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Syntheses and Spectroscopic Study of Some New N-4-Fluorobenzoyl Phosphoric Triamides; Crystal Structures of 4-F-$C_6H_4C(O)N(H)P(O)R_2$, R = NH-$C(CH_3)_3$, NH-$CH_2C_6H_5$, $N(CH_3)(CH_2C_6H_5)$

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Abstract. Some new N-4-Fluorobenzoyl phosphoric triamides with formula 4-F-$C_6H_4C(O)N(H)P(O)X_2$, X = NH-$C(CH_3)_3$ (**1**), NH-CH_2-CH=CH_2 (**2**), NH-$CH_2C_6H_5$ (**3**), $N(CH_3)(C_6H_5)$ (**4**), NH-$CH(CH_3)(C_6H_5)$ (**5**) were synthesized and characterized by ^1H, ^{13}C, ^{31}P NMR, IR and Mass spectroscopy and elemental analysis. The structures of compounds **1**, **3** and **4** were investigated by X-ray crystallography. The P=O and C=O bonds in these compounds are anti. Compounds **1** and **3** form one dimensional polymeric chain produced by intra- and intermolecular -P=O···H-N- hydrogen bonds. Compound **4** forms only a centrosymmetric dimer in the crystalline lattice via two equal -P=O···H-N- hydrogen bonds. ^1H and ^{13}C NMR spectra show two series of signals for the two amine groups in compound **1**. This is also observed for the two α-methylbenzylamine groups in **5** due to the presence of chiral carbon atom in molecule. ^{13}C NMR spectrum of compound **4** shows that $^2J(P,C_{aliphatic})$ coupling constant for CH_2 group is greater than for CH_3 in agreement with our previous study. Mass spectra of compounds **1-3** (containing 4-F-$C_6H_4C(O)N(H)P(O)$ moiety) indicate the fragments of amidophosphoric acid and 4-F-$C_6H_4CN^+$ that formed in a pseudo McLafferty rearrangement pathway. Also, the fragments of aliphatic amines have high intensity in mass spectra.

Keywords: Phosphoric triamides; X-Ray Crystallography; NMR; Mass spectroscopy

Introduction

The widespread researches on phosphoramidates in recent years are due to the different valuable applications of these derivatives as prodrug materials [1−3], insecticides and pesticides [4−7], the efficient ligands in coordination chemistry [8−11], theoretical chemistry [12, 13], synthetic purposes [14−17] and in structural study [18−22]. In so far, the substituent effects on the structural parameters have discussed to some extent [23, 24]. *Chivers* et al. reported the synthesis and crystal structures of some tris(alkyl- and arylamido) orthophosphates [25]. The influence of substituents on the ^{31}P chemical shifts has been reviewed by *Gorenstein* [26]. *Letcher* and *Van Wazer* based on the quantum chemical calculations interpreted the theory of ^{31}P chemical shifts. They showed that the $\delta(^{31}P)$ depends mainly on the electronegativity of P-X bonds [27]. *Turnbull* and his co-workers showed the substituent effects on the ^{13}C NMR chemical shifts in dialkylaminophenylchlorophosphines [28]. There are several studies on the NMR spectra of phosphoramidates [29−32]. *Bourne* et al. described the phosphorus chemical shifts as a function of P-N bonds [33]. The stereochemical dependence of $^nJ(P,E)$ coupling constants (n = 1-4; E = C, H) in some enaminophosphazanes were discussed [34]. In this work, we synthesized some new compounds with general formula 4-F-$C_6H_4C(O)N(H)P(O)X_2$ (X = NH-$C(CH_3)_3$ (**1**), NH-CH_2-CH=CH_2 (**2**), NH-$CH_2C_6H_5$ (**3**), $N(CH_3)(C_6H_5)$ (**4**), NH-$CH(CH_3)(C_6H_5)$ (**5**)). The structures of compounds **1**, **3** and **4** were determined by X-ray crystallography. The effect of various amine groups on the phosphorus chemical shifts, J(Y,Z) coupling constants (where Y = P, F; Z = H, C) and on the structural parameters were discussed in these compounds and the results were compared with their analogous *N*-benzoyl phosphoric triamides.

Results and Discussion

NMR Study

Syntheses of phosphoramidates **1-5** (Scheme 1) were performed by the reaction of N-4-fluorobenzoyl phosphoramidic dichloride [35] with the corresponding amines. ^1H NMR spectrum of compound **1** shows two signals for the two NH protons of two *tert*-butylamine groups. Also, ^{13}C NMR spectrum of this molecule revealed two series of signals for the *tert*-butyl moieties. These phenomena confirm that these two groups are different with each other (Figure 1). Recently, we discussed on the NMR and crystal structure of a similar compound, $C_6H_5C(O)N(H)P(O)[NHC(CH_3)_3]_2$ (**6**) that showed two conformers in solution and solid state [32]. ^1H and ^{13}C NMR of **6** indicates two series of peaks for N-benzoyl and also for the *tert*-butyl groups.

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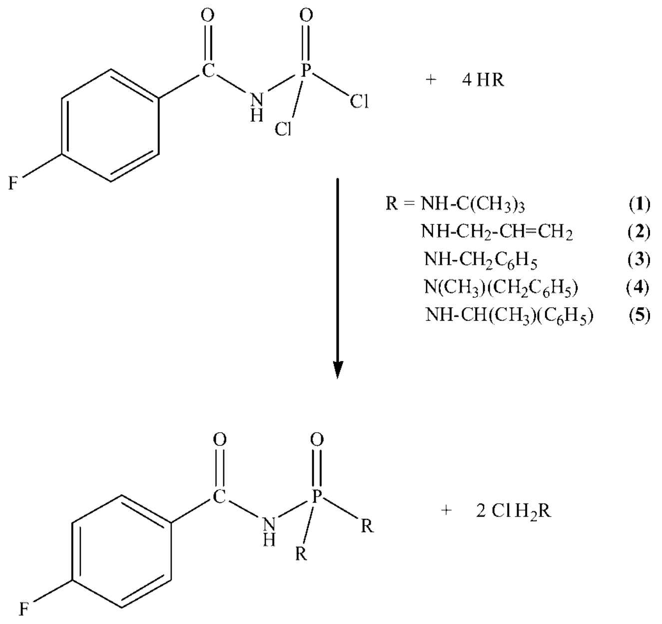

Scheme 1 The preparation of compounds **1-5**.

Compound **1** is the analogous compound of **6** with one conformer in the crystalline lattice (X-ray Section).

^{1}H NMR spectra of compound **1-5** with general formula 4-F-$C_6H_4C(O)N(H)P(O)(NR)_2$ showed the 2J(PNH_{amine}) coupling constant (H_{amine} is the proton atom of NR moiety) for compounds **3** (10.5 Hz) and **5** (10.0 Hz). The ^{2}J(PNH_{amide}) coupling constant (H_{amide} is the proton atom of C(O)N(H) moiety) were not observed in molecules **1-5**. It seems that substitution of benzamide by 4-fluorobenzamide cause a zero value for ^{2}J(PNH_{amide}) coupling constant in these compounds. This constant were observed in compounds **6** (6.9 and 8.0 Hz) and $C_6H_5C(O)N(H)P(O)[NHCH(CH_3)(C_6H_5)]_2$ (**7**), (6.2 Hz). The CH_3 and CH_2 protons of compounds **2-4** couple with phosphorus atom with ^{3}J(PNCH) values in the range of 7.2 Hz (in **3**) to 10.1 Hz (in **4**).

The carbon atoms of CH_3 and CH_2 groups in **4** revealed that the ^{2}J(P,$C_{aliphatic}$) are 4.7 and 5.2 Hz and in compound $C_6H_5C(O)N(H)P(O)[N(CH_3)(CH_2(C_6H_5)]_2$ (**8**) are 5.0 and 5.3 Hz. The ^{2}J(P,$C_{aliphatic}$) coupling constants for CH_3 carbon atoms in compounds **4** and **8** (containing $N(CH_3)(CH_2C_6H_5)$ moieties) are lower than those of CH_2 carbon atoms due to the electron withdrawing of phenyl ring that connected to the CH_2 group. The carbon atom of C(O) group couple with phosphorus atom only in compound **4** with ^{2}J(P,C(O)) = 2.0 Hz.

As mentioned above, the ^{13}C NMR spectrum of **1** indicates two signals for the six carbon atoms of CH_3 groups with ^{3}J(P,$C_{aliphatic}$) = 0 and 4.8 Hz. The ^{3}J(P,$C_{aliphatic}$) values of compound **6** are 4.8 and 4.9 Hz in one conformer with two different *tert*-butyl groups and in another conformer (with two equal *tert*-butyl groups) is 7.5 Hz.

^{1}H NMR spectrum of compound **5** indicates two separate signals for two CH_3 and NH protons of α-methylbenzylamine groups. Furthermore, ^{13}C NMR spectrum of this molecule shows two series of peaks for two α-methylbenzyl moieties. The two carbon atoms of CH_3 moieties in this molecule split with P atom separately and give two different ^{3}J(P,$C_{aliphatic}$) values (4.7 and 6.9 Hz). This was also observed for compound **7** and the ^{3}J(P,$C_{aliphatic}$) values were 6.2 and 7.8 Hz. These observations are due to the presence of chiral carbon atom that cause the two α-methylbenzyl groups be different with each other.

The phosphorus chemical shifts of compounds **1-5** are in the range of 3.06 ppm (in **1**) to 14.63 ppm (in **4**). The δ(^{31}P) in compound **4** containing N-benzylmethyl moiety is in downfield relative to that of **5** with α-methylbenzyl group. Furthermore, the δ(^{31}P) of compounds **1**, **4** and **5** are in upfield compare with its value in their analogous derivatives **6-8**.

IR Study

IR spectra of compounds **1-5** show the vibrational frequencies of P=O; C=O; P-N_{amine} and P-N_{amide} bonds in the range of 1199 (in **5**) to 1228 cm^{-1} (in **1**); 1630 (in **3**) to 1667 cm^{-1} (in **4**); 874 (in **4**) to 969 cm^{-1} (in **5**) and 693 (in **4** and **5**) to 755 cm^{-1} (in **2**), respectively. A comparison between compounds **4** (containing N-benzylmethyl group) and **5** (with α-methylbenzyl moiety) indicates that the C=O bond in **4** is stronger than in **5**, but for the P-N_{amine} bond an opposite result was obtained. The P-N_{amine} in **5** is stronger than in **4**, but the P-N_{amide} frequency in both of them is identical. The P=O bond in molecule **3** with benzylic moiety is stronger than in compounds **4** and **5**, but the C=O bond strength in **3** is weaker than in **4** and **5**. This means that the P=O and C=O bond strengths depend on the electron donation of amine groups connected to the phosphorus atom.

Mass Spectroscopy Investigation

Mass spectra of compounds **1-5** with general formula 4-F-$C_6H_4C(O)N(H)P(O)R_2$ show the existence of the fragment ions at *m/z* = 123 and 121, which are belong to 4-F-$C_6H_4CO^+$ and 4-F-$C_6H_4CN^+$ cations, respectively. In the earlier work, *Lapidot* and *Samuel* reported the pyroylsis of N-benzoyl-phosphoramidates that lead to $PhCN^+$ and amidophosphoric acid cations [39]. It is assumed that the fragmentation pathway contains the P-N cleavage and P-O formation (P-O and P-N linkage isomerism in the transition state) and the rearranged molecule is cleaved in a pseudo McLafferty pathway to 4-F-$C_6H_4CO^+$, 4-F-$C_6H_4CN^+$ and amidophosphoric acid cations, see Scheme 2 for compound **1**. In compounds **1-5**, the 4-F-$C_6H_4CO^+$ and 4-F-$C_6H_4CN^+$ fragments have relatively high intensity in mass spectra, but the amidophosphoric acid fragment only in compounds **1-3** are obviously observed with high intensity. For compounds **4** and **5** this fragment has a very weak intensity. The base peak in these compounds are related to the amine fragments, NH-$C(CH_3)_3$ (in **1**), NH-CH_2-CH=CH_2 (**2**), NH-$CH_2C_6H_5$ (**3**), $N(CH_3)(CH_2C_6H_5)$ (**4**) and NH-$CH(CH_3)(C_6H_5)$ (**5**).

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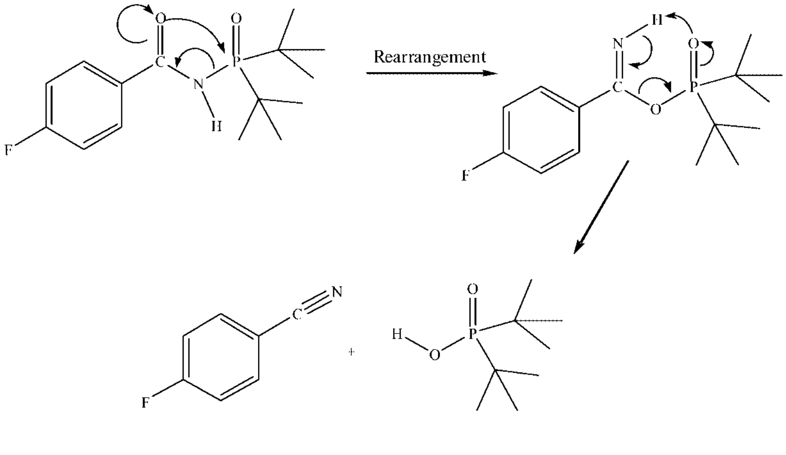

Scheme 2 The fragmentation pathway of compound **1** in mass spectrum.

X-ray crystallography

Single crystals of compounds **1**, **3** and **4** were obtained from the mixtures of methanol-chloroform after slow evaporation at room temperature. Crystallographic data of these compounds are given in Table 1. Selected bond lengths and angles are presented in Table 2. The molecular structures of these compounds are shown in Figures 1-3, respectively.

In the structure of compound **1**, the molecule is not symmetric relative to the two *tert*-butyl groups. These two moieties have some differences in their similar torsion angles. The torsion angles P(1)-N(2)-C(8)-C(9) and P(1)-N(3)-C(12)-C(13) are 65.7(2)° and 83.2(2)°. In our previous study on compound $C_6H_5C(O)N(H)P(O)[NHC(CH_3)_3]_2$ (**6**) we obtained two conformers in solution and solid state [32]. In one conformer (similar to compound **1**) the two *tert*-butyl groups had different spatial orientations relative to the $C_6H_5C(O)N(H)P(O)$ moiety with various values in their related torsion angles.

The P(1)-O(1) bond lengths in compounds **1**, **3** and **4** are 1.478(1), 1.474(1) and 1.4825(9) Å, which are larger than the normal P=O double bond length (1.45 Å) [37]. The P(1)-N(1) bond lengths in these molecules are larger than the P(1)-N(2) and P(1)-N(3) bond lengths due to the resonance interaction with the C=O π system that causes a partial multiple-bond character in N(1)-C(1). The P(1)-N(2) and P(1)-N(3) bond lengths are smaller than P-N single bond length (1.77 Å [37]). They are between the single and double PN bond lengths [37], Table 2. In compound **1**, the angles P(1)-N(1)-C(1), P(1)-N(1)-H(1) and C(1)-N(1)-H(1) are 125.03°, 113.60° and 120.50°. The sum of surrounding angles around N(1) atom is 359.13° and for N(2) and N(3) atoms are 356.27° and 358.01°, respectively. Similar results were obtained for compounds **3** and **4** showed that the environment of the nitrogen atoms is nearly planar.

In molecules **1**, **3**, and **4** the phosphoryl and the carbonyl groups are anti (Figures 1-3). The phosphorus atom P(1) has a distorted tetrahedral configuration with angles in the range of 115.04(6)°-104.90(6)° (for **1**), 116.40(7)°-102.13(7)° (for **3**) and 118.71(6)°-104.59(6) ° (for **4**). In these compounds, the angles OPN_{amide} (N_{amide} is the nitrogen atom of P(O)N(H)C(O) moiety) are lower than the angles OPN_{amine} (N_{amine} is the nitrogen atom of P(O)NR moiety).

In structure of **1**, infinite zigzag chains are built in the crystalline lattice from inter- and intramolecular -N-H···O- hydrogen bonds produced a one dimensional network. The intermolecular N(1)-H(1)···O(1)-P(1) hydrogen bonding [with d(N(1)···O(1) = 2.774(2) Å] produces a centrosymmeric dimer in the lattice. Also, the oxygen atom of C(O) group forms the intermolecular N(2)-H(2)···O(2) [with d(N(2)···O(2) = 3.026(2) Å] and intramolecular N(3)-H(3)···O(2) [with d(N(3)···O(2) = 2.913(1) Å] hydrogen bonds.

In one dimensional network of **3**, there are -N-H···O- hydrogen bonds that produced a polymeric chain. The intermolecular N(1)-H(1N)···O(1)-P(1) hydrogen bonding [with d(N(1)···O(1) = 2.834(2) Å] produces a centrosymmeric dimer in the lattice. Also, the oxygen atom of C(O) group forms the intermolecular N(2)-H(2N)···O(2) [with d(N(2)···O(2) = 3.015(2) Å] and N(3)-H(3N)···O(2) [with d(N(3)···O(2) = 2.937(2) Å] hydrogen bonds. Compound **4** forms only a centrosymmeric dimer via intermolecular N(1)-H(1N)···O(1)-P(1) hydrogen bond [with d(N(1)···O(1) = 2.8055(14) Å].

Experimental Section

X-ray measurements

X-ray data were collected on a Bruker SMART 1000 CCD single crystal diffractometer with graphite monochromated Mo-Kα radiation (λ = 0.71073 Å). The structure of compound **1** was refined with SHELXL-97 [38] by a full-matrix least-squares procedure on F^2. The positions of hydrogen atoms were obtained from the difference Fourier map. Routine Lorentz and polarization corrections were applied and an absorption correction was performed using the SADABS program [39] for compound **1** and Siemens P3/PC [40] for compounds **3** and **4**. Crystallographic data for the struc-

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tures in this paper have been deposited with Cambridge Crystallographic Data Center as supplementary publication nos. CCDC 259188 ($C_{15}H_{25}F_1N_3O_2P_1$), CCDC 265050 ($C_{23}H_{25}F_1N_3O_2P_1$) and CCDC 265049 ($C_{21}H_{21}F_1N_3O_2P_1$). Copies of the data can be obtained, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK, (fax: +44 1223 336033 or e-mail: deposit@ccdc.cam.ac.uk).

Spectroscopic measurements

^{1}H, ^{13}C and ^{31}P NMR spectra were recorded on a Bruker Avance DRS 500 spectrometer. ^{1}H and ^{13}C chemical shifts were determined relative to internal TMS, ^{31}P chemical shifts relative to 85 % H_3PO_4 as external standard. Infrared (IR) spectra were recorded on a Shimadzu model IR-60 spectrometer. Elemental analysis was per-

Table 1 Crystallographic data for **1**, **3** and **4**.

	1	**3**	**4**
Empirical formula	$C_{15}H_{25}FN_3O_2P$	$C_{21}H_{21}FN_3O_2P$	$C_{23}H_{25}FN_3O_2P$
Formula weight	329.35	397.38	425.43
Temperature (K)	120(2)	173(2)	173(2)
Wavelength	0.71073 Å	0.71073 Å	0.71073 Å
Crystal system, space group	triclinic, $P\bar{1}$	triclinic, $P\bar{1}$	monoclinic, P 21/n
Unit cell dimensions	a = 9.908(3) Å	a = 9.925(2) Å	a = 9.0863(16) Å
	b = 10.213(3) Å	b = 10.933(2) Å	b = 12.280(3) Å
	c = 10.473(3) Å	c = 10.942(2) Å	c = 19.606(3) Å
	α = 98.620(5)°	α = 79.19(3)°	β = 96.184(14)°
	β = 102.935(5)°	β = 63.64(3)°	
	γ = 118.150(5)°	γ = 69.89(3)°	
V /Å^3	869.5(4)	998.1(3)	2175.0(7)
Z, Calculated density	2, 1.258 Mg.m^{-3}	2, 1.322 Mg.m^{-3}	4, 1.299 Mg.m^{-3}
Absorption coefficient	0.178 mm^{-1}	0.168 mm^{-1}	0.159 mm^{-1}
F(000)	352	416	896
Crystal size	0.5 × 0.4 × 0.1 mm^3	0.5 × 0.12 × 0.10 mm^3	0.35 × 0.3 × 0.3 mm^3
θ range for data collection	2.09 to 28.00°	2.40 to 26.05°	2.09 to 26.06°
Limiting indices	$-12\le h\le 13$	$0\le h\le 11$	$-2\le h\le 11$
	$-13\le k\le 13$	$-12\le k\le 13$	$-15\le k\le 15$
	$-13\le l\le 13$	$-12\le l\le 13$	$-24\le l\le 24$
Reflections collected / unique	7248 / 4032 [R(int) = 0.0140]	4060 / 3823 [R(int) = 0.0144]	4560 / 4282 [R(int) = 0.0155]
Completeness to theta	95.9 %	96.8 %	99.6 %
Absorption correction	Semi-empirical from equivalents	None	None
Max. and min. transmission	0.862 and 0.666	−-	−-
Refinement method	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2
Data/restraints/parameters	4032 / 0 / 199	3823 / 0 / 253	4282 / 0 / 273
Goodness-of-fit on F^2	1.041	1.036	1.014
Final R indices	R_1 = 0.0487, wR_2 = 0.1291	R_1 = 0.0363, wR_2 = 0.0958	R_1 = 0.0322, wR_2 = 0.0899
R indices (all data)	R_1 = 0.0546, wR_2 = 0.1354	R_1 = 0.0424, wR_2 = 0.1001	R_1 = 0.0411, wR_2 = 0.0914
Largest diff. peak and hole	0.988 and −0.338 e.Å^{-3}	0.303 and −0.344 e.Å^{-3}	0.287 and −0.312 e.Å^{-3}

Table 2 Selected bond lengths/Å and angles/° for compounds **1**, **3** and **4**.

1		**3**		**4**	
P(1)-(O1)	1.478(1)	P(1)-(O1)	1.474(1)	P(1)-(O1)	1.4825(9)
P(1)-N(3)	1.629(1)	P(1)-N(3)	1.635(1)	P(1)-N(3)	1.633(1)
P(1)-N(2)	1.632(1)	P(1)-N(2)	1.628(1)	P(1)-N(2)	1.643(1)
P(1)-N(1)	1.701(1)	P(1)-N(1)	1.705(1)	P(1)-N(1)	1.686(1)
O(2)-C(1)	1.223(2)	O(2)-C(1)	1.231(2)	O(2)-C(1)	1.221(2)
N(1)-C(1)	1.358(2)	N(1)-C(1)	1.357(2)	N(1)-C(1)	1.371(2)
N(2)-C(8)	1.485(2)	N(2)-C(8)	1.457(2)	N(2)-C(8)	1.472(2)
N(3)-C(12)	1.487(2)	N(3)-C(15)	1.465(2)	N(2)-C(9)	1.472(2)
F(1)-C(5)	1.362(2)	F(1)-C(5)	1.362(2)	N(3)-C(16)	1.464(2)
C(1)-C(2)	1.505(2)	C(1)-C(2)	1.497(2)	N(3)-C(17)	1.470(2)
O(1)-P(1)-N(3)	115.04(6)	O(1)-P(1)-N(3)	116.40(7)	O(1)-P(1)-N(3)	109.93(6)
O(1)-P(1)-N(2)	113.48(6)	O(1)-P(1)-N(2)	114.24(7)	O(1)-P(1)-N(2)	118.71(6)
N(3)-P(1)-N(2)	107.16(6)	N(3)-P(1)-N(2)	102.13(7)	N(3)-P(1)-N(2)	104.59(6)
O(1)-P(1)-N(1)	106.92(6)	O(1)-P(1)-N(1)	105.27(6)	O(1)-P(1)-N(1)	105.67(5)
N(3)-P(1)-N(1)	104.90(6)	N(3)-P(1)-N(1)	108.65(7)	N(3)-P(1)-N(1)	112.76(6)
N(2)-P(1)-N(1)	108.89(6)	N(2)-P(1)-N(1)	110.09(7)	N(2)-P(1)-N(1)	105.30(6)
C(1)-N(1)-P(1)	125.03(9)	C(1)-N(1)-P(1)	121.2(1)	C(1)-N(1)-P(1)	126.05(9)
C(8)-N(2)-P(1)	127.84(9)	C(8)-N(2)-P(1)	122.2(1)	C(8)-N(2)-P(1)	116.6(1)
C(12)-N(3)-P(1)	125.8(1)	C(15)-N(3)-P(1)	120.4(1)	C(9)-N(2)-P(1)	122.57(9)
O(2)-C(1)-N(1)	122.1(1)	O(2)-C(1)-N(1)	120.0(1)	C(9)-N(2)-C(8)	113.2(1)
O(2)-C(1)-C(2)	120.9(1)	O(2)-C(1)-C(2)	120.0(1)	C(16)-N(3)-C(17)	114.0(1)
N(1)-C(1)-C(2)	117.0(1)	N(1)-C(1)-C(2)	120.0(1)	C(16)-N(3)-P(1)	125.9(2)
F(1)-C(5)-C(6)	117.9(2)	F(1)-C(5)-C(6)	118.5(2)	C(17)-N(3)-P(1)	120.08(9)

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formed using a Heraeus CHN-O-RAPID apparatus. Mass spectra were obtained with a Shimadzu model QP-1100 EX spectrometer (EI, 70 ev). N-4-fluorobenzoyl phosphoramidic dichloride was prepared as the literature method [35].

Syntheses

N-(4-fluorobenzoyl)-N′,N″-bis(tert-butyl) phosphoric triamide (1): To a stirred mixture of (2.56 g, 10 mmol) N-4-fluorobenzoyl phosphoramidic dichloride in CCl_4 (15 mL), a solution of *tert*-butylamine (2.92 g, 40 mmol) in CCl_4 (25 mL) was added dropwise at −5 °C. After 6 hours, the precipitate was filtered and washed with distilled water and the white powder recrystallized in methanol-chloroform. m.p. = 244 °C. Elemental analysis (%) calcd. for $C_{15}H_{25}FN_3O_2P$: C, 54.70; H, 7.65; N, 12.76; found: C, 54.65; H, 7.61; N, 12.80.

^{1}H NMR (500.13 MHz, [D_6]DMSO, 25 °C, TMS): 1.21 (s, 18 H, 6 CH_3), 3.99 (s, 1 H, NH_{amine}), 4.00 (s, 1 H, NH_{amine}), 7.27 (t, ^{3}J[(H,H), (F,H)] = 8.8 Hz, 2 H, Ar-H), 8.03 (dd, ^{3}J(H,H) = 8.6 Hz, ^{4}J(F,H) = 5.6 Hz, 2 H, Ar-H), 9.50 (s, 1 H, NH_{amide}). **^{13}C NMR** (125.77 MHz, [D_6]DMSO, 25 °C, TMS): 167.06 (s, 1 C, C=O), 163.26 (d, ^{1}J(F,C) = 250.0 Hz, 1 C, CH), 130.70 (d, ^{3}J(F,C) = 9.0 Hz, 2 C, CH), 129.90 (dd, ^{4}J(F,C) = 2.8 Hz, ^{3}J(P,C) = 8.9 Hz, 1 C, CH), 115.04 (d, ^{2}J(F,C) = 22.0 Hz, 2 C, CH), 50.79 (s, 1 C), 50.34 (s, 1 C), 31.20 (d, ^{3}J(P,C) = 4.8 Hz, 3 C, CH_3), 27.12 (s, 3 C, CH_3). **^{31}P NMR** (202.46 MHz, [D_6]DMSO, 25 °C, H_3PO_4 external): 3.06 (t, J(P,H) = 6.5 Hz). **IR** (KBr): $\tilde{\nu}$ = 3350 (NH), 3085 (NH), 2965 (NH), 1640 (C=O), 1593, 1435, 1386, 1228 (P=O), 1201, 1155, 1017, 889 (P-N_{amine}), 846, 791, 754 (P-N_{amide}), 537. **MS** (70 ev) *m/z* (%): 328 (1, [M-1]$^+$), 208 (1, $C_8H_{21}N_2O_2P^+$), 185 (13, $C_7H_5FNO_2P^+$), 138, (11, $C_7H_5FNO^+$), 121 (100, $C_7H_4FN^+$).

N-(4-fluorobenzoyl)-N′,N″-diallyl phosphoric triamide (2): A solution of allylamine (2.28 g, 40 mmol) in CCl_4 (25 mL) was added dropwise to a mixture of (2.56 g, 10 mmol) N-4-fluorobenzoyl phosphoramidic dichloride in CCl_4 (15 mL) at −5 °C. After 5 hours stirring, the white powder was filtered, washed with distilled water and recrystallized in acetonitrile-chloroform. m.p. = 144 °C.

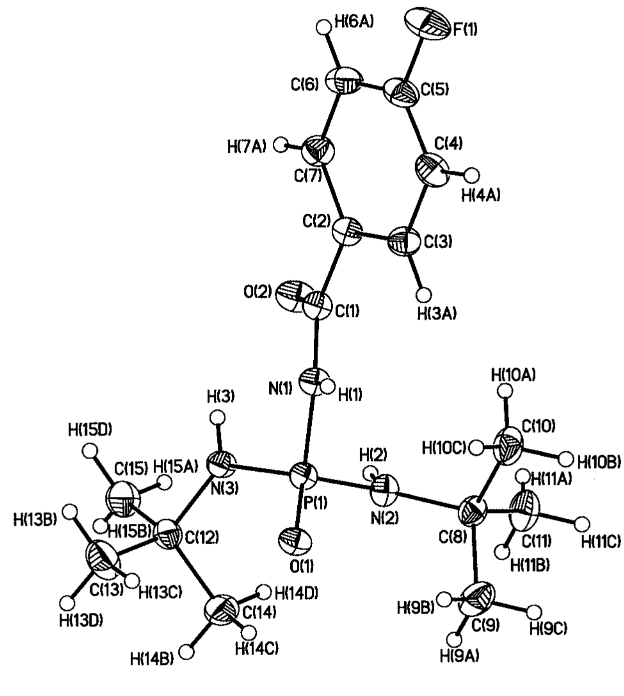

Figure 1 Molecular structure of 4-F-C_6H_4C(O)N(H)P(O)[NH-C$(CH_3)_3]_2$ showing the atom-labeling scheme and 50 % probability level displacement ellipsoids.

Elemental analysis (%) calcd. for $C_{13}H_{17}FN_3O_2P$: C, 52.53; H, 5.76; N, 14.14; found: C, 52.56; H, 5.71; N, 14.10.

^{1}H NMR (500.13 MHz, [D_6]DMSO, 25 °C, TMS): 3.46 (m, 4 H, 2 CH_2), 4.53 (m, 2 H, NH_{amine}), 4.96 (d, ^{2}J$(H,H)_{trans}$ = 10.1 Hz, 2 H, CH), 5.17 (d, ^{2}J$(H,H)_{cis}$ = 17.0 Hz, 2 H, 2 CH), 5.78-5.86 (m, 2 H, CH), 7.27 (t, ^{3}J[(H,H), (F,H)] = 8.7 Hz, 2 H, Ar-H), 8.01 (dd, ^{3}J(H,H) = 8.3 Hz, ^{4}J(F,H) = 5.7 Hz, 2 H, Ar-H), 9.36 (b, 1 H, NH_{amide}). **^{13}C NMR** (125.77 MHz, [D_6]DMSO, 25 °C, TMS): 166.96 (s, 1 C, C=O), 163.34 (d, ^{1}J(F,C) = 249.9 Hz, 1 C, CH), 137.54 (d, ^{3}J(P,CH) = 5.9 Hz, 2 C, CH), 130.75 (d, ^{3}J(F,C) = 9.3 Hz, 2 C, CH), 130.20 (dd, ^{4}J(F,C) = 2.6 Hz, ^{3}J(P,C) = 8.2 Hz, 1 C, CH), 115.10 (d, ^{2}J(F,C) = 21.9 Hz, 2 C, CH), 114.32 (s, 2 C, CH_2), 42.49 (s, 2 C, CH_2). **^{31}P NMR** (202.46 MHz, [D_6]DMSO, 25 °C, H_3PO_4 external): 9.13 (hept, J(P,H) = 11.3 Hz). **IR** (KBr): $\tilde{\nu}$ = 3420 (NH), 3305 (NH), 3085 (NH), 2895, 1649 (C=O), 1593, 1441, 1274, 1225, 1201 (P=O), 1152, 1086, 990, 918 (P-N_{amine}), 887, 845, 792, 755 (P-N_{amide}), 624, 532, 493. **MS** (70 ev) *m/z* (%): 297 (3, M^+), 185 (3, $C_7H_5FNO_2P^+$), 176 (10, $C_6H_{13}N_2O_2P^+$), 158 (49, $C_6H_{12}N_2OP^+$), 138 (8, $C_7H_5FNO^+$), 121 (100, $C_7H_4FN^+$).

N-(4-fluorobenzoyl)-N′,N″-dibenzyl phosphoric triamide (3): To a stirred mixture of (2.56 g, 10 mmol) N-4-fluorobenzoyl phosphoramidic dichloride in CCl_4 (15 mL), a solution of benzylamine (4.28 g, 40 mmol) in CCl_4 (30 mL) was added dropwise at −5 °C. After 8 hours, the white precipitate was filtered and washed with distilled water and recrystallized in methanol-chloroform. m.p. = 171 °C. *Anal.* Calc. for $C_{21}H_{21}FN_3O_2P$: C, 63.47; H, 5.33; N, 10.57. Found: C, 63.44; H, 5.30; N, 10.53.

^{1}H NMR (500.13 MHz, [D_6]DMSO, 25 °C, TMS): 4.04 (dd, ^{3}J(PNCH) = 7.2 Hz, ^{2}J(H,H) = 11.8 Hz, 4 H, 2 CH_2), 4.98 (dd, ^{2}J(PNH) = 10.5 Hz, ^{3}J(H,H) = 6.9 Hz, 2 H, 2 NH_{amine}), 7.15-7.99 (m, 12 H, Ar-H), 7.97 (dd, ^{3}J(H,H) = 8.6 Hz, ^{4}J(F,H) = 5.6 Hz, 2 H, Ar-H), 9.29 (b, 1 H, NH_{amide}). **^{13}C NMR** (125.77 MHz, [D_6]DMSO, 25 °C, TMS): 167.15 (s, 1 C, C=O), 163.43 (d, ^{1}J(F,C) = 249.6 Hz, 1 C, CH), 141.18 (d, ^{3}J(P,C) = 5.8 Hz, 2 C, C_{ipso}), 130.87 (d, ^{3}J(F,C) = 9.2 Hz, 2 C, CH), 130.39 (dd, ^{4}J(F,C) = 2.9 Hz, ^{3}J(P,C) = 8.1 Hz, 1 C, CH), 128.08 (s), 127.32 (s), 126.56 (s), 115.16 (d, ^{2}J(F,C) = 21.6 Hz, 2 CH), 43.87 (s, 2 C, CH_2). **^{31}P NMR** (202.46 MHz, [D_6]DMSO, 25 °C, H_3PO_4 external): 9.26 (hept, J(P,H) = 11.5 Hz). **IR** (KBr): $\tilde{\nu}$ = 3330 (NH), 3130 (NH), 3085 (NH), 2900, 1630 (C=O), 1589, 1429, 1275, 1219 (P=O), 1084, 1061, 909, 882 (P-N_{amine}), 727 (P-N_{amide}), 681, 507, 446. **MS** (70 ev) *m/z* (%): 397 (8, M^+), 276 (10, $C_{14}H_{17}N_2O_2P^+$), 258 (10, $C_{14}H_{15}N_2OP^+$), 185 (14, $C_7H_5FNO_2P^+$), 123 (55, $C_7H_4FO^+$), 121 (53, $C_7H_4FN^+$), 106 (100, $C_7H_8N^+$), 91 (39, $C_7H_7^+$).

N-(4-fluorobenzoyl)-N′,N″-bis(N-benzylmethyl) phosphoric triamide (4): To a stirred mixture of (2.56 g, 10 mmol) N-4-fluorobenzoyl phosphoramidic dichloride in CCl_4 (15 mL), a solution of N-benzylmethylamine (4.84 g, 40 mmol) in CCl_4 (30 mL) was added dropwise at −5 °C. After 6 hours, the white powder was filtered, washed with distilled water and then recrystallized in methanol-chroform. m.p. = 154 °C. Elemental analysis (%) calcd. for $C_{23}H_{25}FN_3O_2P$: C, 64.93; H, 5.92; N, 9.88; found: C, 64.96; H, 5.89; N, 9.84.

^{1}H NMR (500.13 MHz, [D_6]DMSO, 25 °C, TMS): 2.53 (d, ^{3}J(PNCH) = 10.1 Hz, 6 H, 2 CH_3), 4.14 (dq, ^{3}J(PNCH) = 9.4 Hz, ^{2}J(H,H) = 12.3 Hz, 4 H, 2 CH_2), 7.23 (t, ^{3}J[(H,H), (F,H)] = 7.2 Hz, 2 H, Ar-H), 7.30 (t, ^{3}J(H,H) = 7.3 Hz, 6 H, Ar-H), 7.39 (d, ^{3}J(H,H) = 7.5 Hz, 4 H, Ar-H), 8.00 (dd, ^{3}J(H,H) = 8.6 Hz, ^{4}J(F,H) = 5.6 Hz, 2 H, Ar-H), 9.52 (s, 1 H, NH_{amide}). **^{13}C NMR** (125.77 MHz, [D_6]DMSO, 25 °C, TMS): 167.45 (d, ^{2}J(P,C=O) = 2.0 Hz, 1 C, C=O), 163.44 (d, ^{1}J(F,C) = 250.0 Hz, 1 C, CH), 138.25 (d, ^{3}J(P,C) = 4.3 Hz, 2 C, C_{ipso}), 131.06 (d, ^{3}J(F,C) = 9.3 Hz, 2 C, CH), 130.15 (dd, ^{4}J(F,C) = 2.9 Hz, ^{3}J(P,C) = 9.1 Hz, 1 C, CH), 128.50 (s), 128.24 (s), 127.94 (s), 126.97 (s), 115.16 (d, ^{2}J(F,C) = 21.9 Hz, 2 C, CH), 52.00 (d, ^{2}J(P,C) = 5.2 Hz, 2 C, CH_2), 33.41 (d, ^{2}J(P,C) = 4.7 Hz, 2 C, CH_3). **^{31}P NMR** (202.46 MHz, [D_6]DMSO, 25 °C, H_3PO_4 external): 14.63 (hept, J(P,H) = 9.6 Hz). **IR** (KBr): $\tilde{\nu}$ = 3065 (NH), 2900, 1667 (C=O), 1590, 1440, 1266, 1224 (P=O), 1190, 1156, 1106, 995, 909, 874 (P-N_{amine}), 785, 754, 693 (P-N_{amide}), 527, 469. **MS** (70 ev) *m/z* (%): 425 (6, M^+), 185 (12, $C_7H_5FNO_2P^+$), 138 (6, $C_7H_5FNO^+$), 123 (33, $C_7H_4FO^+$), 121 (53, $C_7H_4FN^+$), 120 (100, $C_8H_{11}N^+$), 91 (65, $C_7H_7^+$).

N-(4-fluorobenzoyl)-N′,N″-bis((S)-(-)-α-methylbenzyl) phosphoric triamide (5): A solution of (S)-(-)-α-methylbenzylamine (4.84 g, 40 mmol) in CCl_4 (30 mL) was added dropwise to a mixture of (2.56 g, 10 mmol) N-4-fluorobenzoyl phosphoramidic dichloride in

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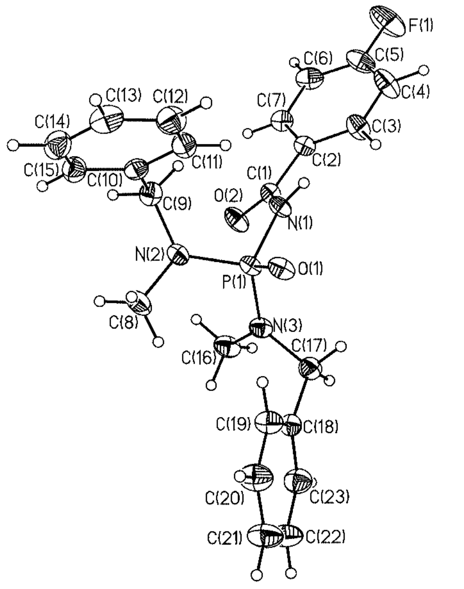

Figure 3 Molecular structure of 4-F-$C_6H_4C(O)N(H)P(O)[N(CH_3)(CH_2C_6H_5)]_2$ showing the atom-labeling scheme and 50 % probability level displacement ellipsoids.

CCl_4 (15 mL) at −5 °C. After 4 hours stirring, the white precipitate was filtered and washed with distilled water and then recrystallized in methanol-heptane mixture. m.p. = 147 °C. Elemental analysis (%) calcd. for $C_{23}H_{25}FN_3O_2P$: C, 64.93; H, 5.92; N, 9.88; found: C, 64.88; H, 5.90; N, 9.82.

^{1}H NMR (500.13 MHz, [D$_6$]DMSO, 25 °C, TMS): 1.33 (s, 3 H, CH_3), 1.34 (s, 3 H, CH_3), 4.30 (m, 2 H, 2 CH), 4.77 (t, ^{2}J(PNH) = 10.0 Hz, ^{3}J(H,H) = 9.6 Hz, 1 H, NH_{amine}), 4.96 (t, ^{2}J(PNH) = 10.0 Hz, ^{3}J(H,H) = 9.6 Hz, 1 H, NH_{amine}), 7.05-7.92 (m, 12 H, Ar-H), 7.90 (dd, ^{3}J[(H,H), (F,H)] = 8.5 Hz, ^{4}J(F,H) = 5.5 Hz, 2 H, Ar-H), 8.38 (b, 1 H, NH_{amide}). **^{13}C NMR** (125.77 MHz, [D$_6$]DMSO, 25 °C, TMS): 166.94 (s, 1 C, C=O), 163.23 (d, ^{1}J(F,C) = 249.5 Hz, 1 C, CH), 146.23 (d, ^{3}J(P,C) = 5.8 Hz, 1 C, C_{ipso}), 145.92 (d, ^{3}J(P,C) = 3.9 Hz, 1 C, C_{ipso}), 130.66 (d, ^{3}J(F,C) = 9.0 Hz, 2 C, CH), 130.29 (dd, ^{4}J(F,C) = 2.9 Hz, ^{3}J(P,C) = 8.7 Hz, 1 C, CH), 128.56 (s), 127.92 (s), 127.81 (s), 126.73 (s), 126.00 (s), 125.84 (s), 114.89 (d, ^{2}J(F,C) = 21.8 Hz, 2 C, CH), 49.92 (s, 1 C, CH), 49.78 (s, 1 CH), 25.31 (d, ^{3}J(P,C) = 6.9 Hz, 1 C, CH_3), 25.13 (d, ^{3}J(P,C) = 4.7 Hz, 1 C, CH_3). **^{31}P NMR** (202.46 MHz, [D$_6$]DMSO, 25 °C, H_3PO_4 external): 5.96 (quin, J(P,H) = 10.0 Hz). **IR** (KBr): $\tilde{\nu}$ = 3245 (NH), 3025 (NH), 2890 (NH), 2600, 1643 (C=O), 1593, 1501, 1479, 1429, 1264, 1229, 1199 (νP=O), 1154, 1113, 1083, 1038, 969 (P-N_{amine}), 886, 845, 784, 758, 693 (P-N_{amide}), 547, 482. **MS** (70 ev) *m/z* (%): 425 (2, M^+), 185 (25, $C_7H_5FNO_2P^+$), 139 (16, $C_7H_6FNO^+$), 123 (31, $C_7H_4FO^+$), 121 (59, $C_7H_4FN^+$), 120 (49, $C_8H_{11}N^+$), 106 (100, $C_8H_{10}^+$).

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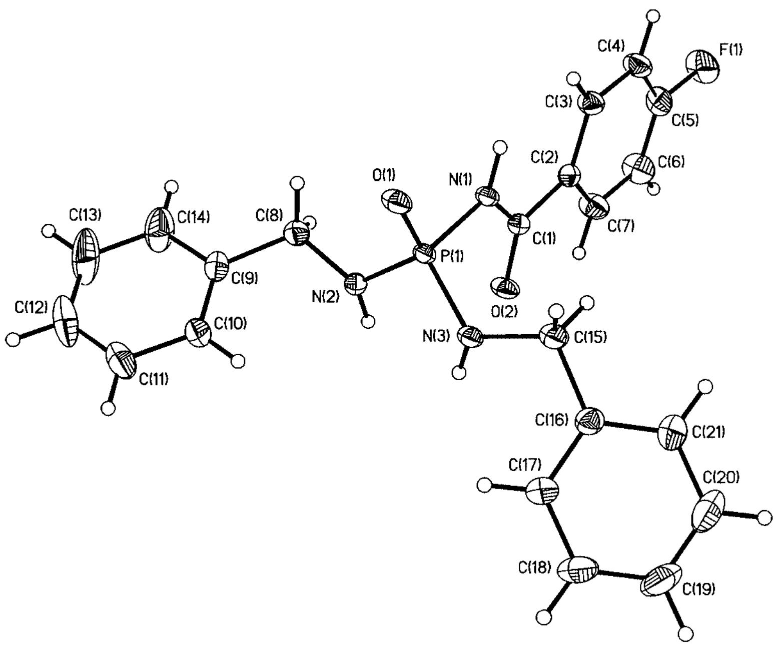

Figure 2 Molecular structure of 4-F-$C_6H_4C(O)N(H)P(O)(NH\text{-}CH_2C_6H_5)_2$ showing the atom-labeling scheme and 50 % probability level displacement ellipsoids.

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