Synthesis, Molecular Structure, and Properties of *in*-Phosphaphanes with Substituted Basal Aromatic Rings

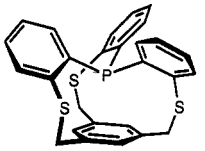
Anthony P. West, Jr.,† Natalie Smyth,† Christina M. Kraml,‡ Douglas M. Ho,† and Robert A. Pascal, Jr.*,†

Department of Chemistry, Princeton University, Princeton, New Jersey 08544, and Wyeth-Ayerst Research Laboratories, CN 8000, Princeton, New Jersey 08543

Received February 25, 1993

A series of nitro-substituted phosphine-containing cyclophanes (2-4) was prepared by base-promoted condensation of various nitrated derivatives of 1,3,5-tris(bromomethyl)benzene with tris(2-mercaptophenyl)phosphine under conditions of high dilution. The mononitro cyclophane 2 was reduced with $TiCl_3$ in THF–EtOH to give the corresponding amino derivative 5. The ^{13}C NMR spectra of these compounds exhibit "through-space" spin–spin coupling between the phosphorus and the substituted basal aromatic ring, and in their ^{31}P NMR spectra the phosphorus resonances are anomalously far downfield. The nitro-substituted phanes are colored, probably due to charge-transfer absorptions between the phosphine and the nitroarene base. The X-ray crystal structures of cyclophanes 4 and 5 reveal a pronounced inward pyramidalization of the phosphines such that the phosphorus atoms are 2.98 and 2.92 Å, respectively, from the centers of the basal rings. These cyclophanes are rigid, molecular propellers, and compound 2 was chromatographically resolved on a chiral HPLC column. The circular dichroism spectra of the pure enantiomers showed a very high molecular ellipticity at 332 nm of 120 000 deg·cm^2·dmol^{-1}.

We recently reported the synthesis, molecular structure, and spectroscopic and chemical properties of the triarylphosphine-containing cyclophane 1, for which an unusual interaction between the phosphine and the basal aromatic ring was indicated by several lines of evidence.[1]



1

Most prominently, the ^{13}C NMR spectrum of 1 exhibited "through-space" spin–spin coupling of the phosphorus atom with the carbons of the basal aromatic ring, and the ^{31}P NMR signal for 1 was 32 ppm downfield from that of an acyclic model compound. In addition, a phosphorus to ring distance of only 2.90 Å in 1 was observed in the X-ray structure, and, due to the steric shielding afforded by the *in*-geometry (pyramidalization of the phosphine toward the basal ring), the phosphorus atom was most unreactive: it was not protonated by anhydrous HBr or oxidized by refluxing hydrogen peroxide in acetic acid.

However, although an electronic interaction between the phosphine and basal ring was evident from the NMR data, it was not clear from these studies whether there was any net donation of electron density from one group to the other or whether the geometry of 1 was influenced by anything other than simple steric repulsion between the phosphorus and the basal carbon atoms. In order to elucidate the nature of these interactions, we have now synthesized and characterized several related cyclophanes bearing electron-withdrawing and electron-donating substituents on the basal aromatic ring.

Results and Discussion

Syntheses of Cyclophanes. The strongly electron-withdrawing properties of the nitro group, as well as the general ease of nitration reactions, motivated us to seek first the mono-, di-, and trinitro derivatives of compound 1. Any direct nitration of 1 would be complicated by substitution of the bridging *o*-phenylene units or oxidation of the thioethers. Instead, the condensation of appropriately nitrated 1,3,5-tris(bromomethyl)benzenes with tris(2-mercaptophenyl)phosphine[2] (8, Scheme I) was chosen for the synthesis of the nitrophosphaphanes.

Nitration of 1,3,5-tris(bromomethyl)benzene[3] (6) under the conditions employed by Vogel for the preparation of *p*-nitrobenzyl cyanide[4] gave a mixture of products, but a simple recrystallization of this material from methanol gave 2-nitro-1,3,5-tris(bromomethyl)benzene (7) in 32% yield. The mononitro phosphaphane 2 was then prepared in 21% yield by slow addition of KOH in ethanol to a dilute solution of 7 and 8 (2.5 mM each) in refluxing 2:1 benzene–ethanol.

Our attempts to nitrate compound 7 further with nitrating acids at higher temperatures resulted only in oily, unresolvable mixtures. Presumably the benzylic bromides are sensitive to oxidation or displacement under these conditions. Better results were obtained by use of nitronium salts,[5] and treatment of 7 with 0.5 M nitronium tetrafluoroborate in sulfolane at 100 °C gave a product

† Princeton University.
‡ Wyeth-Ayerst Research Laboratories.

(1) (a) Pascal, R. A., Jr.; West, A. P., Jr.; Van Engen, D. *J. Am. Chem. Soc.* **1990**, *112*, 6406–6407. (b) L'Esperance, R. P.; West, A. P., Jr.; Van Engen, D.; Pascal, R. A., Jr. *J. Am. Chem. Soc.* **1991**, *113*, 2672–2676.

(2) Block, E.; Ofori-Okai, G.; Zubieta, J. *J. Am. Chem. Soc.* **1989**, *111*, 2327–2329.

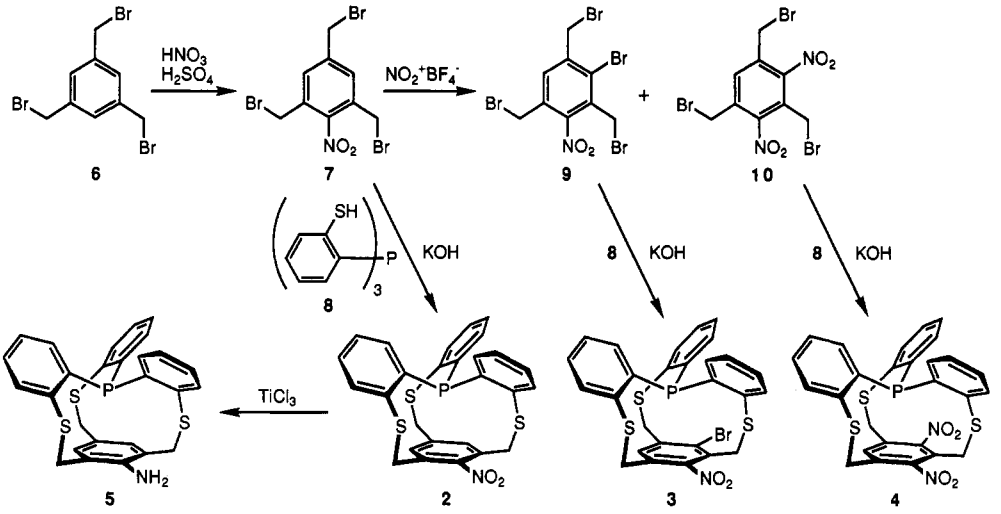
(3) Vogtle, F.; Zuber, M.; Lichtenthaler, R. G. *Chem. Ber.* **1973**, *106*, 717–718.

(4) Vogel, A. *Vogel's Practical Organic Chemistry*, 4th ed.; Longman: New York, 1978; p 628.

(5) (a) Kuhn, S. J.; Olah, G. A. *J. Am. Chem. Soc.* **1961**, *83*, 4564–4571. (b) Fieser, L. F.; Fieser, M. *Reagents for Organic Synthesis*; John Wiley and Sons: New York, 1967; pp 742–743.

0022-3263/93/1958-3502$04.00/0

Scheme I



which could be purified by recrystallization from methanol. However, this crystalline material proved to be a 2:1 mixture of 2,4-dinitro-1,3,5-tris(bromomethyl)benzene (**10**) and 2-bromo-4-nitro-1,3,5-tris(bromomethyl)benzene (**9**). Chromatographic separation was difficult, so the mixture was used for the subsequent cyclophane synthesis. Condensation of the **9**/**10** mixture with **8** under conditions of high dilution gave the bromonitro- and dinitrophosphaphanes **3** and **4**, which were easily separated by preparative TLC.

All attempts to prepare 2,4,6-trinitro-1,3,5-tris(bromomethyl)benzene, either by vigorous nitration of compound **6** or NBS bromination of trinitromesitylene, were unsuccessful.

In order to obtain a cyclophane with a strongly electron-donating amino group on the basal ring, we decided to reduce the nitro group of compound **2**, but the presence of benzylic sulfides in the cyclophane limited the choice of conditions. A procedure for the reduction of hindered nitro groups in benzylic sulfide-containing cyclophanes has been reported by Vogtle et al.[6] which involves heating the nitro compound in phenylhydrazine at 200 °C. Unfortunately, when compound **2** was subjected to this procedure, only decomposition products were obtained from the reaction mixture. We then tested a variety of common reducing agents in very small scale reactions, and, somewhat to our surprise, the treatment of **2** with an excess of $TiCl_3$ in hot ethanol and THF cleanly reduced the nitro group to give the aminophosphaphane **5** in 79% yield.

Spectra. The NMR spectra of the substituted phosphaphanes were of particular interest, since the phosphine–arene interaction in the parent **1** was first evident in its NMR properties. How does substitution affect the ^{31}P-^{13}C "through-space" coupling (coupling via nonbonded interactions[7]) and the ^{31}P chemical shift? Compound **1** possesses C_3 symmetry, and its NMR spectra are correspondingly simple; however, compounds **2**–**5** have no axes of symmetry, so all of their protons and carbons are inequivalent. Many of the carbon resonances in compounds **2**, **4**, and **5** could be assigned by means of standard incremental chemical shift tables[8,9] where compound **1** was taken as the base, and the assignments of many proton-bearing carbons were subsequently confirmed by ^{1}H–^{13}C HETCOR 2D-NMR spectra. Table I contains the ^{31}P–^{13}C coupling constants and ^{13}C chemical shifts for basal ring carbons of compound **1**, **2**, **4**, and **5**. Notably, there is a small decrease in the nonbonded J_{PC} as electron-withdrawing substituents are attached to the basal ring, as one might expect if reduced electron density resulted in reduced spin–spin coupling (but see below). Table I also contains the ^{31}P chemical shifts in these compounds, which vary irregularly in the range δ 5–10, but all are far downfield of the resonances observed in the nonmacro-

Table I. Selected Spectroscopic Data for Phosphaphanes 1, 2, 4, and 5

compd	basal ring substituents	J_{PC} (Hz) (δ_C) for basal methine[a]	J_{PC} (Hz) (δ_C) for basal quarternary ipso to substituent[a]	δ_P[b]	UV λ_{max} (nm, $CHCl_3$)
5	NH_2	8.2 (131.7) 7.8 (133.2)	7.9 (143.7)	9.3	304 (sh), 334
1[c]		7.5 (130.0)		5.0	292, 341
2	NO_2	7.4 (132.3) 7.3 (132.7)	6.5 (149.7)	6.9	298, 328 (sh)
4	NO_2 (2)	7.0 (134.2)	6.5 (150.2) 6.0 (150.4)	5.8	298 (sh), 324 (sh)

[a] Coupling constants are accurate to within ±0.4 Hz. [b] ^{31}P chemical shifts were referenced to an external standard of $(MeO)_3P$ at δ 140. [c] Data from ref 1.

(6) Vogtle, F.; Wieder, W.; Forster, H. *Tetrahedron Lett.* **1974**, 4361–4364.

(7) For excellent examples and discussions of spin–spin coupling via nonbonded interactions involving fluorine, nitrogen, and carbon atoms, see the work of Mallory: (a) Mallory, F. B. *J. Am. Chem. Soc.* **1973**, *95*, 7747–7752. (b) Mallory, F. B.; Mallory, C. W.; Ricker, W. M. *J. Am. Chem. Soc.* **1975**, *97*, 4770–4771. (c) Mallory, F. B.; Mallory, C. W. *J. Am. Chem. Soc.* **1985**, *107*, 4816–4819. (d) Mallory, F. B.; Mallory, C. W.; Baker, M. B. *J. Am. Chem. Soc.* **1990**, *112*, 2577–2581.

(8) Silverstein, R. M.; Bassler, G. C.; Morrill, T. C. *Spectrometric Identification of Organic Compounds*, 5th ed.; John Wiley and Sons: New York, 1991; p 240.

(9) For compound **3**, which consists of two diastereomers which do not interconvert on the NMR time scale, the spectra are very complex. For example, in the ^{1}H NMR spectrum of **3** there appear twelve doublets due to the diastereotopic methylene protons alone, and in the aromatic region of its ^{13}C NMR spectrum, where there is doubling of all resonances from spin–spin coupling to phosphorus, there are approximately 96 lines. This, in combination with the very limited availability of **3**, made assignments extremely difficult. Related problems were encountered in the crystallographic study of **3**. The two diastereomers cocrystallize in such a way that the bromine and nitro groups are disordered in the crystal; thus, both diastereomers of **3** (all four stereoisomers) are accommodated in the crystal lattice. Unfortunately, this limits the precision of the X-ray structure determination. For these reasons, we have chosen not to discuss the spectra and structure of compound **3**.

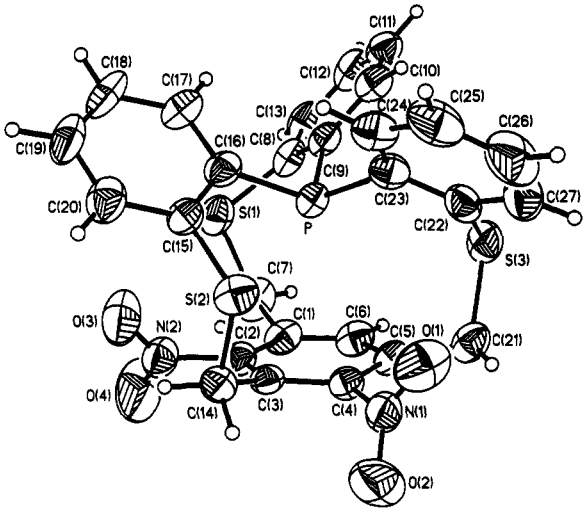
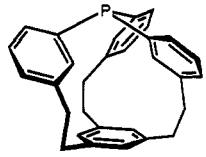


Figure 1. X-ray structure of the dinitro cyclophane **4**. Thermal ellipsoids are drawn at the 50% probability level.

cyclic **8** (δ −26.7,[1] −26.4[2]), its *S,S',S''*-tribenzyl derivative[1b] (δ −27.0), or the interesting *out*-phosphaphane **11** (δ −14.2) of Bohm and Sharpless.[10]



11

A more dramatic effect of substitution is found in the color of these compounds. The parent **1** and its amino derivative **5** are essentially colorless, with no significant absorption in their UV spectra beyond 400 nm. In contrast, the nitro compounds **2** and **4** are bright yellow and orange, respectively, and their UV spectra exhibit very broad, low-intensity bands which extend beyond 500 nm (see Figure 3). The immediate precursors of **2** and **4** are colorless or very pale yellow, so the nitro groups themselves do not impart the color to the cyclophanes. Rather, these low-intensity bands are probably charge-transfer absorptions involving the phosphine and basal nitroarenes. In other respects, however, the UV spectra of compounds **1**–**5** are relatively similar, each having two distinct features in the region from 290–340 nm (Table I) and strong absorption below 270 nm.

Structures. Are the structures of the substituted phosphaphanes significantly different from the parent **1**? Single crystals of compound **4** and **5** formed easily, and the X-ray structures of these molecules are illustrated in Figures 1 and 2. However, suitable crystals of compound **2** were never obtained, despite many attempts at slow crystallization, and the crystals of compound **3** proved to be seriously disordered.[9] We had speculated that there might be less repulsion between the phosphorus lone pair and an electron-deficient basal ring, with perhaps even an attractive electrostatic component, resulting in a shorter distance between the phosphorus to the center of the basal ring (d_{P-Ar}). However, in the parent **1** and its amino derivative **5**, the d_{P-Ar} is almost the same (2.90 Å[1] and 2.92 Å, respectively), and in the dinitro compound **4**, d_{P-Ar} is

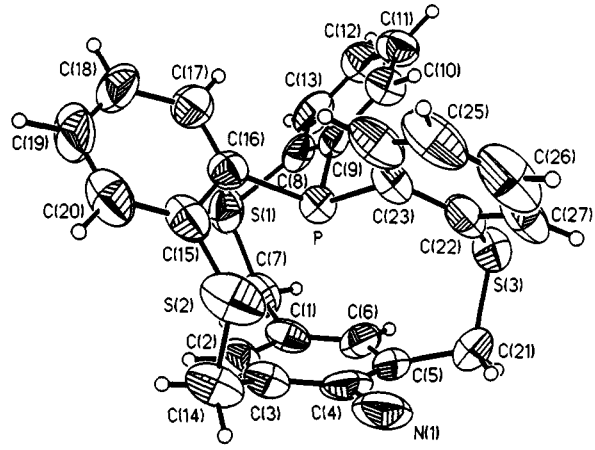


Figure 2. X-ray structure of the amino cyclophane **5**. Thermal ellipsoids are drawn at the 50% probability level. The amino group is disordered between the C(2) and C(4) sites (only one is shown), and the amine hydrogens were not located.

significantly greater (2.98 Å). A closer examination of the structure of **4** shows that the latter increase is not an electronic effect. Steric congestion forces the two nitro groups of compound **4** to rotate out of the plane of the basal ring by about 60° (Figure 1), and in this position one oxygen atom in each of the nitro groups is brought into contact with the bridging *o*-phenylene groups. The interatomic distances are 3.05 Å [O(3)–C(15)] and 3.12 Å [O(1)–C(22)], which are less than the sum of the nominal van der Waals radii of oxygen and aromatic carbon (1.50 + 1.77 = 3.27 Å[11]). Thus, the two nitro groups buttress the phosphine, preventing a closer approach to the basal ring. We had not anticipated this steric effect, since AM1 calculations[12] yield a very different geometry for **4**: the nitro groups are rotated only 45° out of the basal ring plane, and the closest approach of a nitro group to an *o*-phenylene is 3.65 Å. In contrast, the amino group of **5** is sterically unencumbered (see Figure 2), and conjugation with the arene is unimpaired, but it appears to have little effect on the geometry of the cyclophane.

In view of these data, the observed decrease in NMR spin–spin coupling between the phosphorus and basal ring carbons as nitro groups are added (Table I) need not be due to a perturbation of the electron density on the ring, but may instead reflect an increased separation between phosphorus and carbon. The crystallographically observed P–C distances in compound **4** are consistent with this interpretation. In **4**, the nitro-bearing carbons C(2) and C(4) are 3.31 and 3.32 Å, respectively, from the phosphorus and show J_{PC}'s of 6.0–6.5 Hz, while the basal methine C(6) is 3.26 Å from phosphorus and has a J_{PC} of 7.0 Hz. In compounds **1** and **5**, the P–C distances are generally shorter and the coupling constants greater.

Resolution of Cyclophane 2. The *in*-phosphaphanes are chiral molecular propellers, and we suspected that the resolved enantiomers might exhibit great optical activity. Because of its availability, we chose compound **2** for resolution experiments. Once solubility problems were solved, resolution of the enantiomers of **2** was achieved by means of high-performance liquid chromatography (HPLC) on commercial Chiralpak AD columns [amylose tris(3,5-dimethylphenyl carbamate) on silica gel; Chiral Tech-

(10) Bohm, C.; Sharpless, K. B. *Tetrahedron Lett.* **1988**, *29*, 5101–5104.

(11) Bondi, A. *J. Phys. Chem.* **1964**, *68*, 441–451.

(12) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902–3909.

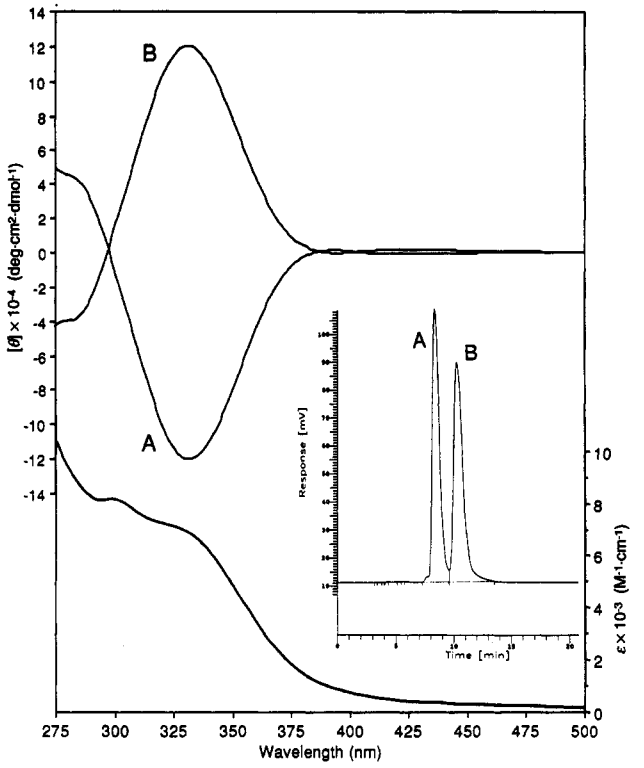


Figure 3. CD spectra of enantiomers A and B of compound **2** (upper two curves) and UV spectrum of (±)-**2** (bottom curve). The inset shows the chromatographic resolution of isomers A and B.

nologies, Inc.]. Figure 3 illustrates the UV spectrum of (±)-**2**, the chromatographic resolution, and the circular dichroism (CD) spectra of the resolved enantiomers. The CD spectra were obtained on samples of enantiomers A and B which were judged to be >99% pure by analysis on the chiral column (detection at 298 nm), and the maximal molecular ellipticity of the resolved enantiomers is 119 900 ±1600 deg·cm²·dmol⁻¹ at 332 nm. For comparison, this degree of ellipticity is slightly greater than that of the molecular propeller perchlorotriphenylamine at 300 nm[13] but substantially less than that of hexahelicene (647 000 deg·cm²·dmol⁻¹ at 325 nm).[14] The solutions of the resolved enantiomers of **2** were indefinitely stable at room temperature, and thus the barrier to enantiomerization of this propeller structure is at least 26 kcal/mol. No attempt was made to resolve the other phosphaphanes.

Conclusion. The parent *in*-phosphaphane **1** is a rigid, chiral, molecular propeller with a fairly high degree of strain.[1] Substitution of the basal ring of **1** with nitro and amino groups produced a series of cyclophanes **2–5** which, apart from the visible charge transfer absorptions in the nitro-substituted derivatives, displayed only relatively minor differences in spectroscopic properties from the parent. The small but significant structural differences observed upon comparison of the crystal structures of **1**, **4**, and **5** are most plausibly attributed to steric, not electronic, effects. However, the conformational rigidity of these compounds, which may account for the relative insensitivity to substitution, does permit their resolution at room temperature, and the the resolved enantiomers of compound **2** exhibit exceptionally high optical activity.

(13) Okamoto, Y.; Yashima, E.; Hatada, K.; Mislow, K. *J. Org. Chem.* **1984**, *49*, 557–558.
(14) Newman, M. S.; Darlak, R. S.; Tsai, L. *J. Am. Chem. Soc.* **1967**, *89*, 6191–6193.

Experimental Section

2-Nitro-1,3,5-tris(bromomethyl)benzene (7). A solution of concentrated nitric acid (12 mL) and concentrated sulfuric acid (13 mL) was cooled in an ice bath. 1,3,5-Tris(bromomethyl)-benzene[3] (5.00 g, 14.0 mmol) was added over a period of 10 min, cooling was continued for 1 h, and then the mixture was allowed to warm to room temperature. Ice–water was added, and the mixture was extracted with ether. The extract was washed with water, dried over $MgSO_4$, and concentrated. The residue was recrystallized from methanol to give compound **7** as very pale yellow needles (1.82 g, 32%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.45 (s, 2H), 4.48 (s, 4H), 7.52 (s, 2H); MS *m/z* 401, (M^+[$^{79}Br_2{}^{81}Br$], 9), 322 (M – Br, 100), 241 (M – Br_2, 12), 143 (30); exact mass 400.8077, calcd for $C_9H_8NO_2{}^{79}Br_2{}^{81}Br$ 400.8084.

Nitrophosphaphane 2. Tris(2-mercaptophenyl)phosphine[2] (**8**, 1.62 g, 4.53 mmol) and 2-nitro-1,3,5-tris(bromomethyl)benzene (**7**, 1.82 g, 4.53 mmol) were mixed in 2:1 benzene–ethanol (1.8 L), and the solution was heated to reflux under argon. An argon-saturated solution of KOH (1.4 g, 21 mmol) in ethanol (100 mL) was added dropwise over 1 h. After 11 h, the solution was cooled, precipitated salt was removed by filtration, and the solvent was evaporated. The residue was chromatographed twice on silica gel: first quickly on a short column (solvent, 2:1 benzene/ethanol) to remove polar impurities and then carefully on a longer column (solvent, benzene). The first component to elute was bright yellow compound **2** (0.49 g, 20.9%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.50 (d, J = 14 Hz, 1H), 3.78 (d, J = 14 Hz, 1H), 3.80 (s, 2H), 4.36 (d, J = 14 Hz, 1H), 4.44 (d, J = 14 Hz, 1H), 6.79 (ddd, J = 8, 1.5, 1.5 Hz, 1H), 6.82 (ddd, J = 8, 1.5, 1.5 Hz, 1H), 6.92 (ddd, J = 8, 1.5, 1.5 Hz, 1H), 7.00 (d, J = 1.5 Hz, 1H), 7.01 (d, J = 1.5 Hz, 1H), 7.24 (m, 3H), 7.32 (m, 3H), 7.71 (ddd, J = 8, 4, 1.5 Hz, 1H), 7.73 (ddd, J = 8, 4, 1.5 Hz, 1H), 7.78 (ddd, J = 8, 4, 1.5 Hz, 1H); ^{13}C{^{1}H} NMR (125.8 MHz, $CDCl_3$) δ 38.7, 42.3, 43.6, 129.3, 129.4, 129.9, 130.0, 130.1, 132.3 (d, J_{PC} = 7 Hz, basal ring methine assigned by ^{1}H–^{13}C HETCOR), 132.7 (d, J_{PC} = 7 Hz, basal ring methine assigned by ^{1}H–^{13}C HETCOR), 134.3 (d, J_{PC} = 3 Hz), 134.96 (d, J_{PC} = 3 Hz), 134.99 (d, J_{PC} = 3 Hz), 137.60 (d, J_{PC} = 39 Hz), 137.64 (d, J_{PC} = 3 Hz), 137.71 (d, J_{PC} = 38 Hz), 138.3 (d, J_{PC} = 39 Hz), 139.3 (d, J_{PC} = 4 Hz), 139.5 (d, J_{PC} = 4 Hz), 139.62 (d, J_{PC} = 4 Hz), 139.68 (d, J_{PC} = 4 Hz), 142.7 (d, J_{PC} = 17 Hz), 143.8 (d, J_{PC} = 17 Hz), 144.6 (d, J_{PC} = 17 Hz), 147.2 (d, J_{PC} = 4 Hz), 149.7 (d, J_{PC} = 6 Hz); ^{31}P{^{1}H} NMR (101.2 MHz, $CDCl_3$) δ 6.9; UV ($CHCl_3$), λ_{max} (log ϵ) 298 (3.91), 3.28 (sh, 3.85); MS *m/z* 517 (M^+, 34), 500 (M – OH, 23), 484 (M – SH, 39), 355 (77), 323 (64), 289 (25), 215 (100), 184 (51), 171 (35), 141 (37), 139 (37); exact mass 517.0390, calcd for $C_{27}H_{20}NO_2PS_3$ 517.0396.

2-Bromo-4-nitro-1,3,5-tris(bromomethyl)benzene (9) and 2,4-Dinitro-1,3,5-tris(bromomethyl)benzene (10). 2-Nitro-1,3,5-tris(bromomethyl)benzene (0.91 g, 2.3 mmol) was added to a solution (0.5 M) of nitronium tetrafluoroborate in sulfolane (6 mL). The reaction mixture was heated to 100 °C for 30 min and then cooled and diluted with water (15 mL). The oil that separated was collected, washed with water, and recrystallized from methanol to give yellow needles (0.17 g). This initial solid contained several impurities, but after several recrystallizations TLC and NMR analysis showed the presence of two compounds in a 2:1 ratio. The major component was the dinitro compound **10** [^{1}H NMR (500 MHz, $CDCl_3$) δ 4.41 (s, 2H), 4.44 (s, 4H), 7.76 (s, 1H)] and the other the minor **9** [^{1}H NMR (500 MHz, $CDCl_3$) δ 4.38 (s, 2H), 4.58 (s, 2H), 4.62 (s, 2H), 7.64 (s, 1H)]. MS data were also consistent with this analysis, and the mixture was used without further purification.

Bromonitrophosphaphane 3 and Dinitrophosphaphane 4. Compound **8** (0.11 g, 0.3 mmol) and the mixture of **9** and **10** (0.14 g, 0.3 mmol) were mixed in 2:1 benzene–ethanol (180 mL), and the solution was heated to reflux under argon. An argon-saturated solution of KOH (0.1 g, 1.8 mmol) in ethanol (10 mL) was added dropwise over 1 h. After 17 h, the solution was cooled, precipitated salt was removed by filtration, and the solvent was evaporated. The residue was fractionated by preparative silica gel TLC (solvent, 1:1 benzene–hexanes). Two orange, major, relatively nonpolar components were isolated and identified: bromonitrophosphaphane **3** (12 mg, R_f = 0.5) and dinitrophosphaphane **4** (20 mg, R_f = 0.4).

Compound 3 consists of a pair of chromatographically inseparable diastereomers in a 1:1 ratio; thus, its NMR spectrum is extremely complicated, and it is not possible to assign any given resonance to a particular diastereomer: ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.46 (d, J = 14 Hz, 1H), 3.66 (d, J = 14 Hz, 1H), 3.80 (d, J = 14 Hz, 1H), 3.89 (d, J = 14 Hz, 1H), 3.92 (d, J = 14 Hz, 1H), 4.07 (d, J = 14 Hz, 1H), 4.098 (d, J = 14 Hz, 1H), 4.103 (d, J = 14 Hz, 1H), 4.21 (d, J = 14 Hz, 1H), 4.39 (d, J = 14 Hz, 1H), 4.77 (d, J = 14 Hz, 1H), 4.88 (d, J = 14 Hz, 1H), 6.89 (m, 6H), 7.06 (s, 1H), 7.08 (s, 1H), 7.25 (m, 6H), 7.33 (m, 6H), 7.74 (m, 6H); MS m/z 597 (M^+[^{81}Br], 24), 595 (M^+[^{79}Br], 21), 564 (M – SH-[^{81}Br], 29), 562 (M – SH[^{79}Br], 26), 452 (23), 355 (85), 323 (66), 289 (24), 215 (100), 184 (48), 183 (35), 171 (32), 139 (32); exact mass 594.9511, calcd for $C_{27}H_{19}NO_2PS_3{}^{79}Br$ 594.9501.

Single crystals of compound 4, suitable for X-ray analysis, were obtained from methylene chloride–methanol:[15] ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.51 (d, J = 14 Hz, 1H), 3.84 (d, J = 14 Hz, 1H), 3.89 (d, J = 14 Hz, 1H), 4.16 (d, J = 14 Hz, 1H), 4.25 (d, J = 14 Hz, 1H), 4.33 (d, J = 14 Hz, 1H), 6.82 (ddd, J = 8, 2, 2 Hz, 1H), 6.90 (ddd, J = 8, 2, 2 Hz, 1H), 6.93 (ddd, J = 8, 2, 2 Hz, 1H), 7.19 (s, 1H), 7.28 (m, 3H), 7.37 (m, 3H), 7.74 (ddd, J = 8, 4, 1 Hz, 1H), 7.77 (ddd, J = 8, 4, 1 Hz, 1H), 7.78 (ddd, J = 8, 4, 1 Hz, 1H); ^{13}C{^{1}H} NMR (67.9 MHz, $CDCl_3$) δ 34.7, 38.3, 41.6, 129.68, 129.78, 129.79, 130.4, 130.5, 130.6, 131.6 (d, J_{PC} = 3 Hz), 134.2 (d, J_{PC} = 7 Hz), 134.6 (d, J_{PC} = 3 Hz), 135.3 (d, J_{PC} = 2 Hz), 136.8 (d, J_{PC} = 37 Hz), 137.4 (d, J_{PC} = 39 Hz), 137.5 (d, J_{PC} = 38 Hz), 138.8 (d, J_{PC} = 4 Hz), 139.74 (d, J_{PC} = 4 Hz), 139.77 (d, J_{PC} = 4 Hz), 139.9 (d, J_{PC} = 4 Hz), 140.3 (d, J_{PC} = 4 Hz), 142.0 (d, J_{PC} = 13 Hz), 142.8 (d, J_{PC} = 14 Hz), 144.0 (d, J_{PC} = 13 Hz), 150.2 (d, J_{PC} = 6 Hz), 150.4 (d, J_{PC} = 6 Hz); ^{31}P{^{1}H} NMR (101.2 MHz, $CDCl_3$) δ 5.8; UV ($CHCl_3$), λ_{max} (log ϵ) 298 (sh, 4.0), 324 (sh, 3.9); MS m/z 562 (M^+, 18), 529 (M – SH, 10), 516 (M – NO_2, 10), 468 (16), 452 (15), 355 (80), 323 (76), 289 (26), 231 (24), 215 (100), 184 (54), 183 (40), 171 (35), 170 (35), 141 (38), 139 (40); exact mass 562.0235, calcd for $C_{27}H_{19}N_2O_4PS_3$ 562.0247.

Aminophosphaphane 5. Compound 2 (50 mg, 0.097 mmol) was dissolved in 1 mL of THF. Solid $TiCl_3$ (0.4 g) was dissolved in 3 mL of ethanol with brief heating. The two solutions were combined in a test tube and heated to reflux for 3 min. Additional $TiCl_3$ (0.2 g) was added, and the mixture was refluxed for another 3 min. A few drops of water were added, and the purple solution was added to ether and aqueous KOH in a separatory funnel. After shaking and separating, the clear ether extract was washed with water, dried over $MgSO_4$, and concentrated to yield crystalline compound 5 (37 mg). Single crystals of compound 5, suitable for X-ray analysis, were obtained from chloroform solution:[15] ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.52 (d, J = 14 Hz, 1H), 3.73 (d, J = 14 Hz, 1H), 3.82 (d, J = 14 Hz, 1H), 3.85 (d, J = 14 Hz, 1H), 3.89 (d, J = 14 Hz, 1H), 3.94 (d, J = 14 Hz, 1H), 4.32 (d, J = 14 Hz, 1H), 6.74 (d, J = 2 Hz, 1H), 6.77 (d, J = 2 Hz, 1H), 6.83 (d, J = 7 Hz, 1H), 6.86 (d, J = 7 Hz, 1H), 6.88 (d, J = 7 Hz, 1H), 7.22 (m, 3H), 7.29 (m, 3H), 7.70 (ddd, J = 8, 4, 1.5 Hz, 1H), 7.73 (ddd, J = 8, 4, 1.5 Hz, 1H), 7.77 (ddd, J = 8, 4, 1.5 Hz, 1H); ^{13}C{^{1}H} NMR (62.9 MHz, $CDCl_3$) δ 38.6, 42.1, 44.4, 128.5 (d, J_{PC} = 4 Hz), 128.9, 129.0, 129.4, 129.67, 129.69, 130.5 (d, J_{PC} = 4 Hz), 131.7 (d, J_{PC} = 8 Hz), 133.2 (d, J_{PC} = 8 Hz), 134.6 (d, J_{PC} = 2 Hz), 134.7 (d, J_{PC} = 2 Hz), 135.1 (d, J_{PC} = 2 Hz), 135.5 (d, J_{PC} = 4 Hz), 137.9 (d, J_{PC} = 39 Hz), 138.5 (d, J_{PC} = 4 Hz), 138.6 (d, J_{PC} = 40 Hz), 138.7 (d, J_{PC} = 40 Hz), 139.5 (d, J_{PC} = 4 Hz), 139.9 (d, J_{PC} = 4 Hz), 143.7 (d, J_{PC} = 8 Hz), 144.0 (d, J_{PC} = 23 Hz), 144.3 (d, J_{PC} = 22 Hz), 144.6 (d, J_{PC} = 22 Hz); ^{31}P{^{1}H} NMR (101.2 MHz, $CDCl_3$) δ 9.3; UV ($CHCl_3$) λ_{max} (log ϵ) 304 (sh, 3.9), 334 (3.8); MS m/z 487 (M^+, 100), 454 (M – SH, 31), 421 (M – 2SH, 8), 355 (53), 346 (19), 323 (42), 215 (39); exact mass 487.0667, calcd for $C_{27}H_{22}NPS_3$ 487.0652.

Resolution of Compound 2. Small samples of 2 were resolved by HPLC on a Chiralpak AD column (25 cm × 0.46 cm; Chiral Technologies, Inc.). The mobile phase composition was chloroform–hexane–2-propanol (1:19:1). For each injection, *ca.* 0.2 mg of 2 was dissolved in 10 μL of chloroform followed by 10 μL of the mobile phase. The injection volume was 20 μL, the flow rate was 1.0 mL/min, and the eluted components were detected by their UV absorption at 298 nm. Circular dichroism (CD) spectra were obtained on chloroform solutions of the resolved enantiomers, the optical path length was 1 cm, and the concentrations of the solutions were determined by their absorbance at 298 nm.

Acknowledgment. This work was supported by National Science Foundation Grant CHE-9106903. We thank Janette Carey for assistance with the CD measurements.

Supplementary Material Available: ^{1}H NMR spectra of compounds 2–5 and 7 (5 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(15) The author has deposited atomic coordinates for 4 and 5 with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK.