

VO(hfac)₂·THTP, 70528-15-3; VO(hfac)₂·py·N-O, 70528-16-4; VO(hfac)₂·MeIm, 70528-17-5.

Supplementary Material Available: Table M-1, raw calorimetry data for VO(hfac)₂ (3 pages). Ordering information is given on any current masthead page.

References and Notes

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The Partial Aminolysis of (NPF₂)_{3,4}¹

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Received November 27, 1978

Unlike the reactions of (NPCl₂)_{3,4} with simple amines, the fluorocyclophosphazenes, (NPF₂)_{3,4}, react with methylamine, *n*-butylamine, or dimethylamine with replacement of only one fluorine atom per phosphorus to yield products such as N₄P₄F₃(NHMe)₃, N₄P₄F₄(NHMe)₄, N₄P₄F₅(NHC₄H₉)₃, N₄P₄F₅(NMe₂)₃, N₄P₄F₄(NMe₂)₄, N₃P₃F₄(NHMe)₂, N₃P₃F₄(NHC₄H₉)₂, or N₃P₃F₄(NMe₂)₂. This behavior cannot be ascribed to steric effects because nucleophiles such as CF₃CH₂ONa, C₆H₅ONa, and (CH₃)₂NLi readily replace all the fluorine atoms. The results are more compatible with an explanation based on the poor leaving-group ability of fluoride combined with the low nucleophilicity of the free amines, compared with the higher leaving-group ability of chloride and the high nucleophilicity of alkoxides, aryl oxides, or metal amides.

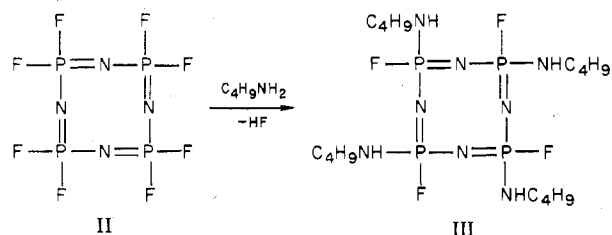
The reactions of cyclic or high polymeric chlorophosphazenes such as (NPCl₂)_{3,4,n} with primary or secondary amines or with alkoxides or aryl oxides have been studied in detail.² Under suitable reaction conditions all the chlorine atoms can normally be replaced by amino, alkoxy, or aryloxy residues to yield cyclic or high polymeric phosphazenes of formula [NP(NHR)₂]_{3,4,m}, [NP(NR₂)₂]_{3,4,m}, or [NP(OR)₂]_{3,4,m}. The only exceptions are reactions that involve highly hindered nucleophiles such as diethylamine, diphenylamine, or amino-azo dyes, especially in reactions with the high polymer (NPCl₂)_n.^{3,4}

Fluorocyclophosphazenes such as (NPF₂)_{3,4} closely resemble chlorophosphazenes in their behavior toward alkoxides or aryl oxides. For example, (NPF₂)₄ reacts readily with CF₃CH₂ONa or C₆H₅ONa to yield [NP(OCH₂CF₃)₂]₄ or [NP(OC₆H₅)₂]₄ (see Experimental Section). However, a survey of the literature revealed a curious absence of reports of fully aminolyzed phosphazene trimers or tetramers derived from (NPF₂)_{3,4}. Compounds such as N₃P₃F₅NHMe, N₃P₃F₃(NMe₂)₃, N₄P₄F₇NH₂, or N₄P₄F₄(NMe₂)₄ had been reported,⁵⁻⁷ but no species containing more than three or four amino residues were described. This was of particular interest to us because of our intention to utilize high molecular weight poly(difluorophosphazene) as a substrate for the synthesis of mixed-substituent poly(aminophosphazenes).

We wish to report here the significant difference that apparently exists between the aminolysis reactions of (NPF₂)₃

(I) or (NPF₂)₄ (II) and those of the corresponding chlorophosphazenes when these compounds are allowed to interact with an excess of primary or secondary amine. Specifically, I and II react with methylamine, *n*-butylamine, or dimethylamine with replacement of only one fluorine atom per phosphorus under conditions that lead to total replacement of chlorine in (NPCl₂)_{3,4}. In fact, so far we have been unable to find reaction conditions that lead to the complete aminolysis of fluorocyclophosphazenes.

The reaction conditions and the results of the present work are summarized in Table I and in the Experimental Section. A typical example is given by the conversion of II to III in



the presence of butylamine. The reaction products were identified by a combination of VPC-mass spectrometric and ³¹P NMR data as three different isomers of the nongeminal species III and two nongeminal isomers of N₄P₄F₅(NHC₄H₉)₃. Only trace amounts, if any, of N₄P₄F₃(NHC₄H₉)₅ were de-

Table I. Reaction Conditions for Halophosphazene Aminolysis Reactions^a

phosphazene	g of phosphazene (mol)	solvent for phosphazene (mL)	amine	g of amine (mol)	solvent for amine (mL)	temp, °C	time, h
(NPF ₂) ₄	1.0 (0.003)	THF (20)	C ₄ H ₉ NH ₂	10.4 (0.144)	THF (100)	reflux	12
(NPF ₂) ₄	1.0 (0.003)	THF (20)	C ₄ H ₉ NH ₂	10.4 (0.144)	THF (100)	25	12
(NPF ₂) ₄	1.0 (0.003)	THF (20)	C ₄ H ₉ NH ₂	10.4 (0.144)	THF (100)	25	336
(NPF ₂) ₄	2.0 (0.006)	THF (20)	C ₄ H ₉ NH ₂	35.1 (0.48)	Et ₂ O (200)	25	14
(NPCl ₂) ₄	2.0 (0.0043)	THF (10)	C ₄ H ₉ NH ₂	25.6 (0.35)	THF (100)	25	12
(NPF ₂) ₄	1.0 (0.003)	THF (10)	C ₄ H ₉ NH ₂	10.4 (0.144)	THF (100)	25	24
			LiBr	2.2 (0.025)			
(NPF ₂) ₄	1.0 (0.003)	THF (10)	C ₄ H ₉ NH ₂	10.4 (0.144)	THF (100)	25	24
			(C ₂ H ₅) ₃ N	2.53 (0.025)			
(NPF ₂) ₄	1.0 (0.003)	THF (10)	CH ₃ NH ₂	7.47 (0.24)	THF (100)	25	24 ^b
(NPF ₂) ₄	1.0 (0.003)	THF (10)	(CH ₃) ₂ NH	12.0 (0.27)	THF (100)	25	24 ^b
(NPCl ₂) ₄	2.0 (0.0043)	THF (10)	CH ₃ NH ₂	10.0 (0.32)	THF (100)	25	12 ^b
(NPCl ₂) ₄	2.0 (0.0043)	THF (10)	(CH ₃) ₂ NH	15.0 (0.33)	THF (100)	25	12 ^b
(NPF ₂) ₃	1.0 (0.004)	THF (20)	CH ₃ NH ₂	5.27 (0.17)	THF (100)	25	24 ^b
(NPF ₂) ₃	1.0 (0.004)	THF (20)	(CH ₃) ₂ NH	7.70 (0.17)	THF (100)	25	24 ^b
(NPF ₂) ₃	1.0 (0.004)	THF (20)	C ₄ H ₉ NH ₂	12.40 (0.17)	THF (100)	25	24
(NPF ₂) ₃	1.0 (0.004)	THF (20)	C ₄ H ₉ NH ₂	12.40 (0.17)	THF (100)	reflux	36

^a All reactions were carried out by the dropwise addition of the solution of the halophosphazene to a stirred solution of the amine. ^b The volatile amines were condensed into each reaction mixture by means of a dry ice condenser, and the solutions of the amines in THF were cooled to 0 °C until the halophosphazene addition was complete. At that point, the mixtures were allowed to warm to 25 °C. Reaction temperatures above 25 °C were not employed with CH₃NH₂ or (CH₃)₂NH because of the volatility of these amines.

tected. Similar results were obtained when II reacted with methylamine to yield N₄P₄F₅(NHMe)₃ and [NPF(NHMe)]₄ or with dimethylamine to yield N₄P₄F₅(NMe₂)₃ and [NPF(NMe₂)]₄. By contrast, (NPCl₂)₄ reacted with *n*-butylamine, methylamine, or dimethylamine under similar reaction conditions to yield [NP(NHC₄H₉)₂]₄, [NP(NHMe)₂]₄, or [NP(NMe₂)₂]₄. A similar reaction pattern was followed when the cyclic trimer (NPF₂)₃ interacted with methylamine, *n*-butylamine, or dimethylamine to yield N₃P₃F₄(NHMe)₂, N₃P₃F₄(NHC₄H₉)₂, or N₃P₃F₄(NMe₂)₂ plus only traces of the triamino derivatives under reaction conditions that lead to complete aminolysis of (NPCl₂)₃.

These differences cannot be ascribed to a simple steric resistance to the second substitution at each phosphorus, even after taking into account the relative shortness of a phosphorus-fluorine bond. Lithium dimethylamide, LiNMe₂, reacted with II to give N₄P₄F₂(NMe₂)₆, N₄P₄F(NMe₂)₇, and a trace of [NP(NMe₂)₂]₄. A similar reaction of LiNMe₂ with I yielded mainly [NPF(NMe₂)₂]₃ and N₃P₃F₂(NMe₂)₄. A reaction between LiNMe₂ and (NPCl₂)₃ gave [NP(NMe₂)₂]₃. Lithium dimethylamide is clearly more reactive toward I and II than is dimethylamine in spite of the similarity in the expected steric hindrance effects. It should also be noted that the aminolysis results cannot be ascribed to the precipitation of partially aminolyzed fluorophosphazenes from the reaction medium. In all these cases the phosphazenes remained in solution until the end of the reaction.

One other mechanistic explanation for the partial-aminolysis behavior seems to be unacceptable. In theory, it is possible that the aminolysis reactions of I and II are equilibrium controlled and that amino groups can be displaced by the hydrogen fluoride formed in the earlier stages of the reaction. Two items of evidence are incompatible with this viewpoint. First, the insolubility of the amine hydrofluorides in the reaction medium would make such a displacement reaction unlikely. Second, reactions between II and *n*-butylamine carried out in the presence of lithium bromide gave products that were virtually identical with those formed in the absence of this latter reagent. In such a system, any free fluoride would be expected to be removed from solution in the form of insoluble lithium fluoride.

The results appear to be more compatible with an explanation based on the relative reactivities of [NP(F)NRR']_{3,4} and [NP(Cl)NRR']_{3,4} (R = H or Me) and on the relative nucleophilicities of the reagents employed. Electron supply

from one amino residue attached to phosphorus probably deactivates the second phosphorus-fluorine bond at that site. The combined influences of the low nucleophilicity of a free amine and the poor leaving-group ability of the fluoride ion would exaggerate this effect. In these terms, the higher reactivities of sodium trifluoroethoxide, sodium phenoxide, and lithium dimethylamide can be attributed to their higher nucleophilicities. The deactivating effect appears to be more pronounced with (NPF₂)₃ than with (NPF₂)₄.

Experimental Section

Materials and Equipment. Hexachlorocyclotriphosphazene, (NPCl₂)₃ (donated by the Firestone Tire and Rubber Co.), was purified by sublimation, followed by two recrystallizations from *n*-heptane. Octachlorocyclotetraphosphazene, (NPCl₂)₄, was obtained from the sublimation residues of the trimer purification. It was purified by resublimation and recrystallization from heptane. Conversion of (NPCl₂)₃ and (NPCl₂)₄ to (NPF₂)₃ and (NPF₂)₄ was accomplished by treatment with sodium fluoride in acetonitrile or nitrobenzene,⁸ followed by fractional distillation. The reaction solvents and amines were dried before use by distillation from calcium hydride. Reagent grade tetrahydrofuran (THF) and diethyl ether were also distilled from lithium aluminum hydride.

The mass spectrometric analyses were obtained with the use of an AEI, M.S. 902 mass spectrometer instrument. ³¹P NMR spectra were obtained by means of a JEOL NMR spectrometer instrument operated at 40 MHz in the FT mode with 32 scans being employed for a typical spectrum. Chemical shifts are reported relative to 85% phosphoric acid in water.⁹

Reaction of (NPF₂)₄ with Sodium Trifluoroethoxide. A sample of (NPF₂)₄ (2.0 g, 0.006 mol) in THF (10 mL) was added to a solution of sodium trifluoroethoxide (prepared from 5.52 g (0.24 mol) of sodium and 31.2 g (0.312 mol) of trifluoroethanol in 150 mL of THF), and the reaction mixture was boiled at reflux for 48 h. The reaction mixture was concentrated to 25 mL on a rotary evaporator and was added to a dilute aqueous hydrochloric acid solution. The solid was then collected by filtration and was recrystallized from a THF-pentane mixture (70:30 ratio). The mass spectral data were consistent with the presence of [NP(OCH₂CF₃)₂]₄, *m/e* 972. A ³¹P NMR spectrum yielded a singlet at -0.96 ppm. The total yield was 60% (mp 63 °C).

Reaction of (NPF₂)₄ with Sodium Phenoxide. A sample of (NPF₂)₄ (2.0 g, 0.006 mol) in 10 mL of THF was added to a solution of sodium phenoxide (prepared from 11.04 g (0.48 mol) of sodium and 58.7 g (0.62 mol) of phenol in 150 mL of THF), and the reaction mixture was boiled at reflux for 48 h. The reaction mixture was evaporated to dryness and 50 mL of diethyl ether was added. The diethyl ether phase was filtered and was then washed consecutively with dilute HCl, Na₂CO₃, and neutral water. The product was then collected by cooling the diethyl ether solution to 0 °C. Mass spectral analysis yielded the

parent ion at m/e 924. ^{31}P NMR data were consistent with the presence of $[\text{NP}(\text{OC}_6\text{H}_5)_2]_4$, with a singlet at -12.88 ppm (THF as solvent). The total yield of this product was 52% (mp 86°C).

Reactions of $(\text{NPF}_2)_4$ and $(\text{NPCI}_2)_4$ with *n*-Butylamine. In each of three addition funnels was placed a solution of $(\text{NPF}_2)_4$ (1.0 g, 0.003 mol) in dry THF (20 mL). Each solution was then added dropwise to reaction vessels that contained *n*-butylamine (10.4 g, 0.144 mol) in THF (100 mL). The first mixture was boiled at reflux for 12 h, the second was allowed to react at 25°C for 12 h, and the third was maintained at 25°C for 336 h. Each reaction mixture was then evaporated to dryness, the solid residue was dissolved in diethyl ether, and this solution was extracted several times with water to remove salts. Removal of the ether yielded products or mixtures of products that were analyzed by gas-liquid chromatography, mass spectrometry, and ^{31}P NMR analysis. The products were as follows: reaction 1, $\text{N}_4\text{P}_4\text{F}_4(\text{NHC}_4\text{H}_9)_4$; reaction 2, $\text{N}_4\text{P}_4\text{F}_4(\text{NHC}_4\text{H}_9)_4$ and $\text{N}_4\text{P}_4\text{F}_3(\text{NHC}_4\text{H}_9)_3$ in a 1:5 ratio; reaction 3, $\text{N}_4\text{P}_4\text{F}_4(\text{NHC}_4\text{H}_9)_4$. The ^{31}P NMR spectra were compatible with a nongeminal substitution pattern. The experimental details for this and other amination reactions are summarized in Table I. Only the isolation procedures are described in detail in the following sections.

Similar reactions were carried out between $(\text{NPCI}_2)_4$ and *n*-butylamine in THF or diethyl ether for 12 or 14 h at 25°C . The product from both reactions was the fully substituted tetramer $[\text{NP}(\text{NH}-\text{C}_4\text{H}_9)_2]_4$ (80% yield from THF, 90% from diethyl ether). It was purified by recrystallization from heptane and was characterized by ^{31}P NMR and mass spectral analysis (mp 87°C).

Reaction of $(\text{NPF}_2)_4$ with *n*-Butylamine in the Presence of NEt_3 and LiBr . The reaction conditions are shown in Table I. After the reactions, the mixtures were evaporated to dryness, redissolved in diethyl ether, and extracted several times with water. The diethyl ether phases were evaporated to dryness and the yellow oils were analyzed by mass spectrometry. Both oils showed the presence of the parent ions for $\text{N}_4\text{P}_4\text{F}_4(\text{NH-}i\text{n-Bu})_4$ (m/e 544) and $\text{N}_4\text{P}_4\text{F}_3(\text{NH-}i\text{n-Bu})_3$ (m/e 491).

Reactions of $(\text{NPF}_2)_4$ with Methylamine and Dimethylamine. The reaction conditions were as shown in Table I. Both reaction mixtures were evaporated to dryness, redissolved in diethyl ether, and extracted several times with water. The diethyl ether solutions were then evaporated to dryness and were subjected to mass spectrometric study. Parent ions were detected for $\text{N}_4\text{P}_4\text{F}_3(\text{NHMe})_3$ (m/e 365) and $\text{N}_4\text{P}_4\text{F}_4(\text{NHMe})_4$ (m/e 376) for the reaction with methylamine and for $\text{N}_4\text{P}_4\text{F}_3(\text{NMe}_2)_3$ (m/e 407) and $\text{N}_4\text{P}_4\text{F}_4(\text{NMe}_2)_4$ (m/e 432) for the reaction with dimethylamine. The ^{31}P NMR spectra of both samples (in THF with D_2O capillary lock) further supported the absence of any geminal amino substitution (complex doublet and triplet structures only were seen). ^{19}F NMR spectra confirmed the presence of PF_2 units [center of doublet 35.5 ppm (relative to an external $\text{C}_6\text{H}_5\text{F}$ reference), coupling constant 894 Hz]. The centers of the doublets for the $\text{PF}(\text{NRR}')_2$ units were, on the average, 9 ppm further downfield.

Reaction of $(\text{NPCI}_2)_4$ with Methylamine and Dimethylamine. The reaction conditions are listed in Table I. The reaction mixtures were added to water and, in the case of the reaction with dimethylamine, the precipitated product was collected. The methylamino-substituted product was obtained by extraction of the aqueous phase with warm CHCl_3 . Mass spectrometric evidence was obtained for the parent ions $\text{N}_4\text{P}_4(\text{NHMe})_8$ (m/e 420) and $\text{N}_4\text{P}_4(\text{NMe}_2)_8$ (m/e 532). No products that contained unreacted chlorine were detected. Isolation of these products gave crystals, mp 206°C ($\text{N}_4\text{P}_4(\text{NHMe})_8$) and 230°C ($\text{N}_4\text{P}_4(\text{NMe}_2)_8$).

Reactions of $(\text{NPF}_2)_3$ and $(\text{NPCI}_2)_3$ with Lithium Dimethylamide. A solution of $(\text{NPF}_2)_3$ (1.0 g, 0.004 mol) in THF (20 mL) was added dropwise to a solution of LiNMe_2 [prepared from methylolithium (0.16 mol) and dimethylamine (7.9 g, 0.18 mol)] in THF (100 mL). The reaction mixture was stirred at 25°C for 12 h before the products were treated with 2-propanol. Removal of the solvent, solution in diethyl ether, extraction of the salts by water, and removal of the ether by evaporation left a white solid. Mass spectral analysis indicated that the main product was nongeminal $\text{N}_3\text{P}_3\text{F}_3(\text{NMe}_2)_3$, but $\text{N}_3\text{P}_3\text{F}_2(\text{NMe}_2)_4$ was also present. A similar reaction with $(\text{NPCI}_2)_3$ yielded $[\text{NP}(\text{NMe}_2)_2]_3$.

Reaction of $(\text{NPF}_2)_4$ with Lithium Dimethylamide. A solution of $(\text{NPF}_2)_4$ (2.0 g, 0.006 mol) in THF (20 mL) was added dropwise to a solution of LiNMe_2 [prepared at 0°C from methylolithium (0.054

mol) and dimethylamine (10 g, 0.22 mol) in THF (100 mL)]. The reaction mixture was stirred at 25°C for 12 h before the product was treated with 2-propanol. The reaction mixture was evaporated to dryness, washed with water, and filtered; the filtrate was dried, redissolved in THF, and filtered; and the solution was evaporated to dryness. The pale yellow solid product yielded mass spectral parent ions for $\text{N}_4\text{P}_4(\text{NMe}_2)_6\text{F}_2$ (m/e 482), $\text{N}_4\text{P}_4(\text{NMe}_2)_7\text{F}$ (m/e 507), and trace amounts of $\text{N}_4\text{P}_4(\text{NMe}_2)_8$ (m/e 532).

Reactions of $(\text{NPF}_2)_3$ with Methylamine, *n*-Butylamine, and Dimethylamine. The reaction conditions are shown in Table I. All three reaction mixtures were evaporated to dryness, redissolved in diethyl ether, and extracted several times with water. The diethyl ether solutions were then evaporated to dryness and the resultant oils were subjected to vapor-phase chromatography-mass spectrometric study. Parent ions were detected for $\text{N}_3\text{P}_3\text{F}_4(\text{NHMe})_2$, $\text{N}_3\text{P}_3\text{F}_4(\text{NH-}i\text{n-Bu})_2$, and $\text{N}_3\text{P}_3\text{F}_4(\text{NMe}_2)_2$. Only small amounts of the tris(amino) derivatives could be detected. The absence of geminal amino structures was confirmed by ^{31}P NMR spectra which indicated only complex doublet and triplet signals from P-F or PF₂ coupling.

The effect of increased reaction temperature was investigated by a reaction between $(\text{NPF}_2)_3$ and *n*-butylamine at the boiling temperature of THF for 36 h. The products were isolated in the manner described above. Mass spectrometric parent ions were detected for $\text{N}_3\text{P}_3\text{F}_4(\text{NH-}i\text{n-Bu})_2$ and for $\text{N}_3\text{P}_3\text{F}_3(\text{NH-}i\text{n-Bu})_3$. The ^{31}P NMR spectra were also compatible with these two products. No species were detected that contained more than three butylamine groups attached to the trimeric ring.

NMR Spectra of Reaction Mixtures. Although only partly aminolyzed cyclophosphazenes were isolated from the reactions of $(\text{NPF}_2)_{3,4}$ with amines, the possibility existed that this was an artifact due to the preferential extraction of the more highly substituted species or their hydrofluoride salts during the washing of the mixture with water. For this reason, ^{31}P NMR spectra were obtained of the crude reaction mixtures from the interaction of $(\text{NPF}_2)_{3,4}$ with methylamine or butylamine before any isolation or purification of products was attempted. These ^{31}P NMR spectra showed mixtures of partly aminolyzed species that were identical with those obtained after isolation and purification of the products. It was estimated that the analytical methods employed (^{31}P NMR and mass spectrometry) could easily have detected more highly substituted species if they had represented only 10% of the total products.

Acknowledgment. We thank the Office of Naval Research for the support of this work through Grant N00014-75-C-0685. We also thank A. Freyer for recording the NMR spectra and R. Minard for the mass spectrometric data.

Registry No. $(\text{NPF}_2)_3$, 15599-91-4; $(\text{NPCI}_2)_3$, 940-71-6; $(\text{NPF}_2)_4$, 14700-00-6; $(\text{NPCI}_2)_4$, 2950-45-0; $[\text{NP}(\text{OCH}_2\text{CF}_3)_2]_4$, 562-88-9; $[\text{NP}(\text{OC}_6\text{H}_5)_2]_4$, 992-79-0; $\text{N}_4\text{P}_4\text{F}_4(\text{NHC}_4\text{H}_9)_4$, 70659-97-1; $\text{N}_4\text{P}_4\text{F}_3(\text{NHC}_4\text{H}_9)_3$, 70659-98-2; $[\text{NP}(\text{NHC}_4\text{H}_9)_2]_4$, 3960-18-7; $\text{N}_4\text{P}_4\text{F}_3(\text{NHMe})_3$, 70659-99-3; $\text{N}_4\text{P}_4\text{F}_4(\text{NHMe})_4$, 70660-00-3; $\text{N}_4\text{P}_4\text{F}_3(\text{NMe}_2)_3$, 25741-64-4; $\text{N}_4\text{P}_4\text{F}_4(\text{NMe}_2)_4$, 25741-65-5; $\text{N}_4\text{P}_4(\text{NHMe})_8$, 1635-65-0; $\text{N}_4\text{P}_4(\text{NMe}_2)_8$, 1678-56-4; $\text{N}_3\text{P}_3\text{F}_3(\text{NMe}_2)_3$, 29871-59-8; $\text{N}_3\text{P}_3\text{F}_2(\text{NMe}_2)_4$, 70660-01-4; $[\text{NP}(\text{NMe}_2)_2]_3$, 974-68-5; $\text{N}_4\text{P}_4(\text{NMe}_2)_6\text{F}_2$, 70659-26-6; $\text{N}_4\text{P}_4(\text{NMe}_2)_7\text{F}$, 70660-02-5; $\text{N}_3\text{P}_3\text{F}_4(\text{NH-}i\text{n-Bu})_2$, 70660-03-6; $\text{N}_3\text{P}_3\text{F}_3(\text{NH-}i\text{n-Bu})_3$, 70660-04-7.

References and Notes

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- 9) The ^{31}P NMR shifts reported here are based on the sign convention recently recommended by IUPAC. Upfield shifts from H_3PO_4 are reported as negative values, and downfield shifts, as positive values. This convention is the opposite of the one used in earlier publications from our laboratory and from most other laboratories in North America.