concentration of $R/5.7 \times 10^{12} = 1.3 \times 10^{-16} M.$[12] Alkoxide ion cannot be an intermediate in this case at least because its concentration, calculated from the autoprotoly-

sis constant[13] of ethanol (4×10^{-20}), is on a thousandth as large as this, viz., 5×10^{-20}.
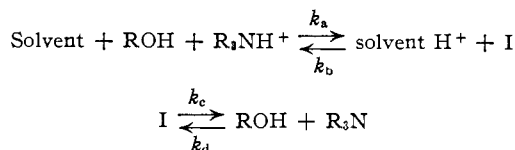

The Mechanism of Exchange of Hydrogen between Ammonium and Hydroxyl Groups. II[1-3]

BY C. GARDNER SWAIN, JAMES T. MCKNIGHT[4] AND V. PETER KREITER

The rate of exchange of hydrogen between substituted ammonium salts and alcohols has been studied as a function of the following variables: isotope used as tracer; concentration and structure of acid, substituted ammonium salt, alcohol and solvent; and temperature. The results are consistent with the mechanism proposed in part I.

In part I, the kinetics of exchange of ammonium bromide with methanol was examined in an inert solvent (dimethylformamide) and found to be consistent with the mechanism

$$\text{Solvent} + \text{ROH} + R_3NH^+ \underset{k_b}{\overset{k_a}{\rightleftarrows}} \text{solvent } H^+ + I$$

$$I \underset{k_d}{\overset{k_c}{\rightleftarrows}} \text{ROH} + R_3N$$

where I is a hydrogen-bonded alcohol–amine complex $(\text{ROH} \cdots \text{NR}_3 \text{ or } \text{RO}^- \cdots \text{HNR}_3^+)$.

$$\text{Rate} = \frac{k_a[\text{ROH}][R_3NH^+]}{1 + (k_b/k_c)[H^+]} \quad (1)$$

In this part, structural influences of the substituted ammonium salt, hydroxyl compound and solvent are examined in the light of this mechanism.

The substituted ammonium salts were always deuterated and the alcohol undeuterated at the start of a run, unless otherwise noted. Triethylammonium chloride ("triethylamine hydrochloride" in "Chemical Abstracts") and the solvent methanol were used unless otherwise noted. We use substituted "ammonium" names for simplicity and uniformity with the "ammonium bromide" ("Chemical Abstracts" name) of the previous paper, although we recognize that primary, secondary and tertiary ammonium halides are all weaker electrolytes than quaternary ammonium halides as a result of hydrogen bonding.

Reproducibility of the Kinetic Results.—A typical kinetic run is presented in detail in the Experimental section (Table VII) to illustrate the constancy of the experimental first-order rate constants (k_e) within runs. The reproducibility of these rate constants is also good from one run to another considering the speed of many of the runs

(1) Cf. C. G. Swain. J. T. McKnight. M. M. Labes and V. P. Kreiter. THIS JOURNAL. 76. 4243 (1954). For further details on deuterium exchanges. cf. J. T. McKnight. Ph.D. Thesis. M.I.T.. September. 1953; all work with tritium was carried out by V. P. K.

(2) Part I. C. G. Swain and M. M. Labes. THIS JOURNAL, 79, 1084 (1957).

(3) This work was supported in part by the research program of the Atomic Energy Commission. Reproduction permitted for any purpose of the United States Government.

(4) Atomic Energy Commission Fellow. 1951-1953.

and the difficulty in quenching the reaction. Table I is a representative sampling of the check runs that were done and shows that the average deviation is under ±5%.

Factors Not Affecting the Rate.—The following variables had little or no effect on the rate (cf. Table I): the procedures used for preparing deuterated salt or for drying the alcohol (cf. runs 67, 80); the initial locus of the deuterium, whether in the salt or the alcoholic hydroxyl (Part I)[2] or its percentage of the total hydrogen (58, 56); the amount of surface (84, 89); the concentration of more rapidly exchanging ammonium ions, either stronger or weaker acids (119, 89, see Discussion in section 3 below); and the choice of anion (runs 34, 40, 41, 30 in Table IV).

Factors Affecting the Rate. 1. Isotope Used as Tracer.—Comparison of Table II with Tables III and IV shows that tritium exchanges approximately 0.8 as fast as deuterium (cf. runs 3 and 106, 4 and 49). If one assumes statistical distribution of deuterium between salt and methanol at equilibrium, as was found to be the case with ammonium bromide and methanol in dimethylformamide solution,[2] the same isotope effect $(k_D/k_T = 1.2)$ must hold for both forward and reverse rate constants.

2. Acid.—Exchange of triethylammonium chloride with methanol was complete in less than 34 sec. at $0°$ when no acids were added to the methanol solution.

The reaction was studied in basic media since the suggestion was made by Ogston[5] that the net proton transfer from ethanol to diethylamine at $25°$ is a slow process. It was found that isotope exchange between deuterated diethylamine and either methanol or ethanol as solvent at $0°$ under comparable experimental conditions was complete in less than 30 sec. Thus hydrogen atoms bound to a free amine are exchanged rapidly in these hydroxylic solvents. A reasonable mechanism might involve either an ammonium ion as an intermediate or a four-center transition state with no intermediate. Higher-speed kinetic methods will have to be used to distinguish these alternatives.

(5) A. G Ogston. J. Chem. Soc.. 1023 (1936).

TABLE I

REPRODUCIBILITY OF RATE CONSTANTS FOR EXCHANGE BETWEEN METHANOL AND 0.90 M TRIETHYLAMMONIUM-d CHLORIDE IN METHANOL SOLUTIONS CONTAINING HYDROGEN CHLORIDE AT 0°

Run	[HCl], M	k_e, sec.$^{-1}$ × 10^3	Deviation from mean, %
55[a]	0.143	0.71	11.0
56[a]	.146	.61	4.7
57[a]	.142	.59	7.8
58[b]	.143	.64	0.0
		0.64	
67[c,d]	0.0028	13.0	4.0
80[c,e]	.0033	12.0	4.0
		12.5	
81[f]	0.424	3.2	3.0
82[f]	.447	3.1	3.0
83[d,f]	.445	3.3	0.0
85[d,f]	.448	3.5	6.1
		3.3	
84[g]	0.456	0.23	0.0
89[d]	.444	.24	4.4
119[h]	.450	.22	4.4
		0.23	
94[i]	0.051	3.0	4.8
102[i]	.052	3.3	4.8
		3.15	

[a] Salt containing 87% D. [b] Salt containing 40% D, recrystallized extra time from chloroform. [c] At 12° rather than 0°. [d] Salt prepared by exchange with heavy water rather than by neutralizing triethylamine with deuterium chloride (from reaction of benzoyl chloride with heavy water) as was done in runs in this table not marked by superscript d. [e] Methanol dried with calcium hydride (instead of magnesium turnings used in run 67). [f] With 0.27 M water added. [g] With Pyrex glass wool added to increase surface area by a factor of 2.6. [h] With 0.05 M deuterated guanidinium chloride and 0.05 M deuterated anilinium chloride. [i] With 0.12 M rather than 0.90 M triethylammonium chloride.

TABLE II

EXCHANGE OF TRIETHYLAMMONIUM-t CHLORIDE IN METHANOL AT 0°

Run	[R₃NHCl], M	[HCl], M	T in salt, μc. mmole^{-1}	k_e, sec.$^{-1}$ × 10^3
3	0.21	0.22	2	0.80
2	.22	.23	2	0.83
6	.88	.00054	14	3.3
5	.86	.0061	14	2.7
4	.86	.018	14	1.7
1	.80	.092	0.7	0.7

Table III shows that the rate is a hyperbolic function of acidity over the range of concentration of hydrogen chloride available for study. There is very little dependence on acidity at low concentrations of acid, but its retarding effect increases very gradually until the rate is sharply dependent on acid concentration at high acidities. It is unlikely that this behavior is due to either weakness or dimerization of the hydrogen chloride since hydrogen chloride behaves as a simple strong electrolyte in methanol in other reactions: e.g., the

TABLE III

EXCHANGE OF TRIETHYLAMMONIUM-d CHLORIDE IN METHANOL AT 0°

Run	[R₃NHCl], M[a]	[HCl], M[b]	k_e, sec.$^{-1}$ × 10^3
107	0.048	0.226	1.3
106	.217	.220	0.99
105	.368	.220	0.89
53[d]	.47	.51	0.32
118	.118	.00030	11.0
116	.118	.00062	10.1
117	.119	.0016	9.6
112	.117	.0035	7.7
111	.119	.0105	5.9
94	.114	.052	3.0
100[c]	.110	.055	3.0[c]
96	.116	.20	1.2
95	.116	.51	0.46

[a] Total concentration of deuterated and undeuterated salt. [b] Stoichiometric concentration. [c] With 0.15 M sodium p-toluenesulfonate added. [d] Data from reference 6 using triethylammonium bromide and hydrogen bromide (rather than chlorides).

TABLE IV

EXCHANGE OF 0.9 M TRIETHYLAMMONIUM-d CHLORIDE IN METHANOL

Run	[HCl], M[a]	Temp., °C.	k_e, sec.$^{-1}$ × 10^3
27	0.35	25	6.1
43	.41	25	5.8
34	.60	25	4.3
40	.76[c]	25	3.9[c]
41	1.2[c]	25	2.4[c]
30	1.4	25	1.8
32	1.6	25	1.3
31	3.1	25	0.33
26	3.5	25	.24
42	10	25	.001[b]
80	0.0033	12	12.0
79	.016	12	6.2
78	.083	12	3.2
70	.404	12	1.0
63	.00074	0	8.1
69	.0027	0	3.8
59	.0063	0	3.0
49	.018	0	2.3
28	.036	0	1.5
48	.046	0	1.2
36	.059	0	1.2
56	.146	0	0.61
72	.404	0	.24
88	.694	0	.14

[a] Stoichiometric concentration. [b] Only approximate. [c] Used triethylammonium p-toluenesulfonate and p-toluenesulfonic acid; no chloride ion in the exchanging solution.

methanolysis of β-naphthyl acetate is first order in hydrogen chloride over this same range of concentrations.[7] The data satisfactorily fit the following empirical relationship between k_e and the concentration of strong acid [H$^+$]

$$\text{Rate} = \frac{0.011 \ [R_3NH^+]}{1 + 42[H^+]} \qquad (2)$$

Comparison of equations 2 and 1 indicates that $k_a[ROH] = 0.011$ and $k_b/k_c = 42$ with 0.1 M salt

(6) M. M. Labes, Ph.D. Thesis, M.I.T., February, 1954.

(7) M. Harfenist and R. Baltzly, THIS JOURNAL, 69, 362 (1947).

at 0°. Table IV shows that similar results are obtained with 0.9 M salt and at different temperatures.

At the highest acidities, above 1 M hydrogen chloride, the repression is greater than calculated from a hyperbolic equation. This is probably a result of the large medium changes. Not only is the concentration of methanol varying significantly, but the large variations in total electrolyte concentration would change activity coefficients in an unpredictable manner in this region. The variation in rate is similar to the variation of the activity coefficient of hydrogen chloride in water in this concentration range above 1 M,[8] and it has been shown that activity coefficients of hydrogen chloride in water and methanol are similar.[9]

In neutral or basic solution, it appeared that the rate was at least five times faster than in weak acid. Since equation 2 does not predict any further increase, this suggests that there may be base catalysis in basic solution. The reaction was too fast in this region to be studied successfully by our aliquot-taking procedure, but it should be interesting to study using flow methods or other fast techniques.

3. Concentration and Structure of Ammonium Salt.

The reaction appears to be first order in amine hydrochloride. Table III shows that a 7.7-fold increase in concentration gives only a 32% decrease in rate constant (runs 107, 96, 106, 105), reasonably interpreted as a salt effect.

The effect of adding 0.15 M of the strong electrolyte, sodium p-toluenesulfonate, in run 100 was also very slight. This supports the conclusion above that the large effect of hydrogen chloride is more than a simple salt effect.

When salts of more basic amines are used, the rate of exchange usually decreases as shown in Table V (cf. triethyl- vs. trimethylamine, or ethylamine vs. aniline). This is reasonable because k_a and k_c should be smaller relative to k_b for the more basic amines.

Guanidinium ion is an exception. Perhaps it exchanges by a different mechanism, utilizing its polyfunctional character.

$$CH_3OH + C(NH_2)_3^+ + CH_3OH \rightleftharpoons$$
$$CH_3OH_2^+ + HN=C(NH_2)NH_3^+ + CH_3O^-$$
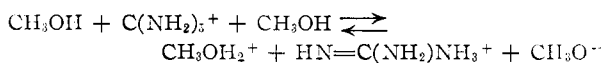
A cyclic process involving only one methanol and giving the same intermediate but avoiding the ions from methanol is another possibility.

The rapidly exchanging guanidinium and anilinium chlorides present in small amounts in run 119 (Table I) did not affect the slower rate of exchange of triethylammonium chloride. This indicates that their rapid exchange is not due to catalytic impurities and that the ammonium salts are not exchanging hydrogens among themselves faster than with the solvent.

Among amines of comparable basicity, the greater the number of exchangeable hydrogens, the slower seems to be the rate of exchange (cf. mono-, di- and triethylamine or ammonia and trimethylamine in Table V). Thus ordinary steric hin-

(8) H. S. Harned and R. W. Ehlers, THIS JOURNAL, **55**, 2179 (1933).

(9) H. S. Harned and B. B. Owen, "Physical Chemistry of Electrolytic Solutions," Reinhold Publ. Corp., New York, N. Y., 1943, p. 340.

TABLE V

RELATIVE RATES OF EXCHANGE WITH DIFFERENT AMMONIUM CHLORIDES IN METHANOL AT 0°

Run	Amine[a]	Concn., M	[HCl], M	k_e, sec.$^{-1}$ × 10³	k_e, relative	K_B,[b] relative
..	(NH₂)₂CNH	1.0	3.3	c	>10³	10³
108	(C₂H₅)₂NH	0.12	0.053	0.32	0.10	2.2
114	C₂H₅NH₂	.12	.065	0.17	0.06	1.0
94	(C₂H₅)₃N	.12	.052	3.0	(1.00)	(1.00)
109	(CH₃)₃N	.11	.51	11.0	20	0.10
107	H₃N	.12	.053	1.6	0.53	0.03
..	C₆H₅NH₂	1.0	3.3	c	>10³	10⁻⁶

[a] As ammonium chloride (amine hydrochloride). [b] Basic dissociation constant relative to triethylamine. [c] Exchange was complete after 60 sec.

drance does not seem to be a very important factor in this reaction.

4. Solvent.—The exchange of triethylammonium chloride with ethylene glycol in ethylene glycol solution containing 0.11 M hydrogen chloride at 0° was extraordinarily slow, with an experimental half-life of about an hour (Table VI). The exchange with ethanol in ethanol solution was faster than with methanol in methanol solution. Exchange between triethylammonium picrate and 0.1 M methanol in toluene solution containing 0.01 M hydrogen chloride had a half-life of less than 5 seconds.[5] Table VI shows that over this range of solvent, rate increases with decreasing dielectric constant.

TABLE VI

EXCHANGE OF TRIETHYLAMMONIUM CHLORIDE WITH DIFFERENT SOLVENTS AT 0°

Run	[R₃NHCl], M	[HCl], M	Solvent	Dielectric constant	k_e, sec.$^{-1}$ × 10³
58[a]	0.25	0.11	HOCH₂CH₂OH	42	0.21
96	.12	.20	CH₃OH	31	1.2
95	.10	.51	CH₃OH	31	0.46
44[a]	.10	.77	C₂H₅OH	26	7.7[b]
48[a]	.30[c]	.01	C₆H₅CH₃[c]	2.4	>100[c]
66[a]	.70	.15	HCONH₂	110	5.3[d]
120[a]	.30[e]	.13	HCON(CH₃)₂[e]	37[f]	0.05[c]

[a] Reference 5. [b] In ethanol solution the rate was also retarded by increasing the concentration of acid. [c] Exchange between 0.30 M triethylammonium picrate (rather than chloride) and 0.10 M methanol in toluene solution. Comparable k_e in methanol solution for run 111 with 0.01 M HCl is 5.9 × 10⁻³. [d] At 5.5°. [e] Exchange of ammonium bromide (rather than triethylammonium chloride) with 1.2 M methanol in dimethylformamide solution. [f] G. R. Leader and J. F. Gormley, THIS JOURNAL, **73**, 5731 (1951).

The reaction normally was stopped by addition of an aliquot of the solution to an ether–petroleum ether mixture which caused the salt to precipitate immediately. If the salt was not precipitated immediately but remained in homogeneous solution diluted 10- to 20-fold for a minute, the reaction was considerably accelerated by the less polar medium.

Thus the exchange is generally faster in less polar solvents, showing that there is less charge or charge separation in the transition state than in the reactants (2 ROH + R₃NH⁺). This is the usual observation for reactions involving one ion. The solvent effect does not distinguish between the two alternative structures for I.

Formamide exchanges deuterium at a rate comparable to that observed with alcohols. Dimethyl-

sormamide has no exchangeable protons and is a fatisfactory solvent in which to study isotope exchange of other molecules such as methanol.[5]

Exchange was complete in less than 30 sec. in either pure formic acid (dielectric constant ϵ 58) or acetic acid (ϵ 10) at 25° (no alcohol, acid as solvent).[1] Pure formic acid is approximately one H_0 unit more acidic than 2.4 M hydrogen chloride in ethanol.[10] The high rate with formic acid in spite of its high acidity and high dielectric constant suggests that its proton lability is much greater than that of the alcohols and that it might be expected to act as a catalyst for exchanges with methanol.

Water (ϵ 80) has been shown to catalyze exchanges with methanol (cf. runs 81 and 89 in Table II) probably by acting as a base, since water is a stronger base and weaker acid than methanol.[11] The catalytic effect appeared proportional to the 1.5 power of the water concentration ($k_e = 0.23$, 0.94 and 3.3 with 0.00, 0.10 and 0.27 M water). Although water thus appears about a thousand times as reactive as methanol, it is not so reactive that minute traces of water can cause difficulty in reproducing the kinetics.

5. Temperature.—Table IV gives data at three different temperatures. Over-all Arrhenius activation energies vary from 22 kcal. at 0.69 M hydrogen chloride to 15 kcal. at 0.016 M hydrogen chloride.

Experimental

Materials Used.—The methanol was reagent grade, dried before use by refluxing over Metal Hydrides Co. calcium hydride[12] for at least 1 hr. or over magnesium turnings[13] for at least 24 hr. and distilling into a graduated dropping funnel which was protected from the atmosphere by a tube of potassium hydroxide chips. The receiver was rinsed three times with the freshly distilled methanol before collecting the methanol used. Anhydrous ethanol was prepared in a similar manner from U.S.P. absolute ethanol. Ethylene glycol was redistilled immediately before use, b.p. 197–198°.

Solutions of hydrogen chloride in dry methanol or ethanol were prepared by passing hydrogen chloride gas through concentrated sulfuric acid and a $-75°$ trap into freshly prepared dry alcohol at 0°. Dry alcohol was used to dilute portions of these solutions to the desired concentrations. Solutions prepared in this way were kept at 0° no longer than one week. The data of Hinshelwood[14] indicate that the reaction $CH_3OH + HCl \rightarrow CH_3Cl + H_2O$ would have proceeded only 0.1% in one week at 0°. Pouring through the air or otherwise exposing dry solvents or solutions to atmospheric moisture was avoided.

Formic acid was prepared by drying reagent grade 98–100% formic acid over reagent boric anhydride for 3 days, then distilling at 25° at 40 mm. Acetic acid was prepared by distilling a mixture of 10 ml. reagent acetic anhydride and 90 ml. of reagent glacial acetic acid. The fraction used boiled 117.8–118.3°. The ether, toluene and petroleum ether were reagent grades, dried over sodium.

The deuterium oxide was "99.8%" from the Stuart Oxygen Co.

Anhydrous solutions of p-toluenesulfonic acid in methanol were prepared from p-toluenesulfonic acid monohydrate (chloride free). The monohydrate was dehydrated and dissolved in benzene by boiling off benzene over the solid acid. The remainder of the benzene was removed under vacuum and the calculated amount of dry methanol added. Sodium p-toluenesulfonate was recrystallized three times

from a mixture of methanol and ethanol and dried at 150° to constant weight.

Tri-n-butylammonium picrate was prepared by adding a nearly saturated hot alcohol solution of picric acid to a slight excess of tri-n-butylamine in alcohol. The crude product was recrystallized from alcohol, m.p. 106.5–107°.

Deuterated Compounds.—Triethylamine deuterochloride was prepared by one to four successive exchanges between ordinary triethylammonium chloride and an approximately six-fold excess of 90–99.8% heavy water. The undeuterated salt was prepared by neutralizing a solution of purified triethylamine in methanol with concentrated hydrochloric acid, pumping off the solvents and recrystallizing the salt from chloroform or ethanol. The triethylamine was commercial grade, redistilled from potassium hydroxide pellets, b.p. 88.5–89.5°, stored over calcium hydride. After the purified salt had been dried, it was dissolved in the calculated amount of heavy water and the heavy water then removed under vacuum. This exchange was repeated several times depending on the concentration and amount of heavy water available and the percentage deuterium desired in the salt.

In another method of synthesis, deuterium chloride gas generated from the reaction of "99.8%" deuterium oxide with excess benzoyl chloride at 100° was carried by a stream of dry nitrogen through a reflux condenser and $-75°$ trap into a four- or fivefold excess of triethylamine at 0°.

The other deuterated salts were prepared by exchange with heavy water. The ammonium chloride was reagent grade. The trimethylammonium chloride, the ethylammonium chloride and the guanidinium chloride were Eastman Kodak Co. white label grade. The diethylammonium chloride was prepared by neutralizing a solution of purified diethylamine in ethanol with concentrated hydrochloric acid, pumping off the solvents and recrystallizing from ethanol. The diethylamine was prepared from commercial grade diethylamine by drying and redistilling, b.p. 54.5–55.5°. The anilinium chloride was prepared by neutralizing a solution of anhydrous hydrogen chloride in ether with redistilled reagent grade aniline dried over calcium hydride and recrystallizing the salt from ethanol.

Triethylammonium p-toluenesulfonate was prepared by neutralizing an anhydrous solution of toluenesulfonic acid in benzene with purified triethylamine and precipitating the salt from the concentrated benzene solution by adding dry ether. After equilibration with a sevenfold excess of heavy water, part of the water was removed under vacuum. The oil was then dissolved in dry benzene. The benzene solution was concentrated to two-thirds its volume and ten volumes of dry ether added. If the salt separated as an oil, the ether layer was discarded, fresh dry benzene added and this extractive process repeated until the salt crystallized immediately upon adding the ether. This salt was extremely hygroscopic and was stored under ether and dried under vacuum immediately before use.

Deuterated methanol was prepared by the following method. Ten volumes of dry bromobenzene were added to a saturated solution of sodium methoxide in methanol and all of the methanol was boiled out while the mixture was stirred with a powerful stirrer. Slightly less than the calculated amount of "99.8%" deuterium oxide was then added and the deuterated methanol distilled out. This method can be made more efficient in the use of deuterium oxide by using magnesium methoxide in place of sodium methoxide and dehydrating the magnesium deuteroxide produced. Deuterated diethylamine was prepared by a method similar to that used by Roberts[15] to prepare deuterated dimethylamine. Deuterated diethylamine hydrochloride was prepared by four successive equilibrations of the undeuterated salt recrystallized from ethanol with a fivefold excess of deuterium in the form of "99.8%" deuterium oxide. The heavy water was removed from the salt under vacuum each time. The deuterated salt was then mixed with a fourfold excess of freshly dried powdered calcium oxide and the mixture heated slightly. The deuterated diethylamine was removed under vacuum and condensed at $-75°$. The liquid diethylamine was partially dried with calcium oxide powder and removed under vacuum. This procedure was repeated and the amine finally dried by treatment with calcium hydride, which reacts only slowly

(10) E. A. Braude, J. Chem. Soc., 1971 (1948).

(11) J. Hine and M. Hine, THIS JOURNAL, **74**, 5266 (1952); W. C. Woodland, R. B. Carlin and J. C. Warner, ibid., **75**, 5835 (1953).

(12) Brochure supplied by Metal Hydrides Co., Beverly, Mass.

(13) H. Lund and J. Bjerrum, Ber., **64**, 210 (1931).

(14) C. N. Hinshelwood, J. Chem. Soc., 599 (1935).

(15) E. R. Roberts, H. J. Emeleus and H. V. A. Briscoe, ibid., 41 (1939).

with diethylamine. For use the diethylamine was removed under vacuum, leaving a moist residue.

Tritiated Triethylammonium Chloride.—Triethylammonium chloride was further purified by two crystallizations from a 2:1 acetone–absolute ethanol mixture, m.p. 257–259°. Each batch of tritiated salt was prepared by exchange with tritiated water, followed by removal of all water under vacuum, with final heating until the salt began to sublime vigorously. The salt was stored in a desiccator.

Procedures Used in Kinetic Runs.—The salt was prepared for each run by weighing out roughly the amount needed and adding it to the dry reaction flask. In some cases the flask was then evacuated to 0.5 mm. for several hours and warmed occasionally. No loss in weight was observed when triethylamine hydrochloride was treated in this way. The calculated amount of the chilled solvent in which the exchange was to be studied was transferred to another dry glass-stoppered flask filled with dry nitrogen. After keeping both flasks in a stirred ice–water-bath or thermostat for 30 minutes, the reaction was started by adding the solvent to the reaction flask and shaking the mixture vigorously in the bath to dissolve the salt.

In all runs with deuterated triethylamine hydrochloride in which the salt concentration was 0.9 M or greater and in which chloride was the only anion, the precipitating medium was reagent grade absolute ether dried over sodium wire. The amount used per ml. of aliquot varied between 10 and 50 ml. In runs with deuterated triethylamine hydrochloride in which the salt concentration was less than 0.8 M and in which chloride was the only anion, the precipitating medium was a mixture of equal volumes of reagent grade petroleum ether, b.p. 30–60°, and absolute ether, dried over sodium wire and cooled to 0°. The amount of this mixture used was 110 ml. per 5-ml. aliquot of exchange solution. In runs containing p-toluenesulfonate anion the precipitating medium was the same except that about 3 ml. of the diethyl ether used was saturated with hydrogen chloride at 0°. Petroleum ether was used for runs in toluene, and dioxane–diethyl ether mixtures for runs in ethylene glycol or formamide.

To stop the reaction an aliquot of the reaction solution was added to the precipitating medium in a separatory funnel with packed glass wool above the stopcock held in place by means of a small filter plate sealed to the walls of the separatory funnel by de Khotinsky cement. The precipitated salt was filtered off under vacuum and the filtrate saved. Six separatory funnels and six complete vacuum trains were used for six aliquots in each run. Each separatory funnel containing the salt was stoppered and attached through the ground-glass joint on its tip to a vacuum train with three traps. The whole system was evacuated for 30 minutes at 0.5 mm. while the second trap, containing a mixture of calcium oxide and potassium permanganate powders, was heated three times with a small flame until the sodium color appeared. A known volume of conductivity water, between 0.35 and 1.40 ml., was added to the dried, precipitated salt in the separatory funnel and equilibrated with it. No additional time was required to equilibrate the salt with the water other than that necessary to dissolve all of the salt in the funnel and drain it. The amount of conductivity water equilibrated with the salt was the same for all aliquots of a given run and was chosen to give 0.1 to 1.0% deuterium in the hydrogen of the water. The stopcock of the funnel was opened and the aqueous salt solution run into the first trap. The water was removed from the salt under 0.5 mm. pressure and condensed in the second trap at −75°. A glass wool plug loosely inserted in the end of the inner part of the ground-glass joint on the first trap which connected it with the second trap served to catch any salt spray from bumping during distillation of the equilibrated salt solution. The ice condensed in the second trap was melted and formed a powerful oxidizing solution by dissolving the powder mixture in the bottom. This oxidizing solution was heated to boiling to oxidize all organic impurities to acids. These acids were converted to non-volatile salts by the base present. The final condensate was then collected at 0.5 mm. in the third trap at −75°. A bulb and another joint packed with glass wool stopped any permanganate spray before it reached the third trap. The percentage deuterium was determined by the falling drop method.[2]

After the distillation the salt in the separatory funnel and first trap was washed four times with distilled water into a filter flask and titrated for chloride with 0.1 N mercuric nitrate. The permanganate and calcium oxide remaining in the second trap was washed out and decomposed with a nitric acid–oxalic acid solution; then the trap was washed four times with distilled water and dried. After use the third trap was filled with 2% hydrofluoric acid cleaning solution for approximately one minute and then rinsed seven times with distilled water.

For each kinetic run the acid concentration ([H$^+$] in equation 2) was determined by titrating a 5 to 10-ml. aliquot with 0.01 M sodium hydroxide. For acid concentrations above 0.01 M this was done with brom thymol blue. Below 0.01 M the aliquot was diluted with 10–15 ml. of conductivity water and titrated potentiometrically under nitrogen with a 0.5-ml. buret, small glass stirrer and glass electrode, with graphical determination of the end-point by averaging intersections of parallel (approx. 45°) tangents with a tangent through the inflection point. As little as 5×10^{-5} M acid could be determined in this way.

For each kinetic run the salt concentration ([R$_3$NH$^+$] in equation 2) was determined by titration with 0.1 N mercuric nitrate.[16] The chloride remaining in the filter flask after evaporating the filtrate from the last three aliquots of the run to dryness on a steam-cone was titrated, and this chloride was added to the chloride in the corresponding precipitated salt equilibrated with the known volume of water. In the runs containing p-toluenesulfonate this was not possible and the concentration of salt was based on the weights of reactants mixed.

In runs containing both chloride and toluenesulfonate as anions, in order to determine the number of equivalents of triethylammonium ion equilibrated with the sample of water, the mixture of triethylammonium salt remaining in the separatory funnel and first trap after removal of the water was titrated as an acid. It was washed four times into a 125-ml. filter flask with the minimum amount of methanol and 60 ml. of dry redistilled triethylamine and six drops of 1% phenolphthalein in ethanol were added. The mixture was then titrated to a pink end-point with 2 M aqueous sodium hydroxide from a 0.5-ml. buret with its tip below the level of the methanol–triethylamine solution. A nitrogen atmosphere was not required for the success of the titration since the end-point did not fade until after 15 minutes. The blank in this titration depended chiefly on the purity of the triethylamine and only very slightly on the methanol.

Tritium Exchanges. The tritium exchanges (Table II) were done after the deuterium exchange work was complete. Extra precautions taken to ensure dryness of all reactants included protection of methanol and solutions by drying tubes of anhydrous magnesium perchlorate and soda-lime, drying of hydrogen chloride with anhydrous magnesium perchlorate and use of dry nitrogen instead of air to blanket solvent and reagents at all times. In spite of these extra precautions, the dependence of rate on concentration of salt or acid appears to be unchanged. The salt was precipitated from aliquot samples as in the exchanges with deuterium and analyzed as previously described.[17]

Analysis of Kinetic Data.—Since the kinetics of isotope exchange were discussed in the previous paper,[2] only the practical details of evaluating the experimental first-order rate constant (k_e) from a kinetic run are given below.

The ratio of the atom % deuterium in the equilibrated water to the ml. of mercuric nitrate used to titrate the salt is proportional to the fraction of the hydrogen atoms which were deuterium in the salt before it was dissolved, since the water was in at least fifty-fold excess over the salt and the volume of water and normality of mercuric nitrate were the same for each aliquot of a given kinetic run. The fraction unexchanged was plotted on semi-logarithmic paper vs. t, the best straight line drawn through the points by eye, the half-life ($t_{1/2}$) taken as the time difference between its intersections with the 1.0 and 0.5 lines and k_e as $0.693/t_{1/2}$.

The observed infinity (equilibrium) value of percentage deuterium per ml. of mercuric nitrate generally was used for calculating percentage reaction and k_e, rather than the one calculated from initial concentrations assuming $K = 1.00$. The observed final percentage reaction varied from 96–100% of the calculated one in different kinetic runs (mostly at 0°), with an average of 97.5%.

(16) F. E. Clarke, *Anal. Chem.*, **22**, 553, 1458 (1950).

(17) C. G. Swain, V. P. Kreiter and W. A. Sheppard, *ibid.*, **27**, 1157 (1955).

TABLE VII

RUN 111. EXCHANGE OF 0.119 M TRIETHYLAMMONIUM CHLORIDE WITH METHANOL IN METHANOL SOLUTION CONTAINING 0.0105 M HYDROGEN CHLORIDE AT 0°

Time,[a] sec.	d,[b] sec.	D,[c] %	Hg-$(NO_3)_2$,[d] ml.	D/Hg-$(NO_3)_2$,[e] %/ml.	Reaction,[f] %	k_e[g], sec.$^{-1}$ × 10^3
0	...	...	..	0.1540	0.0	..
55	73.7	0.260	3.28	.0793	48.5	..
91	68.7	.306	4.71	.0650	57.8	5.5
125	75.0	.249	4.72	.0528	65.7	6.1
166	83.3	.188	4.56	.0413	73.1	6.0
211	91.5	.140	4.47	.0313	79.6	6.2
269	99.0	.104	4.61	.0226	85.3	5.6
2000	131.0	.000	..	.000	100.0	..

[a] Between mixing reactants and adding aliquot to precipitating medium. [b] Average dropping time of the water obtained by equilibrating the precipitated salt with 0.46 ml. of conductivity water, separating the water and purifying it. [c] Atom per cent. deuterium in the water obtained from difference of reciprocals of dropping times (d) of water sample and conductivity water (d = 130.6) and the calibration curve. [d] Ml. of 0.106 N (0.053 M) Hg(NO₃)₂ used to titrate salt equilibrated with water. [e] Ratio of two previous columns. [f] Percentage of the total variation (0.1540) in the previous column that has occurred. The initial % D/ml. Hg(NO₃)₂ was calculated from an analysis on the dried salt used, which contained 74.2 atom % exchangeable deuterium. The final % D/ml. corresponds to 100.5%

reaction assuming random distribution of deuterium among the exchangeable hydrogens, but the experimental error is more than 1%. [g] Experimental first-order rate constant identical with k_e of equation 1 in reference 2. Calculated, in this table only, from the formula k_e = 2.303 log [(1 − F_1)/(1 − F_2)]/(t_2 − t_1), where F = % reaction/100, from successive pairs of kinetic points to magnify trends. Ordinarily k_e was evaluated instead by the graphical method described under "analysis of kinetic data."

In a number of cases the straight line did not pass through zero % reaction at zero time. This may be due to several factors. In runs in which the salt was as concentrated as 1 M, there was a significant cooling effect; dissolving and warming back to thermostat temperature required about one minute. Furthermore, the reaction is accelerated by dilution with an inert non-polar liquid; this increases rate of exchange during the quenching process unless precipitation is extremely rapid and quantitative. In some of the kinetic runs it was shown by taking aliquots immediately after mixing that as much as 10% exchange occurred in the quenching process, even though 98% of the salt was precipitated. However, the percentage exchange during quenching proved independent of a fivefold variation of initial percentage deuterium in the salt used. These errors in percentage reaction caused by neglecting exchange during quenching affect only the intercept, since the time and conditions of quenching were the same for all aliquots of a given kinetic run. Hence k_e should still be accurate since it is determined from $t_{1/2}$, which is a measure of the slope.

A typical kinetic run is presented in Table VII.

CAMBRIDGE 39, MASS.

The Effects of Substituents at the 1- and 3-Positions on the Visible Absorption Spectrum of Azulene[1]

BY EDWARD J. COWLES

A study is presented of the visible absorption spectra of twelve 1-substituted and 1,3-disubstituted azulenes prepared by electrophilic substitution reactions. For the position of the principal absorption peak, the equation $(\bar{\nu}_{max})^2 = \bar{\nu}_0^2 (1 + A_1 + A_3)$ fits the data better than the equation $\lambda_{max} = \lambda_0 + B_1 + B_3$, where the A's and B's are constant increments characteristic of substituents, both bathochromic and hypsochromic, at positions 1 and 3. The effects of solvent are discussed briefly.

The visible absorption spectra of the alkyl-substituted azulenes have been studied extensively. Various workers have considered the effects of substituents on the position of the principal absorption peak,[2] on that of the longest-wave length band,[3] and on the "average position" of all the bands of the spectrum.[4] Effects of alkyl substituents at various positions in the azulene nucleus have been found to be additive. The visible spectra have therefore been useful in the identification of natural and synthetic azulenes.

The present paper will be concerned with the position of the principal absorption peak in the visible spectra of 1-substituted and 1,3-disubstituted azulenes prepared by electrophilic substitution reactions.[5-8] Sufficient spectral data to warrant a detailed study were available for only the 12 compounds, besides azulene, listed in Table II.

The data were obtained for the compounds in various solvents: petroleum ether, n-hexane, cyclohexane, n-heptane and chloroform. For the purposes of this study, as is indicated in Table II, the saturated hydrocarbons have been lumped together as a single type of solvent, to be compared or contrasted with the more polar chloroform. The effects of solvent are discussed briefly below.

Not only alkyl groups (including benzyl[7]), but also other o,p-directing groups (halogens and acetylamino[6]) are found to exert a bathochromic effect when substituted at the 1- and 3-positions in the azulene nucleus. On the other hand, m-directing groups (acetyl, nitro and carbomethoxy[5,6]), as 1- and 3-substituents, cause a hypsochromic shift of the absorption bands.

In many of these compounds, 1,3-substituents

(1) This work was supported in part by a grant from the Research Corporation.

(2) P. A. Plattner. A. Fürst and K. Jirasek, Helv. Chim. Acta, 30, 1320 (1947).

(3) A. J. Haagen-Smit. Fortschr. Chem. Org. Naturstoffe, V, 40 (1948).

(4) H. Pommer, Angew. Chem., 62, 281 (1950).

(5) A. G. Anderson, Jr., and J. J. Tazuma. THIS JOURNAL, 75, 4979 (1953).

(6) A. G. Anderson, Jr., J. A. Nelson and J. J. Tazuma, ibid., 75, 4980 (1953).

(7) A. G. Anderson, Jr., E. J. Cowles, J. J. Tazuma and J. A. Nelson. ibid., 77, 6321 (1955).

(8) According to a private communication from A. G. Anderson, Jr., a satisfactory analysis of dinitroazulene has been obtained, and the 1,3-structure of the dinitro and diacetyl derivatives has been proved with reasonable certainty since the publication of the references just cited.