1081. *The Reactivity of Organophosphorus Compounds. Part VIII.*[1] *The Reactions of Chloramine-*T *with Triethyl Phosphorothiolate and Related Compounds.*

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Aqueous chloramine-T and triethyl phosphorothiolate give diethyl hydrogen phosphate, ethanesulphonic acid, *S*-ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine, and sulphuric acid in amounts varying according to the conditions. The mechanism of the reaction is discussed in the light of evidence collected from this reaction and those carried out with related thiolates and sulphidimines, and it is concluded that the sulphidimine is an intermediate product. Triethyl phosphorothionate and aqueous chloramine-T give triethyl phosphate, sulphur, and sulphuric acid.

CHLORAMINE-T is known to react readily with organic sulphur compounds. Clarke, Kenyon, and Phillips [2] were the first to show that ethanethiol and aqueous chloramine-T gave *S*-ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine (II; R = Et). Alexander and McCombie [3] found that reaction with diethyl disulphide gave the same product. Bulmer and Mann [4] later showed that the thiol was oxidised by chloramine-T to the disulphide, which then reacted to give the sulphidimine. More recently Weibull [5] noted the formation of sulphidimines in the reactions between chloramine-B and *S*-esters of thioacetic, thiobenzoic, and thiosulphonic acid. The reactions between chloramine-T and phosphorothioates such as triethyl phosphoro-thiolate (I; R = Et) and -thionate [$(EtO)_3PS$] and related compounds are now described in this paper. The work was undertaken in the expectation that thiolates (I) would give the corresponding sulphidimines (II) which, as solids, would be acceptable derivatives of the type required for another investigation.

It has now been shown that fission of the phosphorus–sulphur bond occurs when triethyl phosphorothiolate (I; R = Et) reacts with aqueous chloramine-T. The *S*-ethyl group appears as ethanesulphonic acid and *S*-ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine (II; R = Et). Inorganic sulphate, toluene-*p*-sulphonamide, and diethyl hydrogen phosphate are also produced in the reaction, which is heterogeneous when carried out in water. The addition of ethanol as a homogenising agent affects the relative proportions, but not the nature, of the products formed; the proportions also vary with the temperature and the relative proportions of the reactants, as shown in the Table. In unbuffered solution there is an induction period followed by rapid reaction during which the pH drops from 8, that of aqueous chloramine-T, to 2.

The reaction with *S*-benzyl diethyl phosphorothiolate (I; R = $Ph{\cdot}CH_2$), carried out in boiling aqueous ethanol, gives benzyl alcohol and sulphate (81%), but no sulphidimine.

$(EtO)_2PO{\cdot}SR$ (I)

$p\text{-}C_6H_4Me{\cdot}SO_2{\cdot}N{:}SR{\cdot}NH{\cdot}SO_2{\cdot}C_6H_4Me\text{-}p$ (II)

$(EtO)_2PO{\cdot}NH{\cdot}SO_2{\cdot}C_6H_4Me\text{-}p$ (III)

In the reaction with phosphorothiolates it was considered possible that the sulphidimine was formed by chlorination of the ester followed by reaction of the products of chlorination with chloramine-T. Sulphenyl trichlorides and sulphenyl chlorides [6] are considered to be intermediates in the chlorination of phosphorothiolates. Neither the reaction between ethanesulphenyl trichloride and chloramine-T, nor that with toluene-*p*-sulphonamide, gave the sulphidimine. The sulphidimine (II; R = Et) was isolated, however, with ethanesulphonic acid, after reaction of ethanesulphenyl chloride and chloramine-T in

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[1] Part VII, Cadogan and Moulden, *J.*, 1961, 3080.
[2] Clarke, Kenyon, and Phillips, *J.*, 1930, 1225.
[3] Alexander and McCombie, *J.*, 1932, 2087.
[4] Bulmer and Mann, *J.*, 1945, 666.
[5] Weibull, *Arkiv Kemi*, 1951, **3**, 171.
[6] Stirling, *J.*, 1957, 3597.

Reactions of chloramine-T with thiolates and sulphidimines.[a]

Compound (P)	$(EtO)_2PO{\cdot}SEt$								X[i]	Y		Z
Molar ratio, CT/P	1	2	2	2	2[b]	4	4[c]	4[d]	4·2	2[g]	2	2
Temp.	20	20	20	80	20	20	80	20	80	100	80	100
Time (hr.)	48	48	48	0·25	18	24	0·25	0·5	0·5	28	0·25	0·25
EtOH (v/v)	0	0	30	30	30	0	30	0	20	0	20	0
$Ar{\cdot}SO_2{\cdot}NH_2$[e]	0·78	0·74	0·49	0·86	0·96	0·74	0·90	0·91	0·99	3·4[f]	3·0[f]	3·37
Sulphidimine	0·22	0·20	0·53	0·09	0	0·20	0·02	0·02	0	0	0·09	0
SO_4	0·02	0·03	0·03	0·05	0·01	—	0·44	—	0·81	0·60	0·45	0·98
$Et{\cdot}SO_3H$	0·32	0·30	—	—	—	—	—	—	—	—	0·14	—
$(EtO)_2PO_2H$	0·79	0·77	—	—	—	—	—	—	0·99[h]	—	—	—
Thiolate recovered (%)	56	25	17	29	12	0	0	0	0	—	—	—

X, $(EtO)_2P(O){\cdot}S{\cdot}CN_2Ph$. *Y*, $ArSO_2{\cdot}NH{\cdot}SEt{:}N{\cdot}SO_2Ar$. *Z*, $ArSO_2{\cdot}NH{\cdot}S(CH_2Ph){:}N{\cdot}SO_2Ar$.

[a] Products given in moles per mole of sulphur compound reacted. [b] In the presence of HCl; $Et{\cdot}SO_2H$ was also formed. [c] $(EtO)_3PO$ (0·07 mole/mole) was also formed. [d] In the presence of HCl; $Et{\cdot}SO_2Cl$ (55%) was also formed. [e] Moles/mole of chloramine-T. [f] Moles/mole of sulphidimine. [g] In the presence of HCl. [h] Impure. [i] $Ph{\cdot}CH_2{\cdot}OH$ (0·44 mole/mole) was also isolated. [j] $Ph{\cdot}CH_2{\cdot}OH$ (0·26 mole/mole) was also isolated.

aqueous ethanol, a small quantity of impure diethyl disulphide being also obtained. Disulphides[7] and thiolsulphonates[8] have been isolated after reaction of sulphenyl halides and alcohols, so the formation of the sulphidimine in the reaction of sulphenyl chloride with chloramine-T can be rationalised. It is particularly significant in this connection that the yield of sulphidimine from triethyl phosphorothiolate was greatest when the reaction was carried out in aqueous ethanol. Further, a small quantity of diethyl disulphide was detected in the products of the reaction of two mol. of triethyl phosphorothiolate with one of chloramine-T; the sulphidimine (II; R = Et) and unchanged phosphorothiolate were also isolated. It is possible therefore that some, at least, of the sulphidimine is formed by way of the disulphide.

Weibull[5] isolated *N*-benzoylbenzenesulphonamide from the reaction products of *S*-cyclohexyl thiobenzoate and chloramine-B. A re-investigation, with chloramine-T and *S*-ethyl thiobenzoate, has confirmed this and, in addition, toluene-*p*-sulphonamide, the sulphidimine (II; R = Et), benzoic acid, and inorganic sulphate were isolated, and the odour of benzoyl chloride was apparent after the reactants had been mixed.

In contrast, the analogous diethyl *N*-*p*-toluenesulphonylphosphoramidate (III) was not isolated from or detected in reactions with triethyl phosphorothiolate, although a careful search was made. The amidate (III) was shown to be unaffected by boiling aqueous-ethanolic chloramine-T, and was recovered from a reaction mixture of triethyl phosphorothiolate and chloramine-T to which it had been added. It thus appears that attack on the phosphorus atom by the *N*-chlorotoluene-*p*-sulphonamide anion occurs only to a very small extent, if at all, providing a further example of the reduced electrophilicity of phosphoryl phosphorus compared with carbonyl carbon.

As a result of the pH change during the reaction of aqueous chloramine-T with thiolates, it is necessary to examine the consequence of such a change on chloramine-T.

Chloramine-T, in aqueous solution, is partly converted into toluene-*p*-sulphonamide and dichloramine-T by the addition of acid. This has been demonstrated for chloramine-B by Zil'berg.[9] Morris, Salazar, and Wineman[10] have assumed that the following equibria exist in slightly acid solutions and have calculated equilibrium constants:

$$H_2O + p\text{-}C_6H_4Me{\cdot}SO_2{\cdot}NCl_2 \rightleftharpoons p\text{-}C_6H_4Me{\cdot}SO_2{\cdot}NHCl + HOCl$$

$$2p\text{-}C_6H_4Me{\cdot}SO_2{\cdot}NHCl \rightleftharpoons p\text{-}C_6H_4Me{\cdot}SO_2{\cdot}NCl_2 + p\text{-}C_6H_4Me{\cdot}SO_2{\cdot}NH_2$$

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[7] Zinke and Farr, *Annalen*, 1912, **391**, 57.

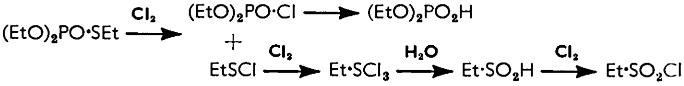
[8] Zinke and Esmayer, *Ber.*, 1918, **51**, 751.

[9] Zil'berg, *J. Gen. Chem. U.S.S.R.*, 1946, **16**, 2145.

[10] Morris, Salazar, and Wineman, *J. Amer. Chem. Soc.*, 1948, **70**, 2036.

Also, chloramine-T in the presence of hydrochloric acid has been used to chlorinate acetanilide, and Orton and Bradfield[11] considered the chlorinating agent to be molecular chlorine. Thus, in the reaction with phosphorothiolates, when the reaction mixture becomes acidic several reactive species are almost certainly involved and may include chlorine, *N*-chlorotoluene-*p*-sulphonamide, and the H_2OCl^+ ion produced from hypochlorous acid or by hydrolysis of *N*-chlorotoluene-*p*-sulphonamide.

Stirling[6] found that aqueous chlorination of triethyl phosphorothiolate produced ethanesulphonyl chloride and diethyl hydrogen phosphate, and suggested the following mechanism:



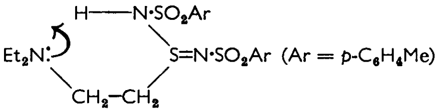
$$(EtO)_2PO{\cdot}SEt \xrightarrow{Cl_2} \begin{array}{l} (EtO)_2PO{\cdot}Cl \longrightarrow (EtO)_2PO_2H \\ + \\ EtSCl \xrightarrow{Cl_2} Et{\cdot}SCl_3 \xrightarrow{H_2O} Et{\cdot}SO_2H \xrightarrow{Cl_2} Et{\cdot}SO_2Cl \end{array}$$

Since molecular chlorine is almost certainly present when the reaction mixture is acidic, it is possible that the formation of ethanesulphonic acid in reactions with chloramine-T proceeds by a similar mechanism. This is supported by the isolation of ethanesulphonyl chloride from a reaction in acid solution between chloramine-T and triethyl phosphorothiolate, and the isolation of triethyl phosphate from a reaction carried out in aqueous ethanol is considered to be evidence for the formation of diethyl phosphorochloridate at one stage of the reaction. Ethanesulphinic acid, isolated as benzyl ethyl sulphone, was also a product of the reaction of chloramine-T and triethyl phosphorothiolate in the presence of hydrochloric acid, and, in fact, Stirling[6] found that sulphinic acids were products of partial aqueous chlorination of phosphorothiolates. It is probable therefore that that part of the reaction between chloramine-T and triethyl phosphorothiolate which occurs at low pH is initially a chlorination, although participation of other species mentioned above cannot be excluded.

Epstein and Lordi[12] have shown that alkaline hydrolysis of triethyl phosphorothiolate to ethanethiol and diethyl hydrogen phosphate is catalysed by hypochlorite ion. It was therefore possible that the reaction between chloramine-T and phosphorothiolate also involves catalysis [equation (1)] by the $Ar{\cdot}SO_2{\cdot}NCl^-$ ion or a similar species. Ethanethiol, which would be produced by such a reaction, is known to react with chloramine-T to give the sulphidimine (II; R = Et). Such catalysis was, however, shown not to occur.

$$(EtO)_2PO{\cdot}SR \xrightarrow{Ar{\cdot}SO_2{\cdot}NCl^-} RS^- + (EtO)_2PO{\cdot}NCl{\cdot}SO_2Ar \xrightarrow{HO^-} (EtO)_2PO_2H + Ar{\cdot}SO_2{\cdot}NCl^- \quad . \quad (1)$$

Reaction between triethyl phosphorothiolate and chloramine-T in aqueous sodium hydrogen carbonate was very slow and no sulphidimine was formed. Similarly, *S*-2-diethylaminoethyl thiobenzoate, which acts as its own buffer, did not react in 20 hr., whereas the hydrochloride of this base reacted very rapidly with aqueous chloramine-T to give *S*-2-diethylaminoethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine (II; $R = Et_2N{\cdot}CH_2{\cdot}CH_2$). It can be concluded, therefore, that sulphidimine formation occurs in acid solution, *i.e.*, under conditions where products derived by chlorination of the ester have been shown to be formed. It is noteworthy that the sulphidimine (II; $R = Et_2N{\cdot}CH_2{\cdot}CH_2$) crystallised directly from hydrochloric acid solution and not as the hydrochloride, showing that zwitterion formation had occurred.



The formation of sulphate from the *S*-alkyl group of the phosphorothiolates is considered to involve two distinct stages, namely, the formation of the sulphidimine (II)

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[11] Orton and Bradfield, *J.*, 1927, 986.

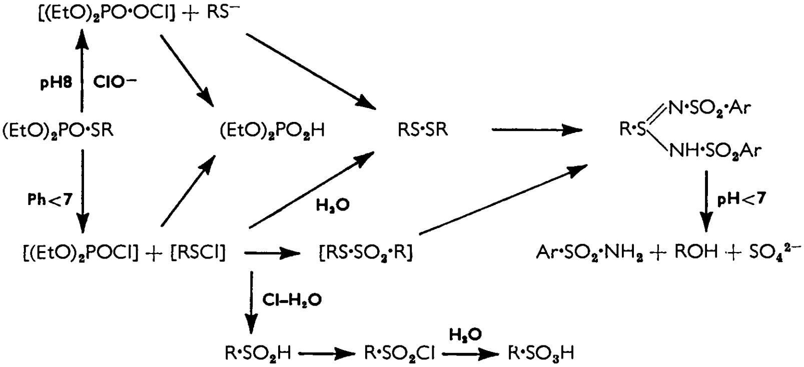
[12] Epstein and Lordi, *J. Amer. Chem. Soc.*, 1958, **80**, 509.

and its subsequent reaction with chloramine-T (or its transformation products) in acid solution. This follows from the observations that both *S*-benzyl- (II; R = Ph·CH$_2$) and *S*-ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine (II; R = Et) reacted readily with chloramine-T in unbuffered and in acid solution, but not in alkaline solution, to give sulphate. Thus during the reaction of phosphorothiolates with chloramine-T, when the reaction medium becomes acidic, the reactions of the remaining chloramine-T (or its equivalent in acid solution) with phosphorothiolate and sulphidimine are in competition. The variations in yields of products with changes in conditions are explicable on this basis.

No identifiable intermediate products of the reaction of chloramine-T and the sulphidimine (II; R = Et) could be isolated, but a hygroscopic mixture was obtained which gave more sulphate on treatment with chloramine-T. We have no evidence that the initial stages of the decomposition of the sulphidimine (II; R = Et) involve fission of sulphur–nitrogen bonds, since ethanesulphinic acid, ethanesulphonic acid, and ethanesulphonyl chloride, possible intermediates in such a reaction, give only traces of sulphate under these conditions.

Weibull [5] noted the formation of sulphate in reactions of chloramine-B with dicyclohexyl disulphide and with *S*-cyclohexyl thioacetate and thiobenzoate but proposed a mechanism for its formation which neglected the reaction between sulphidimine and chloramine-T.

Our suggestions concerning the reaction between phosphorothiolates and chloramine-T can be summarised as annexed, where hypothetical intermediates are indicated in square brackets.



Spontaneous hydrolysis of chloramine-T to give hypochlorous acid is first invoked, followed by hypochlorite-ion catalysis of the hydrolysis at pH 8 of the ester to give thiol anion and diethyl hydrogen phosphate.[12] This hydrolysis is relatively slow at pH 8 but is replaced as the main mode of decomposition as soon as the medium becomes acid. At this point the many possible reactions referred to above can become operative, including aqueous chlorination leading to the formation of disulphide, thiosulphonate, and sulphenyl chloride, all of which react with chloramine-T to give the sulphidimine. The possibility that the sulphidimine can be formed by way of *N*-ethanesulphenyltoluene-*p*-sulphonamide exists but has not been confirmed by isolation of this substance as an intermediate product in any of our experiments.

Triethyl phosphorothionate, (EtO)$_3$PS, with chloramine-T gives triethyl phosphate, sulphur, inorganic sulphate, and toluene-*p*-sulphonamide. When the proportion of chloramine-T to ester and the temperature are both increased, a greater yield of sulphate is obtained; chloramine-T and sulphur in boiling water give good yields of sulphate, and it is probably this reaction which accounts for the increased yield of sulphate.

EXPERIMENTAL

Extracts were dried over magnesium sulphate. The light petroleum used had b. p. 40—60°. A Perkin-Elmer " Fraktometer " model 116, fitted with a high-sensitivity dual thermal conductivity detector, was used. The response was tested by analysis of mixtures of known composition and found to be satisfactory. The column packings were " A," di-n-decyl phthalate on Celite, and " C " Silicone oil D.C. 200 on Celite.

Preparation of Compounds.—Triethyl phosphorothiolate, b. p. 95°/12 mm., n_D^{25} 1·4553 (lit.,[6] b. p. 79°/1·3 mm., n_D^{25} 1·4570), was prepared from sodium *OO*-diethyl phosphorothiolate and ethyl bromide. Triethyl phosphorothionate, b. p. 121—124°/60 mm., n_D^{25} 1·4464 (lit.,[13] b. p. 95°/12 mm., n_D^{20} 1·4480 [14]), was obtained after addition of sulphur to triethyl phosphite at room temperature. *S*-Benzyl diethyl phosphorothiolate, b. p. 130°/0·2 mm., n_D^{25} 1·5234 (lit.,[6] b. p. 130°/0·2 mm., n_D^{25} 1·5229), was prepared from benzyl chloride and sodium *OO*-diethyl phosphorothioate in ethanol. *S*-Ethyl thiobenzoate was prepared by boiling thiobenzoic acid (50 g.), sodium ethoxide solution (sodium, 8·33 g.; ethanol, 250 ml.) and ethyl iodide (64 g.) for 90 min.; removal of the low-boiling components followed by treatment with water gave the ester (15·5 g.), b. p. 128—130°/12 mm., n_D^{25} 1·5703 (Wolfrom and Karabinos [15] report n_D^{20} 1·5721).

Ethanesulphenyl Chloride.[16]—Diethyl disulphide [17] (5·0 g.) was stirred in methylene chloride (20 ml.) at $-20°$ while a solution of chlorine (3·0 g.) in methylene chloride (50 ml.) was added. Distillation gave ethanesulphenyl chloride, b. p. 20—30°/14 mm. (2·44 g.). Ethanesulphenyl trichloride was prepared by chlorination of ethanesulphenyl chloride in carbon tetrachloride at $-20°$ as described by Douglass and Poole.[18] *S*-Ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine, m. p. 189° (decomp.), was prepared by Clarke, Kenyon, and Phillips's method;[2] they reported m. p. 189°. *S*-Benzyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine, m. p. 177—178° (decomp.), was prepared from chloramine-T and dibenzyl disulphide by the method of Bulmer and Mann,[4] who reported m. p. 171—171·5°.

Reduction of ethanesulphonyl chloride with aqueous sodium sulphite [19] gave sodium ethanesulphinate (20%), characterised as benzyl ethyl sulphone, m. p. 84°.

Diethyl *N*-toluene-*p*-sulphonyl phosphoramidate, m. p. 106—107°, was prepared by Ratz's method.[20]

S-2-*Diethylaminoethyl*-S-*toluene*-p-*sulphonamido*-N-*toluene*-p-*sulphonylsulphidimine*.—Iodine (10·3 g.) was added to 2-diethylaminoethanethiol (10·8 g.) and sodium ethoxide [from sodium (1·87 g.) and ethanol (100 ml.)]. Removal of the solvent followed by addition of water and extraction with ether gave bis-2-diethylaminoethyl disulphide (8·16 g.), b. p. 106—114°/0·05 mm., n_D^{25} 1·5026 (Found: C, 54·6; H, 10·5. Calc. for $C_{12}H_{23}N_2S_2$: C, 54·5; H, 10·7%); [*dimethiodide*, m. p. 213—214° (from methanol–ether) (Found: C, 30·7; H, 6·1. $C_{14}H_{34}I_2N_2S_2$ requires C, 30·7; H, 6·25%)].

The disulphide (1·32 g.) in methanol (10 ml.), and chloramine-T (5·821 g., 4 mol.) in methanol (20 ml.) and water (50 ml.), were stirred together for 30 min. S-2-*Diethylaminoethyl*-S-*toluene*-p-*sulphonamido*-N-*toluene*-p-*sulphonylsulphidimine* (2·50 g.), which separated from acid solution, crystallised from ethanol and then had m. p. 189—190° (decomp.) (Found: C, 51·4; H, 6·4; S, 19·9. $C_{20}H_{29}N_3O_4S_3$ requires C, 50·95; H, 6·2; S, 20·4%).

S-2-Diethylaminoethyl thiobenzoate, b. p. 110°/0·1 mm., n_D^{25} 1·5460, was prepared as described by Stirling [21] who reported n_D^{25} 1·5465.

Reactions with Chloramine-T.—Some of the reactions carried out are described in detail below. Where reaction conditions or methods of isolation of products are only slightly different, details have not been given. The reaction conditions and results of these experiments are given in the Table. In these cases the identities of the products were confirmed by mixed m. p. determinations and/or comparison of infrared spectra.

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[13] Strecker and Spitaler, *Ber.*, 1926, 1772.

[14] Arbuzov and Vinogradova, *Izvest. Akad. Nauk S.S.S.R.*, 1947, 459.

[15] Wolfrom and Karabinos, *J. Amer. Chem. Soc.*, 1946, **68**, 1455.

[16] Cf. Britzinger and Langheck, *Chem. Ber.*, 1953, **86**, 557.

[17] Vogel and Cowan, *J.*, 1943, 16.

[18] Douglass and Poole, *J. Org. Chem.*, 1957, **22**, 536.

[19] Cf. Smiles and Berl, *Org. Synth.*, Coll. Vol. I, p. 7.

[20] Ratz, *J. Org. Chem.*, 1957, **22**, 372.

[21] Stirling, *J.*, 1958, 4524.

Reaction of Triethyl Phosphorothiolate with Aqueous Chloramine-T.—(a) 1 : 1 *Mole*. Chloramine-T (28·2 g.), in water (250 ml.) at 5°, was added during ½ hr. to a stirred suspension of triethyl phosphorothiolate (20 g.) in water (20 ml.). The mixture was stirred for a further 10 min., during which the pH of the mixture changed from 8 to 2 and a white solid separated. The white solid liberated iodine from potassium iodide but the supernatant liquid gave no reaction. The mixture was set aside for 48 hr. at room temperature and then boiled under reflux for 10 min. The white crystals which separated on cooling gave no reaction with potassium iodide and were filtered off and washed with light petroleum (4 × 60 ml.). Recrystallisation from dilute sodium carbonate solution gave toluene-*p*-sulphonamide (10·12 g.), m. p. and mixed m. p. 139—140°. Extraction of the mother liquors with ether gave more sulphonamide (1·41 g.), m. p. and mixed m. p. 138—139°. The mother liquors were acidified with hydrochloric acid; the white precipitate was fractionally crystallised from ethanol, to give *S*-ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine (3·90 g.), m. p. and mixed m. p. 186—187° (decomp.), and a white solid (0·24 g.), m. p. 126—140° (decomp.), shown by its infrared spectrum to be impure sulphidimine. Extraction of the acid mother liquors with ether gave toluene-*p*-sulphonamide (0·69 g.), m. p. 130—132°. The filtered reaction mixture was made alkaline (Na_2CO_3) and extracted continuously with ether. The ether extracts, combined with the light petroleum washings of the sulphonamide fraction, were distilled, giving a colourless liquid (11·49 g.), b. p. 30—50°/0·1 mm., n_D^{25} 1·4584, and left a black residue (1·39 g.), b. p. >120°/0·1 mm., which on crystallisation from aqueous ethanol yielded toluene-*p*-sulphonamide (1·07 g.), m. p. 129—137°, whose identity was confirmed by its infrared spectrum. The distillate was shown to contain 97 ± 1% of triethyl phosphorothiolate, by comparison of its infrared spectrum with that of authentic material (method of Augood, Hey, and Williams [22]) in chloroform with optical density measured at 1161, 1391, and 1441 cm.$^{-1}$. However, the material absorbed strongly at 1129 and 1323 cm.$^{-1}$. Triethyl phosphorothiolate has no absorption bands at these frequencies. Gas–liquid chromatography of this fraction (2 m. column, packing " C," at 190°) confirmed that it contained 97% of triethyl phosphorothiolate and revealed the presence of four other components having slightly lower b. p.

The reaction mixture, which had been extracted with ether, was made just acid with hydrochloric acid and extracted with ether (5 × 50 ml.). The material in the extracts, on crystallisation from benzene–light petroleum, gave toluene-*p*-sulphonamide (0·08 g.), m. p. 130—133°, and an oil (0·19 g.) whose infrared spectrum was consistent with that of a mixture of toluene-*p*-sulphonamide and diethyl hydrogen phosphate. No diethyl *N*-toluene-*p*-sulphonylphosphoramidate was isolated, and its presence could not be detected by examination of the infrared spectrum of the oil. After addition of sodium chloride and an excess of hydrochloric acid, the aqueous reaction mixture was continuously extracted with ether (24 hr.). The ether extracts gave diethyl hydrogen phosphate (5·46 g.) b. p. 120—140°/0·01 mm., n_D^{25} 1·4122, which was identified by comparison of its infrared spectrum with that of authentic material. The aqueous layer was then neutralised with sodium carbonate and evaporated to dryness. Ethanol extracts of the residue gave sodium ethanesulphonate (2·15 g.) (Found: S, 21·9. Calc. for $C_2H_5NaO_3S,H_2O$: S, 21·3%). Its identity was confirmed by comparison of its infrared spectrum with that of authentic material. The residue from the ethanol extraction was dissolved in dilute hydrochloric acid and treated with aqueous barium chloride, to give barium sulphate (0·223 g.).

Other experiments were carried out with the following molar ratios of thiolate to chloramine-T: 1 : 2; 1 : 2 in aqueous ethanol at 20° and 80°; 1 : 4 in aqueous ethanol at 80°. The products were isolated in the usual way and the results are summarised in the Table given above.

(b) 1 : 2 *Moles, with added diethyl* N-*toluene*-p-*sulphonylphosphoramidate*. Triethyl phosphorothiolate (10·0 g.) and chloramine-T (28·2 g.), in water (250 ml.), were allowed to react as described above, in the presence of an aqueous solution of the amidate (2·0 g.) which had been neutralised with sodium carbonate (0·35 g.). The aqueous sodium carbonate extracts of the sulphonamide–sulphidimine fraction, filtered off from the reaction mixture, were shown to be free from amidate by fractional crystallisation from ethanol and by spectroscopic examination of each fraction. After unchanged triethyl phosphorothiolate had been extracted the basified

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[22] Augood, Hey, and Williams, *J.*, 1953, 44.

reaction mixture was then strongly acidified with hydrochloric acid and extracted continuously with ether (24 hr.). The ether extracts was evaporated and the residue dissolved in saturated aqueous sodium hydrogen carbonate and continuously extracted with ether (24 hr.). The aqueous layer was acidified with hydrochloric acid and extracted with ether (4 × 50 ml.), giving a colourless oil (1·89 g.) whose infrared spectrum was identical with that of the amidate. The oil crystallised from dilute hydrochloric acid, containing sodium chloride, and gave the amidate, m. p. and mixed m. p. 102—104°.

(c) 2 : 1 *Moles.* The ester (10·0 g.) and chloramine-T (7·05 g.) were allowed to react in water (100 ml.) for 10 min. at room temperature. The mixture was extracted with light petroleum (4 × 50 ml.). Distillation of the water-washed extracts gave a fraction (4·58 g.), b. p. 100—125°/15 mm., n_D^{25} 1·4545, which contained triethyl phosphorothiolate (90%), diethyl disulphide (3%), and traces of light petroleum, as shown by gas–liquid chromatography as described above. *S*-Ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine (1·02 g.), m. p. and mixed m. p. 185° (decomp.), was isolated from a similar experiment carried out with the ester (5·0 g.) in 10% aqueous ethanol (30 ml.).

(d) 1 : 2 *Moles, at 20°, with added hydrochloric acid.* The reaction was carried out with the ester (5 g.) and hydrochloric acid (1·4 g.) in aqueous ethanol, working up being in the usual way. The results are summarised in the Table. The fraction (4·54 g.) containing sodium diethyl phosphate, on treatment with benzyl bromide in aqueous ethanol at 90°, gave benzyl ethyl sulphone, m. p. and mixed m. p. 81—82°. After a reaction with 4 equiv. of chloramine-T (see Table) the precipitate of sulphonamide and sulphidimine was washed with light petroleum. Distillation of the dried washings gave ethanesulphonyl chloride (55%), b. p. 72—75°/20 mm., n_D^{25} 1·4470 (anilide, m. p. and mixed m. p. 56°).

Reaction of S-*Benzyl Diethyl Phosphorothiolate with Aqueous Chloramine*-T.—The ester (5 g.) was used in 20% aqueous ethanol (300 ml.); details of products and conditions are given in the Table. Extraction of the basified reaction mixture with chloroform (8 × 100 ml.) gave benzyl alcohol (0·90 g.), b. p. 90—100°/20 mm. (3,5-dinitrobenzoate, m. p. and mixed m. p. 113°). No sulphidimine was detected. Benzyl alcohol was also isolated from a complementary experiment (see Table for details) with the sulphidimine (10·0 g.) in water (250 ml.).

Reaction of S-*Ethyl Thiobenzoate with Chloramine*-T.—Chloramine-T (21·2 g.) in water (270 ml.) was added slowly to a stirred suspension of *S*-ethyl thiobenzoate (5·0 g.) in water (10 ml.) at room temperature. White crystals appeared after 5 min. and there was an odour of benzoyl chloride. The mixture was left for 48 hr. at room temperature and then boiled under reflux, for 10 min. The solid which separated on cooling was collected, washed with light petroleum, and extracted with saturated aqueous sodium hydrogen carbonate. This left toluene-*p*-sulphonamide (3·31 g.), m. p. and mixed m. p. 136—137°. The petroleum washings gave benzoic acid (0·85 g.), m. p. and mixed m. p. 122—122·5°. The sodium hydrogen carbonate extracts were washed with chloroform, and the washings gave toluene-*p*-sulphonamide (2·73 g.), m. p. 136—138° (from aqueous ethanol). The alkaline solution was acidified with hydrochloric acid and the white precipitate was collected. The filtrate, on extraction with methylene dichloride, gave benzoic acid (1·0 g.), m. p. and mixed m. p. 120—121° (from water). The white precipitate crystallised from ethanol, giving *S*-ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine (2·67 g.), m. p. and mixed m. p. 185—186° (decomp.). The mother liquors were evaporated to dryness and the residue extracted with boiling water, leaving *N*-benzoyltoluene-*p*-sulphonamide (1·05 g.), m. p. and mixed m. p. 146—147° (from aqueous ethanol). The aqueous extract was fractionally crystallised from aqueous ethanol, giving more *N*-benzoyltoluene-*p*-sulphonamide (0·05 g.), m. p. and mixed m. p. 145—146°, and benzoic acid (0·33 g.), m. p. 110° undepressed on admixture with authentic material. The filtered reaction mixture was neutralised with sodium hydrogen carbonate and extracted with ether, to give toluene-*p*-sulphonamide (0·75 g.), m. p. 138—140° (from aqueous ethanol). The aqueous layer was evaporated under reduced pressure and the residue extracted with ethanol (2 × 50 ml.). The remaining solid was dissolved in dilute hydrochloric acid and treated with barium chloride, to give barium sulphate (0·296 g.). The ethanol extracts were reduced in volume to about 10 ml. and treated with ether, giving an unidentified white precipitate (1·05 g.) which recrystallised from ethanol–ether (Found: C, 26·4; H, 3·2; S, 16·35; Na, 19·0%).

Reaction of Ethanesulphenyl Chloride with Aqueous Chloramine-T.—Chloramine-T (8·89 g.) in 30% aqueous ethanol (90 ml.) was added to ethanesulphenyl chloride (3·05 g.). The orange colour of the sulphenyl chloride rapidly disappeared and heat was evolved. The mixture was left for 5 days at room temperature and a white precipitate was collected. This crystallised from dilute aqueous sodium carbonate, giving toluene-*p*-sulphonamide (3·74 g.), m. p. and mixed m. p. 138°, and the mother liquor, on acidification with hydrochloric acid, yielded *S*-ethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine (0·20 g.), m. p. and mixed m. p. 185—186° (decomp.). Chloroform extracts of the filtrate were digested with light petroleum and gave a fraction (0·2 g.), b. p. 80—140°/760 mm., whose infrared spectrum showed the presence of diethyl disulphide. Toluene-*p*-sulphonamide (0·50 g.), m. p. 137—138°, was extracted from the residue from the light petroleum extracts with aqueous ethanol. The extracted reaction mixture was neutralised with sodium carbonate and evaporated to dryness. Ethanol extracts gave sodium ethanesulphonate (1·77 g.); the residue, on treatment with barium chloride, gave barium sulphate (0·054 g.).

Reaction of freshly prepared ethanesulphenyl trichloride with aqueous-ethanolic toluene-*p*-sulphonamide or aqueous-ethanolic chloramine-T gave no sulphidimine.

Reactions of S-*Ethyl*-S-*toluene*-p-*sulphonamido*-N-*Toluene*-p-*sulphonylsulphidimine*.—(a) *With chloramine*-T. The details of the reaction carried out with the sulphidimine (10·0 g.) are given in the Table. The working up was standard. Evaporation of the ethanol extracts of the residue gave a hygroscopic solid mixture (3·0 g.). A portion (1·0 g.) gave sodium ethanesulphonate (0·13 g.). Another portion (1·28 g.) was extracted with acetone, and a solid was precipitated from the extracts on the addition of ether; recrystallisation from acetone–ether gave a very hygroscopic, unidentified substance (0·28 g.) (Found: C, 36·9; H, 4·6; N, 4·5; S, 22·3; Na, 8·3%). A third portion (1·0 g.) of the hygroscopic mixture (which contained no sulphate) was boiled with chloramine-T (7·05 g.) in water (100 ml.) for 16 hr.: barium sulphate (0·42 g.) and toluene-*p*-sulphonamide (3·48 g.) were isolated.

(b) *With chloramine*-T *and hydrochloric acid*. Hydrochloric acid (2·0 g.; *d* 1·18) was added to a solution of the sulphidimine (5·0 g.) and chloramine-T (7·05 g.) in water (150 ml.) (pH 2), and the mixture was boiled under reflux for 28 hr. Toluene-*p*-sulphonamide (7·21 g.) and barium sulphate (1·679 g.) were isolated as described above.

The sulphidimine was partially hydrolysed to toluene-*p*-sulphonamide and ethanesulphonic acid after treatment with hydrochloric acid alone under these conditions, but no sulphate was formed. The sulphidimine was recovered quantitatively after only 15 min. under the same conditions, and after being boiled (19 hr.) with aqueous chloramine-T (2 mol.) in the presence of sodium carbonate.

Reaction of Chloramine-T *with* S-2-*Diethylaminoethyl Thiobenzoate Hydrochloride*.—*S*-2-Diethylaminoethyl thiobenzoate (1 mol.) was dissolved in an excess of dilute hydrochloric acid, and aqueous chloramine-T (2 mol.) was added in 15 min. Reaction took place immediately. The mixture was treated as described for the reaction with ethyl thiobenzoate and give toluene-*p*-sulphonamide, benzoic acid, barium sulphate, and *S*-2-diethylaminoethyl-*S*-toluene-*p*-sulphonamido-*N*-toluene-*p*-sulphonylsulphidimine.

The free base was unchanged after treatment with chloramine-T (2 mol.) for 20 hr.

Reactions of Ethanesulphonic Acid and Related Compounds with Chloramine-T.—Sodium ethanesulphonate (9·0 g.) (prepared by hydrolysis of ethanesulphonyl chloride), hydrochloric acid (5·43 g.; *d* 1·18), and chloramine-T (30·21 g.) in water (350 ml.) were boiled under reflux for 10 hr. Barium sulphate (0·62 g.), toluene-*p*-sulphonamide (13·60 g.), and unchanged sodium ethanesulphonate were isolated.

A similar reaction with ethanesulphonyl chloride (10·0 g.) gave sodium ethanesulphonate (11·15 g.) and barium sulphate (0·72 g.).

A solution of sodium ethanesulphinate (2·0 g.), hydrochloric acid (1·43 g.; *d* 1·18), and chloramine-T (4·02 g.) in 20% aqueous ethanol (110 ml.) was boiled under reflux for $\frac{3}{4}$ hr. Toluene-*p*-sulphonamide, (2·35 g.), m. p. and mixed m. p. 130°, sodium ethanesulphonate (1·38 g.), and barium sulphate (0·237 g.) were isolated.

Reaction of Diethyl N-*Toluene*-p-*sulphonylphosphoramidate with Chloramine*-T.—(a) *At* pH 2. The amidate (1·0 g.) and chloramine-T (0·90 g.) were dissolved in 30% aqueous ethanol (30 ml.). The solution was acidified with hydrochloric acid and boiled for 30 min., then basified with sodium carbonate solution and extracted continuously with ether (12 hr.). The extracts gave toluene-*p*-sulphonamide (0·56 g.), m. p. and mixed m. p. 137—138°. The aqueous layer was acidified and extracted with ether, giving an oil (1·0 g.) which slowly crystallised. Recrystallisation from dilute hydrochloric acid gave the unchanged amidate, m. p. and mixed m. p. 100°.

(b) *At* pH 10. A solution of the amidate (1·0 g.), sodium carbonate (0·34 g.), and chloramine-T (0·90 g.) in 25% aqueous ethanol (40 ml.) was boiled for 6½ hr. Toluene-*p*-sulphonamide and the unchanged amidate (0·95 g.) were isolated.

Kinetics of the Alkaline Hydrolysis of Triethyl Phosphorothiolate.—The method described by Thain [23] was used. The following rate constants (l. mole^{-1} sec.$^{-1}$, at 25°) were obtained: (*a*) Thiolate (1 g.) in 0·05N-KOH (250 ml.), $k_2 = 0{\cdot}154$. (*b*) With added chloramine-T (5%), $k_2 = 0{\cdot}158$. (*c*) With added chloramine-T (10%), $k_2 = 0{\cdot}155$.

Reaction of Triethyl Phosphorothionate with Chloramine-T.—(a) 1 : 2 *Moles at* 25°. Chloramine-T (14·1 g.) in 30% aqueous ethanol (140 ml.) was added slowly to triethyl phosphorothionate (5·0 g.) in ethanol (30 ml.) and the mixture left at room temperature for 15 hr. The pale yellow solid which separated was collected, washed with light petroleum, and extracted with boiling water, leaving sulphur (0·11 g.), m. p. 114·5° (Found: S, 98·1%). The aqueous extracts yielded toluene-*p*-sulphonamide (7·0 g.), m. p. and mixed m. p. 137—138°. Ethanol was distilled from the filtrate and the residue, after basification with aqueous sodium carbonate, was extracted with chloroform. These extracts, combined with the light petroleum washings of the sulphonamide fraction, yielded an oily solid, which was washed with light petroleum, leaving toluene-*p*-sulphonamide (0·75 g.), m. p. 130°. The light petroleum washings were distilled, giving a fraction (3·15 g.), b. p. 108—114°/20 mm., n_D^{25} 1·4209, which was identified by its infrared spectrum as a mixture of unchanged triethyl phosphorothionate and triethyl phosphate. This finding was confirmed by gas-liquid chromatography (2 m. column, packing " C ", 194°, column pressure 0·6 kg. cm.$^{-2}$) which showed that the mixture contained 50% of triethyl phosphorothionate. The extracted reaction mixture, when acidified and treated with barium chloride, gave barium sulphate (1·903 g.).

(b) 1 : 4·7 *Moles at* 80°. Triethyl phosphorothionate (5·0 g.) and chloramine-T (26·29 g.) in 10% aqueous ethanol (350 ml.) were boiled under reflux for 2 hr. Toluene-*p*-sulphonamide (15·12 g.), sulphur (0·13 g.), barium sulphate (4·795 g.), and triethyl phosphate (2·16 g.), b. p. 100—101°/12 mm., n_D^{25} 1·4030, were isolated, but no triethyl phosphorothionate was recovered.

Reaction of Sulphur with Chloramine-T.—Sulphur (0·64 g.) and chloramine-T (11·28 g.) in water (150 ml.) were boiled under reflux for 2 hr. Unchanged sulphur (0·28 g.) was separated from the hot reaction mixture, which was then allowed to cool. Toluene-*p*-sulphonamide (4·83 g.), m. p. and mixed m. p. 137—138°, was collected and the mother-liquors were extracted with chloroform to give more sulphonamide (1·35 g.), m. p. 132°. The aqueous layer, on treatment with barium chloride, gave barium sulphate (2·613 g.).

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[23] Thain, *J.*, 1957, 4694.