Reaction of Thiolo and Selenolo Esters of Phosphorus Acids with Halogens. Part 3.† Interaction of *O, O,S*-Trialkyl Phosphorothioates and *O,S*-Dialkyl t-Butylphosphonothioates with Sulphuryl Chloride and Halogens

Bożena Krawiecka * and Elżbieta Wojna-Tadeusiak
Polish Academy of Sciences, Centre of Molecular and Macromolecular Studies, Sienkiewicza 112, 90-363 Łódź, Poland

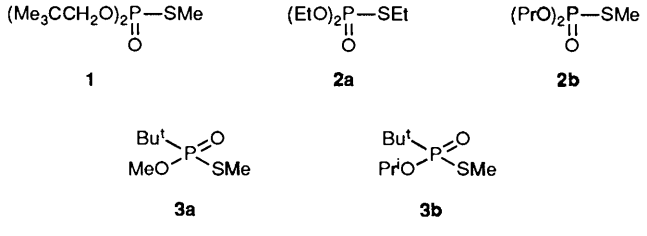
The reaction of the title phosphono- and phosphoro-thiolates with sulphuryl chloride and halogens involves in every case the formation of intermediates containing two phosphorus atoms $>\overset{+}{P}(SR)OP(O)< X^-$ (X = SO_2Cl or halogen). The formation of the latter in the course of chlorinolysis of phosphorus thiolesters is suggested to be responsible for the occurrence of a mechanism involving retention of configuration. The effect of the structure of the reactants and the nature of solvent on the reaction stereochemistry is discussed.

In our previous papers,[1] we have demonstrated that the reaction of t-butyl(phenyl)- and di-t-butyl-phosphinothiolates with sulphuryl chloride and halogens involves the formation of halogenosulphonium salts, $>P(O)\overset{+}{S}(X)R\ Y^-$, and phosphoryl-oxyphosphonium salts, $>\overset{+}{P}(Z)OP(O)< Y^-$ (where X = Cl, Br, I; Y = X or X_3, SO_2Cl; Z = SR or Cl) as intermediates. The stereochemical consequences of the participation, in the reaction course, of intermediates containing two phosphorus atoms were demonstrated using *S*-(−) and *R*-(+) *S*-methyl t-butyl(phenyl)phosphinothioates as models for the stereochemical studies.[1a–d] The careful analysis of all known stereochemical studies[1b,c,2] concerning the chlorinolysis of phosphorus thiolesters shows that this reaction is strongly dependent on the reaction parameters, such as the structure of the thiolester, the nature of the chlorinating agent, and the solvent. The effect of the substituent on the sulphur atom on the stereochemical course of the chlorinolysis of phosphorus thiolesters has been described elsewhere.[1e]

The present work involves a spectroscopic study of the reaction of several phosphoro- and phosphono-thiolates with sulphuryl chloride and elemental halogens both in benzene (toluene), and methylene dichloride, to demonstrate the dependence of the reaction course on the character of substituent on the phosphorus atom and on the nature of solvent.

Results and Discussion

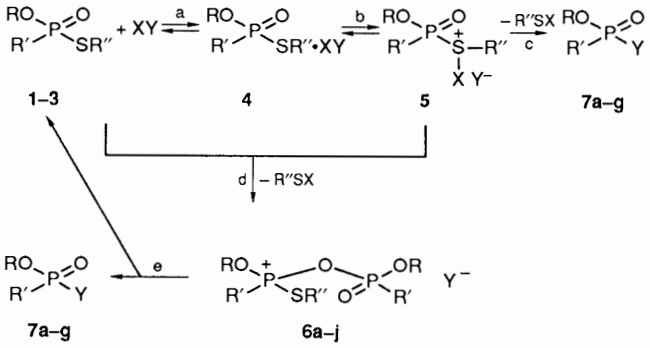
The phosphorothiolates **1**, **2a**, **b** and the phosphonothiolates **3a**, **b** were treated with sulphuryl chloride, elemental chlorine, bromine, and iodine both in methylene dichloride and in toluene. The reaction course was followed using ^{31}P NMR spectroscopy. The ^{31}P NMR studies of the reaction mixtures were performed in the range 183–293 K as described in previous papers.[1a,b] The stereochemistry of the reaction of the optically active model **3a** was also examined.



Reaction of S-*Methyl* O,O-*Dineopentyl Phosphorothioate* **1** *with Sulphuryl Chloride and Halogens.*—Ester **1** reacts with chlorine and sulphuryl chloride very cleanly with scission of the P–S bond of phosphorothioic ester and the formation of dineopentyl phosphorochloridate **7a**. The only side reaction observed is the hydrolysis of the latter product to tetraneopentyl pyrophosphate **16a**, caused probably by traces of moisture from external sources and/or from the solvent. The ^{31}P NMR spectrum of ester **1** reacting with SO_2Cl_2 in the temperature range 183–193 K shows, in addition to the signals of **1** and the reaction product **7a**, a characteristic doublet of doublets, which is consistent with the presence of species containing two different phosphorus atoms bridged by oxygen. On the basis of our previous experience[1] with intermediates formed during the chlorinolysis of phosphorus thiolesters, we assumed that these signals came from the phosphoryloxyphosphonium salt **6a** (Scheme 1, Table 1). This structural assignment was confirmed by an independent synthesis of the analogous salt with a chloride anion **6b** from the tetraneopentyl ester of phosphorous phosphoric anhydride **8**, and methanesulphenyl chloride. The chemical shift values of compound **6b** from the above reaction are in agreement with those of the salts **6a** and **6b** formed from the interaction of thiolester **1** with SO_2Cl_2 and Cl_2 (Table 1). In contrast with the results described in previous papers,[1] we did not find any ^{31}P NMR signal which could be assigned to the sulphonium salt **5a** or to any complex between the two starting materials, although some shifting of the δ_P-value of the starting ester **1** to lower field ($\Delta\delta$ < 2.1 ppm) may be considered as being due to a consequence of the equilibrium **1** + $X_2 \rightleftharpoons$ **4** $\rightleftharpoons$ **5** (Scheme 1). It would seem therefore to be very likely that the conversion of intermediate **5a** into the secondary intermediate **6a**, **b** and/or into the reaction product **7a** is as fast as the rate of its formation, and that there is no possibility for the accumulation of compounds **4a**, **b** and/or **5a**, **b** in the reaction mixture. Table 2 presents the results obtained from studies of the reaction system **1** + SO_2Cl_2 using different approaches: (i) at constant temperature (203 K) as a function of time and (ii) by varying both the temperature and time in the temperature range 183–293 K. There is no essential difference between the results of these two series of experiments.

A considerable decrease in the concentration of the diphosphorus-containing intermediate **6a** was observed when toluene was used as the solvent (Table 2, data in parenthesis). Unfortunately, it is difficult to draw any conclusion from this fact, because the reaction system **1** + SO_2Cl_2 in toluene is not fully homogeneous at lower temperatures.

† For Part 2, see ref. 1*a*.



1 R = Me_3CCH_2, R′ = RO, R″ = Me
2a R = R″ = Et, R′ = EtO
2b R = Pr, R′ = PrO, R″ = Me
3a R = R″ = Me, R′ = Bu^t
3b R = Pr^i, R′ = Bu^t, R″ = Me

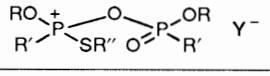
6a–j see Table 1

4a, 5a R,R′,R″ as for **1**; X = Cl, Y = $ClSO_2$
4b, 5b R,R′,R″ as for **1**; X = Cl, Y = Cl or Cl_3
4c, 5c R,R′,R″ as for **1**; X = Br, Y = Br or Br_3
4, 5 R,R′,R″ as for **3a**; X = Br, Y = Br or Br_3

7a R = Me_3CCH_2, R′ = RO, Y = Cl
7b R = Me_3CCH_2, R′ = RO, Y = Br
7c R = Et, R′ = EtO, Y = Cl
7d R = Pr, R′ = PrO, Y = Cl
7e R = Me, R′ = Bu^t, Y = Cl
7f R = Me, R′ = Bu^t, Y = Br
7g R = Pr^i, R′ = Bu^t, Y = Cl

Scheme 1

Table 1 ^{31}P NMR chemical shifts[a] and coupling constants of phosphonium salts **6a–j**



Compd.	R	R′	R″	Y	δ_{P+} (ppm)	$\delta_{P(O)}$ (ppm)	$J_{P\text{-}O\text{-}P(O)}$ (Hz)	Temp.[b] (K)
6a	Me_3CCH_2	Me_3CCH_2O	Me	SO_2Cl	+40.97 (d)	−13.66 (d)	25	203
6b	Me_3CCH_2	Me_3CCH_2O	Me	$Cl(Cl_3)$	+41.21 (d)	−13.33 (d)	25	193
6b[c]	Me_3CCH_2	Me_3CCH_2O	Me	Cl	+41.14 (d)	−13.24 (d)	25	193
6c	Me_3CCH_2	Me_3CCH_2O	Me	$Br(Br_3)$	+40.54 (d)	−13.50 (d)	25	203
6d	Pr	PrO	Me	SO_2Cl	+38.26 (d)	−15.14 (d)	25	193
6e	Et	EtO	Et	SO_2Cl	+38.62 (d)	−14.68 (d)	27[d]	263
6f	Et	EtO	Et	$Br(Br_3)$	+38.82 (d)	−14.35 (d)	27	203
6g$_1$	Me	Bu^t	Me	SO_2Cl	+95.88 (d)	+38.53 (d)	54	203
6g$_2$	Me	Bu^t	Me	SO_2Cl	+92.10 (d)			
6h$_1$	Me	Bu^t	Me	$Cl(Cl_3)$	+96.69 (d)	+39.48 (d)	54	193
6h$_2$	Me	Bu^t	Me	$Cl(Cl_3)$	+92.58 (d)			
6i$_1$	Me	Bu^t	Me	$Br(Br_3)$	+96.75 (d)	+39.49 (d)	54	263
6i$_2$	Me	Bu^t	Me	$Br(Br_3)$	+93.17 (d)			
6j$_1$	Pr^i	Bu^t	Me	$Br(Br_3)$	+90.81 (d)	+36.49 (d)	59	263
6j$_2$	Pr^i	Bu^t	Me	$Br(Br_3)$	+86.94 (d)			

[a] Solvent CH_2Cl_2; δ_P (24.3 MHz). [b] Temperature of spectral measurement. [c] From reaction of $(Me_3CCH_2O)_2P\text{–}O\text{–}P(O)(OCH_2CMe_3)_2$ **8** with MeSCl. [d] δ_P (36.4 MHz).

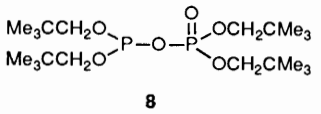


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Table 3 presents the results of the reaction of compound **1** with halogens. Comparison of the data obtained for the reaction system **1** + Cl_2 with those for **1** + SO_2Cl_2 shows that the former reaction is considerably faster than the latter. This observation seems to imply that the intact molecule of sulphuryl chloride acts as an electrophile, which after attacking the nucleophile dissociates with the formation of the anion $ClSO_2^-$. This anion evolves SO_2 in a subsequent step of the reaction. However, the salt **5a** formed from the interaction of thiolester **1** and SO_2Cl_2 must have a different anion from the salt formed from thiolester **1** and Cl_2. Owing to the low nucleophilicity of anion $ClSO_2^-$ towards phosphorus, the salt **5a** exhibits no tendency to decompose with the formation of the reaction

Table 2 ^{31}P NMR analysis of the reaction system **1** + SO_2Cl_2 in CH_2Cl_2 (toluene) showing relative integrals of ^{31}P NMR signals (%)

Compd. present in reaction mixture	Temp. (K) Time (min)	195[a]				193	223	233
		15	105	230	260	15	75	90
1		42	17	9	6	82 (88)[b]	13 (30)	(21)
6a		42	39	19		12 (4)	54 (10)	(0)
7a		16	44	69	87	4[c] (7)[c]	33[c] (56)[c]	86[c] (70)[c]

[a] At constant temperature. [b] Mixture was heterogeneous. [c] **16a** was additionally present in the reaction mixture.

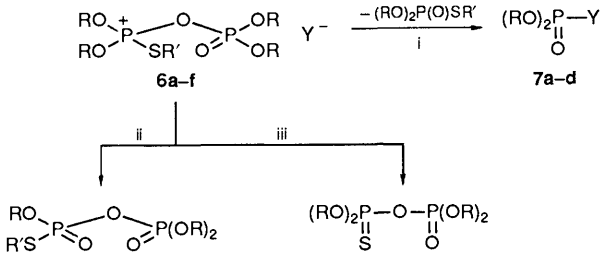
product **7a**. Instead, the phosphoryl oxygen of the ester **1** attacks salt **5a**, forming intermediate **6a** which is observable up to 223 K in high concentration (see Table 2). In the case of the reaction system **1** + Cl_2, the chlorosulphonium salt **5b** is able to

Table 3 ^{31}P NMR analysis of the reaction system **1** + X_2 in CH_2Cl_2 [relative integrals of ^{31}P NMR signals (%)]

Compds. present in reaction mixture	X_2	Cl_2				Br_2				I_2		
	Temp. (K)	193	203	223	293	203	253	283	298	193	273	293
1 + X_2 (⇌ **4** ⇌ **5**)		5				45	37	44	29	100	100	100[a]
6b, c		20	21	8		55	63	22				
7a, b		57	78	86[b]	94[b]			*c*	6[d]			

[a] After 18 weeks δ_P +29.01 ppm ($\Delta\delta$ 1.61 ppm). [b] Additionally, compound **16a** was present. [c] The reaction mixture also contained compounds **9a** (6%), **18** (3%), **14a** (5%), **16a** (18%) and dineopentyl hydrogen phosphate (traces). [d] Additionally, compounds **9a** (13%), **10a** (10%), **18** (7%), **16a** (20%) and dineopentyl hydrogen phosphate (15%) were present.

decompose directly to the reaction product **7a** (Scheme 1, pathway c) in competition with the reaction pathway d + e (Scheme 1). However, any intermediate **6b** formed would decompose relatively rapidly to monophosphorus products due to the higher *P*-nucleophilicity of the chloride anion. As the consequence of the character of the different anions in the two systems, the phosphonium salt **6a** formed in the case of the reaction system **1** + SO_2Cl_2 is more stable and still present in the reaction mixture at 223 K, while for the system **1** + Cl_2 the salt **6b** is not observed at temperatures >223 K. It is possible that just above 220 K the anion $ClSO_2^-$ decomposes rapidly ($ClSO_2^- \longrightarrow Cl^- + SO_2$) and then there will be no difference between the two reaction systems.



6a–f **7a–d**

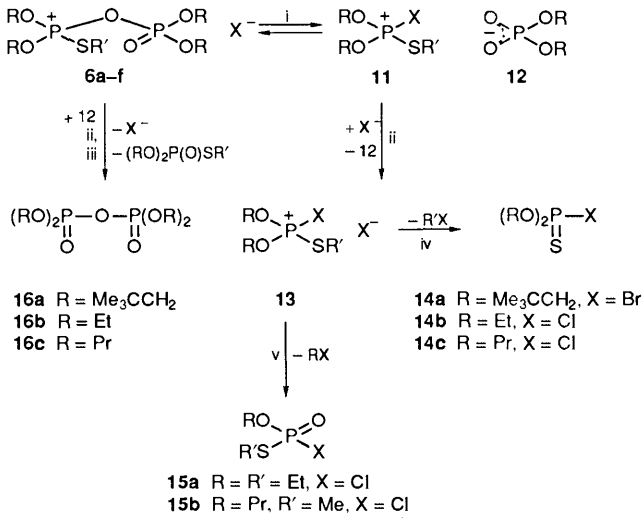
9a R = Me_3CCH_2, R′ = Me
9b R = R′ = Et
9c R = Pr, R′ = Me

10a R = Me_3CCH_2

Scheme 2 Proposed routes of the stabilization of salts **6**. Path i: attack of X^- on phosphoryl centre; ii: attack of X^- on carbon attached to O; iii: attack of X^- on carbon attached to S

When thiolester **1** was treated with bromine in methylene dichloride, the phosphonium salt **6c** (Tables 1 and 3) was formed as the main product, which was stable to 283 K, apparently due to the poor *P*-nucleophilicity of Br^-. In addition to the signals characteristic for the salt **6c**, only one further peak was observed, reflecting the equilibrium between the starting materials and the intermediates **4c** and **5c** (at 273 K, δ_P +32.55, $\Delta\delta$ *ca.* 5.25 ppm). At room temperature the phosphonium salt **6c** decomposed giving, in addition to a low yield (6%) of dineopentyl phosphorobromidate **7b**, several other products. According to ^{31}P NMR studies some starting ester **1** was recovered (29%), contaminated with tetraneopentyl thiopyrophosphate **10a** (10%), *S*-methyl *O,O,O*′-trineopentyl thiopyrophosphate **9a** (13%), probably bis(dineopentoxyphosphoryl) disulphide **18** (7%), and two hydrolysis products, dineopentyl phosphate (15%) and tetraneopentyl pyrophosphate **16a** (20%). Analysis by GC–MS showed the presence of starting thiolester **1**, dineopentyl phosphorobromidothionate **14a**, tetraneopentyl thiopyrophosphate **10a**, and tetraneopentyl pyrophosphate **16a**. The presence of the products observed may be explained by assuming that at room temperature the transient phosphonium salt **6c** decomposes by several reaction pathways (Schemes 2 and 3). The disulphide **18** could be formed *via* the reaction sequence shown in eqn. (1).

An interesting ^{31}P NMR spectrum was observed for the



6a–f **11** **12**

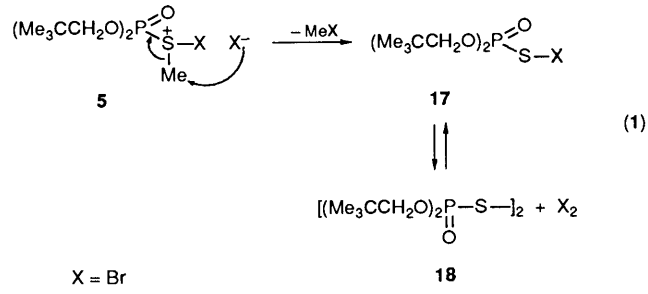
16a R = Me_3CCH_2
16b R = Et
16c R = Pr

13

14a R = Me_3CCH_2, X = Br
14b R = Et, X = Cl
14c R = Pr, X = Cl

15a R = R′ = Et, X = Cl
15b R = Pr, R′ = Me, X = Cl

Scheme 3 Proposed routes to the formation of compounds **14**, **15** and **16**. Paths i: ligand exchange at phosphonium P; ii: exchange of anions; iii: attack of anion **12** on phosphoryl P; iv: attack of X^- anion on carbon attached to S; v: attack of X^- anion on carbon attached to O

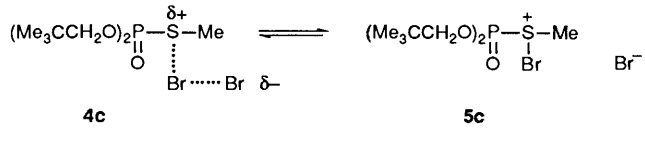


5 **17** **18**

(1)

X = Br

reaction system **1** + Br_2 in toluene. Only two distinct signals (at δ_P +35.86 and +37.31 in the ratio 4:6) were observed in the temperature range 198–273 K. These signals coalesced at room temperature into a single peak at δ_P +35.13. Addition of cyclohexene to the reaction mixture resulted in the regeneration of the thiolester **1**. This means that the chemical shifts observed for the reaction mixture must correspond to different structures of the complex between **1** and bromine. On the basis of our previous experience[1] of this type of species, we assume that in this experiment we observe an equilibrium between the molecular complex (charge transfer) **4c** and the bromosulphonium salt **5c**.



4c **5c**

In view of the lower tendency of bromine to form

Table 4 ^{31}P NMR analysis of the reaction of compound **2a** with sulphuryl chloride and halogens in CH_2Cl_2 [relative integrals of ^{31}P NMR signals (%)]

Compds. present in reaction mixture	X_2	SO_2Cl_2			Cl_2			Br_2			I_2		
	Temp. (K)	203	263	293	203	233	293	203	263	293	193	273	293
2a		8	7					54[a]	49[a]	19[a]	100	100	
6e,f		28	9		6	3		19	26				traces
7c		43	38	41	62	63	67			traces			
9b								3	6	14			traces
15a			7	7						*b*			*b*

[a] The chemical shift responds to equilibrium **2a** + $Br_2 \rightleftharpoons$ **3** $\rightleftharpoons$ **4**, δ_P +35.21 ppm ($\Delta\delta$ 8.12 ppm) at 263 K. [b] Unidentified dealkylation product δ_P −27 ppm was also present.

Table 5 ^{31}P NMR analysis of the reaction system **2b** + SO_2Cl_2 in the mixture CH_2Cl_2–toluene (1:1) and toluene (data in parentheses) [relative integrals of ^{31}P NMR signals (%)]

Compds. present in reaction mixture	Temp. (K)			
	193	213	253	293
2b	45 (66)[a]	21 (25)[a]	17 (5)	14 (0)
6d	23 (9)	16 (9)	(0)	(0)
9c	(0)	8 (4)	16 (10)	16 (5)
7d	18 (20)	30 (44)	39 (68)	44 (65)
15b	(0)[b]	3 (3)[b]	9 (6)[b]	9 (6)[b]

[a] Mixture was heterogeneous. [b] Additionally **14c** (3–4%) was present in both reaction systems.

sulphuranes, the participation of $(Me_3CCH_2O)_2P(O)S(Br)_2Me$ was not considered. The spectroscopic picture observed suggests that practically all the ester **1** is engaged in the formation of the complex. There is, therefore, no free ester **1** in the reaction medium, and consequently the formation of the salt **6**, which would require the attack by the phosphoryl oxygen of the free ester **1** on the phosphoryl centre of the salt **5c**, does not occur.

GC–MS analysis of the reaction mixture after the reaction with cyclohexene showed the presence of the starting thiolester **1** as the only phosphorus-containing product. In addition to substrate **1** and dibromocyclohexane, two products from the bromination of the solvent were found: benzyl bromide and *p*-bromotoluene. The presence of the latter compounds indicates that adduct **4c** and/or salt **5c** may catalyse the bromination of toluene.

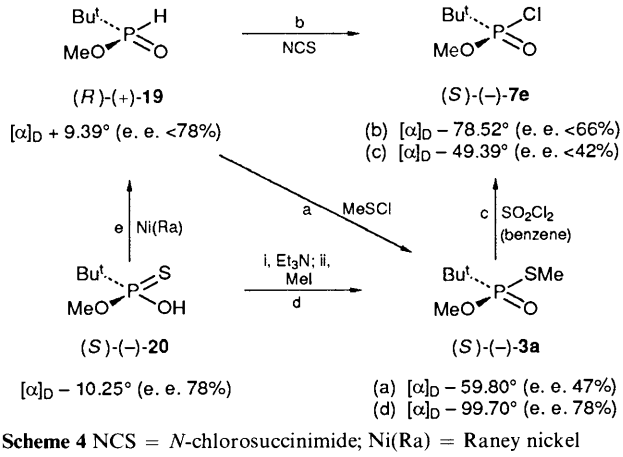
The reaction of ester **1** with iodine did not proceed at low temperature. When the reaction system **1** + I_2 was kept at room temperature, the ^{31}P NMR signal corresponding to the equilibrium **1** + $I_2 \rightleftharpoons$ **4** $\rightleftharpoons$ **5** gradually shifted to low field, reaching the value δ_P +30.82 ($\Delta\delta$ 3.53 ppm) after 7 months. In addition to **1**·I_2, the ^{31}P NMR spectrum showed the presence of a trace of bis(dineopentoxyphosphoryl) disulphide **18**, which could be formed according to the reactions shown in equation (1). The low reactivity of the ester **1** towards elemental iodine is in agreement with our results described in Part 2.[1a] We have assumed that the slowest reaction step in the reaction of thiolesters with iodine is the formation of the transient iodosulphonium salt, $>P(O)\overset{+}{S}(R)I\ I^-$.

Reaction of O,O,S-*Triethyl and* S-*Methyl*-O,O-*Dipropyl Phosphorothioates with Sulphuryl Chloride and Halogens.*—The behaviour of the reaction systems **2a**, **b** + SO_2Cl_2 and **2a**, **b** + Cl_2 is generally similar to the reactions of the ester **1** with the same reagents. In both cases (**2a** and **2b**), diphosphorus-containing intermediates **6d**, **e** were observed in the temperature range 193–233 K (Tables 1, 4 and 5). However, the yields of the corresponding phosphorochloridates **7c**, **d** are lower than those observed in the reaction of thiolester **1** with SO_2Cl_2 and Cl_2. The presence of readily dealkylated groups provides additional ways for stabilization of the intermediates **6d**, **e**, leading to the formation of side products such as the thiopyrophosphates **9b**, **c** and the chlorides **15a**, **b** (Schemes 2 and 3).

S-Methyl(ethyl), *O*,*O*′,*O*′-trialkyl thiopyrophosphates **9b**, **c** were detected in the reaction mixtures in *ca.* 18–25% yield, while *S*-methyl *O*-propyl phosphorochloridothioate **15b** was found in the reaction system **2b** + SO_2Cl_2 in *ca.* 10% yield. The intermediate **6f** was present in the reaction system **2a** + Br_2 at low temperatures; however, at room temperature mainly an unidentified dealkylation product, $\delta_P \sim -27$, was observed (Table 4). Esters **2a**, **b** did not react with iodine at low temperatures; at room temperature the above mentioned dealkylation product, $\delta_P \sim -27$, was the main reaction product.

We conclude from the above results that in the case of phosphorothiolates containing alkoxy groups which readily undergo dealkylation only the chlorinolysis reaction is of some importance from a synthetic point of view. The use of non-polar solvents at low temperatures is recommended for the prepation of phosphorochloridates in reasonable yields.

Reaction of O,S-*Dimethyl and* O-*Isopropyl* S-*Methyl t-Butylphosphonothioates with Sulphuryl Chloride and Halogens.*—(a) *Stereochemical studies.* The chlorinolysis of the enantiomers of *O*,*S*-dimetyl t-butylphosphonothioate **3a** was studied in our laboratory many years ago,[2e] but the stereochemical course of the reaction was not elucidated. Now, on the basis of two stereochemical cycles (Scheme 4), the reaction of ester **3a** with SO_2Cl_2 in benzene has been found to proceed with retention of configuration. Reactions of the type e and b are known to proceed with retention of configuration,[3] while reaction d does not affect any bond attached to the chiral phosphorus atom. Since there is no ligand metathesis[4] in the cycles, reaction a occurs with retention of configuration, therefore reaction c,



Scheme 4 NCS = *N*-chlorosuccinimide; Ni(Ra) = Raney nickel

Table 6 Stereochemistry of the reaction

$$\text{Bu}^t(\text{MeO})\text{P(O)SMe} \xrightarrow[(Cl_2)]{SO_2Cl_2} \text{Bu}^t(\text{MeO})\text{P(O)Cl}$$

dependent on the solvent and chlorinating agent

Expt.	Bu^t(MeO)P(O)SMe $[\alpha]_D$ (°)	o.p. (%)[a]	Configuration	Bu^t(MeO)P(O)Cl $[\alpha]_D$ (°)	o.p. (%)[b]	Configuration	Stereochemistry	Optical yield	Solvent	Chlorinating agent
1	−73.22	57	*S*	−67.1	57	*S*	Ret.	100	benzene	SO_2Cl_2
2	+74.00	58	*R*	+62.2	53	*R*	Ret.	91	benzene	SO_2Cl_2
3	−54.00	42	*S*	−34.42	29	*S*	Ret.	69	CCl_4	Cl_2
4	+81.47	63	*R*	−21.00	18	*S*	Inv.	28	CH_2Cl_2	SO_2Cl_2
5	+77.00	60	*R*	−30.88	26	*S*	Inv.	43	CH_2Cl_2	SO_2Cl_2
6	+118.78	93	*R*	−18.91	16	*S*	Inv.	17	CH_2Cl_2	SO_2Cl_2
7	−61.03	48	*S*	+55.53	47	*R*	Inv.	98	CH_2Cl_2/CCl_4 (9:1)	Cl_2

[a] It was assumed that the optical purity of (*R*) and (*S*) esters **3a** was the same as that of the corresponding acid **20**. Bu^t(MeO)P(S)OH **20**, $[\alpha]_D$ +13.18°, was found (Ref. 1*e* and M. Mikotajczyk, M. Para, A. Ejchert and J. Jurozak, *Chem. Commun.*, 1970, 654) 100% optically pure; **20**, $[\alpha]_D$ −10.25° (e.e. 77.7%) gave Bu^t(MeO)P(O)SMe, **3a**, $[\alpha]_D$ −99.70 (e.e. 77.7%). [b] The highest rotation value of Bu^t(MeO)P(O)Cl **7e**, estimated from experiment 1 as 117.7°, was assumed as responding to e.e. 100% and this value was used for the calculation of the optical purity of the other samples of compound **7e**.

Table 7 ^{31}P NMR analysis[a] of the reaction system **3a** + SO_2Cl_2 in CH_2Cl_2 (toluene)

Compds. present in reaction mixture	Temp. (K)[b] 193	233	253	293	*T* 195 K[c] Time (min) 0	35	70	135	250	1 070
3a	88 (79)[d]	67 (64)[d]	28 (52)	(7)	85	61	47	38	31	10
6g	8 (3)	8 (trace)	5 (0)	(0)	11	26	29	30	31	
21a, b	(7)	11 (16)	31 (20)	31 (20)		1	5	7	11	50
22	(0)	(0)	6 (0)	9 (7)		1	3	5	6	6
7e	4 (11)	14 (20)	35 (28)	60 (65)	4	11	16	20	23	34

[a] Relative integrals of ^{31}P NMR signals (%). [b] Dependent on the temperature. [c] At constant temperature. [d] Mixture was heterogeneous.

representing the chlorinolysis of the phosphorus–sulphur bond in **3a** also proceeds with retention of configuration.

An interesting solvent effect was noted when optically active phosphonothiolate **3a** was treated with sulphuryl chloride or elemental chlorine in methylene dichloride instead of benzene or carbon tetrachloride. In the former case the stereochemistry was reversed, *i.e.* inversion of configuration was observed. Table 6 presents the stereochemical results of the reaction of compound **3a** with sulphuryl chloride and elemental chlorine in benzene, CCl_4, and methylene dichloride.

(b) *Spectroscopic investigations.* ^{31}P NMR studies of the reaction systems **3a**, **b** + SO_2Cl_2 were carried out in the temperature range 193–293 K in methylene dichloride or toluene. No essential differences in the reaction course of esters **3a** and **3b** were observed, so in Tables 7 and 8 only the results obtained for compound **3a** are shown. Table 7 presents a comparison of the behaviour of the reaction system **3a** + SO_2Cl_2 in both solvents: CH_2Cl_2 and toluene.

The only difference noted when toluene was used as the solvent was that the intermediate **6g** was observed in low concentration at <233 K. The reaction mixture was not homogeneous at low temperatures.

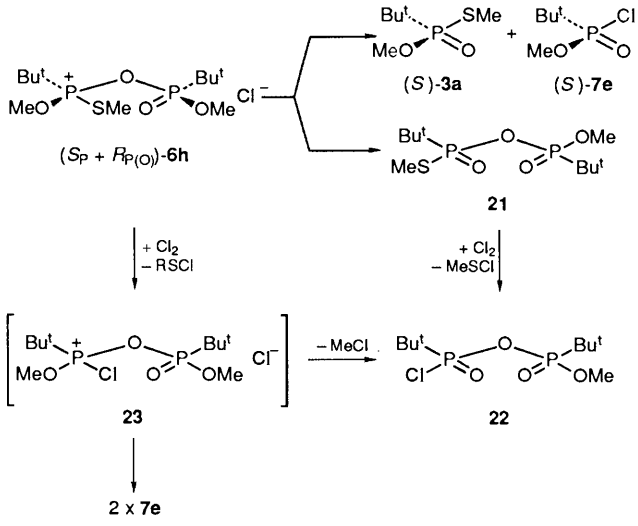
The spectroscopic observations together with the stereochemical results could be rationalized by assuming that in the two solvents different reaction pathways are favoured. The formation of the reaction product **7e** requires attack of the chloride anion on the phosphorus atom of one of the intermediates **5** or **6**. When sulphuryl chloride is employed as the chlorinating agent, the primary anion $ClSO_2^-$ is formed. This anion must undergo decomposition with the release of chloride anion. Such a process probably proceeds with different rates in the two solvents used for the reaction: slower in toluene, faster in methylene dichloride. Therefore, the formation of the salt **5e** from salt **5d** and the subsequent decomposition of chloride salt **5e** producing the reaction product **7e**, with inversion of configuration, occurs more readily in methylene dichloride. However, this reaction is not very fast (due to steric reasons), and competing with it is the reaction leading to the phosphonium salts **6g** and **6h**, which result from the competitive attack by the phosphoryl oxygen of ester **3a** on the phosphorus atom of both salts **5d** and **5e**. The salt **6h** undergoes stabilization in two ways: either by attack of chloride anion on the phosphoryl centre of the salt **6h** which leads to the formation of chloride **7e** with retention of configuration (by two subsequent inversions), with the decrease of the net reaction stereoselectivity, or by attack of chloride anion on the electrophilic carbon of the methoxy group, which leads to the formation of the product **21a, b** (two diasteroisomers) containing two phosphorus atoms. When toluene is used as solvent, the chlorosulphonium salt **5d** probably exhibits a low tendency to convert into the salt **5e**, but rather undergoes reaction with starting ester **3a** to form the intermediate **6g**. The gradual release of chloride anion from $ClSO_2^-$ prompts the transformation of **6g** into **6h**, which decomposes as the result of the attack of Cl^- on the phosphoryl centre, thus forming the chloride **7e** with retention of configuration. The competitive attack on the carbon atom produces, as in the previous case, a diphosphorus-containing product, thiopyrophosphonate **21** (Scheme 5).

Comparison of the reaction course of ester **3a** with SO_2Cl_2 (Table 7) and elemental chlorine (Table 8) confirms the assumption that in these two cases different counter-anions participate. System **3a** + $2Cl_2$ reacts dramatically faster than does system **3a** + SO_2Cl_2. A similar situation was observed for other esters. However, the difference in the reaction of ester **3a**

Table 8 ^{31}P NMR analysis of the reaction systems **3a** + X_2 in CH_2Cl_2 (toluene) [relative integrals of ^{31}P NMR signals (%)]

Compds. present in reaction mixture	X_2	Cl_2[a]		Br_2				I_2	
	Temp. (K)	193	233	198	228	273	293	293[b]	293[c]
3a				74 (100)	71 (90)	67 (83)	14 (43)	92 (13)	24 (16)
4 ⇌ **5**				(0)	(5)	(10)	(17)	(0)	(0)
6h, i		15		22 (0)	28 (3)	27 (3)	7 (0)	(0)	(0)
21		8		(0)	(3)	6 (5)	55 (40)	8 (54)	60 (56)
22		57	75	(0)	(0)	(0)	(0)	(0)	(0)
7e		20	25	(0)	(0)	(0)	(0)	(0)	(0)

[a] Molar ratio of **3a** to Cl_2 was 1:2. [b] 0.5 h after mixing of the reactants. [c] After 14 days.



Scheme 5

with the two chlorinating agents is more spectacular, because in this case different products, both containing two phosphorus atoms, are obtained.

In the system **3a** + SO_2Cl_2, in addition to the chloride **7e**, P^1-*O*-methyl P^2-*S*-methyl P^1,P^2-bis(t-butyl)thiopyrophosphonate **21** is formed in 39–51% yield, while with chlorine the reaction product **7e** is contaminated with P^1-*O*-methyl P^1,P^2-bis(t-butyl)pyrophosphono-P^2-chloridate **22** (75%).* A minute amount of compound **22** was also observed in the reaction system **3a** + SO_2Cl_2: more in methylene dichloride, less in toluene. This fact seems to confirm the assumption that the decomposition $ClSO_2^- \longrightarrow Cl^- + SO_2$ is favoured in CH_2Cl_2.

The formation of chloropyrophosphonate **22** could be assumed to result from the decomposition of the corresponding chlorophosphonium salt **23** (Scheme 5). The latter would be formed *via* ligand exchange at the phosphonium salt **6h**, followed by chlorination of the ^-SR anion as has been proposed in the preliminary paper.[1d] Such a pathway for the reaction has also been demonstrated for the reaction system $Bu^tPhP(O)SMe + Cl_2$.[1b] In this latter case the chlorophosphonium salt $Bu^tPh\overset{+}{P}(Cl)OP(O)Bu^tPh\ Cl^-$ could be observed in the ^{31}P NMR spectrum. The presence in the model ester **3a** of the readily dealkylated methoxy group did not allow us to observe salt **23**. However, the above described route for the formation of compound **22** seems to be probable.

One problem concerning the stereochemistry of the reaction of ester **3a** with chlorine still remains ambiguous: why the reaction in CCl_4 proceeds with retention of configuration although the use of chlorine seems to favour inversion.[2f] One of the reasons may be the low reactivity of ester **3a** in the reaction under investigation (see Conclusions, below). Additionally, participation of the weakly nucleophilic anion Cl_3^- can be of importance. It is known[5] that the formation of such anions in chloroalkane solvents is strongly promoted and that it can play a role similar to that of the $^-SO_2Cl$ anion in toluene medium.

The reaction of ester **3a** with chlorine exhibits an interesting feature in both methylene dichloride and toluene. Unlike the other examples of chlorinolysis, in this case an equimolar amount of chlorine seems to be insufficient to bring about the completion of the reaction. The ^{31}P NMR spectrum for the system **3a** + Cl_2 in CH_2Cl_2 shows, at low temperatures, only a trace of intermediate **6h**. At room temperature, in addition to the main peak corresponding to starting ester **3a**, signals for the products **7e** and **21a**, **b** (together *ca.* 30%) were observed. The addition of a second mole of chlorine causes the appearance of the typical spectroscopic picture of the reaction. This is a unique observation and the reason for this phenomenon is not clear. It can be supposed that the above mentioned tendency of chlorine to co-ordinate with Cl^- rather than with ester **3a** may play some role.

Reaction of ester **3a** with elemental bromine in CH_2Cl_2 leads to the formation of the relatively stable phosphoryloxyphosphonium salt **6i**, which at temperatures >273 K decomposes mainly with the formation of P^1-*O*-methyl P^2-*S*-methyl P^1,P^2-bis(t-butyl)thiopyrophosphonate **21** and the product of the hydrolysis of $Bu^t(MeO)P(O)Br$, the pyrophosphonate **24**. In toluene, intermediate **6i** is visible only between 228–273 K (the reason may be the same as in the case of the reaction with SO_2Cl_2 in toluene); however, in addition to the starting ester, an additional peak appears at δ_P +76.2 ppm. Its position is shifted to low field with increasing temperature and at room temperature reaches +80.9 ppm ($\Delta\delta$ 14.7 ppm). It seems reasonable to assume that this chemical shift is associated with the equilibrium **4d** ⇌ **5d**.

Thiopyrophosphonate **21**, contaminated with traces of hydrolysis products, is the final result of the reaction of ester **3a** with Br_2 in toluene.

Ester **3a** does not react with iodine in the temperature range 213–273 K in CH_2Cl_2 or in toluene. The reaction at room temperature occurs slowly and leads to the formation of the thiopyrophosphonate **21** (Table 8). At the same time the chemical shift of the starting ester undergoes a gradual shift towards low field. The same reaction in acetonitrile was found to be faster: after the reagents were mixed ^{31}P NMR spectroscopy showed ester **3a** and thiopyrophosphonate **21** in the ratio 1:1. After the reaction mixture had been stored for 14 days at room temperature ^{31}P NMR spectroscopy showed the presence of ester **3a** (12%), thiopyrophosphonate **21** (68%) and unidentified dealkylation products.

* The use of a low concentration of the reactants when the experiments were carried out on a preparative scale allowed us to reduce the quantity of the diphosphorus-containing product **22** to <20%.

Table 9 Stereochemistry of the reaction

$$RR'P(O)SR'' \xrightarrow[(Cl_2)]{SO_2Cl_2} RR'P(O)Cl$$

dependent on the character of R and R', chlorinating agent, and solvent

Experiment	RR'P(O)SR'' R	R'	R''	Chlorinating agent	Solvent	Stereochemistry	Stereoselectivity (%)	Ref.
1	Me	Phen[a]	CH_2Ph	Cl_2	CCl_4	Inv.	>54	2*a*
2	EtO	Et	Et	SO_2Cl_2	benzene	Inv.	>16	2*b*
3	EtO	MeO	Me	SO_2Cl_2	benzene	Ret.	95	2*f*
4	EtO	MeO	Me	Cl_2	CCl_4	Inv.	90	2*f*
5	Et_2N	Et	Et	SO_2Cl_2	*b*	Inv.	>28	2*c*
6	Ph	Bu^t	Me	SO_2Cl_2	benzene	Ret.	86	1*b*
7	Ph	Bu^t	Me	Cl_2	CCl_4	Ret.	85	1*b*
8	Ph	Bu^t	Me	Cl_2	CH_2Cl_2/CCl_4	Ret.	43	1*b*
9	Ph	Bu^t	Me	SO_2Cl_2	CH_2Cl_2	Ret.	34	1*b*
10	EtO	PhO	Me(Pr)	SO_2Cl_2	*b*	Ret.	*b*	2*g*
11	EtO	PhO	Me(Pr)	Cl_2	*b*	Ret.	*b*	2*g*
12	EtO	$CHCl_3$	Me	Cl_2	CCl_4	Ret.	>95	2*h*

[a] Phen = 3-phenanthryl. [b] Experimental details are not available.

Conclusions.—A careful consideration of our experimental results leads to the conclusion that the stereochemistry of the reaction under discussion is determined by the competition of two different nucleophiles attacking the phosphoryl centre of the primary intermediate—the chlorosulphonium salt **5**. One of them is the chloride anion, the other is the phosphoryl oxygen of the starting ester. The attack by the former leads directly to the reaction product with inversion of configuration, while the attack by the latter gives the secondary intermediate, containing two phosphorus atoms, which decomposes forming the reaction product with a net retention of configuration. The extent of the attack by the particular nucleophile should depend on the structure of both the starting ester and the chlorinating agent, and apparently on the nature of solvent. The structure of the thiolesters and especially the character of the substituents attached to the phosphorus atom can influence the reaction course in a variety of ways, since it affects: (i) the electrophilic character of the phosphoryl reaction centre, (ii) the nucleophilicity of the phosphoryl oxygen atom, and (iii) the nucleophilicity of the sulphur atom of the thiolester.

It is known that the electrophilicity of the phosphorus atom and the nucleophilicity of the oxygen atom follow the order phosphinic esters > phosphonic esters > phosphoric esters.[6] The nucleophilicity of the sulphur atom should follow the reversed order and is additionally strongly affected by the structure of the substituent on the sulphur atom. Table 9 presents a literature review of all stereochemical studies of the chlorinolysis of phosphorus thiolesters. Only esters containing the simplest alkyl groups (Et, Me) (with the exception of R'' = CH_2Ph) are included in the Table. The influence of the character of the substituents attached to the sulphur atom is discussed in a separate paper.[1e] From the collected data, one can conclude that inversion of configuration is the normal stereochemical course when we deal with more reactive thiolesters (*e.g.*, *S*-benzyl methylphenanthrylphosphinothiolate, *O*,*S*-diethyl ethylphosphonothiolate).

The esters which are less reactive due to electronic (phosphorothiolates) or steric (t-butylphosphono- and -phosphino-thiolates) effects exhibit some inconsistencies. The stereochemistry of the chlorinolysis of such esters is strongly dependent on the remaining factors, such as the solvent and the chlorinating agent. There is no doubt that the use of non-polar solvent (benzene, CCl_4) favours retention of configuration, while the use of the more polar CH_2Cl_2 promotes inversion.

Among the chlorinating agents, sulphuryl chloride favours retention of configuration and elemental chlorine inversion, although even then the solvent exerts greater influence (see Table 6, experiments 3, 7). The spectacular examples of the inconstancy of the stereochemical course of the reaction under discussion, are: *O*-ethyl *O*,*S*-dimethyl phosphorothioate (Table 9, experiments 3, 4) and *O*,*S*-dimethyl t-butylphosphonothioate (Table 6, experiments 1, 7).

In a situation where there is a complex dependence of the stereochemistry of the discussed reactions on all the reaction parameters, it seems hardly probable that the stereochemistry of the reaction could be predicted with any great certainty. However, consideration of all structural and other effects should allow us to assess which stereochemistry is most likely obeyed and to choose the most suitable reaction conditions.

Experimental

M.p.s were measured on a Boëtins PHMK apparatus, and all m.p.s and b.p.s are uncorrected. Solvents and commercial reagents were purified by conventional methods before use. Extracts were dried over $MgSO_4$. NMR spectra were recorded with JEOL JNM-FX 60 FT (60 MHz, ^1H; 24.3 MHz, ^{31}P), Bruker HX-72 (90 MHz, ^1H; 36.4 MHz, ^{31}P), and Tesla BS 487 (80 MHz, ^1H) spectrometers; positive chemical shifts are downfield from external 85% H_3PO_4 and internal Me_4Si.

Products were identified with a LKB Model 2091 gas chromatograph-mass spectrometer and/or ^{31}P NMR spectrometer. Optical rotations were measured at 589 nm and 20 ± 2 °C on a Perkin-Elmer 141 polarimeter in benzene solution unless specified otherwise.

Starting Materials.—*O*,*O*,*S*-Trialkyl phosphorothioates **1** and **2a**, **b** and *O*,*S*-dialkyl t-butylphosphonothioates **3a**, **b** were obtained as previously reported[1b] for *S*-methyl t-butyl(phenyl)-phosphinothioate. ^{31}P NMR chemical shifts: **1**; $\delta_P(CH_2Cl_2)$ +27.40, δ_P(toluene) +26.69; **2a**, $\delta_P(CH_2Cl_2)$ +27.09; **2b**, δ_P(toluene) +25.70; **3a**, $\delta_P(CH_2Cl_2)$ +67.36, δ_P(toluene) +65.35; **3b**, $\delta_P(CH_2Cl_2)$ +64.45.

O,*O*-Dineopentyl hydrogen phosphorothioate[7] and *O*,*O*-diethyl and *O*,*O*-dipropyl hydrogen phosphorothioates[8] were synthesized by known methods. *O*-Methyl hydrogen t-butylphosphonothioate **20** was prepared and resolved into optical antipodes as described previously.[2e]

Table 10 ^{31}P NMR data of the final reaction products **7a–g** and the side products containing one phosphorus atom[a]

Compound	δ_P (ppm)	Compound	δ_P (ppm)
7a	+3.94[b]	**7f**	+55.76[b]
7b	−7.15[b]	**7g**	+55.38
7c	+3.59[b]	**14b**	+67.81[b]
7d	+2.82[b,c]	**15b**	+34.30
7e	+58.22[b,d]	**15a**	+36.13[e]

[a] Spectra recorded in CH_2Cl_2; δ_P-values (24.3 MHz). [b] Product was identified by spectral comparison with an authentic specimen. [c] In toluene. [d] In $CDCl_3$. [e] Ref. 10 reports δ_P +34.1.

Table 11 ^{31}P NMR data of the final reaction products containing two phosphorus atom[a]

Compound	δ (P_1) (ppm)	δ (P_2) (ppm)	$J_{P\text{-}O\text{-}P}$ (Hz)
10a	+53.75 (d)	−14.06 (d)	24[b]
9b	+19.21 (d)	−14.05 (d)	23
9c	+17.44 (d)	−14.38 (d)	24
21a	+63.65 (d)	+32.19 (d)	47[b]
21b	+62.81 (d)	+32.19 (d)	47
22	+46.13 (d)	+33.96 (d)	49
16a	−13.46[b]		
16b	−14.68[b]		
16c	−13.78[b]		
24a	+24.01[b]		
24b	+23.12[b]		
18	+22.96[c]		

[a] Spectra recorded in CH_2Cl_2; δ_P-values (24.3 MHz). [b] Product was identified by spectral comparison with an authentic specimen. [c] Authentic sample showed δ_P +20.34.

Methanesulphenyl chloride[9] was prepared from the corresponding disulphide by chlorination with sulphuryl chloride and the crude product was used in subsequent reactions.

Low-temperature ^{31}P *NMR Measurements.*—The samples were prepared and the spectra recorded as previously described.[1b] The concentration of solutions was *ca.* 0.1 mol dm^{-3}. The composition of the reaction mixtures is presented in Tables 2–5, 7 and 8. The chemical shifts of the intermediates **6** are given in Table 1, those of the reaction final products and side products in Tables 10 and 11. The experimental details are given below only in the cases when the components in the reaction mixtures were additionally identified chemically and/or by GC–MS method.

Reaction of Compound **1** *with Bromine* (*Table* 3).—(a) *In methylene dichloride.* The reaction mixture at room temperature contained compound **1** complexed with bromine (29%), δ_P +35.86; *S*-methyl *O,O′,O′*-trineopentyl thiopyrophosphate **9a** (13%); dineopentyl phosphorobromidate **7b** (6%); *O,O,O′,O′*-tetraneopentyl thiopyrophosphate **10a** (10%); probably bis-(dineopentoxyphosphoryl) disulphide **18** (7%); and the hydrolysis products tetraneopentyl pyrophosphate, **16a** (20%) and dineopentyl hydrogen phosphate (15%). The red reaction mixture was decolourized by the addition of cyclohexene. Analysis by GC–MS (15 eV) showed the presence of 1,2-dibromocyclohexane, *m/z* 244 (M^+ + 4, 1%), 242 (M^+ + 2, 2), 240 (M^+, 1), 163 (18), 161 (19) and 81 (100); 1-bromo-2-methylthiocyclohexane, *m/z* 210 (M^+ + 2, 19%), 208 (M^+, 18), 129 (M^+ − Br, 69), 87 (14), 82 (17) and 81 (100); dineopentyl phosphorobromidothionate **14a**, *m/z* 318 (M^+ + 2, 6%), 316 (M^+, 3), 249 (15), 247 (14), 179 (15), 177 (14), 71 (100) and 70 (81); *S*-methyl *O,O*-dineopentyl phosphorothioate **1**, *m/z* 269 (M^+ + 1, 0.8%), 268 (M^+, 0.5), 199 (37), 183 (22), 142 (38) and 129 (100); tetraneopentyl pyrophosphate **16a**, *m/z* 460 (M^+ + 2, 7%), 458 (M^+, 0.1), 403 (12), 374 (11), 333 (27), 332 (30), 319 (19), 318 (13), 303 (25), 262 (11), 249 (43), 248 (55), 233 (68), 193 (38), 192 (100), 191 (23), 179 (77), 71 (14), and 55 (10); tetraneopentyl thiopyrophosphate **10a**, 475 (M^+ + 1, 2%), 474 (M^+, 3), 335 (20), 267 (52), 249 (17) and 197 (100).

(b) *In toluene.* In the temperature range 198–273 K only two peaks were observed [at 273 K $\delta(P_1)$ +36.26; $\delta(P_2)$ +33.76]. At 293 K these two signals coalesced to give one peak, δ_P +35.13. After the dark red reaction mixture had been decolourized by the addition of cyclohexene, ^{31}P NMR spectroscopy showed one peak, with a chemical shift δ_P +30.29. The reaction mixture was analysed by GC–MS (15 eV). The only phosphorus-containing product found was *S*-methyl *O,O*-dineopentyl phosphorothiolate **1**. In addition to compound **1** the reaction mixture also contained 1,2-dibromocyclohexane; *p*-bromotoluene, *m/z* 172 (M^+ + 2, 30%), 170 (M^+, 32), 91 (100), 90 (12), 89 (15), 65 (20), 63 (16) and 49 (17), and benzyl bromide, *m/z* 172 (M + 2, 5%), 170 (M^+, 6), 91 (100) and 65 (16).

Reaction of O,S-*Dimethyl t-Butylphosphonothiolate* **3a** *with Sulphuryl Chloride in Methylene Dichloride* (*for Reaction in Benzene see ref.* 2e).—To a stirred solution of thiolester **3a** (1.6169 g, 8.9 mmol) in methylene dichloride (10 cm^3) at 0 °C was added dropwise a solution of sulphuryl chloride (1.2180 g, 8.9 mmol) in methylene dichloride (2 cm^3). The mixture was stirred for 0.5 h at room temperature. After removal of the solvent, the residue was distilled at 30 °C/0.3 mmHg (bath temp.) to give *O*-methyl t-butylphosphonochloridate **7e** (0.60 g, 40%). Starting from (*R*)-**3a**, $[\alpha]_D$ +118.78° (*c* 2.62) (*S*)-(−)-*O*-methyl t-butylphosphonochloridate **7e**, $[\alpha]_D$ −18.91 (*c* 20.52), was obtained.

Reaction of O,S-*Dimethyl t-Butylphosphonothioate* **3a** *with Chlorine.*—(a) *In carbon tetrachloride.* To a stirred solution of thiolester **3a** (0.8848 g, 4.85 mmol) in carbon tetrachloride (5 cm^3) at −15 °C was added dropwise a solution of chlorine in carbon tetrachloride (30 cm^3; 0.42 mol dm^{-3}; *ca.* 12.6 mmol). The mixture was stirred for 2 h at room temperature. *O*-Methyl t-butylphosphonochloridate **7e** was purified as in the previous experiment to give pure ester **7e** (0.7861 g, 95%). Starting from (*S*)-(−)-**3a**, $[\alpha]_D$ −54.00° (*c* 1.5), (*S*)-(−)-*O*-methyl t-butylphosphonochloridate **7e**, $[\alpha]_D$ −34.42° (*c* 1.22), was obtained.

(b) *In a mixture of methylene dichloride and carbon tetrachloride* (9:1). By the same procedure as in the previous experiment, (*R*)-(+)-(*O*-methyl t-butylphosphonochloridate **7e** (0.1995 g, 65%), $[\alpha]_D$ +55.53° (*c* 1.16), was obtained from (*S*)-(−)-*O,S*-dimethyl t-butylphosphonothioate **3a** (0.3272 g, 1.79 mmol); $[\alpha]_D$ −61.03° (*c* 1.16), in methylene dichloride (100 cm^3) and chlorine (12 cm^3; 0.42 mol dm^{-3} in CCl_4; *ca.* 5 mmol).

Preparation of Salt **6b** *from Tetraneopentyl Ester of Phosphorous Phosphoric Anhydride* **8**.—Anhydride **8** was prepared in an NMR tube from equimolar amounts of dineopentyl hydrogen phosphate and dineopentyl phosphorochloridite[7] as previously described[1b] for the analogue with C–P bonds; δ_P (24.3 MHz; CH_2Cl_2) +127.81 (d), −9.47 (d), $^2J_{PP}$ 9.76 Hz. To a solution of crude anhydride **8** (0.5 mmol) in methylene dichloride (3 cm^3) at 193 K was added methanesulphenyl chloride[9] (0.5 mmol). The ^{31}P NMR spectrum of the product showed the absence of anhydride **8** and the presence of salt **6b** (chemical shift given in Table 1), dineopentyl phosphorochloridate **7a**, *S*-methyl *O,O*-dineopentyl phosphorothioate **1** and tetraneopentyl pyrophosphate **16a**.

Optically Active O-*Methyl t-Butylphosphinate* **19**.—A procedure described for the synthesis of analogous compounds[3] was followed. To a stirred, boiling solution of (*R*)-(+)-*O*-methyl hydrogen t-butylphosphonothioate[2e] **20** (11.40 g, 0.068 mol), $[\alpha]_D$ +13.10° (*c* 3.13), in ethanol (120 cm^3) was added portionwise a suspension of freshly prepared Raney nickel (*ca.* 20 g) in ethanol (250 cm^3) (in 15 portions) during 7 h. After the addition was complete, the reaction mixture was refluxed for 2 h. The mixture was filtered, the solvent was evaporated off under reduced pressure, and the residue was distilled, b.p. 35 °C/1 mmHg, to give (*S*)-(−)-*O*-methyl t-butylphosphinate **19**, $[\alpha]_D$ −10.10 (neat) (6.00 g, 65%); δ_P (24.3 MHz; neat) +48.75 [lit.,[11] δ_P (neat) +48.7]. In another experiment from (*S*)-(−)-*O*-methyl hydrogen t-butylphosphonothioate **20**, $[\alpha]_D$ −11.80 (neat), (*R*)-(+)-*O*-methyl t-butylphosphinate **19**, $[\alpha]_D$ +11.9 (neat), was obtained.

Addition of Sulphur to Optically Active O-*Methyl t-Butylphosphinate* **19**.—To a stirred solution of compound **19** (0.1 mol) and triethylamine (0.1 mol) in benzene (250 cm^3) at 40–50 °C (water-bath) was added portionwise sulphur (0.12 mol). The mixture was stirred at this temperature for 2 h. The excess of sulphur was filtered off, and the solvent was removed under reduced pressure. The residue was treated with aq. NaOH (0.11 mol) and the triethylamine was extracted with diethyl ether (3 × 5 cm^3). The aqueous layer was acidified with conc. H_2SO_4 and extracted with chloroform (10 × 15 cm^3). The combined extracts were evaporated and distilled to give *O*-methyl hydrogen t-butylphosphonothioate **20**, b.p. 75–77 °C/0.15 mmHg (76%); δ_P (24.3 MHz; benzene) +104.67. Starting from (*S*)-(−)-**19**, $[\alpha]_D$ −10.10° (neat), and (*R*)-(+)-**19**, $[\alpha]_D$ +11.90 (neat), were obtained (*R*)-(+)-**20**, $[\alpha]_D$ +11.20° (*c* 5.81) and (*S*)-(−)-**20**, $[\alpha]_D$ −11.70 (*c* 4.92), respectively.

Reaction of Optically Active O-*Methyl t-Butylphosphinate* **19** *with Methanesulphenyl Chloride*.—To a stirred solution of (*R*)-(+)-**19** (1.00 g, 7.35 mmol), $[\alpha]_D$ +9.39 (neat), in benzene (10 cm^3) at 0 °C was added dropwise a solution of freshly prepared methanesulphenyl chloride[9] (7.5 mmol) in benzene (5 cm^3). The solvent was evaporated off under reduced pressure, and the residue was distilled to give (*S*)-(−)-*O*,*S*-dimethyl t-butylphosphonothiolate **3a**, $[\alpha]_D$ −59.80 (*c* 15.67), δ_P (24.3 MHz; benzene) +65.59.

Reaction of Optically Active O-*Methyl t-Butylphosphinate* **19** *with* N-*Chlorosuccinimide*.—To a solution of (*R*)-(+)-**19**, $[\alpha]_D$ +9.39 (neat) (2.00 g, 0.015 mol) in carbon tetrachloride (3 cm^3) at 0 °C was added portionwise *N*-chlorosuccinimide (2.00 g, 0.015 mol) under dry argon. Succinimide was filtered off, the solvent was evaporated off under reduced pressure, and the residue was distilled to give (*S*)-(−)-*O*-methyl t-butylphosphonochloridate **7e** (1.79 g, 70%), $[\alpha]_D$ −78.52° (*c* 12.34); δ_P (24.3 MHz; benzene) +58.1.

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