The synthesis, X-ray and solid state NMR studies of 2-*N*,*N*-diisopropylamino-1,3,2λ^5-oxaselenaphospholane-2-selone

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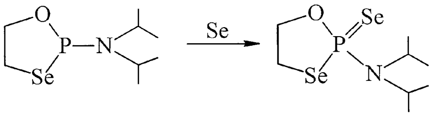
^{31}P and ^{77}Se high resolution solid state NMR spectroscopy was employed to study structural properties of 2-*N*,*N*-diisopropylamino-1,3,2λ^5-oxaselenaphospholane-2-selone 5 the compound made in the course of developing reagents for stereocontrolled synthesis of nucleoside–phosphorothioates. Both ^{31}P CP/MAS and ^{77}Se CP/MAS experiments revealed that the asymmetric unit consists of two independent molecules with different geometry around phosphorus and selenium centres. The principal elements δ_{ii} of the ^{31}P chemical shift tensor were calculated from spinning sideband intensities employing the WIN-MAS program. The established values of anisotropy and asymmetry parameters reflect the distortion of the phosphorus environment and correspond well with X-ray diffraction data. Crystals of 2-*N*,*N*-diisopropylamino-1,3,2λ^5-oxaselenaphospholane-2-selone grown from diethyl ether are triclinic, space group $P1$ with $a = 7.586(2)$, $b = 13.003(1)$, $c = 13.649(1)$ Å, $\alpha = 89.683(8)°$, $\beta = 75.42(1)°$, $\gamma = 8.74(1)°$, $V = 1285(6)$ Å^3, $D_c = 1.722(2)$ g cm^{-3} and $Z = 4$. Refinement using 5243 reflections for 235 variables gives $R = 0.047$.

Introduction

The polymer supported solid-phase synthesis of natural products and their analogues, initiated in the 1960s by Merrifield and Letsinger *et al.*, has developed rapidly during the last three decades.[1–3] Within the field of oligonucleotides and their analogues different classes of substrates were employed including phosphate triesters, H-phosphonates and phosphoramidites.[4–6] However, it should be stressed that reactions which can potentially be used in machine-based automated syntheses have to fulfill at least two conditions: (1) the yield per nucleotide addition has to be higher than 98% per cycle, (2) the reaction time for step-coupling should be no longer than 10 minutes. As reviewed by Caruthers, phosphoramidites fulfill these prerequisites and are now used with great success in automated DNA synthesis.[6]

In recent years, much attention has been paid to oligo(nucleoside phosphorothioate)s (PS-Oligos) owing to their prospective medical applications and usefulness as models in the study of the nature of internucleotide linkage.[7–9] PS-Oligos synthesized by commercially developed methodologies consist of the mixture of 2^n diastereomers where n is the number of phosphorothioate linkages. Stec and co-workers developed the oxathiaphospholane method and demonstrated its applicability for stereocontrolled synthesis of PS-Oligos.[10] Although the stereochemistry of 1,8-diazobicyclo[5.4.0]undec-7-ene (DBU) assisted 1,3,2-oxathiaphospholane ring opening condensation has been elucidated, mechanistic details of the process, and especially the function of DBU, are still not well understood. Since knowledge about the mechanism of the chemical processes occurring in the solid phase is crucial for better understanding and improving the synthesis method, the techniques which allow investigation of substrates, intermediates and products are strongly desired. Most of the above-mentioned substrates used in automated solid-phase syntheses of oligonucleotides are amorphous powders or glasses. Therefore, solid state NMR spectroscopy which allows study of all kinds of solids can be considered as a technique of choice.[11]

This work presents the results of preliminary high-resolution solid state NMR and X-ray diffraction (XRD) structural studies on 2-*N*,*N*-diisopropylamino-1,3,2λ^5-oxaselenaphospholane-2-selone **5**. The unique atomic composition of the analysed oxaselenaphospholane enabled us to use the ^{31}P and ^{77}Se magic angle spinning with cross polarization (CP/MAS) technique for expanding structural data obtained in parallel with that obtained from X-ray crystallography. The results are discussed in terms of crystal and molecular structure established from XRD and the relationship between ^{31}P and ^{77}Se spectral parameters and phosphorus and selenium local geometry is described.



3 **5**

Scheme 1

Results and discussion

Chemical synthesis

In the course of our studies on the stereocontrolled synthesis of oligo(nucleoside phosphorothioate)s **1** 5′-*O*-DMT-thymidine 3′-*O*-(2-thiono-1,3,2λ^5-oxaselenaphospholanes) **2** have been obtained for the first time as potential substrates for the synthesis of **1**.[12] Compound **2** was prepared in tetrazole-assisted reaction of 5′-*O*-DMT-thymidine with *N*,*N*-diisopropylamino-1,3,2λ^5-oxaselenaphospholane **3** followed by sulfurization with elemental sulfur. Careful inspection of several batches of **2** revealed, however, their consistent contamination with 3–5% of unknown material which was then identified by mass spectrometry and independent chemical synthesis as a diastereomeric mixture of 5′-*O*-DMT-thymidine 3′-*O*-(2-seleno-1,3,2λ^5-oxaselenaphospholane) **4**.[12] The mechanism of formation of **4** is obscure. During the course of its evaluation[13] *N*,*N*-diisopropylamino-1,3,2-oxaselenaphospholane **3** has been obtained. Surprisingly, when **3** is exposed to α-methylbenzyl-

Table 1 ^{31}P Chemical shift parameters (in ppm) for two molecules of **5**^{a}

Compound **5**	δ_{iso}	δ_{11}	δ_{22}	δ_{33}	$\lvert\Delta\delta\rvert$	Ω	η	κ
Molecule A	63.6	163	40	−12	149	175	0.52	−0.40
Molecule B	57.4	170	23	−20	168	190	0.38	−0.53

[a] Spectrum was calculated employing the commercially available WIN-MAS program, version 940108, Bruker–Franzen Analytik GMBH, Bremen 1994. Estimated errors in δ_{11}, δ_{22}, δ_{33} and $\Delta\delta$ are −/+5 ppm; errors in δ_{iso} are −/+ 0.2 ppm. The principal components of the chemical shift tensor are defined as follows: $\delta_{11} > \delta_{22} > \delta_{33}$. The isotropic chemical shift is given by $\delta_{iso} = (\delta_{11} + \delta_{22} + \delta_{33})/3$.

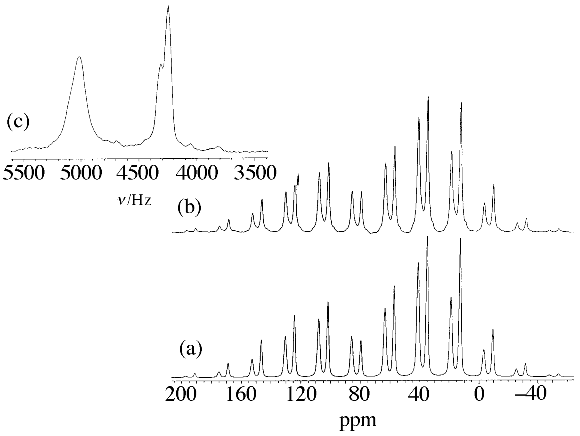


Fig. 1 (*a*) 121.49 MHz ^{1}H–^{31}P CP/MAS experimental spectrum of **5**. The spectrum has 8K data points with 10 Hz line broadening, a contact time of 1 ms and 100 scans and $\nu_{rot} = 2114$ Hz. (*b*) Theoretical spectrum calculated employing the WIN-MAS program, version 940108, Bruker–Franzen Analytik GMBH, Bremen 1994. (*c*) Expanded central part of spectrum (*a*).

amine in the absence of tetrazole, subsequent sulfurization leads to a mixture of *N*,*N*-diisopropylamino-1,3,2λ^{5}-oxaselenaphospholane-2-thione **6** (71%) and 2-*N*,*N*-diisopropylamino-1,3,2λ^{5}-oxaselenaphospholane-2-selone **5** (29%). Attempts to separate **5** from **6** by chromatographic methods using different elution systems have failed. Pure **5** was obtained independently when **3** was treated with elemental selenium (Scheme 1). Crystallization of **5** from diethyl ether gave crystals, mp 97–98 °C. Since to date the molecular and crystal structures of 1,3,2-oxaselenaphospholanes have not been reported in the chemical literature and the geometry and conformation of similar compounds were described only recently,[14] we decided to investigate the structural chemistry of this class of heterocycles. Structure of **5** was elucidated by means of ^{1}H NMR and mass spectrometry.

^{31}P CP/MAS and ^{77}Se CP/MAS solid state NMR studies

Fig. 1(*a*) displays the ^{31}P CP/MAS spectrum compound **5** recorded at room temperature. The spectrum shows a number of spinning sidebands (SSB) due to large chemical shielding anisotropy (CSA). The dipolar coupling from the protons was eliminated by proton decoupling during data acquisition. The principal components of the ^{31}P chemical shift tensors δ_{ii} were calculated from spinning sideband intensities employing the WIN-MAS program that is based on the Berger–Herzfeld algorithm.[15,16] The problems associated with analysing slow spinning MAS NMR spectra were discussed by Clayden *et al.*[17] as well as Wasylishen and co-workers.[18,19] As shown, the Berger–Herzfeld procedure, when the span, $\Omega = \delta_{11} - \delta_{33}$, is small and the chemical shift tensor has near axial symmetry, is least reliable. Moreover, the influence of ^{31}P–^{14}N dipole spin–spin interactions on the ^{31}P MAS NMR spectra established *via* second moment analysis is given elsewhere.[18] With these precautions, the calculated values of principal tensor elements δ_{ii} and shielding parameters are collected in Table 1.

From analysis of the spectrum shown in Fig. 1 the presence of two spinning sideband systems is apparent. Thus we can conclude that the unit cell contains at least two independent molecules in the asymmetric unit. Moreover, the analysis of ^{31}P chemical shift parameters indicates that the molecular structures around phosphorus centres for both molecules in the unit cell are slightly different. The absolute values of the anisotropy parameters $\lvert\Delta\delta\rvert$ differ by *ca.* 19 ppm whereas the asymmetry η values are different by *ca.* 0.14. The values of $\Delta\delta$ and Ω (at 150–170 ppm and 170–190 ppm, respectively) are characteristic of distorted tetrahedral phosphorus compounds. The high field set of sidebands shows that the local environment of the phosphorus is more distorted relative to the second molecule. The η and κ parameters (see Experimental section for explanation) indicate that the phosphorus shielding depends not only on the local bonding but also on the tetrahedral structure as a whole.

Further results were obtained from analysis of the expanded central part of the ^{31}P CP/MAS spectrum. As reported by several authors the MAS line shape for the isotropic signal of a spin $I = 1/2$ nucleus bonded to an $I = 1$ nucleus with a large electric field gradient (efg) is usually observed as an asymmetric doublet.[20–23] The residual splitting S depends on the quadrupole coupling constant of the quadrupolar nuclei Q_{cc}, the asymmetry parameter η of the quadrupolar tensor, the dipolar coupling constant D, the Zeeman frequency of the nitrogen nucleus in the applied magnetic field and the Euler angles β and α which define the orientation of the internuclear vector in the principal axis system (PAS) of the electric field gradient. This approach was found to reproduce experimental residual splitting S with remarkable accuracy for several ^{13}C–^{14}N systems.[24] On the other hand, Curtis *et al.* showed that for ^{31}P–^{14}N systems the quadrupolar nucleus can cause only broadening of the ^{31}P resonances.[25]

Inspection of the isotropic part of the ^{31}P CP/MAS spectrum displayed in Fig. 1(*c*) shows that the higher frequency resonance occurs as a broadened peak whereas the lower frequency resonance forms an asymmetric doublet. We speculate that the different line shapes of the resonances are related to differences in the β and α orientation of the P–N internuclear vector in the PAS of the electric field gradient for A and B molecules of oxaselenaphospholane in the asymmetric part of the unit cell (the description of β and α is shown in pictorial form in Chart 1). This explanation is supported when we further determined the differences in Se–(=)P–N–C and/or O–P–N–C torsional angles in both moieties.

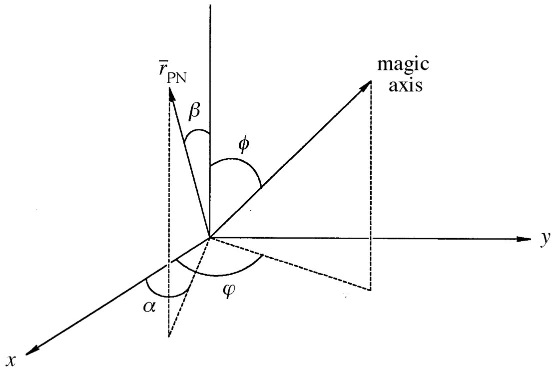


Chart 1

^{77}Se NMR experiments can be another source of information about molecular structure of the oxaselenophospholanes. Fig. 2 displays the spectrum of the compound under investigation recorded in liquid form at room temperature. The ^{77}Se resonances are clearly resolved and can be unambiguously assigned. The upfield doublet with $^{1}J(^{31}P - {}^{77}Se)$ 885 corresponds to a P=Se bond and the downfield doublet [$^{1}J(^{31}P - {}^{77}Se)$ 381] cor-

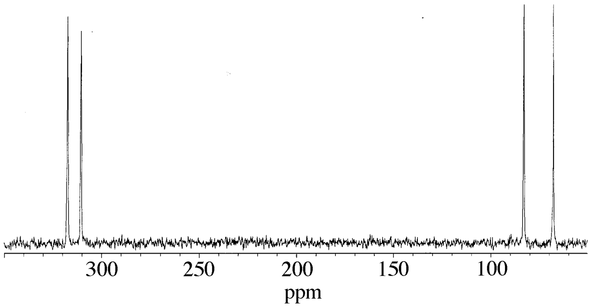


Fig. 2 57.26 MHz ^{77}Se NMR spectrum of **5** recorded in liquid phase at ambient temperature

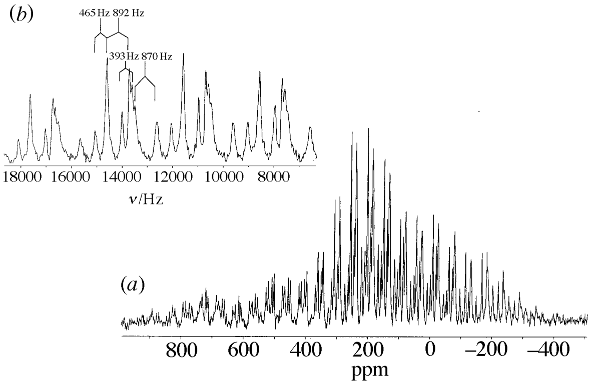


Fig. 3 (*a*) 57.26 MHz ^{1}H–^{77}Se CP/MAS experimental spectrum of **5**. The spectrum has 8K data points with 10 Hz line broadening, a contact time of 5 ms and 12000 scans and $\nu_{rot} = 3500$ Hz. (*b*) Expanded central part of spectrum (*a*).

responds to a Se–P bond; the chemical shifts differ by *ca.* 245 ppm.

The ^{77}Se CP/MAS spectrum was found to be much more complex [Fig. 3(*a*)]. Since the unit cell contains two independent molecules in the asymmetric unit, the presence of eight resonances in the isotropic part was predicted. Moreover, as shown by Collins *et al.*[26] as well as Potrzebowski and co-workers[27,28] the ^{77}Se anisotropic shielding is extremely sensitive to even small departures from spherical symmetry. For lower symmetry environments the large anisotropy leads to a large number of spinning sidebands. In the case of phosphorus–selenium systems, for isolated $I = 1/2$ spin pairs ^{31}P–^{77}Se, spin–spin and dipolar interaction as well as *J*-coupling anisotropy have to be taken into consideration.

The dipolar interaction constant $D_{\mathrm{P–Se}}$ expressed by the equation $D_{\mathrm{P–Se}} = [(\gamma_{\mathrm{P}}\gamma_{\mathrm{Se}}h)/2\pi]\langle r_{\mathrm{P–Se}}^{-3}\rangle(\mu_0/4\pi)$ is dependent only on the inverse cube of the separation of the two nuclei P and Se. For static spectra the dipolar coupling constant is diminished by one third of the anisotropy of the *J* coupling ($D_{\mathrm{eff}} = D_{\mathrm{P–Se}} - \Delta J/3$). Cogne *et al.* reported the anisotropy of P–Se *J*-coupling at *ca.* −600.[29] For this case the line shape and spinning sidebands pattern are affected by chemical shielding and dipolar interaction. Because of the complexity and overlapping effect, in the case of oxaselenaphospholane the effective dipolar/chemical shift tensor parameters T_{ii} cannot be unambiguously assigned. It can only be concluded that ^{77}Se anisotropy of the intracyclic P–Se unit is *ca.* twice as high as the ^{77}Se of P=Se fragment. These differences are due to different local selenium atoms. The five-membered ring causes significant distortion of tetrahedral geometry.

The values of δ_{iso} and of the isotropic coupling constant $^1J(^{31}\mathrm{P}-^{77}\mathrm{Se})$ can be obtained directly. The phosphorus–selenium coupling constants taken from analysis of the expanded isotropic part of ^{77}Se CP/MAS spectrum [Fig. 3(*b*)] indicate that the values established in the solid phase are different from those monitored in liquid and were found to be 465 and 393 for the P–Se bond; 892 and 870 for the P=Se bonds.

Table 2 Crystal data and experimental details for **5**

Molecular formula	$C_8H_{18}NOPSe_2$
Crystallization solvent	Diethyl ether
Crystallographic system	Triclinic
Space group	$P\bar{1}$
a/Å	7.586(2)
b/Å	13.003(1)
c/Å	13.649(1)
α/°	89.683(8)
β/°	75.42(1)
γ/°	80.74(1)
V/A^3	1285.2(4)
Z	4
D_c/g cm^{-3}	1.722(2)
μ/cm^{-1}	83.6
F(000)	656
Crystal dimensions/nm	0.3, 0.4, 0.7
Maximum 2θ/°	150
Radiation, λ/Å	Cu-Kα, 1.541 78
Scan mode	$\omega/2\theta$
Scan width/°	$0.74 + 0.14 \tan\theta$
hkl ranges	*h*: 0 to 9
	k: −16 to 16
	l: −17 to 17
DECAY correction: min	1.000 05
max	1.063 37
avg.	1.029 96
Adsorption correction (EAC):	
min	0.7834
max	0.9985
avg.	0.9192
Transmission (%): min	61.38
max	99.71
avg.	84.49
No. of reflections: unique:	5243
with $I \geqslant 3\sigma(I)$:	5129
No. of parameters refined	235
Weighting scheme	Unit weight
Largest difference peak e A^{-3}	1.079
Largest difference hole e A^{-3}	−0.985
R	0.047

These discrepancies suggest that both P–Se and P=Se bond lengths for A and B molecules in the asymmetric unit are different. Moreover, it is interesting that the intensity of one of the spinning sideband systems which corresponds to selenium of the P=Se fragment is significantly higher than the others. We speculate that the differences in the signal intensities are due to cross-polarization effects. Efficient cross-polarization requires the ^{1}H and ^{77}Se nuclei close. Even small geometrical changes can cause considerable changes in the signal intensities. For **5** the closest proton–selenium distance is between the diisopropylamino group and the P=Se unit. Thus, we conclude that Se=P–N–C torsional angles for A and B molecules are different. This conclusion is consistent with the previous explanation of the different line shapes of the ^{31}P resonances. As can be seen multinuclear solid state NMR studies show several geometrical differences between oxaselenaphospholane molecules in the unit cell. In order to verify these observations further results were obtained from X-ray studies of single crystals.

X-Ray analysis

Compound **5** crystallizes in the triclinic system, in space group $P\bar{1}$. Crystal data and experimental details are shown in Table 2. The X-ray analysis showed that an asymmetric part of the unit cell contains two independent molecules A and B (Fig. 4).

Selected geometrical parameters of two independent molecules A and B are given in Table 3. Comparison of bond lengths and valence angles in both molecules shows some important differences. The significant difference occurs in the lengths of the P=Se bond and reaches 0.012 Å (6σ). The differences are also seen in endocyclic P–O and O–C bond lengths

Table 3 Bond lengths (Å) and valence angles (°) for **5**. The asymmetric part of the unit cell contains two molecules A and B

	A	B		A	B
P1–Se2	2.089(2)	2.077(2)	Se1–P1–O1	95.6(2)	95.5(2)
P1–Se1	2.257(2)	2.269(2)	P1–Se1–C1	88.8(2)	89.1(2)
Se1–C1	1.938(7)	1.940(7)	P1–O1–C2	116.2(3)	115.9(4)
P1–O1	1.622(4)	1.605(4)	Se1–C1–C2	108.0(4)	107.7(5)
O1–C2	1.421(6)	1.442(8)	O1–C2–C1	110.4(5)	111.3(6)
C1–C2	1.500(10)	1.490(10)	Se1–P1–N1	110.4(2)	111.3(2)
P1–N1	1.626(4)	1.620(4)	O1–P1–N1	104.3(2)	103.2(2)
N1–C3	1.491(7)	1.491(7)	P1–N1–C3	127.4(3)	126.7(3)
N1–C4	1.496(6)	1.494(7)	P1–N1–C4	117.1(3)	117.5(3)
C3–C5	1.514(8)	1.511(8)	C3–N1–C4	114.9(4)	115.4(4)
C3–C6	1.514(9)	1.531(9)	N1–C3–C5	113.4(5)	113.3(5)
C4–C7	1.533(10)	1.522(9)	N1–C3–C6	113.2(5)	112.7(4)
C4–C8	1.517(9)	1.517(7)	C5–C3–C6	113.3(5)	113.2(5)
Se1–P1–Se2	112.7(1)	112.3(1)	N1–C4–C7	110.1(5)	111.8(4)
Se2–P1–O1	114.2(2)	114.2(2)	N1–C4–C8	112.3(5)	110.7(4)
Se2–P1–N1	117.3(2)	117.8(2)	C7–C4–C8	113.4(5)	112.1(5)

Table 4 Conformation of two independent molecules A, B of **5**; torsion angles (°) and asymmetry parameters of oxaselenaphospholane rings

Torsion angles

	A	B		A	B
Se1–C1–C2–O1	45.2(5)	44.1(6)	Se2–P1–N1–C4	176.0(3)	−177.7(3)
P1–O1–C2–C1	−52.3(5)	−52.5(7)	O1–P1–N1–C3	114.3(4)	137.5(4)
Se1–P1–O1–C2	29.8(4)	30.2(4)	O1–P1–N1–C4	−56.6(4)	−50.9(4)
O1–P1–Se1–C1	−2.7(3)	−3.9(3)	P1–N1–C3–C5	71.8(6)	59.4(6)
P1–Se1–C1–C2	−21.6(4)	−20.3(5)	P1–N1–C3–C6	−59.0(6)	−70.7(6)
Se2–P1–Se1–C1	116.5(2)	115.1(2)	C4–N1–C3–C5	−117.2(5)	−112.4(5)
N1–P1–Se1–C1	−110.2(3)	−110.4(3)	C4–N1–C3–C6	112.0(5)	117.5(5)
Se2–P1–O1–C2	−88.2(4)	−87.3(4)	P1–N1–C4–C7	−125.5(4)	−114.0(4)
N1–P1–O1–C2	142.5(4)	143.6(4)	P1–N1–C4–C8	107.1(5)	120.2(4)
Se1–P1–N1–C3	−144.0(4)	−121.1(4)	C3–N1–C4–C7	62.6(6)	58.6(6)
Se1–P1–N1–C4	45.1(4)	50.6(4)	C3–N1–C4–C8	−64.8(6)	−67.2(6)
Se2–P1–N1–C3	−13.2(5)	10.6(5)			

Asymmetry parameters

	A	B		A	B
ΔCs(1)	55.7(2)	54.7(2)	ΔC$_2$(P1–Se1)	77.9(2)	77.1(2)
ΔCs(Se1)	55.7(2)	55.3(2)	ΔC$_2$(Se1–C2)	67.2(2)	67.6(2)
ΔCs(C1)	42.3(2)	43.3(2)	ΔC$_2$(C1–C2)	31.6(2)	33.2(2)
ΔCs(C2)	7.7(2)	9.2(2)	ΔC$_2$(C2–O1)	17.2(2)	15.2(2)
ΔCs(O1)	34.0(2)	32.5(2)	ΔC$_2$(O1–P1)	58.8(2)	57.1(2)

which are equal to 0.017 (5σ) and 0.021 Å (3σ), respectively. The differences in other bond lengths do not exceed three times the corresponding esd values (3σ). The differences in corresponding valence angles in both molecules do not exceed 6σ; the largest difference is observed for the O–P–N angle (Table 3). The differences in geometry of both independent molecules of **5** are consistent with NMR data.

The conformation of both molecules A and B is, only in general, similar, but some important differences are seen (Table 4). The most significant differences occur in torsion angles around the P–N bond. The situation is illustrated in the Newman projections shown in Fig. 5(*a*). The carbon atom C3 in both molecules is synperiplanar with respect to the phosphoryl selenium atom Se2, but in both molecules on opposite sides; the difference in value of the Se2–P1–N1–C3 angles is 23.8°. The Newman projection of the substituents around the N1–C3 bond in molecules A and B [Fig. 5(*b*)] shows a synclinal arrangement of the phosphorus atom with respect to both carbon atoms C5 and C6, and an anticlinal arrangement with respect to the hydrogen atom H31. The Newman projection perpendicular to the N1–C4 bond [Fig. 5(*c*)] shows that two carbon atoms of the isopropyl groups (C7 and C8) in molecules A and B are both anticlinal with respect to the phosphorus atom P1. Respectively, the hydrogen atom H41 in both molecules occupies a synperiplanar position.

The values of torsion angles and asymmetry parameters[30] given in Table 4 show that the oxaselenaphospholane rings A and B have the conformation of a deformed envelope, with the carbon atom C2 being in the flap position. The dihedral angles between the least-squares plane passing through atoms P1,Se1,O1,C1 and the plane C1,C2,O1 are 44.3(4)° and 44.1(6)° for molecules A and B, respectively. In the crystal lattice of **5** there are no intra- nor inter-molecular hydrogen contacts with the hydrogen–bonding acceptor distances shorter than 2.50 Å.

No structures containing an oxaselenaphospholane ring system were found in the Cambridge Structural Database.[31] The P=Se bond lengths in compound **5** correspond well with the literature data; the 'cyclic' P–Se bonds (Table 3) are longer than the P–Se bond (acyclic) found in the literature (average 2.227 Å).[32]

It is interesting to compare the geometry and conformation of the oxaselenaphospholane ring of **5** with that for oxathiaphospholane rings.[14] The envelope conformation of oxaselenaphospholane ring with the carbon atom next to the ring oxygen in the flap position, is also observed for most oxathiaphospholane structures with the envelope ring conformations. The dihedral angle between the basic ring plane (P,Se,O,C) and the plane passing through C1,C2,O1 atoms in oxaselenaphospholane ring (44.2°) is similar to the respective angle in oxathiaphospholane rings having the envelope conformation (avg. 42.7°). The deformation of the endocyclic valence angles in the oxaselenaphospholane ring is similar to that

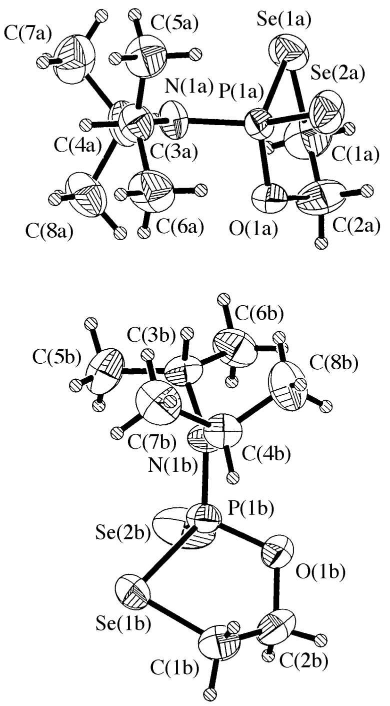


Fig. 4 Thermal ellipsoidal view and atom numbering scheme of two independent molecules A and B in asymmetric part of the unit cell of **5**

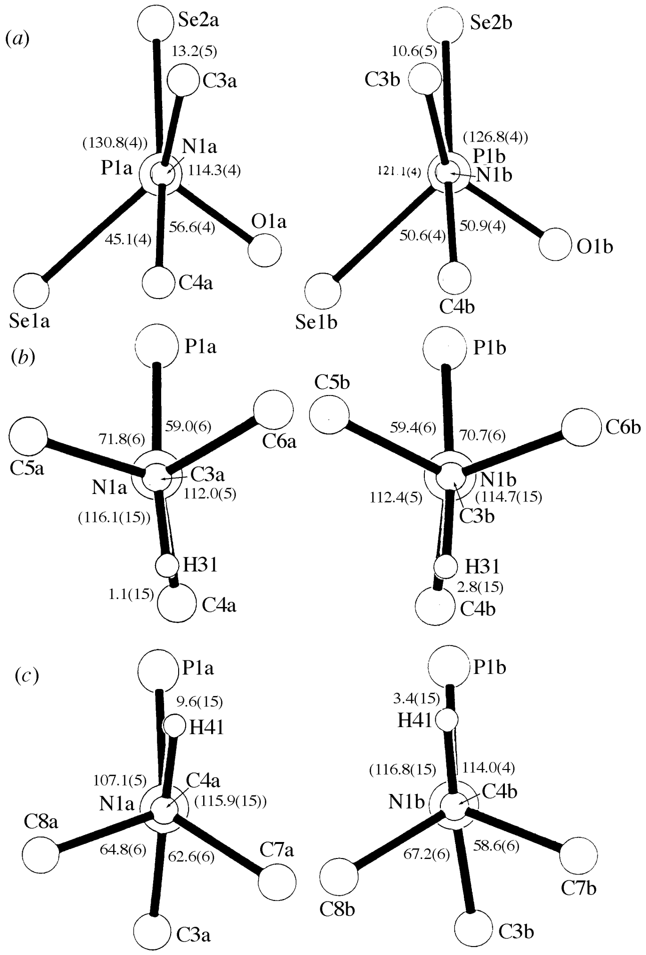


Fig. 5 The Newman projections for molecules A and B of **5**, perpendicular to (*a*) P1–N1, (*b*) N1–C3 and (*c*) N1–C4 bonds

observed for oxathiaphospholane rings. Similarly, as in compounds containing an oxathiaphospholane ring system,[14] the endocyclic valence angle at the selenium atom in the oxaselenaphospholane ring of **5** is smaller than that at phosphorus (Table 3). Moreover, the exocyclic valence angle O–P=Se is more than O–P=S by an average 0.9°, and Se–P=Se angle is smaller than average S–P=S angle by *ca.* 4.1°.

Conclusions

In this work we were attracted by the prospect of comparing ^{31}P and ^{77}Se chemical shift parameters obtained by means of solid state NMR spectroscopy with X-ray diffraction data for **5**. ^{31}P CP/MAS experiments unambiguously revealed the presence of two independent molecules of oxaselenaphospholane in the asymmetric part of the unit cell. Moreover, NMR parameters show great sensitivity even to very subtle changes of geometry around phosphorus centres. Both anisotropy $\Delta\delta$ and asymmetry η as well as line shape analysis reflect the distortion of the phosphorus geometry. The results obtained from ^{31}P solid state NMR are consistent with XRD.

^{77}Se CP/MAS NMR data were found to be more complex and their interpretation is not straightforward. The analysis of the ^{77}Se isotropic values of the chemical shifts show the 245 ppm difference between selenium nuclei for P=Se and P–Se– bonds. The incredible sensitivity of the ^{77}Se chemical shifts to changes in environment is well known and is discussed in detail elsewhere.[33] Our work also shows that changes in indirect spin–spin phosporus–selenium coupling constants correlates very well with P=Se and P–Se bond alternation.[34]

^{31}P CP/MAS NMR and ^{77}Se CP/MAS NMR show excellent sensitivity to changes of molecular structure of **5** in the unit cell. On the other hand, because of low natural abundance of the ^{77}Se isotope (7.56%) and, as a consequence, long accumulation times required to obtain good quality spectra, ^{31}P CP/MAS seems to be a more applicable technique.

Experimental

Synthesis of 2-*N*,*N*-diisopropylamino-1,3,2λ^5-oxaselenaphospholane-2-selone

2-*N*,*N*-diisopropylamino-1,3,2λ^5-oxaselenaphospholane (516 mg, 2 mmol) was dissolved in dry benzene (10 ml) and powdered selenium (236 mg, 3 mmol) was added under argon atmosphere. The mixture was stirred overnight and then the excess selenium was filtered off. The filtrate was concentrated under reduced pressure and the crude product was purified on silica gel, 230–400 mesh (20 g), using benzene–heptane (1:1, v/v) as eluent. Appropriate fractions (TLC control in benzene, $R_f = 0.52$) were collected and evaporated to dryness. The residual solid was crystallized from diethyl ether to give the title compound **5** (520 mg, 78% yield), mp 97–98 °C, *m/z* 334.9462; δ_H(200 MHz, CDCl$_3$) 1.37 (d, *J* 6.9, 12 H); 3.43–3.57 (m, 1 H); 3.64–3.82 (m, 1 H); 3.95 (dq, *J* 21.7, 6.9, 2 H); 4.33–4.60 (m, 2 H); δ_P(CDCl$_3$) 67.4 ($^1J_{P-Se}$ 864, 392); MS(EI), *m/z* 335 ($M^+ - CH_3$, 22, 2Se).

NMR measurements

Cross-polarization magic-angle-spinning solid-state ^{31}P and ^{77}Se NMR spectra were recorded on a Bruker 300 MSL instrument with high-power proton decoupling at 121.496 MHz for ^{31}P and 57.206 MHz for ^{77}Se. A powder sample of oxaselenaphospholane was placed in a cylindrical rotor and spun at 2.0–4.5 kHz. For the ^{31}P experiments, the field strength for ^1H decoupling was 1.05 mT, a contact time of 5 ms, a repetition of 6 s and spectral width of 50 kHz were used and 8K data points represented the FID. Spectra were accumulated 100 times which gave a reasonable signal-to-noise ratio. ^{31}P chemical shifts were calibrated indirectly through bis(dineopentoxythiophosphoryl) disulfide set at 84.0 ppm.

For ^{77}Se CP/MAS experiments the Hartmann–Hahn condition was established using the powdered sample of ammonium selenate. The field strength for ^1H decoupling was 1.05 mT, a contact time of 5 ms, repetition of 10 s and spectral width of 50 kHz were used and 8K data points represented the FID. Spectrum of oxaselenaphospholane was accumulated 12 000 times in order to achieve a reasonable signal-to-noise ratio. The ^{77}Se chemical shifts were calibrated indirectly through ammonium selenate used as a secondary chemical shift reference standard, set at $\delta = 1040.2$.

The principal elements of the ^{31}P chemical shift tensor and shielding parameters were calculated employing the WIN-MAS program. The details describing the method and accuracy of calculations are discussed exhaustively elsewhere.[15,16]

The principal components δ_{ii} were used for calculation of the chemical shift parameters, anisotropy $\Delta\delta$, asymmetry η, span Ω and skew κ.[35]

$$\text{If } |\delta_{11} - \delta_{\text{iso}}| > |\delta_{33} - \delta_{\text{iso}}| \text{ then } \Delta\delta = \delta_{11} - (\delta_{22} + \delta_{33})/2 \tag{1}$$

$$\eta = (\delta_{22} - \delta_{33})/(\delta_{11} - \delta_{\text{iso}}) \tag{2}$$

$$\text{If } |\delta_{11} - \delta_{\text{iso}}| < |\delta_{33} - \delta_{\text{iso}}| \text{ and } \delta_{11} > \delta_{22} > \delta_{33} \text{ then } \Delta\delta = \delta_{33} - (\delta_{11} + \delta_{22})/2 \tag{3}$$

$$\eta = (\delta_{22} - \delta_{11})/(\delta_{33} - \delta_{\text{iso}}) \tag{4}$$

Moreover,

$$\Omega = \delta_{11} - \delta_{33} \tag{5}$$

$$\kappa = 3(\delta_{22} - \delta_{\text{iso}})/\Omega \tag{6}$$

X-Ray crystallography

The crystal and molecular structure of **5** was determined using data collected on a CAD4 diffractometer.[36] Compound **5** crystallized in the triclinic system, space group $P\bar{1}$. Intensity data were collected at room temp. using graphite monochromatized Cu-Kα radiation. Lattice constants were refined by a least-squares fit of 25 reflections in θ range of 19.5–27.8°. The decline in intensities of three standard reflections (2, −4, −2; 3, −3, 6; 2, −4, 4) was 11.6% during 56.6 h of exposure, and all measured intensities were corrected using the DECAY program (Table 2).[37] Empirical absorption correction was applied using ψ scan method.[38,39] A total of 5129 observed reflections with $I \geqslant 3\sigma(I)$ were used to solve the structure by direct methods and to refine it by full-matrix least-squares using F values.[39,40] Hydrogen atoms were placed geometrically at idealized positions and set as riding, with fixed isotropic thermal parameters. Anisotropic thermal parameters were refined for all non-hydrogen atoms. The final refinement converged to $R = 0.047$ with unit weight for 235 refined parameters. The supplementary data for this structure can be obtained, on request, from Cambridge Crystallographic Data Centre (CCDC).†,[31]

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