Registry No.—Lithio diethyl malonate, 34727-00-9; diethyl sodio-*n*-butylmalonate, 22600-93-7; sodio-3-phenyl-2-benzofuranone, 34727-02-1; *n*-butyl bromide, 109-65-9; sodio diethyl malonate, 18424-75-4; lithio-3-phenyl-2-benzofuranone, 34727-03-2; lithium *p*-cresolate, 1121-69-3; sodium *p*-cresolate, 1121-70-6; lithium *p*-nitrophenolate, 1124-32-9; sodium *p*-nitrophenolate, 824-78-2.

Specific Solvent Effects. VIII. The Solvation of Sodiomalonate Ion Pairs by the Tertiary Amide Group

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The rate of alkylation of sodio *n*-butylmalonate with *n*-butyl bromide has been used to probe the mechanism of ion-pair solvation by the tertiary amide function. Changes in catalytic effect produced by varying the distance between two amide groups in the same molecule have been measured. Mutual assistance of the two groups is observed for separations of 4 and 5 carbon atoms (adipamide and pimelamide), but smaller separations (*i.e.*, glutaramide, succinamide, and oxamide) result in mutual hindrance of ion-pair solvation. These findings are consistent with the view that the tertiary amide function solvates the sodium ion by a π-donor mechanism and that, when two such groups are a proper distance apart, intramolecular disolvation of the cation can occur by such a mechanism.

The distinctly superior catalytic action of 1,2-dimethoxyethane (DME) over tetrahydrofuran (THF) and certain geometrically constrained diethers (*e.g.*, 1,3-dioxolane and 1,4-dioxane) in accelerating the alkylation of sodio diethyl *n*-butylmalonate in benzene solution was interpreted[1] in terms of selective cation solvation resulting from the bidentate donor character of DME. This view was reinforced by the observation that the hexadentate donor, dicyclohexyl-18-crown-6 polyether, is vastly more effective than DME.[2] Also explained in terms of selective cation solvation was the marked acceleration caused by the addition of small amounts of N,N-disubstituted amides and certain *P*-, *S*-, and *N*-oxides.[1,3] Evidence indicated[3] that these substances act as π donors for the cation in the same way that the polyethers serve as n donors.

Work described in the preceding papers[2,4] strongly suggested that the alkylation of sodio diethyl *n*-butylmalonate in benzene–dimethylformamide (DMF) media is a process involving an ion-pair species containing a sodium ion that is at least disolvated. This, together with the observed increased effectiveness of the multidentate ethers, leads to the prediction that certain diamides structurally permitted to disolvate the cation by an intramolecular π-donor mechanism should accelerate the alkylation more effectively than either monamides or diamides unable to undergo bidentate π interaction with the cation. To check this prediction, the effect of a series of diamides on the alkylation rate is examined in the present work. The distance between the two amide functions is varied systematically, and rate comparisons are made with the monoamide, *N*,*N*-dimethylacetamide, serving as a standard.

Because these amides are more polar than the ethers studied previously,[1,2] the dielectric constants of several benzene–amide mixtures were measured to check any possible correlation of this bulk solvent effect with corresponding rate accelerations.

Experimental Section

Materials.—Hexamethylphosphoramide (Monsanto) was purified by distillation, bp 121° (19 mm), n^{25}D 1.4570. The N,N,N^1,N^1-tetramethyldiamides of the following acids were prepared according to published procedures: oxalic,[5] mp 78–80°; dimethylmalonic,[6] mp 79–80.5; succinic,[5] mp 83.5–84.5°; glutaric,[7] mp 45–47°; adipic,[5] mp 82–83°; pimelic,[5] bp 162–166° (0.7 mm), n^{25}D 1.4828; phthalic,[8,9] mp 121–123°; isophthalic,[9] mp 135–136°. Specifications for the other reagents used in this work are listed in the preceding paper.

Kinetics.—Rate measurements were conducted as described in the preceding paper.[2] Log–log plots of additive concentration *vs.* rate were statistically analyzed to determine the slopes (*i.e.*, kinetic orders of participation) of the lines and their standard deviations from linearity.

Dielectric Measurements.—Dielectric constants were measured at 25° and at a frequency of 2 MHz, using a Model 3A dielectric constant meter of the Yellow Springs Instrument Co., Inc., Yellow Springs, Ohio. Benzene ($\epsilon_{25°}$ 2.3) was used as a standard.

Results

Figure 1 shows the log–log plots of the alkylation rate *vs.* amide group concentration in benzene for six homologous diamides determined in the present work, and for acetamide, which was previously measured.[10] For the diamides, amide group concentrations, [CON-$(CH_3)_2$], are equal to twice the molar concentrations, and for acetamide the two factors are obviously equal. From the equation (Figure 1), the empirical kinetic order of additive participation, n, is given by the slope of the log–log plot. The numerical n values also are listed in Figure 1.

The seven amides of Figure 1 can be divided into three groups of participation orders: n = 0.8, 1.1, and 1.4. These results are consistent with previous measurements carried out in this concentration range.[1,10] It was found that, among a number of miscellaneous addi-

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(1) H. E. Zaugg, *J. Amer. Chem. Soc.*, **83**, 837 (1961); part IV in the series "Specific Solvent Effects."

(2) H. E. Zaugg, J. F. Ratajczyk, J. E. Leonard, and A. D. Schaefer, *J. Org. Chem.*, **37**, 2249 (1972).

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(7) P. A. Meerburg, *ibid.*, **18**, 374 (1899); *Beilstein*, **4**, 63.

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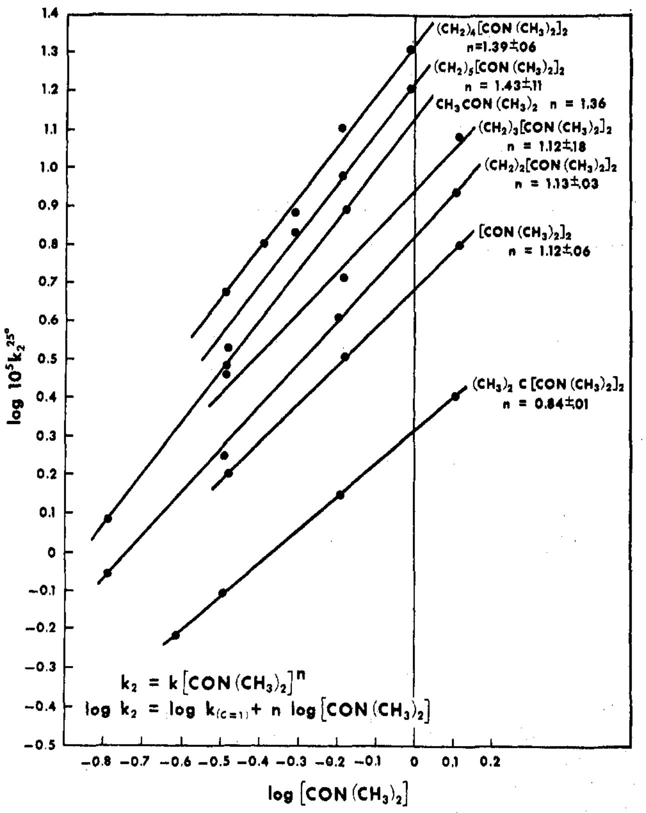

Figure 1.—Log–log plots of the rate of alkylation at 25° of diethyl sodio-*n*-butylmalonate with *n*-butyl bromide *vs.* the amide group concentration in benzene of six diamides and acetamide. (The horizontal base line at −0.5 represents the rate in the absence of amide.)

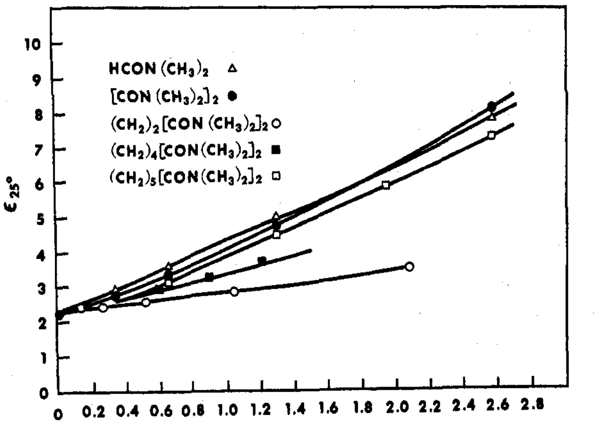

Figure 2.—Dielectric constant at 25° *vs.* concentration of amide group in benzene of one monoamide and four diamides.

tives in benzene, relatively ineffective examples (*e.g.*, acetone, pyridine, nitrobenzene, THF) showed fractional *n* values, moderately active ones (*e.g.*, DME, ethanol) gave roughly unit orders of participation, and the best ones (*e.g.*, DMSO and many N,N-disubstituted amides) had *n* values in the range 1.3 to 1.5.[11]

Because of the inequality of participation orders in

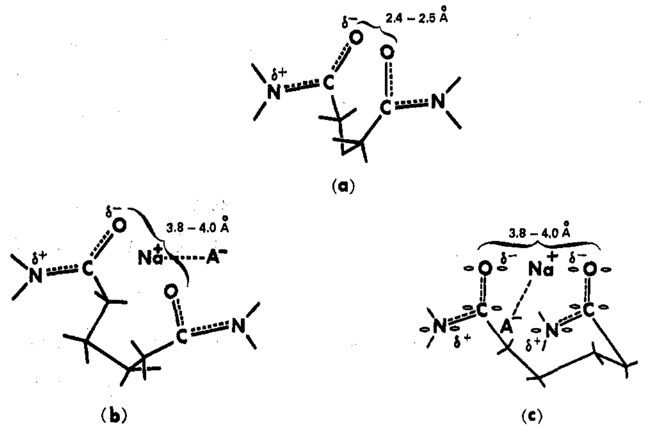

Figure 3.—Plane-parallel conformations for maximum separation of the amide groups in glutaramide (a) and adipamide (b, c).

the present work, valid comparisons of catalytic activity must be made at the *y* intercept of Figure 1 (*i.e.*, $n \log [CON(CH_3)_2] = 0$). It is apparent that activity in the series of diamides increases with increasing distance between the polar groups to an optimum separation of four carbon atoms. Anything less than this results in activity lower than that of the reference compound, but a five-atom separation still provides for augmented activity.[12,13]

Figure 2 illustrates the increase in dielectric constant with increasing amide group concentration in benzene for four of the diamides studied kinetically, and for DMF used as a reference. The concentration range encompasses that of the kinetic work, and once again for the diamides amide group concentrations are twice the molar concentrations. It is apparent that the first and last members of the diamide series behave most nearly like the reference amide. The other two, including the catalytically most active diamide, deviate significantly from the standard, both showing lower than normal dielectric constants.

Discussion

It is apparent from Figures 1 and 2 that there is no correlation between the dielectric constant of the medium and the corresponding alkylation rate. This is consistent with the long-held view[1,3,10] that the rate accelerations are produced through a specific solvation mechanism. Furthermore, in accord with prediction, a synergism is observed when two amide groups are a correct distance apart in the same molecule. The 4–5 carbon-atom separation required for optimum activity can be rationalized with the aid of Figure 3.

It is assumed that, to attain maximum π-donor capacity for both oxygen atoms simultaneously, their π orbitals must be directed collinearly toward a single, central sodium ion. A Dreiding model of glutaramide (Figure 3a) in this required conformation reveals that the maximum attainable distance between oxygen

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[11] DMF is almost identical with *N,N*-dimethylacetamide with respect to catalytic activity (see Figure 1 of the preceding paper). Also, hexamethylphosphoramide, $[(CH_3)_2N]_3PO$, a solvent receiving considerable recent attention, was found[10] to be the best catalyst of all at 0.32 *M* concentrations. Its participation order, measured in the present work, is 1.37 ± 0.09.

[12] For obvious reasons, the unsubstituted malonamide could not be used as a chemically inert additive. The reason for the extremely poor catalytic activity of its dimethyl derivative is probably steric in nature. *N,N*-Dimethylpivalamide, for example, was found to be only half as active as dimethylacetamide.[10]

[13] *N,N,N*¹*,N*¹-Tetramethylphthalic and isophthalic amides also were studied in the present work. Both gave *n* values and intercepts nearly identical with those of tetramethyloxamide.

centers is 2.4–2.5 Å.[14] It is our contention that, considering the space occupied by the extended oxygen π orbitals possessing the bulk of the electron density, this is not a sufficient separation[15] to accommodate a sodium ion (diameter 1.90 Å). A similar model for adipamide (Figure 3b) gives a maximum distance between oxygens of 3.8–4.0 Å with enough flexibility in the carbon chain to adjust downward to whatever minimum-energy dimension is required by the cation. The even greater distance afforded by the pimelamide provides no further advantage, since the optimum has been reached in the adipamide. Indeed, the larger number of conformational degrees of freedom in the pimelamide results in a less favorable entropy for disolvation so that its activity decreases with respect to the adipamide. Presumably, further chain extension would provide even less intramolecular synergism, and catalytic activity would approach that of *N*,*N*-dimethylacetamide.

An alternate mechanism involving intramolecular π-donor–π-acceptor solvation of both ions of the ion pair (Figure 3c) is not considered to be important for three reasons: (1) it is not likely that the steric demands for simultaneous and optimal solvation of both a small cation and a large anion could be met by any such scheme; (2) in fact, it is known[17] that dipolar aprotic compounds usually coordinate with small cations more readily than with anions; and (3) the anion in such a solvated ion pair would not possess greatly increased nucleophilic reactivity, because any decrease in sodium-ion influence would be offset by the proximity of the two positively charged nitrogen atoms.

The low activity of the other diamides compared to the standard monoamide shows that the second amide group is actually counterproductive with respect to cation solvation. Part of this effect, especially for the lower homologs, may be steric.[12] However, the abnormally low dielectric constant for the succinamide (Figure 2) suggests the occurrence of considerable intramolecular neutralization of the amide dipoles. This would tend to reduce the π-donor capacity of either amide function below that of the monoamides in which such interaction occurs only through intermolecular association. The highly active adipamide also shows some evidence of such intramolecular amide interaction. In the presence of sodium ion, however, the capacity of the two functions to act synergistically (*cf.* Figure 3b) clearly supplants the deactivating effect of the dipole neutralization.

Registry No.—HCON(CH$_3$)$_2$, 68-12-3; [CON(CH$_3$)$_2$]$_2$, 1608-14-6; (CH$_2$)$_2$[CON(CH$_3$)$_2$]$_2$, 7334-51-2; (CH$_2$)$_4$[CON(CH$_3$)$_2$]$_2$, 3644-93-7; (CH$_2$)$_5$[CON(CH$_3$)$_2$]$_2$, 34712-64-6; diethyl *n*-butylsodiomalonate, 22600-93-7; *n*-butyl bromide, 109-65-9.

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[14] A similar model of succinamide shows that the collinear requirement cannot be met.

[15] Although the "hole" in dicyclohexyl-18-crown-6 polyether is not much larger than this (2.6–3.2 Å),[16] the space occupied by the oxygen n orbitals in ethers is considerably less than that required by the π orbitals in amides.

[16] C. J. Pedersen, *J. Amer. Chem. Soc.*, **92**, 386 (1970).

[17] A. J. Parker, *Quart. Rev., Chem. Soc.*, **16**, 163 (1962).

Thermal Reactions of Alkyl Isocyanates. I

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The gas-phase thermal reactions of alkyl isocyanates have been investigated using a static manometric technique. While the ethyl compound decomposes through a complex and partly heterogeneous series of reactions, isopropyl and *tert*-butyl isocyanates yield isocyanic acid and olefins by a well-defined, homogeneous, first-order process. The effect of temperature on the rate constants is given by the following equations: isopropyl isocyanate, $\log k_1$ (sec^{-1}) $= 12.71 - (53{,}300/2.30RT)$; *tert*-butyl isocyanate, $\log k_1$ (sec^{-1}) $= 13.59 - (52{,}400/2.30RT)$. The results are discussed with special reference to those for alkyl isothiocyanates. It is found that substitution of sulfur by oxygen in these species results in a decrease in reactivity of three orders of magnitude. The transition state for these reactions is regarded as a six-centered structure of moderate polarity.

The results previously obtained with isothiocyanates[1] have prompted us to investigate the thermal reactions of organic isocyanates in the gas phase. The most relevant work in this field has been that of Back, *et al.*, on the photolysis[2] and the pyrolysis[3] of isocyanic acid itself at temperatures above 550°. These authors conclude that the thermal decomposition of isocyanic acid occurs through a complex mechanism of appreciable heterogeneous character. Preliminary experiments carried out in these laboratories on ethyl isocyanate between 440 and 500° showed that this, too, is a complex reaction of no well-defined stoichiometry and which is presumably heterogeneous to a large extent. The situation is complicated by the tendency of this compound to polymerize in the liquid state through a reaction which appears to be catalyzed by traces of a variety of substances, among which are the products of the pyrolysis. On the other hand, isopropyl and *tert*-butyl isocyanates decompose in carbon-coated vessels in a much simpler manner. The purpose of this work is to investigate this last reaction and to compare the results with those from the sulfur analogs, namely, alkyl isothiocyanates, in an attempt to draw general conclusions about the mechanism of elimination of pseudohalides of type RXCY (X,Y = O,S,N).

Results

Isopropyl Isocyanate.—When the pyrolysis occurs in a clean Pyrex reaction vessel, the initial rate of pressure increase was erratic, and CH$_4$, CO, and CO$_2$

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[2] R. Back and R. Ketcheson, *Can. J. Chem.*, **46**, 531 (1968), and references therein.