The Infrared Spectra of Some Sulphonamides.

By J. N. BAXTER, J. CYMERMAN-CRAIG, and J. B. WILLIS.

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The infrared spectra of various unsubstituted and *N*-substituted sulphonamides have been measured, and characteristic frequencies for the $SO_2\cdot NRR'$ group are discussed. From intensity measurements on the N–H bands at various concentrations, association constants have been obtained for solutions of several *N*-monosubstituted sulphonamides. The structure of the molecular compound prepared by Baxter, Cymerman-Craig, and Gilbert (*J.*, 1953, 2400) has been clarified by means of infrared measurements.

ALTHOUGH fairly detailed studies have been made of the infra-red spectra of the carboxyamides (Richards and Thompson, *J.*, 1947, 1248; Lenormant, *Ann. Chim.*, 1950, 5, 459; Davies and Hallam, *Trans. Faraday Soc.*, 1951, **47**, 1170; Letaw and Gropp, *J. Chem. Phys.*, 1953, **21**, 1621; Gierer, *Z. Naturforsch.*, 1953, **8**, *B*, 644, 654) little discussion of the sulphonamides has appeared. A few isolated observations have been made on the infra-red and Raman spectra of benzene- and toluene-sulphonamides (Schreiber, *Analyt. Chem.*, 1949, **21**, 1168; Angus, Leckie, and Williams, *Trans. Faraday Soc.*, 1938, **34**, 793) but these were not primarily concerned with the spectroscopy of the $SO_2\cdot NH_2$ group as such. Adams and Tjepkema (*J. Amer. Chem. Soc.*, 1948, **70**, 4204) found a strong band in the infra-red spectra of several *NN*-disubstituted sulphonamides at 1160—1180 cm.$^{-1}$ which could be assigned to the sulphonyl group.

TABLE 1.

No.	Compound
1	2-*N*-*p*-Diphenylylaminoethanol
2	*N*-*p*-Diphenylyltoluene-*p*-sulphonamide + *N*-*p*-Diphenylyl-*N*-2′-hydroxyethyltoluene-*p*-sulphonamide
3	*N*-*p*-Diphenylylethylamine
4	*N*-*p*-Diphenylyl-*N*-ethyltoluene-*p*-sulphonamide *
5	*N*-*p*-Diphenylyl-2-methoxyethylamine *
6	*N*-*p*-Diphenylyl-*N*-2′-methoxyethyltoluene-*p*-sulphonamide *
7	*N*-*p*-Diphenylyltoluene-*p*-sulphonamide
8	Benzenesulphonamide
9	Toluene-*p*-sulphonamide
10	Benzenesulphonanilide
11	Sulphanilamide
12	*o*-Sulphobenzoimide (saccharin)
13	*N*-Benzenesulphonyl-*p*-phenetidine
14	*N*-Benzenesulphonyl-*p*-nitroaniline
15	*N*-Methyl-*p*-acetamidobenzenesulphonanilide *
16	*NN*-Diethyltoluene-*p*-sulphonamide
17	Methanesulphonanilide
18	Methanesulphonamide
19	*N*-Methylmethanesulphonamide *
20	*N*-Ethyltoluene-*p*-sulphonamide
21	*N*-*p*-Diphenylyl-*N*-2′-hydroxyethyltoluene-*p*-sulphonamide *
22	2-Anilinoethanol
23	*N*-Phenyl-*N*-*n*-propylaminoethanol *
24	Acetanilide
25	Diphenylamine

* See Experimental.

In the present work the spectra of the 25 compounds listed in Table 1 have been measured between 400 and 4000 cm.$^{-1}$ both in the solid state and, over the 1100—1400 cm.$^{-1}$ and 2700—4000 cm.$^{-1}$ regions, in solution. The principal results are summarised in Table 2, where compounds are classified as unsubstituted, *N*-monosubstituted, and *NN*-disubstituted sulphonamides. The spectroscopic method is then applied to the solution of the structure of the molecular compound (No. 2) formed between *N*-*p*-diphenylyltoluene-*p*-sulphonamide (No. 7) and *N*-*p*-diphenylyl-*N*-2′-hydroxyethyltoluene-*p*-sulphonamide (Baxter, Cymerman-Craig, and Gilbert, *loc. cit.*).

EXPERIMENTAL

Source of Materials.—Compounds 1, 2, and 3 were the pure samples described by Baxter, Cymerman-Craig, and Gilbert (*loc. cit.*). Nos. 7—14, 16—18, 20, 24, and 25 had the m. p.s recorded in the literature. 2-Anilinoethanol (No. 22) had b. p. 103—104°/0·01 mm., n_D^{24} 1·5755.

Compound 4 was unchanged after 38 hours' boiling with 24% aqueous or alcoholic hydrochloric acid, or after 6 hours' refluxing with alcoholic potassium hydroxide, and was hydrolysed to No. 3 only by concentrated sulphuric acid. Similarly, hydrolysis of No. 6 could be effected only by concentrated sulphuric acid, which gave equal quantities of compounds 1 and 5 in low yield. Attempted reaction of 2-methoxyethyltoluene-*p*-sulphonate and 4-acetamidodiphenyl failed. Reaction of 4-aminodiphenyl and methoxyacetic acid gave 4-methoxyacetamidodiphenyl, readily reduced by lithium aluminium hydride to compound 5 in excellent yield. Compound 21 was prepared by reaction of toluene-*p*-sulphonyl chloride with No. 1, and an equimolecular mixture of compounds 21 and 7 yielded the molecular compound (No. 2) previously described.

Alkylation of *N*-*n*-propylaniline with 2-bromoethanol gave *N*-phenyl-*N*-*n*-propylaminoethanol (No. 23), previously prepared by a different route (Bergmann, Lavie, and Pinchas, *J. Amer. Chem. Soc.*, 1951, **73**, 5662).

N-*Methylmethanesulphonamide.*—A solution of methanesulphonyl chloride (11·45 g., 0·1 mole; b. p. 99°/35 mm.; $n_D^{21.5}$ 1·4522) in dry ether was added gradually to ethereal methylamine (0·3 mole) at 0°. When the exothermic reaction had subsided, the mixture was kept at room temperature for 1 hr. and the precipitate filtered off and washed with ether and chloroform (methylammonium chloride; 5·95 g., 88%). Distillation of the filtrate gave the sulphonamide (9·8 g., 90%) as a hygroscopic oil, b. p. 117—118°/0·3 mm., n_D^{23} 1·4508, miscible with cold water (Found: C, 21·95; H, 6·45. Calc. for $C_2H_7O_2NS$: C, 22·0; H, 6·45%). Helferich and Grunert (*Ber.*, 1940, **73**, 1131) give b. p. 118°/0·3 mm., and 60% yield.

N-p-*Diphenylyl*-N-*ethyltoluene*-p-*sulphonamide.*—A mixture of *N*-*p*-diphenylyltoluene-*p*-sulphonamide (16·16 g.), sodium ethoxide (from sodium, 1·15 g.) and ethyl iodide (4·3 c.c.) in alcohol (500 c.c.) was refluxed for 10 hr. On cooling, the clear solution deposited the above *sulphonamide* (11·77 g., 67%), crystallising from alcohol as needles, m. p. 120·5—121° (Found: C, 71·55; H, 6·1. $C_{21}H_{21}O_2NS$ requires C, 71·75; H, 6·0%). The residue left on evaporation of the mother-liquors was separated by sodium hydroxide (0·5N) into (i) a further 1·6 g. (9·5%) of product (m. p. 117—118°) and (ii) starting material (2·7 g., 17%), m. p. 152—154°.

Hydrolysis. The preceding sulphonamide (3·04 g.) was refluxed with sulphuric acid (100 c.c.; 14N) for 21 hr. Dilution with water (100 c.c.) precipitated starting material (1·45 g., 47·5%), m. p. 117·5—119°. The aqueous filtrate was basified and extracted with ether. The dried (Na_2SO_4) extracts afforded *N*-*p*-diphenylylethylamine (0·65 g., 38%), m. p. 68—69° (Baxter, Cymerman-Craig, and Gilbert, *loc. cit.*, give m. p. 67—69°).

N-p-*Diphenylyl*-N-2′-*methoxyethyltoluene*-p-*sulphonamide.*—(*a*) A mixture of *N*-*p*-diphenylyltoluene-*p*-sulphonamide (18·64 g.), 2-methoxyethyl bromide (6·2 c.c., 10% excess), and anhydrous potassium carbonate (4·4 g., 10% excess) in dry acetone (350 c.c.) was refluxed for 26·5 hr. The residue left on evaporation of the solvent was extracted with boiling sodium hydroxide solution (400 c.c.; 0·5%), and acidification of the filtrate gave starting material (6·35 g., 34%). The water-insoluble portion crystallised from alcohol or light petroleum (b. p. 60—90°) as needles, m. p. 99·5—100·5°, of N-p-*diphenylyl*-N-2′-*methoxyethyltoluene*-p-*sulphonamide* (8·17 g., 37%) (Found: C, 68·95, 69·0; H, 5·9, 6·1; O, 12·4; N, 4·05. $C_{22}H_{23}O_3NS$ requires C, 69·25; H, 6·05; O, 12·6; N, 3·7%).

(*b*) Reaction of *N*-*p*-diphenylyl-2-methoxyethylamine and toluene-*p*-sulphonyl chloride in pyridine at 90° for 2 hr. gave prisms, m. p. 100—100·5° (from alcohol), undepressed on admixture with the material prepared as in (*a*).

Hydrolysis. The preceding sulphonamide (3·8 g.) was refluxed with hydrochloric acid (90 c.c.; 24% w/v) for 19 hr. The hot solution was filtered, and the residue extracted with boiling water, leaving starting material (2 g., 52%; m. p. and mixed m. p. 98—99°). The combined filtrates were basified and extracted with ether. Evaporation of the dried extracts and crystallisation of the residue from light petroleum gave 2 fractions: (i) 2-*N*-*p*-diphenylylaminoethanol (0·3 g., 14%), m. p. and mixed m. p. 111—112°; (ii) *N*-*p*-diphenylyl-2-methoxyethylamine (0·25 g., 13%), m. p. 54—57°, undepressed on admixture with the pure material (m. p. 59·5—60·5°) described below.

4-*Methoxyacetamidodiphenyl.*—A mixture of 4-aminodiphenyl (28 g.) and methoxyacetic acid (14·9 g.; Rothstein, *Bull. Soc. chim.*, 1932, **51**, 839) was heated for 2 hr. at 150—160°. Water distilled off, and the cooled melt crystallised from alcohol as plates (31·7 g., 79%) of 4-*methoxyacetamidodiphenyl*, m. p. 142·5—143° (Found: C, 74·85; H, 6·6. $C_{15}H_{15}O_2N$ requires C, 74·65; H, 6·3%).

N-p-*Diphenylyl*-2-*methoxyethylamine.*—Powdered 4-methoxyacetamidodiphenyl (23·35 g.) was placed in the thimble of a Soxhlet extractor and refluxed with a solution of lithium aluminium hydride (3·7 g.) in ether (400 c.c.) for 17·5 hr.; unchanged amide (3·3 g.; m. p. 143°) remained in the thimble. The complex was decomposed with water and extracted with ether, giving N-p-*diphenylyl*-2-*methoxyethylamine* (17·6 g., 92% calc. on amide changed), needles, m. p. 59·5—60·5° (Found: C, 79·25; H, 7·45; N, 6·25. $C_{15}H_{17}ON$ requires C, 79·25; H, 7·55; N, 6·15%), from light petroleum.

N-p-*Diphenylyl*-N-2′-*hydroxyethyltoluene*-p-*sulphonamide.*—Reaction of toluene-*p*-sulphonyl chloride and 2-*N*-*p*-diphenylylaminoethanol in dry pyridine at 100° for 0·5 hr. gave needles (90% yield) of N-p-*diphenylyl*-N-2′-*hydroxyethyltoluene*-p-*sulphonamide*, m. p. 125—126° (Found: C, 68·7; H, 5·8; O, 13·1; S, 8·3. $C_{21}H_{21}O_3NS$ requires C, 68·65; H, 5·7; O, 13·1; S, 8·7%), from aqueous methanol.

N-*Methyl*-p-*acetamidobenzenesulphonanilide.*—A mixture of *p*-acetamidobenzenesulphonyl chloride and excess of *N*-methylaniline was heated at 100° for 10 min., giving N-*methyl*-p-*acetamidobenzenesulphonanilide* as plates (from alcohol), m. p. 152·5—153° (Found: C, 59·7; H, 5·6; N, 8·9. $C_{15}H_{16}O_3N_2S$ requires C, 59·25; H, 5·25; N, 9·2%).

N-*Phenyl*-N-n-*propylaminoethanol.*—A mixture of *N*-*n*-propylaniline (5·4 g.; n_D^{24} 1·5390) and 2-bromoethanol (5 g.) was heated at 150° for 1·5 hr., poured into water, and basified with sodium hydroxide. Extraction with ether and distillation of the dried (Na_2SO_4) extracts, finally through a 10 cm.-long Vigreux column, gave (i) unchanged *N*-*n*-propylaniline, b. p. 66—76°/0·001 mm., n_D^{25} 1·5339 (0·5 g., 9%), and (ii) *N*-phenyl-*N*-*n*-propylaminoethanol, b. p. 87—89°/0·001 mm., n_D^{25} 1·5507 (4·5 g., 64%) (Found: C, 73·15; H, 9·5; N, 7·55. Calc. for $C_{11}H_{17}ON$: C, 73·6; H, 9·5; N, 7·8%). Bergmann, Lavie, and Pinchas (*J. Amer. Chem. Soc.*, 1951, **73**, 5662) give b. p. 131°/3 mm., n_D^{21} 1·5470.

Spectroscopic Technique.—The infra-red spectra were measured with a Perkin-Elmer Model 12C spectrometer, converted into a double-pass instrument by Walsh's method (*J. Opt. Soc. Amer.*, 1952, **42**, 96), and using optics of potassium bromide for the region 400—700 cm.$^{-1}$, sodium chloride for 700—1400 cm.$^{-1}$, and calcium fluoride for 1400—4000 cm.$^{-1}$.

Solid specimens were measured either as vacuum-sublimed layers or as mulls in "Nujol." Sometimes slight differences were noted in the low-frequency region of the spectrum of the same substance measured by the two different methods, and in such cases the spectrum in "Nujol" was accepted as being the more reliable.

Solutions in methyl cyanide, carbon tetrachloride, carbon disulphide, and chloroform were measured in cells ranging from 0·05 cm. to 4 cm. in length. The solvents used were of "AnalaR" quality and were not further purified but were dried with silica gel before use. The 2% of ethanol used as a stabiliser in the "AnalaR" chloroform was removed immediately before use by repeated shaking with silica gel.

RESULTS AND DISCUSSION

Characteristic Vibrations of the Sulphonyl Group.—As with the sulphones (Barnard, Fabian, and Koch, *J.*, 1949, 2442) and the thiolsulphonates (Cymerman and Willis, *J.*, 1951, 1332) the sulphonamides all show two strong bands at frequencies near 1160 and 1350 cm.$^{-1}$ which leave no doubt that they are due to the symmetric and antisymmetric vibrations of the two S–O bonds, corresponding to the ν_1 and ν_3 vibrations of the SO_2 molecule (see Table 2). Both frequencies, and particularly the higher one, are somewhat greater than for the sulphones, which have their frequencies at 1130—1164 and 1312—1336 cm.$^{-1}$ in carbon tetrachloride and at 1124—1150 and 1299—1313 cm.$^{-1}$ in the solid state (Barnard, Fabian, and Koch, *loc. cit.*). They are, however, lower than the corresponding frequencies for the sulphonyl chlorides (1168—1183, 1361—1384 cm.$^{-1}$) or sulphonyl fluorides (1167—1197, 1401—1412 cm.$^{-1}$) as found in the Raman spectra of the liquids by Ham and Hambly (*Australian J. Chem.*, 1953, **6**, 135).

The lower frequency, at 1155—1170 cm.$^{-1}$, is little affected by the change from solid to solution, but the higher frequency is 10—20 cm.$^{-1}$ higher in carbon tetrachloride or carbon disulphide solution than in chloroform or in the solid state. Barnard, Fabian, and Koch also found in the sulphones a greater change in the higher than in the lower frequency on going from solid to solution, and explained this by pointing out that the higher frequency corresponds to the antisymmetric vibration, which has a more purely bond-stretching character than does the symmetric one, and is thus more strongly affected by intermolecular forces.

Both frequencies, and particularly the higher one, show slight increases on passage from the unsubstituted through the mono- to the di-substituted sulphonamides. Substitution by aromatic groups, as far as can be judged from the compounds studied, causes a greater increase than substitution by aliphatic groups. It is shown later that the *N*-mono-substituted sulphonamides are strongly associated in carbon tetrachloride solution, but less so in chloroform, while the *NN*-disubstituted compounds are known from the work of Chaplin and Hunter (*J.*, 1937, 1114) and Le Fèvre and Vine (*J.*, 1938, 1790) to be practically non-associated. Since association tends to reduce the frequency of the S–O vibrations, it is understandable that the frequencies of the *NN*-disubstituted sulphonamides are about 20 cm.$^{-1}$ higher than those of the other compounds in carbon tetrachloride and carbon disulphide solution but only about 10 cm.$^{-1}$ higher in chloroform or in the solid state.

A peculiar anomaly is found with methanesulphonamide in carbon disulphide solution, where the lower frequency occurs at 1215 instead of 1160 cm.$^{-1}$.

o-Sulphobenzoimide (saccharin) shows its higher frequency at a value somewhat above those for the other *N*-monosubstituted sulphonamides. This is probably due to ring strain, and analogous cases are found in the abnormally high carbonyl frequencies of *cyclo*pentanone (Hartwell, Richards, and Thompson, *J.*, 1948, 1436) and γ-butyrolactone (Rasmussen and Brattain, *J. Amer. Chem. Soc.*, 1949, **71**, 1073).

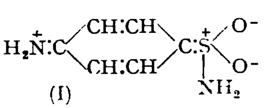
Sulphanilamide was completely insoluble in any of the solvents used except methyl cyanide. Both the S–O vibrations are 10 cm.$^{-1}$ lower than for benzenesulphonamide in the same solvent. Kumler and Halverstadt (*J. Amer. Chem. Soc.*, 1941, **63**, 2182) have suggested, on the basis of dipole-moment data, that the structure of sulphanilamide contains a contribution from the form (I). The infra-red measurements support this view, since the S–O bonds in this structure, having more single-bond character than in the conventional formula, should have lower vibration frequencies.

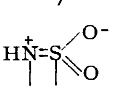
The third fundamental of the sulphur dioxide molecule, *viz.*, the symmetrical deformation vibration ν_2, occurs at 519 cm.$^{-1}$, and a search was made for a characteristic band in this region in the spectra of the sulphonamides. In the simplest compounds, methane- and *N*-methylmethane-sulphonamide, a strong band is readily discernible at 525—526 cm.$^{-1}$. In the more complex molecules there is usually more than one band in the 500—600 cm.$^{-1}$ region, but in every case a strong band, which may reasonably be attributed to this vibration, occurs between 520 and 550 cm.$^{-1}$. The fact that the frequency is always higher than in the sulphur dioxide molecule itself is to be attributed to the strong intermolecular bonding which must exist between adjacent molecules in the solid state and which will raise the frequency of the $-SO_2-$ deformation vibration (cf. Herzberg, " Infra-red and Raman Spectra," Van Nostrand, New York, 1945, p. 535).

Characteristic Vibration Frequency of the S–N *Bond.*—From a study of the Raman spectra of five compounds of different types containing the S–N linkage, Angus, Leckie, and Williams (*loc. cit.*) concluded that this bond has a characteristic stretching frequency at about 1070 cm.$^{-1}$. Almost all the sulphonamides measured during the present investigation show at least one strong absorption band between 1070 and 1100 cm.$^{-1}$, usually near 1090 cm.$^{-1}$, which may tentatively be identified with the S–N frequency. This assignment must be accepted with caution, however, for the following reasons : (*a*) Methanesulphonamide has no absorption between 990 and 1140 cm.$^{-1}$; (*b*) monosubstituted benzene rings, which occur in many of the compounds, are known to absorb weakly in this region (Colthup, *J. Opt. Soc. Amer.*, 1950, **40**, 397) ; and (*c*) recent work by Hoffmann and Andress (*Naturwiss.*, 1954, **4**, 94) indicates that the S–N frequency may be as low as 550 cm.$^{-1}$.

Deformation Frequencies of the Amino- and Imino-groups.—There is still no general agreement on the assignment of characteristic frequencies to the deformation vibrations of these groups in amides (Sutherland, *Adv. in Protein Chem.*, 1952, **7**, 291), on account of the interaction of the vibrations with the stretching vibration of the C–N bond, which occurs at an abnormally high frequency owing to the partial double-bond character of this bond in amides (Fraser and Price, *Nature*, 1952, **170**, 490). From the work of Barnard, Fabian, and Koch (*loc. cit.*) it seems that the sulphonyl group, having a different geometry from the carbonyl group, cannot readily take part in conjugative shifts within the molecule, so it is unlikely that the form (II) plays such an important part in determining the structure of the sulphonamides as its counterpart (III) does with the amides. It was hoped, therefore, that the identification of amino and imino bending frequencies would be easier in the sulphonamides than in the carboxyamides.

Unfortunately the well-known absorption due to the benzene ring at about 1500 and 1600 cm.$^{-1}$ clouds the issue in some of the compounds, but methanesulphonamide shows a band at 1583 cm.$^{-1}$ which can be attributed to the amino deformation vibration, and the other unsubstituted sulphonamides have bands in this neighbourhood also. *N*-Methylmethanesulphonamide shows a moderately weak band at 1626 cm.$^{-1}$ which may be due to the imino deformation, but the *N*-monosubstituted sulphonamides in general do not seem to show any band characteristic of this vibration : certainly there is no band near 1560 cm.$^{-1}$, which is the frequency near which the imino deformation probably occurs in *N*-monosubstituted amides (Richards and Thompson, *loc. cit.*).


(I)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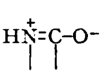

(III)

Characteristic Frequencies of the N–H *Stretching Vibrations.*—In the unsubstituted carboxyamides in dilute solution in carbon tetrachloride the two N–H stretching vibrations occur at very much the same frequencies as in the primary amines (3400 and 3520 cm.$^{-1}$, according to Richards and Thompson, *loc. cit.*), and in concentrated solution association leads to additional bands at about 100—200 cm.$^{-1}$ below these frequencies. In the solid state only the latter bonds are found.

The unsubstituted sulphonamides are only sparingly soluble in carbon tetrachloride, and show their N–H frequencies at about 3360 and 3455 cm.$^{-1}$, these values falling to 3265—3285 and 3340—3365 cm.$^{-1}$ in the solid. No sign of association can be detected at the concentrations attainable in carbon tetrachloride solution, though the very weak band at 3270 cm.$^{-1}$ in the solution of benzenesulphonamide may be due to such association. Sulphanilamide is completely insoluble in carbon tetrachloride and can only be studied in the solid, where it shows bands at 3395 and 3450 cm.$^{-1}$, attributable to the "amino" —NH_2 group, and at 3250 and 3330 cm.$^{-1}$, attributable to the N–H vibrations of the sulphonamide group. The latter are slightly lower in frequency than the corresponding bands for the other unsubstituted sulphonamides studied, which is understandable if the form (I) contributes appreciably to the structure of the molecule, as is indicated by Kumler and Halverstadt's dipole-moment measurements (*loc. cit.*). The greater negative charge on the oxygen atoms will attract more strongly the hydrogen atoms of the sulphonamido-group of the adjacent molecule. The frequencies of the " amino " NH_2 group are not far below those for a " free " NH_2 group, which suggests that this NH_2 group is relatively free, even in the solid state. The high frequencies are also in accord with the presence of structure (I), involving the $=NH_2^+$ group, where it may be expected that the N–H frequencies will be raised by the presence of the positive charge on the nitrogen atom (Flett, *Trans. Faraday Soc.*, 1948, **44**, 767).

The *N*-monosubstituted sulphonamides show their N–H vibration at about 3390 cm.$^{-1}$ in dilute solution in carbon tetrachloride. This value is about 40 cm.$^{-1}$ lower than that for the corresponding amides, and this is undoubtedly due to the strongly electronegative sulphonyl group, which will tend to weaken the N–H bond. Parallel to this effect is the great increase in acidity in passing from an amide to a sulphonamide, which can be as acid as a phenol (Bell and Roblin, *J. Amer. Chem. Soc.*, 1942, **64**, 2905). In addition to the

3390 cm.$^{-1}$ band, the carbon tetrachloride solutions also show a band at about 3270 cm.$^{-1}$, which on dilution becomes weaker relative to the 3390 cm.$^{-1}$ band, and this behaviour, reminiscent of that of the *N*-monosubstituted amides, suggests that the 3270 cm.$^{-1}$ band is due to associated molecules, whereas the 3390 cm.$^{-1}$ band is due to monomeric molecules. Some of the compounds (see Table 2) have a slight shoulder on the side of the 3390 cm.$^{-1}$ band. The reason for this is obscure, but is possibly to be sought in the existence of two equilibrium positions of the hydrogen atom attached to the nitrogen [cf. an analogous effect observed in the O–H vibration band of benzyl alcohol (Fox and Martin, *Trans. Faraday Soc.*, 1940, **36**, 897)]. The intensity of the shoulder relative to the main peak remains unchanged on dilution, which seems to preclude the shoulder's being due to some form of associated molecule. An interesting difference between the sulphonamides and the amides is that the " associated " band in the former is quite sharp, whereas in the latter it is broad and ill-defined. There is strong evidence that the association of *N*-monosubstituted amides takes place through the formation of chain polymers (Badger and Rubalcava, *Science*, 1953, **117**, 465; Worsham and Hobbs, *J. Amer. Chem. Soc.*, 1954, **76**, 206), whereas the evidence available on the association of *N*-monosubstituted sulphonamides (Le Fèvre and Vine, *loc. cit.*) points to the formation of cyclic molecules on association. The " associ-

TABLE 2.

Ref. No.	S–O Stretching vibrations (cm.$^{-1}$)				O–H and N–H Stretching vibrations (cm.$^{-1}$)								
	CCl$_4$ Solution		Solid		CCl$_4$ Solution					Solid			
					Unsubstituted sulphonamides								
18	1162	1362	1169	1336	—	3455	3360	—	—	—	3340	3265	3130
8	1159^{1}	—	1160	1336^{2}	—	3455	3355	—	—	—	3360	3265	—
9	1161	1363	1155	1330^{2}	—	3455	3355	3270^{1}	—	—	3365	3285	—
11	Insoluble		1152	1337	Insoluble				3450	3390	3330	3250	—
					N-*Monosubstituted sulphonamides*								
19	1159	1333	1135	1315	—	3406^{5}	3300^{6}	—	—	—	—	3300	—
			1155										
17	1160	1348	1154	1327	—	3390^{5}	3265^{6}	—	—	—	3260	3225^{4}	—
10	1166	1333	1160	1333	$3390^{4,5}$	3380^{5}	3260^{6}	—	—	—	—	3215	—
		1348^{2}											
13	1170	1342	1161	1334	—	3385^{5}	3265^{6}	—	—	—	—	3270	—
14	1170	1347	1165	1348	—	3390^{5}	3245^{6}	—	—	—	—	3335	—
20	1166	1336	1161	1322	3400^{5}	$3385^{4,5}$	3280^{6}	—	—	—	—	3265	—
7	1165	1339	1164	1345	—	3380^{5}	3250^{6}	—	—	—	—	3275	—
12	1162	1354	1164	1377	—	3400^{1}	—	—	—	—	3405	3100	—
					NN-*Disubstituted sulphonamides*								
16	1161	1343	1161	1337	—	—	—	—	—	—	—	—	—
		1358											
4	1159^{1}	1363	1155	1350	—	—	—	—	—	—	—	—	—
	1178	1370											
6	1172	1363	1158	1346	—	—	—	—	—	—	—	—	—
21	1169	1366	1159	1348	3635	3550	—	—	—	3475^{4}	3390^{3}	—	—
15	1160	1366	1171	1336	—	3440	—	—	—	—	3335	3295	—
					Molecular compound								
2	1168	1341	1158	1340	3635	3550	—	—	—	3455	3280^{1}	3155^{1}	—
		1361											
	—	—	—	—	—	3380^{5}	3250^{6}	—	—	—	—	—	—
					Reference compounds								
22	—	—	—	—	3640	3440^{4}	3410	—	—	—	—	3395^{3}	—
1	—	—	—	—	3640	3440^{4}	3410	—	—	—	$3420^{1,4}$	3365^{3}	—
23	—	—	—	—	3640	3485^{3}	—	—	—	—	—	3370^{3}	—
5	—	—	—	—	—	—	3410	—	—	—	3392	3340^{4}	—
3	—	—	—	—	—	—	3435	—	—	—	3400	—	—
24	—	—	—	—	—	—	3440	3365^{3}	—	—	—	3260^{3}	—
25	—	—	—	—	—	—	3435	—	—	—	3380	—	—

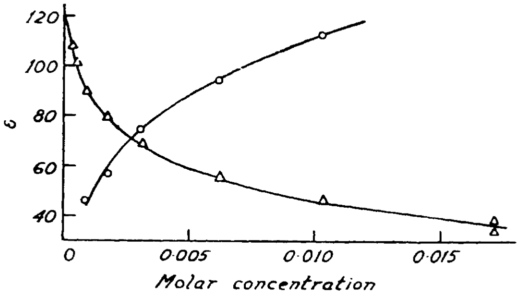
[1] Very weak. [2] Absorption maximum. [3] Broad. [4] Shoulder. [5] Relative intensity increases with dilution. [6] Relative intensity decreases with dilution.

ated " band in the *N*-monosubstituted sulphonamides persists even at concentrations below 0·001M in carbon tetrachloride solution, whereas in acetanilide, for instance, it is of negligible intensity below 0·003M, and in the secondary amines there is no appreciable association at concentrations as high as 0·1M. In the solid state the *N*-monosubstituted sulphonamides show a sharp band at almost the same position as the " associated " band found in solution, so that it may be assumed that the same type of association occurs both in the solid and in solution.

To study further the nature of the association, quantitative measurements were made on solutions of methanesulphonanilide in carbon tetrachloride and in chloroform. In chloroform solution the " free " and " associated " bands occur at 3375 and 3270 cm.$^{-1}$. The half-width in carbon tetrachloride solution of the " free " N–H band is 36 cm.$^{-1}$ and that of the " associated " band 66 cm.$^{-1}$, the corresponding figures for chloroform solution being 38 and about 80 cm.$^{-1}$, respectively. These half-widths do not vary appreciably with concentration, nor do the shapes of the bands, so that for comparative purposes the extinction coefficients measured at the peaks of the bands can be used instead of the integrated intensities.

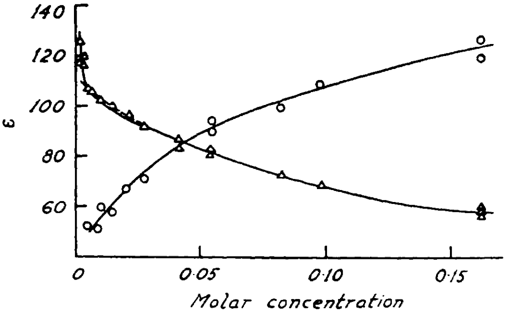
Figs. 1 and 2 show the values, in carbon tetrachloride and chloroform solution respectively, of $\varepsilon = D/cl$ for the " free " and " associated " bands, where D is the optical density at the peak of the band, c is the stoicheiometric concentration of $\mathrm{Me{\cdot}SO_2{\cdot}NHPh}$ in formula-weights per litre, and l the path length in cm. As infinite dilution is approached it may be assumed that only the monomer is present, so that the limiting value as $c \rightarrow 0$ of D/cl for the " free " band will be ε_m, the molar absorbance of the monomer. If c_m and c_a are the stoicheiometric concentrations of the monomer and the associated molecules respectively, then $c = c_m + c_a$. Let γ be the degree of association, defined by $\gamma = c_a/c$, then $\gamma = 1 - c_m/c = 1 - \varepsilon/\varepsilon_m$, and can be calculated for any concentration from measurements on the " free " band alone. If all the non-monomeric molecules contribute equally to the density of the " associated " band and do not contribute to the " free " band, the plot of ε for the associated band against γ should be a straight line.

FIG. 1. *Absorption of* $\mathrm{Me{\cdot}SO_2{\cdot}NHPh}$ *in* $\mathrm{CCl_4}$ *solution.*



△ 3390 cm.$^{-1}$ band.
○ 3265 cm.$^{-1}$ band.

FIG. 2. *Absorption of* $\mathrm{Me{\cdot}SO_2{\cdot}NHPh}$ *in* $\mathrm{CHCl_3}$ *solution.*



△ 3375 cm.$^{-1}$ band.
○ 3270 cm.$^{-1}$ band.

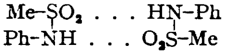
It will be seen from the curve for the chloroform solution that there is some ambiguity about the extrapolation to infinite dilution, an ambiguity which is not removed by plotting the results on a logarithmic scale. The rapid rise of ε at concentrations below 0·004M was verified by two completely independent series of measurements, though on account of inaccuracies inherent in the measurement of the absorption of very dilute solutions the experimental points show a fair scatter.

When γ is plotted against ε for the " associated " band, both for carbon tetrachloride and chloroform solutions, a straight line is obtained, at any rate down to concentrations where the exact measurement of ε for the " associated " band becomes impossible. There are thus good grounds for the assumption that only one type of associated molecule exists to any appreciable extent in the solutions under consideration. If it is assumed to be the ring dimer (IV), the law of mass action gives $K = \gamma/2c(1 - \gamma)^2$. Table 3 shows the values of γ and of K calculated on this basis. The ε values for carbon tetrachloride solution readily yield on extrapolation a value $\varepsilon_m = 120$, and the two sets of figures given for chloroform solutions show the values calculated by extrapolation with and without the inclusion of the points below 0·004M.

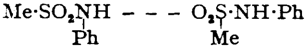
It is clear that K remains constant to within the limits of experimental error in carbon tetrachloride solution, and, if the points below 0·004M are neglected, in chloroform solution also. There is certainly no drift of the K values over the concentration ranges studied. The relatively large random variation in K values is due to the high sensitivity of the function $\gamma/(1 - \gamma)^2$ to small changes in γ, and since γ is dependent on an extrapolated quantity ε_m, and the ε values in the region where the extrapolation has to be made are inherently somewhat inaccurate, the constancy of K is very satisfactory.

Association takes place to a much greater extent in carbon tetrachloride than in chloroform solution, a result which is entirely in agreement with Fox and Martin's observations (*Proc. Roy. Soc.*, 1937, **162**, *A*, 419) on the association of aromatic alcohols. If the higher absorption values for very dilute chloroform solutions are accepted as being real, the data can be interpreted to point to the existence in very dilute solution of appreciable amounts of the "chain" dimer (V). The "free" vibration occurs at a frequency about 15 cm.$^{-1}$ lower in chloroform than in carbon tetrachloride solution, while the "associated" N–H vibration occurs at almost the same frequency in both solvents. Clearly, the chloroform molecules interact with the "free" N–H groups to a greater extent than do those of carbon tetrachloride, whereas the "associated" N–H groups, which are concerned in intermolecular bonding with other molecules of solute, are relatively unaffected by the solvent. Through this interaction with the solvent the monomer is stabilised to a greater extent in chloroform than in carbon tetrachloride solution, and this is reflected in the lower value of K.

(IV)



$$\begin{array}{l} \mathrm{Me{-}SO_2\ .\ .\ .\ HN{-}Ph} \\ \mathrm{Ph{-}NH\ .\ .\ .\ O_2S{-}Me} \end{array}$$



$$\mathrm{Me{\cdot}SO_2\underset{Ph}{N}H\ -\ -\ -\ O_2\underset{Me}{S}{\cdot}NH{\cdot}Ph}$$

(V)

TABLE 3. *Association in solutions of* $\mathrm{Me{\cdot}SO_2{\cdot}NHPh}$.

Carbon tetrachloride			Chloroform				
	$\varepsilon_m = 120$			$\varepsilon_m = 130$		$\varepsilon_m = 112$	
c, M	γ	K	c, M	γ	K	γ	K
0·0160	0·693	223	0·160	0·540	7·98	0·468	5·17
0·0130	0·656	213	0·120	0·498	8·23	0·421	5·23
0·0100	0·613	205	0·080	0·434	8·47	0·340	4·88
0·0070	0·558	204	0·040	0·333	9·36	0·228	4·78
0·0050	0·513	217	0·020	0·260	11·9	0·145	4·96
0·0030	0·422	211	0·015	0·238	13·7	0·120	5·17
0·0020	0·363	224	0·010	0·217	17·7	0·093	5·65
0·0010	0·263	242	0·005	0·185	27·9	0·054	5·76
0·0005	0·158	223	0·0025	0·135	36·1	0·033	5·53
			0·0015	0·104	43·2	0·022	(7·67)
	Mean	218				Mean	5·24

Experiments on the molecular compound (No. 2) and on *N*-ethyltoluene-*p*-sulphonamide in carbon tetrachloride solution over the concentration range 0·001—0·014M showed similar results, with the values of K of about 133 and 121 respectively.

Le Fèvre and Vine (*loc. cit.*) measured the orientation polarisation of the closely similar compound *p*-$\mathrm{Me{\cdot}C_6H_4{\cdot}SO_2{\cdot}NHMe}$ at different concentrations in benzene, chloroform, and ether solutions, and on the assumption that the associated form of the molecule has zero dipole moment, calculated values of γ and K in benzene solution for association to a cyclic dimer. From their figures for chloroform solutions the corresponding values have been calculated for this solvent also (Table 4). For ease of comparison with the present work, molar concentrations, c, as well as weight fractions, w_1, are given. Le Fèvre and Vine found an appreciable drift of the K values in benzene solution, but in chloroform, though the K values are somewhat erratic, there is no apparent drift. It seems then that over the range of concentrations studied by Le Fèvre and Vine association takes place to dimers only, and that the dipole moment of the dimeric molecule is zero in chloroform solution. This being so, it is difficult to see why the moment should be non-zero in benzene solution, and the drift of K in this solvent must then be attributed to failure of the mass-action law brought about by the presence of more than one type of associated molecule.

TABLE 4. *Calculation of results from Le Fèvre and Vine's data on* p-Me·C_6H_4·SO_2·NHMe *in chloroform solution.*

$10^5 w_1$	245	353	543	868	1282	1977	3402	6326
c	0·0196	0·0282	0·0434	0·0693	0·1023	0·1575	0·2704	0·5002
γ	0·056	0·067	0·117	0·143	0·180	0·232	0·307	0·429
K	1·60	1·36	1·74	1·41	1·31	1·25	1·18	1·32

It may be noted that infra-red spectroscopy provides a more rigorous means of investigating this type of association than do dielectric measurements, since in the latter method the dubious assumption has to be made that the dimer has zero dipole moment.

Structure of the Molecular Compound.—Treatment of *N*-*p*-diphenylyltoluene-*p*-sulphonamide with 2-bromoethanol (Baxter, Cymerman-Craig, and Gilbert, *loc. cit.*) gave a 1 : 1 molecular compound of the starting sulphonamide and the desired *N*-*p*-diphenylyl-*N*-2′-hydroxyethyltoluene-*p*-sulphonamide, which could itself not be obtained from the molecular compound. Two substances of similar structure but lacking the hydroxyl group, *N*-*p*-diphenylyl-*N*-ethyl- and *N*-*p*-diphenylyl-*N*-2′-methoxyethyl-toluene-*p*-sulphonamide, were prepared. As these did not form molecular compounds with *N*-*p*-diphenylyltoluene-*p*-sulphonamide, it appeared that hydrogen bonding was probably responsible for the stability of the molecular compound isolated previously.

The study of the way in which the molecules of *N*-*p*-diphenylyl- and *N*-*p*-diphenylyl-*N*-2′-hydroxyethyl-toluene-*p*-sulphonamide are held together requires examination of the spectra of 2-aminoethanols, and as some discrepancies were found in Bergmann, Gil-Av, and Pinchas's paper (*J. Amer. Chem. Soc.*, 1953, **75**, 68) a more detailed study of two spectra was made. The spectra of 2-anilinoethanol (No. 22) and *N*-phenyl-*N*-*n*-propylaminoethanol (No. 23) at concentrations from about 0·002 to 0·15M in carbon tetrachloride solution were measured over the 3000—4000 cm.$^{-1}$ range by using the calcium fluoride prism, which gives far better resolution and enables more accurate frequency measurements to be made than did the sodium chloride prism used by the previous workers.

Bergmann *et al.* found that 2-anilinoethanol in carbon tetrachloride solution shows bands at 3590 cm.$^{-1}$ (due to " free " O–H vibrations) and 3360 cm.$^{-1}$ (attributed to intramolecularly bonded O–H · · · N vibrations). The occurrence of the expected N–H vibration was not mentioned, though Bergmann, in a private communication, says : " We have based our conclusions on the observation that the observed effect [the occurrence of a band in the 3350—3450 cm.$^{-1}$ region] occurs in the same way for tertiary and secondary amines. As in the former no NH vibration is possible, we have assumed that the effect is actually due to the intramolecular hydrogen bond."

Repetition of Bergmann's work showed that for both 2-anilino- and 2-*N*-*p*-diphenylylamino-ethanol (Nos. 22 and 1) the " free " O–H vibration band occurred at 3640 cm.$^{-1}$, and the other band occurred at 3410 cm.$^{-1}$ with a shoulder at 3440 cm.$^{-1}$. Both bands were sharp. *N*-*p*-Diphenylyl-2-methoxyethylamine (No. 5) shows its N–H vibration at 3410 cm.$^{-1}$, so it seems that the 3410 cm.$^{-1}$ band of 2-anilinoethanol is the N–H vibration, and the shoulder at 3440 cm.$^{-1}$, which Bergmann's instrument failed to resolve, can then be attributed to the intramolecular O–H · · · N vibration. The intensity ratios of the 3410, 3440, and 3640 cm.$^{-1}$ bands are independent of concentration, which rules out the possibility that any of these bands might be due to intermolecular bonding. Remeasurement for *N*-phenyl-*N*-*n*-propylaminoethanol (No. 23) for which Bergmann claimed bands at 3600 and 3380 cm.$^{-1}$, showed a sharp band at 3640 cm.$^{-1}$ (clearly due to the " free " O–H vibration) and a very broad band, centred at about 3485 cm.$^{-1}$, apparently due to O–H · · · N vibrations. Bergmann states that in all cases the " free " O–H band is weak in comparison with the O–H · · · N band, but the present measurements show that this is not so : both in the secondary and the tertiary aminoethanols studied the intensity of the " free " O–H band was at least as great as that of the O–H • • • N band. In the tertiary compound the broad O–H • • • N band resembles in shape and frequency the bands due to intermolecular association in alcohols, and since its intensity, relative to that of the " free " O–H band, seems to decrease with decrease of concentration it is probably due in part to intermolecular O–H • • • O bonds.

The molecular compound (No. 2) and *N*-*p*-diphenylyl-*N*-2′-hydroxyethyltoluene-*p*-sulphonamide (No. 21) were studied to the limit of concentration imposed by solubility in carbon tetrachloride (*ca.* 0·02M), and each shows two sharp absorption peaks, with intensities of the same order of magnitude, at 3635 and 3550 cm.$^{-1}$. The higher-frequency band can readily be ascribed to " free " O–H vibrations, but the lower one is not considered to be due to dimerisation through O–H • • • O–H linkages, as the frequency of such a band would be about 3500 cm.$^{-1}$ (Smith and Creitz, *J. Res. Nat. Bur. Stand.*, 1951, **46**, 145); moreover, at concentrations below 0·02M the concentration of dimers would be extremely small. In view of the above discussion it is extremely unlikely that the 3550 cm.$^{-1}$ band is due to intramolecular O–H • • • N bonding,* so it must be attributed to O–H • • • O_2S bonds, which could be formed intra- or inter-molecularly. Now in both compounds Nos. 2 and 21 the ratio of the intensity of the 3550 cm.$^{-1}$ band to that of the 3635 cm.$^{-1}$ band decreases with dilution, a fact which suggests that the bonds are intermolecular. At any given molar concentration this intensity ratio is greater for the molecular compound No. 2 than for compound No. 21, which also points to the existence of intermolecular bonds, for the concentration of molecules with SO_2 groups, suitable as acceptors for the proton of the OH group, is twice as great in the former as in the latter.

The relatively small shift of the O–H frequency from the free state to the O–H • • • O_2S state (85 cm.$^{-1}$) is in accordance with the known weakness of the SO_2 group as a chelating agent. For instance, Amstutz, Chessick, and Hunsberger (*Science*, 1950, **111**, 305; *J. Amer. Chem. Soc.*, 1951, **73**, 1220) found that, even in a compound such as *o*-hydroxydiphenyl sulphone, where conditions are ideal for chelation, the shift of the O–H frequency is only 300 cm.$^{-1}$, as compared with a shift of at least 600 cm.$^{-1}$ found for *o*-hydroxydiphenyl sulphoxide or for *o*-hydroxyacetophenone (Martin, *Nature*, 1950, **166**, 474).

The existence of intermolecular O–H • • • O_2S bonding was substantiated by the following experiments: (*a*) Addition of *N*-*p*-diphenylyl-*N*-ethyltoluene-*p*-sulphonamide (No. 4) to a solution of 2-*N*-*p*-diphenylylaminoethanol (No. 1) in carbon tetrachloride solution leads to the development of an extra O–H band at 3570 cm.$^{-1}$, whose intensity relative to the original O–H band at 3640 cm.$^{-1}$ increases with increasing concentration of compound No. 4. It could, of course, be argued that the new band is due to an intermolecular O–H • • • N bond between the O–H group of compound No. 1 and the tertiary nitrogen atom in compound No. 4, but this is ruled out by the fact that no such band appears when a solution of compound No. 1 is mixed with tribenzylamine, a compound in which the nitrogen, being much more basic than in compound No. 4, would be more likely to attract the proton from the OH group. The N–H vibration band in compound No. 1, at 3410 cm.$^{-1}$, is completely unaffected by mixing either with compound No. 4 or with tribenzylamine. (*b*) The addition of compound No. 4 to compound No. 21 in solution increases the intensity of the 3550 cm.$^{-1}$ band and decreases that of the 3635 cm.$^{-1}$ band.

In these experiments, on account of the difficulties of measuring small changes in band intensity in a region where water vapour absorbs fairly strongly, it is necessary to use a concentration of compound No. 4 somewhat greater than that of compound No. 1 or 21. Because of the very low solubility of compound No. 7 it is not possible to demonstrate with certainty interaction in solution between this compound and compound No. 21, but the above experiments leave no doubt that such interaction does occur through the O–H • • • O_2S linkage.

Evidence shows clearly that, in the solid state, the OH group takes part in the bonding between the two components of the molecular compound. Both compounds Nos. 1 and 21 show typical spectra of hydroxy-compounds, having broad bands centred at 3365 and

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* It is noteworthy that there is no trace in No. 21 of OH • • • N bonding of the type found in *N*-*n*-propyl-2-anilinoethanol (No. 23). This is readily explained by the much lower basicity of the nitrogen atom in the former compound and its consequent inability to accept the proton from the OH group.

3390 cm.$^{-1}$, respectively, with half-widths of ~240 and ~170 cm.$^{-1}$, indicating the existence of chains of polymers (Smith and Creitz, *loc. cit.*), whereas in compound No. 2 there is an intense and fairly sharp band at 3455 cm.$^{-1}$ (half-width ~90 cm.$^{-1}$). The shoulder occurring at 3475 cm.$^{-1}$ in No. 21 is taken to indicate that intermolecular O–H · · · O_2S bonds exist to some extent in this compound also. The N–H frequency in compound No. 2 occurs at almost exactly the same frequency, 3280 cm.$^{-1}$, as in compound No. 7, which supports the view that this group plays no part in holding together the two components of the molecular compound.

It is concluded then that compounds Nos. 7 and 21 are held together in the molecular compound (No. 2) through the linkage O–H · · · O_2S, and it is also shown that interaction between these two compounds takes place in solution through the same linkage and by no other form of hydrogen bond.

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CHEMISTRY DEPARTMENT, UNIVERSITY OF SYDNEY (J. N. B. and J. C.-C.).
CHEMICAL PHYSICS SECTION, DIVISION OF INDUSTRIAL CHEMISTRY,
COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION,
MELBOURNE (J. B. W.).

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