

probably not the cause of the discrepancy, as higher energy $\text{CH}_3\text{C}_6\text{H}_4\text{Br}^+$ ions should have even less tendency to undergo the tight-complex isomerization reaction than the loose complex $\text{CH}_3\text{C}_6\text{H}_4\text{Br}^{\cdot+}$ reaction. It would appear that the energy requirements for the reactions 7 or $7' \rightarrow 5 \rightarrow 1$ and 7 or $7' \rightarrow 11$ or $11' \rightarrow 2$ are higher than that for $6 \rightarrow 2$, but still lower than that for 7 or $7' \rightarrow 3$ or 9 .

Norbornadienyl Ions. The CA spectra of C_7H_7^+ ions from 7-acetoxy- and, especially, 7-benzyloxynorbornadiene also appear to be distinctive, although the dif-

ferences are less pronounced. The CA m/e 74 peak is smaller than that found for the tolyl ions, and the m/e 77 peak is smaller than in the CA spectra of **1** and **2**; we conclude that a major portion of the C_7H_7^+ ions have the norbornadienyl structure, **4**. Norbornadiene and the other derivatives studied give C_7H_7^+ CA spectra indicating that appreciable quantities of **2** ions are formed, although the remaining C_7H_7^+ ions could be **1** and/or **4**. Labeling experiments of Skell²⁸ show that the norbornadiene cation can undergo a specific elimination of C_2H_2 .

1-Phosphabicyclo[2.2.1]heptane 1-Oxide and 1-Phosphabicyclo[2.2.2]octane 1-Oxide. Syntheses and Some Properties Relative to Their Monocyclic and Acyclic Analogs¹

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Abstract: 1-Phosphabicyclo[2.2.1]heptane 1-oxide (**1**) was prepared in 11% yield by Grignard cyclization of diethyl 5-bromo-3-bromoethylpentylphosphonate (**13**) in refluxing tetrahydrofuran. In an analogous fashion, 1-phosphabicyclo[2.2.2]octane 1-oxide (**2**) was prepared in 6% yield. The sublimable solids were characterized by elemental analyses, mass spectral fragmentation patterns, and by both proton and carbon-13 nmr spectroscopy. The proton nmr spectra at 60 MHz of both **1** and **2** were resolved using the shift reagent tris(dipivalomethanato)-europium(III). The lanthanide-induced shifts for the α protons of **1** and **2** are discussed with respect to the corresponding shifts of various acyclic and monocyclic phosphine oxide analogs. The $J_{\text{P-CH}}$ coupling constant to the proton on the bridgehead carbon of **1** was unusually large (28 Hz). In the proton-decoupled ^{13}C nmr spectra of **1** and **2** each of the different types of carbons appeared as doublets due to coupling to phosphorus. The $J_{\text{P-}^{13}\text{C}}$ values for coupling between bridgehead atoms in **1** and **2** were 35 and 47 Hz, respectively, the unusually large magnitudes of which suggest a Karplus relationship for correlation of $J_{\text{P-}^{13}\text{C}}$ values. The infrared spectra of **1**, **2**, and an isoelectronic series of acyclic and monocyclic phosphine oxides were determined at various percentages of ^{18}O enrichment. The natural abundance spectra of **1** and 1-ethyl-2,2,3-trimethylphosphetane 1-oxide (**3**) showed multiple bands attributable to the phosphoryl stretch, presumably due to Fermi resonance. The phosphoryl-stretching frequencies of this group of compounds, as well as of other phosphine oxides reported in the literature, indicate a correlation between ring strain and phosphoryl bond energy.

Studies on bicyclic compounds with carbon at the bridgehead position have led to useful generalizations^{3,4} about geometrical requirements for certain reactions involving carbon. Similar studies have been carried out with bicyclic compounds having silicon⁵ and sulfur⁶ at the bridgehead position. Since phosphorus, like silicon and sulfur, is a second row element which can utilize d orbitals to form pentavalent compounds⁷ and intermediates^{8,9} with trigonal-bipyramidal struc-

tures, we anticipated that by constraining the geometry of the substituents around phosphorus certain modes of reactivity and spectral properties characteristic of monocyclic and acyclic analogs might be altered for the corresponding bicyclic compounds. Moreover, as discussed in an accompanying paper,¹⁰ we anticipated that certain recent ideas about geometrical constraints on stereomutation, or positional interchange, of pentavalent intermediates in reactions at phosphorus^{8,9,11} might be testable experimentally.

In this paper we describe the syntheses and some of the spectral properties of 1-phosphabicyclo[2.2.1]heptane 1-oxide (**1**)¹² and 1-phosphabicyclo[2.2.2]octane 1-

(1) Communicated, in part, previously: R. B. Wetzel and G. L. Kenyon, *J. Amer. Chem. Soc.*, **94**, 9230 (1972); R. B. Wetzel and G. L. Kenyon, *J. Chem. Soc., Chem. Commun.*, 287 (1973).

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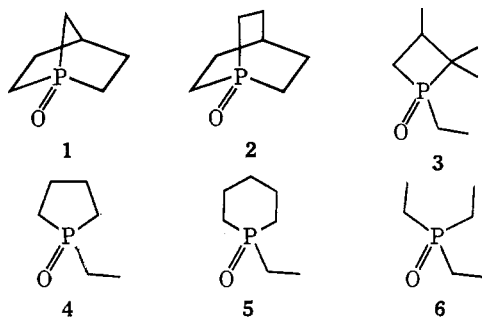
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oxide (2),¹³ as well as 1-ethyl-2,2,3-trimethylphosphetane 1-oxide (3), 1-ethylphospholane 1-oxide (4), and 1-ethylphosphorinane 1-oxide (5). Triethylphosphine oxide (6) was available commercially.



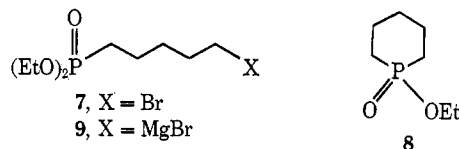
Compound 1 is the first example of a bicyclo[2.2.1] system which has a phosphorus at a bridgehead position and which contains no other heteroatoms in the ring framework.¹² Synthetic approaches to the unsubstituted 1-phosphabicyclo[2.2.2]octane system have been sought in vain for over a decade.¹⁴⁻¹⁷ Unsaturated, substituted systems prepared by routes very different from that described here have been reported recently.¹⁸⁻²⁰ Examples of both bicyclo[2.2.1] and -[2.2.2] bridgehead phosphorus compounds with other heteroatoms in the ring framework have been prepared.²¹

In the course of this study many physical measurements were made on the series of phosphine oxides 1-6, not only for confirmation of structure and as background for the necessary infrared kinetic studies reported in the accompanying paper,¹⁰ but also because the series promised to give some especially valuable comparisons. The isoelectronic nature of the series allows one to factor out the electronic substituent effects on the spectra, so that strain, steric, and conformational effects become at times unequivocal. The spectral techniques where comparisons have proved most fruitful are infrared, carbon-13 nmr, and lanthanide shift effects in proton nmr.

Results and Discussion

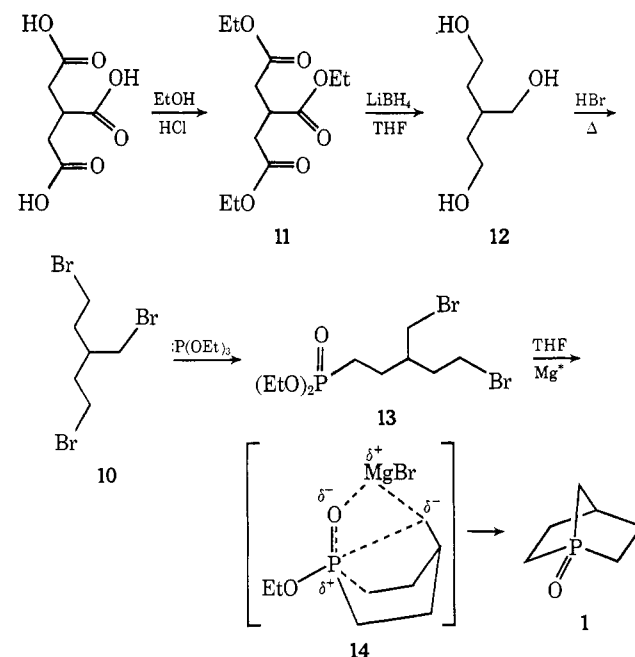
Synthetic Approaches to 1-Phosphabicyclo[2.2.1]heptane 1-Oxide (1) and 1-Phosphabicyclo[2.2.2]octane 1-Oxide (2). Several previous attempts at preparing compounds with the ring framework of 2 have proved un-

successful, leading to polymerization after formation of a monocyclic monomer.^{14,17} Thus, it appeared necessary to develop some new methods for carbon-phosphorus bond formation which would adapt well to the use of high-dilution techniques. Using compound 7 as a model, several high-dilution approaches were tested for their ability to effect cyclization of 7 to 8. It was found that a Grignard approach, presumably proceeding *via* intermediate 9, gave the best yield of 8 (37%).



The overall route to compound 1 is shown in Scheme I. The tribromide 10 had been reported previously,²²

Scheme I



but these earlier methods were inefficient and very time-consuming. A revised method, centered on the improved conversion of the triester of tri-carballic acid to triol 12 using lithium borohydride, conveniently gave the tribromide in 72% yield. This was converted to the dibromophosphonate 13 in 47% yield by Michaelis-Arbusov reaction with triethyl phosphite. The modified Grignard reaction gave the phosphine oxide 1 in 11% yield. Formation of the transition state 14 for the second cyclization leading to the strained bicyclic system is presumably aided by favorable dipolar alignment in the monocyclic Grignard intermediate. The preparation of 2 paralleled that of 1. The final cyclization to compound 2 was effected in 6% yield.

Purification of dibromophosphonate 13 was made difficult by the instability of this compound at temperatures necessary for vacuum distillation. This instability is presumably due to the known high-temperature reaction of the phosphoryl group with an alkyl halide to give transesterification,²³ a reaction which occurs

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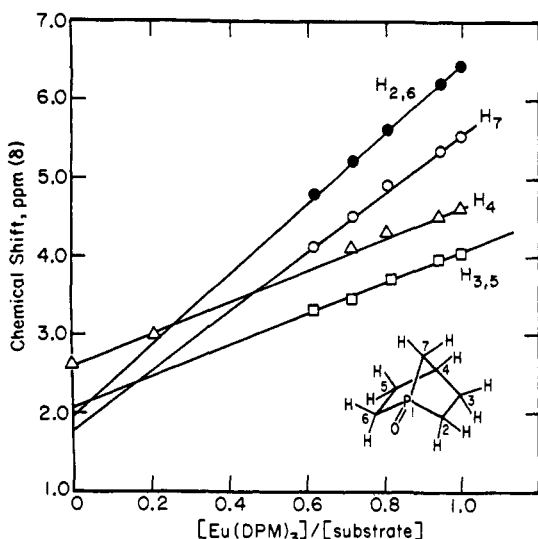


Figure 1. A plot of chemical shift vs. $[\text{Eu}(\text{DPM})_3]/[\text{substrate}]$ ratio for various groups of peaks in the proton NMR spectrum of **1** (CDCl_3) measured at 60 MHz. In the case of H_4 the chemical-shift data shown are for the downfield half of the doublet.

especially readily when it results in formation of a five- or six-membered phosphonate ring.²⁴

Syntheses of 1-Ethyl-2,2,3-trimethylphosphetane 1-Oxide (3), 1-Ethylphospholane 1-Oxide (4), and 1-Ethylphosphorinane 1-Oxide (5). Phosphetane **3** was synthesized following the general procedure by which Cremer and Chorvat prepared the corresponding 1-phenyl-2,2,3-trimethylphosphetane 1-oxide.²⁵ The phosphine oxide product was recrystallized to a constant melting point range and so undoubtedly is a single stereoisomer. Compounds **4** and **5** were prepared in low yield using our previously reported aluminum hydride method.²⁶ Compounds **4** and **5** were recently prepared by a different, higher yield route by Marsi and Oberlander.²⁷

Compounds **1–5** were characterized by their elemental analyses, mass spectral parent ions and fragmentation patterns, and by both ^1H and ^{13}C NMR spectroscopy. In addition, a molecular weight determination by the osmometric method confirmed the monomeric nature of **1**.

Use of Lanthanide Shift Reagents in Pmr Studies of Phosphine Oxides. The 60-MHz proton NMR spectra of the cyclic and bicyclic phosphine oxides **1–5** synthesized for this study consist of inscrutable aliphatic envelopes. Use was made of the recent development of lanthanide shift reagents^{28,29} to magnify artificially the inherent differences in proton environments in these compounds so that greatly simplified spectra could be obtained.

Figure 1 shows a standard plot of observed lanthanide-induced shifts (LIS) for each kind of proton vs. the molar ratio of lanthanide reagent [in this, and subsequent cases, tris(dipivalomethano)europium(III), $\text{Eu}(\text{DPM})_3$]

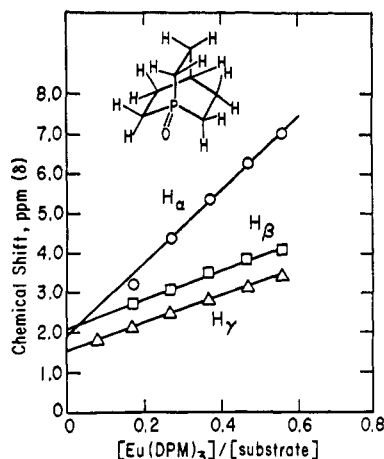


Figure 2. A plot of chemical shift vs. $[\text{Eu}(\text{DPM})_3]/[\text{substrate}]$ ratio for various groups of peaks in the proton NMR spectrum of **2** (CDCl_3) measured at 60 MHz.

($\text{DPM})_3$ to phosphine oxide. It can be seen that the assumed downfield half of the doublet assigned to H_4 of **1** disappeared as it was overtaken by the other absorptions and then reemerged as these absorptions became more spread out. At a $[\text{Eu}(\text{DPM})_3]/[\text{substrate}]$ ratio of approximately 0.7 or greater, protons on each type of carbon fall into distinct groups.¹² Decoupling of phosphorus caused collapse of the H_4 doublet to a singlet, which became a shoulder on the upfield absorption multiplet. The absorptions were assigned as shown in Figure 1 based on a combination of their relative responses to added $\text{Eu}(\text{DPM})_3$ and their relative integrations. As a rule, those protons closest to the functionality being complexed, in this case the phosphoryl oxygen, give the largest LIS values.^{28,29}

The 220-MHz spectrum of pure compound **1** separated the absorptions enough to uncover the H_4 doublet, from which was obtained a value of 28 Hz for $J_{\text{PCC}^1\text{H}}$. This value is quite large (the corresponding value for triethylphosphine oxide is only 16.3 Hz)³⁰ and may be due to the fact that the dihedral angle between the coupled atoms is rigidly held at 180° . Recent studies indicate an angular dependence of $J_{\text{PCC}^1\text{H}}$ similar to the Karplus relationship for J_{HCHH} values.^{31–33} An unusually large $J_{\text{PCC}^1\text{H}}$ value of 15.9 Hz has been reported for the analogous coupling in compound **20**.³⁴

The spectrum of compound **2** was simplified by $\text{Eu}(\text{DPM})_3$ in an analogous manner (Figure 2). Three absorptions quickly separated out and gave integrations in agreement with the proposed structure.

Compound **3** presented by far the most difficult structural determination of the series, owing to the greater number of magnetically distinct protons in the molecule. Total resolution of the spectrum was not achieved even after addition of $\text{Eu}(\text{DPM})_3$ to a $[\text{Eu}(\text{DPM})_3]/[\text{substrate}]$ ratio of 1.2:1. At this state most of the absorptions could be identified, however, and the remaining hidden peaks could be located approximately

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by integration. The assignments were made based on expected splitting patterns, as well as relative responses to $\text{Eu}(\text{DPM})_3$ and relative integrations. The stereochemistry is assumed to be trans, as has been found for the major isomers of analogously prepared phosphitanes.³⁵ The inability to locate exactly the position of the 3-hydrogen in the $\text{Eu}(\text{DPM})_3$ spectra of compound **3**, plus the fact that its *approximated* LIS value is well outside of the ranges found by Corfield and Trippett³⁶ for both cis and trans hydrogens in similar compounds, made definitive assignment of stereochemistry impossible.

Table I is a compilation of LIS values for some of the

Table I. Lanthanide Induced Shift Values for Some Phosphine Oxides in the Presence of $\text{Eu}(\text{DPM})_3^a$

Compd	α protons	β protons	γ protons
$(\text{CH}_3)_3\text{P}=\text{O}$	5.7		
	4.0, 7.6		
	4.6, 6.3	2.0	
	7.8, 4.5 (endo), 5.0 (exo)	3.1, 4.3 (ring methyl), 4.7 (PCH_2CH_3)	1.8
	4.5, 3.7 (bridge)	1.9, 2.0 (bridgehead)	
	9.1*	3.6*	3.5*

^a Asterisk indicates extrapolated values.

phosphine oxides used in this study. The phenyl-substituted phospholane and phosphorinane gave simpler spectra than compounds **4** and **5**, and so europium studies were conducted on them.³⁷ Corfield and Trippett's work suggests³⁶ that a change from phenyl to aliphatic substitution has a negligible effect on LIS, so that LIS values for the phenyl-substituted compounds in Table I should be meaningful in making comparisons. It was not possible to assign values for the β and γ protons of the phosphorinane, due to the complicating presence of an impurity peak.

It is likely that europium reagents act mainly through pseudo-contact interactions, which depend both on the distance between europium and the proton and on the angle between this direct line and a "crystal field axis," which is usually assumed to be the line between europium and the heteroatom being complexed.²⁹ As

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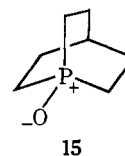
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(37) Other workers report similar values for 1-ethylphospholane 1-oxide: 6.6 and 5.5 for the α protons in the ring, 3.0 for the β -ring protons. The values for the α and β protons of the ethyl group, 6.6 and 4.3, are similar to those found for the ethyl group in compound **3**. Values for the α and β protons of triethylphosphine oxide were 7.1 and 4.8, respectively. Values are for $\text{Eu}(\text{DPM})_3$ in CDCl_3 [B. D. Cuddy, K. Treon, and B. J. Walker, *Tetrahedron Lett.*, 4433 (1971)].

a first approximation it is possible to ignore the angular contributor to the LIS. If this be done, one can often "find" the equilibrium position of the europium atom by obtaining a best fit in a correlation of LIS values of a certain substrate with interatomic distances derived from assumed positions of europium.²⁹

In comparing then the LIS values for the α hydrogens of the phosphine oxides in Table I, one is actually comparing distances of europium with respect to the phosphoryl group in each of the phosphine oxides (but see the discussion below on equilibrium constants). Comparison is difficult in some of the compounds owing to a ring system which places α hydrogens cis to the phosphoryl much closer to the europium than the trans hydrogens, a circumstance which gives two LIS values, neither of which is solely reflective of the electronic attraction of the phosphoryl oxygen for the europium atom. Several correlations have been made between the basicity of a complexed heteroatom and the equilibrium heteroatom-lanthanide atom distance, as determined by substrate responses to [lanthanide]/[substrate] ratios.²⁸ Thus, in those cases in which steric effects as discussed above can be standardized, LIS values should be indicative of the relative amounts of electron density on the phosphoryl oxygen.

This is important in the present study because of the unusually high response of the protons of compound **2** to europium, as reflected by the LIS value for the α protons when compared with the corresponding values of the other oxides. A better comparison would be among compounds **1** and **2** and trimethylphosphine oxide. These three molecules are very close in symmetry properties; distances between the proton and europium will not be affected by ring constraints, as is the case, for example, in compound **3**, whose α hydrogen cis to the phosphoryl has a relatively high LIS value. The LIS values for these three compounds thus imply a ranking of relative basicity $2 > (\text{CH}_3)_3\text{P}=\text{O} > 1$. This implied high-electron density on the oxygen in **2** can only be explained by a relative reluctance of the d orbitals of phosphorus to accept electrons from oxygen. That is, the charge-separated resonance structure **15** is



apparently more important in **2** than in most phosphoryl compounds. If, as construction of molecular models indicates, compound **2** is essentially strain-free, it is difficult to rationalize this weakened $p\pi-d\pi$ overlap. But how else can the striking preference by europium for **2** over **1** be explained?³⁸

It should be mentioned that the general method for determining LIS values in this study has been questioned in recent publications.^{39,40} It is argued that, since the observed shift is actually an average value for both

(38) Ignoring steric effects, the general trend in this series is for stronger attraction for lanthanide by phosphine oxides which exhibit lower phosphoryl-stretching frequencies. This kind of behavior in phosphoryl compounds has been observed before for complexes with iodine cyanide [R. Dahl, P. Klabe, and T. Gramstad, *Spectrochim. Acta, Part A*, **25**, 207 (1969)].

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bound and unbound substrate present in solution, this shift depends on the binding equilibrium constants. Although most equilibria studied in detail strongly favor complexation over free substrate, in some cases plots of observed shift *vs.* [lanthanide]/[substrate] ratio show curvature near ratios of 1.0, indicating complexation equilibrium constants of lower values. In these cases the standard procedure involving extrapolation of the linear portion to a ratio of 1:1 may not give a true value for LIS (or "bound chemical shift"). LIS values are meaningful only in comparisons between substrates if they describe the shift induced in the *complexed molecules* of comparable equilibrium constants (as opposed to the average shift induced in an equilibrium).

Although procedures have been described which yield not only the true LIS but also the equilibrium constant, they would be methodologically very difficult to apply in the present case, except perhaps for trimethylphosphine oxide. The complexity of the nmr spectra of most of the phosphine oxides studied makes discernment and assignment of peaks impossible at the low europium reagent concentrations called for by these methods.

There is reason to believe that complexation with the phosphine oxides is strong, however. The fact that it is possible to approach $[\text{Eu}(\text{DPM})_3]/[\text{substrate}]$ ratios of 1:1 at all with the very insoluble, relatively weak Lewis acid $\text{Eu}(\text{DPM})_3$ indicates an unusually great ability of the substrates to "pull" the shift reagent into solution. Also, in those cases in which a 1:1 ratio was surpassed, linearity was observed all the way to 1:1, after which the plot flattened markedly. These facts indicate that the LIS values in Table I are good values which can be compared meaningfully.

Finally, even if these LIS values are somewhat reflective of a difference in equilibrium constants as well as difference in equilibrium interatomic distances, it is obvious that the relative values would imply the same trend in electron density discussed above. If the large LIS of compound **2** is due in part to a greater ratio of bound substrate to unbound substrate present at equilibrium, this too must be due to a greater attraction for europium by the phosphoryl group.

Carbon-13 Nmr Spectra of 1-Phosphabicyclo[2.2.1]heptane 1-Oxide (1) and 1-Phosphabicyclo[2.2.2]octane 1-Oxide (2). In order to characterize bicyclic phosphine oxides **1** and **2**, their ^{13}C nmr spectra at natural abundance and under conditions of proton decoupling were measured (Figure 3). The $J^{31\text{P}-^{13}\text{C}}$ values for coupling to the α and β carbons of **2** and to the $\text{C}_{2,6}$, $\text{C}_{3,5}$, and C_7 carbons of **1** were typical of $J^{31\text{P}-^{13}\text{C}}$ values already reported for one- and two-bond couplings.⁴¹ In both compounds coupling of phosphorus to the bridgehead carbons was unusually high; in fact, they were higher than any previously reported $J^{31\text{PCC}^{13}\text{C}}$ values.⁴¹ In compound **1** the signals in the spectrum attributed to the bridgehead carbon C_4 are easily assigned by their relatively low intensities. The $J^{31\text{P}-^{13}\text{C}}$ value between the bridgehead atoms in this molecule is 35 Hz. As shown in Figure 3, in the spectrum of compound **2** there is only one small intensity absorption which corresponds to the bridgehead carbon.

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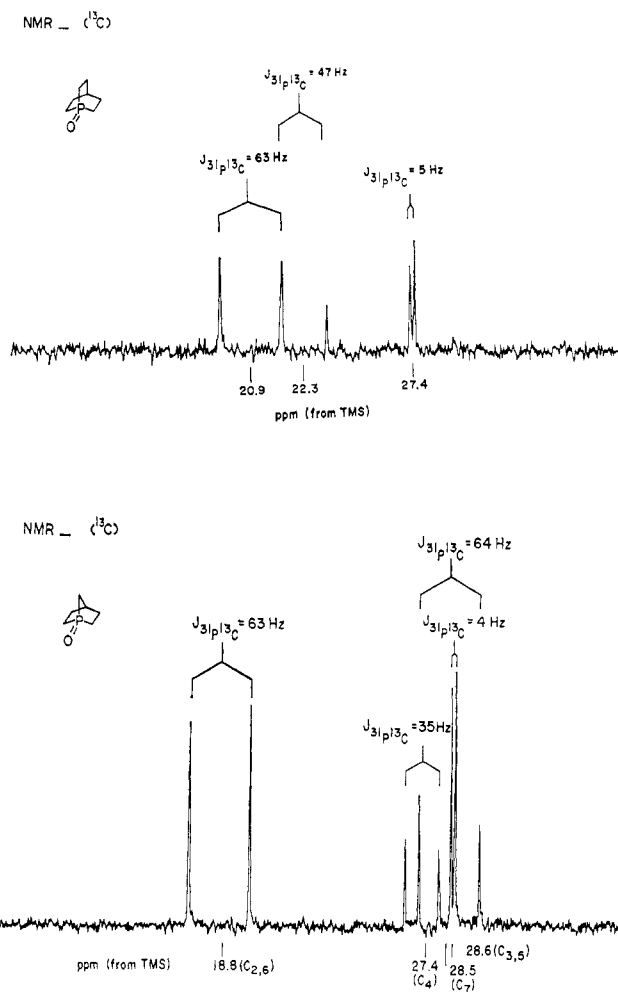


Figure 3. ^{13}C nmr spectra of **1** and **2** (CDCl_3) determined at 24 kG under conditions of proton noise decoupling; scale, parts per million relative to carbons of tetramethylsilane.

Anticipating the possibility of a fortuitous overlap, we measured a spectrum at a different field strength (14 kG); the weaker field strength changed the relative chemical shifts such that the second half of the doublet corresponding to the bridgehead carbon became apparent. The $J^{31\text{P}-^{13}\text{C}}$ value between bridgehead atoms of **2** is 47 Hz.

The high $J^{31\text{PCC}^{13}\text{C}}$ value for compound **2** indicates that the large coupling constant between the bridgehead atoms in **1** is probably mainly due to the vicinal coupling paths, even though there is also a two-bond (geminal) coupling path ($J^{31\text{P}^{13}\text{C}}$ in both **1** and **2** is about 5 Hz). It seems quite possible that these large three-bond couplings are due to the dihedral angle of 0° in the vicinal coupling pathways (a molecular model of compound **1** shows it to be highly rigid; compound **2**, however, displays a twisting mode along the axis connecting the bridgehead atoms and so the adjacent pairs of methylene hydrogens may not be completely eclipsed), in analogy to the Karplus relationship originally proposed for correlation of $J_{\text{HCC}^1\text{H}}$ values³³ and subsequently for other couplings, including $J^{31\text{PCC}^1\text{H}}$ values (as mentioned in the previous section, the large $J^{31\text{PCC}^1\text{H}}$ to the bridgehead proton in **1**, 28 Hz, is thus explained by the $\text{P}-\text{C}-\text{C}-\text{H}$ dihedral angle of 180°).

Examination of the recent literature on ^{13}C nmr of organophosphorus compounds supports this hypoth-

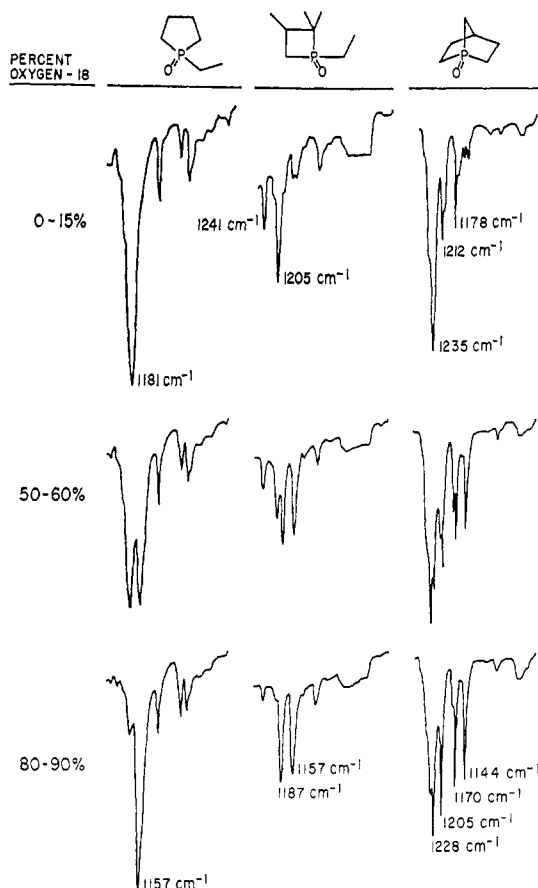
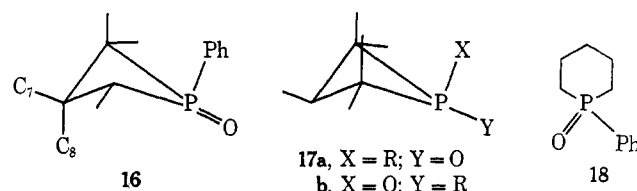


Figure 4. Infrared spectra showing the phosphoryl-stretching regions of 4, 3, and 1 at various percentages of ^{18}O enrichment.

esis. Notably, the work of Gray and Cremer⁴¹ on phosphetanes similar to compound 3 provides confirmatory data. For example, in phosphetane 16 a $J^{31\text{PCC}^{13}\text{C}}$ value of only 1.6 Hz was found for coupling between phosphorus and methyl carbon C_8 , whereas the corresponding $J^{31\text{PCC}^{13}\text{C}}$ value to methyl carbon C_7 was 24.9 Hz. Inspection of molecular models, carefully constructed in accord with X-ray diffraction data available for similar phosphetanes,⁴² indicates that the relevant dihedral angle to C_8 is *ca.* 90° , the Karplus minimum, while the dihedral angle to C_7 is *ca.* 140° , an angle where an intermediate *J* value is predicted.

Some of the data of Gray and Cremer are difficult to explain, however, if coupling to C_7 (the pseudoequatorial substituent on the 3-ring position) and C_8 (the pseudoaxial substituent) is determined solely by the appropriate dihedral angles. In another differently substituted phosphetane series,⁴¹ there is no obvious pattern in the $J^{31\text{PCC}^{13}\text{C}}$ values for carbons 7 and 8; these values lie in a range intermediate between the extreme values discussed for the series of which phosphetane 16 is a typical example. In yet another series of phosphetanes, symbolized by the general compounds 17a and 17b, while the $J^{31\text{PCC}^{13}\text{C}}$ values to C_7 are large, there is a significant effect on these vicinal *J* values by the orientation (in a *cis,trans* sense) of the carbon relative to the phosphoryl oxygen. If the ring system is rigid so that the dihedral angle is fixed, it is difficult to rationalize the effect of stereochemistry at phosphorus (which should not affect ring angles) on coupling to C_7 . Yet

in series 17a,b the $J^{31\text{PCC}^{13}\text{C}}$ value to C_7 is consistently larger in the isomers in which C_7 is *cis* to the phosphoryl oxygen.



It has been suggested that large couplings between bridgehead atoms in systems like compound 1 and 2 may be due in part to the presence of multiple coupling paths.^{34,43} Adjusting the $J^{31\text{PCC}^{13}\text{C}}$ values for 1 and 2 as well as the compounds studied by Gray and Cremer according to this assumption, does not alter the fact that the coupling of 47 Hz for 2 is by far the largest reported $J^{31\text{PCC}^{13}\text{C}}$ value for phosphine oxides and, indeed, for any organophosphorus compound. If the $J^{31\text{PCC}^{13}\text{C}}$ value of 6.8 Hz reported for compound 18 is due to two coupling paths, we can consider a value of 3.4 Hz to be typical for single path $J^{31\text{PCC}^{13}\text{C}}$ coupling constants in flexible phosphine oxide systems. This compares to the " $J^{31\text{PCC}^{13}\text{C}}$ per coupling path" values of 6.1–14.1 Hz calculated from Gray and Cremer's data for coupling to the pseudoequatorial phosphetane substituent C_7 and to the " $J^{31\text{PCC}^{13}\text{C}}$ per coupling path" value of *ca.* 16 Hz for compound 2. If the two vicinal coupling paths predominate in the bridgehead to bridgehead coupling in compound 1, a value of 32 Hz would be expected based on the "single path" $J^{31\text{PCC}^{13}\text{C}}$ value of 16 Hz derived from compound 2. This is close to the observed value of 35 Hz for 1.

Infrared Spectra of Phosphine Oxides 1–6. Since the main technique used in following oxygen-exchange kinetics discussed in the accompanying paper¹⁰ relied on the shift in the phosphoryl absorption in the infrared, it was important that all the compounds being studied display strong, uncomplicated $\text{P}=\text{O}$ bands. While the acyclic and unstrained cyclic oxides each gave a simple, strong band for $^{16}\text{O}=\text{P}$ and a corresponding band at about 30 cm^{-1} lower frequency for $^{18}\text{O}=\text{P}$, the strained phosphetane and [2.2.1] bicyclic oxides each gave complicated patterns.

Figure 4 shows the phosphoryl-stretching region of compound 4 at various percentages of ^{18}O enrichment. A similar series of spectra was observed for compounds 5 and 6. Thus, exchange of oxygen-18 into compounds 4, 5, and 6 with 90% ^{18}O -enriched water gave spectra which showed only one new strong band in each case, shifted as indicated in Table II. The [2.2.2] bicyclic oxide 2 was never obtained with any significant incorporation of oxygen-18, so it was impossible to demonstrate the $\text{P}=\text{O}$ band unequivocally as above, but there is no reason to believe that the strong band at 1169 cm^{-1} in this compound's spectrum is not the $\text{P}=\text{O}$ band.

The spectra of the phosphetane 3 (Figure 4) are of intermediate complexity. In this compound, as the relative amount of ^{18}O increases, both the strong band at 1205 cm^{-1} and the weaker band at 1241 cm^{-1} disappear, and a symmetric doublet at 1187 and 1157 cm^{-1} emerges. This doubling is not due to decomposition since it is entirely reversible; that is, starting with highly

(43) R. D. Bertrand, D. A. Allison, and J. G. Verkade, *J. Amer. Chem. Soc.*, **92**, 71 (1970).

(42) M. Haque, *J. Chem. Soc. B*, 938 (1970); 117 (1971).

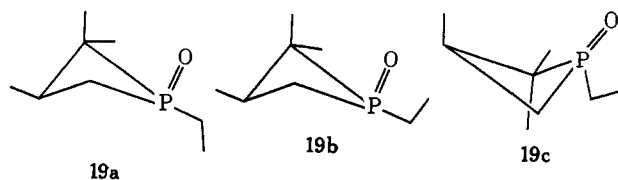
Table II. Phosphoryl Infrared Stretching Frequencies for Some Phosphine Oxides

Compd	$\nu^{16}\text{O}=\text{P}$, cm^{-1}	$\nu^{18}\text{O}=\text{P}$, cm^{-1}
	1265 ^a	
(3)	1223 ^b (1241 1205)	1172 ^b (1187 1157)
(1)	1215 ^b (1235 1212 1178)	1187 ^b (1228 1205 1170 1144)
	1205 ^c	
	1187 ^c	
(4)	1181	1157
(6)	1178	1145
(5)	1172	1142
(2)	1169	

^a E. W. Koos, *et al.*, *Chem. Commun.*, 1085 (1972). ^b Average of the Fermi resonance bands. ^c E. W. Turnblom and T. J. Katz, *J. Amer. Chem. Soc.*, **95**, 4292 (1973).

¹⁸O-enriched material which shows only this latter doublet in the phosphoryl region, one can generate the original natural abundance spectrum by heating in aqueous acid.

There are several possible explanations for the doubling of phosphoryl bands. There may exist in solution two forms of compound 3, each with a unique phosphoryl stretch. While rotamers 19a and 19b are possible in compound 3, they are not possible in its 1-phenyl analog, which shows remarkably similar phosphoryl regions.³⁵ Rotational isomerism, which has been invoked previously to explain doubling of phosphoryl absorptions,⁴⁴ is therefore probably not a factor



(44) R. A. Nyquist and W. J. Potts, Jr., in "Analytical Chemistry of Phosphorus Compounds," M. Hallmann, Ed., Wiley, New York, N. Y., 1972, p 192.

in this case. Rapidly interconverting puckered forms (19b \rightleftharpoons 19c), as postulated by Gray and Cremer,⁴¹ might be responsible for the doubling phenomena, but details of the spectrum of compound 1, discussed below, lead us to believe that there exist several small absorptions in the 1150–1220- cm^{-1} region which undergo Fermi resonance⁴⁵ with phosphoryl absorptions which fall into their spheres of influence.

Fermi resonance is fairly commonplace in the infrared spectra of ethyl phosphonates, whose phosphoryl bands are often doublets.^{45,46} The interfering band in this case appears to be a weak doublet due to the phosphorus-ethyl grouping, absorbing around 1250 cm^{-1} .⁴⁶ All the compounds in the phosphine oxide series 1–6 possess a phosphorus-ethyl or at least a P–C–C linkage, but only two show any Fermi resonance. Since these two compounds are by far the most strained in the series, it is likely that the strain effect on raising phosphoryl energies (see below), plus a strain effect of lowering the P–C–C bands due to a corresponding decrease in the amount of s character in the endocyclic bonds, juxtaposes these two absorptions so that Fermi resonance is possible.

Isotopic shifts for those phosphine oxides which possess single phosphoryl absorptions range from 24 to 33 cm^{-1} , which is about what would be predicted based on calculations of mass effects. If the doubling of bands in the phosphatane 3 were due to interconverting puckered forms, comparable isotopic shifts would be expected for each set of ¹⁶O and ¹⁸O conformers. The actual shifts, 54 cm^{-1} for the high-frequency band and 48 cm^{-1} for the low-frequency band, cannot be justified if conformers are responsible. These distortions are consistent, however, with an interpretation based on Fermi resonance, since the actual position of the phosphoryl absorption is obscured; that is, its position is not a simple average of the doublet frequencies.

Figure 4 also shows the phosphoryl region of compound 1 at various percentages of ¹⁸O enrichment. In this compound there are two different set of peaks which appear to be due to the phosphoryl stretch. The most prominent peak in the natural abundance spectrum is the band at 1235 cm^{-1} , which with ¹⁸O incorporation is shifted and apparently brought into Fermi resonance as the 1228, 1205 cm^{-1} doublet. There is another doublet (1178, 1212 cm^{-1}) in the phosphoryl region of the natural abundance spectrum, however, and it is also shifted downfield (1144, 1170 cm^{-1}) in molecules which contain the heavier oxygen isotope. This is essentially the same state of affairs that exists in the phosphatane 3.

Compound 1 possesses only one possible rotamer and conformer, so that, while multiple Fermi resonances of this magnitude are very unusual, there appears to be no other explanation. The effect is completely reversible, and all peaks correlate well with the amount of ¹⁸O incorporation as determined by mass spectroscopy.¹⁰ Presumably there are several absorptions of the necessary symmetry in this frequency range, such that multiple Fermi resonance interactions are possible. Triple Fermi resonance has been postulated recently by

(45) G. Herzberg, "Molecular Spectra and Molecular Structure. II. Infrared and Raman Spectra of Polyatomic Molecules," Van Nostrand, New York, N. Y., 1945, p 215.

(46) L. C. Thomas and R. A. Chittenden, *Spectrochim. Acta*, **20**, 468 (1964).

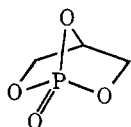
Russian workers⁴⁷ and has been treated theoretically by Konarski.⁴⁸

Strain and Infrared Phosphoryl-Stretching Frequency in Phosphine Oxides. After the appearance of some of Westheimer's early work on hydrolysis of ethylene phosphates,⁸ Jones and Katritzky⁴⁹ determined the phosphoryl-stretching frequencies for an acyclic, a five-membered cyclic, and a six-membered cyclic phosphate, hoping to observe a strain effect similar to that found in cyclic carbonyl compounds. They found values of 1261, 1287, and 1290 cm^{-1} , respectively, and thus were not able to correlate these values with hydrolysis rates and, presumably, strain.

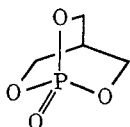
Table II shows that, in cyclic phosphine oxides, if one goes to more highly strained structures than five-membered rings, one can observe an increase in phosphoryl energy with increasing strain. By far the most highly strained compound is the phosphirane (with phosphorus in a three-membered ring) recently reported by Stille and coworkers.⁵⁰ It should be noted that neither phenyl nor vinyl substitution generally has much effect on phosphoryl frequencies,^{44,51} so this compound can be compared qualitatively with the rest of the series.

The Fermi resonance already described complicates the ranking of the phosphetane and the [2.2.1] oxides (Table II). Weighted averaging of the Fermi bands might give somewhat more reliable values, for example. Assumption of multiple Fermi resonance and simple averaging of the 1235 and 1195 cm^{-1} values gives an apparent 1215- cm^{-1} value for the bicyclo[2.2.1] compound. This is lower than the 1223- cm^{-1} average for the phosphetane, and this relative order is what one would expect from the relative oxygen exchange rates of these two compounds, since strain is directly reflected in these rates (see accompanying paper¹⁰). However, the parallel averages for oxygen-18 phosphine oxides are in the opposite order.

The last four compounds in Table II absorb at about the same frequency. In analogy to the findings of Jones and Katritzky,⁴⁹ the phospholane's value is essentially no different than those of the other, presumably less strained, compounds. There is evidence that, in the absence of extenuating electronic effects, phospholane spectra and reaction rates show strain in the five-membered ring. It appears that the phosphoryl frequency does not respond linearly with strain, but, after a certain point, there is a correspondence. Thus, in relation to the phosphate work, compound **20** was found to have a phosphoryl stretch of 1340 cm^{-1} ⁵² (the same workers, however, also report a value of 1340 cm^{-1} for **21**).



20



21

(47) M. P. Lisitsa, N. E. Ralko, and A. M. Yaremko, *Opt. Spectrosc.*, **28**, 235 (1970).

(48) J. Konarski, *Phys. Lett. A*, **35**, 251 (1971).

(49) R. A. Y. Jones and A. R. Katritzky, *J. Chem. Soc.*, 4376 (1960).

(50) E. W. Koos, J. P. Vander Kooi, E. E. Green, and J. K. Stille, *J. Chem. Soc., Chem. Commun.*, 1085 (1972).

(51) L. J. Bellamy, "The Infrared Spectra of Complex Molecules," Wiley, New York, N. Y., 1958, p 314.

(52) D. B. Denney and S. L. Varga, *Tetrahedron Lett.*, 4935 (1966).

The dependency of exocyclic bond strength on endocyclic strain has been explained⁵³ in terms of a change in hybridization of atomic orbitals in the ring atoms which, in the present case, puts more p character into the endo P-C bonds with a concomitant increase in s character in the exo-phosphorus hybrid orbital forming the σ bond to oxygen. This increase in s character strengthens the resulting bond. As opposed to the simplified case of carbonyl bonds, however, the phosphoryl bond may be partially further strengthened by back-bonding of some of the electron density on the oxygen into empty d orbitals of phosphorus. The energy of these orbitals, and therefore their ability to overlap, depends on the amount of positive charge on phosphorus.⁵⁴ This complex state of affairs may be the reason for the difficulty in making a clean correlation of strain with phosphoryl frequency.

Experimental Section

General. Microanalyses and the osmometric molecular weight determination were performed by the Microanalytical Laboratory, Department of Chemistry, University of California, Berkeley. Infrared spectra were recorded on a Perkin-Elmer 421 recording spectrometer. Proton nmr spectra were measured using a Varian T-60, HA-100, or HR-220 spectrometer. Unless otherwise specified, CCl_4 was used as nmr solvent. Phosphorus-31 decoupling experiments were carried out with an NMR Specialties heteronuclear decoupler at 40.5 MHz. Carbon-13 nmr spectra were recorded either on a Varian XL-100 spectrometer modified for Fourier transform operation or the 15-MHz spectrometer previously described.⁵⁵⁻⁵⁷ Mass spectra were obtained on either a Consolidated Model 21-103c spectrometer or a Consolidated Model 21-110B double-focusing high-resolution spectrometer. Melting points are uncorrected.

Materials. Triethylphosphine oxide was obtained from K & K Labs., Inc., Hollywood, Calif. Trimethylphosphine oxide was a gift of Orgmet, Inc., Haverhill, Mass., which was also the source of ethyldichlorophosphine. Sodium bis(2-methoxyethoxy)aluminum hydride was obtained from Eastman. Sodium aluminum diethyl dihydride (OMH-1) was from Ethyl Corp., Baton Rouge, La. Diethyl ethylphosphonate, tricarballic acid, diethyl glutaconate, and 3,3-dimethyl-1-butene were purchased from Aldrich Chemical Co. Tris(dipivalomethanato)europium(III) was obtained from Willowbrook Labs. 1-Phenylphospholane 1-oxide and 1-phenylphosphorinane 1-oxide were reported previously.²⁶ Phosphine oxides were enriched with ^{18}O by heating for various periods of time in a solution of 2-4 N DCl in ca. 90% ^{18}O -enriched D_2O (Miles Laboratories, Elkhart, Ind.). Other common reagents were obtained commercially in high purity.

Diethyl 5-Bromopentylphosphonate (7). This compound was prepared after the method of Eberhard and Westheimer.²⁴ Fractional distillation of the residue gave a fraction boiling at 122.5-125° (0.5 mm), 31.1 g (64% yield based on triethyl phosphite) of diethyl 5-bromopentylphosphonate. *Anal.* Calcd for $\text{C}_9\text{H}_{20}\text{BrO}_5\text{P}$: C, 37.75; H, 6.98; P, 10.80. Found: C, 37.38; H, 6.83; P, 10.53. Nmr peaks were found at δ 1.32 (6 H, t, $J = 7$ Hz), 1.60 (8 H, m), 3.41 (2 H, t, $J = 7$ Hz), and 4.02 (4 H, m). During distillation, an oil bath temperature of 195° was not exceeded in order to minimize decomposition of **7**.

1-Ethoxy-1-oxophosphorinane (8). A 3-l., round-bottom flask was fitted with a stirring paddle and a reflux condenser, on top of which was subsequently mounted a precision dropping funnel. After heating for 20 min in a 150° oven, the system was cooled in a stream of N_2 . Meanwhile, approximately 3 l. of tetrahydrofuran (THF) was dried by heating at reflux over lithium aluminum hy-

(53) C. A. Coulson and W. E. Moffitt, *Phil. Mag.*, **40**, 1 (1949).

(54) R. F. Hudson, "Structure and Mechanism in Organo-Phosphorus Chemistry," Academic Press, New York, N. Y., 1965, Chapter 3.

(55) W. Horsley, H. Sternlicht, and J. S. Cohen, *J. Amer. Chem. Soc.*, **92**, 680 (1970).

(56) H. Sternlicht, G. L. Kenyon, E. L. Packer, and J. Sinclair, *J. Amer. Chem. Soc.*, **93**, 199 (1971).

(57) D. M. Wilson, Ph.D. Thesis, University of California, Berkeley, Calif., 1973.

dride (LiAlH_4) for at least 2 hr, also under an N_2 atmosphere. The reflux column was subsequently removed and replaced by a distillation column, and, after discarding a small forerun, several hundred milliliters of THF was collected and put aside in a flask fitted with a CaCl_2 drying tube. Immediately after removal of this flask of THF, the previously dried 3-l. flask was fitted to the distillation receiver tube and about 1.5 l. of the THF was distilled, under N_2 , into the flask. Meanwhile the THF collected separately was used to wash the previously prepared, activated magnesium into the 3-l. receiver flask. When 1.5 l. of THF had been collected, the 3-l. flask containing activated THF and Mg^{88} was put aside, under N_2 , and a 250-ml round-bottom flask containing 6.3 g of diethyl 5-bromopentylphosphonate (7), previously dried by several hours vacuum pumping at 50° , was placed on the receiver tube; after about 150 ml of THF was collected, the flask was removed and swirled to dissolve the phosphonate, and the solution was quickly poured into the precision dropping funnel. The flask, containing 1.5 l. of THF and Mg, was secured on a steam bath and heated to reflux. The stirring paddle was connected to a mechanical stirrer and a nitrogen blanket imposed by attachment to the top of the dropping funnel.

With vigorous stirring to keep the Mg dispersed throughout the THF, addition of the THF solution of 7 was begun and the solution was added over a period of 5 hr. It is generally advisable, to ensure success, to add a fraction of 1 ml of 1,2-dibromoethane occasionally. Reflux with stirring was continued for 20 more hr, after which time the reaction mixture was cooled and hydrolyzed with 10 ml of a saturated ammonium chloride solution. The hydrolyzed mixture was filtered, the THF removed by rotary evaporation, and the residue dissolved in ethyl acetate and filtered again. The ethyl acetate was removed, and the residue chromatographed on 90 g of silica gel with a 90/10 (v/v) mixture of ethyl acetate and methanol as eluent, giving the following fractions: 180 ml, no material; 80 ml, 1.9 g of diethyl pentylphosphonate; 100 ml, no material; 300 ml, 1.3 g (37% yield) of 1-ethoxy-1-oxophosphorinane (8). Diethyl pentylphosphonate distilled at bp $62\text{--}63^\circ$ (0.2 mm). *Anal.* Calcd for $\text{C}_9\text{H}_{21}\text{O}_3\text{P}$: C, 52.00; H, 10.10. Found: C, 51.67; H, 9.71. Nmr peaks were found at δ 0.88 (3 H, t, $J = 5$ Hz), 1.23 (6 H, t, $J = 7$ Hz), 1.60 (8 H, m), and 3.98 (4 H, m). 1-Ethoxy-1-oxophosphorinane (8) distilled at bp $71\text{--}72^\circ$ (0.2 mm). *Anal.* Calcd for $\text{C}_7\text{H}_{15}\text{O}_3\text{P}$: C, 51.90; H, 9.26; P, 19.14. Found: C, 51.66; H, 9.27; P, 19.04. Nmr peaks were found at δ 1.35 (3 H, t, $J = 7$ Hz), 1.62 (10 H, m), and 4.00 (2 H, m).

3-Bromomethyl-1,5-dibromopentane (10). Triethyl tricarballoylate (53 g, 0.20 mol, prepared by Fischer esterification of tricarballoylic acid) was dissolved in 900 ml of THF in a 2-l. flask fitted with mechanical stirrer. To this was carefully added 10 g (0.46 mol) of LiBH_4 , in increments, under N_2 with ice cooling. The slurry was heated at reflux on a steam bath, with stirring under N_2 , for 6 hr. The cooled reaction mixture was transferred to a 4-l. beaker containing a magnetic stirrer. With vigorous stirring, 100 ml of water was slowly added, with cooling when necessary, in increments and the hydrolyzed mixture stirred for 2 hr. This mixture was then filtered, and the filtrate reduced in volume to give an oil, 25.7 g (94% based on 11), of 3-hydroxymethyl-1,5-pentanediol⁵⁹ (12): bp (0.5 mm) $165\text{--}167^\circ$; nmr peaks (D_2O) at δ 1.58 (5 H, m), 3.57 (6 H, m).

The viscous triol 12 (65.5 g, 0.49 mol) was heated in a 250-ml round-bottom flask at $100\text{--}115^\circ$; with magnetic stirring, HBr gas was bubbled in until the flask reached a constant weight (about 15 hr). The cooled oil was dissolved in ether and washed with aqueous Na_2CO_3 and then water. The ether layer was dried overnight over CaCl_2 and evaporated. The residue, 144 g, was vacuum distilled giving 132.4 g (72% based on tricarballoylic acid) of 3-bromomethyl-1,5-dibromopentane²² (10): bp $104\text{--}118^\circ$ (0.8 mm); nmr peaks at δ 2.00 (5 H, m) and 3.50 (6 H, m).

Diethyl 5-Bromo-3-bromomethylpentylphosphonate (13). Tribromide 10 (60.7 g, 0.19 mol) in a 100-ml three-neck flask fitted with dropping funnel and small distillation arm with N_2 inlet was heated to 140° . With stirring, 7.6 g (0.04 mol) of triethyl phosphite was added over a 30-min period, and the solution was stirred at 140° for another 20 min. The residue was vacuum distilled, keeping the bath temperature under 165° , until an increase in pressure due to decomposition of the desired product commenced. Most of the excess tribromide as well as the diethyl ethylphosphonate side product was thus removed. This product could be used without further purification in the next step without effect on yield. For

purposes of preparing pure product, however, the residue was chromatographed on silica gel, using 4:1 (v/v) ethyl acetate-methanol as eluent, which gave the following fractions: 2 l., no material; 1100 ml, tribromide; 200 ml, mixture of tribromide and desired product 13; 500 ml, 7.4 g (47% yield based on unrecovered tribromide) of diethyl 5-bromo-3-bromomethylpentylphosphonate (13). *Anal.* Calcd for $\text{C}_{10}\text{H}_{21}\text{Br}_2\text{O}_3\text{P}$: C, 31.61; H, 5.53; Br, 8.16. Found: C, 31.65; H, 5.42; Br, 8.39. Nmr peaks were found at δ 1.30 (6 H, t, $J = 7$ Hz), 1.80 (6 H, m), 3.51 (4 H, m), and 4.02 (4 H, m).

1-Phosphabicyclo[2.2.1]heptane 1-Oxide (1). Using 4.22 g (0.011 mol) of diethyl 5-bromo-3-bromomethylpentylphosphonate (13), a Grignard cyclization was carried out using the same general procedure as that used to prepare compound 8. The phosphonate was added under reflux in five increments over a period of 42 hr, and the reaction mixture was heated at reflux for another 72 hr. With each addition of 13, some I_2 or $\text{BrCH}_2\text{CH}_2\text{Br}$ initiator was added. The cooled mixture was hydrolyzed, filtered, and evaporated as before leaving an oily white residue. This oil was taken up in 40 ml of water to give a white slurry, which was first extracted with portions of CCl_4 totalling 250 ml, then by portions of CHCl_3 totalling 250 ml. The CHCl_3 layer was evaporated giving 0.34 g of a hygroscopic yellow solid, which was sublimed *in vacuo* twice to give 161 mg (11% yield) of 1-phosphabicyclo[2.2.1]heptane 1-oxide (1), as hygroscopic, colorless prisms, mp $207\text{--}210^\circ$ (sealed tube). *Anal.* Calcd for $\text{C}_6\text{H}_{11}\text{OP}$: C, 55.30; H, 8.46; P, 23.85. Found: C, 54.7; H, 8.3; P, 23.5. The following mass spectral fragments were identified by accurate mass measurements: m/e 130 (parent ion, $\text{C}_6\text{H}_{11}\text{OP}^+$, 96% of base peak), 102 ($\text{C}_4\text{H}_7\text{OP}^+$, 98%), 101 ($\text{C}_4\text{H}_6\text{OP}^+$, 83%), 84 ($\text{C}_4\text{H}_5\text{P}^+$, 7%), 75 ($\text{C}_3\text{H}_4\text{OP}^+$, 27%), 55 (C_3H_7^+ , base peak), and 47 (PO^+ , base peak). A molecular weight determination by the osmometric method (CHCl_3) gave a value of 124 ± 6 (calcd, 130). The proton nmr spectrum at 220 MHz showed three sets of peaks: δ 1.74–1.87 (6 H, complex multiplet), 1.96 (4 H, symmetric multiplet), and 2.23 (1 H, doublet of multiplets, $J_{\text{HPOCH}} = 28$ Hz). See discussion for other details of the proton nmr, ^{13}C nmr, and infrared spectra. The ^{13}C nmr spectrum is shown in Figure 3.

Triethyl Methanetriacetate. To 450 ml of absolute ethanol (previously dried over molecular sieves type 3-A) in a 1 l. flask was added, with cooling, 14.9 g (0.65 mol) of sodium. When reaction of sodium was complete, a mixture of 118.4 g (0.64 mol) of freshly distilled diethyl glutaconate and 123 g (0.77 mol) of freshly distilled diethyl malonate was added over a 20-min period. The reaction mixture was heated at reflux for 1 hr, at which point the reflux column was replaced by a distillation head, and the mixture heated (maximum bath temperature 135°) to distil the ethanol. When most of the ethanol had been removed, the residue was cooled and 100 ml of water was slowly added with cooling and rapid stirring. Continuing to cool the mixture, concentrated HCl was added dropwise until no more white solid appeared to be forming, then more was added to make a total of 300 ml of HCl. This mixture was heated at reflux for 10 hr, at which point the reflux column was replaced by a distillation head and the oil bath raised to $165\text{--}175^\circ$, initiating distillation of volatile components, which continued for about 4 hr. The oily residue was heated at $180\text{--}190^\circ$ until foaming (evolution of CO_2) was essentially over. The methanetriacetic acid residue was dissolved in 200 ml of absolute ethanol, acidified, and esterified as in the preparation of 11, giving 81.3 g (46% yield based on diethyl glutaconate) of triethyl methanetriacetate:⁶⁰ nmr peaks at δ 1.21 (9 H, t, $J = 7$ Hz), 2.18 (7 H, m), and 4.07 (6 H, q, $J = 7$ Hz).

3-(2-Bromoethyl)-1,5-dibromopentane. Triethyl methanetriacetate was not further purified but was dissolved in 1200 ml of THF and reduced with 14 g of LiBH_4 following the procedure used to prepare triol 12. Thus, 47 g of 3-(2-hydroxyethyl)-1,5-pentanediol⁶⁰ was obtained as a viscous oil: nmr peaks (D_2O) at δ 1.61 (7 H, m) and 3.62 (6 H, t, $J = 7$ Hz). This oil was not distilled but was hydrobrominated following the procedure for the preparation of tribromide 10, giving, after 6 hr of bubbling HBr into the hot triol, work-up, and distillation, 32.4 g (32% yield based on triethyl methanetriacetate; 15% based on diethyl glutaconate) of 3-(2-bromoethyl)-1,5-dibromopentane:⁶⁰ bp $131\text{--}136^\circ$ (0.7 mm); nmr peaks at δ 1.92 (7 H, m) and 3.38 (6 H, t, $J = 7$ Hz).

Diethyl 5-Bromo-3-(2-bromoethyl)pentylphosphonate. To 43.6 g (0.13 mol) of tribromide 19 heated under N_2 at 150° was added over a 30-min period 5.9 g (0.032 mol) of triethyl phosphite, and the

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mixture was heated an additional 30 min at 150°. The reaction mixture was fractionally distilled to give diethyl ethylphosphonate, bp 54° (0.7 mm), and excess tribromide, 21.6 g. The pot residue, which would not further distil, was put aside and the recovered tribromide was treated with 3 g more of triethyl phosphite as before, and this mixture was fractionally distilled, giving, besides side product, 11.8 g of tribromide. This remaining tribromide was treated with 1.6 g of triethyl phosphite. The three combined pot residues were chromatographed on 1400 g of silica gel with ethyl acetate eluent: 1000 ml, no material; 600 ml, tribromide; 1100 ml, mixture of tribromide and desired product; 1400 ml, 6.15 g (25% yield based on unrecovered tribromide) of diethyl 5-bromo-3-(2-bromoethyl)pentylphosphonate. *Anal.* Calcd for $C_{11}H_{23}Br_3O_3P$: C, 33.53; H, 5.84; Br, 40.70; P, 7.88. Found: C, 33.76; H, 5.75; Br, 40.86; P, 7.74. Nmr peaks were found at δ 1.32 (6 H, t, $J = 7$ Hz), 1.78 (9 H, m), 3.39 (4 H, t, $J = 6$ Hz), and 4.02 (4 H, m).

1-Phosphabicyclo[2.2.2]octane 1-Oxide (2). Using 7 g of activated magnesium and 6.15 g (0.156 mol) of diethyl 5-bromo-3-(2-bromoethyl)pentylphosphonate, the Grignard cyclization was effected in analogy to the preparation of 1. The addition was over a 50-hr period, which was followed by additional reflux for 12 hr. The work-up was the same as in the preparation of 1, with the additional feature that an aqueous solution of the magnesium salts from the Grignard reaction was extracted with $CHCl_3$ giving a substantial additional amount of product. The total amount of 1-phosphabicyclo[2.2.2]octane 1-oxide (2) obtained was 145 mg (6.4% yield). Phosphine oxide 2 was sublimed (80° at 1 mm) to give white prisms which melted at 291–293° (sealed tube). It was noticeably less hygroscopic than 1, and, in fact, than most phosphine oxides encountered in this study. *Anal.* Calcd for $C_7H_{13}OP$: C, 58.30; H, 9.04; P, 21.53. Found: C, 58.1; H, 8.9; P, 21.56. The proton and carbon-13 nmr spectra, as well as the infrared spectrum, of 2 are described in the Results and Discussion section. The following mass spectral fragments were identified by accurate mass measurements: m/e 144 (parent ion, $C_7H_{13}OP^+$, 48% of base peak), 101 ($C_4H_6OP^+$, 17%), 88 ($C_3H_5OP^+$, 31%).

1-Ethyl-2,2,3-trimethylphosphetane 1-Oxide (3). Following the procedure of Cremer and Chorvat,²⁵ 19.6 g (0.15 mol) of dichloroethylphosphine, 20 g of $AlCl_3$, and 19.2 ml (12.6 g, 0.15 mol) of 1,1-dimethyl-3-butene were allowed to react and hydrolyzed to give 11 g of an oil. The oil was distilled [bp 73–76° (0.4 mm)] to give a hygroscopic solid which was dried by warming under vacuum and crystallized from petroleum ether, melting range 39–48°. Two recrystallizations gave a constant melting, hygroscopic material, melting range 54–56°. The yield of the mixture of isomers was about 35%. *Anal.* Calcd for $C_8H_{17}OP$: C, 60.00; H, 10.62; P, 19.38. Found: C, 60.2; H, 10.8; P, 19.2. The proton nmr showed a complex multiplet ranging from δ 0.9 to 2.8.

1-Ethylphospholane 1-Oxide (4). In a 3-l. round-bottom flask, fitted with a mechanical stirrer and two pressure-equalizing addition funnels, were placed 1.5 l. of THF and 35 g (0.162 mol) of 1,4-dibromobutane. In one funnel was placed a solution of 0.175 mol of $NaAlH_4$ (CH_2CH_3)₂ in 60 ml of THF, in the other funnel a solution of 27 g (0.163 mol) of diethyl ethylphosphonate, also in 60 ml of THF. Stirring at 60–65°, the phosphonate and reducing

agent solutions were added simultaneously over a period of 40 min. The reaction mixture was then stirred for 16 hr at 65° and carefully hydrolyzed with 25 ml of water, ethane gas being evolved during hydrolysis. This solution was filtered, and the aluminum salts were washed with 100 ml of $CHCl_3$, which was added to the filtrate. Removal of volatile components of the filtrate by rotary evaporation gave 28 g of an oil consisting primarily of unreacted starting materials and the desired product. This oil was dissolved in 60 ml of water and extracted with 80 ml of petroleum ether, which removed the unreacted dihalide and some phosphonate. The aqueous layer was then extracted with three portions of $CHCl_3$, totalling 200 ml. Removal of solvent gave an oil which, upon fractional distillation, yielded 8.6 g of diethyl ethylphosphonate and 1.55 g of slightly impure 1-ethylphospholane 1-oxide²⁷ (4), bp 80–83° (0.3 mm). Hexane extraction of an aqueous solution of impure phospholane removed the major impurity. Several extractions with CCl_4 removed most of the minor impurity, but it was still necessary to redistil in order to obtain a good microanalysis. The product was obtained analytically pure in 8% yield based on unrecovered phosphonate. *Anal.* Calcd for $C_5H_{11}OP$: C, 54.50; H, 9.86; P, 23.50. Found: C, 54.67; H, 9.74; P, 23.38. Nmr peaks were found at δ 1.05 (3 H, t, $J = 6$ Hz) and 1.80 (10 H, m).

1-Ethylphosphorinane 1-Oxide (5). Following the same procedure used to prepare 4, 28.6 g (0.124 mol) of 1,5-dibromopentane, 20.6 g (0.124 mol) of diethyl ethylphosphonate, and 69 ml (0.246 mol) of sodium bis(2-methoxyethoxy)aluminum hydride²⁸ solution were allowed to react and were heated at reflux for an additional 27 hr. The work-up when using this reagent is slightly more involved than when using $NaAlH_4(CH_2CH_3)_2$, since hydrolysis gives high-boiling 2-methoxyethanol. This can be removed by rotary evaporation of the crude oil with a vacuum pump at about 50° or, alternately, as a forerun of the fractional distillation. Fractional distillation of the crude oil obtained in the work-up gave 2.25 g of an oil, bp 95–105° (0.3 mm), which solidified in the condenser. This turned out to be desired phosphorinane of about 90% purity. Extractions of an aqueous solution of this crude material with CCl_4 , coupled with fractional vacuum sublimation, gave 310 mg (3% yield based on unrecovered phosphonate) of analytically pure 1-ethylphosphorinane 1-oxide²⁷ (5) as hygroscopic white prisms, melting range 67–70°. *Anal.* Calcd for $C_7H_{13}OP$: C, 57.53; H, 10.28; P, 21.22. Found: C, 57.18; H, 10.14; P, 21.01. Nmr peaks were found at δ 1.00 (3 H, t, $J = 7$ Hz) and 1.80 (12 H, m).

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