TABLE I

TAUTOMERIC EQUILIBRIUM CONSTANT TEMPERATURE DEPENDENCE

Compd	Temp, °K	K_{eq}[a]	Compd	Temp, °K	K_{eq}[a]
1	293	0.25	2	322	0.95
	283	0.34		311	1.13
	264	0.54		303	1.33
	252	0.84		293	1.54

[a] K_{eq} = [hydrazone]/[azo] or [b]/[a], determined from an average of four integrations, estimated error of ±5% in K_{eq}.

the calculated equilibrium constant temperature dependences for compounds **1** and **2** in acetone-d_6. The assignment of the δ 16.2 ppm signal in compound **2** is further substantiated by the fact that the experimental data in Table I are in general agreement with the work of Bekarek, *et al.*,[10] who used ^{15}N–H coupling constants to evaluate tautomer ratios for the parent phenylazo-2-naphthol. Thermodynamic parameters derived from the equilibrium constant (K_{eq} = [b]/[a]) temperature dependence data allow, for the first time, a quantitative comparison of the phenylazo-1- and -2-naphthol systems (see Table II).

TABLE II

TAUTOMERIC THERMODYNAMIC PARAMETERS

Compd	$\Delta G°_{293°}$, cal/mol	$\Delta H°$, kcal/mol[a]	$\Delta S°_{293°}$, cal/(mol deg)[a]
1	807	−4.5	−18.1
2	−250	−3.1	−9.7

[a] Estimated errors are *ca.* ±0.5 kcal/mol in $\Delta H°$ and *ca.* ±2.0 cal/mol deg in $\Delta S°$.

The thermodynamic data show the 2-naphthol derivative (at 293°K) to be mainly hydrazone **2b**, while the 1-naphthol analog, on the other hand, is predominantly azo **1a**. The enthalpy and entropy contributions to the thermodynamic free-energy difference between tautomers, for both systems, are of the same sign but differ in magnitude.

The enthalpy for the equilibrium process favors the hydrazone tautomer in both systems. The smaller $\Delta H°$ for system **2** is attributed to stabilization of the azo tautomer **2a** relative to the hydrazone species **2b** by intramolecular hydrogen bonding present only in system **2**.

The entropy term, however, favors the less polar azo species for both systems. The larger negative entropy term in system **1** is ascribed to the existence of a more polar hydrazone species **1b** relative to the azo tautomer **1a**, than is present in system **2**.

From the results which we have presented, it can be concluded that the difference in the tautomeric behavior between systems **1** and **2** is due to the fact that in system **1** the entropy term dominates and governs the free-energy difference between tautomers, while in system **2** the enthalpy contribution is the dominating factor (at 293°K in acetone solvent).

Experimental Section

Materials Characterization.—1-(*p*-Methoxyphenylazo)-2-naphthol (**2**) (mp 141–142°; lit.[17] mp 141°) and 4-(*p*-methoxyphenylazo)-1-naphthol (**1**) (mp 172–173°; lit.[18] mp 168°) were prepared from the corresponding substituted aniline by diazotization and coupling with 2- and 1-naphthol, respectively.

Spectroscopic Characterization.—A JEOL C-60-H nuclear magnetic resonance spectrometer equipped with a JES-VT-3 variable-temperature controller was employed for equilibrium constant determinations in acetone-d_6; the solutions were *ca.* 10% (w/v). The nmr probe temperature control was calibrated, with an estimated accuracy of ±1°, using anhydrous methanol and ethylene glycol solutions. The probe temperature accuracy was periodically checked by using a 5-mm probe thermometer supplied by JEOL.

Registry No.—**1a**, 3009-53-8; **1b**, 32159-06-1; **2a**, 13411-91-1; **2b**, 15096-03-4.

Acknowledgment.—Stimulating discussions with Lewis B. Leder, as well as the synthesis of 4-(*p*-methoxyphenylazo)-1-naphthol by Richard L. Schank, are gratefully acknowledged.

A General Method of Preparation of Tetramethyl Alkyl-1-hydroxy-1,1-diphosphonates

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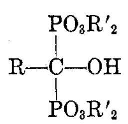
We recently developed a need in our laboratories for a series of esterified alkyl-1-hydroxy-1,1-diphosphonic acids (I). Where the specific acid was available, esterification was accomplished by the published[1] orthoformate route. For most of the esters envisioned the corresponding acids were either difficult to synthesize or not previously reported in the chemical literature. Hence, a search was begun for a direct method of preparation of tetraalkyl alkyl-1-hydroxy-1,1-diphosphonates.

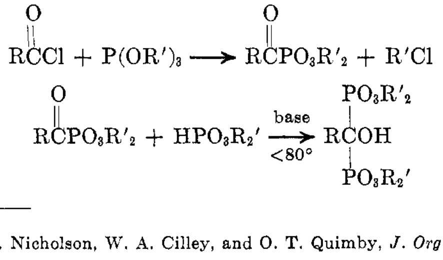


$$\mathrm{R{-}\underset{PO_3R'_2}{\overset{PO_3R'_2}{C}}{-}OH}$$

I

The chemical literature describing this class of compounds is very ambiguous. Fitch and Moedritzer[2] and Pudovik, *et al.*,[3,4] have described the synthesis of I, where R = CH_3 and R′ = C_2H_5, by the route shown in Scheme I. The reaction is complicated by rearrange-

SCHEME I



$$\mathrm{R\overset{O}{\overset{\|}{C}}Cl + P(OR')_3 \longrightarrow R\overset{O}{\overset{\|}{C}}PO_3R'_2 + R'Cl} \tag{1}$$

$$\mathrm{R\overset{O}{\overset{\|}{C}}PO_3R'_2 + HPO_3R_2' \xrightarrow[<80°]{base} R\underset{PO_3R_2'}{\overset{PO_3R'_2}{C}}OH} \tag{2}$$

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[17] J. M. Tedder, *J. Amer. Chem. Soc.*, **79**, 6090 (1957).

[18] L. N. Ogoleva and B. I. Stepanov, *Zh. Org. Khim.*, **1** (12), 2083 (1965).

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[1] D. A. Nicholson, W. A. Cilley, and O. T. Quimby, *J. Org. Chem.*, **35**, 3149 (1970).

[2] S. J. Fitch and K. Moedritzer, *J. Amer. Chem. Soc.*, **84**, 1876 (1962).

[3] A. N. Pudovik and I. V. Konovalova, *Dokl. Akad. Nauk SSSR*, **143**, 875 (1962); *Chem. Abstr.*, **57**, 3480*a* (1962).

[4] A. N. Pudovik, I. V. Konovalova, and L. V. Dedova, *Dokl. Akad. Nauk SSSR*, **153**, 616 (1963); *Chem. Abstr.*, **60**, 8060*a* (1964).

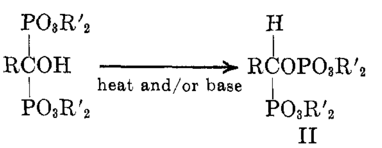
Table I

Tetramethyl Alkyl-1-hydroxy-1,1-diphosphonates

Compd	Registry no.	Mp, °C	^{31}P nmr, ppm	Yield, %	Calcd (found), % C	H	P	Mol wt (found)
$C_6H_5C(OH)[PO_3(CH_3)_2]_2$	32249-59-5	130–133[a]	−18.0	96	40.8 (40.9)	5.6 (5.6)	19.3 (19.6)	324 (340)
$CH_3C(OH)[PO_3(CH_3)_2]_2$	15207-88-2	68–71[b]	−22.0	70	27.4 (27.3)	6.1 (6.1)	23.7 (23.9)	262 (265)
m-$BrC_6H_4C(OH)[PO_3(CH_3)_2]_2$	32249-61-9	120–122[a]	−18.0	95	32.8 (32.5)	4.2 (4.3)	15.4 (16.1)	403 (435)
$CH_2{=}CH(CH_2)_8C(OH)[PO_3(CH_3)_2]_2$	32249-62-0	*c*	−22.0	86	46.6 (45.8)	8.3 (8.2)	15.9 (15.8)	388 (410)
$(CH_3)_3CC(OH)[PO_3(CH_3)_2]_2$	32249-63-1	108–110[b]	−22.0	75[d]	35.9 (36.0)	7.2 (7.3)	20.4 (20.8)	304 (330)
$CH_3(CH_2)_7CH{=}CH(CH_2)_7C(OH)[PO_3(CH_3)_2]_2$	32304-07-7	*c*	−22.0	91	54.6 (54.7)	9.5 (9.4)	12.8 (12.8)	484 (525)
p-$CH_3OC_6H_4C(OH)[PO_3(CH_3)_2]_2$	32304-08-8	103–104[a]	−18.0	81	40.7 (40.8)	5.7 (6.0)	17.5 (18.0)	354 (380)

[a] Crystallized from ethyl ether. [b] Crystallized from a 50:50 mixture of benzene and hexane. [c] Compound failed to crystallize; yield based on crude oil isolated from reaction mixture. [d] Yield based on crude solid isolated from reaction mixture.

ment of the tetraalkyl alkyl-1-hydroxy-1,1-diphosphonate (I) to the phosphate phosphonate (II) (eq 3).[2-4]



$$\underset{PO_3R'_2}{\overset{PO_3R'_2}{RCOH}} \xrightarrow[\text{heat and/or base}]{} \underset{\underset{\text{II}}{PO_3R'_2}}{\overset{H}{RCOPO_3R'_2}} \qquad (3)$$

No materials of structure I with R other than CH_3 have apparently been prepared. Fitch and Moedritzer attempted the synthesis of I where R = C_6H_5 and R′ = C_2H_5.[2] They could find no reaction conditions which prevented rearrangement to II.

Compounds purported to have structure I have been described.[5-7] However, the methods of preparation employed by these workers involved both a strong base (Na or NaOR) and elevated temperatures (>120°). When Fitch and Moedritzer[2] repeated portions of these studies only rearranged products (II) were obtained. Our own early efforts in this area, using the methods of McConnell and Coover[5] and Cade,[7] also yielded only phosphate phosphonates.

In an attempt to remove some of the confusion in the literature concerning esters of hydroxydiphosphonic acids, we have reexamined the reactions leading to compounds I and II. By making some relatively minor but very significant changes in procedure, we have devised a general method for preparing pure materials of structure I.

When the acylphosphonates prepared *via* eq 1 (Scheme I) were sufficiently pure, addition of the hydrogen dialkyl phosphite to the carbonyl group (Scheme I, eq 2) occurred at low temperatures (0°) in ether solution in the presence of a relatively weak base, di-*n*-butylamine. Apparently this secondary amine is not a strong enough base to promote isomerization under the conditions employed.

We chose to work exclusively with methyl esters, since they are much more prone to crystallize than are longer chain esters. Purification of compounds of structure I can be a problem since the alternative of vacuum distillation results in isomerization.[2,4] Even when the hydroxydiphosphonates do not crystallize there is an advantage to working with methyl esters. While the starting materials in eq 2 are soluble in cold ether, the products (I) are not and can be rapidly removed from the reaction system. The resulting short contact time with the basic reaction medium probably helps to prevent rearrangement to II.

Table I lists the tetramethyl alkyl-1-hydroxy-1,1-diphosphonates prepared by the above procedure. That we are dealing with materials of structure I and not II is demonstrated conclusively by ^{31}P nmr spectroscopy. Fitch and Moedritzer[2] have shown that the diphosphonate structure (I) results in a single ^{31}P resonance at about −20 ppm (relative to 85% H_3PO_4) while the phosphate phosphonate isomer (II) gives two resonances of equal intensity, one in the range of −16 to −21 ppm and one at 0 to +1 ppm. Phosphorus nmr spectra of our compounds were devoid of signals other than the one in the −18 to −22 ppm range.

As indicated earlier, acyl phosphonates were prepared *via* eq 1.[8] They were generally purified by vacuum distillation. Purity was determined by ^{31}P nmr spectroscopy; all acyl phosphonates gave a single resonance in the 0 to +2 ppm range.

As opposed to treatment with base, exposure of esters of structure I to acid does not result in rearrangement. Hydrolysis of the phenyl derivative (compound I, R = C_6H_5, R′ = CH_3) proceeded normally to the expected acid.

Experimental Section

All melting points reported herein are uncorrected. Elemental analyses were carried out in these laboratories. Phosphorus nmr spectra were recorded on a Varian HR-60 spectrometer operating at 24.3 MHz. Chemical shifts are accurate to ±0.5 ppm and were measured from an external 85% H_3PO_4 reference. Molecular weights were determined on a Model 302 Mechrolab osmometer.

Tetramethyl alkyl-1-hydroxy-1,1-diphosphonates were all prepared by the same general procedure. The preparation of $C_6H_5C(OH)[PO_3(CH_3)_2]_2$ is considered typical and is given in detail below. Table I reports yields, analyses, and physical characteristics of the materials prepared in this study.

Tetramethyl Phenylmethanehydroxydiphosphonate.—Benzoyl chloride (14.05 g, 0.1 mol) was placed in a mechanically stirred reaction flask and cooled to 0°. Trimethyl phosphite (12.4 g,

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(5) R. L. McConnell and H. W. Coover, *J. Amer. Chem. Soc.*, **78**, 4450 (1956).

(6) P. Schmidt, Swiss Patent 321,397 (1957).

(7) J. A. Cade, *J. Chem. Soc.*, 2272 (1959).

(8) G. M. Kosolapoff, "Organophosphorus Compounds," Wiley, New York, N. Y., 1950, p 122.

0.1 mol) was added dropwise with rapid stirring. Vigorous evolution of a gas (CH_3Cl) was noted. After addition was complete the reaction mixture was allowed to warm to room temperature and then vacuum distilled. Dimethyl benzoylphosphonate (18.2 g, 85%) was collected as a yellow oil, bp 130–134° (3 Torr). A ^{31}P nmr spectrum of the product showed a single resonance at +1 ppm.

Hydrogen dimethyl phosphite (5.16 g, 0.047 mol) was placed in a reaction flask to which 100 ml of diethyl ether had been added. Following the addition of di-*n*-butylamine (0.5 g, 0.0026 mol), the solution was cooled to 0°. Dimethyl benzoylphosphonate (10.0 g, 0.047 mol) was introduced slowly with rapid stirring. The reaction was moderately exothermic; external cooling was required to maintain the temperature at 0°. A white solid began to form almost immediately. After all the dimethyl benzoylphosphonate had been introduced the reaction mixture was allowed to warm to room temperature. Filtration yielded 14.6 g (96%) of the title compound.

The tetramethyl ester of phenylmethanehydroxydiphosphonic acid was hydrolyzed by refluxing for 3 hr with an excess of concentrated HCl. The monosodium salt was crystallized by the method of Pflaumer and Filcik.[9] A ^{31}P nmr spectrum consisted of a single resonance at −15.5 ppm.

Anal. Calcd for $C_7H_9O_7P_2Na$: C, 29.0; H, 3.1; P, 21.2; Na, 7.9. Found: C, 28.6; H, 3.0; P, 21.0; Na, 8.3.

Registry No.—Phenylmethane hydroxydiphosphonic acid (monosodium salt), 32247-16-8.

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[9] P. F. Pflaumer and J. P. Filcik, Belgian Patent 712,159 (1968).

On the Mechanism of the Desulfonylation of Phenyl Sulfone in Molten Sulfur

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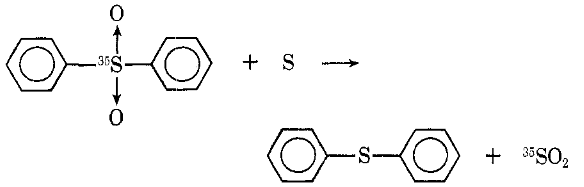
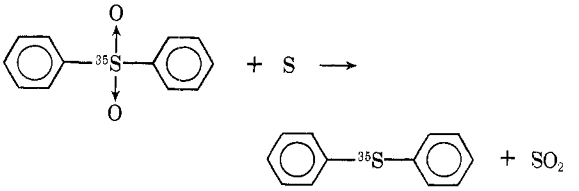
The reaction between sulfur-35 labeled phenyl sulfone and ordinary sulfur has been studied[1] at temperature above 300°. It has been found that, in addition to reaction 1, the reduction process 2 also takes place in about 25% yield. This work has some serious limitations since it is based upon 80% recovery of products.



I

(1)



II

(2)

Suggestions have been made that thermal decomposition of sulfones normally occurs by homolytic cleavage of RSO_2R into R· and RSO_2· radicals, followed by loss of sulfur dioxide and subsequent recombination of the two R· radicals.[2]

Since the reaction studied in these laboratories proceeds in molten sulfur, the attack by sulfur radical should also be considered. If the rate-determining step were to be a concerted displacement by sulfur radical, then a very small sulfur-34 isotope effect should be found. On the other hand, in a homolytic cleavage into RSO_2· and R· radicals a substantial isotope effect should be observed.

The kinetics of the overall process in nitrogen atmosphere at 243, 262, 288, and 297° were studied, and the corresponding first-order rate constants, $k \times 10^6$ sec^{-1}, found to be 5.21 ± 0.12, 19.2 ± 0.3, 120 ± 1, and 209 ± 9, respectively (uncertainties are standard deviations of the mean). Using the technique of least squares the energy of activation for the overall reaction was found to be 41 ± 1 kcal mol^{-1}, and the frequency factor 1.0×10^{12} sec^{-1}. The entropy of activation was found to be −7 eu. Oae, *et al.*,[1] determined that the ratio of product yields from reactions 1 and 2 (I/II) remain unchanged even at the boiling point of sulfone (379°). This observation indicates that the energies of activation of both reactions must be similar and approximately equal to the energy of activation determined by us for the overall process (41 kcal mol^{-1}).

The maximum isotope effect in breaking a C–S bond can be calculated from Bigeleisen theory.[3] Assuming the C–S stretching frequency[4] of 700 cm^{-1} the maximum isotope effect for decomposition of the hypothetical C–S molecule was calculated to be 1.07% ($^{32}k/^{34}k = 1.0107$) at 243°.

The sulfur-34 isotope effect for the overall reaction at 243° was determined with $^{32}k/^{34}k = 1.0043 \pm 0.0012$. On the assumption that about 75% of SO_2 is formed by reaction 1 with an isotope effect (IE), and 25% of SO_2 by reaction 2 with an isotope effect (IE′), it follows that 0.43 = 0.75 IE + 0.25 IE′. The isotope effect (IE) of reaction 1 can only be estimated, since the isotope effect of reaction 2 (IE′) is not known. Reaction 2 may occur by a bimolecular attack of sulfur radicals from the melt. In this case a positive isotope effect related to the formation of sulfur radicals by sulfur–sulfur bond breaking will be reduced by the negative isotope effect caused by the bimolecular attack of sulfur radicals on the substrate. The resulting isotope effect of reaction 2, IE′, is therefore most probably not far from zero. If zero, IE is about 0.6%. It can be concluded that the measured isotope effect is primarily that due to reaction 1, and that its value is roughly one-half of the maximum isotope effect for breaking a C–S bond. This substantial isotope effect for reaction 1 indicates appreciable C–S bond weakening in the transition state, suggesting dissociation as a rate-determining step, followed by loss of sulfur dioxide and subsequent recombination of Ph· and S· radicals. The negative entropy of activation of −7 eu can be explained by assuming almost free rotation about the two C–S bonds in starting material, while this rotation may be quite

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[1] S. Oae and S. Kawamura, *Bull. Chem. Soc. Jap.*, **36**, 163 (1963).

[2] W. K. Busfield and K. J. Ivin, *Trans. Faraday Soc.*, **57**, 1044 (1961); W. K. Busfield, K. J. Ivin, H. Mackle, and P. A. G. O'Hare, *ibid.*, **57**, 1054 (1961); E. M. Lacombe and B. Stewart, *J. Amer. Chem. Soc.*, **83**, 3457 (1961).

[3] J. Bigeleisen and M. G. Mayer, *J. Chem. Phys.*, **15**, 261 (1947); J. Bigeleisen, *ibid.*, **17**, 675 (1949).

[4] W. O. George, R. C. W. Goodman, and J. H. S. Green, *Spectrochim. Acta*, **22**, 1749 (1966).