2-Adamantyl *p*-Bromobenzenesulfonate. Recrystallization at −78° gave white crystals: mp 112.8–113.6°; ir includes 7.44, 8.54, 11.10, 13.60, 14.94 μ; pmr[39] δ 7.77 (d, 2, J = 9 Hz), 7.65 (d, 2, J = 9 Hz), 4.73 (s, 1, $-CH(OSO_2Ar)-$), 2.3–1.2 (complex, 14). *Anal.* Calcd for $C_{16}H_{19}SBrO_3$: C, 51.76; H, 5.16; S, 8.64; Br, 21.52. Found: C, 51.7; H, 5.08; S, 8.67; Br, 21.62.

2-Adamantyl *p*-Nitrobenzenesulfonate. Recrystallization at −78° gave very pale yellow crystals: mp 144–145°; ir includes 6.55, 7.37 (sh), 7.43, 8.51, 11.01, 13.56, 14.69 μ; pmr[39] δ 8.37 (d, 2, J = 9 Hz), 8.13 (d, 2, J = 9 Hz), 4.83 (s, 1, $-CH(OSO_2Ar)-$), 2.3–1.2 (complex, 14). *Anal.* Calcd for $C_{16}H_{19}NSO_3$: C, 56.97; H, 5.68; N, 4.15; S, 9.50. Found: C, 57.2; H, 5.81; N, 4.11; S, 9.56.

2-Adamantyl *m*-Nitrobenzenesulfonate. Recrystallization at −78° gave very pale yellow crystals: mp 113–114°; ir includes 6.55, 7.40, 7.45 (sh), 8.50, 11.08, 13.66, 14.99, 15.18 μ; pmr[36,39] δ 8.75 (s, 1), 8.50 (d, 1, J = 8 Hz), 8.26 (d, 1, J = 8 Hz), 7.80 (t, 1, J = 8 Hz), 4.87 (s, 1, $-CH(OSO_2Ar)-$), 2.3–1.2 (complex, 14). *Anal.* Calcd for $C_{16}H_{19}NSO_3$: C, 56.97; H, 5.68; N, 4.15; S, 9.50. Found: C, 57.3; H, 5.62; N, 3.97; S, 9.38.

Kinetic Procedures. For the ethanolysis of the 1-adamantyl arenesulfonates, the technique paralleled that previously reported[3] for the solvolysis of 1-adamantyl *p*-toluenesulfonate. The initial concentration of substrate was 0.02–0.03 M, except for the sparingly soluble nitro-substituted derivatives where concentrations of 0.003–0.004 M were employed and 5-ml aliquots were removed from 50 ml of bulk solution, as opposed to 2-ml aliquots from 25 ml. Two illustrative runs are given in Table VI.

For the less reactive 2-adamantyl arenesulfonates higher temperatures and extended reaction times were required. The solutions, usually about 0.065 M but about 0.02 M for the less soluble nitro-substituted compounds, were made up at 25° and, from 50 ml of bulk solution, nine 5-ml aliquots were transferred to Kimble "neutraglas" ampoules. These ampoules were sealed, placed in the appropriate constant-temperature bath, and allowed to equilibrate, and an initial ampoule, followed by others at suitable time intervals, was removed and the contents titrated.[3] For 2-adamantyl *p*-toluenesulfonate at 85°, it was shown that variation of the initial concentration within the range 0.03–0.1 M did not influence the specific ethanolysis rate. Two illustrative runs are given in Table VI. Experimental infinity titers were estimated by adding 0.5 ml of water to 1 ml of ethanol solution prior to sealing and also placing within the appropriate constant-temperature bath. Under these considerably more ionizing conditions, the solvolysis was complete within a period of less than 2 weeks. These experimental infinity titers were always within 1% of values calculated based upon the weight of 2-adamantyl arenesulfonate used within the bulk solution.

Methylation of Anisole by Methyl-d_3 Chloroformate. Intermolecular Reaction of an n Complex in Electrophilic Aromatic Substitution

Peter Beak,*[1a] Jerome T. Adams,[1a] Peter D. Klein,[1b] Patricia A. Szczepanik,[1b] David A. Simpson,[1a] and Stanley G. Smith[1a]

Contribution from the Department of Chemistry, University of Illinois, Urbana, Illinois 61801, and the Division of Biological and Medical Research, Argonne National Laboratory, Argonne, Illinois 60439.
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Abstract: The methylation of anisole by methyl-d_3 chloroformate and silver hexafluoroantimonate in chlorobenzene gives anisole-*methyl*-d_3 and a mixture of unlabeled, methyl-d_3, and dimethyl-d_6 *o*-, *m*-, and *p*-methylanisoles, consistent with the principal reaction *via* initial formation of methylmethyl-d_3-phenyloxonium ion and its subsequent intermolecular reaction with anisole. No evidence is found for significant intermolecular rearrangement of the oxonium ion to methylanisoles under these reaction conditions. These results suggest that in electrophilic aromatic substitutions on rings bearing a substituent with a free electron pair a high yield of ortho product is not a necessary consequence of n complex formation and a low yield of ortho product is not a sufficient criterion to exclude an n complex intermediate.

Substituent effects in electrophilic aromatic substitution have been studied from several different points of view and continue to be of practical and theoretical interest. One of the probable roles for a substituent with unshared electron pairs in these reactions is participation in bond formation with the electrophile to give an n complex. It is particularly appealing to consider such species to be involved in reactions which give high yields of ortho products because intramolecular rearrangement of the complex, in most cases by a formal 1,3-sigmatropic shift, to a direct precursor of the ortho substituted compound can be readily envisioned.[2-7] In fact, n complexes are not usually considered to be reactive intermediates in electrophilic aromatic substitution unless disproportionately high yields of ortho products are observed, suggesting that the latter has become an informal criterion for the intermediacy of n complexes on the reaction pathway. We have communicated a preliminary study of the silver promoted methylation of anisole by methyl chloroformate, a reaction which

(1) (a) University of Illinois; (b) Argonne National Laboratory.

(2) R. O. C. Norman and R. Taylor, "Electrophilic Substitution of Benzenoid Compounds," Elsevier, New York, N. Y., 1965, pp 303–305, and references cited therein; H. J. Shine, "Aromatic Rearrangements," Elsevier, New York, N. Y., 1967, pp 82–89.

(3) D. E. Pearson and C. A. Buehler, *Synthesis*, 460 (1971), and references cited therein.

(4) (a) M. J. S. Dewar, "Molecular Rearrangements," P. de Mayo, Ed., Wiley, New York, N. Y., 1963, pp 306–321, and references cited therein; (b) M. J. S. Dewar and P. A. Spanninger, *J. Chem. Soc., Perkin Trans. 2*, 1204 (1972).

(5) E. C. Taylor and A. McKillop, *Accounts Chem. Res.*, **3**, 345 (1970).

(6) (a) P. Kovacic and J. J. Hiller, *J. Org. Chem.*, **30**, 1581 (1965); (b) R. A. Kretchmer and M. B. McCloskey, *ibid.*, **37**, 1989 (1972).

(7) J. H. Ridd and E. F. V. Scriven, *J. Chem. Soc., Chem. Commun.*, 641 (1972); P. Haberfield and D. Paul, *J. Amer. Chem. Soc.*, **87**, 5502 (1965).

Table I. Yields and Deuterium Distribution of the Isomeric Methylanisoles and Anisole-*methyl*-d_3 from the Reaction of 0.5 *M* Anisole and 0.5 *M* Methyl-d_3 Chloroformate with 0.1 *M* Silver Hexafluoroantimonate in Chlorobenzene at 30°

Time, min	Total yield of methylanisoles $\times 10^4$ *M*[a]	Per cent composition of methylanisoles[b] 2	3	4	5	[6] $\times 10^3$ *M*
15	*o* 23.5 ± 4.2	28.0 ± 1.2[c]	71 ± 6[c]			9.8 ± 1.5[c]
	p 26.9 ± 3.3	22.7 ± 1.2[c]	78 ± 9[c]			
45	*o* 92 ± 12	50.9 ± 1.2	44.6 ± 3.0		1.98 ± 0.03[c]	28 ± 6
	p 107 ± 9	48.2 ± 0.9	47.6 ± 4.8		3.37 ± 0.33[c]	
	m 7.4 ± 5.4[c]					
90	*o* 185 ± 18	54.7 ± 1.5	38.7 ± 2.1	3.4 ± 3.0[c]	3.2 ± 0.9	47 ± 6
	p 217 ± 12	51.4 ± 1.2	38.6 ± 1.8	5.3 ± 2.7	4.68 ± 0.54	
	m 10.5 ± 3.6					
181	*o* 253 ± 15	55.1 ± 1.5	33.5 ± 1.8	7.2 ± 3.0	4.23 ± 0.30	63 ± 1.2
	p 318 ± 18	51.8 ± 1.5	34.3 ± 1.8	8.2 ± 3.0	5.67 ± 0.36	
	m 18.8 ± 1.2					
360	*o* 277 ± 18	54.8 ± 1.8	33.1 ± 1.2	7.5 ± 2.7	4.62 ± 0.44	65 ± 9
	p 346 ± 21	50.9 ± 1.8	34.2 ± 1.5	8.6 ± 2.7	6.17 ± 0.57	
	m 18.5 ± 2.4					

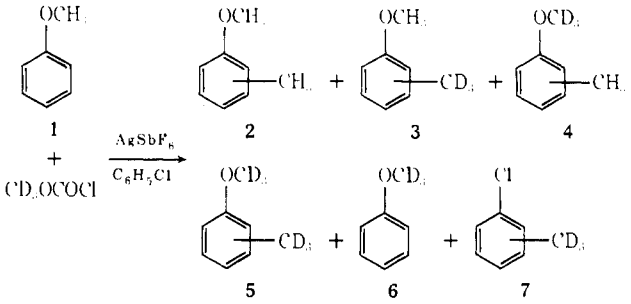
[a] The errors are limits of error given as three times the standard deviations for three determinations or three times estimated standare deviations from two determinations. [b] The errors are limits of error given as three times estimated standard deviations based on 1% of thd value of the isotopic ratio plus half the variation in the background count and a normal propagation of error. [c] The first determinations of concentration are based on smaller concentrations and probably have considerably larger errors in accuracy than indicated by the error cited.

does not give a high yield of ortho product although the n complex, dimethylphenyloxonium ion, appears to be a reaction intermediate.[8] The present report describes a more complete investigation of the deuterium distribution in the products from the reaction of methyl-d_3 chloroformate and anisole, including a study of the formation and deuterium distribution of the *o*- and *p*-methylanisoles as a function of time.

Results

The alkylation of aromatics by chloroformates has been known for almost a century.[9] Recent studies of such alkylations have focused on the idea that silver promoted dechlorodecarboxylations of chloroformates could produce intermediates comparable to those involved in amine deaminations.[10-12]

The reaction of 0.5 *M* anisole (**7**) and 0.5 *M* methyl-d_3 chloroformate with 0.1 *M* silver hexafluoroantimonate at 30° in chlorobenzene for 6 hr gives 27.7% *o*-, 1.9% *m*-, and 34.6% *p*-methylanisoles, as well as 32% chlorotoluenes. The ortho/para ratio of 0.8 is below the value, 1.0 or greater, that has been considered to imply the intermediacy of an n complex.[2-7] The methylanisoles are a mixture of all possible methyl-d_3 isomers, **2** ($CH_3C_6H_4OCH_3$), **3** ($CD_3C_6H_4OCH_3$), **4** ($CH_3C_6H_4OCD_3$), and **5** ($CD_3C_6H_4OCD_3$), and 13% of the anisole initially present is converted to anisole-*methyl*-d_3 (**6**). The yields and isotopic composition of **2**–**6** are given as a function of reaction time in Table I. The chlorotoluenes (**7**) produced in this reaction have a gross methyl-d_3 incorporation of 96 ± 1%.



Analysis of the isomeric and isotopic methylanisoles was achieved with the GMA (gas chromatography–mass spectrometry–accelerating voltage alternation) system.[13] This technique is not affected by isotope effects on retention times[14] and allows correction for isotope effects on the ratios of peak intensities, although the latter adjustment was not necessary in this case.[15] The isotopic composition of a given isomer of the methylanisoles was obtained from the molecular ion and the molecular ion minus methyl signals in the mass spectrum. If isotope effects are ignored, the ratio of the molecular ions at *m/e* 122, 125, and 128 gives the relative ratios of **2** (d_0), **3** + **4** (d_3), and **5** (d_6), and the ratio of (**2** + **4**):(**3** + **5**) can be obtained from the ratio of *m/e* 107 and 110 peaks since the latter are due to the exclusive loss of the oxygen methyl from the molecular ion. The latter assignment has been established for the meta and para isomers[16] and in the present study is confirmed for the para isomer and established for the ortho isomer by the preparation and mass spectra of the isotopically substituted ortho and para isomers **3**, **4**, and **5**. A synthetic mixture of the methylanisoles **2**–**5** of known composition was prepared and analyzed for the ortho and para isomers with the GMA system, and they are found to give the correspondence summarized in Table II. A second independent, if imprecise, test

(8) D. A. Simpson, S. G. Smith, and P. Beak, *J. Amer. Chem. Soc.*, 92, 1071 (1970).
(9) C. Friedel and J. M. Crafts, *C. R. Acad. Sci.*, 84, 1450 (1877); F. A. Drahowzal, "Friedel-Crafts and Related Reactions," G. A. Olah, Ed., Interscience, New York, N. Y., 1965, Vol. I, p 122; Vol. II, p 644.
(10) P. Beak, R. J. Trancik, and D. A. Simpson, *J. Amer. Chem. Soc.*, 91, 5073 (1969).
(11) D. N. Kevill, W. A. Reis, and J. B. Kevill, *Tetrahedron Lett.*, 957 (1972).
(12) For an excellent review see D. N. Kevill, "The Chemistry of Acyl Halides," S. Patai, Ed., Wiley-Interscience, New York, N. Y., 1972, pp 425–433.
(13) P. D. Klein, J. R. Haumann, and W. J. Eisler, *Anal. Chem.*, 44, 490 (1972).
(14) P. D. Klein, J. R. Haumann, and W. J. Eisler, *Clin. Chem.*, 17, 735 (1971).
(15) For details see J. T. Adams, Ph.D. Thesis, University of Illinois, 1973, Dissertation Abstracts, Ann Arbor, Mich.
(16) F. Meyer and A. G. Harrison, *Can. J. Chem.*, 42, 2008 (1964).

of the GMA analytical method for these compounds was carried out by glpc collection and nmr analysis of the products after 360 min of reaction. The values obtained by this method, 0.062 ± 0.007 *M* for anisole-*methyl-d*$_3$ and 17 ± 4 and 36 ± 5% for the gross *O*-methyl-*d*$_3$ and *C*-methyl-*d*$_3$ content of the methylanisoles, are consistent with the concentrations shown for the same time in Table I.

Table II. Quantitative Analysis for Per Cent Unlabeled and Isotopic Methyl-*d*$_3$ and Dimethyl-*d*$_6$ Isomers of *o*- and *p*-Methylanisoles in a Test Mixture

No.	Isomer	Actual composition[a]	Analysis[a]
	o-Methylanisole		
2	$CH_3C_6H_4OCH_3$	54.6 ± 3.9	56.7 ± 1.5
3	$CD_3C_6H_4OCH_3$	26.6 ± 1.8	24.3 ± 1.5
4	$CH_3C_6H_4OCD_3$	13.0 ± 1.2	13.7 ± 2.7
5	$CD_3C_6H_4OCD_3$	5.8 ± 0.9	5.3 ± 0.6
	p-Methylanisole		
2	$CH_3C_6H_4OCH_3$	52.9 ± 3.9	53.4 ± 2.1
3	$CD_3C_6H_4OCH_3$	32.3 ± 2.7	31.9 ± 1.2
4	$CH_3C_6H_4OCD_3$	9.0 ± 1.2	9.4 ± 3.0
5	$CD_3C_6H_4OCD_3$	5.8 ± 0.9	5.3 ± 0.6

[a] Errors are determined as described in Table I.

The constant ratio of products of 0.84:1.00:0.06 for the ortho:para:meta mixture for the reaction times at which all products were determined (Table I), in conjunction with the low yield of meta products over the course of the reaction, indicates that isomerization of the ortho compound to meta and para isomers is not an important process under these experimental conditions.[17] The results in Table I further show that the isotopic compositions of the *o*- and *p*-methylanisoles are very similar, with the ortho isomer apparently containing slightly more **2** and slightly less **5** than the para isomer, although it is possible that these small differences arise from overlap of the isomers on glpc. The reaction conditions used in the present study differ somewhat from those reported earlier[8] and were selected after an extensive experimental search for conditions which would minimize side reactions and maximize yields and stabilities of products. Although the present conditions give reproducible results and stable products, it should be noted that careful purification of all starting materials and solvents is required and a heterogeneous phase of silver chloride, which could play an unsuspected role,[18] is produced with the initiation of the reaction.

An experiment carried out at the same concentrations and temperature as cited in Table I showed that methyl chloride does not react with silver hexafluoroantimonate in chlorobenzene. The 130% yield of methyl-*d*$_3$ products (relative to silver hexafluoroantimonate, Table I) suggests that alkylation of aromatics by methyl chloroformate can be induced by acid. A control experiment was carried out by addition of gaseous hydrogen chloride to a solution of silver hexafluoroantimonate in anisole until the precipitation of silver chloride was complete, followed by addition of methyl-*d*$_3$ chloroformate. After 360 min the products are methylanisoles (42%), as a mixture of isomers composed of **2** (58%), **3** and **4** (39%), and **5** (3%) comparable in deuterium distribution to the products in Table I, 9% methyl-*d*$_3$ chlorotoluenes (**7**), and 34% anisole-*methyl-d*$_3$ (**6**). Accordingly, the present study does not define the nature of the species involved in the transfer of the methyl group from the chloroformate to the aromatic substrate. A unifying conjecture is that the methylcarboxylium[10] ion, produced by either acid or silver ion, is involved at some stage of the reaction, but a number of reasonable alternatives exist.

In the acid catalyzed reaction of the chloroformate with anisole, 6 ± 2% phenol is observed, suggesting that self-alkylation of anisole, giving 1 equiv each of phenol and methylanisole from 2 equiv of anisole, occurs under the reaction conditions. Support for this conclusion is provided by a control experiment analogous to the above acid catalyzed reaction but with no chloroformate added, which gives a 44 ± 2% yield of methylanisoles and a 48 ± 4% yield of phenol relative to the silver chloride precipitated after 360 min. The amount of product from acid catalyzed routes in the silver promoted reaction will clearly be less since in the control experiments 1 equiv of acid is present for the 360-min reaction period whereas in the reaction with methyl-*d*$_3$ chloroformate and silver hexafluoroantimonate an equivalent acid accumulates as the reaction proceeds. Although a more complete description of the reaction could be given if the rates and products of the competitive reactions were known in detail, it is possible to judge the extent of the acid catalyzed self-alkylation by the amount of phenol formed. The stability of phenol to the experimental conditions was established in separate reactions of silver hexafluoroantimonate and methyl chloroformate with anisole in chlorobenzene for 420 min at 30°. With 3.5% phenol initially present, a final yield of 10.5 ± 2% phenol was observed; under the same conditions in the absence of added material, a 5 ± 2% yield of phenol was found. The experiment reported in Table I yields 7 ± 2% phenol after 360 min, which suggests that no more than 10% of the methylanisoles could come from self-alkylation.

Discussion

The results of the reaction of methyl-*d*$_3$ chloroformate with silver hexafluoroantimonate and anisole in chlorobenzene summarized in Table I can be used to rule out the exclusive operation of different possible mechanisms more easily than to establish a single reaction pathway. Neither direct ring alkylation by the methylating agent nor initial formation of an n complex followed by only intramolecular rearrangement or by only intermolecular reaction adequately accounts for even a major portion of the products. The fact that **3** ($CD_3C_6H_4OCH_3$) is not the major product precludes a predominance of direct alkylation of the anisole ring by methyl chloroformate.[19] Even if this mechanism were operative, the yield of **3** (and the assumption that equal

(17) Isomerizations of ortho products to meta and para compounds are frequently observed in Friedel–Crafts reactions: D. A. McCaulay, "Friedel-Crafts and Related Reactions," Vol. II, G. A. Olah, Ed., Interscience, New York, N. Y., 1965, Chapter XXIV.

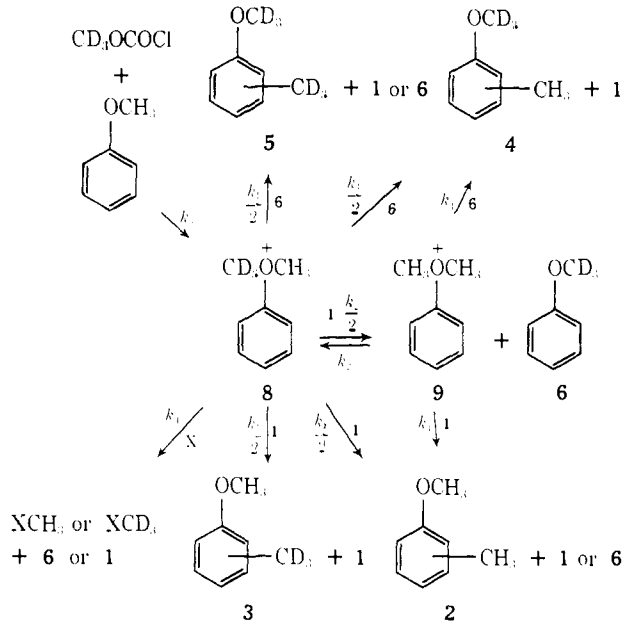
(18) E. D. Hughes, C. K. Ingold, and S. Masterson, *J. Chem. Soc.*, 1237 (1937); R. A. Bartsch and G. M. Pruss, *J. Org. Chem.*, 37, 458 (1972).

(19) It was established (see Experimental Section) that less than 5% methyl exchange between the chloroformate and anisole occurs under the reaction conditions.

amounts[20] of **3** and **4** should be produced by any scheme which makes the methyl groups of anisole and the chloroformate equivalent) limits the amount of alkylation reaction which could proceed by direct ring alkylation to no more than *ca.* one-quarter (34–8%) of the reaction under these conditions. Since substantial amounts of products with oxygen methyl-d_3 groups are found, it is reasonable that the n complex, methylmethyl-d_3-phenyloxonium ion (**8**), plays a major role in the reaction.[8,21] However, the formation of **2** and **5** shows that the reaction does not involve predominant intramolecular rearrangement of **8** to product without further involvement of additional anisole, since in that case **3** and **4** would be the only methylanisoles produced. In the absence of a significant isotope effect[20] such a rearrangement would give equal amounts of **3** and **4** and the yield of **4** can then be used to set an upper limit of one-tenth on this reaction pathway. However, if it is presumed that complete equilibration of the deuteriomethyl groups with all of the methyls of anisole occurs *via* oxygen–oxygen transfer involving the oxonium ion **8** and anisole prior to formation of the methylanisoles, an upper limit of one-third of the reaction could proceed by intramolecular rearrangement of a dimethylphenyloxonium ion. Finally, initial reaction of methyl-d_3 chloroformate to give the oxonium ion **8** followed by only intermolecular attack of anisole on **8** to yield **2** and **3** can be estimated[20] from the yield of **3** to account at most for one-third of the reaction. If product formation were to occur only after complete equilibration of the methyl groups between the oxonium ion and anisole had occurred, an approximately one to five statistical distribution of the deuteriomethyl groups among the products would be expected and **3** and **4** would comprise 13% of the total methylanisoles. Comparison with the 34% of **3** produced suggests that no more than two-fifths of the reaction could be rationalized in such a manner.

The above analysis shows that the exclusive operation of any single mechanism considered does not adequately explain the observed isotopic distribution. However, the analysis does indicate that, as previously proposed,[8] a combination of intermolecular processes involving methyl transfer from methylmethyl-d_3-phenyloxonium ion[6a,8,21] (**8**) to both the carbon and oxygen of anisole can provide a unifying picture. The proposed mechanism is summarized in Scheme I. The initial process is considered to be formation of **8** followed by methyl transfer from it to either anisole, anisole-*methyl*-d_3, or a nucleophile X, to give anisole and anisole-*methyl*-d_3.

Scheme I



The necessity for the latter pathway is seen in the fact that without this process the yield of **6** is constrained to an amount equal to that of **2**–**5**, whereas in fact the amount of **6** obtained is more than twice that of **2** (Table I). Two logical candidates for the adventitious nucleophile are chloride and fluoride. It is found by nmr and glpc mass spectrometric analysis of the reaction that *ca.* 1.2 times as much methyl chloride as methylanisoles is in fact formed in the reaction of methyl chloroformate with silver hexafluoroantimonate and anisole in chlorobenzene. However, reaction of methyl-d_3 chloroformate under the same conditions gives 91 ± 2% methyl-d_3 chloride, suggesting[20] that only *ca.* 18% of the total methyl chloride is produced by the route shown in the scheme, while most of the methyl chloride is produced by some variant of the SNi reaction, perhaps silver catalyzed.[22] Accordingly, the formation of **6** by chloride attack on **8** accounts for at most one-half of the excess **6** produced and the remainder is attributed to a route which has not been investigated in which the nucleophile is fluoride ion.

An abbreviated version of this mechanism was previously proposed, and the yields of **2**, **3**, **4**, and **6** at the end of the reaction and under slightly different conditions were found to be consistent with the results of a kinetic analysis.[8] The data in Table I allow a more complete analysis in that information about **5** and about the formation of the products over the period of the reaction is available. The results obtained by analog computer analysis of the reaction scheme are summarized in Figure 1.[23] With a ratio of rate constants for $k_1 : k_2 : k_3$ of 3 : 1 : 56, the process shown fits the products **2**, **3**, and **6** well but gives a low prediction for the oxygen methyl-d_3 materials **4** and **5**.[24] The good

(20) Isotope effects for solvolyses of methyl-d_3 halides and esters vary from 0.97 to 1.00 k_H: k_D per deuterium (A. Streitwieser, "Solvolytic Displacement Reactions," McGraw-Hill, New York, N. Y., 1962, p 173) and are assumed to be negligible for intermolecular processes in the present analysis. The value for the α isotope effect is a function of mechanism with a range of 1.00–1.23 suggested for the range from nucleophilic to limiting solvolyses: V. J. Shiner, M. W. Rapp, and H. R. Pinnick, Jr., *J. Amer. Chem. Soc.*, **92**, 233 (1970).

(21) (a) Dimethylphenyloxonium hexafluoroantimonate has been reported by F. A. Klages, A. Meureusch, and W. Steppich, *Justus Liebigs Ann. Chem.*, **592**, 81 (1955). Despite considerable effort we have been unable to secure this compound; (b) H. Prest, "Oxonium Ions in Organic Chemistry," Academic Press, The Hague, 1971; (c) V. G. Granik, B. M. Pyatin, and R. G. Glushkov, *Usp. Khim.*, 40, 747 (1971); M. S. Newman and C. D. Beard, *J. Amer. Chem. Soc.*, 92, 7564 (1970); (d) for closely related oxonium ions see M. K. Eberhardt and G. Chuchani, *J. Org. Chem.*, **37**, 3654 (1972); B. G. Ramsey, J. A. Cook, Jr., and J. A. Manner, *ibid.*, **37**, 3310 (1972); C. E. Spivak and F. L. Harris, *ibid.*, 37, 2494 (1972); A. J. Copson, H. Heaney, A. A. Logan, and R. P. Shaima, *J. Chem. Soc., Chem. Commun.*, 315 (1972); R. A. Abramovich and O. A. Kolcoso, *J. Chem. Soc. B*, 779 (1969).

(22) Internal return of halide in halide–silver ion complexes has been reported: Y. Pocker and D. N. Kevill, *J. Amer. Chem. Soc.*, **87**, 4778 1965); P. G. Gassman and R. L. Cryberg, *ibid.*, **91**, 2047 (1969); ref 12, p 432.

(23) A copy of the analog computer program may be obtained from the authors.

(24) The better fit of the reaction to the mechanism with the more limited data which were previously reported is consistent with the suggestion (*vide infra*) that **2**, **3**, and **6** are involved in further reactions since the reaction previously reported was run to lower conversion, and reactions of the products would not have been detected.

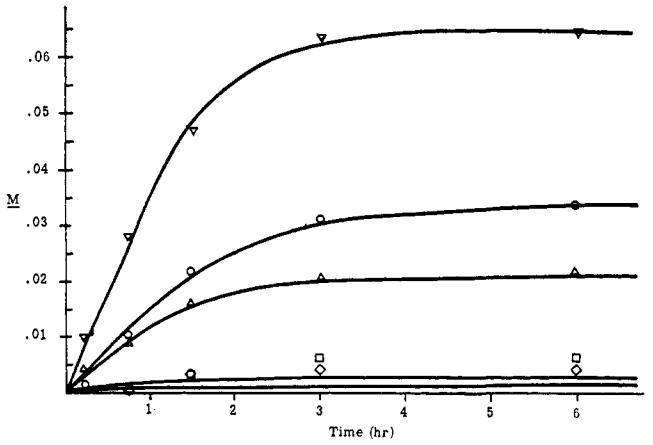


Figure 1. Methylanisoles from the reaction of methyl-d_3 chloroformate and silver hexafluoroantimonate with anisole: ○, **2**; △, **3**; □, **4**; ◇, **5**; ▽, **6**.

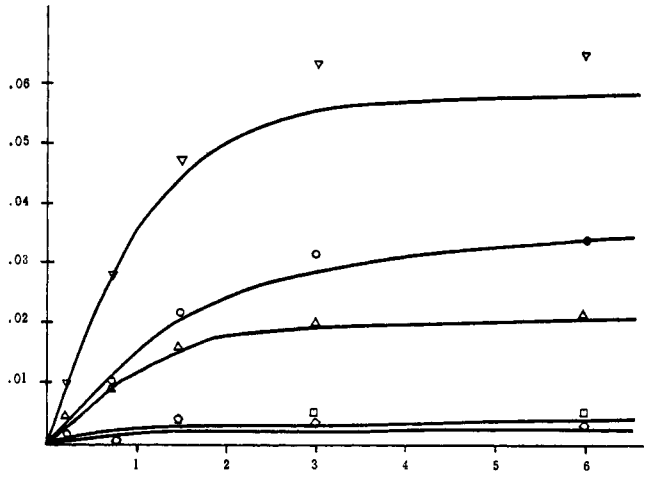
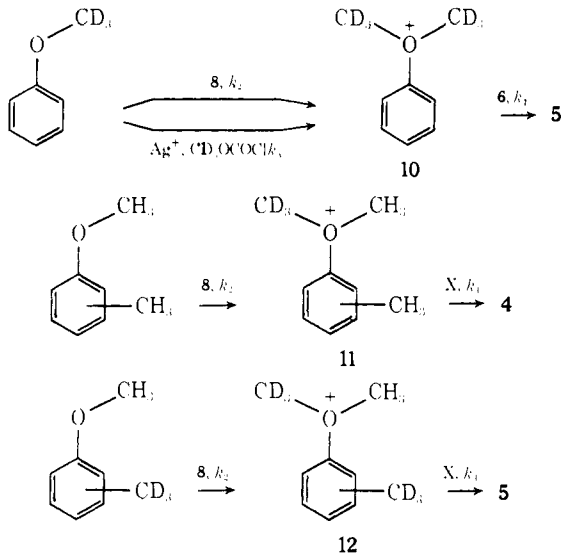


Figure 2. Methylanisoles from the reaction of methyl-d_3 chloroformate and silver hexafluoroantimonate with anisole: ○, **2**; △, **3**; □, **4**; ◇, **5**; ▽, **6**.

fit for anisole-*methyl*-d_3 (**6**) is not significant in view of the adjustable nature of k_1, which was treated as a first-order reaction of **8**, and the low predictions for **4** and **5** are consistent with the operations of pathways which are reasonable but were truncated in order to make the analysis feasible with the available analog computer. Specifically, the reaction scheme does not include the dimethyl-d_6-phenyloxonium ion **10** which could be formed from **6** and **8** or **6** and methyl-d_3 chloroformate nor does it include formation of the corresponding oxonium ions **11** and **12** from **2** and **3** by reaction with



8. An effort to assess the importance of these processes was made by adding these reactions and the reaction of **9** with nucleophile X to Scheme I and analyzing the modified mechanism with a Runge–Kutta numerical integration[25] scheme on the PLATO IV computer system.[26] The results of this analysis with a ratio of rate constants $k_1:k_2:k_3:k_4$ of 0.010:0.015:1:0.0027 are shown in Figure 2. Although an improved fit to the data is found for **4** and **5**, the prediction for **6** is low. Inclusion of **11** and **12** in the scheme suggests that some dimethylanisoles would also be produced in low yields by competitive carbon alkylation of **2** and **3**. An effort was made to detect such products, but under the analysis conditions the small amounts predicted would not have been observed. It is possible that by including isotope effects and the reactions of **2** and **3** with methyl chloroformate and silver ion to produce **11** and **12** and by investigating the deuterium distribution in self-alkylation better agreement between the observed and calculated products as a function of time could be obtained. It also may be that other pathways from reactants to products are operative. For example, the ratio of **2** to **3** (Table I) appears to increase in the early stages of the reaction. This effect could be attributed to initial formation of a short-lived reactive methyl-d_3 methylating species which perturbs the ratio of **2** to **3** by direct ring alkylation of anisole at short reaction times before appreciable amounts of product are formed from **8**. If the more stable ratio of **2** to **3** at longer reaction times is taken to be characteristic of the reaction as represented in the scheme, 14% of the products could arise from direct ring alkylation at 45 min. In the total reaction a possible 5–10% direct ring alkylation could occur. This estimate is certainly of low accuracy but, along with previous arguments, does show that direct ring alkylation is, at most, a minor reaction under these conditions. Overall, the close correspondence of the results with the proposed scheme satisfactorily establishes that the principal reaction of anisole with the methylating species from methyl chloroformate is oxygen alkylation which is followed by intermolecular reaction of dimethylphenyloxonium ion with anisole competitively on carbon and oxygen.

If intramolecular rearrangement of **8** to the ortho product were concomitant with intermolecular reactions, large amounts of *ortho*-**3** and -**4** relative to *ortho*-**2** early in the reaction along with relatively decreasing amounts of *ortho*-**3** and -**4** at later stages would be observed, and, if detectably different secondary isotope effects are operative for intra- and intermolecular reactions, different isotopic compositions of ortho and para products would be found throughout the reaction. Indication that such a rearrangement of **8** is not an important reaction under these conditions is provided by the low yield of *ortho*-**4** at short reaction times, the fact that a similar isotopic composition is observed for *o*-methylanisole throughout the reaction and the fact

(25) H. Margenau and G. M. Murphy, "The Mathematics of Physics and Chemistry," Van Nostrand, New York, N. Y., 1956, p 486.
(26) D. Alpert and D. L. Bitzer, *Science*, 167, 1582 (1970).

that the *o*- and *p*-methylanisoles have a similar isotopic composition. Apparently no special mechanism operates to give the ortho compound and both isomers are products of intermolecular reaction of an n complex. Accordingly, the formation of a predominantly ortho product in electrophilic aromatic substitution on aromatic rings bearing a substituent with a free electron pair is not a necessary consequence of the intermediacy of an n complex. It follows that a low yield of ortho product should not be a sufficient criterion to exclude an n complex as a reaction intermediate. This is not to imply that high yields of ortho products are not formed by essentially intramolecular rearrangement of n complexes[2-7] but rather to suggest that n complexes may be much more widely involved in electrophilic aromatic substitutions than has been suspected. Since our initial report,[8] other suggestions that n complexes of aromatics play a role in electrophilic aromatic substitutions have appeared in the literature.[27,28]

The intermolecular reaction of **8** suggested by the present study, in apparent contrast to an earlier suggestion[6a] of its intramolecular rearrangement, under other conditions could be attributed to the absence of nucleophiles which could promote ortho substitution by double displacements involving oriented species. If that is the case, it is conceivable that ortho substitution could be enhanced by judicious choice of solvent and/or counterions for electrophilic aromatic substitutions which might involve n complexes. Alternatively, if the groups potentially involved in migration from a substituent to the ring are capable of bearing a positive charge, rearrangement could proceed by intimate ion pairs; such an intramolecular mechanism has been suggested by Spanninger and von Rosenberg for the acid catalyzed rearrangement of aryl ethers to alkyl phenols,[29] a reaction which is formally closely related to the current study. These authors also report that the rearrangement has an intermolecular component which is analogous to the mechanism proposed above. Another interesting feature of the involvement of n complexes in electrophilic aromatic substitutions is a possible leveling effect by electron pair bearing substituents of a substrate or solvent on electrophilic reactivity.

The chlorotoluenes-*methyl-d*$_3$ are not included in the reaction scheme, since the greater than 95% incorporation of methyl-d_3 suggests that less than 10% of these isomers results from reaction of chlorobenzene with **8**.[20] A proposal consistent with previous suggestions for related reactions but not required by the present data is that the chlorotoluenes and **8** arise by reaction of chlorobenzene and anisole with the methylcarboxylium ion[10] although phenylmethylchloronium ion[4b,27b] could also be involved. In any case, an apparent dilemma seems to exist: a reactive methylating species appears to alkylate chlorobenzene on carbon and anisole on oxygen while the methylating species **8**, clearly less reactive in that it does not react with chlorobenzene to an appreciable extent, alkylates anisole competitively on both oxygen and carbon. However, studies of reactivities in electrophilic aromatic substitution suggest that ring positional and substrate selectivities[30] should not be coupled in the absence of detailed information about the mechanism of the reaction and the present results suggest such caution should be extended to the formation of n complexes.

Experimental Section[31]

Materials. Anisole was purified by preparative glpc with a 3 ft × 0.25 in. 15% SE-30 column at 140°, followed by three successive distillations, and chlorobenzene was distilled from calcium hydride and redistilled. Silver hexafluoroantimonate was available commercially from Ozark-Mahoning and was dried at 0.01 Torr over P_2O_5 for 5 days. All reagents used were stored under either nitrogen or argon. Methyl-d_3 chloroformate was prepared from methanol-d_4 (99% D) (Stohler Isotope Chemicals) and phosgene and purified by distillation at atmospheric pressure: ir 2300–2080 (C–D), 1775 (C=O), 1200, and 1090 cm^{-1}; dmr δ −3.34 (s) relative to $CDCl_3$; mass spectrum (11.5 eV) *m/e* (rel intensity) 62 (100), no peak detected at *m/e* 59. An isotope ratio run showed only d_3 material and it is estimated that less than 1% unlabeled chloroformate is present. Methyl-d_3 (Stohler Isotope Chemicals) and lithium aluminum deuteride (Merck), with respective isotope purities of 99.5 and 99%, were used as received to prepare samples of **3**, **4**, and **5**. *o*- and *p*-methylanisoles-*O-methyl-d*$_3$ were prepared by the addition of methyl-d_3 iodide to the sodium salt of the corresponding methyl methylbenzoates with lithium aluminum deuteride–$AlCl_3$ and hydrolysis with D_2O to give the desired product. Doubly labeled *o*- and *p*-methyl-d_3-anisole-*O-methyl-d*$_3$ were prepared by addition of methyl-d_3 iodide to the sodium salt of the desired methyl hydroxybenzoate and subsequent reduction of the methyl methoxy-d_3-benzoate with lithium aluminum deuteride–$AlCl_3$ and hydrolysis with D_2O.[16] Samples of three compounds, *para*- **5**, *ortho*-**3**, and *ortho*-**4**, were collected by preparative glpc and upper limits of impurities were estimated at 7% d_2, 0.7% d_2, and 5% d_3 by the defocused metastable analysis performed on a Varian MAT 730 double focusing mass spectrometer and no absorptions were observed for methyl protons from isotopic impurities in the nmr spectra of these materials. The authentic mixtures of the isotopically substituted methylanisole isomers were prepared by dilution of the individual compounds to known volumes with chlorobenzene and determination of the amount of compound by internal standard addition and glpc.

Reaction of Methyl-d_3 Chloroformate and Silver Hexafluoroantimonate with Anisole. To a solution of 340 mg (0.990 mmol) of $AgSbF_6$ were added 540 mg (5.00 mmol) of anisole and 45.03 mg of 1,3,5-trichlorobenzene in 13 ml of chlorobenzene. The mixture was allowed to equilibrate at 30.00 ± 0.05° and was stirred under nitrogen blanket and then methyl-d_3 chloroformate, 491 mg (5.04 mmol), was added. Samples were quenched with pentane and 10% aqueous NaOH. The pentane solutions were used for analysis of the isotopic incorporation of the methylanisoles (**2**–**5**) by gas chromatography–mass spectral measurements on a Perkin-Elmer MS 270 using a 6 m × 1/8 in. 2% Bentone 34, 4% diethylene glycol succinate, and 5% Dow 710 column at 130°. The analysis for anisole and chlorotoluenes was performed using a 5 m × 1/8 in. 1% Bentone 34, 4% diethylene glycol succinate, and 5% Dow 710 column at 85° and the ratio of anisole to chlorotoluenes was also determined by glpc on the same column with initial temperature at 85° and linear temperature programming at 2°/min to 145°. The analysis of anisole and chlorotoluenes together and the individual isomers of the methylanisoles was performed on a 5 m × 1/8 in. 2% Bentone 34 and 8% diisodecyl phthalate column at 135°. Checks

(27) (a) E. Baciocchi, F. Cacace, F. Ciranni, and G. Illuminati, *J. Amer. Chem. Soc.*, **94**, 7030 (1972); (b) G. A. Olah and E. G. Melby, *ibid.*, **94**, 6221 (1972).

(28) Dimethylphenyloxonium ion has been observed by Professor G. A. Olah and found to rearrange intermolecularly to methylanisoles; private communication from Professor Olah, May, 1973.

(29) P. A. Spanninger and J. L. von Rosenberg, *J. Amer. Chem. Soc.*, **94**, 1970, 1973 (1972), and references cited therein.

(30) P. Rys, P. Skrabal, and H. Zollinger, *Angew. Chem., Int. Ed. Engl.*, **11**, 874 (1972); G. A. Olah, *Accounts Chem. Res.*, **4**, 240 (1971), and references cited therein.

(31) The nmr data were recorded on Varian Associates A60A, A56/60A HA-100, or HR-220 nmr spectrometers using CCl_4 as solvent with TMS as internal standard. Preparative glpc was performed on a Varian Aerograph A90-P3 gas chromatograph, and analytical data were recorded with a Varian Aerograph 1860 flame ionization glpc. The gas chromatograph–mass spectral data were obtained on a Perkin-Elmer MS 270 and Varian MAT CH-7 mass spectrometers, the former being used for the analysis of the methylanisoles and the latter for the analysis of anisole and chlorotoluenes. All glpc yields were determined by addition of 1,3,5-trichlorobenzene to the reaction mixture as an internal standard.

on the analysis of the amount of **6** were performed by collection of the anisole from preparative glpc at 115° using a 5 ft × 0.25 in. 20% SE-30 column. Methylanisoles were collected by preparative glpc at 160° using a 2.2 m × 3/8 in. 16% SE-30 column. Analysis for phenol was performed by pentane extraction of the acidified quench of the last reaction sample (360 min) with 1,3,5-trichlorobenzene added as an internal standard for glpc analysis with a 3.25 m × 1/8 in. 10% Dow 710 column at 105°. Control experiments were carried out under the same conditions and with the same analysis as that specified above except for methyl chloride and methyl chloroformate. The yield of methyl chloride was determined relative to cyclohexane as an internal standard by integration of peak areas in a reaction carried out in a sealed nmr tube with the yield of methylanisoles subsequently determined by glpc. The amount of methyl chloride relative to methyl-d_3 chloride was determined from mass spectral analysis of a reaction of methyl-d_3 chloroformate. An nmr experiment similar to the above but with methyl-d_3 chloroformate was monitored for methyl chloroformate in the presence of cyclohexane as an internal standard and showed that no more than 1% methyl chloroformate was produced under the reaction conditions.

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Electrochemical Studies of the Formation and Decomposition of the Fluorobenzonitrile Radical Anions

Kent J. Houser, Duane E. Bartak, and M. Dale Hawley*

Contribution from the Department of Chemistry, Kansas State University, Manhattan, Kansas 66502. *Received January 23, 1973*

Abstract: The electrochemically generated radical anions of the three isomeric fluorobenzonitriles have been shown to be unstable in *N,N*-dimethylformamide and to decompose by at least four different reaction pathways. Benzonitrile, the final reduction product of 2-fluorobenzonitrile, is suggested to arise by a pathway involving the dimerization ($k_d = 1.35 \times 10^3\ M^{-1}\ sec^{-1}$) of 2-fluorobenzonitrile radical anions and the subsequent, slow disproportionation ($k = 1.0 \times 10^{-2}\ sec^{-1}$) of a dimeric dianion intermediate. Benzonitrile and 4,4′-dicyanobiphenyl are the products observed for the reduction of 4-fluorobenzonitrile. Benzonitrile is shown to arise by a pathway involving the loss of fluoride ion ($k = 11\ sec^{-1}$) from the 4-fluorobenzonitrile radical anion and the subsequent rapid abstraction of a hydrogen atom by the 4-cyanophenyl radical. The formation of 4,4′-dicyanobiphenyl is proposed to occur by the dimerization ($k_d \sim 10^3\ M^{-1}\ sec^{-1}$) of 4-fluorobenzonitrile radical anions, followed by the rapid loss of two fluoride ions from the dimeric dianion which is formed as an intermediate. 3-Fluorobenzonitrile radical anion is the only one of the three radical anions which decomposes by loss of cyanide ion. The 3-fluorophenyl radical which results then abstracts a hydrogen atom from a component of the solvent system to form fluorobenzene, the observed reduction product.

The first extensive electrochemical and electron spin resonance studies of substituted benzonitrile radical anions were reported by Rieger, *et al.*[1] These workers found that reduction of the cyano and nitro derivatives of benzonitrile gave stable radical anions, but that the radical anions of 4-amino- and 4-fluorobenzonitrile decomposed rapidly. Since the esr spectrum of the radical anion of 4,4′-dicyanobiphenyl was observed upon reduction of these two benzonitriles, it was suggested that 4-amino- and 4-fluorobenzonitrile radical anions decomposed with loss of amide and fluoride ions, respectively, to give the 4-cyanophenyl radical. Dimerization of 4-cyanophenyl radicals and the subsequent reduction of 4,4′-dicyanobiphenyl to its radical anion were postulated to be the remaining steps in the decomposition pathway.

The loss of an anionic group has since been reported to occur in many other substituted benzonitrile[2-4] and nitroaromatic radical anions.[5-10] However, in contrast to the results reported for the 4-fluoro- and 4-aminobenzonitrile radical anions, the formation of a biphenyl has not been observed in the decompositions of the radical anions of the iodonitrobenzenes and the other halogenated benzonitriles.[4-7] Since the intermediacy of phenyl radicals has been demonstrated unequivocally in the decomposition of these radical anion systems,[4,11] it seems unlikely that the formation of 4,4′-dicyanobiphenyl could be the result of 4-cyanophenyl radical dimerization. Accordingly, we have undertaken more detailed electrochemical studies of the decomposition pathways of the three isomeric fluorobenzonitrile radical anions.

Results and Discussion

2-Fluorobenzonitrile. Cyclic Voltammetry. The only

(1) P. H. Rieger, I. Bernal, W. H. Reinmuth, and G. K. Fraenkel, *J. Amer. Chem. Soc.*, **85**, 683 (1963).
(2) A. R. Buick, T. J. Kemp, G. T. Neal, and T. J. Stone, *J. Chem. Soc. A*, 666 (1969).
(3) K. W. Bowers in "Radical Ions," E. T. Kaiser and L. Keevan, Ed., Interscience, New York, N. Y., 1968, p 242.
(4) D. E. Bartak, K. J. Houser, B. C. Rudy, and M. D. Hawley, *J. Amer. Chem. Soc.*, **94**, 7526 (1972).
(5) T. Kitagawa, T. P. Layloff, and R. N. Adams, *Anal. Chem.*, **35**, 1086 (1963).
(6) T. Fujinaga, Y. Deguchi, and K. Umemoto, *Bull. Chem. Soc. Jap.*, **37**, 822 (1964).
(7) J. G. Lawless and M. D. Hawley, *J. Electroanal. Chem. Interfacial Electrochem.*, **21**, 365 (1969).
(8) J. G. Lawless, D. E. Bartak, and M. D. Hawley, *J. Amer. Chem. Soc.*, **91**, 7121 (1969).
(9) A. R. Metcalfe and W. A. Waters, *J. Chem. Soc. B*, 918 (1969).
(10) P. Peterson, A. K. Carpenter, and R. F. Nelson, *J. Electroanal. Chem. Interfacial Electrochem.*, **27**, 1 (1970).
(11) D. E. Bartak and M. D. Hawley, *J. Org. Chem.*, **35**, 1206 (1970).