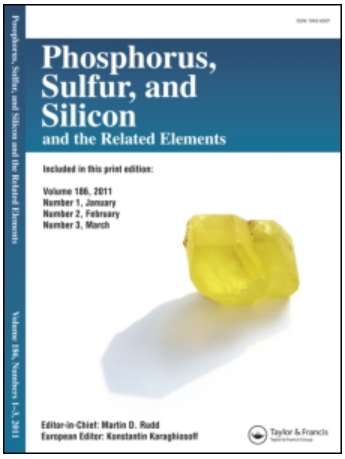

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SYNTHESIS AND STRUCTURE OF THE MESOCYCLIC COMPOUNDS, 5-PHENYL-l-THIA-5-PHOSPHACYCLOOCTANE, *CIS*- AND *TRANS*-1,5-DIPHENYL-1,5-DIPHOSPHACYCLOOCTANE AND THEIR PHOSPHINE OXIDES

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SYNTHESIS AND STRUCTURE OF THE MESOCYCLIC COMPOUNDS, 5-PHENYL-1-THIA-5-PHOSPHACYCLOOCTANE, *CIS*- AND *TRANS*-1,5-DIPHENYL-1,5-DIPHOSPHACYCLOOCTANE AND THEIR PHOSPHINE OXIDES

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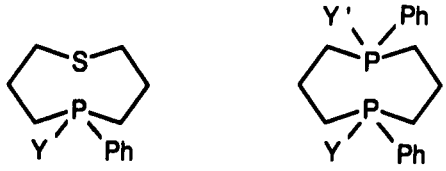
Three 1,5-disubstituted eight-membered ring mesocycles, 5-phenyl-1-thia-5-phosphacyclooctane, **2**, *cis*- and *trans*-1,5-diphenyl-1,5-diphosphacyclooctane, **5a** and **5b**, have been synthesized. The diastereomers **5a** and **5b** were separated by preparative HPLC and the stereochemical assignments confirmed by an X-ray crystal structure of **5b**. The X-ray crystal structures of 5-phenyl-1-thia-5-phosphacyclooctane 5-oxide, **1**, and *trans*-1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, **3b**, are also reported. Mesocycles **1**, **3b** and **5b** are in the boat-chair conformation and are devoid of any indications of transannular interactions.

Key words: Medium rings; Mesocycles; diastereomeric diphosphines; phosphine sulfides; phosphine oxides; X-ray structures.

INTRODUCTION

There has been a long-standing interest in the synthesis, structure, reactivity, and coordination chemistry of heteroatom-containing ring systems. Eight-membered ring systems (mesocycles) containing heteroatoms in the one and five positions are especially interesting since they often exhibit unusual structural and chemical properties due to transannular interactions between the functional groups. The cyclic dithioether, 1,5-dithiacyclooctane, 1,5-DTCO, forms a long-lived S—S bonded cation radical as well as the corresponding dication upon oxidation with one or two equivalents of $NOBF_4$, respectively.[1] The cyclic amine-thioether, 5-methyl-1-thia-5-azacyclooctane (1,5-TACO), possessing two dissimilar heteroatoms, also forms both a long-lived N—S bonded cation radical and the corresponding dication.[2] Aqueous iodine oxidation of 1,5-DTCO and 1,5-TACO to their sulfoxides revealed a significant rate enhancement of about 10^6 times that of common thioethers due to transannular interactions. Interestingly, the iodine oxidations were found to be both rapid and reversible.[3]

Cyclic polyhetero compounds are also of interest because of their applicability as possible ligands in catalytic processes, especially due to the steric constraints placed upon the catalyst due to the incorporation of the heteroatom(s) of the ligand into a ring structure. Horner[4] has prepared a number of cyclic benzyl or phenyl substituted bis-phosphonium salts, phosphines and phosphine oxide derivatives with ring sizes ranging from seven to eighteen, and Gallagher *et al.*[5] has reported the



Scheme 1 Compounds prepared in this study. Derivatives of 1-thia 5-phosphacyclooctane: **1**, Y = O; **2**, Y = lone pair. Derivatives of 1,5-diphosphacyclooctane: **3a**, Y = Y′ = O, *cis*; **3b**, Y = Y′ = O, *trans*; **4a**, Y = O, Y′ = lone pair, *cis*; **5a**, Y = Y′ = lone pair, *cis*; **5b**, Y = Y′ = lone pair, *trans*.

preparation and stereochemistry of phenyl substituted diphosphacycloalkanes with ring sizes from five to eight. Although Gallagher *et al.*[5] prepared one of the diastereomeric 1,5-diphenyl-1,5-diphosphacyclooctanes which he believed was the *trans* isomer, he gave only a limited discussion of its properties and failed to isolate and characterize the other isomer. In continuing our study of 1,5-disubstituted cyclooctanes, we report the synthesis, structure and properties of the phosphorus-containing mesocycles, 5-phenyl-1-thia-5-phosphacyclooctane, **2**, the diastereomeric *cis*- and *trans*-1,5-diphenyl-1,5-diphosphacyclooctanes, **5a** and **5b**, and their corresponding oxides. The X-ray crystal structures of 5-phenyl-1-thia-5-phosphacyclooctane 5-oxide, **1**, *trans*-1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, **3b**, and *trans*-1,5-diphenyl-1,5-diphosphacyclooctane, **5b**, were also obtained. Although NMR data is included in the experimental section of this paper, an interpretation of the data will be treated in a subsequent paper.

RESULTS AND DISCUSSION

Synthesis of 5-Phenyl-1-thia-5-phosphacyclooctane 5-oxide, 1. High dilution cyclization of bis(3-iodopropyl)phenylphosphine oxide[6] with thioacetamide and KOH[7] gave the phosphine oxide, **1**. A ^{31}P NMR spectrum of the cyclized product revealed only one P-containing product, as evident by a peak at δ 39.05, which is in a region of the spectrum characteristic for phosphine oxides.[8] The GC-MS consisted of only one peak which had a mass-to-charge ratio of 240 corresponding to $C_{12}H_{17}PSO^+$. A number of other sizable ion fragment peaks also appeared. Two of the peaks, m/e = 179 (M-61) and 193 (M-47), are common for unbranched aliphatic sulfides; the M-61 peak corresponds to loss of HS^+—CH_2—CH_2, while the M-47 peak is probably due to the loss of $CH_2{=}S^+H$[9] although it could also correspond to loss of PO from the molecular ion.[10]

Crystal Structure of 5-phenyl-1-thia-5-phosphacyclooctane 5-oxide, 1. Crystals of **1** were grown by slow diffusion of diethylether into a concentrated solution of the compound in methylene chloride. The mesocycle exists in the solid state in the boat-chair form; the phenyl substituent on the phosphorus atom occupies an equatorial position, while the oxygen is axial. The experimental parameters for the X-ray structure determination are given as Supplementary Material. A computer projection of the structure is reproduced in Figure 1. The phenyl ring in the six-membered ring, 1-phenylphosphorinane 1-oxide, is also equatorial, suggesting that the steric requirement of phenyl is greater than that of oxygen.[11] The boat-chair

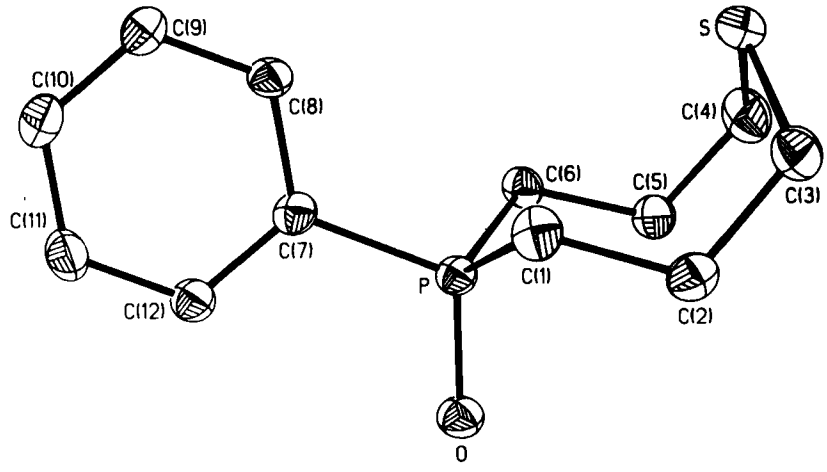


FIGURE 1 Computer-generated drawing of 5-phenyl-1-thia-5-phosphacyclooctane 5-oxide, **1**. The 50% probability ellipsoids are shown.

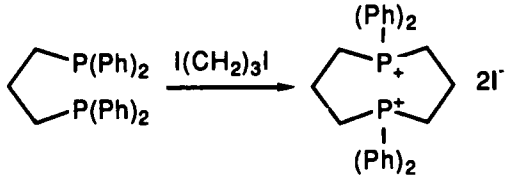
conformation is common to other eight-membered phosphorus-containing heterocycles; *trans*-2,6-dimethyl-1,3-dioxa-2,6-diphosphacyclooctane 2,6-disulfide and its corresponding diselenide.[12] There is no indication of a transannular P(O)—S interaction. The non-bonded phosphorus-sulfur distance in this molecule is 3.838 Å, which is 0.09 Å longer than the sum of the van der Waals radii. In a related mesocyclic 1,5-hetero-substituted thioether-sulfoxide, 3-methoxy-1,5-dithiacyclooctane 1-oxide, the transannular thioether interacts with the sulfoxide as illustrated by its alignment with the sulfoxide S—O bond, S-S-O angle of 175.4(1)°, and the non-bonded S—S(O) distance of 3.135(2) Å, which is 0.56 Å shorter than the sum of the van der Waals sulfur-sulfur distance.[13] Another eight-membered mesocycle, 1-thiacyclooctane 5-one, was also shown to exhibit a transannular 1,5-interaction by a number of indirect methods such as infrared and ultra-violet spectroscopy and dipole moment measurements.[14] All bond distances and angles are normal for this mesocycle and are given as Supplementary Material.

Synthesis of 5-Phenyl-1-thia-5-phosphacyclooctane, 2. Reduction of the phosphine oxide, **1**, with hexachlorodisilane[15] gave **2** in very high yield (98%). Kauffman[16] has similarly synthesized the arsine analog (5-phenyl-1-thia-5-arsacyclooctane) in 30% yield by treatment of bis(3-chloropropyl)phenylarsine with sodium sulfide nonahydrate in ethanol-water. The phosphine ligand **2** is a colorless oil at room temperature. A proton-decoupled phosphorus NMR of **2** contains one peak at δ-19.7 which is in the region characteristic of a phosphine.[17]

A low resolution mass spectrum of **2** revealed a parent peak with a mass-to-charge ratio of 224. The base peak is a fragment with a m/e of 182 indicating a $C_9H_{11}PS^+$ ion (loss of trimethylene); the preponderance of this thiaphosphacyclopentane fragment in the mass spectrum is evidence for sulfur-phosphorus interaction in the parent cation radical. This fragmentation pattern in which a polymethylene fragment is lost from a mesocyclic compound has been noted in all ring systems in which a transannular reaction can occur between two heteroatoms to give a five- or six membered ring cation (1,5-dithiacyclooctane, 1,5-dithiacyclo-

nonane, 1,6-dithiacyclodecane, 5-methyl-1-thia-5-azacyclooctane, etc.).[18] The mass spectrum of **2** revealed the presence of the sixteen-membered ring dimer, 5,11-diphenyl-1,8-dithia-5,11-diphosphacyclohexadecane, which was identified as its palladium complex.[19]

Synthesis of *cis* and *trans*-1,5-Diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, 3. The preparation of 1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, **3,** was undertaken in a straightforward manner by first treating 1,3-diiodopropane with 1,3-bis(diphenylphosphino)propane, DPP, under high dilution conditions in dimethylformamide to yield the cyclic bisphosphonium salt.

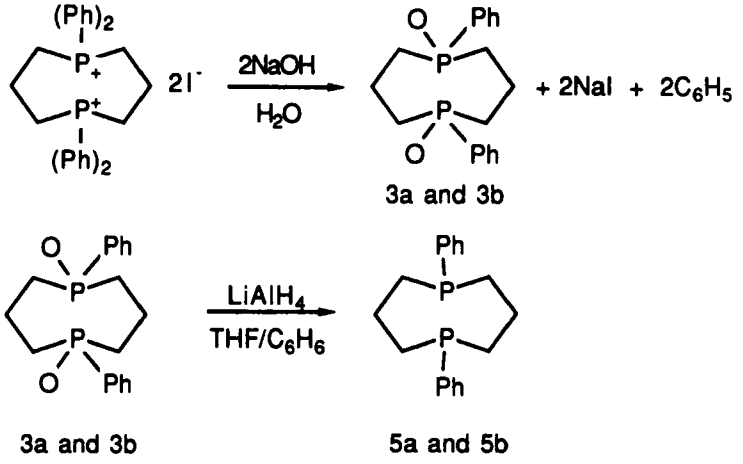


Scheme 2 Synthesis of the cyclic diphosphonium salt.

Horner and co-workers used a similar procedure to synthesize a number of cyclic benzyl-substituted phosphonium salts containing either two or four phosphorus atoms.[4] The ^{1}H NMR spectrum in DMSO-d_6 is consistent for the cyclic biphosphonium salt. The ^{31}P NMR contains one major resonance at δ 26.4 which is in the region of the spectrum which is characteristic of phosphonium salts.[20] Due to the insolubility of the bis phosphonium salt basic hydrolysis was carried out without purification to give a mixture of the isomeric dioxides, *cis*- and *trans*-1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, **3a** and **3b,** respectively. Due to the hygroscopic nature of phosphine oxides and their tendency to retain solvents,[21] the oily product(s) were repeatedly triturated with diethyl ether and dried under vacuum to produce a crude mixture of **3a** and **3b**.[4]

The mixture was readily separated by flash column chromatography; **3a,** was isolated in 16% yield, while **3b** was isolated in 22% yield.

The assignment of stereochemistry to each of the isolated phosphine oxides was



Scheme 3 Synthesis of *cis* and *trans*-1,5-diphenyl-1,5-diphosphacyclooctane.

first predicted on the basis of the R_f values: **3a** was expected to have a smaller R_f value than **3b** due to the preferential hydrogen bonding interaction of the more polar *cis* phosphine oxide with the silica gel adsorbent of the TLC plates. This assumption was substantiated by single crystal X-ray analysis of **3b**.

The IR spectra of **3a** and **3b** differ very little. A strong, broad P—O stretch is observed for both isomers.[10] The *cis*-phosphine oxide, **3a,** exhibits a broad P—O doublet absorption band with components at 1172 and 1155 cm^{-1}, and an additional sharp, medium-to-strong absorption at 1109 cm^{-1}. The *trans*-phosphine oxide, **3b,** similarly possesses a strong, broad absorption band at 1159 cm^{-1}, and a sharp, medium-to-strong absorption at 1110 cm^{-1}. These infrared absorbance bands are absent in the IR spectra of the fully reduced products.

The high resolution mass spectra of **3a** and **3b** are vastly different. The mass spectrum of **3b** displays only two prominent ion fragments in addition to the molecular ion peak (m/e 332). The base peak, with a mass number of 291, most likely arises from loss of a trimethylene fragment from 1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, followed by hydrogen transfer to one of the oxygens to form the corresponding five-membered ring ion, 1-hydroxy-2-oxo-1,2-diphenyl-1,2-diphospholane. The other prominent ion, [M-153], (m/e 179), may arise by loss of two phenyl groups from the molecular ion, followed by hydrogen transfer. Neither **3a** nor **3b** exhibits significant loss of oxygen.

In contrast, the mass spectrum of **3a** contains several prominent ion fragments; the abundance of the [M + 1] ion (3.4%) was higher than that of the molecular ion peak, [M], (2.7%). An [M-1] fragment (2.5%) was also observed; the production of [M-1] ions from aromatic phosphine oxides is commonly observed and has been attributed to the loss of an aromatic hydrogen to form bridged ions.[10] The base peak, [M-77], arises from elimination of a phenyl group; this fragment is not observed in **3b**. As expected, both isomers display prominent [M-41] fragments arising from loss of a trimethylene unit and migration of a hydrogen atom. Small [M-93] ions are found for both **3a** and **3b**; this is attributed to loss of C_6H_5O and has been observed in the fragmentation of other phosphine oxides.[10] It is generally thought to arise from a phosphine oxide-phosphinite rearrangement.

Crystal structure of *trans*-1,5-Diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, 3b. To confirm the stereochemistry of the dioxides, the crystal structure of *trans*-1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, **3b**, was determined. The experi-

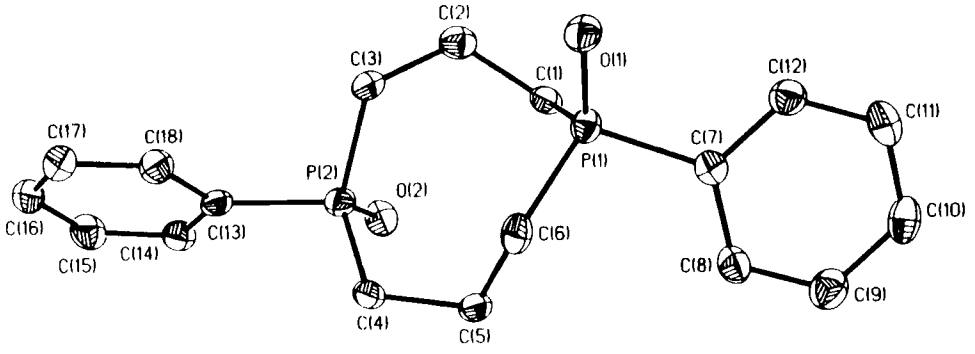


FIGURE 2 Computer-generated drawing of *trans*-1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, **3b**. The 50% probability ellipsoids are shown.

mental parameters for the X-ray structure determination are given as Supplementary Material. A computer projection of the structure is reproduced in Figure 2. The central 1,5-diphosphacyclooctane ring crystallizes in an asymmetric boat-chair conformation with a pseudo mirror plane passing through C(3) and C(6). Similar solid state ring conformations were reported for the *trans* eight-membered heterocycles, *trans*-2,6-dimethyl-1,3-dioxa-2,6-diphosphacyclooctane-2,6-disulfide and the corresponding *trans*-2,6-diselenide.[12] The oxygen atoms occupy pseudo-axial positions while the phenyl groups are pseudo-equatorial. All bond distances and angles are given as Supplementary Material. They are normal and compare favorably with those reported in the literature.[22,23] Both P—O bond distances are identical to within experimental error.

Synthesis of *cis* and *trans*-1,5-Diphenyl-1,5-diphosphacyclooctane, 5. Reduction of **3a** and **3b** to the corresponding phosphines, **5a** and **5b,** was first attempted with two different silicon based reducing agents, trichlorosilane and hexachlorodisilane. The silane reagents are often favored over $LiAlH_4$ and $Ca(AlH_4)_2$ because of their high degree of stereospecificity and reasonably high product yields.[15,23] Unfortunately, all attempts to reduce **3a** with either hexachlorodisilane or trichlorosilane were unsuccessful, even with the most rigorous exclusion of oxygen. Gallagher *et al.*[5] also reported that only one of the diastereomers of 1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, **3b,** could be reduced upon treatment with trichlorosilane and it gave only one of the isomeric diphosphines (δ -21.1). In contrast, we found that both isomeric phosphines are formed using this reagent.

Although some limitations, such as aryl cleavage,[24] have been observed in reducing arylphosphines with the hydride reagents, we found that both **3a** and **3b** can be reduced to mixtures of **5a** and **5b** with lithium aluminum hydride without difficulty. The yields were generally around 70%; the partially reduced monoxides, **4a** and **4b,** were obtained as minor products but were separable from the fully reduced diphosphines by column chromatography. Isomers **4a** and **4b** were readily identified in the ^{31}P NMR spectra; each appears as two peaks of approximately equal intensity, one in the downfield, phosphine oxide region of the spectrum, and the other in the upfield, phosphine region (δ 40.8, -23.9; δ 39.89, -25.8). A strong P—O stretch in the IR spectrum at 1168 cm^{-1} also supports the formation of monoxides.

The cyclic diphosphines, diastereomers **5a** and **5b,** appear in the ^{31}P NMR spectrum at δ -20.3 and -22.9 ($\Delta\delta$ = 2.6), respectively.[25] This $\Delta\delta$ value is typical for phosphorus ring diastereomer differentiation. In fact, although one would predict that as ring size increases the difference in δ values for diastereomers should become smaller, this does not appear to be the case.[25] The peak at δ-20.3 is generally larger than the peak at δ-22.9 (typical ratio ~3:1) and indicates that one isomer is formed in higher yield than the other. A similar result was reported by Horner who observed two sharp peaks with an integration ratio of 1:2 in the ^{31}P NMR spectrum of the diastereomeric 1,6-dibenzyl-1,6-diphosphacyclodecanes, δ-16.0 and -19.0 ($\Delta\delta$ = 3.0).[4]

Several techniques were attempted in an effort to separate the mixture of **5a** and **5b**; neither flash chromatography nor fractional sublimation was successful. Fractional crystallization was not attempted due to the ease with which these diphosphines react with oxygen. The diastereomers were, however, separable by HPLC.

The total amount of material recovered after HPLC was rather low, with yields of recovered compound ranging from 36 to 45%. The isolated yields correlate well with the relative integration values obtained for the two diastereomers from the ^{31}P NMR spectra and indicate that the phosphorus spectra were fairly quantitative. Marsi reported the tendency of a mixture of *cis* and *trans*-4-*tert*-butyl-1-phenylphosphorinanes to oxidize after about 10–11 hours in solution, despite the careful exclusion of oxygen from the samples.[11]

Upon dissolving **5a** and **5b** in separate tubes of degassed chloroform-*d*, and monitoring the ^{31}P NMR spectra over time, it became apparent that one isomer was much more stable in solution than the other. The spectrum of the *cis*-isomer, **5a,** was virtually unchanged after thirty six hours at room temperature, whereas after thirty-six hours under identical conditions, the *trans* isomer, **5b,** had completely decomposed to an apparent mixture of oxidized products.

Characterization and Assignment of Stereochemistry. Both **5a** and **5b** were characterized by a number of techniques in addition to ^{31}P NMR. The mass spectra of **5a** and **5b** differed significantly, although the number of prominent ion fragments obtained for both isomers was relatively small. The parent peak in the spectrum of **5a** was a prominent quasimolecular [M + 1] ion, m/e 301. Some phosphorus compounds, such as phosphorus esters, have been shown to undergo ion-molecule reactions to give significant [M + 1] peaks.[26] The base peak, with a mass number of 273, appears to arise from loss of ethylene from the quasimolecular ion fragment. This fragmentation pattern seems to be unusual, however, the mass spectrum of a five-membered phosphorus heterocycle, phospholane, also loses ethylene to give the base peak.[27] Other fragments arise from loss of phenyl from the molecular ion, m/e 223, in addition to ions Ph-P-H, m/e 109, and Ph-P-CH, m/e 121, which are all commonly observed fragments in the mass spectra of aromatic or mixed aromatic-aliphatic phosphines.[26] Surprisingly, the fragment corresponding to the loss of trimethylene, m/e 258, is not present in the mass spectrum of **5a** and therefore this is the first mesocycle which fails to fragment in this manner. Thus, the *cis* diposition of lone pairs must inhibit a transannular reaction in the radical cation.

The mass spectrum of **5b** reveals a prominent molecular ion peak, m/e 300, as well as an almost equally intense [M-1] peak, m/e 299. A trace of the oxidized product, [M + 16], was also observed. The base peak, [M-77], occurs due to loss of a phenyl group from the molecular ion. The second most intense peak in the mass spectrum of **5b** arises from loss of a trimethylene fragment from the molecular ion, m/e 258; this fragmentation pattern was also observed for **2** and is evidence of a transannular reaction. An ion fragment with a mass number of 271 also appears in the mass spectrum of **5b,** which has been attributed to loss of an ethylene unit; this parallels the base peak observed for **5a**.

A very small fragment with a mass-to-charge ratio of 183 is seen in the spectrum of **5a;** this ion is always observed in compounds containing Ph_2P-units and can be formed by a variety of paths.[26] A rather significant ion fragment, m/e 182 (7.45%), is also observed in the spectrum of the diphosphonium salt of **5** and probably arises from loss of a proton from the m/e 183 ion. Gallagher has claimed that *trans* isomers in general show greater phenyl transfer from one phosphorus to the other than the *cis* isomers, as reflected in the relative abundance of the m/e 183 ion in the EI mass spectra.[5] While a significant disparity in the abundance of this ion is not

obvious from a comparison of the mass spectrum of **5a** and **5b**, the relative amount of the closely related m/e 182 fragment of **5b** is greater than that of the m/e 183 ion fragment of **5a** and may be attributed cautiously to the *trans* stereochemistry of **5b**.

At first glance the infrared spectra of **5a** and **5b** appear to be similar; however, closer examination of the region from 1500–500 cm^{-1} reveals that most of the absorptions seen in **5b** are split into two closely spaced bands in the spectrum of **5a**. This may be an indication of the non-symmetric *cis* stereochemistry of **5a**. Similar reasoning has been stated by Gallagher, who has suggested that the IR spectra of isomeric diphosphorus heterocycles show striking differences in the 750–800 cm^{-1} region, with one of the isomers exhibiting two strong peaks and the other four. He has attributed this trait to phenyl group absorptions in either identical or slightly different environments.[5] The IR spectra of **5a** and **5b** do not possess any striking differences in the aforementioned region, although two strong absorbances are observed at 699, 747 cm^{-1} for **5a**, in addition to a medium absorbance at 769 cm^{-1}, accompanied by a weak band at 791 cm^{-1}. In contrast, examination of the identical region of **5b** reveals only two strong absorption bands at 696 and 740 cm^{-1}.

Crystal Structure of *trans*-1,5-Diphenyl-1,5-diphosphacyclooctcane (5a). Crystals of both **5a** and **5b** formed in a flask containing a mixture of the diphosphine isomers which had been stored in the freezer. The distinctly different crystals were separated manually on the basis of appearance (**5a:** parallelopipeds; **5b:** rectangular), and identified as either **5a** or **5b** on the basis of melting points. An X-ray analysis of **5b** confirmed our assignment as *trans*-1,5-diphenyl-1,5-diphosphacyclooctane and is in agreement with interpretation of ^{31}P and ^{1}H NMR analysis (to be reported later). The experimental parameters for the X-ray structure determination are given as Supplementary Material. A computer projection of the structure is reproduced in Figure 3. The conformation of the eight-membered ring is boat-chair. All bond distances and angles are normal for this mesocycle and are given as Supplementary Material. The only feature worthy of note is that the internal C—P—C angles may be larger (104.2 and 105.1°) than that normally seen in phosphines, i.e., 1,1,1-tris-(diphenylphosphinomethyl)ethane[28] (angles vary from 97° to 106°) and 4,4-dimethoxy-1-phenyl-1-phosphacyclohexane (100°).[29] It appeared that the corresponding phosphine oxide, **3b**, also had larger internal C—P—C angles (108.5° and 109.5°)

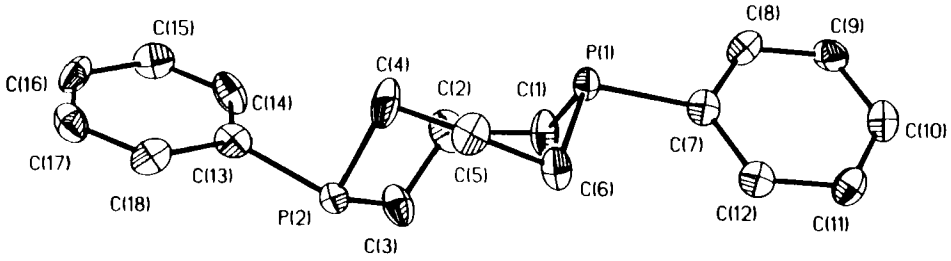


FIGURE 3 Computer-generated drawing of *trans*-1,5-diphenyl-1,5-diphosphacyclooctane, **5b**. The 50% probability ellipsoids are shown.

than normal but the ten-membered-ring analog, *trans*-1,6-diphenyl-1,6-diphosphacyclodecane, also has a large C—P—C angle (110.8°).[30]

EXPERIMENTAL

Melting points were determined using either a Nagle hot stage or a Thomas-Hoover capillary melting point apparatus. Infrared spectra were recorded on an IBM IR-32 spectrophotometer; all IR samples were prepared as KBr pellets unless noted otherwise. All microanalyses were carried out by the Berkeley Microanalytical Laboratory, Berkeley, California. All mass spectral data were collected by the Facility for Advanced Instrumentation, University of California, Davis. Gravity column chromatography was performed using silica gel purchased from J. T. Baker Chemical Co. as the solid support, 60–200 mesh. Flash column chromatography was performed using silica gel 60 purchased from E. M. Science, 230–400 mesh ASTM, 0.040–0.063 mm. Thin layer chromatography was carried out using pre-coated silica gel 60 F_{254} plastic sheets, 0.2 mm layer thickness, purchased from Merck. High pressure liquid chromatography was carried out on a Varian Model 500 liquid chromatograph fitted with a Lichrosorb Si-60, 7 mm column for preparative work; a 254 nm filter was used for UV-detection.

Spectral Data. Routine proton and carbon-13 NMR spectra were run on either Nicolet NT-360 or General Electric QE-300 spectrometers. Chemical shift values are given in ppm downfield from internal tetramethylsilane. ^{31}P broad band proton decoupled spectra were collected on a Nicolet NT-200 FT spectrometer, operating at 80.99 MHz. All chemical shift values are reported relative to an external 85% H_3PO_4 reference standard and are reported as positive if downfield.

Crystal Structures*. The crystals of the title complexes were mounted in the cold stream of a Syntex $P2_1$ graphite monochromated diffractometer (MoKα, λ = 0.71069 Å) equipped with a locally modified Syntex LT-1 low temperature device (T = 130 K). All crystallographic computing was carried out by using SHELXTL, Version 5, installed on a Data General MV/10000 Eclipse Series computer. The details of the crystal data and refinement procedures for complexes **1**, **3b** and **5b** are given as supplementary material.

Preparation of 5-Phenyl-1-thia-5-phosphacyclooctane 5-oxide, 1. Bis(3-hydroxypropyl)phenylphosphine oxide was prepared by oxidizing bis(3-hydroxypropyl)phenylphosphine (Alfa Products) with hydrogen peroxide using a modification of the method of Nappier *et al.*[6] The yield was essentially quantitative and the product was used without purification. R_f = 0.13, 5% EtOH-$CHCl_3$. ^1H NMR ($CDCl_3$): 7.85 (*m*, 1), 7.70 (*m*, 4), 3.75 (*t*, 4), 1.90 ppm (*m*, 8). IR: 3350 (-OH), 1190 (P-O), 1050 cm^{-1} (P-C).

Bis(3-chloropropyl)phenylphosphine oxide was synthesized by chlorination of the corresponding bis(3-hydroxypropyl)phenylphosphine oxide (12.75 g, 5.26 × 10^{-2} mol) using PCl_5.[6] The crude oil was flash chromatographed using 5% EtOH-$CHCl_3$ to yield a white solid, (9.4 g, 64%). R_f = 0.74, 20% EtOH-$CHCl_3$. ^1H NMR ($CDCl_3$): 7.5 (*m*, 5), 3.5, (*t*, 4), 2.0 ppm, (*m*, 8), IR: no -OH stretch.

Bis(3-iodopropyl)phenylphosphine oxide was prepared by refluxing bis(3-chloropropyl)phenylphosphine oxide (6.20 g, 22 mmol) with anhydrous sodium iodide (8.32 g, 55.5 mmol) in 67 mL dry acetone under nitrogen for 20 h. The NaCl was filtered and the supernatant concentrated. The residual yellow oil was dissolved in $CHCl_3$, the organic solution was extracted with aq. $Na_2S_2O_3$, and dried with Na_2SO_4. The decanted solution was evaporated to give an off-white solid (9.34 g, 20.2 mmol) in 92% crude yield. The product is light sensitive and was stored in a foil-covered vial at 0°C. ^1H NMR ($CDCl_3$): δ 7.6 (*m*, 5), 3.25 (broadened *t*, due to coupling with phosphorus, 4), 2.1 (*m*, 7.8).

The cyclization is a modification of the procedure described by Vogtle.[7] In a two-liter, three-necked Morton flask equipped with an overhead stirrer, two dilution arms with condensers, and three syringe inlets was refluxed 600 mL of absolute ethanol. Three ethanolic solutions (100 mL each) were prepared: (1) KOH, 5.16 g, 0.080 moles, (2) thioacetamide, 2.40 g, 0.032 moles, (3) bis(3-iodopropyl)-phenylphosphine oxide, 12 g, 0.032 moles. Under N_2 the solutions were added via syringe pump (KOH and thioacetamide in one arm and diiodide in the other) over a period of 48 h. The solution was then refluxed for an additional 2 h before cooling. The ethanol was distilled off through a Vigreaux column, water was added to dissolve all solids, and the organic product was extracted with $CHCl_3$. The organic layers were washed with a small amount of H_2O, and dried briefly over Na_2SO_4. The solvents were distilled off, leaving a mustard colored oil, 7.0 g, which was chromatographed on Baker silica gel using $CHCl_3$, 5% C_2H_5OH in $CHCl_3$, and 10% C_2H_5OH in $CHCl_3$, successively. The main product was a white solid (54% yield) which had an R_f = 0.44 (10% C_2H_5OH in $CHCl_3$). ^1H NMR ($CDCl_3$): δ 7.635, 7.374 (*m*, 5); 2.748 (*m*, 2), 2.608 (*m*, 2), 2.273 (*m*, 4), 2.030–1.833 (*m*, 4). ^{31}P NMR ($CHCl_3$/CCl_4 = 2:3): δ 39.052. HRMS m/e: Calcd. 240.0737, Found 240.0746000, $C_{12}H_{17}PSO^+$. Low Resolution MS,

m/e 91, 125, 139, 154, 166, 179, 193, 207, 225. Molecular weight determination (Signer Method):[31] 238 + 6% (240), standard = 4-bromo-biphenyl. M.p. 155–156°C.

5-Phenyl-1-thia-5-phosphacyclooctane, 2. The phosphine oxide **1** (0.304 g, 1.27 mmol suspended in dry benzene) was reduced under nitrogen to the corresponding phosphine with Si_2Cl_6 (0.481 g, 1.2M in benzene).[15] After treatment with 5 mL of 30% NaOH and 10 mL of benzene, the benzene layer was removed by pipet and the cloudy aqueous phase was extracted 6 times with $CHCl_3$. The combined organic layers were dried, decanted and evaporated to leave a colorless oil. The oil was chromatographed on Baker silica gel with $CHCl_3$ followed by 5% C_2H_5OH in $CHCl_3$. The main fraction (0.28 g, 1.24 mmol, 98%) had an R_f = 0.95 (5% C_2H_5OH in $CHCl_3$): Anal.: Calcd. for C_{12} $H_{17}PS$:C, 64.26; H, 7.64, Found C, 63.97; H, 7.56. ^1H NMR ($CDCl_3$): δ 7.406 (*m*, 2), 7.246 (*m*, 3), 2.786 (*m*, 2), 2.537 (*m*, 2), 2.010 (*m*, 6), 1.838 (*m*, 2). ^{31}P NMR ($CDCl_3$): δ -19.684. HRMS, m/e Calcd. 224.0789: Found 224.0772, $C_{12}H_{17}PS^+$; Low Resolution MS, m/e (relative intensity): 109 (100) $C_6H_5PH^+$, 224 (33) $C_{12}H_{17}PS^+$, 448 (1.4) $C_{24}H_{34}P_2S_2^+$ and m/e 155, 182, 196, 209, 233, 255, 297, 405.

Preparation of *cis*- and *trans*-1,5-Diphenyl-1,5-diphosphacyclooctane, 5.

1,1,5,5-Tetraphenyl-1,5-diphosphacyclooctane Diiodide.[21] 1,3-diiodopropane (0.7084 g, 2.39 mmol) and 1,3-bis(diphenylphosphino)propane (0.9850 g, 2.39 mmol) were each dissolved in 25 mL DMF and the solutions added dropwise via addition funnels over a 5 hr period to 50 mL of refluxing DMF under a dry nitrogen atmosphere. The reaction mixture was then refluxed for an additional 20 hr. The reaction mixture was cooled to room temperature and worked up in 25 mL portions. Dry toluene (110 mL) was added slowly, with stirring, to a 25 mL aliquot of the reaction mixture to precipitate a white powder. The mixture was centrifuged, and the solid washed with small portions of toluene and diethyl ether and dried *en vacuo*. (Toluene added to the original decantate failed to precipitate any additional product). The overall crude yield for this reaction was 1.27 g, 75%. Analysis by ^{31}P NMR and HPLC methods revealed a mixture of three phosphorus-containing products, with one major product formed in approximately 85% yield. The diiodide salt is light sensitive and was stored in the dark in a foil-covered vial. The hydrolysis reaction was carried out without further purification of the crude quaternary phosphonium salt.

***cis* and *trans*-1,5-Diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, 3a and 3b.** 1,1,5,5,-tetraphenyl-1,5-diphosphacyclooctane diiodide (1.27 g, 1.79 mmol) was converted to a mixture of the corresponding-isomeric diphosphine oxides by the method of Benn *et al.*[21] Repeated trituration of the colorless, oily product with diethyl ether, followed by drying several hours under vacuum, resulted in a white solid. (Crude yield: 0.535 g, 90%). The white solid was dissolved in a minimum amount of $CHCl_3$ and purified by flash chromatography on EM Merck Kieselgel 60 silica gel (230–400 mesh) using 20% EtOH-$CHCl_3$. Two products were obtained as white solids and subsequently identified as *cis*-1,5-diphenyl-1,5-diphosphacyclooctane, 1.5-dioxide, **3a,** (0.093 g, 16%) and *trans*-1,5-diphenyl-1,5-diphosphacyclooctane 1,5-dioxide, **3b,** (0.131 g, 22%).

Upon concentration under vacuum, a solution of **3b** in 20% EtOH-$CHCl_3$ yielded crystals suitable for X-ray analysis, which verified the structure of the *trans* bis-phosphine oxide. Compound **3a:** R_f = 0.34 (20% EtOH-$CHCl_3$), mp. 214–215°C, ^{31}P NMR ($CDCl_3$): 38.7 ppm. ^1H NMR ($CDCl_3$): δ 7.8 (*m*, 4), 7.5 (*m*, 6), 2.6 (*m*, 7), 2.2 (*m*, 7). ^{13}C NMR ($CDCl_3$): (Ph ipso C not observed); δ 131.9 (*s*, para); 129.6 (*d*, ortho), ^2J(P, C) 8.9 Hz; 128.8 (*d*, meta), ^3J(P, C) 11.3 Hz; 30.0 (*d* of *d*), ^1J(P, C) 65 Hz, ^3J(P, C) 1.5 Hz; 14.5 (*t*), ^2J(P, C) 4.1 Hz. MS, m/e (relative intensity) 332 (27) $C_{18}H_{22}P_2O_2^+$. MS, m/e 179, 213, 239, 255, 256, 291, 331, 332, 333. IR: 3056, 2931, 1437, 1172, 1155 cm^{-1} (P—O, *s*, broad) 1109 cm^{-1} (P—O, *s*), 1070, 970, 937 cm^{-1}.

Compound **3b:** R_f = 0.55 (20% EtOH-$CHCl_3$), mp: darkens at 200°C, melts from 220–222°C, ^{31}P NMR ($CDCl_3$): 39.1 ppm. Anal.: Calcd for $C_{18}H_{22}P_2O_2$: C, 65.06; H, 6.67, Found: C, 64.85; H, 6.74. ^1H NMR ($CDCl_3$): δ 7.7 (*m*, 4), 7.5 (*m*, 6), 2.65 (*m*, 4), 2.35 (*m*, 8). ^{13}C NMR ($CDCl_3$): δ 135.0 (*d*, ipso), ^1J(P, C) 96 Hz; 131.6 (*s*, para); 129.4 (*d*, ortho), ^2J(P, C) 8.8 Hz; 128.7 (*d*, meta), ^3J(P, C) 11.3 Hz; 29.8 (*d* of *d*), ^1J(P, C) 64.5 Hz, ^3J(P, C) 1.6 Hz; 15.1 (*t*), ^2J(P, C) 4.7 Hz. MS, m/e (relative intensity) 179, 213, 239, 291, 332 (7.7), $C_{18}H_{22}P_2O_2^+$, IR: 3056, 2935, 1436, 1159 (P—O, *s*, broad), 1110 (P—O, *s*), 1071, 929 cm^{-1}.

***cis* and *trans*-1,5-Diphenyl-1,5-diphosphacyclooctane, 5a and 5b.** Various methods were utilized in an attempt to synthesize the fully reduced bis-phosphines; they are briefly outlined below. All reduction reactions were carried out under a dry nitrogen atmosphere using dry, deoxygenated solvents.

Reduction of **3b** with Si_2Cl_6. The *trans* diphosphine dioxide, **3b,** (0.132 g, 0.40 mmol suspended in 2 mL of benzene) was reduced with Si_2Cl_6 (0.270 g, 0.5 M in benzene) in the manner described by Mislow[15] (total reflux time, 1h). The crude oil (0.140 g) was column chromatographed using 5% EtOH-$CHCl_3$ as the eluent. Two isomers of the fully reduced product, **5a** and **5b,** were not separable by

column chromatography (0.0484 g, 41%). TLC: (5% EtOH-$CHCl_3$), R_f = 0.74, 0.63. ^{31}P NMR ($CDCl_3$): δ -20.3(3), -22.9(1). The relative integration values in parentheses are based on relative peak heights; no attempt was made to ensure that the values are quantitative. The infrared spectrum supports the formation of the fully reduced isomeric products by the absence of a strong P—O stretch.

An additional product was obtained from the chromatography as a white solid, one of the partially-reduced isomeric compounds, **4**. (0.03095 g, 25%). ^{31}P NMR: δ 39.9, -25.5. mp. (uncorrected) 126.5–128°C. R_f (5% EtOH-$CHCl_3$) = 0.16. IR: 1168 cm^{-1}, (P—O, *s*, broad).

Reduction of **3b** with $SiCl_3H$. A 1.34 M solution of $SiCl_3H$ (0.271 mL, 2.69 mmol) in benzene was added dropwise to a suspension of **3b** (0.112 g, 0.336 mmol) in 4 mL of benzene.[15] Upon addition of the silane, the reaction mixture turned a chalky-white. The reaction mixture was stirred for 1 h at room temperature and then refluxed for 7.5 h. The reaction mixture was then cautiously hydrolyzed and the organic phase separated, extracted with $CHCl_3$, dried over $MgSO_4$, decolorized with Norite and concentrated under vacuum to yield a yellow oil (0.122 g). The oil was chromatographed twice (eluent = 5% EtOH-$CHCl_3$) to yield a mixture of both **5a** and **5b** (0.0517 g, 51%), and **4a** and **4b** (0.0248 g, 23%).

Reduction of **3a** with $SiCl_3H$, Si_2Cl_6. All attempts to reduce **3a** with the commonly employed silane reagents, $SiCl_3H$ and Si_2Cl_6, in an identical manner as described for the reduction of **3b** above, were unsuccessful.

Reduction of **3b** with $LiAlH_4$.[32] The solvents THF (6.0 mL) and benzene (4.0 mL) were added to a reaction flask containing **3b** (0.2138 g, 6.44×10^{-4} mol) and a five-fold excess of $LiAlH_4$ (0.2450 g, 6.44×10^{-3} mol) and the resultant mixture was refluxed for 17 h, cooled in an ice-bath and hydrolyzed using the method of Fieser.[33] The products were purified by chromatography as described above: a mixture of **5a** and **5b**: 0.166 g, 86%, a mixture of **4a** and **4b**, 0.024 g, 12%. ^{31}P NMR (**4a** and **4b**): δ 40.8, -23.9; 39.89, -25.8. R_f (5% EtOH-$CHCl_3$) = 0.10, 0.13.

Reduction of **3a** with $LiAlH_4$. The procedure followed was identical to that described above for the reduction of **3b** with $LiAlH_4$. Yields: **5a** and **5b**, 69%; **4a** and **4b**, 20%.

Separation of **5a** and **5b**. The separation and subsequent isolation of the two diphosphine isomers was attained by HPLC: eluent, CH_2Cl_2; flow, 5 mL/min; elution times, isomer **5a**, 5–8 min; isomer **5b**, 12–20 min. The HPLC was fitted with a 1 mL injection loop; a typical solution of the *cis/trans* mixture contained 57.4 mg of compound dissolved in 3.0 mL of methylene chloride.

Cis-isomer, **5a** (1st eluting isomer): white solid, R_f = 0.74 (5% EtOH-$CHCl_3$), mp. 76–78°C, ^{31}P NMR ($CDCl_3$): δ -20.4, MS, m/e = 301 (M + 1), $C_{18}H_{22}P_2^+$, 273, 223, 183, 121, 109. ^{1}H NMR ($CDCl_3$): δ 7.25 (4, *m*), 7.15 (6, *m*), 2.09 (8, *m*), 1.95 (4, *m*). ^{13}C NMR ($CDCl_3$): δ 140.8 (*d*), ^1J(P, C) 11.5 Hz; 131.6 (*d*), ^2J(P, C) 17.6 Hz; 128.3 (*d*), ^3J(P, C) 6.2 Hz; 128.1 (*s*); 27.2 (*d* of *d*), ^1J(P, C) 14.9 Hz, ^3J(P, C) 5.84 Hz; 22.1 (*t*), ^2J(P, C) 12.1 Hz. IR (KBr) 2918, 1433, 1420, 792(*w*), 770, 748, 699 cm^{-1}. *Trans*-isomer, **5b** (2nd eluting isomer): white solid, R_f = 0.62 (5% EtOH-$CHCl_3$), mp. 70–73°C, ^{31}P NMR ($CDCl_3$): δ -23.2, MS, m/e = 300, $C_{18}H_{22}P_2^+$, 299, 271, 258, 223, 182. ^{1}H NMR ($CDCl_3$): δ 7.25 (4, *m*), 7.15 (6, *m*), 2.2–1.95(12), broad featureless resonance. IR (KBr) 2918, 1431, 741, 696 cm^{-1}. After elution, the total amount of material recovered ranged from 36 to 45%.

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***Supplementary Material**: Tables of crystal data, data collection, structure refinement procedures, atomic coordinates, intramolecular distances and angles have been deposited with the Cambridge Crystallographic Data Center, United Kingdom. They are available on request by writing to the Director, CCDC, University Chemical Laboratory, Lensfield Road, Cambridge, CB2 1EW. Requests should be accompanied by the full literature citation.

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