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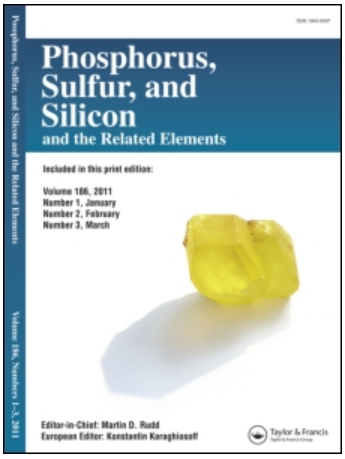

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SOME PHOSPHORYLATED DERIVATIVES OF *EXO*-AND *ENDO*-NORBORNEOL

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SOME PHOSPHORYLATED DERIVATIVES OF *EXO*- AND *ENDO*-NORBORNEOL

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endo- and *exo*-Norborneols have been phosphorylated with phosphorus oxychloride, and phenylphosphorodichloridate to the corresponding phosphorodichloridates and phenylphosphorochloridates. With thiophosphoryl chloride, both isomeric norborneols gave the dichloridothioates. When the norborneols (2 mol. equivs.) were treated with phosphorus oxychloride (1 mol. equiv.) the corresponding phosphorochloridates were isolated. The various liquid phosphorochloridates and dichloridothioates were characterized as solid derivatives, e.g. phenylhydrazides, diamidates, and hydrazones. Several of the phosphorohydrazides have been reacted with isocyanates and phenylisothiocyanate to form the carbamoyl and *N*-phenylthiocarbamoyl derivatives. *exo*-Norbornyl *O*-phenylphosphorochloridate by partial hydrolysis (aq. pyridine) gave the corresponding $P^1:P^2$-diphenylpyrophosphate; *exo*-norbornyl *N*-phenylphosphoramidic chloride similarly afforded the $P^1:P^2$-dianilinopyrophosphate. The aqueous hydrolysis of *exo*- and *endo*-norbornylphosphorodichloridates is discussed in terms of competing reactions between substitution at carbon and substitution at phosphorus. The spectral data of the phosphorylated derivatives are briefly discussed.

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INTRODUCTION

Previous studies[1–3] described the phosphorylation of *cis*- and *trans*- 4-t-butylcyclohexanol and *l*-menthol and their conversion into a range of phosphorylated derivatives. Such compounds are of interest as potential pesticides, and in this paper the work has been extended to an investigation of the phosphorylation of the bicyclic terpenes *endo*- and *exo*-norborneol.

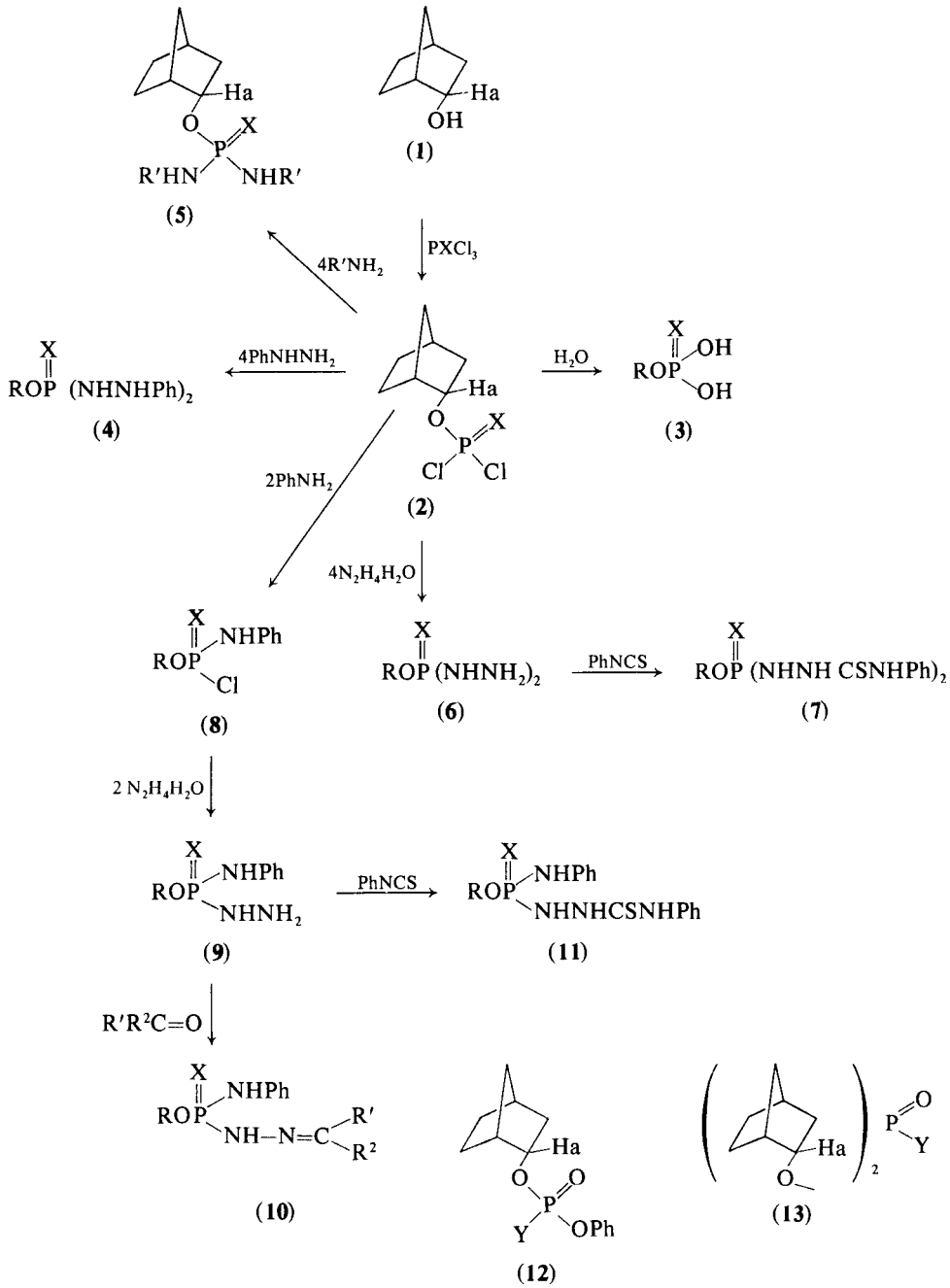
DISCUSSION

endo-Bicyclo[2,2,1]heptanol (*endo*-norborneol) (**1**) (Scheme 1) with an equimolar amount of phosphorus oxychloride at 0° gave the phosphorodichloridate (**2**; X = O) (89% yield). This was converted into a number of derivatives: hydrolysis gave the phosphate (**3**; X = O); phenylhydrazine (4 mol. equivs.) afforded the diphenylhydrazide (**4**; X = O), and aniline (4 mol. equivs.) similarly gave the *N*,*N*′-diphenyldiamidate (**5**; X = O; R′ = Ph). Condensation with hydrazine gave the dihydrazide (**6**; X = O) which with phenylisocyanate (2 mol. equivs.) gave the di(*N*-phenylthiocarbamoyl) derivative (**7**; X = O).

When the phosphorodichloridate (**2**; X = O) was reacted with less aniline (2 mol. equivs.), the *N*-phenylamidic chloride (**8**; X = O) was isolated. This contains a reactive chlorine atom which, with hydrazine, afforded the *N*-phenylphosphoramidic hydrazide (**9**; X = O) and the latter was converted into three hydrazones (**10**; X = O). With phenylisothiocyanate the *endo*-norbornyl *N*-phenylphosphoramidic hydrazide (**9**; X = O) gave the *N*-phenylthiocarbamoyl derivative (**11**; X = O) which, although affording correct microanalytical data, showed two spots on the tlc with two different solvent systems. The corresponding *exo*-norbornyl *N*-phenylthiocarbamoyl derivative also gave two spots, as did the *exo*-*N*-methylcarbamoyl compound, although the *exo*-*N*-phenylcarbamoyl derivative showed only one spot. The two spots may well be due to the presence of tautomers: in the case of the thiocarbamoyl derivatives this is to be expected since the C=S group readily tautomerizes.

Thiophosphorylation of *endo*-norborneol (**1**) with thiophosphoryl chloride (1 mol. equiv.) gave the dichloridothioate (**2**; X = S) (51%) as an oil which was characterized by the formation of solid derivatives. Cyclohexylamine (4 mol. equivs.) gave the dicyclohexyldiamidothioate (**5**; X = S, R′ = C_6H_{11}), and dimethylamine (4 mol. equivs.) gave the corresponding *N*,*N*,*N*′,*N*′-tetramethyl derivative (**5**; X = S). Phenylhydrazine (4 mol. equivs.) afforded the diphenylhydrazide (**4**; X = S).

endo-Norborneol (**1**) was also reacted with phenylphosphorodichloridate to give the *O*-phenylphosphorochloridate (**12**; Y = Cl) (64%). This was



(R = *endo*- or *exo*-norbornyl)

SCHEME 1

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characterized by the formation of two derivatives: the phenylhydrazide (**12**; Y = NHNHPh) and the *p*-nitroacetophenone hydrazone (**12**, Y = NHN=C(CH_3)$C_6H_4NO_2$-*p*).

The *bis*[*endo*-norbornyl]phosphorochloridate (**13**; Y = Cl) was obtained (51%) by reaction of *endo*-norborneol (2 mol. equivs.) with phosphorus oxychloride (1 mol. equiv.). This was converted into solid derivatives: the phenylhydrazide (**13**; Y = NHNHPh) and the cyclohexylamidate (**13**; Y = $C_6H_{11}NH$).

Phosphorylation of *exo*-norborneol (**1**; OH *exo*-) was effected with an equimolar quantity of phosphorus oxychloride at low temperature (−10°) and yielded the *exo*-phosphorodichloridate (**2**; X = O) (60%) as a fuming liquid. This was characterized by formation of the dicyclohexyl diamidate (**5**; X = O, R′ = C_6H_{11}), the diphenylhydrazide (**4**; X = O), the dianiline diamidate (**5**; X = O, R′ = Ph) and the *p*-nitrobenzaldehyde dihydrazone. With less aniline (2 mol. equivs.) the *exo*-*N*-phenylphosphoramidic chloride (**8**; X = O) was obtained as an oil which was converted into several solid derivatives: the hydrazide (**9**; X = O); six hydrazones (**10**; X = O); the *N*-*p*-toluenesulphonyl derivative, and the phenylhydrazide. The *exo*-amidic chloride (**8**; X = O) with sodium azide gave the amidic azide, which with triphenylphosphine formed the triphenylphosphinimine derivative. The *exo*-*N*-phenylphosphoramidic hydrazide (**9**; X = O) has been reacted with phenylisothiocyanate, phenylisocyanate, and methylisocyanate to give the corresponding carbamoyl and thiocarbamoyl derivatives (e.g. **11**; X = O).

Hydrolysis (water) of the *exo*-phosphorodichloridate (**2**; X = O) gave the *exo*-dihydrogen phosphate (**3**; X = O) as an oil which was converted into the solid dianilinium salt. Partial hydrolysis (aqueous pyridine) of the *exo*-*N*-phenylamidic chloride (**8**; X = O) afforded the corresponding $P^1:P^2$-dianilinopyrophosphate. This was stable to boiling water (4 h) but was hydrolysed to the *N*-phenylphosphoramidic acid by boiling 4N sodium hydroxide (1 h) ; the pyrophosphate bond was also split by treatment with cyclohexylamine. The resistance to hydrolysis by boiling water is a reflection of the greater stability of amidic phosphates compared to simple tetra-alkyl pyrophosphates.[4]

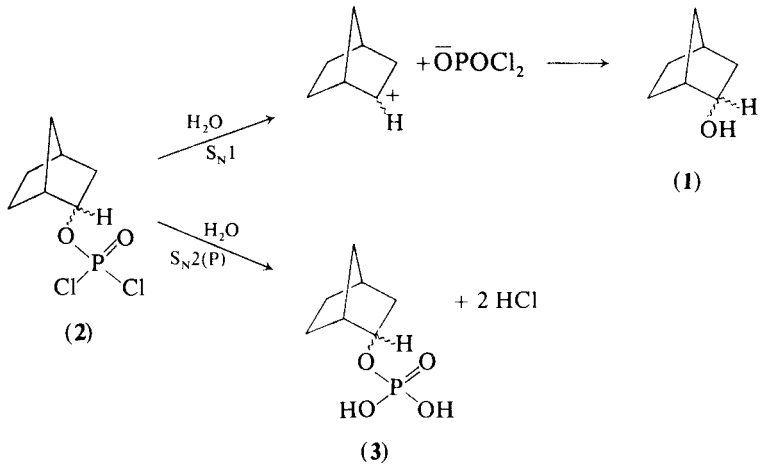
exo-Norborneol (**1**; OH *exo*-) was reacted with phenylphosphorodichloridate (1 mol. equiv.) to form the *O*-phenylphosphorochloridate (**12**; Y = Cl) (61%) as an oil which was characterized by formation of the *p*-nitroacetophenone and pyridine-2-aldehyde hydrazones, and the phenylhydrazide (**12**; Y = NHNHPh). The *exo*-O-phenylphosphorochloridate (**12**; Y = Cl), by partial hydrolysis (aqueous pyridine), gave the $P^1:P^2$-diphenylpyrophosphate.

Thiophosphorylation of *exo*-norborneol (**1**; OH *exo*-) with thiophosphoryl chloride (1 mol. equiv.) gave the *exo*-dichloridothioate (**2**; X = S) (76%) as an oil which was characterized as two solid derivatives: the diphenylhydrazide (**4**; X = S) and the di-isopropyldiamidate (**5**; X = S, R′ = Me_2CH).

The *bis*[*exo*-norbornyl]phosphorochloridate (**13**; Y = Cl) (76%) was obtained, by condensation of *exo*-norborneol (**1**; OH *exo*-) (2 mol. equivs.) with phosphorus oxychloride (1 mol. equiv.), as an oil which was converted into solid derivatives: the phenylhydrazide (**13**; Y = NHNHPh); the cyclohexylamidate (**13**; Y = $C_6H_{11}NH$), and the anilinium phosphate (**13**; Y = $O^-H_3N^+Ph$).

exo- and *endo*-Norborneols have similar thermodynamic stabilites,[4] although a marked difference in chemical reactivity towards phosphorylating agents might have been expected since attack from the *exo*-direction is generally preferred over *endo*- attack in norbornyl systems.[5a] While this holds for direct attack by the reagent on the C(2) and C(3) ring carbons, attack by reagents on atoms one-removed from these carbon atoms is less affected by the steric constraints of the bridged system. Thus (+) *exo*-norborneol is racemized at a slightly faster rate than (+) *endo*-norborneol with acid,[6] and *exo*- and *endo*-norborneols associate as hydrogen-bonded dimers in benzene to the same extent.[7] The rates of phosphorylation of *exo*- and *endo*-norborneols (monitored by the disappearance of the OH band in the ir spectra of samples taken from the reaction mixtures) are very similar, in agreement with this pattern.

We also observed that whilst the *endo*-phosphorodichloridate (**2**; X = O) was stable to air, the *exo*-isomer produced fumes of hydrogen chloride and rapidly darkened in colour. Hydrogen chloride is presumably formed by nucleophilic attack of water at the phosphorus atom ($S_N2(P)$), but since phosphorus is now two atoms removed from the C(2) ring carbon atom, this difference in reactivity can not be due to preferential *exo*- attack. Solvolysis of secondary alkyl and cycloalkyl phosphorodichloridates normally involves nucleophilic attack by solvent solely at the more electrophilic phosphorus atom, to produce hydrogen chloride and the phosphate.[8] Any competing (S_N1) attack on the



SCHEME 2

less electrophilic carbon involving the phosphorodichloridate anion as a leaving group only seems to occur when there is extra stabilization of the carbonium ion produced; for instance in the solvolyses of cholesteryl and ergosteryl phosphodichloridates involving the homoallylic cation.[9] Analysis of the products from the hydrolysis of *exo*- and *endo*-norbornyl phosphorodichloridates (2) in water at room temperature indicates that these two completing processes are both operative (Scheme 2). The *exo*- isomer produced 85% alcohol (**1**) and 15% phosphate (**3**) while the *endo*-isomer gave 22% alcohol (**1**) and 78% phosphate (**3**). These reactions may proceed *via* a σ-bridged nonclassical norbornyl cation or a pair of rapidly equilibrating classical cations [5b] dependent on which can provide the necessary degree of stabilization of the intermediate carbonium ion.

The ir spectra of the norbornyl phosphoramidic compounds showed general agreement with the values previously reported[10] for the P=O and NH stretching vibrations. The P—O—C band appeared in the region 970–1040 cm^{-1} while that associated with the P—O—P group was at 925–945 cm^{-1} (cf. Ref. 11). The P=S absorption appeared, generally as a single band, in the region 820–850 cm^{-1} in good agreement with our previous assignment[3] (cf. Ref. 12).

In the nmr spectra the signals due to the Ha protons appear as multiplets within the range δ 4.74–4.06 as a result of coupling with the phosphorus atom through oxygen, and with the other alicyclic protons. The *endo*- or *exo*-configuration of the proton Ha could not therefore be readily assigned on the basis of the nmr spectrum.

EXPERIMENTAL

Ir spectra were determined as liquid films or Nujol mulls using a Perkin Elmer 237 spectrometer.

Nmr spectra were measured with a Varian A60A spectrometer using tetramethylsilane as internal standard. In the nmr data signals marked with an asterisk are removed by treatment with D_2O. Mass spectra were measured with an AEI MS9 spectrometer at 70 eV.

Melting points were determined with a Kofler hot-stage apparatus and are uncorrected. Tlc was carried out on silica gel G plates developed with iodine vapour. Microanalyses were carried out by Butterworth Microanalytical Consultants Ltd., Teddington, England.

endo-Bicyclo[2,2,1]heptylphosphorodichloridate (**2**; X = O)

A solution of *endo*-bicyclo[2,2,1]heptanol (*endo*-norborneol) (**1**) (11.2 g; 1 mol. equiv.) and triethylamine (12.12 g; 1.2 mol. equivs.) in toluene (100 ml) was gradually added during 45 min to a stirred solution of phosphorus oxychloride (18.3 g; 1.2 mol. equivs.) in toluene (50 ml) at 0°. After 6 h at 4°, the precipitate of triethylamine hydrochloride (13.8 g) was collected, and the filtrate evaporated at 40° (7 mm) to a fuming red liquid (18 g, 89%). The phosphorodichloridate (**2**; X = O) was characterized by the preparation of a number of solid derivatives:

Dihydrogen Phosphate (**3**; X = O)

The phosphorodichloridate (1 g) was boiled under reflux in aqueous acetone (20 ml of 50% v/v) for 4 h and the solution concentrated. The resultant solid was dissolved in 5N-NaOH (10 ml) and the alkaline solution extracted with ether (3 × 25 ml). The aqueous layer was acidified with 2N-hydrochloric acid, and extracted with ether (2 × 50 ml). The extract was washed with H_2O, dried ($MgSO_4$), and evaporated to give a crystalline solid. Recrystallization from acetone afforded the *phosphate* (3) (0.2 g), mp 196–199°. (Found: C, 43.9; H, 6.6. $C_7H_{13}O_4P$ requires C, 43.75; H, 6.8%.) Tlc (EtOAc–petroleum ether 60–80° 1:1) showed one spot remaining at the base line. ν_{max} 2345–2290 (P—OH), 1210–1190 (P=O), 1020–1000 (P—O—C) cm^{-1}.

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endo-Bicyclo[2,2,1]heptylphosphoro-N,N'—Diphenylhydrazide (**4**; X = O)

The phosphorodichloridate (**2**; X = O) (2.28 g; 1 mol. equiv.) was added dropwise to a stirred solution of phenylhydrazine (4.32 g; 4 mol. equivs.) in acetonitrile (25 ml) at 0°. After 10 h at 4°, the precipitate was filtered off and the solid was washed with water (500 ml) (to remove phenylhydrazine hydrochloride). The solid was stirred with water (150 ml), filtered and recrystallized from ethanol to give *the diphenylhydrazide* (**4**; X = O) (2.7 g, 73%), mp 170–172°. (Found: C, 61.3; H, 6.8; N, 15.1 · $C_{19}H_{25}N_4O_2P$ requires C, 61.3; H, 6.7; N, 15.05%.) Tlc ($CHCl_3$–EtOH 8:1) showed a single spot, R_F 0.67. Pr^{i}OH–toluene–EtOAc–H_2O 5:1:2.5:1.25, one spot R_F 0.84. ν_{max} 3330, 3280 (NH), 1610, 1500 (arom C=C), 1215, 1205 (P=O), 1020 (P–O–C) cm^{-1}. Nmr δ ($CDCl_3$) 7.34–6.77 m (10 ArH), 5.68–5.60 br (2H, 2 × PhN*H*), 5.23–5.17 br (2H, 2 × P–N*H*), 4.55–4.36 br (1 H, *exo*-Ha), 2.30–0.72 m (10 alicyclic H).

endo-Bicyclo[2,2,1]heptyl-N,N'-Diphenylphosphorodiamidate (**5**; X = O, R' = Ph)

The phosphorodichloridate (**2**; X = O) (2.28 g; 1 mol. equiv.) was added gradually to a stirred solution of aniline (3.72 g; 4 mol. equivs.) in acetonitrile (20 ml). The mixture was left at room temperature overnight, the precipitate of aniline hydrochloride was filtered off, and the filtrate evaporated. The residue, was stirred with dil. HCl and H_2O (to remove traces of the hydrochloride), and recrystallized from acetone to give the *diphenylphosphorodiamidate* (3.1 g, 65%) mp 157–159°. (Found: C, 66.9; H, 6.4; N, 8.0. $C_{19}H_{23}N_2O_2P$ requires C, 66.7; H, 6.7; N, 8.2%.) ν_{max} 3210, 3090, 3050 (NH), 1610 (arom C=C), 1205, 1195 (P=O), 1015, 1005 (P–O–C) cm^{-1}. Nmr δ($CDCl_3$) 8.06 br (2H, 2N*H*), 7.27–6.80 (10 ArH), 4.62–4.48 br (1H, *exo*-Ha), 2.55–0.80 (10 alicyclic H). Tlc ($CHCl_3$–EtOH 8:1) gave a single spot, R_F 0.76. Pr^{i}OH–toluene–EtOAc–H_2O 5:1:2.5:1.25, one spot R_F 0.82.

endo-Bicyclo[2,2,1]heptylphosphorodihydrazide (**6**; X = O)

The phosphorodichloridate (**2**; X = O) (2.28 g) was gradually added to a solution of hydrazine hydrate (3 g; 6 mol. equivs.) in ethanol (20 ml) with cooling (ice). After 8 h at room temperature, the ethanol was removed *in vacuo*, and the residual solid washed with water and crystallized (aq EtOH) to give the *dihydrazide* (0.5 g), mp 83–85°. (Found: C, 37.9; H, 7.8; N, 25.1. $C_7H_{17}N_4O_2P$ requires C, 38.2; H; 7.7; N, 25.45%.) Heating the dihydrazide with phenylisocyanate (2 mol. equivs.) in boiling 60–80° petroleum ether (6 h) gave the *di(N-phenylcarbamoyl)dihydrazide* (7) (80%), mp 221–225°. Found: C, 55.0; H, 6.1; N, 18.3. $C_{21}H_{27}N_6O_4P$ requires C, 55.0; H, 5.9; N, 18.3%.) ν_{max} 3290, 3230 (NH), 1670 (CO), 1220 (P=O), 1030 (P–O–C) cm^{-1}. Tlc ($CHCl_3$–EtOH 8:1) showed a single spot, R_F 0.64. Pr^{i}OH–toluene–EtOAc–H_2O 5:1:2.5:1.25, single spot R_F 0.83.

endo-Bicyclo[2,2,1]heptyl N-Phenylphosphoramidic chloride (**8**; X = O)

Aniline (1.86 g, 2 mol. equivs.) was gradually added to a stirred solution of the phosphorodichloridate (2) (2.28 g; 1 mol. equiv.) in benzene (20 ml). After 8 h at room temperature, aniline hydrochloride (1.1 g) was filtered off, and the filtrate evaporated *in vacuo* to give the *amidic chloride* as a clear oil (3.2 g). ν_{max} 3160 (NH), 1605, 1505 (arom C=C), 1250, 1230 (P=O), 1025 (P–O–C) cm^{-1}. The amidic chloride (**8**; X = O) was characterized by the preparation of the following solid derivatives:

N-Phenylphosphoramidic hydrazide (**9**; X = O)

The *N*-phenylphosphoramidochloridate (**8**; X = O) (2.85 g; 1 mol. equiv.) was added to a solution of hydrazine hydrate (1 g; 2 mol. equivs.) in ethanol (25 ml). After 3 h, the mixture was evaporated *in vacuo*, and the residual solid stirred with H_2O overnight. Recrystallization ($CHCl_3$–EtOH) gave the *hydrazide* (0.8 g), mp 166–168°. (Found: C, 55.4; H, 7.3; N, 14.8. $C_{13}H_{20}N_3O_2P$ requires C, 55.5; H, 7.1; N, 14.95%.) ν_{max} 3320 (NH_2), 3240, 3120, 3080 (NH), 1610 (arom C=C), 1215 (P=O), 1045, 1030 (P–O–C) cm^{-1}. The following hydrazones were obtained: *o-Nitrobenzaldehyde* (**10**; X = O, R = H, R' = 2-$NO_2C_6H_4$) (80%), mp 139–142°. (Found: C, 58.1; H, 5.7; N, 13.4. $C_{20}H_{23}N_4O_4P$ requires C, 58.0; H, 5.6; N, 13.5%.) ν_{max} 3150 (NH), 1610, 1500 (arom C=C), 1530 (NO_2), 1205 (P=O), 1020, 1005 (P–O–C) cm^{-1}. Tlc ($CHCl_3$–EtOH 8:1) gave a single spot, R_F 0.79. *p-Nitrobenzaldehyde* (**10**; X = O, R = H, R' = 4-$NO_2C_6H_4$) (75%), mp 189–192°. (Found: C, 57.6; H, 5.5; N, 13.5. $C_{20}H_{23}N_4O_4P$ requires C, 58.0; H, 5.6; N, 13.5%.) ν_{max} 3160 (NH), 1610, 1510 (arom C=C), 1530 (NO_2), 1220 (P=O), 1000 (P–O–C) cm^{-1}. Acetone (**10**; X = O, R = R' = Me) (90%), mp 173–176°. (Found: C, 60.1; H, 7.7; N, 12.9. $C_{16}H_{24}N_3O_2P$ requires C, 59.8; H, 7.5; N, 12.9%.) ν_{max} 3240, 3160, 3100 (NH), 1610, 1510 (arom C=C), 1210 (P=O), 1015 (P–O–C) cm^{-1}. Tlc (Pr^{i}OH–toluene–EtOAc–H_2O 5:1:2.5:1.25) showed a single spot, R_F 0.81. Nmr ($CDCl_3$) 7.30–6.93 m (5 ArH), 6.66 br (1H, PhN*H*), 5.84 br (1H, N–N*H*), 2.50–0.83 (10 alicyclic H), 1.92, 1.75 d (6H, 2× C*H*$_3$) due to non-rotation about N=C bond.

endo-Bicyclo[2,2,1]heptyl N-Phenylphosphorodiamidic N'-Phenylthiocarbamoyl Hydrazide (**11**; X = O)

The *N*-phenylphosphorodiamidic hydrazine (**9**; X = O) (0.14 g) was boiled under reflux with phenylisothiocyanate (0.67 g; 1 mol. equiv.) in 60–80° petroleum ether (20 ml) for 4 h. Evaporation gave a solid residue which was shaken with dil. NaOH and H_2O to give the *N'-phenylthiocarbamoyl hydrazide* (0.1 g), mp 196–200°. (Found: C, 57.5, H, 6.2; N, 13.6 $C_{20}H_{25}N_4O_2PS$ requires C, 57.7; H, 6.0; N, 13.5%.) ν_{max} 3330, 3230, 3090 (NH), 1145 (C=S), 1220 (P=O), 1015 (P–O–C) cm^{-1}. Tlc ($CHCl_3$–EtOH 8:1) gave two spots R_F 0.70, 0.44. Pr^{i}OH–toluene–EtOAc–H_2O 5:1:2.5:1.25, two spots R_F 0.84, 0.74.

endo-Bicyclo[2,2,1]heptylphosphorodichloridothioate (**2**; X = S)

A solution of *endo*-bicyclo[2,2,1]heptanol (*endo*-norborneol) (**1**) (11.2 g; 1 mol. equiv.) and pyridine (7.9 g, 1 mol. equiv.) in acetone (20 ml) was added to a stirred solution of thiophosphoryl chloride (16.9 g, 1 mol. equiv.) in dry acetone (100 ml) at 0°. After 24 h at room temperature, the acetone was evaporated *in vacuo* to give the crude *endo*-dichloridothioate as a purple oil (12.5 g, 51%). The *endo*dichloridothioate was characterized by preparation of the following solid derivatives:

N,N'-Dicyclohexylphosphorodiamidothioate (**5**; X = S, R' = C_6H_{11})

The phosphorodichloridothioate (**2**; X = S) (1.22 g) was reacted with cyclohexylamine (1.98 g; 4 mol. equivs.) in acetonitrile (20 ml) for 23 h. The solid was filtered off, stirred with dil. NaOH and H_2O for 4 h, and dried to give the *phosphorodiamidothioate* (0.7 g), mp 146–148°. (Found: C, 61.4; H, 9.6; N, 7.6. $C_{19}H_{35}N_2O$ PS requires C, 61.6; H, 9.5; N, 7.55%.) ν_{max} 3350, 3240 (NH), 1000, 990 (P–O–C), 840 (P=S) cm^{-1}. Tlc ($CHCl_3$–EtOH 8:1) R_F 0.82. Pr^{i}OH–toluene–H_2O 5:1:2.5, a single spot R_F 0.83.

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N,N,N',N'-Tetramethylphosphorodiamidothioate (**5**; X = S)

The phosphorodichloridothioate (**2**; X = S) (2.45 g) was treated with dimethylamine (5.4 g of 33% ethanolic solution; 4 mol. equivs.) in ethanol (10 ml) overnight and then warmed at 50–60° for ½ h. Evaporation gave an oil which was extracted with ether (100 ml), washed with dil. HCl (3 × 20 ml), H_2O (2 × 20 ml), dried ($MgSO_4$), and evaporated to give a pale yellow oil (1.9 g). Vacuum distillation gave the *tetramethyldiamidothioate* as a colourless liquid (1.0 g), bp 107°/0.8 mm. (Found: C, 50.2; H, 9.0; N, 10.8. $C_{11}H_{23}N_2OPS$ requires C, 50.4; H, 8.8; N, 10.7%.) ν_{max} 990 (P–O–C), 835 (P=S) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5 : 1 : 2.5 : 1.25), showed one spot R_F 0.62. MS showed the molecular ion (M^+, 262), and other major fragment ions were at 235, 168, 141, 140, 126, 95, 94, 92, 80, 79.

endo-Bicyclo[2,2,1]heptyl N,N'-Diphenylhydrazinophosphorodiamidothioate (**4**; X = S)

The phosphorodichloridothioate (**2**; X = S) (1.43 g) was added dropwise to a stirred solution of phenylhydrazine (4 mol. equivs.) in acetonitrile (30 ml). After 24 h at room temperature, evaporation *in vacuo* gave an oily solid. Treatment with H_2O, and aq. KOH for 4 h followed by crystallization from petroleum ether (60–80°) afforded the *diphenylhydrazinothioate* (0.56 g), mp 169–173°. (Found: C, 59.0; H, 6.6; N, 14.6. $C_{19}H_{25}N_4OPS$ requires C, 58.8; H, 6.4; N, 14.4%.) ν_{max} 3310, 3265, 3180 (NH), 1610 (arom C=C), 995 (P–O–C), 840 (P=S) cm^{-1}. Nmr $\delta(CDCl_3)$, 7.32–6.77 m (10 ArH), 5.52 br (2H, 2 × PhN*H*), 5.03 br (2H, 2 × P-N*H*], 4.67–4.52 m (1H, *exo*-Ha), 2.42–0.73 (10 alicyclic H).

endo-Bicyclo[2,2,1]heptyl O-Phenylphosphorochloridate (**12**; Y = Cl)

A solution of *endo*-bicyclo[2,2,1]heptanol (*endo*-norborneol) (**1**) (5.6 g; 1 mol. equiv.) and triethylamine (5.05 g; 1 mol. equiv.) in ether (10 ml) was added dropwise to a stirred solution of *O*-phenylphosphorodichloridate (11.05 g; 1 mol. equiv.) in ether (50 ml) at room temperature. After 30 h, the precipitate of triethylamine hydrochloride (6.35 g) was collected. The filtrate was washed with H_2O (3 × 100 ml), $NaHSO_3$ (100 ml of 10%), dried ($MgSO_4$) and evaporated under reduced pressure to give the *phenylphosphorochloridate* as a pale yellow oil (9.5 g, 64%). (Found: C, 54.2; H, 5.7; P, 11.0. $C_{13}H_{16}ClO_3P$ requires C, 54.45; H, 5.6; P, 10.8%.) ν_{max} 1590, 1490 (arom C=C), 1305, 1280 (P=O), 1010, 995 (P–O–C) cm^{-1}. Tlc (EtOAc–petroleum ether 60–80° 1 : 1) gave a single spot, R_F 0.70. The chloridate (**12**; Y = Cl) was characterized as solid derivatives:

Phenylhydrazide (**12**; Y = NHNHPh)

endo-Bicycloheptylphenylphosphorochloridate (2.86 g) on condensation with phenylhydrazine (2.2 g, 2 mol. equivs.) in acetonitrile (20 ml) overnight at 4°, afforded the *N-phenylhydrazide* (1.5 g), mp 165–167° (from ethanol). (Found: C, 63.8; H, 6.5; N, 7.8. $C_{19}H_{23}N_2O_3P$ requires C, 63.7; H, 6.4; N, 7.8%.) ν_{max} 3300, 3200 (NH), 1600, 1590, 1490 (arom C=C), 1215, 1200 (P=O), 1010 (P–O–C) cm^{-1}. Tlc (EtOAc–petroleum ether 60–80° 1 : 1) showed one spot, R_F 0.59. Nmr $\delta(CDCl_3)$ 7.24 s (5H, OC_6H_5), 7.10–6.80 m (5H, NC_6H_5) 5.45, 5.39 d (2H, 2 N*H*), 4.76–4.69 m (1H, *exo*-Ha), 2.42–0.74 m (10 alicyclic H).

Hydrazide (**12**; Y = NH NH_2)

Reaction of *endo*-bicycloheptylphenylphosphorochloridate (2.86 g) with hydrazine hydrate (1.5 g; 3 mol. equivs.) in acetonitrile (30 ml) at room temperature for 4 h gave the *phosphorohydrazide* as a yellow oil (1.5 g), n_D^{25} 1.5191. (Found: C, 55.5; H, 6.8; N, 9.75. $C_{13}H_{19}N_2O_3P$ requires C, 55.3; H, 6.7; N, 9.9%.) ν_{max} 3340 (NH_2), 3230 (NH), 1590, 1490 (arom C=C), 1205 (P=O), 1005 (P–O–C) cm^{-1}. This was converted to the *p-nitroacetophenone hydrazone*, yellow plates (EtOH) (56%), mp 120–122°. (Found: C, 58.6; H, 5.4; N, 9.6. $C_{21}H_{24}N_3O_5P$ requires C, 58.7; H, 5.6; N, 9.8%.) ν_{max} 3130 (NH), 1595, 1490 (arom C=C), 1515 (NO_2), 1250 (P=O), 1005 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5 : 1 : 1.25) gave a single spot, R_F 0.89. MS showed the molecular ion (M^+, 429) and major fragment ions at 336 (M–OPh), 335, 241, 178, 163, 162, 116, 94, 93 (OPh), 92, 80.

bis(endo-Bicyclo[2,2,1]heptyl)phosphorochloridate (**13**; Y = Cl)

A solution of *endo*-bicyclo[2,2,1]heptanol (1) (11.2 g; 2 mol. equivs.) and triethylamine (10.1 g; 2 mol. equivs.) in toluene (75 ml) was added dropwise to a stirred solution of phosphorus oxychloride (7.67 g; 1 mol. equiv.) in toluene (75 ml) at 0°. After 24 h at room temperature, the precipitated triethylamine hydrochloride (16 g) was collected. The filtrate was evaporated *in vacuo* to give the *phosphorochloridate* (**13**; Y = Cl) as a brown oil (7.7 g; 51%). ν_{max} 1290 (P=O), 1030–1000 br (P–O–C) cm^{-1}. The phosphorochloridate was characterized by the preparation of solid derivatives: *N-Phenylphosphorohydrazide* (**13**; Y = NHNHPh), pale yellow needles recrystallized twice from ethanol (30%), mp 199–202°. (Found: C, 63.5; H, 7.7; N, 7.2. $C_{20}H_{29}N_2O_3P$ requires C, 63.8; H, 7.7; N, 7.45%.) ν_{max} 3300, 3200 (NH), 1610, 1500 (arom C=C), 1220, 1210 (P=O), 1025, 1005 (P–O–C) cm^{-1}. Nmr $\delta(CDCl_3)$ 7.41–6.76 m (5 ArH), 5.76–5.70 br (1H, PhN*H*), 5.15–5.30 br (1H, P–N*H*), 4.56–4.35 m (2H, 2X *exo*-Ha), 2.31–0.70 m (20 alicyclic H). Tlc (EtOAc–petroleum ether 60–80° 1 : 1) showed one spot, R_F 0.53.

N-Cyclohexylphosphoramidate (**13**; Y = $C_6H_{11}NH$)

(25%) from $CHCl_3$–petroleum ether 60–80°, mp 217–220°. (Found: C, 65.3; H, 8.95; N, 3.6. $C_{20}H_{34}NO_3P$ requires C, 65.4; H, 9.25; N, 3.8%.) ν_{max} 3180 (NH), 1245, 1230 (P=O), 1000 (P–O–C) cm^{-1}. Tlc (EtOAc–petroleum ether 60–80° 1 : 1) gave one spot, R_F 0.66. Pr^iOH–toluene–EtOAc–H_2O 5 : 1 : 2.5 : 1.25, one spot R_F 0.85.

exo-Bicyclo[2,2,1]heptylphosphorodichloridate (**2**; X = O)

A solution of *exo*-bicyclo[2,2,1]heptanol (*exo*-norborneol) (**1**; OH *exo*) (5.6 g; 1 mol. equiv.) and triethylamine (5.05 g; 1 mol. equiv.) in ether (75 ml) was gradually added to a stirred solution of phosphorus oxychloride (7.67 g; 1 mol. equiv.) in ether (50 ml) at −10°. After 3½ h at 5°, the usual work up procedure afforded the *exo-phosphorodichloridate* (**2**; X = O) as a fuming yellow oil (6.9 g, 60%). ν_{max} 1315–1290 br (P=O), 1025–990 (P–O–C) cm^{-1}. This was characterized as the following solid derivatives:

p-Nitrobenzaldehyde exo-Bicyclo[2,2,1]heptylphosphorodihydrazone

Condensation of the *exo*-dichloridate (**2**; X = O) (2.29 g) with hydrazine hydrate (2 g; 4 mol. equivs.) in ethanol (30 ml) at 0°

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for 4 h gave the *dihydrazide* (**6**; X = O) as an oil (1.5 g). Boiling with p-nitrobenzaldehyde (2.06 g; 2 mol. equivs.) in ethanol (30 ml) for 4 h gave the *p-nitrobenzaldehyde dihydrazone* as yellow plates from ethanol (2.2 g, 67%), mp 187–189°. (Found: C, 51.6; H, 4.9; N, 20.0. $C_{21}H_{23}N_6O_6P$ requires C, 51.85; H, 4.7; N, 19.75%.) ν_{max} 3240 (NH), 1600, 1500 (arom C=C), 1560 (NO_2), 1215 (P=O), 1025 (P–O–C) cm^{-1}.

exo-Bicyclo[2,2,1]heptylphosphoro-N,N'-Diphenylhydrazide (**4**, X = O)

Reaction of the *exo*-phosphorodichloridate (**2**; X = O) (2.29 g) with phenylhydrazine (4.3 g; 4 mol. equivs.) in acetonitrile (40 ml) overnight gave the *diphenylhydrazide* from ethanol (2.2 g), mp 168–170°. (Found: C, 61.5; H, 6.7; N, 14.8. $C_{19}H_{25}N_4O_2P$ requires C, 61.3; H, 6.7; N, 15.05%.) ν_{max} 3370, 3280 (NH), 1215, 1205 (P=O), 1015 (P–O–C) cm^{-1}. Nmr ($CDCl_3$) δ 7.32–6.59 m (10 ArH), 5.10 s (2H, 2 × PhN$\overset{*}{H}$), 4.58 (2H, 2 × P–N$\overset{*}{H}$), 4.38–4.06 m (1H, *endo*-Ha), 2.20–0.72 m (10 alicyclic H). Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) showed one spot, R_F 0.86.

exo-Bicyclo[2,2,1]heptyl N,N'-Dicyclohexylphosphorodiamidate (**5**; X = O, R' = C_6H_{11})

Condensation of the *exo*-phosphorodichloridate (2.29 g) with cyclohexylamine (3.96 g; 4 mol. equivs.) in acetonitrile (40 ml) for 12 h gave the *dicyclohexylphosphorodiamidate* (from propanol) (1.5 g), mp 210–212°. (Found: C, 64.6; H, 10.0; N, 7.9. $C_{19}H_{35}N_2O_2P$ requires C, 64.4; H, 9.9; N, 7.9%.) ν_{max} 3180 (NH), 1205 (P=O), 1010 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) gave one spot, R_F 0.85.

N,N'-Diphenylphosphorodiamidate (**5**, X = O, R' = Ph)

Condensation of the *exo*-dichloridate (2.29 g) with aniline (3.72 g; 4 mol. equivs.) in acetonitrile (30 ml) overnight, afforded the *diphenylphosphorodiamidate* from petroleum ether 40–60°) (2.1 g), mp 179–182°. (Found: C, 66.8; H, 6.6; N, 8.3. $C_{19}H_{23}N_2O_2P$ requires C, 66.7; H, 6.7; N, 8.2%.) ν_{max} 3160, 3090, 3050 (NH), 1245–1225 (P=O), 1030, 1010 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) gave one spot, R_F 0.83.

exo-Bicyclo[2,2,1]heptyl N-Phenylphosphoramidic Chloride (**8**; X = O)

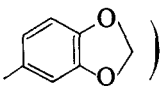
Reaction of the *exo*-dichloridate (10.96 g) with aniline (8.9 g, 2 mol. equivs.) in benzene (100 ml) for 15 h gave the *amidic chloride* as a light brown oil (12 g, 88%). ν_{max} 3160 (NH), 1605, 1500 (arom C=C), 1255, 1230 (P=O), 1015 (P–O–C) cm^{-1}.

The *exo*-N-phenylphosphoramidic chloride (**8**; X = O) was characterized by formation of the following solid derivatives:

The Hydrazide (**9**, X = O) (CH_3CN) (75%), mp 196–198°. (Found: C, 55.3; H, 7.4; N, 15.1. $C_{13}H_{20}N_3O_2P$ requires C, 55.5; H, 7.1; N, 14.95%.) ν_{max} 3320 (NH_2), 3230, 3150 (NH), 1610, 1505 (arom C=C), 1215 (P=O), 1180 (P–N) 1030 (P–O–C) cm^{-1}. The hydrazide was converted into the following hydrazones:

Acetone (**10**; X = O, R = R' = Me) (CH_3CN) (60%), mp 168–170°. (Found: C, 59.6; H, 7.55; N, 12.9. $C_{16}H_{24}N_3O_2P$ requires C, 59.8; 7.5; N, 12.9%.) ν_{max} 3230 br (NH), 1610, 1508 (arom C=C), 1205 (P=O), 1015 (P–O–C) cm^{-1}.

p-Nitrobenzaldehyde (**10**; X = O, R = H, R' = 4-$NO_2C_6H_4$) (CH_3CN) (63%), yellow plates, mp 175–176°. (Found: C, 57.8; H, 5.7; N, 14.3. $C_{20}H_{23}N_4O_4P$ requires C, 58.0; H, 5.6; N, 13.5%.) ν_{max} 3320, 3150 (NH), 1605, 1585, 1503 (arom C=C), 1520 (NO_2), 1230, 1190 (P=O), 1100 (P–O–C) cm^{-1}.

Piperonaldehyde (**10**; X = O, R = H, R' = ) (C_6H_6–petroleum ether 60–80°) (92%), mp 160–161°. (Found: C, 60.9; H, 5.9; N, 10.3. $C_{21}H_{24}N_3O_4P$ requires C, 61.0; H, 5.8; N, 10.2%.) ν_{max} 3210, 3155 (NH), 1610, 1505 (arom C=C), 1215, 1195 d (P=O), 1040, 1020 (P–O–C) cm^{-1}.

Pyridine-2-aldehyde (**10**; X = O, R = H, R' = 2-pyridyl) (EtOH) (81%), mp 187–189°. (Found: C, 61.7; H, 6.3; N, 15.3. $C_{19}H_{23}N_4O_2P$ requires C, 61.6; H, 6.2; N, 15.1%.) ν_{max} 3120 (NH), 1608, 1585, 1505 (arom C=C), 1215 (P=O), 1005, 980 (P–O–C) cm^{-1}.

Norcamphor (EtOH) (86%), mp 184–186°. (Found: C, 64.1; H, 7.6; N, 11.1. $C_{20}H_{28}N_3O_2P$ requires C, 64.3; H, 7.5; N, 11.3%.) ν_{max} 3200 (NH), 1608, 1505 (arom C=C), 1215 (P=O), 1015 (P–O–C) cm^{-1}.

Thiophene-2-aldehyde (**10**; X = O, R = H, R' = 2-thienyl) (EtOH) (93%), mp 177–178°. (Found: C, 57.5; H, 5.7; N, 11.5. $C_{18}H_{22}N_3O_2PS$ requires C, 57.6; H, 5.9; N, 11.2%.) ν_{max} 3160 (NH), 1610, 1530, 1505 (arom C=C), 1200 (P=O), 1015, 1005 (P–O–C) cm^{-1}.

N'-p-Toluenesulphonyl Hydrazide

The *exo-N*-phenylphosphoramidic hydrazide (**9**; X = O) (0.3 g) was reacted with p-toluenesulphonyl chloride (0.20 g; 1 mol. equiv.) and triethylamine (0.11 g; 1 mol. equiv.) in boiling benzene (30 ml) for 8 h. Triethylamine hydrochloride was filtered off and evaporation of the filtrate afforded the *p-toluenesulphonyl hydrazide* (from petroleum ether 60–80°) (0.34 g, 74%), mp 125–126°. (Found: C, 55.2; H, 5.7; N, 9.8. $C_{20}H_{26}N_3O_4PS$ requires C, 55.2; H, 6.0; N, 10.0%.) ν_{max} 3240 (NH), 1608, 1505 (arom C=C), 1340, 1165 (SO_2), 1202 (P=O), 1015 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) gave a single spot, R_F 0.72.

N'-Phenylhydrazide (CH_3CN) (33%), mp 132–134°. (Found: C, 63.9; H, 6.5; N, 11.6. $C_{19}H_{24}N_3O_2P$ requires C, 63.9; H, 6.7; N, 11.8%.) ν_{max} 3330, 3220, 3200 (NH), 1605, 1505 (arom C=C), 1220 (P=O), 1010 (P–O–C) cm^{-1}.

exo-Bicyclo[2,2,1]heptyl N-Phenylphosphoramidic Azide

The *exo*-N-phenylamidic chloride (**8**; X = O) (2.85 g) was reacted with sodium azide (0.65 g; 1 mol. equiv.) in aqueous acetone (20 ml) for 4 h. Evaporation *in vacuo* followed by ether extraction afforded the *phenylphosphoramidic azide* as an oil (2 g). (Found: C, 53.6; H, 6.1; N, 19.0. $C_{13}H_{17}N_4O_2P$ requires C, 53.4; H, 5.8; N, 19.2%.) ν_{max} 3160 (NH), 2150 (N_3), 1605, 1500 (arom C=C), 1250, 1230 (P=O), 1005 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1:1.25) showed one spot, R_F 0.79.

Reaction of the Azide with Triphenylphosphine

The *exo*-azide (1.6 g) was boiled under reflux with triphenylphosphine (1.43 g) in benzene (50 ml) for 8 h to give

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triphenyl(exo-bicyclo[2,2,1]heptyl N-phenylphosphorimido) phosphorane (from benzene-tetrahydrofuran) (2.2 g, 76%), mp 216–218°. (Found: C, 70.7; H, 5.9; N, 5.2. $C_{31}H_{32}N_2O_2P_2$ requires C, 70.7; H, 6.1; N, 5.3%.) ν_{max} 3140 (NH), 1605, 1500 (arom C=C), 1290, (P=O), 1120 (P–N), 1005 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) showed one spot, R_F 0.79.

exo-Bicyclo[2,2,1]heptyl N-Phenylphosphorodiamidic N'-Phenylthiocarbamoyl Hydrazide (**11**; X = O)

Reaction of the *exo*-N-phenylhydrazide (**9**; X = O) with phenylisothiocyanate (1 mol. equiv.) in boiling benzene (5 h) gave the *phenylthiocarbamoyl hydrazide* (60%), mp 173–175°. (Found: C, 57.5; H, 5.9; N, 13.7. $C_{20}H_{25}N_4O_2PS$ requires C, 57.7; H, 6.0; N, 13.5%.) ν_{max} 3320, 3225, 3120 (NH), 1608, 1545, 1505 (arom C=C), 1215 (P=O), 1030 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) showed two spots R_F 0.82, 0.72.

Similar reaction with phenylisocyanate afforded the corresponding *phenylcarbamoyl hydrazide* (petroleum ether) (87%), mp 146–149°. (Found: C, 59.7; H, 6.4; N, 13.8. $C_{20}H_{25}N_4O_3P$ requires C, 60.0; H, 6.25; N, 14.0%.) ν_{max} 3260–3200 (NH), 1680 (CO), 1600, 1545, 1505 (arom C=C), 1230 (P=O), 1010 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) showed one spot R_F 0.81.

Reaction with methylisocyanate gave the *methylcarbamoyl hydrazide* (74%), mp 207–209°. (Found: C, 53.0; H, 6.6; N, 16.9. $C_{15}H_{23}N_4O_3P$ requires C, 53.25; H, 6.8; N, 16.6%.) ν_{max} 3300, 3240–3200 br (NH), 1665 (CO), 1605, 1560, 1505 (arom C=C), 1230 (P=O), 1010 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25), showed 2 spots, R_F 0.66, 0.75.

exo-Bicyclo[2,2,1]heptyl Dihydrogen Phosphate (**3**; X = O)

The *exo*-phosphorodichloridate (1 g), by treatment with H_2O (25 ml) overnight, afforded the dihydrogen phosphate as an oil (0.7 g). ν_{max} 3420–3340 (OH), 1610–1595 (P–OH), 1095 (P=O), 1030, 1010 (P–O–C) cm^{-1}. Reaction with aniline gave the *dianilinium phosphate* mp 146–150°. (Found: C, 60.2; H, 7.3; N, 7.85. $C_{19}H_{27}N_2O_4P$ requires C, 60.3; H, 7.15; N, 7.4%.) ν_{max} 2680–2560, 2190–2110 (H_3N^+Ph), 1610, 1570, 1500 (arom C=C), 1195 (P=O), 1055, 1040, 1020, 1010 (P–O–C) cm^{-1}. Tlc (EtOH) showed one spot, R_F 0.76.

P^1:P^2-Dianilino-P^1:P^2-Di(exo-Bicyclo[2,2,1]heptyl) pyrophosphate

The *exo*- *N*-Phenylphosphoramidic chloride (**8**; X = O) (2.85 g; 2 mol. equivs.) was reacted with water (150 mg; 1 mol. equiv.) in pyridine (10 ml) overnight to give the *pyrophosphate* (35%), mp 172–173°. (Found: C, 60.4; H, 10.7; N, 5.4. $C_{26}H_{34}N_2O_5P_2$ requires C, 60.5; H, 10.9; N, 5.4%.) ν_{max} 3150 (NH), 1610, 1505 (arom C=C), 1255, 1240 d (P=O), 1045, 1025 (P–O–C), 945 (P–O–P) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O) 5:1:2.5:1.25) showed one spot, R_F 0.84.

The pyrophosphate was unaffected after boiling with water for 4 h. In contrast, treatment with boiling 4N aq. NaOH for 1 h gave *exo-bicyclo[2,2,1]heptyl N-phenylphosphoramidic acid* (Me_2CO, 70%), mp 154–158°. (Found: C, 58.2; H, 6.9; N, 5.3. $C_{13}H_{18}NO_3P$ requires C, 58.4; H, 6.75; N, 5.2%.) ν_{max} 3260 (NH), 2680–2640, 2300–2260 (P–OH), 1605, 1500 (arom C=C), 1190 (P=O), 1015 (P–O–C) cm^{-1}.

Reaction of the Pyrophosphate with Cyclohexylamine

The pyrophosphate (0.258 g) was boiled with cyclohexylamine (0.198 g; 4 mol. equivs.) in benzene-petroleum ether (60–80°) (1:1; 30 ml) for 6 h. Cooling (0°) gave *cyclohexylammonium exo-bicyclo[2,2,1]heptyl N-phenylphosphoramidic phosphate* (0.20 g), mp 188–190° (after recrystallization from ethanol). (Found: C, 62.6; H, 8.5; N, 7.8. $C_{19}H_{31}N_2O_3P$ requires C, 62.3; H, 8.5; N, 7.65%.) ν_{max} 3270 (NH), 2670–2620, 2190, 2140 (N^+H_3), 1605, 1505, 1495 (arom C=C), 1190, 1180 (P=O), 1060, 1015 (P–O–C) cm^{-1}.

exo-Bicyclo[2,2,1]heptyl O-Phenylphosphorochloridate (**12**; Y = Cl)

Reaction of *exo*-bicyclo[2,2,1]heptanol (1, OH *exo*) (5.6 g; 1 mol. equiv.) with phenylphosphorodichloridate (11.05 g; 1 mol. equiv.) and triethylamine (5.05 g; 1 mol. equiv.) in ether (50 ml) for 3 h at 0° and 12 h at 15° gave the *exo-phenylphosphorochloridate* (**12**; X = Cl) as a yellow oil (9.1 g, 61%). ν_{max} 1600, 1495 (arom C=C), 1295 (P=O), 1025, 1000 (P–O–C) cm^{-1}. Tlc (EtOAc–petroleum ether 60–80° 1:1) showed one spot, R_F 0.66. This was characterized by preparation of the *N-phenylhydrazide derivative* (**12**; Y = NH–NHPh (EtOH) (60%), mp 170–172°. (Found: C, 63.8; H, 6.5; N, 7.9. $C_{19}H_{23}N_2O_3P$ requires C, 63.7; H, 6.4; N, 7.8%.) ν_{max} 3300, 3195 (NH), 1600, 1585 d, 1495, 1485 d (arom C=C), 1215, 1200 (P=O), 1030 (P–O–C) cm^{-1}. Nmr $\delta(CDCl_3$–$(CD_3)_2SO)$ δ 7.22 s (5H, OC_6H_5), 7.10–6.70 m (5H, NC_6H_5), 5.45–5.24 br (2H, 2NH), 4.74–4.65 m (1H, *endo*-Ha), 2.48–0.75 m (10 alicyclic H). Tlc (EtOAc–petroleum ether 60–80° 1:1) showed one spot, R_F 0.62.

exo-Bicyclo[2,2,1]heptyl O-Phenylphosphorohydrazide (**12**; Y = $NH.NH_2$)

Condensation of *exo*-bicyclo[2,2,1]heptyl *O*-phenylphosphorochloridate (2.86 g) with hydrazine hydrate (1.05 g; 2 mol, equivs.) in acetonitrile (40 ml) for 4 h gave the *O-phenylhydrazide* as a liquid (2.2 g). ν_{max} 3350, 3240 (NH), 1590, 1490 (arom C=C), 1230, 1210 (P=O), 1030 (P–O–C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) gave one spot, R_F 0.84. The hydrazide (**12**; Y = $NHNH_2$) was characterized by preparation of the following hydrazones:

p-Nitroacetophenone (EtOH) (80%), mp 155–156°. (Found: C, 58.8; H, 5.4; N, 9.7. $C_{21}H_{24}N_3O_5P$ requires C, 58.7; H, 5.6; N, 9.8%.) ν_{max} 3130 (NH) 1595, 1585, 1495 (arom C=C), 1520 (NO_2), 1260 (P=O), 1030, 1015 (P–O–C) cm^{-1}.

Pyridine-2-aldehyde (EtOH) (75%), mp 163–165°. (Found: C, 61.2; H, 6.0; N, 11.1. $C_{19}H_{22}N_3O_3P$ requires C, 61.5; H, 5.9; N, 11.3%.) ν_{max} 3130 (NH), 1580, 1485 (arom C=C), 1235 (P=O), 1015 (P–O–C) cm^{-1}.

P^1:P^2-Diphenyl-P^1:P^2-Di(exo-Bicyclo[2,2,1]heptyl] pyrophosphate

exo-Bicyclo[2,2,1]heptyl *O*-phenylphosphorochloridate (2.96 g; 2 mol. equivs.) by reaction with water (100 mg; 1 mol. equiv.) in pyridine (10 ml) overnight, afforded the *pyrophosphate* (1.1 g), mp 42–45°. (Found: C, 64.2; H, 6.7; P, 6.3. $C_{26}H_{32}O_7P$ requires C, 64.1; H, 6.6; P, 6.4%.) ν_{max} 1600, 1595 d, 1495 (arom C=C), 1260 (P=O), 1020 (P–O–C), 925 (P–O–P) cm^{-1}.

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MS did not show the molecular ion (M^+, 518); major fragment ions were at 269 ($C_7H_{11}OP(OH)_2OPh$), 268, 176 (268—OPh), 175, 174, 95, 94, 93, 91, 80, 79.

exo-Bicyclo[2,2,1]heptylphosphorodichloridothioate (**2**; X = S)

exo-Bicyclo[2,2,1]heptanol (*exo*-norborneol) (1, OH *exo*) (6.45 g) was reacted with thiophosphoryl chloride (9.76 g; 1 mol. equiv.) and pyridine (4.55 g; 1 mol. equiv.) in toluene (125 ml) for 2 h at room temperature and 1½ h at the boiling point. The crude *exo-dichloridothioate* was a yellow oil (7.25 g; 51%) ν_{max} 990–970 (P—O—C), 820 (P=S) cm^{-1}.

The *exo*-dichloridothioate was characterized as the following derivatives:

Diphenylhydrazide (**4**; X = S) (EtOH) (80%), mp 137–139°. (Found: C, 58.7; H, 6.4; N, 14.3. $C_{19}H_{25}N_4OPS$ requires C, 58.8; H, 6.4; N, 14.4%.) ν_{max} 3310, 3280 (NH), 1610, 1500 (arom C=C), 1005 (P—O—C), 850 (P=S) cm^{-1}.

Di-isopropyl diamidate (**5**; X = S, R′ = Me_2CH) (CH_3CN–petroleum ether, 69%) mp 127–129°. (Found: C, 53.8; H, 9.4; N, 9.7. $C_{13}H_{27}N_2OPS$ requires C, 53.8; H, 9.3; N, 9.7%.) ν_{max} 3260–3210 br (NH), 1185 (P=O?), 1015 (P—O—C), 820 (P=S) cm^{-1}. MS showed the molecular ion (M^+, 290), and other major fragment ions at 233 ($M-NHCHMe_2$), 196, 182, 168, 153, 138, 94, 92, 80.

bis (*exo-Bicyclo[2,2,1]heptyl*) *Phosphorochloridate* (**13**; Y = Cl)

Reaction of *exo*-bicyclo[2,2,1]heptanol (*exo*-norborneol) (**1**; OH *exo*) (5.6 g; 2 mol. equivs.) with phosphorus oxychloride (3.83 g; 1 mol. equiv.) and triethylamine (5.05 g; 2 mol. equivs.) in toluene (100 ml) for 24 h at room temperature. After removal of the triethylamine hydrochloride, the filtrate gave the *phosphorochloridate* (**13**; Y = Cl) as a brown oil (5.8 g; 76%). ν_{max} 1285 (P=O), 1030–1005 br (P—O—C) cm^{-1}.

The phosphorochloridate was characterized by formation of the following solid derivatives:

N-Phenylhydrazide (**13**; Y = NH.NHPh) (EtOH) (40%), mp 188–190°. (Found: C, 63.6; H, 7.6; N, 7.6. $C_{20}H_{29}N_2O_3P$ requires C, 63.8; H, 7.7; N, 7.45%.) ν_{max} 3295, 3190 (NH), 1605, 1500 (arom C=C), 1215, 1205 (P=O), 1025, 1000 (P—O—C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) gave one spot, R_F 0.82.

Cyclohexylamidate (**13**; Y = NHC_6H_{11}) (pentane, 70%), mp 215–217°. (Found: C, 65.3; H, 9.1; N, 3.9. $C_{20}H_{34}NO_3P$ requires C, 65.4; H, 9.25; N, 3.8%.) ν_{max} 3165 (NH), 1245, 1230 (P=O), 1125, 1115 (P—N?), 1030, 1000 (P—O—C) cm^{-1}. Tlc (Pr^iOH–toluene–EtOAc–H_2O 5:1:2.5:1.25) gave one spot, R_F 0.83.

Phosphate (**13**; Y = OH)

The phosphorochloridate (**13**; Y = Cl) (1 g) on treatment with H_2O (30 ml) for 15 h gave the phosphate (**13**; Y = OH) as an oil (0.5 g). ν_{max} 2370–2280, 1640–1600 (P—OH), 1240 (P=O), 1040, 1015 (P—O—C) cm^{-1}. Reaction with aniline (0.5 g) in petroleum ether (60–80°) (10 ml) gave the *anilinium phosphate* (0.36 g), mp 147–151°. (Found: C, 63.35; H, 7.7; N, 3.7. $C_{20}H_{30}NO_4P$ requires C, 63.3; H, 7.9; N, 3.7%.) ν_{max} 2640–2540, 2180–2120 (N^+H_3), 1610, 1570, 1500 (arom C=C), 1195 (P=O), 1040, 1020, 1005 (P—O—C) cm^{-1}. Tlc (Pr^iOH–toluene–H_2O 5:1:2.5:1.25) gave one spot, R_F 0.77.

exo-Norbornyl Phosphorodichloridate (**2**; X = O)

A solution of *exo*-norborneol (3.7 g) (1; OH *exo*) and triethylamine (3.3 g; 1 mol. equiv.) in ether (50 ml) was added dropwise to a stirred solution of phosphorus oxychloride (5.12 g; 1 mol. equiv.) at −10°. After 70 min at room temperature, the reaction was complete (OH band disappeared from ir spectrum). Triethylamine hydrochloride was filtered off and the filtrate evaporated *in vacuo* to give a fuming oil (4.8 g, 63%) which darkened on standing. ν_{max} 1290 (P=O), 990 (P—O—C) cm^{-1}.

endo-Norbornyl Phosphorodichloridate (**2**; X = O)

endo-Norborneol (**1**) was similarly treated with phosphorus oxychloride in the same molar ratio and solvent at 0°. The reaction was complete after 2 h at room temperature and gave the phosphorodichloridate (5.3 g, 69%) as a clear oil which did not fume.

Hydrolysis of exo- and endo-Norbornyl Phosphorodichloridates

Both phosphorodichloridates (2 g) were treated with water (20 ml) at room temperature for 3 h. The reaction mixture was extracted with diethyl ether (100 ml), washed with H_2O (3 × 10 ml), dried ($MgSO_4$), and evaporated under reduced pressure to give: (a) *endo*-norbornyl dihydrogen phosphate as an oil (1.2 g). ν_{max} 3400–3300 (OH), 1730–1710 (P—OH), 1090 (P=O), 1030–1010 (P—O—C) cm^{-1}. Tlc (EtOAc–petroleum ether 60–80° 1:1) showed one spot, R_F 0.74 (b) *exo*-norbornyl dihydrogen phosphate as an oil (0.95 g). ν_{max} 3380–3290 (OH), 1720–1690 (P—OH), 1090 (P=O), 1030, 1000 (P—O—C). Tlc (EtOAc–petroleum ether 60–80° 1:1) gave two spots, R_F 0.80, 0.53. The latter is due to the unreacted alcohol.

The products of hydrolysis were reacted with aniline (2 mol. equivs.) in ether (20 ml) for 15 mins and the precipitates were filtered off to give the dianilinium salts: *exo-Norbornyl dianilinium phosphate* (0.18 g, 15%), mp 140–144°. (Found: C, 60.2; H, 7.2; N, 7.5. $C_{19}H_{27}N_2O_4P$ requires C, 60.3; H, 7.1; N, 7.4%.) ν_{max} 2580–2540, 2160–2130, 1570 (PhN^+H_3), 1610, 1500 (arom C=C), 1190 (P=O), 1050, 1000 (P—O—C) cm^{-1}.

endo-Norbornyl dianilinium phosphate (0.76 g, 78%), mp 146–149°. (Found: C, 60.1; H, 7.3; N, 7.5. $C_{19}H_{27}N_2O_4P$ requires C, 60.3; H, 7.1; N, 7.4%.) ν_{max} 2600–2560, 2160–2130, 1570 (PhN^+H_3), 1610, 1500 (arom C=C), 1190 (P=O), 1030, 1010 (P—O—C) cm^{-1}.

REFERENCES

1. R. J. W. Cremlyn, B. B. Dewhurst and D. H. Wakeford, *Synthesis* 648 (1971).
2. R. J. W. Cremlyn, B. B. Dewhurst, D. H. Wakeford and R. A. Raja, *J. Chem. Soc., Perkin 1*, 1171 (1972).
3. R. J. W. Cremlyn, R. M. Ellam and N. Akhtar, *Phosphorus and Sulphur* (in press).
4. C. H. DePuy and P. R. Strong, *J. Amer. Chem. Soc.* **82**, 627 (1960).
5. H. C. Brown, *The Non-Classical Ion Problem* (Plenum Press, New York, 1977) (a) p. 125 (b) p. 83.

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6. S. Winstein and D. S. Trifan, *J. Amer. Chem. Soc.* **74**, 1147 (1952).
7. J. Berson, "Carbonium ion rearrangements in bridged bicyclic systems" in *Molecular Rearrangements*, Edited by P. de Mayo, Part 1 (Interscience, New York, 1963), p. 128.
8. R. J. W. Cremlyn and N. A. Olsson, *J. Chem. Soc.* (*C*) 2023 (1971)
9. R, J. W. Cremlyn, B. B. Dewhurst and I. Khattak. *Phosphorus* **6**, 201 (1976).
10. R. J. W. Cremlyn, B. B. Dewhurst and D. H. Wakeford, *J. Chem. Soc.* (*C*) 301 (1971).
11. L. C. Thomas, *Interpretation of Infra Red Spectra of Phosphorus Compounds* (Heydon, London, 1974).
12. L. J. Bellamy, *The Infra Red Spectra of Complex Molecules* (Methuen, London, 1964), 2nd ed., p. 321.

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