TABLE II

MOLAL ENTROPY OF MERCURIC OXIDE IN CAL./DEG.

Low temp. C_p (B. and J.)[11]	16.80 ± 0.1
Ag_2O cell (H. and C.)[2]	17.56 ± .5
Ag_2O cell (G. and P.)[7]	17.4 ± .6
H_2 cell, various authors[2,10,11]	17.3 ± .3

ments of Bauer and Johnston[11] from 15 to 300°K. with a Debye function extrapolation to 0°K. In addition, several workers have studied the galvanic cell with the reaction

$$H_2(g) + HgO(s) = H_2O(l) + Hg(l) \qquad (2)$$

and the results have been reviewed recently by several authors[2,10,11] and combined with other data to yield the final value in Table II.

The entropy values from the two types of cell are quite concordant, but the presumably more precise value based on the low temperature heat capacity data is slightly outside the estimated limits of error on the low side. The structure of red or yellow orthorhombic HgO was shown by Aurivillius[12] to involve long chains –O–Hg–O–Hg–O–Hg– with 180° angles at Hg and 109° angles at oxygen. Such a structure might lead to an abnormal heat capacity curve at temperatures below 15°K. where Bauer and Johnston's measurements began. The results of our measurements below 15°K. on macrocrystalline Ag_2O indicate that substantial deviation from the Debye curve is possible for heavy metal oxides.

(11) T. W. Bauer and H. L. Johnston, *J. Am. Chem. Soc.*, **75**, 2217 (1953).

(12) K. Aurivillius, *Acta Chem. Scand.*, **10**, 852 (1956).

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The Chemical Behavior of Fluorine 18 Produced by the $O^{16}(H^3,n)$ Nuclear Reaction

BY M. ANBAR AND P. NETA

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Fluorine 18 atoms produced by the $Li^6(n,\alpha)H^3$, $O^{16}(H^3,n)F^{18}$ nuclear reactions were found to substitute hydrogen on organic molecules. The extent of labelling of a given organic molecule was found to be proportional to the number of hydrogens per molecule. In solid lithium salts, irradiated by slow neutrons, the yield of organically bound fluorine 18 was 0.6–1.0% per aliphatic hydrogen, as compared to 0.3–0.6% per aromatic hydrogen. Compounds were also labelled in solutions and the yield was dependent on the concentration of the solute. The yield of labelling of aliphatic solutes was higher than that of aromatic. The addition of aromatic compounds to an aliphatic solvent diminished the labelling yield of the solvent, however no appreciable labelling of the aromatic solute was observed. Aliphatic solutes, on the other hand, did not affect the yield of labelling of aliphatic solvents. Formic acid and nitrite ions were found to diminish considerably the yield of labelling in aqueous or alcoholic solutions. The results suggest that the active chemical species in the fluorine labelling reactions are non-excited fluorine atoms. Interactions with electron donors are of primary importance in the behavior of fluorine atoms in organic media.

Labelling of organic compounds by radioactive halogens formed by the (n,γ) reactions has been extensively studied.[1] In a series of experiments on bromine formed by (n,γ) reactions and by isomeric transitions, the participation of positively charged bromine ions has been suggested.[2] In other cases halogen atoms were suggested as the main active species. The results of the (n,γ) recoil labelling were recently compared with the hot atom chemistry of chlorine and bromine produced by (n, α) reactions.[3]

The "hot atom" chemistry of fluorine 18 has been examined first by Aten[4] who studied the retention of F^{18} in fluorobenzene following the (n, $2n$) nuclear reaction. The inorganic and organic fractions of the irradiated samples were separated and their activities were measured. The organic products were neither purified nor identified. No attempt was made to utilize the "hot" F^{18} atoms for recoil labelling of other, fluorine free, organic compounds.

The purpose of the present study was to investigate the mechanism of recoil labelling of organic compounds by fluorine generated by the $O^{16}(H^3,n)F^{18}$ nuclear reaction. The $Li^6(n,\alpha)H^3$, $O^{16}(H^3,n)F^{18}$ reactions have been previously utilized for the production of fluorine 18 in a nuclear reactor,[5] and it was of interest to evaluate the feasibility of this technique for the production of fluorine 18 labelled organic compounds.

Experimental

Materials. Organic reagents used for irradiation were of C.P. grade and were further purified by recrystallization or distillation as necessary. Each reagent was tested for purity by checking on its physical properties, *e.g.* melting point or refractive index. Organic reagents of C.P. grade were used for the preparation of derivatives without further purification. Inorganic reagents used were of analytical grade and did not undergo any further purification. Triple distilled conductivity-tested water was used as solvent.

Lithium salts of the organic reagents were prepared by neutralizing an aqueous solution of the organic acid or phenol with lithium hydroxide. The water was then evaporated under vacuum and the lithium salt was dried until constant weight. Lithium 6 salts were prepared by dissolving metallic lithium 6 (96%) in water, followed by

(1) A. H. Gordus and J. E. Willard, *J. Am. Chem. Soc.*, **79**, 4609 (1957); I. C. Chien and J. E. Willard, *ibid.*, **79**, 4872 (1957); J. B. Evans, J. E. Quinland, M. C. Sauer and J. E. Willard, *J. Phys. Chem.*, **62**, 1351 (1958); J. B. Evans, J. E. Quinland and J. E. Willard, *Ind. Eng Chem.*, **50**, 192 (1958).

(2) G. Gavoret, *J. Chim. Phys.*, **50**, 183, 434 (1953); N. Ivanoff and G. Gavoret, *ibid.*, **50**, 524 (1953).

(3) M. Vlatkovic and A. H. W. Aten, *J. Inorg. Nuclear Chem.*, **13**, 331 (1960); **14**, 134 (1960).

(4) A. H. W. Aten, B. Koch and I. Kommander, *J. Am. Chem. Soc.*, **77**, 5498 (1955).

(5) R. B. Bernstein and I. I. Katz, "*Nucleonics*," Vol. XI, [10] 46 (1953); L. G. Stang, *et al.*, Proc. Internat. Conf. on Radio-isotopes in Sci. Research, Vol I, Paris, 1957, p. 50 (1958).

neutralization with the corresponding acid. The dry lithium 6 salt was then treated as described above.

Lithium 6 cyanate was prepared from lithium perchlorate. A lithium 6 hydroxide solution prepared as described above was neutralized with 72% perchloric acid; an equal volume of ethanol was added followed by a concentrated solution of potassium cyanate. $KClO_4$ which precipitated was filtered off at 5° and the supernatant was then evaporated under vacuum to dryness.

Procedure-General. Solid Organic Lithium Salts.—1–2 grams of organic lithium salts were encapsulated and sealed in polyethylene containers and irradiated in the pneumatic tube of the Israel Research Reactor 1 (swimming pool type reactor). The thermal neutron flux of irradiation was 7.10^{11} n/cm.²/sec. at a cadmium ratio of 4.3. The samples were irradiated for 6 minutes, resulting in an irradiation dose $2.5.10^{14}$ nvt. cm.². A weighed amount of the irradiated salt was dissolved in a known volume of water and 1 ml. of 0.001 molar NaF solution was added as a hold-back carrier. The solutions at pH 7–8 were passed through a column of chromatographic alumina, carrier fluoride was added and the procedure was repeated once or twice until constant specific activity was attained. The chromatographic alumina columns were shown to hold back fluoride activity better than 98% on a single passage. Certain irradiated solids were annealed for 30 minutes in an oil bath at 150° prior to dissolving. Lithium salts of phenols were dissolved in a known amount of 50% ethanol and treated as stated above.

Lithium salts irradiated in aqueous solutions were sealed in polyethylene containers. The irradiation solution was then treated as described.

Irradiations in organic solutions were carried out by the same procedure as in water, only that an equal volume of water was added before passing through the alumina columns.

Aliphatic and aromatic amines and alcohols were irradiated in liquid form to which a small amount of lithium-6 hydroxide or lithium-6 cyanate was added. A weighed amount of the irradiated compound was then dissolved in a known volume of an aqueous acid solution and then treated as stated above.

The specific activities (c./m./ml.) of the primary and of the eluted solutions were determined. The solution was then treated to isolate the particular compound or its derivative as described below. Wherever possible a procedure for derivative preparation was chosen which could be carried out in aqueous alkaline solutions.

Radioassay.—The activity was determined in a NaI well-type scintillation counter with a discriminator setting at 0.4 Mev. Each sample was measured for 6 hr. at 1 hr. intervals, starting about 2 hr. after end of irradiation and then at 20 and 28 hr. after end of irradiation. The measured activity was graphically plotted and corrected for radiocontaminants, *e.g.* Na^{24}. After correcting for the longer lived activities the points were found to correspond to a half life of 105–115 minutes. The activity at time zero (stop or irradiation) was obtained by graphical extrapolation, using a slope corresponding to $t_{1/2}$ = 112 min. Following this procedure there was no necessity for corrections due to the presence of short lived radiocontaminants in the irradiated samples. All activities referred to in the following presentation are activities at zero time.

Weighed amounts of the solid irradiated salts or of the irradiated liquids were taken for radioassay. Aliquots of the aqueous solutions were taken before and after passing through the alumina columns. The final derivatives of the organic labelled compounds were weighed after being dried to a constant weight and their activities determined.

Calculation of the Yield of Labelled Organic Compounds. A.—Pure Compounds.—The labelling yield was calculated by relating the total F^{18} activity in the irradiated sample to the organically bound activity found in the purified labelled compound or in its derivative. The *total F^{18} activity per mole* (T) was calculated from the *initial specific activity* (S_i) (c./min./g.), of the irradiated compound, multiplied by the molecular weight (M); $T = S_i \times M$. The *molar activity of the final product* (F) was calculated from the *final specific activity* (S_f) multiplied by the molecular weight on the final derivative (M_d); $F = S_f \times M_d$. The per cent. yield of labelling (Y) is defined $Y = 100F/T = 100 \frac{S_f}{S_i} \frac{M_d}{M}$. The *yield of labelling* per hydrogen atom (Y_H) is defined as the quotient of Y and the number of hydrogen atoms (n) in the irradiated compound $Y_H = Y/n$.

B. Solutions.—The molar labelling yield in aqueous solutions (Y_s) containing C moles *per gram* organic solute was calculated from the total activity (T_s) produced *per gram* solution, compared with the molar activity of the pure labelled solute (F). $Y_s = 100 \frac{FC}{T_s}$. Correspondingly the labelling yield per hydrogen atom is $Y_{Hs} = Y_s/n$.

C. Determination of Decomposition Yield (D).—After dissolving the weighed sample in water the initial specific activity (T_i) (c./m./ml.) of the solution was determined. The solution was then passed through alumina columns until constant specific activity(T_f) was attained. The yield of *all* the organically bound fluorine (Y_0) is given by $Y_0 = 100T_f/T_i$. The decomposition yield (D) is defined $D = 100 (Y_0 - Y)/Y_0$. The yield per organic hydrogen including fluoroderivatives of decomposition products (Y_{Ht}) is defined $Y_{Ht} = 100Y_H/(100 - D)$.

Isolation of Fluorine Labeled Compounds and Their Derivatives.—1. Acetic, propionic and malonic acids were precipitated as their silver salts in presence of fluoride carrier. The silver salt was separated by centrifuge and then dissolved in ammonia, next it was precipitated by acidification with nitric acid. This procedure was repeated 3 times. The specific activities of the silver salts did not change between the second and third precipitation. Formic acid was separated as its lead salt. Acetic and propionic acids were also separated by forming their *p*-bromophenacyl esters.[6a] This procedure was found to give products of higher radiochemical purity than the silver salts.

2. Benzoic, toluic, hydrocinnamic, salicylic, phthalic, *o*-nitrobenzoic, orotic acid and uracil were all recrystallized in their acid form in presence of carrier fluoride, either by dissolving in alkali and acidifying or from hot water. Wherever possible the procedures were used interchangeably.

3. Glycine and glutamine were precipitated from their aqueous solutions in the presence of carrier fluoride by an excess of acetone. The precipitate was redissolved in water and the procedure was repeated three times. An alternative procedure was to prepare the 3,5-dinitrobenzoate derivatives of these compounds[6b] which were subsequently recrystallized.

4. *n*-Butylamine was determined as its picrate[6c] and alternatively as its N-acetic acid derivative.[6d]

5. Anthranilic acid was determined as its N,N-diacetic acid derivative,[6d] which was then recrystallized from water.

6. Phenol and beta-naphthol were separated as their O-acetic acid derivatives.[6d]

7. Aniline was crudely separated from water by adding sodium hydroxide, it was dried over Na_2SO_4 and then the *p*-toluene-sulfonate[6e] derivative was prepared and recrystallized.

8. Aliphatic alcohols and diisopropyl ether were separated by distillation from an alkaline solution containing carrier fluoride and dried over anhydrous sodium sulfate; the 3,5-dinitrobenzoate derivatives of methyl, ethyl and *n*-propyl alcohols were separated and recrystallized. *t*-Butyl alcohol was also separated as the *t*-butyl chloride which was prepared by adding concentrated HCl to the alcoholic aqueous solution. The *t*-butyl chloride was then distilled.

9. Benzyl alcohol was separated by distillation after repeated washing with sodium hydroxide solution containing sodium fluoride.

In order to find out whether the fluorine distribution was equivalent for all hydrogen positions in a molecule, several degradation procedures were undertaken and the specific activities of the fragments or of their derivatives were determined.

1. *o*-Methyl salicyclic acid. The methyl group was cleaved off by hydriodic acid,[6f] the methyl iodide was distilled off, dried and assayed, the salicyclic acid was treated as described above.

2. Toluic and hydrocinnamic acids as well as benzyl alcohol were oxidized by permanganate in alkaline solutions to phthalic and benzoic acids, respectively,[6g] which were then purified by recrystallization. The separation between phthalic acid and residual toluic acid was achieved by dissolving the former at pH = 3 leaving the toluic acid undis-

(6) (a) Vogel, "Practical Organic Chemistry," Longmans, 3rd Ed., p. 362; (b) p. 436; (c) p. 422; (d) p. 682; (e) p. 653; (f) p. 671; (g) p. 520.

solved. This procedure was repeated after adding fresh toluic acid as a holdback carrier.

Results

The labelling yield of aliphatic compounds is presented in Table I. The compounds were irradiated either as solid lithium salts (1.1–1.4, 1.11–1.14) or as liquids in which lithium salts were dissolved (1.5–1.10, 1.15–1.16). The concentrations of the dissolved lithium salts were 0.1–0.5 molar. The irradiated solids were not annealed before processing. (Annealing of irradiated solids prior to dissolving increased the labelling yield Y by 10–30%.)

TABLE I

FLUORINE 18 LABELLING OF PURE ALIPHATIC COMPOUNDS

	Compound	Y	Y_H	D	Y_{Ht}
1.1	Formic acid	0.1	0.1	..	..
1.2	Acetic acid	3.0	1.0	2[a]	1.0
1.3	Propionic acid	3.5	0.7	5	0.75
1.4	Malonic acid	1.5	.75	..	..
1.5	Methyl alcohol	1.85	.61	5	.68
1.6	Ethyl alcohol	3.5	.7	..	..
1.7	*n*-Propyl alcohol	3.6	.51	..	..
1.8	*i*-Propyl alcohol	2.2	.31	10	.34
1.9	*t*-Butyl alcohol	6.1	.7	5	.7
1.10	Benzyl alcohol	4.1	.7[b]	..	..
1.11	Glycine	0.8	.4	45	.7
1.12	Glutamine	3.0	.6	15	.7
1.13	Orotic acid	0.7	.7	..	..
1.14	Uracil	1.5	.75	..	..
1.15	*n*-Butylamine	4.5	.5	30	.7
1.16	Acetone	6.2	1.0	..	..

[a] CH_3F^{18} was formed at a yield of 1%. [b] The yield of the aliphatic hydrogens; the yield of the aromatic hydrogens is given in Table II.

It can be seen in Table I that the yield of labelling per hydrogen atom in aliphatic compounds reaches the value of about 0.7 in most compounds investigated. In some cases (1.11, 1.12, 1.15) a lower yield is observed which can be accounted for by the presence of fluorine labelled decomposition products. In these cases the yield per organic hydrogen including the fluoro derivatives of the decomposition products amounts again to about 0.7. In two other cases, namely formic acid and isopropyl alcohol low labelling yields are observed which cannot be accounted for by the formation of labelled decomposition products.

Aromatic labelled fluoroderivatives were similarly produced; the results are summarized in Table II. All compounds with the exception of benzyl alcohol and aniline were irradiated as solid lithium salts. The aromatic compounds are labelled with a yield per hydrogen ranging from 0.35–0.7. Unlike aliphatic compounds the labelling yield seems to depend on the nature of the substituted compound. The aliphatic radicals of the aliphato-aromatic compounds which have been separately assayed for fluorine labelling show a labelling yield of about 0.7.

A series of compounds were irradiated in organic solutions using *t*-butyl, isopropyl alcohols and acetic acid as solvents. The results are given in Table III. The parameter investigated here was the effect of solutes on the total yield of organically

TABLE II

FLUORINE 18 LABELLING OF PURE AROMATIC COMPOUNDS

	Compound	Y	Y_H aromatic	Y_H aliphatic	D	Y_{Ht} aromatic
2.1	Toluic acid	3.6	0.35	0.7	..	..
2.2	Hydrocinnamic acid	5.0	.4	.75	..	..
2.3	Salicylic acid	1.5	.37	..	5	0.40
2.4	*o*-Methyl-salicylic acid	3.2	.35	.6	..	..
2.5	Phenol	2.0	.4	..	..	..
2.6	Aniline	2.0	.4	..	5	.45
2.7	Anthranilic acid	0.8	.2	..	47	.4
2.8	Benzoic acid	2.8	.56	..	5	.58
2.9	Benzyl alcohol	4.1	.55	.7	..	..
2.10	beta-Naphthol	4.2	.6	..	..	..
2.11	beta-Naphthoic acid	5.0	.7	..	..	..
2.12	Phthalic acid	2.8	.7	..	..	..
2.13	*o*-Nitrobenzoic acid	2.8	.7	..	..	..

bound fluorine (T) which is derived from the molecular yield and the mole fractions of the two components: $T = fY_{\text{solute}} + (1 - f)Y_{\text{solvent}}$.

TABLE III

FLUORINE 18 LABELLING IN ALIPHATIC SOLVENTS

	Solvent	Solute	Mole fraction of solute	Y_s solv.	Y_s solute	Total labelling yield (T)
3.1	*t*-Butanol	.....	0	6.0	..	6.0
3.2	*t*-Butanol	Acetic acid	0.06	5.5	0.37	5.4
3.3	*t*-Butanol	Benzoic acid	.04	0.75	.78	0.75
3.4	*t*-Butanol	Phthalic acid	.02	4.5	.45	4.40
3.5	*t*-Butanol	Phenol	.175	0.73	1.0	0.77
3.6	*t*-Butanol	Aniline	.17	0.3	0.25	.29
3.7	*t*-Butanol	*i*-Propyl ether	.143	0.8	.8	.80
3.11	*i*-Propanol	.....	0	2.2	..	2.2
3.12	*i*-Propanol	Acetic acid	0.215	2.1	.25	2.2
3.13	*i*-Propanol	Formic acid	.14	0.6	0	0.6
3.14	*i*-Propanol	Butylamine	.134	1.5	3.5	1.8
3.15	*i*-Propanol	Benzoic acid	.09	0.28	0.54	0.3
3.16	*i*-Propanol	Phthalic acid	.003	1.27	1.4	1.27
3.17	*i*-Propanol	Phenol	.08	0.35	0.39	0.35
3.18	*i*-Propanol	*i*-Propyl ether	.10	.3	0.55	.75
3.19	*i*-Propanol	Lithium nitrite	.05	.4	..	.4
3.21	Acetic acid	.....	0	3.0	..	3.0
3.22	Acetic acid	*t*-Butanol	0.2	1.5	1.5	2.3
3.23	Acetic acid	2-Propanol	0.2	1.5	0.14	1.2

From Table III it can be seen that the addition of certain solutes including formic acid, nitrite ions, 2-propanol, isopropyl ether and certain aromatic compounds diminishes the *total* yield of organic bound fluorine.

The behavior of fluorine 18 generated in aqueous solutions was investigated and a series of lithium salts of various aliphatic and aromatic compounds were irradiated in water. The results are summarized in Table IV. It was of interest to compare the efficiency of labelling of organic compound with the competing reaction of fluorine 18 with water molecules. This could be evaluated by calculating the labelling efficiency per hydrogen (E_H) in solution, which may be expressed as the quotient of the atomic labelling yield Y_H and the hydrogen atom fraction f_H. (The hydrogen atom fraction is derived from the mole fractions (f) and the number of hydrogen atoms per molecule (n)).

$$f_H = \frac{f_1 n_1}{f_1 n_1 + f_2 n_2}$$

$$E_H = Y_H / f_H$$

TABLE IV

FLUORINE 18 LABELLING IN AQUEOUS SOLUTIONS

	Solute	Concn. mole l.$^{-1}$ (c)	Hydrogen atom fraction (f_H)	Y_s	$Y_{Hs\ aliph.}$	$Y_{Hs\ aromatic}$	$E_H = \frac{Y_{Hs\ aliph.}}{f_H}$	$E_H = \frac{Y_{Hs\ aromatic}}{f_H}$
4.1	Acetic acid, pH = 3	15.8	0.82	2.4	0.8	..	0.9	..
4.2	Lithium acetate, pH = 5	3.9	.088	1.07	.36	..	4.1	..
4.3	Propionic acid, pH = 4	8	.49	2.18	.44	..	0.9	..
4.4	Lithium propionate	4.1	.16	2.3	.46	..	2.9	..
4.5	Lithium propionate, pH = 13	4.1	.16	2.48	.49	..	3.06	..
4.6	Propionic acid, pH = 1	4.1	.16	2.2	.43	..	2.7	..
4.7	Propionic acid, pH = 1	1.35	.058	1.8	.36	..	6.2	..
4.8	Lithium malonate	3.75	.0675	0.72	.36	..	5.4	..
4.9	Lithium malonate	2.8	.047	1.2	.6	..	12.8	..
4.10	Lithium malonate	1.9	.035	1.22	.61	..	17.7	..
4.11	Lithium malonate	1.3	.023	0.7	.35	..	15.0	..
4.12	Lithium benzoate	1.0	.043	1.2	..	0.24	..	5.6
4.13	Lithium benzoate, pH = 13	1.0	.043	1.1	..	.22	..	5.1
4.14	Lithium benzoate	0.15	.007	0.22	..	.044	..	6.3
4.15	Lithium benzoate + 2 M formic ac.	.15	.007	.05	..	.010	..	1.4
4.16	Lithium benzoate + 0.15 M $LiNO_2$	.15	.007	.106	..	.021	..	3.1
4.17	Lithium benzoate	.074	.0035	.125	..	.025	..	7.1
4.18	Lithium benzoate	.048	.0022	.09	..	.018	..	8.2
4.19	Lithium benzoate	.022	.0010	.06	..	.012	..	12.0
4.20	Lithium phthalate	1.45	.05	.86	..	.21	..	4.2
4.21	Lithium phthalate	0.6	.021	.55	..	.14	..	6.9
4.22	Lithium phthalate	.51	.018	.70	..	.175	..	9.8
4.23	Lithium phthalate	.14	.005	.46	..	.115	..	33.0
4.24	Lithium phthalate	.064	.0023	.38	..	.09	..	39.2
4.25	Phenol	.9	.04	.15	..	.03	..	0.75
4.26	Resorcinol	1.6	.055	.14	..	.035	..	0.64
4.27	Anthranilic acid, pH = 7	0.45	.016	.135	..	.027	..	1.7
4.28	Anthranilic acid, pH = 1	.45	.016	.145	..	.029	..	1.8
4.29	Orotic acid	.33	.003	.024	0.024	..	8.0	..

There are three major conclusions which may be derived from the experimental data of Table IV.

a. The molar labelling yield (Y_s) decreases with decreasing concentration of the solute, however there is a definite increase in the labelling efficiency per hydrogen of solute (E_H) with decreasing concentration.

b. Formic acid and nitrite ions have a scavenging effect on Y_s or Y_{Hs}.

c. The labelling yield is not affected by the acidity of the aqueous solution and comparable yields are obtained in acid, neutral and alkaline solutions.

Discussion

The labelling reactions investigated in this study are reactions of fluorine produced by a nuclear process at extremely low concentrations. It is hard to conceive *a priori* the chemical nature of the fluorine involved in these labelling processes. From the results it may be possible to derive information on the chemical identity of the active species in these reactions.

Fluorine 18 is formed by the interaction of tritons with oxygen-16 atoms. The tritons are produced by the Li^6 $(n,\alpha)H^3$ reaction with an initial energy of 2.7 MeV. The excitation function of the $O^{16}(H^3,n)F^{18}$ reaction shows a cross-section of 500 millibarns at 2.7 MeV[7] with a drop to 100 millibarns at 2.2 MeV; there is a small change in the cross-section down to 1.5 MeV (70 millibarn) and below this energy the cross-section drops sharply[8] (4 millibarns at 1.0 MeV and 0.4 millibarns at 0.6 MeV).

The linear energy transfer for tritons in water in the energy range 1–3 MeV is 60–30 electron volts per millimicron.[9] This means that a triton produced may penetrate through a range of about 30 microns in organic material before losing chances for producing F^{18}. From the excitation functions and the range-energy relations it may be calculated that the nuclear reaction producing F^{18} will occur at an average distance of 10 microns from the site of the triton production. This means that there is very little chance for a triton formed from a lithium atom to interact with oxygen of the same molecule or of its closer neighbors.

The nuclear reaction $O^{16}(H^3,n)F^{18}$ is an exoergic reaction with a Q value[10] of 1.256 MeV. The average triton which will produce F^{18} has an energy of 2.2 MeV, thus the average recoil energy of the fluorine will amount to 120 KeV. It is hard to estimate the range of the fluorine 18 in organic material or in water, because the atom formed will be highly charged and it will rapidly regain electrons from matter before being slowed down. By comparison with fission fragments we may estimate that the range of F^{18} is longer than 10 millimi-

(7) R. Sher and J. J. Floyd, *Phys. Rev.*, **102**, 242 (1956).

(8) N. Jarmie, *ibid.*, **98**, 41 (1955).

(9) F. Hutchinson and E. Pollard, "Physical Principles of Radiation Action—Mechanism in Radiobiology," M. Errera and A. Forsberg, editors, Academic Press, Inc., New York, N. Y., 1961.

(10) F. Everling, *et al.*; Nuclear Data Tables, U. S. Natl. Acad. Sci. Res. Council (1961).

crons.[11] This means that there is little chance for the fluorine 18 to interact with the molecule which carried the transformed O^{16}. After passing through some 10 molecules, while causing heavy radiation damage, the fluorine should slow down to an energy level where chemical binding may occur. It should be noted that owing to its low mass, fluorine 18 may lose almost all its kinetic energy in a single event, when it collides head-on with a nucleus of C^{12}, N^{14} or O^{16}.

The decelerated fluorine atom may be either positively charged before undergoing chemical combination with a carbon atom (the only fluorine cation capable of substituting a hydrogen on a carbon[12] is F^+) or it may be a neutral fluorine atom.

The fluorine may possess excessive kinetic energy before being thermalized, still it may be capable of chemical binding. "Hot" atoms which may include F^+, F and F^- are expected to have a short lifetime, of the order of a single collision, *i.e.* 10^{-10} sec. It is evident that fluorine will pass through the stage of a monovalent cation, which may react with an organic molecule and substitute a hydrogen on a carbon, or it may eventually pick up an electron and form a fluorine atom.

$$F^+ + RH \longrightarrow RF + H^+$$
$$F^+ + e^- \longrightarrow F$$

The fate of the fluorine atom may follow three alternative pathways: it may substitute a hydrogen, it may abstract a hydrogen atom or it may pick up an electron, in the two last cases a fluoride ion will be formed.

$$F + RH \longrightarrow RF + H$$
$$F + RH \longrightarrow R + HF$$
$$F + e^- \longrightarrow F^-$$

The following conclusions may be inferred from the experimental data:

The labelling yields of pure aliphatic compounds (Table I) point out two major facts: (a) that the labelling yield (Y) is proportional to the number of available sites of substitution; namely the number of hydrogen atoms per molecule, the *atomic* labelling yield per aliphatic hydrogen ranges from 0.6 to 1.0. (b) The labelling yields for formic acid (1.1) and for isopropyl alcohol (1.8) were considerably lower than those of the other aliphatic compounds examined. In mixtures of aliphatic compounds a constant atomic labelling yield of substituted aliphatic hydrogens is observed as long as isopropanol or formic acid are not involved. (Table III: 3.1–3.2, 3.11–3.12, 3.21–3.23). On the other hand it is clearly demonstrated that both formic acid and isopropanol as well as isopropyl ether diminish the labelling yields of their aliphatic solvents (3.1–3.7, 3.11–3.13, 3.18, 3.21–3.23), in other words they act as scavengers for the precursors of fluorine labelling.

The constant atomic labelling yield shows that the substitution of hydrogen on one hand and the formation of fluoride ions in organic systems are two independent competing processes. The yield of substituted hydrogens as compared to fluoride ions produced is dependent only on the number of sites available for substitution. The fact that formic acid and isopropyl alcohol show less tendency to form substituted fluoro derivatives means at first glance that their sites for substitution are of lower reactivity towards fluorine. However, the effect of formic acid and of isopropanol on the labelling yield of their aliphatic solvents suggests that a reaction of the nature $RH + F \rightarrow R + HF$ increases the relative yield of fluoride ions.[13] The existence of such competitive reactions excludes the participation of "hot" fluorine ions or atoms as the major active species in the substitution reaction, hot atoms should react at collision frequency and their behavior should be independent of small concentrations of "scavengers."[14]

When lithium trifluoro-acetate was irradiated by thermal neutrons only (the only source for F^{18} being the $O^{16}(H^3,n)F^{18}$ reaction), a labelling yield of 0.07 was obtained. This result implies that no "billiard ball" substitutions occur under our conditions, nor does it occur when F^{18} was produced by the $(n,2n)$ reaction.[15] From the results of aliphatic substitution reactions, it is still hard to decide between F^+ and F as the active species because both may be scavenged by formic acid (by electron or hydrogen transfer) as well as by isopropanol (by hydride or hydrogen transfer). The scavenging effect of nitrite ions (3.19) which corroborates the former conclusions may again be explained by the reaction of nitrite with either F^+ or F.

From the results of aromatic substitution one may infer three general conclusions. (a) The substitution yield per aromatic hydrogen is lower than that per aliphatic hydrogen. (b) The substitution yield per aromatic hydrogen is higher in compounds which are less reactive toward electrophilic reactants (2.10, 2.11, 2.12, 2.13). On the other hand aromatic compounds with a high density of pi-electrons show relatively lower yields (2.3, 2.4, 2.5, 2.6). (c) In solutions of aromatic solutes in aliphatic solvents the labelling yield of the solvent is considerably diminished, *i.e.* they act as scavengers (3.3, 3.5, 3.6, 3.15, 3.16, 3.17). Comparable to the aliphatic scavengers mentioned above, the aromatic solutes do not pick up the scavenged fluorine, but they increase the relative yield of fluoride ions.

The facts that aromatic substitution by fluorine proceeds to a smaller degree than in aliphatic compounds and that the extent of substitution does not follow the sequence of reactivity of electrophilic substitution confute the existence of F^+ as a species having a lifetime long enough to undergo chemical reactions. The fact that aromatic compounds were shown to act as scavengers for the reactive species *without undergoing substitution* corroborates this conclusion, because it is very unlikely that an aromatic nucleus would transfer a hydride ion to a F^+

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(12) The ionization potentials of the first, second and third electrons of fluorine are 17.5, 35 and 62.5 ev., respectively; R. T. Sanderson, "Chemical Periodicity," Reinhold Publishing Co., New York, N. Y., 1960.

(13) *Cf.* A. O. Allen, "The Radiation Chemistry of Water and Aqueous Solutions," Van Nostrand, Princeton, N. J., 1961.

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to form HF. On the other hand, it is reasonable to assume that an electron transfer reaction of the type $PhH + F \rightarrow PhH^+ + F^- \rightarrow Ph + H^+ + F^-$ may take place.

This reaction is analogous to that of nitrite ions which were also found to be efficient scavengers: $NO_2^- + F \rightarrow NO_2 + F^-$. It is suggested that aromatic compounds scavenge *fluorine atoms* by electron transfer rather than by a hydrogen transfer process, because compounds of higher pi-electron density are shown to be relatively better scavengers (3.4–3.5, 3.16–3.17). The lower labelling yields of aromatic compounds with high pi-electron density may be explained by the competitive scavenging property of these compounds, because the homolytic substitution by fluorine atoms should hardly be affected by *ortho–para* directing substituents. A similar behavior of aromatic compounds was observed towards OH radicals.[16]

It may be concluded therefore that fluorine atoms are the active species in organic systems; their behavior in aqueous solutions is discussed below.

Formic acid and nitrite ions act as scavengers in aqueous solutions (4.14, 4.15, 416); higher values of E_H are obtained for aliphatic as compared with aromatic solutes at equal concentrations (4.7–4.26; 4.9–4.12; 4.11–4.21) and higher labelling yields are obtained for phthalic acid as compared with benzoic acid (4.17–4.23) and for benzoic acid as compared with phenol (4.12; 4.25). All these findings are in complete agreement with the results obtained in non-aqueous systems, and it is reasonable to assume that the same mechanism prevails in both media.

The fact that the labelling efficiency per hydrogen of solute (E_H) increases significantly in dilute solutions again exludes the participation of "hot" fluorine atoms, and it means that water is a relatively poor competitor for fluorine atoms when compared with organic substrates. Water may react with fluorine atoms in three ways: either by hydrogen abstraction $F + H_2O \rightarrow HF + OH$, by direct substitution $F + H_2O \rightarrow FOH + H$ or by electron transfer $F + H_2O \rightarrow F^- + H_2O^+$; $H_2O^+ \rightarrow H^+ + OH$. The direct substitution reaction seems energetically less probable compared with the hydrogen abstraction. It was shown that at pH = 13 no appreciable scavenging effect is observed (4.4–4.5, 4.12–4.13) due to the reaction $F + OH^- \rightarrow F^- + OH$; this suggests that the electron transfer processes in aqueous solutions may be of little importance as compared with the hydrogen abstraction reaction. It should be noted that this hydrogen transfer process is a rather slow process when compared with hydrogen substitutions on a carbon atom. It might be stated that the fluorine atoms have a finite lifetime in aqueous solutions, long enough to interact with electron donors like nitrite ions or with hydrocarbons. A question of interest is the chemical structure of a solvated fluorine atom in water, however little can be inferred from the results of the present study.

(16) M. Anbar and M. Bobtelsky, to be published.

[CONTRIBUTION FROM THE GENERAL DYNAMICS/CONVAIR SCIENTIFIC RESEARCH LABORATORY, SAN DIEGO, CALIFORNIA]

The Kinetics of the Reduction of Iodate Ion by Borohydride Ion in Basic Aqueous Solutions

BY T. FREUND[1a] AND N. NUENKE

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In this study it was shown that the chemistry of basic aqueous solutions containing IO_3^- and BH_4^- can be described by two independent chemical reactions: $BH_4^- + 2H_2O = BO_2^- + 4H_2$ and $3BH_4^- + 4IO_3^- = 3BO_2^+ + 4I^- + 6H_2O$. The rate of disappearance of IO_3^- is first order in IO_3^-, BH_4^-, H^+ and independent of I^-. The third order specific rate constant at 25° is $7.4 \times 10^7\ M^{-2}$ sec.$^{-1}$ and has a temperature coefficient corresponding to an activation energy of 7.9 kcal. The rate of disappearance of BH_4^- was shown to be given by the expression $k_H[H^+][BH_4^-] - {}^3/_4 d[IO_3^-]/dt$, where k_H is the specific rate constant for the hydrolysis of BH_4^-. The mechanism of the iodate reaction will be considered in terms of the various oxidation states of iodine. Also the behavior of this chemical system will be compared with our previous work on the reactions of BH_4^- with $Fe(CN)_6^{-3}$, MnO_4^-, Sn(III) and $(CH_3)_2CO$.

Introduction

This investigation was undertaken as part of a series of studies on the mechanisms of the reduction of common oxidizing agents by the borohydride ion in aqueous solutions. The mechanisms for aqueous borohydride reductions have been investigated for water,[1a–6] for ferricyanide,[7,8] for permanganate[9] and for antimonyl tartrate.[10] Some chemical studies[5,11,12] have been made in which the kinetics were not investigated.

Our kinetic studies of the ferricyanide and hydrolysis reactions have shown that the rate determining step for both reactions is the same; the activated complex has the chemical composition, $H^+BH_4^-$. In contrast, the kinetics of the permanganate reaction show that the activated complex of the rate determining step contains only permanganate and borohydride ions but no hydrogen ion.

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