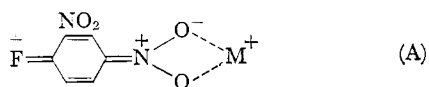A possible explanation for this decrease involved the *intimate* association of M^+ with oxygens of the nitro group, as in diagram A.

(A)

If this form is less readily attacked by the nucleophile, the over-all rate for the fluoro compound should be decreased. Since fluorine has the greatest tendency to resonate with the benzene ring,[12] est tendency to resonate with the benzene ring,[12]

(12) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, p. 75.

this rate-decreasing association would be greatest with 2,4-DNFB. The salt which would be expected to form the most stable association or complex (A) would be that with the smallest ionic radius, Li^+. Some support concerning (A) is given by Taft's observation that the contribution
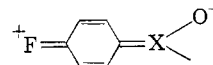
of the resonance form is increased in more polar solvents.[13]

(13) R. W. Taft, Jr., R. C. Olick, Irwin C. Lewis, Irwin Fox and Stenton Ehrenson, *J. Am. Chem. Soc.*, **82**, 756 (1960).

[CONTRIBUTION FROM THE ORGANIC CHEMISTRY DEPARTMENT, RESEARCH DIVISION, ABBOTT LABORATORIES, NORTH CHICAGO, ILL.]

Specific Solvent Effects in the Alkylation of Enolate Anions. IV. Kinetic Order of Solvent Participation

BY HAROLD E. ZAUGG

The rates of alkylation at 25° of diethyl sodio-*n*-butylmalonate with *n*-butyl bromide in mixtures of benzene with increasing amounts of each of the additives tetrahydrofuran (THF), ethylene glycol dimethyl ether (monoglyme), dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) have been measured. Participation orders for DMF and monoglyme are constant over the approximate concentration range 5 to 95%. For DMF the participation order is roughly three-halves and for monoglyme it is one. Participation orders for THF and DMSO are not constant but increase with concentration to maximum values of 1.4 and 1.7, respectively, after starting at orders of less than one at low concentrations. The relative rates (at 25°) of this reaction in five pure solvents are as follows: benzene = 1, THF = 14, monoglyme = 80, DMF = 970 and DMSO = 1420. The two diethers 1,4-dioxane and 1,3-dioxolane have been examined for catalytic action and participation order. In both respects they resemble the ineffective tetrahydrofuran more than the moderately effective monoglyme. In line with expectation, the cyclic N,N'-dimethylethyleneurea exhibits catalytic action quite superior to that of its acyclic analog tetramethylurea and slightly above that of N-methyl-2-pyrrolidone, the most active of the saturated amides previously found. Implications of these results relating to the mode of specific cation solvation, and to a previously proposed mechanism of rate acceleration, are discussed.

The rate of the reaction of alkyl halides with sodium enolates of malonic esters in benzene solution is variously influenced by the addition of small quantities (5–10%) of different polar substances.[1] Addition of esters, ketones, nitriles, simple ethers, sulfones, amines and nitro compounds causes only slight increases in the rate. In contrast, the presence of small amounts of many N,N-disubstituted amides and certain coördinate covalent P-, S- and N-oxides exerts a striking accelerating effect on the reaction. For example, a 5% concentration of dimethylformamide (DMF) serves to bring about roughly a 20-fold increase in reaction rate over that in benzene alone.

Preliminary study[1] of the rate acceleration as a function of additive concentration in the alkylation of diethyl sodio-*n*-butylmalonate with *n*-butyl bromide revealed at least four types of participation. The ineffective additives (*i.e.*, acetone, pyridine and tetrahydrofuran) possessed fractional participation orders. Two borderline cases (ethanol and monoglyme) displayed roughly a first-order relationship between concentration and rate acceleration. Five N,N-disubstituted amides showed an approximate three-halves order, and N-methyl-2-pyridone furnished the only example encountered of a second-order concentration dependency. All of these measurements were

(1) H. E. Zaugg, B. W. Horrom and S. Borgwardt, *J. Am. Chem. Soc.*, **82**, 2895 (1960).

conducted over a limited range of concentration (0.162 to 1.296 *M*, maximum).

It was the main purpose of the present work to extend this study to higher additive concentrations. To this end, tetrahydrofuran (THF), ethylene glycol dimethyl ether (monoglyme) and DMF, examples of the fractional order, first-order and three-halves-order types, respectively, were examined for their effect on the rate of this alkylation reaction at gradually increasing concentrations. Indeed, the concentration range was extended to the point where the additives constituted the only solvent species present in the reaction mixture (no benzene diluent). In addition, dimethyl sulfoxide (DMSO), an effective additive of the coördinate covalent class whose participation order had not been determined previously, was examined in the same way.

Three new compounds also were tested for their accelerating efficiency at low additive concentration. Two of them, 1,4-dioxane and 1,3-dioxolane, were included for comparison with the moderately effective diether, monoglyme. The third, N,N'-dimethylethyleneurea, was examined in order to test the validity of a prediction previously derived[2] as a consequence of the hypothesis that the presence of a high π-moment in the additive molecule is a primary requirement for outstanding catalytic efficiency.

(2) H. E. Zaugg, *ibid.*, **82**, 2903 (1960).

Experimental

Materials.—Reagent grade benzene was dried by distillation. Diethyl n-butylmalonate, b.p. 128–129° (20 mm.), $n^{25}D$ 1.4209, 99.6% pure by v.p.c. analysis, and n-butyl bromide, b.p. 100–101°, $n^{25}D$ 1.4362, were used in all rate experiments. Dimethylformamide, b.p. 152–153°, $n^{25}D$ 1.4281; dimethyl sulfoxide, b.p. 190°, $n^{23}D$ 1.4774; and N,N'-dimethylethyleneurea,[3] b.p. 95–97° (12 mm.), $n^{26}D$ 1.4700; were dried by distillation from calcium hydride. Tetrahydrofuran, b.p. 65–65.5°, $n^{25}D$ 1.4038; 1,4-dioxane, b.p. 100–100.5°, $n^{26}D$ 1.4193; 1,3-dioxolane,[4] b.p. 75–76°, $n^{26}D$ 1.3972; and ethyleneglycol dimethyl ether, b.p. 84.5°, $n^{26}D$ 1.3765; were dried by distillation from lithium aluminum hydride.

Procedure.—Rates were all measured at one temperature (25 ± 0.02°), using the procedure previously described[1] except when no benzene diluent was utilized. In these cases, the sodio-derivative was prepared in the particular solvent used (employing sodium hydride in the usual way[5]) at approximately four times the final concentration desired. A 25-ml. aliquot of this stock solution (clarified by centrifugation, if necessary) then was added to a 100-ml. volumetric flask and made up to volume with more of the same solvent plus the requisite amount of n-butyl bromide. Aliquots then were withdrawn at regular intervals and the course of the reaction was followed by titration in the usual way. Initial concentrations of the sodio-derivative in nearly all runs varied between the extremes, 0.100 to 0.120 M.

Sufficient excess of n-butyl bromide was employed to ensure attainment of first-order kinetics. The pseudo-first-order rate constants and their standard deviations were calculated statistically from the logarithmic change with time (in seconds) of the concentration of sodio-derivative. The second-order rate constants were then obtained by dividing the pseudo-first-order constants by the molar concentrations of n-butyl bromide. Results are summarized in Table I. The slowest reactions of this work were carried to 25–30% of completion, and the fastest ones to 75–80%. No significant deviations from linearity were encountered over these ranges. The rate discontinuity previously observed (Table II, footnote f of ref. 1) at lower THF concentrations was not encountered at the higher concentrations used here.

The solvent participation order, n, defined by the relation $k_2 = k[A]^n$ (or $\log k_2 = n \log [A] + \log k$, where [A] is the concentration of additive), was derived from the slope of the plot of $\log k_2$ vs. $\log [A]$. Plots for four of the additives are shown in Fig. 1, and values of n for the two straight lines (DMF and monoglyme) are included in Table I at the end of section A (DMF) and section D (monoglyme), together with their calculated standard deviations from linearity.

An idea of the limits of accuracy of the present work can be derived by looking at the variation in rate constant with change in n-butyl bromide concentration at a given concentration of additive. Rates at 1.296, 1.944 and 2.59 M concentrations of DMF (see Table IA) were measured at more than one concentration of n-butyl bromide, as also were rates at 1.398 and 2.80 M concentrations of DMSO (Table IB). Maximum variation was ±9%, and, almost invariably, the higher rate was obtained at the higher concentration of n-butyl bromide. This implies that, at the lower concentrations of n-butyl bromide used, the measured rate may be slightly lower than a true pseudo-first-order rate, even though apparent linearity was observed in all plots of log c vs. t (the 0.474 M concentration of n-butyl bromide represents only a fourfold excess over the initial concentration of sodio-derivative). The six runs in 2.59 M DMF (Table IA) were carried out as a preliminary test of the feasibility of going to such low concentrations of n-butyl bromide. A plot of log M (n-BuBr) vs. log k_1 (pseudo first-order constant) gave a straight line of slope 1.06 ± 0.04. Hence, the 0.474 M value was chosen as a compromise which would provide reasonably good first-order kinetics and still keep the fast reactions (high concentrations of DMF and DMSO) within conveniently measurable limits.

(3) M. W. Farlow, U. S. Patent 2,422,400 (1947); C. A., **41**, 6279 (1947).

(4) British Patent 739,022 (1955); C. A., **50**, 15592 (1956).

(5) Sodium hydride, 50% suspension in mineral oil, was used without prior removal of the suspending agent.

TABLE I

RATES OF ALKYLATION AT 25° OF DIETHYL SODIO-n-BUTYL-MALONATE WITH n-BUTYL BROMIDE IN THE PRESENCE OF ADDITIVES

Concn., M	Concn. of n-BuBr, M	$k_2 \times 10^5$, l. mole^{-1} sec.$^{-1}$	Concn., M	Concn. of n-BuBr, M	$k_2 \times 10^5$, l. mole^{-1} sec.$^{-1}$
A. Dimethylformamide (DMF)			**C. Tetrahydrofuran (THF)**		
0.324	2.37	2.45 ± 0.04[a]	0.324	2.37	0.34 ± 0.04[a]
0.648	2.37	7.09 ± .09	0.648	2.37	.39 ± .01[a]
1.296	0.474	15.40 ± .50	2.44	0.474	.93 ± .03
1.296	2.37	17.43 ± .17[b]	4.88	.474	1.54 ± .04
1.944	0.474	25.5 ± .46	8.65	.474	3.61 ± .04
1.944	2.37	31.9 ± .4[b]	11.10[c]	.474	4.87 ± .04
2.59	0.474	44.3 ± .4[b]	**D. CH$_3$OCH$_2$CH$_2$OCH$_3$**		
2.59	.664	41.0 ± .2	0.324	2.37	0.99 ± 0.01[a]
2.59	.948	43.6 ± .4[b]	0.648	2.37	2.23 ± .03[a]
2.59	1.422	46.3 ± .8	1.895	0.474	5.93 ± .04
2.59	1.896	46.0 ± .6	2.84	.474	9.32 ± .08
2.59	2.37	48.3 ± .6	3.79	.474	13.48 ± .06
3.89	0.474	73.6 ± .4	5.69	.474	19.85 ± .08
5.18	.474	113.7 ± 1.1	6.76	.474	23.9 ± .2
6.48	.474	167.7 ± 3.4	8.69[c]	.474	27.9 ± .4
7.78	.474	219.0 ± 4.0	(n = 1.05 ± 0.05)		
9.07	.474	274 ± 4	**E. 1,4-Dioxane**		
11.85[c]	.474	339 ± 5	0.648	2.37	0.620 ± 0.02
(n = 1.43 ± 0.02)			1.296	2.37	0.624 ± 0.02
B. Dimethyl sulfoxide (DMSO)			**F. 1,3-Dioxolane**		
0.280	2.37	4.34 ± 0.28	0.648	2.37	0.608 ± 0.01
.324	2.37	5.14 ± .07[a]	1.296	2.37	0.624 ± 0.01
.699	2.37	9.03 ± .25	**G. N,N'-Dimethylethyleneurea**		
1.398	0.474	15.27 ± .17			
1.398	2.37	18.86 ± .42	0.494	2.37	8.00 ± 0.09
2.80	0.474	36.4 ± .30	.741	2.37	14.18 ± .21
2.80	2.37	44.7 ± .3	.988	2.37	22.7 ± .3
4.19	0.474	71.7 ± .8	(n = 1.50 ± 0.07)		
5.59	.474	115.6 ± 1.3			
6.99	.474	167.7 ± 2.1	**H. No additive (benzene alone)**		
8.39	.474	227 ± 3			
12.93[c]	.474	498 ± 8	0	2.37	0.35 ± 0.02[a]

[a] Previously determined.[1] These values were chosen from the previous work for two reasons. They were measured rates for all but the first 13% of reaction, and hence are more representative of the whole. Furthermore, they fit the curve (perhaps fortuitously) whereas the faster rates observed prior to the discontinuity do not. [b] Average of two runs. [c] Represents concentration when only the additive (no benzene) serves as solvent under conditions of the given run (0.474 M n-butyl bromide + 0.10 to 0.12 M diethyl sodio-n-butylmalonate)

For use in determining the participation orders, both graphically (Fig. 1) and statistically, those k_2 values obtained at more than one n-butyl bromide concentration were merely averaged. No more weight was given to them than to those determined by only a single measurement.

Results

The participation orders of the four additives, studied in most detail, are revealed by the slopes of the four lines of Fig. 1. Participation of both DMF and monoglyme is clearly constant over the whole range of concentrations. Furthermore, the approximate three-halves order for DMF (Table IA) and unit order for monoglyme (Table ID) are essentially equal to the corresponding values found for these two solvents in the preliminary study.[1]

In contrast, the participation order of THF is not constant. Rather it increases from fractional values at low concentration, through unity, to somewhat less than three-halves (1.36 ± 0.10) at 4.9 M concentration where it remains constant. DMSO behaves analogously though at a higher level of activity. Starting at slightly less than

unity at low concentrations its order of participation increases to a maximum ($n = 1.73 \pm 0.03$) at about 2.8 M concentration and remains constant thereafter.

It is interesting to compare the accelerating effects of these four solvents at the highest attainable equimolar concentration, namely, 8.69 M (monoglyme in the absence of diluent). At this concentration, k_2 for THF is approximately 3.6, or about ten times the rate in benzene alone (see Table IH). In monoglyme $k_2 = 28$, and in both DMF and DMSO, k_2 at 8.7 M concentration is about 250. Thus at each step in going from benzene to THF to monoglyme to DMF or DMSO, the rate increases by roughly one power of ten. Some practical consequences of this striking accelerating effect of pure DMF on the rate of many alkylation reactions (10^3 times that in pure benzene, in the present case) already have been reported.[6]

The two diethers, 1,4-dioxane and 1,3-dioxolane, both exhibit little catalytic action and only fractional participation orders at low concentration (Table I, E and F). In this they resemble THF much more closely than the diether, monoglyme, to which they are more nearly related, structurally.

N,N'-Dimethylethyleneurea (Table IA) possesses potent catalytic action and a three-halves participation order. At a concentration of 0.324 M (Table IG, extrapolated) it produces a 12-fold increase in rate over that in benzene alone. The corresponding relative rates of tetramethylurea and N-methyl-2-pyrrolidone are 6 and 11, respectively.[7] Although the difference between 11 and 12 is within the usual limits of experimental error of the present work, several carefully determined simultaneous runs comparing the effect of N-methyl-2-pyrrolidone with that of N,N'-dimethylethyleneurea clearly showed the superiority of the latter.

Discussion

Several conclusions can be drawn from these results. The constancy of participation order common to DMF and monoglyme means that, for these two solvents, the mode of interaction (whatever it is) with the sodio-derivative[8] remains essentially unchanged over the entire range of concentration studied. For DMF this entails an over-all change from 2.5 to 95% DMF, and a 5- to 10-fold increase in dielectric constant. Further evidence for a specific solvation mechanism of catalytic activity derives from the 6-fold rate difference observed in THF and monoglyme despite the fact that these two solvents possess nearly identical dielectric constants ($\epsilon = 7.3$ for THF and 6.8 for monoglyme[9a]). A similar contrast between THF and monoglyme was observed by Wittig and Stahnecker[9a] in their study of the rearrangement of lithium benzhydryl phenyl ether

(6) H. Zaugg, D. Dunnigan, R. Michaels, L. Swett, T. Wang, A. Sommers and R. DeNet. *J. Org. Chem.*, **26**, in press (1961).

(7) Reference 1, Table II.

(8) Evidence clearly indicates[1] that the effective additives bring about rate acceleration through interaction with the sodio-derivative and not with the alkyl halide.

(9) (a) G. Wittig and E. Stahnecker, *Ann.*, **605**, 69 (1957); (b) H. Zook and T. Russo, *J. Am. Chem. Soc.*, **82**, 1258 (1960).
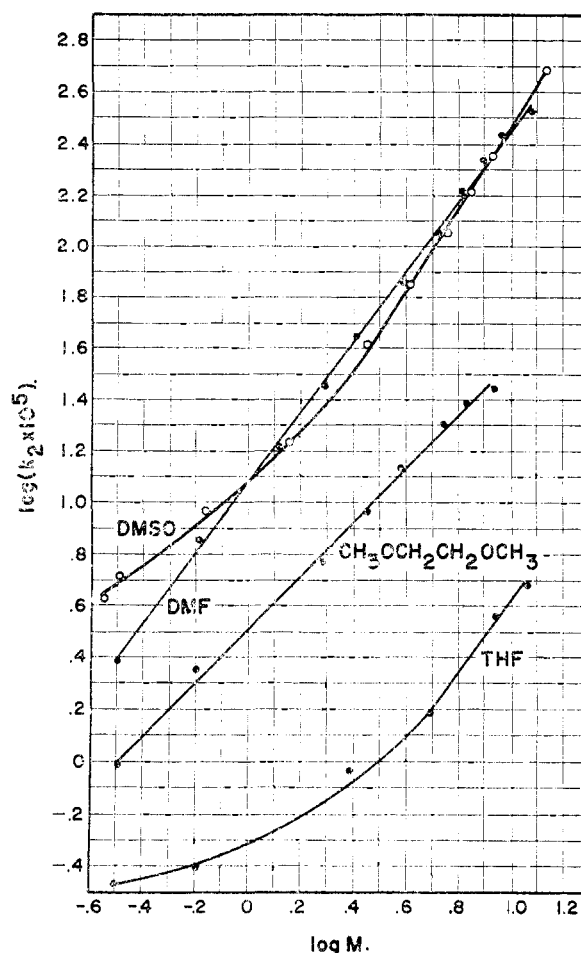

Fig. 1.

to lithium tritylate. The marked difference in the rates observed in these two solvents was ascribed by them to the increased ability of monoglyme to solvate lithium ion by a bidentate donor mechanism I. A similar picture has been drawn recently by Zook and Russo[9b] to explain the enhanced reactivities of certain enolate ions in monoglyme solution. This notion receives support from

I
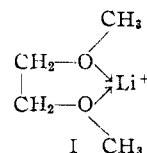
the present work. 1,4-Dioxane and 1,3-dioxolane are diethers like monoglyme. Yet their ring structure prevents them from assuming, without strain, a conformation like I, whereby both oxygens can donate to a single cation. Lacking this ability, they behave more like THF as cation solvators, in possessing little catalytic activity and only fractional participation orders at low concentrations (Table I, E and F).

Previously,[10] the prediction was made that, if catalytic effectiveness in the amide series is dependent on the extent of nitrogen lone-pair delocalization, N,N'-dimethylethyleneurea should be

(10) Reference 2, footnote 23.

a much better accelerator than tetramethylurea, and even better than N-methylpyrrolidone, the most active of the saturated amides so far discovered. This expectation arose from the hypothesis[2] that selective solvation of sodium ion by amides primarily involves a region of high electron density in the π-orbital surrounding the amide oxygen atom. The planar geometry of N,N'-dimethylethyleneurea, with consequent maximum overlap of the p-orbitals of the sp[2]-hybridized N, C and O atoms, presents an ideal situation for producing a relatively high order of negative charge around the oxygen atom. The observation that N,N'-dimethylethyleneurea is twice as effective in accelerating the alkylation reaction as its acyclic analog tetramethylurea accords with expectation. That it is only slightly better than N-methyl-2-pyrrolidone indicates that the second nitrogen lone pair is not equal to the first in contributing to the π-orbital electron density of the oxygen atom.

Although it is an effective catalyst, DMSO, like THF but unlike DMF, increases its participation with increasing concentration. DMSO has already been found[1] to differ from DMF in that its presence resulted in a measurable increase in activation enthalpy of the alkylation reaction. In view of their differing geometries (DMF is predominantly planar at room temperature and DMSO is pyramidal) and probable differing modes of electron delocalization (DMF uses a pπ-orbital while DMSO very likely uses a dπ-orbital[2]), the

discovery of differences in their behavior as cation solvators is not surprising.

One more conclusion can be derived from the present work. Previously,[1] a mechanism for solvent acceleration was proposed involving specific solvation of the cation by the effective additive with resulting dissociation of the high molecular weight ion pair aggregate shown to be present in benzene solution. Production of a low molecular weight solvated species would then result in the observed acceleration of alkylation rate. The extent of acceleration would depend on the intrinsic cation-solvating capacity of the additive and on its concentration, since these two factors would determine the position of the equilibrium between ion pair aggregate and reactive solvated species. The present work shows that with increasing concentrations of two very effective additives (DMF and DMSO) no rate maximum is achieved. This means that, if the proposed mechanism is correct, some high molecular weight aggregate must still be present even in nearly pure DMF and DMSO, at the concentrations (ca. 0.1 M) of sodio-derivative employed. This appears, a priori, to be rather unlikely. Appropriate physical measurements should settle the question, and these are being planned.

The Free Radical Addition of Trifluoromethanethiol to Fluoroölefins
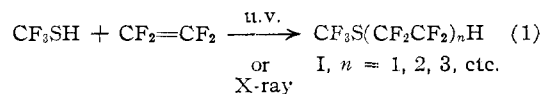
BY JOHN F. HARRIS, JR., AND F. W. STACEY

Trifluoromethanethiol adds readily to terminal fluoroölefins under the influence of X-rays or ultraviolet radiation. The addition to hexafluoropropylene gives both possible 1:1 adducts in nearly equal amounts, in contrast to previously studied radical additions to this olefin which have been reported to give only one product.

Introduction.—Although considerable work has been reported on the free radical addition of a variety of substances to fluoroölefins,[1] there appears to be very little in the literature about the free radical addition of thiols to fluoroölefins. Apparently, the only reports concern the benzoyl peroxide-initiated addition of thiophenol to perfluoro-1,5-hexadiene[2a] and the addition of ethanethiol to tetrafluoroethylene with the same initiator.[2b] The structures of the products were not determined. The free radical addition of thiols to hydrocarbon olefins is well known.[3] There have been a few reports of the base-catalyzed addition of thiols to fluoroölefins.[2a,4] Apparently, there is

no report of the addition of a fluorinated thiol to a fluoroölefin.

Results.—We have found that the addition of thiols and more particularly trifluoromethanethiol to tetrafluoroethylene, chlorotrifluoroethylene, trifluoroethylene, hexafluoropropylene, 1,1-difluoroethylene and trifluorovinyl methyl ether (all terminal fluoroölefins) proceeds smoothly under the influence of ultraviolet radiation or X-rays. With two olefins, hexafluoropropene and trifluoroethylene, both possible 1:1 adducts were obtained. The results are summarized in equations 1–10.

Tetrafluoroethylene

$$CF_3SH + CF_2{=}CF_2 \xrightarrow[\substack{\text{or} \\ \text{X-ray}}]{\text{u.v.}} CF_3S(CF_2CF_2)_nH \quad (1)$$

$$I, \; n = 1, 2, 3, \text{etc.}$$

(1) R. N. Haszeldine, et al., J. Chem. Soc., 1592, 3559, 3565 (1953); 923, 3747 (1954); 3005 (1955); 61 (1956); 2193, 2800 (1957).

(2) (a) W. T. Miller, U. S. Patent 2,864,867 (1958); (b) W. E. Hanford, U. S. Patent 2,443,003 (1948).

(3) C. Walling, "Free Radicals in Solution," John Wiley and Sons, Inc., New York, N. Y., 1957, pp. 313–326.

(4) (a) I. L. Knunyants and A. V. Fokin, Bull. acad. sci. USSR Div. Chem. Sci. (Eng. Trans.), 279 (1952); (b) I. L. Knunyants,

A. I. Shchekotikhin and A. V. Fokin, ibid., 255 (1953); (c) K. E. Rapp, et al., J. Am. Chem. Soc., 72, 3642 (1950).