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Relative Velocities of Reaction of Alcohols with Phenyl Isocyanate

BY TENNEY L. DAVIS AND JAMES McC. FARNUM

The reaction of phenyl isocyanate with alcohols (or with amines) is particularly well adapted to a study of the relative reactivities of the latter substances, for the reasons (1) that it takes place rapidly, (2) that it is complete, and all of the phenyl isocyanate is used up if an excess of the alcohols (or of the amines) is present, and (3) that it is not reversible at ordinary temperatures, and the products of the reaction may be separated quantitatively at ordinary temperatures from the unreacted excess of alcohols (or of amines) without reacting with that excess or with each other.

We have caused one equivalent of phenyl isocyanate to react with a mixture of one equivalent each of two alcohols in dry benzene solution at 26° under such conditions that the materials, reagents and products, were in solution, and have collected the resulting mixture of two products and determined the relative amount of each. From the resulting data we have calculated the relative velocity of the reaction of phenyl isocyanate with one alcohol compared with that of its reaction with the other, and, taking the relative reaction velocity of methyl alcohol as unity, the relative reaction velocities of a series of alcohols. The figures represent the relative reactivities of the alcohols toward phenyl isocyanate.

When an alcohol reacts with phenyl isocyanate to form an ester of phenylcarbamic acid, the net result is (1) that the active hydrogen of the alcohol parts company with the rest of the molecule and (2) that the RO- and the H- attach themselves in their respective positions upon the molecule of phenyl isocyanate. The first of these involves the rupture of the hydrogen-oxygen bond of the alcohol, and its ease may be supposed to depend upon the reactivity of that linkage. But the ease of the second depends upon the chemical forces which hold the phenylcarbamic ester together, and the chemical forces existing in the phenylcarbamic ester formed from one alcohol cannot be taken as equal to those existing in the phenylcarbamic ester formed from another. The relative rates of reaction of the alcohols with phenyl isocyanate are therefore not measures of the relative reactivities of the alcohols in general, but are measures merely of the relative reactivities of the alcohols toward phenyl isocyanate.

Experimental Procedure

An accurately known amount of phenyl isocyanate from a calibrated pipet (about one gram) was dissolved in dry benzene at 26°. A mixture of two alcohols, an amount of each exactly equivalent to the phenyl isocyanate, was dissolved in dry benzene at 26° and added to the phenyl isocyanate solution in a tube which was sealed promptly and set aside in a thermostat at 26° for at least twenty-four hours. The benzene solution was evaporated in a current of air at room temperature, and the composition of the residue was determined by means of a freezing point determination and a freezing point-composition diagram. It was found impossible to obtain good check melting points on mixtures which melted below 40°. Our mixtures, therefore, whether unknown from the reactions or known for the preparation of the diagrams, were subjected to a freezing point determination in a Dewar bulb in the usual way, the bulb being immersed in cold water in those cases in which the freezing point was below room temperature. Seeding with the components of the mixture was generally necessary to prevent serious supercooling. Checks to 0.1° were secured in every case, except in that of the product from the reaction of phenyl isocyanate with a mixture of ethyl and methyl alcohols. The product of that experiment froze at 19.8, 20.0 and 20.3°, and the average of the three results was taken. In every case, because of supercooling, it was found impossible to read the freezing point curves closer than 0.1°.

The alcohols were all especially purified and dried, and they boiled sharply. The phenyl isocyanate yielded with the alcohols pure phenylcarbamic esters which contained no carbanilide.

In addition to a possible error of 0.1° in the determination of the freezing point, the accuracy of the analyses of the unknown mixtures was further influenced by the form of the freezing point composition diagrams. When the curve representing the rate of change of freezing point with change of composition happened to be relatively flat, the uncertainty of 0.1° in the freezing point corresponded to a greater uncertainty in the composition of the mixture than when the curve sloped more steeply. Also, since the calculations of the relative reaction velocities are based upon the ratio of the components, errors in the composition of the mixtures are magnified more as the ratios differ more widely from one.

Calculation of Relative Velocities

The experimentally determined ratios in which one equivalent of phenyl isocyanate distributes itself between one equivalent each of two alcohols are shown in Table I. From these ratios the relative velocities of the two reactions, shown in the same table, are calculated by a method suggested to us by Professor George Scatchard, in accordance with the formula developed below.

TABLE I

RELATIVE VELOCITIES OF COMBINATION OF ALCOHOLS WITH PHENYL ISOCYANATE

Values from Single Experiments

Expt.	Alcohols	Observed distribution ratio	Calculated ratio of velocity constants
a	Ethyl/methyl	47.7/52.3	0.876
b	*n*-Butyl/methyl	52.0/48.0	1.122
c	*n*-Propyl/ethyl	45.6/54.4	0.775
d	*i*-Propyl/ethyl	31.0/69.0	0.317
e	*n*-Butyl/ethyl	51.2/48.8	1.072
f	*t*-Butyl/ethyl	1.4/98.6	0.00330
g	*n*-Butyl/*n*-propyl	54.0/46.0	1.260
h	*t*-Amyl/*i*-propyl	6.4/93.6	0.0241
i	*i*-Butyl/*n*-butyl	44.5/55.5	.707
j	*s*-Butyl/*n*-butyl	30.9/69.1	.315
k	*n*-Amyl/*n*-butyl	48.8/51.2	.935
l	*s*-Butyl/*i*-butyl	36.8/63.2	.459

Taking c_a, c_b and c_c as the concentrations at any time of the first alcohol, of the second alcohol and of phenyl isocyanate, respectively, x and y as the amounts of the first and of the second alcohol used up, and a and b as the amounts originally present, we have

$$\frac{dx}{dt} = c_a c_c K_a, \text{ and } \frac{dy}{dt} = c_b c_c K_b$$

$$\frac{K_a}{K_b} = \frac{c_b}{c_a}\frac{dx}{dy} = \frac{b - y}{a - x}\frac{dx}{dy}$$

This, separating the variables and integrating between limits, gives

$$\frac{K_a}{K_b} = \frac{\log (1 - x/a)}{\log (1 - y/b)}$$

The relative reaction velocities of the various alcohols with phenyl isocyanate, compared with the reaction velocity of methyl alcohol as unity, are shown in Table II. The letters in the second column indicate the experiments from the data of which the relative velocities are calculated. Thus, *n*-propyl alcohol was not compared directly with methyl alcohol, but it was compared with ethyl alcohol in experiment c and ethyl alcohol was compared with methyl alcohol in experiment a. The relative velocities are calculated in as many different ways as possible from the various experiments, except that a combination of experiments which yields the desired ratio is not used more than once for the purpose. In the case of *i*-butyl alcohol, since experiments b and i give the desired ratio, b and i are not again used together, as for example in the combination becgi, for the calculation of the same ratio. Experiments b and i, however, are used independently in combination with other experiments, as aei and bjl, for the calculation of the same ratio. The agreement between the values calculated from different experiments is taken as evidence of the propriety of our method and as evidence that the numbers correspond more or less closely to the actual relative reaction velocities.

TABLE II

RELATIVE VELOCITIES OF COMBINATION OF ALCOHOLS WITH PHENYL ISOCYANATE

Values from All Relevant Experiments

Alcohol	Expts.	K	K av.	Av. dev. from av.	Probable error, %
Methyl	..	1.000	1.000		
Ethyl	a	0.876			
	be	1.047	0.962	0.086	8.8
n-Propyl	ac	0.678			
	bec	.812			
	bg	.891			
	aeg	.746	.782	.095	12.1
i-Propyl	ad	.277			
	bed	.332	.305	.027	6.6
n-Butyl	b	1.122			
	ae	0.939			
	acg	.854	.972	.070	7.2
i-Butyl	bi	.793			
	aei	.664			
	acgi	.604			
	bjl	.769			
	aejl	.644			
	acgjl	.586	.693	.075	10.8
s-Butyl	bj	.353			
	aej	.295			
	acgj	.269			
	bil	.364			
	aeil	.305			
	acgil	.277	.321	.036	11.2
t-Butyl	af	.00289			
	bef	.00346	.00318	.00028	8.8
n-Amyl	bk	1.049			
	aek	0.877			
	acgk	.798	.908	.094	10.3
t-Amyl	adh	.00657			
	bedh	.00798	.00728	.00070	9.6

Summary

The relative reaction velocities of a number of alcohols with phenyl isocyanate in dry benzene solution at 26° have been measured.

The relative reaction velocities of the primary alcohols, ethyl, *n*-propyl, *n*-butyl, *i*-butyl and

n-amyl, have been found to lie between 0.7 and 1.0, those of secondary propyl and butyl alcohols to be about one-third, and those of tertiary butyl and amyl alcohols to be less than one per cent. of the relative reaction velocity of methyl alcohol.

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Relative Velocities of Reaction of Amines with Phenyl Isocyanate

BY TENNEY L. DAVIS AND FRED EBERSOLE

The relative reaction velocities of several amines with phenyl isocyanate have been determined by a method similar to that described in the preceding paper, except that the experiments were carried out in dry ether solution at 0° and the compositions of the mixtures resulting from the reactions were ascertained by means of melting point determinations and melting point–composition diagrams.

The relatively high melting points of phenylurea and the N′-substituted phenylureas made the determination of the melting point (taken as the temperature of the first appearance of the meniscus) perfectly feasible and adequate for the determination of the composition of the mixtures resulting from the reactions. The ether solutions were evaporated rapidly at room temperature, blank experiments having shown that the phenylureas present in the solution at 0° were not affected during the evaporation at room temperature by the amines which were also present. The residues, after being powdered, were freed from last traces of amines by drying over concd. sulfuric acid and phosphorus pentoxide in a desiccator. They were then just barely fused, cooled, powdered, and again dried for the melting point determination. The results, treated in the same way as in the preceding paper, are summarized in Tables I and II.

TABLE I

RELATIVE VELOCITIES OF COMBINATION OF AMINES WITH PHENYL ISOCYANATE

Values from Single Experiments

Expt.	Amines	Observed distribution ratio	Calcd. ratio of velocity constants
a	*n*-Propyl/ammonia	81.0/19.0	7.88
b	Aniline/ammonia	41.0/59.0	0.576
c	*n*-Butyl/*n*-amyl	50.0/50.0	1.00
d	*n*-Propyl/aniline	88.0/12.0	16.6
e	Ethyl/*n*-propyl	53.0/47.0	1.19
f	Ethyl/*n*-butyl	51.2/48.8	1.07

TABLE II

RELATIVE VELOCITIES OF COMBINATION OF AMINES WITH PHENYL ISOCYANATE

Values from All Relevant Experiments

Amine	Expts.	K	K av.	Av. dev. from av.	Probable error, %
Ammonia	. .	1.00	1.00		
Ethyl	ae	9.37			
	bde	10.17	9.72	0.35	3.6
n-Propyl	a	7.88			
	bd	8.56	8.22	.34	4.1
n-Butyl	aef	8.74			
	bdef	9.59	9.17	.42	4.6
n-Amyl	aefc	8.74			
	bdefc	9.59	9.17	.42	4.6
Aniline	b	0.576			
	ad	.478	0.53	.049	9.3

The relative reaction velocity of aniline with phenyl isocyanate, about half that of ammonia, and those of the aliphatic primary amines, between eight and ten times that of ammonia, accord with qualitative observations on the urea dearrangement. Phenylurea dearranges more readily than urea, the monoalkylureas distinctly less so.

The relative reaction velocities of ethyl-, *n*-propyl-, *n*-butyl- and *n*-amylamine with phenyl isocyanate, while they are of the same order of magnitude, are by no means identical. In Table III the relative reaction velocities of the amines in ether at 0° are compared with the relative

TABLE III

COMPARISON OF THE RELATIVE REACTION VELOCITIES OF ALCOHOLS AND OF AMINES WITH PHENYL ISOCYANATE

	Relative reaction velocities				
	Alcohols relative to methyl in benzene at 26°	Amines relative to ammonia in ether at 0°	Ratio	Dev. from av. ratio	% Dev.
Ethyl	0.962	9.72	0.0989	0.0008	0.8
n-Propyl	.782	8.22	.0951	.0046	4.8
n-Butyl	.972	9.17	.1059	.0062	5.9
n-Amyl	.908	9.17	.0990	.0007	0.7