difficulties will not be insuperable and that the vector method will provide a means of determining molecular geometry in such complex systems.

URBANA, ILLINOIS

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, FLORIDA STATE UNIVERSITY]

Specific Solvent Effects in the Hydrolysis of *p*-Nitrobenzhydryl Bromide

BY BILL B. SMITH AND J. E. LEFFLER

RECEIVED NOVEMBER 5, 1954

The hydrolysis of *p*-nitrobenzhydryl bromide in aqueous acetone is accelerated and the activation enthalpy changed when part of the acetone is replaced by hexane or by aromatic compounds. An explanation in terms of preferential solvation and complex formation is proposed.

Although certain macroscopic properties of the solvent, as for example the dielectric constant, are of importance in determining the effect of solvent changes on reaction rates, such macroscopic properties are quite inadequate for any complete explanation of solvent effects. This is especially noticeable in the case of mixed solvents[1] or when an attempt is made to explain the effect of solvent changes on activation parameters as well as on rates.[2] One of the special solvent effects that must be considered is the formation of molecular complexes. Another is the tendency of solvent in the vicinity of a solute molecule to have a different composition from that in the bulk of the solvent in the case of mixed solvents.

The partial positive charge on the central carbon atom of the transition state for *p*-nitrobenzhydryl bromide hydrolysis should confer an enhanced stability on π-complexes formed by the transition state as compared to those formed by the ground state. As a result the free energy of activation of the hydrolysis should be lower in the presence of appropriate complexing agents even though the addition of the complexing agent may lower the dielectric constant of the solvent. We have carried out the indicated experiments and find a rate effect in the predicted direction. The effect is a small one, however, and seems to be superimposed on a larger effect having nothing to do with the formation of π-complexes.

Table I shows the effect of replacing part of the acetone in a standard aqueous acetone solvent with various aromatic compounds and with hexane in concentrations about 1 molar. The most conspicuous result is the acceleration (14 to 39%) of the reaction in any of the other mixtures as compared with aqueous acetone. The null hypothesis for these rate differences has a negligible probability.[3] The difference in activation enthalpy for the reaction in aqueous acetone and in aqueous acetone–*p*-dimethoxybenzene has only a 15% probability of being null while the differences in entropy of activation have a rather high probability of being null except in the case of hexane. It is therefore reasonable to seek explanations of the rate effect that predict it on the basis of a decrease in activation enthalpy. The next most conspicuous feature of Table I is the fact that hexane not only accelerates the reaction but has a larger effect on the activation parameters than any of the other addends. Since π-complexing can be neglected in the case of hexane, and since hexane certainly does not make the reaction mixture more polar, at least one additional factor must be at work.

In a three-component solvent system there is no difficulty in finding explanations of the experimental facts but only in defending a preferred explanation selected from many. The explanation presented here is by no means the only possible one but does make use of the predicted effect of complexing by aromatic compounds Large, relatively non-polar organic molecules like *p*-nitrobenzhydryl bromide and its transition state for hydrolysis will tend to surround themselves preferentially with the organic components of a mixed solvent. Some, but not all, of the organic solvent molecules must be displaced to make room for water molecules in the transition state. The most easily displaced solvent component will be hexane. The solvent that contains hexane in place of some of the acetone therefore has a lower activation enthalpy. Acetone and the aromatic compounds interact more than hexane with the alkyl bromide and are less easily ejected to make room for water molecules. Since they are more firmly held, their release is attended by an increase in entropy, hence the generally higher activation enthalpies and less negative entropies for acetone and the aromatic compounds. In the case of the aromatic compounds those molecules that remain in the aggregation about the transition state partly counteract the general increase in activation energy by complexing with the transition state. Thus the aromatic molecules give a lower activation energy than acetone, an effect which is greater with the substituted benzenes than with benzene itself.

Table II shows the effect of increasing the water content on the rates in aqueous acetone. Since added water seems to accelerate the reaction almost entirely by an entropy effect, the activation enthalpies being unchanged within their probable errors, it is unlikely that the non-polar solvents produce their acceleration by releasing water, for example from an acetone–water complex. Any purely entropy effect on changing the concentration of a reagent can be described either as a medium effect or as a concentration effect. If the effect of adding water to these solutions is merely that of changing

---

[1] N. Farinacci and L. P. Hammett, THIS JOURNAL, **59**, 2542 (1937); **60**, 3097 (1938).

[2] H. E. Cox, *J. Chem. Soc.*, **119**, 142 (1921).

[3] W. J. Youden, "Statistical Methods for Chemists," John Wiley and Sons, Inc., New York, N. Y., 1951.

TABLE I

REPLACEMENT OF ACETONE WITH OTHER SOLVENTS

Solvent[a]	Temp., °C.	Rate const. min.$^{-1}$	$\Delta H^{\ddagger}$, kcal./mole	$\Delta S^{\ddagger}$, cal./mole deg.
RBr 0.0321	49.99 ± 0.02	1.61×10^{-4}		
H_2O 4.61	49.99	1.63×10^{-4}		
Acetone 12.48	75.68	1.78×10^{-3}	20.13 ± 0.07[b]	−21.82 ± 0.21[b]
	75.68	1.83×10^{-3}		
	92.47 ± .03	7.01×10^{-3}		
	92.47	6.95×10^{-3}		
RBr 0.0322	50.01 ± .02	2.22×10^{-4}		
H_2O 4.62	50.02	2.11×10^{-4}		
Acetone 10.77	75.61	2.06×10^{-3}	19.34 ± 0.09	−23.71 ± 0.27
Hexane 0.973	75.71	2.15×10^{-3}		
	92.45 ± .03	8.03×10^{-3}		
	92.56	8.00×10^{-3}		
	92.56	8.42×10^{-3}		
RBr 0.0321	49.98 ± .02	2.09×10^{-4}		
H_2O 4.64	49.98	2.06×10^{-4}		
Acetone 10.87	75.53	2.24×10^{-3}	19.90 ± 0.07	−22.05 ± 0.19
p-Dimethoxybenzene 0.990	75.57	2.16×10^{-3}		
	92.33 ± .03	8.43×10^{-3}		
	92.35	8.57×10^{-3}		
RBr 0.0321	50.00 ± .02	2.26×10^{-4}		
H_2O 4.61	50.00	2.25×10^{-4}		
Acetone 10.79	75.68	2.40×10^{-3}	19.94 ± 0.08	−21.75 ± 0.23
m-Dimethoxybenzene 0.944	75.72	2.51×10^{-3}		
	92.56 ± .03	9.55×10^{-3}		
	92.62	9.37×10^{-3}		
RBr 0.0321	50.00 ± .02	2.19×10^{-4}		
H_2O 4.61	50.00	2.21×10^{-4}		
Acetone 10.79	75.60	2.45×10^{-3}	20.07 ± 0.08	−21.41 ± 0.23
Nitrobenzene 1.230	75.67	2.42×10^{-3}		
	92.45 ± .03	9.37×10^{-3}		
	92.47	9.29×10^{-3}		
RBr 0.0321	49.98 ± .02	1.86×10^{-4}		
H_2O 4.61	49.98	1.89×10^{-4}		
Acetone 10.79	75.59	2.06×10^{-3}	20.09 ± 0.06	−21.65 ± 0.18
Benzene 1.399	75.59	2.07×10^{-3}		
	92.38 ± .03	7.91×10^{-3}		
	92.43	8.05×10^{-3}		

[a] Figures in this column represent molarity of *p*-nitrobenzhydryl bromide, water, acetone and added substance. [b] Probable error.

TABLE II

INCREASE IN WATER CONCENTRATION[b]

Solvent[a]	Temp., °C.	Rate const. min.$^{-1}$	$\Delta H^{\ddagger}$, kcal./mole	$\Delta S^{\ddagger}$, cal./mole deg.
RBr 0.0321	49.99 ± 0.02	3.80×10^{-4}		
H_2O 6.00	50.01	3.60×10^{-4}		
Acetone 12.08	50.02	3.64×10^{-4}	20.07 ± 0.14[c]	−20.39 ± 0.42[c]
	75.72	3.89×10^{-3}		
	75.74	3.75×10^{-3}		
	75.71	4.26×10^{-3}		
	92.50 ± .03	1.52×10^{-2}		
	92.55	1.64×10^{-2}		
RBr 0.0321	49.89	2.44×10^{-4}		
H_2O 5.32	49.89	2.39×10^{-4}		
Acetone 12.25	74.99	2.40×10^{-3}	20.25 ± .12	−20.68 ± 0.37
	74.99	2.47×10^{-3}		
	74.99	2.50×10^{-3}		
	92.55	1.13×10^{-2}		
	92.58	1.06×10^{-2}		

[a] Molarities *p*-nitrobenzhydryl bromide, water and acetone. [b] See also Table I for 4.61 *M* H_2O. [c] Probable error.

the concentration of a reagent, then the molecularity of the reaction with respect to water is about 2 to 4.

Experimental

***p*-Nitrobenzhydrol**[4] was made from *p*-nitrobenzophenone.[5] It is crystallized by adding petroleum ether to the chilled benzene solution over a period of several hours. The chief impurity is unreduced ketone. Four crystallizations are usually needed to give alcohol of sufficient purity melting at 73.0–75.5°.

***p*-Nitrobenzhydryl bromide**[6] is made by adding purified *p*-nitrobenzhydrol (17 g.) to a stirred mixture of 60 cc. of concd. sulfuric acid and 160 cc. of 48% hydrobromic acid. After 20 hours of stirring at room temperature the solution is poured into a slurry of ice and water and extracted with ether. The ether solution, washed with water, dried over sodium sulfate and evaporated leaves a brown oil. The oil is distillable in a Hickman molecular still, boiling in the neighborhood of 155–165° at 10^{-3} to 10^{-4} mm. The product is 15 g. of a light yellow oil. It usually assays about 98.2 to 99.0% *p*-nitrobenzhydryl bromide as estimated by treating an acetone solution of the bromide with aqueous silver nitrate and weighing the silver bromide. Further distillations do not raise the assay and the infrared spectrum indicates that the impurity is the innocuous *p*-nitrobenzophenone.

Anal. Calcd. for $C_{13}H_{10}NO_2Br$: C, 53.44; H, 3.45; Br, 27.35. Calcd. for 98.8% $C_{13}H_{10}NO_2Br$ and 1.2% $C_{13}H_9NO_3$: C, 53.62; H, 3.89; Br, 27.03. Found: C, 54.09; H, 3.77; Br, 27.09.[7]

Solvents.—Acetone (Baker and Adamson Technical) was dried over calcium chloride for one week, then distilled through a 19-plate bubble-cap column, b.p. 56.5°. Water was distilled and redistilled from alkaline permanganate. *p*-Dimethoxybenzene and *m*-dimethoxybenzene were Eastman White Label grades. Benzene, nitrobenzene and hexane were reagent grade materials dried and distilled from calcium hydride through a one-meter helix-packed column.

Kinetic Runs.—Sealed ampoules were withdrawn from the thermostat at noted times and quenched in ice-water. In the case of solutions containing hexane it was found necessary to freeze the evacuated ampoules in liquid nitrogen while sealing them. Hexane vapor evidently decomposes in contact with the hot glass and prevents a good seal. A 5-ml. aliquot was removed from each ampoule after quenching, poured into about 15 cc. of acetone and titrated with 0.02 to 0.04 *N* sodium hydroxide using one drop of a 2% solution of methyl red in 84% acetone as the indicator.

Calculations.—Zero time was the time of withdrawal of the first ampoule, usually after about five minutes to allow thermal equilibration. The reactions were followed to over 80% of completion. Acid titers were converted to concentrations of alkyl bromide treating the infinity titer as a parameter adjustable to give the best first-order kinetics. In all cases the value used was close to the theoretical value but slightly higher than the experimental one. There appears to be a very slow acid-consuming side reaction. Calculations were made using the weighed least squares formula

$$k = 2.303\Sigma \log \frac{C_0}{C_0 - C} \Big/ \Sigma(t - t_0)$$

in which C is the infinity acid titer minus the titer at time t. Activation parameters and their probable errors were calculated by the method of least squares to give the best fit to the equation[8]

$$k = \frac{\bar{k}T}{h} e^{-\frac{\Delta H^{\ddagger}}{RT}} e^{\frac{\Delta S^{\ddagger}}{R}}$$

Effect of Dimethoxybenzene on the Spectrum.—The addition of *p*-dimethoxybenzene to acetone solutions of *p*-nitrobenzhydryl bromide produces a yellow color. This is not, however, due to the charge-transfer band of a molecular complex but is merely the result of a moderate shift in wave length of one of the *p*-nitrobenzhydryl bromide bands from a position almost entirely in the ultraviolet to a position partly in the visible region. The shift in wave length takes place without change in shape of the band. Because of the opacity of acetone to shorter wave lengths and the irrelevance of results in other solvents, no further search was made for a band assignable to a complexed ground state.

Acknowledgment.—This work was supported by the Office of Ordnance Research, U. S. Army. The experiments with hexane and with 6 *N* aqueous acetone were done by Mr. Harold Perkins of this Laboratory.

TALLAHASSEE, FLORIDA

---

[4] Directions for the reduction of benzophenone itself were followed. A. L. Wilds, "Organic Reactions," Vol. II, John Wiley and Sons, Inc., 1944, p. 205.

[5] We wish to thank Dr. Don Carroll for synthesizing some of the *p*-nitrobenzophenone.

[6] Several people working in our laboratory reported a severe dermatitis on the fingers, arms or face while working with the bromide and its precursors. Experiments with mice confirmed the irritant nature of these compounds.

[7] Carbon–hydrogen analysis by Clark Microanalytical Laboratory.

[8] S. Glasstone, K. J. Laidler and H. Eyring, "The Theory of Rate Processes," McGraw-Hill Book Co., Inc., New York, N. Y., 1941.