkylamino)phosphines, Hargis and Worley<sup>5</sup> concluded that our original model was correct but presented a slightly different spectral assignment. In the most recent UV PES work on free and coordinated (Me<sub>2</sub>N)<sub>3</sub>P, Yarbrough and Hall<sup>6</sup> concluded that our original assignments were correct. To probe this question further we have performed molecular orbital (MO) calculations on the model compound, (H<sub>2</sub>N)<sub>3</sub>P, and determined the X-ray crystal structure of [(Me<sub>2</sub>N)<sub>3</sub>P]<sub>2</sub>Fe(CO)<sub>3</sub>.<sup>7,8</sup>

The MO calculations on (H<sub>2</sub>N)<sub>3</sub>P were performed with the GAUSSIAN 76<sup>9</sup> and the FORCE<sup>10</sup> programs using STO3G and STO3G\* basis sets. Regardless of the presence or absence of d orbitals in the basis set, the C<sub>3</sub> conformation, **3**, emerged as the most stable. However, the geometry-optimized structures corresponding to the C<sub>3</sub> (**3**) and C<sub>s</sub> (**4**) conformations are rather close in energy.<sup>11</sup> With the STO3G basis set conformation **3** is computed to be more stable than **4** by 3.53 kcal/mol, while with the STO3G\* basis set the energy difference is reduced to 1.19 kcal/mol.

Colorless crystals of [(Me<sub>2</sub>N)<sub>3</sub>P]<sub>2</sub>Fe(CO)<sub>3</sub> were grown from acetone solution. The complex crystallizes in the monoclinic system, space group P2<sub>1</sub>/c, with 4 molecules per unit cell:  $a = 11.177$  (1),  $b = 15.778$  (1),  $c = 13.270$  (2) Å;  $\beta = 90.09$  (1)°. X-ray data were collected on a Syntex P2<sub>1</sub> automated diffractometer. The structure was solved by conventional heavy-atom methods using 4233 observed reflections. Full-matrix least-squares refinement afforded a conventional  $R$  value of 0.041.

The overall geometry of [(Me<sub>2</sub>N)<sub>3</sub>P]<sub>2</sub>Fe(CO)<sub>3</sub> is trigonal-bipyramidal with the aminophosphine ligands occupying axial positions. By far the most interesting structural feature is the fact that the two (Me<sub>2</sub>N)<sub>3</sub>P ligands adopt different conformations;<sup>12</sup> one (P-1) possesses approximately C<sub>s</sub> skeletal symmetry, while the other (P-2) has an unsymmetrical structure of roughly C<sub>3</sub> symmetry (Figures 1 and 2). It seems clear, therefore, that conformations **3** and **4** are rather close in energy as indicated in the MO calculations.

Also significant is the fact that the nitrogen atoms with lone pairs approximately trans (dihedral angle,<sup>13</sup>  $\phi \sim 180^\circ$ ) to the

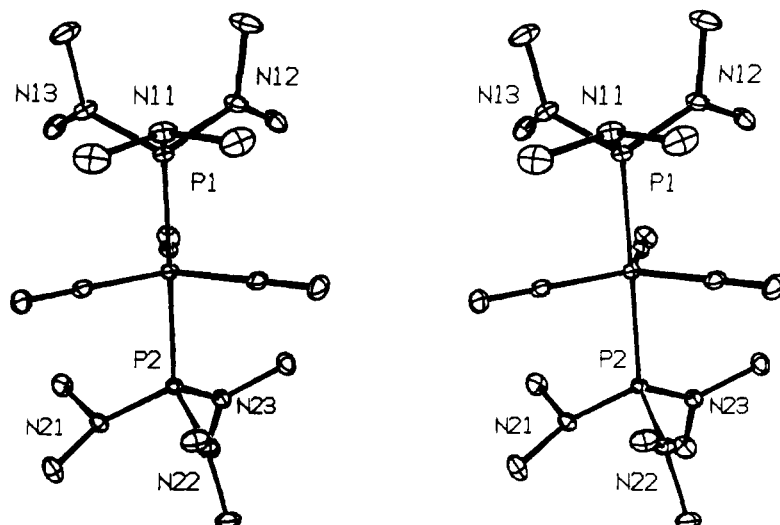


Figure 1. Stereoview of the [(Me<sub>2</sub>N)<sub>3</sub>P]<sub>2</sub>Fe(CO)<sub>3</sub> molecule, illustrating the atom numbering scheme. The hydrogen atoms are omitted; all other atoms are shown as ellipsoids of 30% probability.