perature of $-60°$, $\phi = 50°$ for the *p*-diethoxybenzene cation radical. As the temperature decreases, ϕ would be expected to decrease, leading to the observed increase in the β-proton splitting constant.

For the larger *p*-di-*n*-alkoxybenzene cation radicals, a similar temperature dependence would be expected, and is observed (see Table V). The torsional amplitude, ϕ, would be expected to decrease with increased size of the substituent, leading to an increased β-proton splitting constant, and this is observed for the *n*-propoxy compound (*cf.* Tables III and IV). Further lengthening of the side chain does not give rise to any significant changes, presumably because the effective size of the substituent is not altered on passing from *n*-propyl to *n*-octyl (*cf.* also ref 19).

Molecular models of the *p*-diisopropoxybenzene cation radical (see Figure 6; $R_1 = R_2 = CH_3$) indicate an equilibrium conformation in which $\theta \approx 90°$ for the lone CH proton, suggesting $a_{\beta\text{-H}} = 0$ in the absence of torsional oscillation. Increased torsional oscillation with temperature would be expected to lead to an increase in the value of $a_{\beta\text{-H}}$. Although the spectrum is not well resolved, because of line broadening, such an increase is indeed observed (see section on *p*-diisopropoxybenzene). The experimentally obtained value of $a_{\beta\text{-H}} = ca.\ 2.60$ is consistent with a torsional amplitude of about 57°.

The experimentally observed line-width increase of the *p*-diisopropoxybenzene cation compared with that of the other *p*-dialkoxybenzenes (*ca.* 250 mgauss to 70 mgauss) could be explained if the period of torsional oscillation, τ, in the isopropoxy compound was of the same order as the hyperfine splitting ($\sim 10^{-7}$ sec), thus leading to line broadening. Alternatively, it may be caused by small unresolved splittings of the β-CH_3 groups.

In the above discussion, changes because of the inductive effect of substituents have been ignored. The justification for this is based on the near-constancy of (i) the *g* values (see Table VI) and (ii) the ring proton splitting constants.

Acknowledgments. The authors are indebted to the National Research Council of Canada for a studentship (to P. D. S.) and continued financial assistance.

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(19) A. Carrington and P. F. Todd, *Mol. Phys.*, 7, 533 (1964).

Mass Spectrometry in Structural and Stereochemical Problems. CXXX.[1] A Study of Electron Impact Induced Migratory Aptitudes[2]

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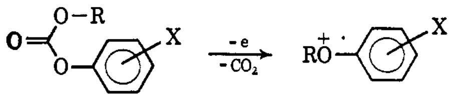
Contribution from the Department of Chemistry, Stanford University, Stanford, California 94305. *Received January 6, 1967*

Abstract: The electron impact induced decarboxylation of aryl methyl and aryl phenyl carbonates has been investigated in some detail, using low-voltage and isotope-labeling techniques, and by studying substituent effects on the rate of loss of carbon dioxide. In the substituted-aryl methyl compounds, exclusive methyl group migration is observed, whereas in the aryl phenyl carbonates, competition between the two possible itinerant moieties is apparent, and aryl group relative migratory aptitudes can be assigned. In addition, the substituent dependence of the abundance of the CH_3OCO^+ ion from α cleavage in aryl methyl carbonates has been correlated with Hammett σ values.

Of the unimolecular processes energetically accessible to ions generated by electron impact, that of skeletal rearrangement[4] (in compounds other than hydrocarbons) has only recently been accorded recognition as a relatively common possibility. Despite the elegant application[5-7] of accepted physical organic techniques to simple mass spectral bond cleavages, no similar studies on systems undergoing alkyl or aryl group migrations have as yet been reported. We therefore elected to examine in some detail the necessary requirements for methyl migration in aryl methyl carbonates[8] (I → III) and aryl *vs.* phenyl migration in aryl phenyl carbonates[8] (II → IV), each with concomitant ejection of carbon dioxide as the neutral species.



I, $R = CH_3$
II, $R = C_6H_5$

III, $R = CH_3$
IV, $R = C_6H_5$

M - 44

The rearrangement reactions proved to be relatively facile, giving rise to intense peaks in the 70-ev spectra.[8] Reduction of the ionizing voltage to approxi-

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(1) Paper CXXIX: A. M. Duffield, W. Carpenter, and C. Djerassi, *Chem. Commun.*, 109 (1967).

(2) Financial support from the National Institutes of Health (Grant No. AM-04257) is gratefully acknowledged. The purchase of the Atlas CH-4 mass spectrometer was made possible through NASA Grant No. NsG 81-60.

(3) Postdoctoral Fellow, 1964–1966.

(4) P. Brown and C. Djerassi, *Angew. Chem. Intern. Ed. Engl.*, in press.

(5) (a) M. M. Bursey and F. W. McLafferty, *J. Am. Chem. Soc.*, **88**, 529 (1966); (b) *ibid.*, **88**, 4484 (1966).

(6) (a) F. W. McLafferty, M. M. Bursey, and S. M. Kimball, *ibid.*, **88**, 5022 (1966); (b) M. M. Bursey and F. W. McLafferty, *ibid.*, **88**, 5023 (1966); (c) *ibid.*, **89**, 1 (1967).

(7) J. L. Mateos and C. Perez, *Bol. Inst. Quim. Univ. Nal. Autón. Méx.*, 17, 202 (1965).

(8) P. Brown and C. Djerassi, *J. Am. Chem. Soc.*, **88**, 2469 (1966).

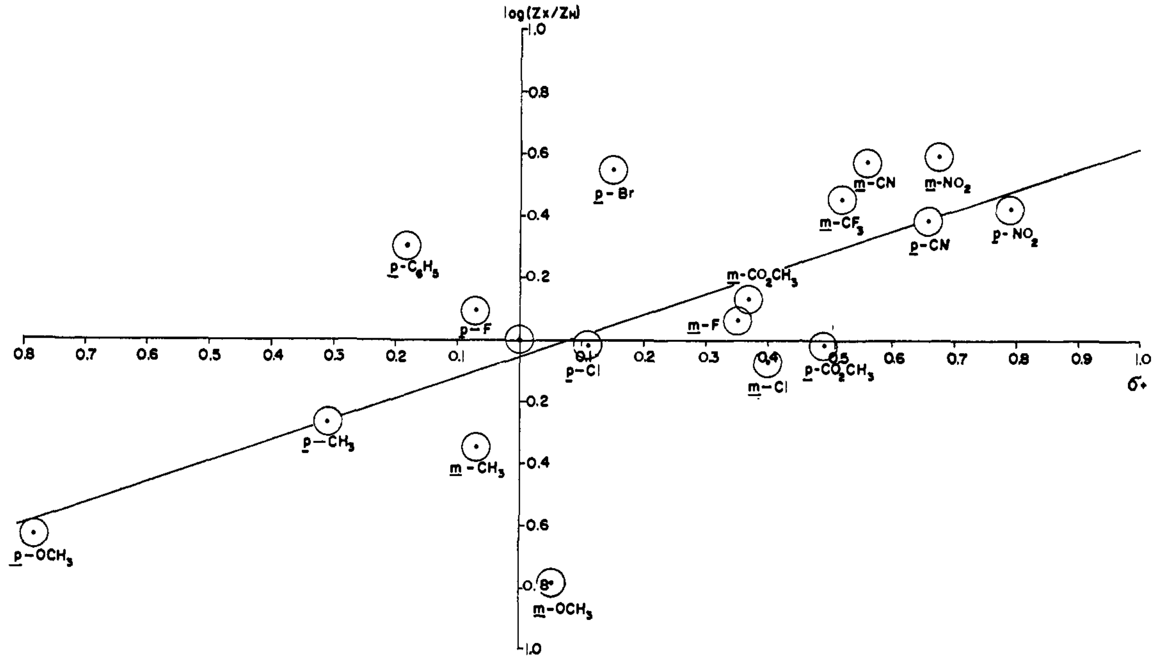


Figure 1. Correlation of the M − 44 ion III intensity in the 12-ev mass spectra of substituted aryl methyl carbonates I with σ^+. Least-squares slope (ρ) = +0.67, standard deviation = 0.18.

mately 12 ev[9] greatly simplified the spectra, the peaks due to the molecular ion and the M − 44 species together accounting for at least 95% of the total ionization (Σ_{40}) with compounds I, and at least 60% Σ_{40} with compounds II.[10] Thus by variation of the nuclear substituents X in I and II, it was hoped to secure data pertaining to both the electronic nature of the migrating group and of the receptor site in these particular systems.

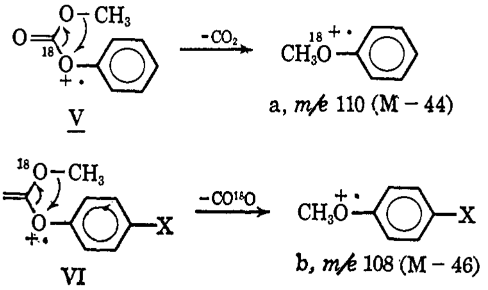
Aryl Methyl Carbonates. The results obtained in the electron impact induced[11] decarboxylation of substituted aryl methyl carbonates (I → III) are presented as a Hammett[5a,12] plot in Figure 1, using relationship 1 as modified by McLafferty[5a] to permit kinetic evaluation of mass spectra. Thus $Z = [A]/[M]$, where [A] and [M] are the relative abundances of the peaks due to the M − 44 fragment (III) and the molecular ion respectively, and the subscripts X and H refer to substituted and parent compounds, respectively. In these

$$\log (Z_X/Z_H) = \rho\sigma \qquad (1)$$

systems, the M − 44 species (III) have compositions dependent on the substituent X, and at normal ionizing voltages (*i.e.*, 70 ev), further decompositions of III will also depend on the nature of X. At lower voltages, however (*i.e.*, 12 ev), all peaks in the spectra of compounds of type I except for the M − 44/molecular ion pair[13] are absent, indicating that competing and consecutive reactions have been totally eliminated. The relative peak heights at 12 ev were therefore employed exclusively in all calculations of relative kinetics of the rearrangement processes.

Although the correlation (Figure 1) displays considerable scatter, sufficient substituents were employed to show that a very definite trend exists. Thus in general, electron-attracting groups increase the rate of the reaction I → III, and electron-releasing substituents depress it. Use of σ constants[15a] did not obviously improve the quality of the fit over that obtained with σ^+ values,[15b] and the latter appear in Figure 1.[15c] The least-squares value of the slope (ρ = +0.67) was obtained by computer.

In order to elucidate further[8] the mechanism of electron impact induced decarboxylation of compounds of type I, the ^{18}O-labeled carbonates V and VI (X = H) were prepared. In the mass spectrum of V, the rearrangement peak moved cleanly to *m/e* 110 (a, M − 44),



whereas with VI (X = H) it remained[8] entirely at *m/e* 108 (b, M − 46). These observations are consistent

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[9] *Cf.* O. L. Chapman, T. H. Kinstle, and M. T. Sung, *J. Am. Chem. Soc.*, **88**, 2618 (1966).

[10] P. Natalis and J. L. Franklin, *J. Phys. Chem.*, **69**, 2943 (1965), report 10.78 ± 0.05 ev for the appearance potential of the M − 44 ion derived from diphenyl carbonate (II, X = H).

[11] Supported by the appropriate metastable peaks.

[12] L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940, Chapter 7.

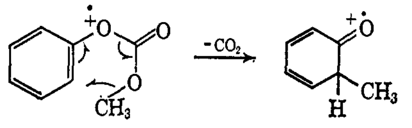
[13] With the *m*- and *p*-nitrophenyl methyl carbonates (I, X = NO_2), small peaks corresponding to M − 16 and M − 30 processes[14] are still apparent even at 12 ev.

[14] J. H. Beynon, R. A. Saunders, and A. E. Williams, *Ind. Chim. Belge*, **29**, 311 (1964).

[15] (a) J. Hine, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, Chapter 4. (b) H. C. Brown and Y. Okamoto, *J. Am. Chem. Soc.*, **80**, 4979 (1958). (c) A referee has pointed out that the rate terms for *meta* and *para* electron-donating substituents are nearly the same. A similar observation had been made earlier[6a] with substituted phenetoles, and the suggestion had been made that equilibration of substituents occurred in the molecular ion. If such a rearrangement is also operating in our compounds with electron-donating substituents, then the Hammett correlations in Figures 1, 3, and 4 would be considerably improved.

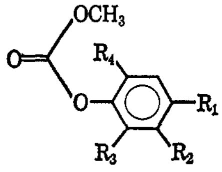
with preferential charge location[16] in the molecular ion on the phenoxy group, followed by exclusive methyl migration to the electron-deficient site. The data also rule out isomerizations of the molecular ion analogous to those encountered[17] in methyl phenyl thioncarbonates. The mass spectra of the ^{18}O-labeled compounds VI (X = OCH_3) and VI (X = CN) were also run, and total loss of the heavy isotope as carbon dioxide-^{18}O indicates that only methyl migration is occurring, regardless of the electronic nature of the substituent X.

Some preference for the phenoxy oxygen atom (*e.g.*, V → a) over the *ortho* position of the aromatic ring (VII → c) as the receptor site for methyl migration has already been expressed.[8] Additional evidence against operation of a six-center transfer (VII → c) is contained in the per cent total ionization figures for the M − 44 rearrangement peak in the spectra of the isomeric 3,4-, 2,3-, and 2,6-dimethylphenyl methyl carbonates (VIII, IX, and X, respectively, Table I). It is clear that there is no abnormal steric effect intervening in the case of isomer X.[18]



VII c

Table I. Σ_{40} Values for M − 44 Species from Dimethylphenyl Methyl Carbonates

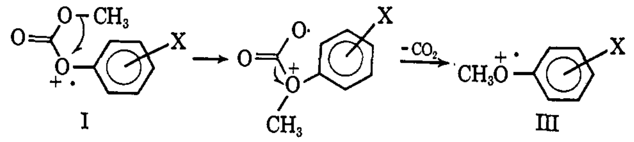


		% Σ_{40}
VIII	$R_1 = R_2 = CH_3; R_3 = R_4 = H$	6.1
IX	$R_1 = R_4 = H; R_2 = R_3 = CH_3$	4.4
X	$R_1 = R_2 = H; R_3 = R_4 = CH_3$	4.6

Evidence of a more compelling nature for representing the M − 44 species from decarboxylation of aryl methyl carbonates I as the aryl methyl ether molecular ion was adduced by comparison of the metastable peaks observed in the mass spectra of the parent carbonate (I, X = H) and anisole (III, X = H). Not only are the spectra of these two compounds extremely similar[8] below *m/e* 108 (M − 44 for I, X = H) (except for the presence of an additional peak at *m/e* 59 in I, X = H, due to the CH_3OCO^+ species), but the positions, relative intensities, and peak shapes[19] of all six metastable peaks[20] in the anisole spectrum (Figure 2b) are faithfully reproduced in that of methyl phenyl carbonate (Figure 2a). This correspondence is demonstrated in a particularly striking fashion in Figures 2a and 2b, which show the direct record obtained by means of a logarithmic transfer recorder,[21] operating in conjunction with an Atlas CH-4 mass spectrometer.

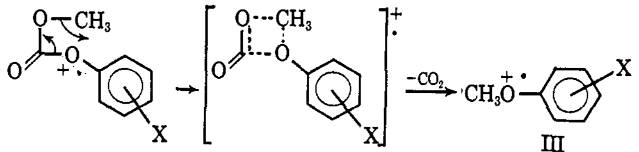
Two of the more plausible mechanisms consistent with the labeling results that may be entertained for the M − 44 rearrangement process are depicted in Schemes I and II.

Scheme I



I da III

Scheme II



I db III

In Scheme I, methyl radical migration to electron-deficient phenoxy oxygen (I → da) is envisaged initially, followed by homolysis of the O–CO bond and loss of carbon dioxide (da → III). If the process is concerted, *i.e.*, methyl migration and carbon dioxide ejection occurring simultaneously, then the situation is described by Scheme II. There appear to be no authenticated precedents for 1,3-methyl radical migrations outside of mass spectrometry.[22] Even 1,2-methyl radical shifts are rare,[23,24] although 1,2 migration as a potential carbanion to an electrophilic center is much more common[25] (*e.g.*, Wagner–Meerwein, Baeyer–Villiger, pinacol rearrangements).

Scheme II envisages a four-center transition state db, and accounts satisfactorily for the observed positive slope of the Hammett plot (Figure 1) by invoking a shift of the methyl group with its bonding pair of elec-

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(16) It is assumed that electron impact can displace an electron from anywhere in the neutral molecule, and that the resulting radical ion decays extremely rapidly to a state in which the net charge is stabilized and distributed over the whole system, and that this type of molecular ion then decomposes into the major ions of the mass spectrum. The convenient approximation of "charge localization" involves the writing down of apparently favorable resonance structures of an ion, and then using the formal electron deficiency to rationalize subsequent fragmentations. Thus the single electron deficiency of the molecular ion of methyl phenyl carbonate can be accommodated in more low energy resonance forms of the phenoxy rather than the methoxy portion of the molecule (*e.g.*, V and VI are preferred formalisms). With aryl phenyl carbonates, the charge distribution in the molecular ion is expected to be somewhat more symmetrically disposed on either side of the carbonyl group, and to be sensitive to the electronic nature of aromatic substituents.

(17) J. B. Thomson, P. Brown, and C. Djerassi, *J. Am. Chem. Soc.*, **88**, 4049 (1966).

(18) C. P. Lewis, *Anal. Chem.*, **36**, 176 (1964), reports that 2,6-dimethyl substitution does not deter an analogous skeletal rearrangement involving loss of carbon dioxide in ethyl N-phenylcarbamate.

(19) T. W. Shannon and F. W. McLafferty, *J. Am. Chem. Soc.*, **88** 5021 (1966), call attention to the fact that ions identical in structure and energy should exhibit identical decomposition reactions and, therefore, the spectra should also show the same metastable peaks, with identical peak shapes and intensities relative to the parent ion.

(20) These appear at *m/e* 80.0 ($93^2/108$), *m/e* 57.9 ($79^2/108$), *m/e* 56.4 ($78^2/108$), *m/e* 45.4 ($65^2/93$), *m/e* 33.8 ($51^2/77$), and *m/e* 23.4 ($39^2/65$). The only additional metastable peak discernible in the carbonate spectrum (Figure 2a) occurs at *m/e* 76.8 ($108^2/152$), and corresponds to the loss of carbon dioxide from the molecular ion.

(21) R. T. Aplin, H. Budzikiewicz, H. S. Horn, and J. Lederberg, *Anal. Chem.*, **37**, 776 (1965).

(22) A formal 1,3-methyl shift has been detected in the pyrolysis of diazoisofenchone by P. Yates and S. Danishefsky, *J. Am. Chem. Soc.*, **84**, 879 (1962), although the electronic nature of the migrating species is not known.

(23) C. Walling, "Molecular Rearrangements," P. de Mayo, Ed., Interscience Publishers Inc., New York, N. Y., 1963, p 416.

(24) C. McKnight and F. S. Rowland, *J. Am. Chem. Soc.*, **88**, 3179 (1966), report tritium-labeling evidence for a 1,2-methyl radical migration pathway in the reaction of triplet methylene with *trans*-2-butene.

(25) H. E. Zimmerman and A. Zweig, *J. Am. Chem. Soc.*, **83**, 1196 (1961), have provided a rationale for 1,2 shifts of methyl and phenyl groups based on MO calculations.

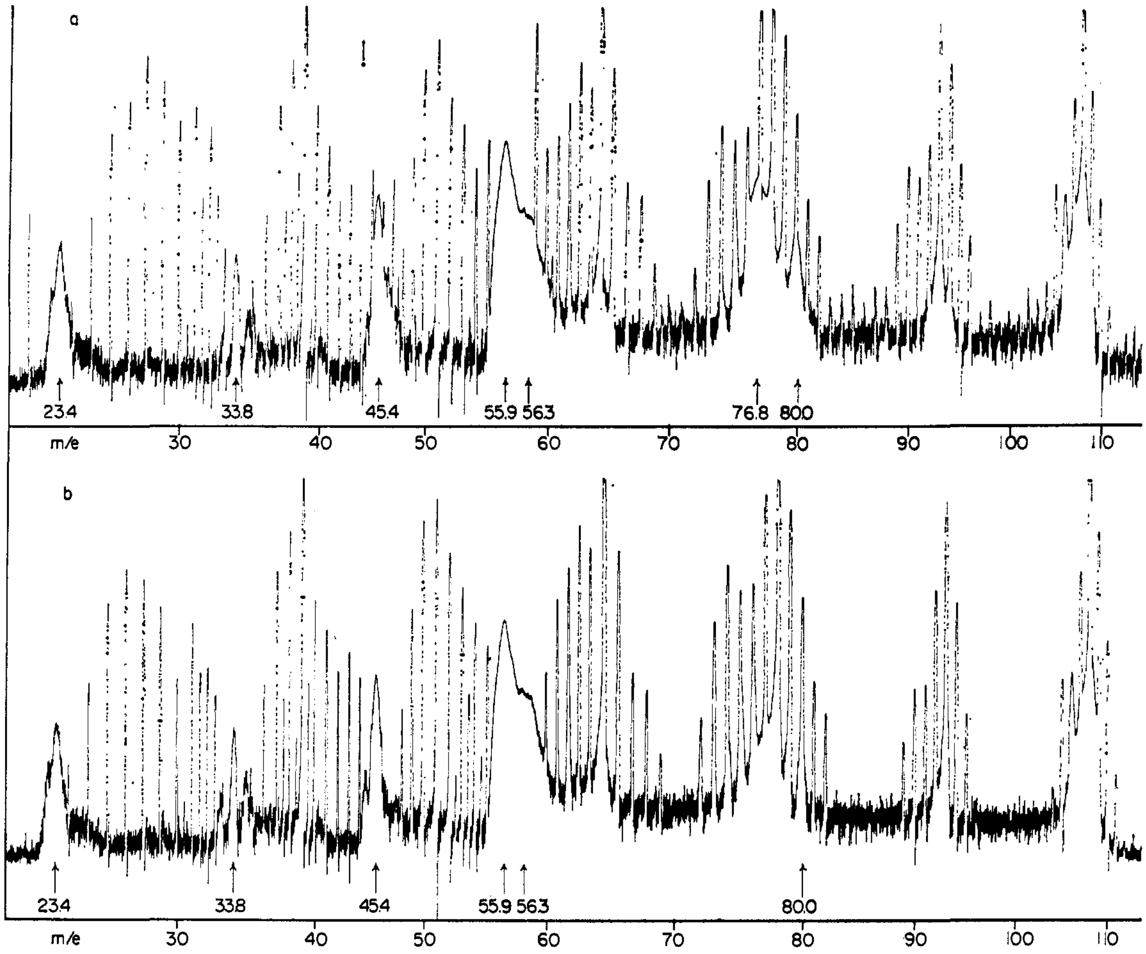
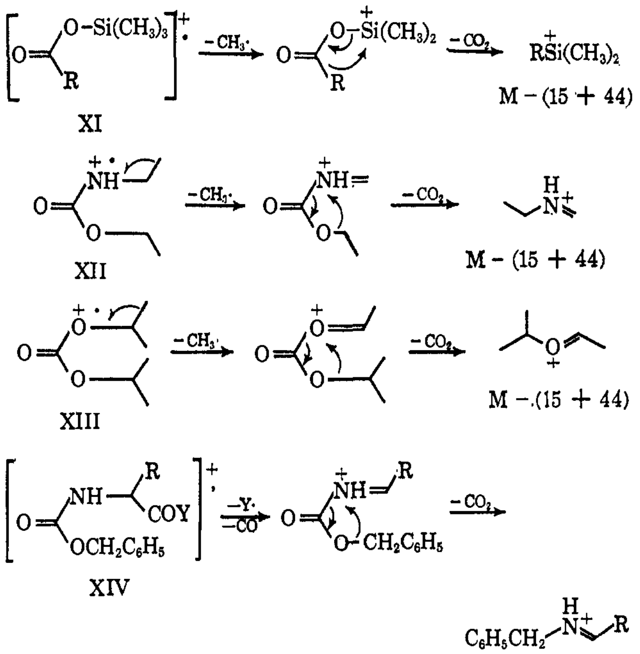


Figure 2. a. Logarithmic transfer recorder trace of the low-resolution mass spectrum of methyl phenyl carbonate. b. Logarithmic transfer recorder trace of the low-resolution mass spectrum of anisole.

trons to the most electrophilic site available. Thus in the transition state, the partial charge on the phenoxy oxygen will become less positive in character, and bond forming to the methyl group will be more advanced than bond breaking of the O–CO bond. Scheme I, on the other hand, would predict a negative ρ value if the rate-determining transition state lies between I and da, since its formation would be inhibited by electron-withdrawing substituents and facilitated by electron-releasing groups.

Other instances of electron impact induced group migrations accompanied by carbon dioxide expulsion have been documented.[4] These reactions are most prevalent in gaseous ions where an especially electron-deficient center is developed adjacent to the carbonyl moiety, and can then be visualized as involving a nucleophilic 1,3-group shift to that positive site.

For example, alkyl group migration apparently occurs only after initial cleavage has generated a full positive charge in the vicinity of the migration receptor site in trimethylsilyl esters of some fatty acids[26] (XI), in ethyl N-ethylcarbamate[17] (XII), in dialkyl carbonates such as XIII,[8] and with benzyloxycarbonyl derivatives of certain amino acid esters[27] (XIV).



Other processes that can be rationalized similarly are the successive loss of a methyl group and hydrogen cyanide from amidines,[28] and of a methyl group and formaldehyde from formaldehyde acetals of secondary and tertiary alcohols[29] and also from the trimethylsilyl derivative of benzyl alcohol.[30]

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[26] R. M. Teeter, Abstracts of the Tenth Annual Conference on Mass Spectrometry, A.S.T.M. Committee E-14, New Orleans, La., 1962, p 51.

[27] R. T. Aplin, J. H. Jones, and B. Liberek, *Chem. Commun.*, 794 (1966).

[28] A. K. Bose, I. Kugachevsky, P. T. Funke, and K. G. Das, *Tetrahedron Letters*, 3065 (1965).

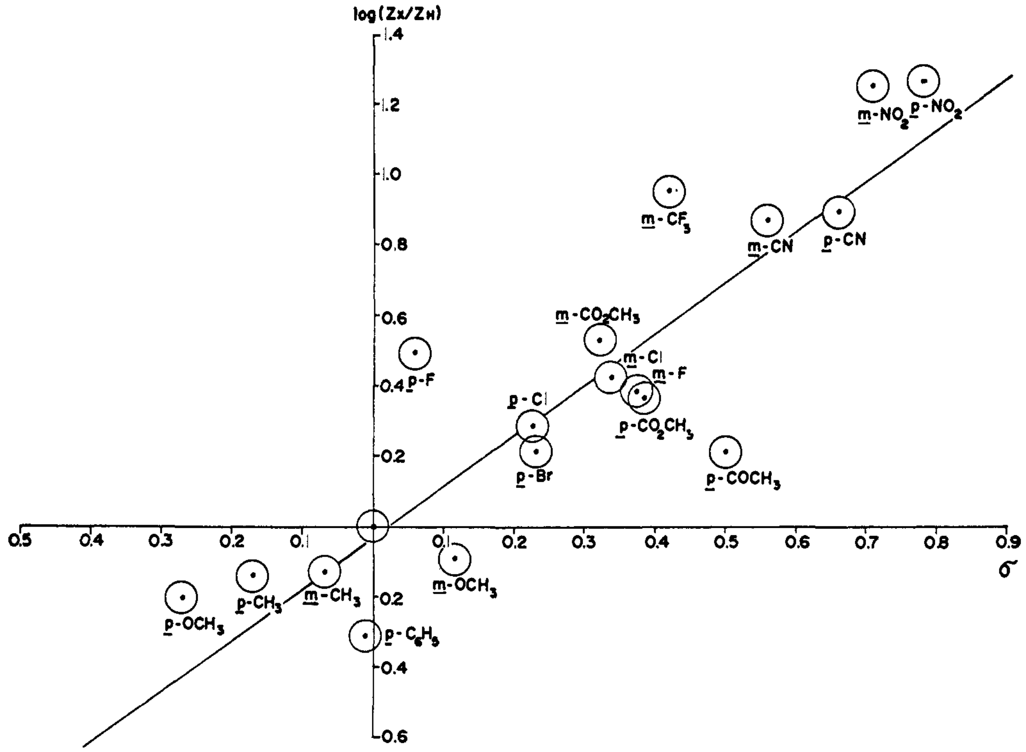
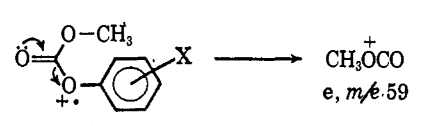


Figure 3. Correlation of the *m/e* 59 ion (e) intensity in the 70-ev mass spectra of substituted aryl methyl carbonates I with σ. Least-squares slope (ρ) = +1.43, standard deviation = 0.18.

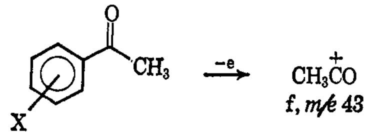
It should be pointed out, however, that group migrations with concomitant expulsion of carbon dioxide can also operate in radical ions where initial α cleavage is prohibited, for example, in esters of α,β-unsaturated acids,[31] aryl methyl and aryl phenyl carbonates,[8] and ethyl N-arylcarbamates.[32]

A characteristic peak appears at *m/e* 59 in the 70-ev mass spectra of all aryl methyl carbonates I, consistently due to an ion of composition $C_2H_3O_2^+$ (e). At 12 ev, this process is completely suppressed. The contribution of fragment e to the higher voltage total ionization is strongly dependent on the aryl substituent X, ranging from 1.8% Σ_{40} (I, X = *p*-OCH_3) to 18.0% Σ_{40} (I, X = *p*-NO_2). The relevant data (in which the abundance of e is compared with that of the molecular ion I) are reproduced as a Hammett[5a,12] plot in Figure 3.



I

In this case, σ constants[16a] gave a correlation with less point scatter than that obtained using σ^+ values.[16b] It is interesting to compare the slope of ρ = +1.43 for the reaction I → e with that of ρ = +0.78 for the formation of α cleavage ion f in substituted acetophenones,[5a] and ρ = +0.67 for the production of e (*m/e* 59) from substituted methyl benzoates.[7] This implies that bond breaking has proceeded to a greater extent in the transition state for cleavage in the carbonates (I → e) compared with the acetophenones (XV → f) and the methyl benzoates.



XV

It is pertinent at this point to comment briefly on the application of Hammett σρ studies to electron impact induced rearrangements and fragmentations. In ground electronic state (thermal) reactions, those processes which develop relatively large fractional charges in the transition state (compared to the reactants) at the reaction site exhibit the largest numerical reaction constants[33] (ρ), whereas processes in which charge is merely redistributed in the transition state are characterized by small ρ values.[34]

In conventional mass spectrometry, one is dealing with gaseous unimolecular endothermic reactions, where the transition state may be expected to resemble the products rather than the reactant,[35] and where both reactant and transition state bear a full positive charge. This description allows the possibility of relatively large reaction constants. On the other hand, it has been pointed out[36] that the transition state for a gas-

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[29] P. Brown, C. Djerassi, G. Schroll, H. J. Jakobsen, and S.-O. Lawesson, *J. Am. Chem. Soc.*, **87**, 4559 (1965).

[30] J. B. Thomson, J. Diekman, and C. Djerassi, to be published.

[31] J. H. Bowie, D. H. Williams, P. Madsen, G. Schroll, and S.-O. Lawesson, *Tetrahedron*, **23**, 305 (1967).

[32] C. P. Lewis, *Anal. Chem.*, **36**, 1582 (1964).

[33] For example, quoted in ref 15b, ρ = −4.67 for SN1 solvolysis of *t*-cumyl chlorides in ethanol at 25°, and −4.74 for ionization of substituted benzylidene alcohols. K. Wiberg and T. M. Shryne, *J. Am. Chem. Soc.*, **77**, 2774 (1955), report ρ = −3.86 and −3.56 for the thermal rearrangement of α-arylethyl chlorocarbonates in dioxane and toluene, respectively.

[34] For example, ρ = = +0.81 for the SN2 reaction of iodide ion with substituted benzyl chlorides in acetone: G. M. Bennett and B. Jones, *J. Chem. Soc.*, 1815 (1935); and ρ = +0.023 for homolytic C–Br bond dissociation in substituted benzyl bromides in toluene: M. Swarc, C. H. Leigh, and A. H. Sehon, *J. Chem. Phys.*, **19**, 657 (1951).

[35] G. S. Hammond, *J. Am. Chem. Soc.*, **77**, 334 (1955).

[36] H. M. R. Hoffmann and A. Maccoll, *ibid.*, **87**, 3774 (1965).

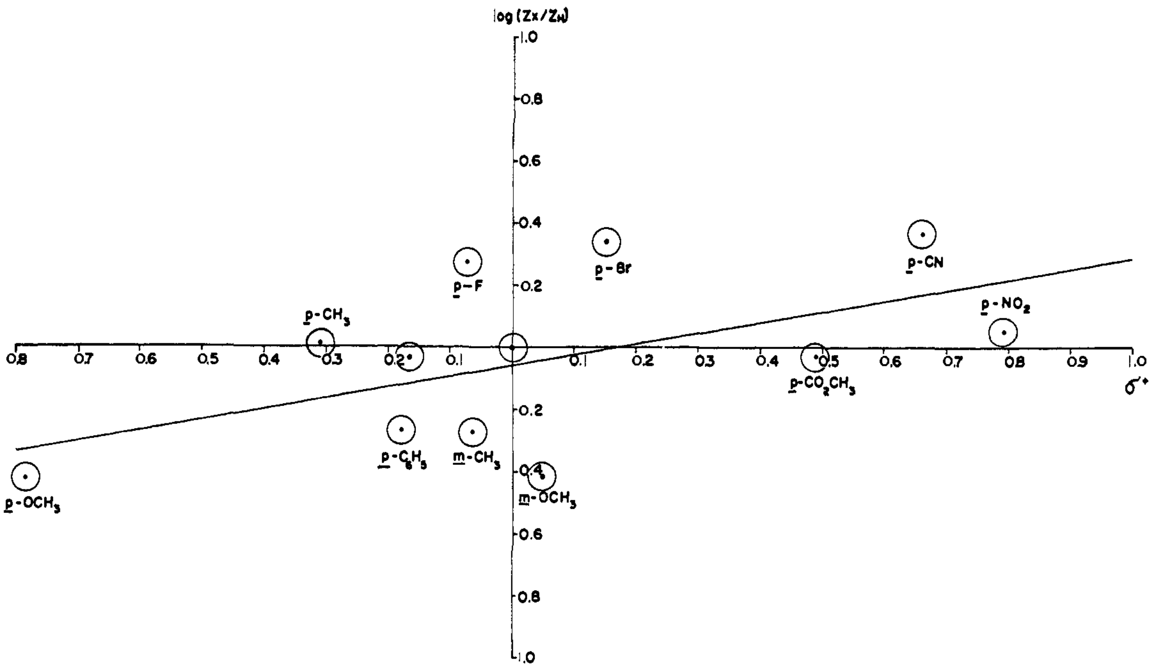


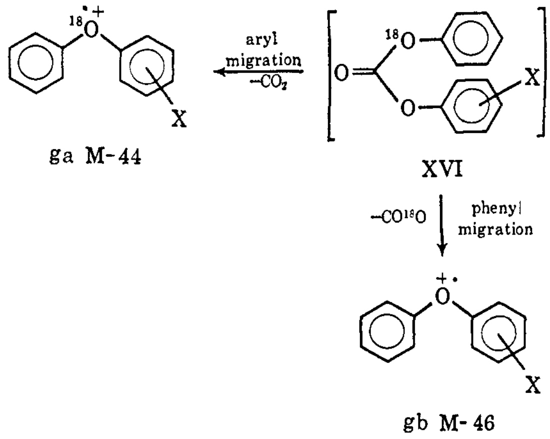
Figure 4. Correlation of the M − 44 ion IV intensity in the 12-ev mass spectra of substituted aryl phenyl carbonates II with σ^+. Least-squares slope (ρ) = +0.34, standard deviation = 0.18.

phase heterolysis will be considerably less ionic than the equivalent process in solution, due to the absence of external solvation. Applying this argument to gaseous ions under low pressure leads to the prediction of relatively small reaction constants. Insufficient data are available at present, but $\rho = +1.43$ for the reaction I → e represents the largest numerical reaction constant obtained so far.

Aryl Phenyl Carbonates. The high- and low-voltage mass spectra of diphenyl carbonate[8,10] (II, X = H) and of its substituted analogs all display important peaks due to the expulsion of carbon dioxide (II → IV).[11] As with the aryl methyl compounds (I), the M − 44 process persists at low voltage, at the expense of all other competing reactions. To avoid approaching the threshold of the appearance potential[10] of the M − 44 species IV too closely, spectra for kinetic treatment were again recorded at 12 ev.

Group migration to oxygen as the receptor site is also envisaged in the aryl phenyl series, by analogy with methyl migration in the aryl methyl carbonates I. In support of this contention may be cited the fact that the mass spectrum of diphenyl carbonate (II, X = H) contains all the peaks characteristic of diphenyl ether (IV, X = H) itself, and especially all the metastable peaks[37] displayed by diphenyl ether, with identical peak shapes and abundances,[19] relative to the molecular ion. It should be noted, however, that although there is some positive evidence for representing the M − 44 radical ion from diphenyl carbonate and the molecular ion of diphenyl ether by the same structure (formalism IV, X = H), the rearrangement ion is apparently formed with some excess energy. The heats of formation of $C_{12}H_{10}O^+$ have been reported[10] as 257 and 220 kcal/mole for diphenyl carbonate and diphenyl ether, respectively.

Since decarboxylation can occur with either aryl or phenyl group migration, ^{18}O-labeling of the phenoxy moiety was effected (XVI). Thus aryl migration then



furnishes the M − 44 ion ga (with label retention), whereas phenyl migration affords the M − 46 species gb. In this way, the over-all rate of decarboxylation for each aryl phenyl carbonate can be divided into two partial rates, for aryl and phenyl group migration, respectively.

In Figure 4 the kinetic data for phenyl migration (XVI → gb) are correlated with σ^+ values,[15b] the use of which gave a plot with slightly less scatter than did σ constants.[15a] The smaller slope of $\rho = +0.34$ for phenyl compared to $\rho = +0.67$ for methyl migration could be interpreted as a lesser dependence on substituent effects at the receptor site for shifting of the more electronically versatile phenyl group, but the uncertainty in the magnitude of the slope in Figure 4 is rather large.

Two possible mechanisms for decarboxylation by phenyl migration are described in Schemes III and IV. Scheme *III* is analogous to Scheme *I* for aryl methyl carbonates I, and is considered less probable on the same grounds. Making the reasonable assumption

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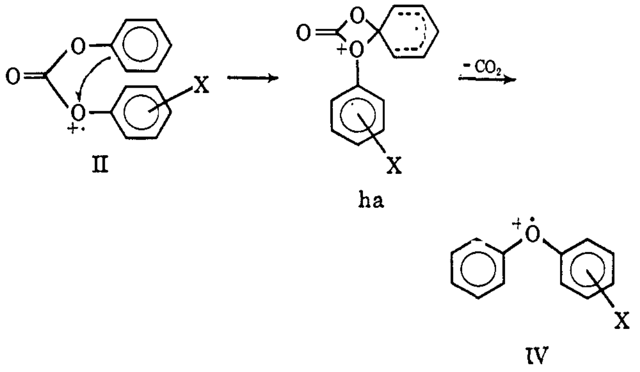
(37) These appear at *m/e* 140.0 ($141^2/142$), *m/e* 118.6 ($142^2/170$), *m/e* 93.8 ($115^2/141$), *m/e* 50.9 ($93^2/170$), *m/e* 33.8 ($51^2/77$), and *m/e* 23.4 ($39^2/65$), and were observed as before employing the logarithmic transfer recorder.

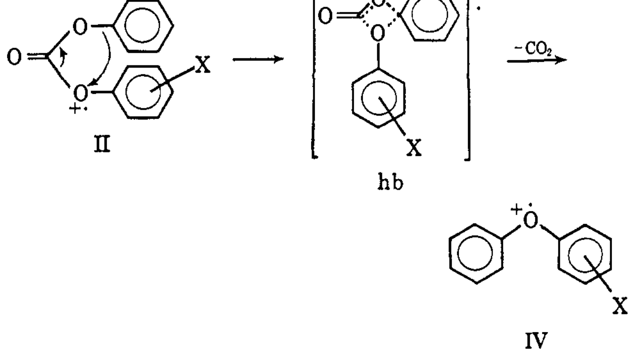
that the rate-controlling transition state would lie between II and ha, a negative ρ value for the Hammett correlation would be anticipated. In this system, therefore, the occurrence of phenyl bridging (as in a σ-bonded intermediate such as ha) appears unlikely.

Scheme III



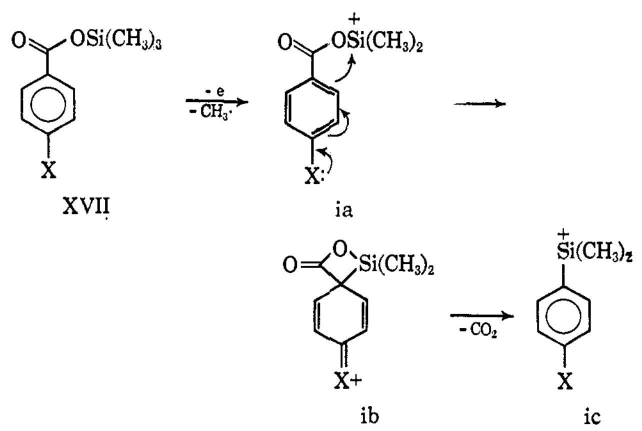
Scheme IV is the phenyl analog of Scheme II for the methyl compounds I, and as before, satisfactorily accounts for the positive ρ value obtained. In view of the small numerical value of ρ, and the as yet unknown range of reaction constant magnitudes for a representative cross section of electron impact induced processes, it is perhaps too early at present to assess finally the significance of ρ in this case, except to note that it has a positive sign.

Scheme IV

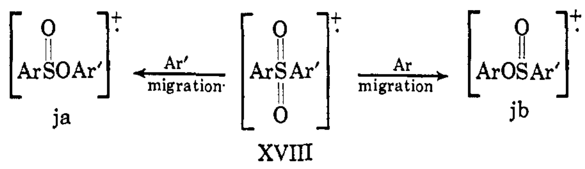


Relative Migratory Aptitudes of Aryl Groups. In addition to revealing the electronic requirements at the receptor site for migration, the model carbonate system also produced information pertaining to the nature of the itinerant group. Despite the wide-spread occurrence in mass spectrometry of rearrangement processes involving intramolecular transfer of atoms or groups other than hydrogen,[4] the literature to date still contains only a few isolated references to the relative migratory propensities of the peripatetic groups.

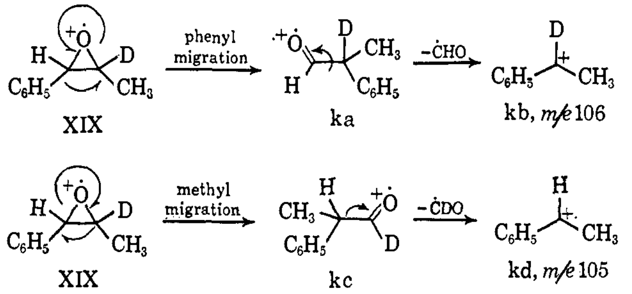
In the mass spectra of trimethylsilyl esters of substituted benzoic acids XVII, an approximate correlation between relative abundance of the rearrangement ion ic and the electronic character of the aromatic substituent X was noted.[26] In fact, electron-donating groups X increased the extent of rearrangement by aryl migration (ia → ib → ic), relative to electron-withdrawing substituents. However, the intensity of a mass spectral peak depends on the rates of decomposition of the ions contributing to it, as well as on their rates of formation, and unfortunately both sets of rates are very probably dependent on X in this instance.



In a study of the mass spectra of diaryl sulfones, evidence was adduced[38] for the operation of an aryl rearrangement process XVIII → ja, jb. In a series of unsymmetrical diaryl sulfones, preferential migration of the more nucleophilic aryl group was consistently observed, although it was clearly recognized that different rates of decomposition of different rearrangement ions contributed to the lack of internal consistency in the formulation of a relative migratory aptitude scale.



It has been reported recently[39] that phenyl migration is more favored than a methyl shift in the fragmentation of 1-phenyl-2-*d*-epoxypropane (XIX). This estimate was made by comparing the relative intensities of the extremely small peaks at *m*/*e* 106 and 105, due to species kb and kd, respectively, and is uncomplicated by the absence of any necessity to allow for different rates of further decomposition of the rearrangement ions (kb, kd), apart from a H/D isotope effect.



In the aryl phenyl carbonate system, aryl migration (XVI → ga) and phenyl migration (XVI → gb) both furnish formally the same aryl phenyl ether radical ion, except for the isotope label in ga. Therefore, any further minor decomposition[40] suffered by the rearrangement ions at 12 ev is independent of which group has shifted. The extent of rearrangement occurring

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[38] S. Meyerson, H. Drews, and E. K. Fields, *Anal. Chem.*, **36**, 1294 (1964).

[39] H. E. Audier, J. F. Dupin, M. Fétizon, and Y. Hoppilliard, *Tetrahedron Letters*, 2077 (1966).

[40] Most of the carbonates II contain in their mass spectra small M − (44 + 28) peaks, due to further loss of carbon monoxide from the aryl phenyl ether radical ion,[41] for which no correction was made.

[41] J. H. Beynon, G. R. Lester, and A. E. Williams, *J. Phys. Chem.*, **63**, 1861 (1959).

Table II. Relative Migratory Aptitude Data for Aryl Groups in the Electron Impact Induced Decarboxylation of Aryl Phenyl Carbonates II

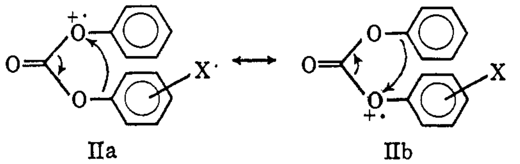
$$[C_6H_5OCOOC_6H_4X]\cdot^+ \longrightarrow [C_6H_5OC_6H_4X]\cdot^+ + CO_2$$

Substituent	Migrating group[a] Phenyl	Migrating group[a] Aryl	Total rate	σ^{+b}	Aryl migratory aptitudes Carbonates	Aryl migratory aptitudes Pinacols[c,d]
p-OCH_3	48	52	0.396	−0.778	1.1	500
m-OCH_3	30	70	0.636	−0.047	2.3	1.6
o-OCH_3	>98	<2	0.340	...	<0.02	0.3
α-Naphthyl (= C_6H_4X)	95	5	0.989	...	0.05	...
p-C_6H_5	39	61	0.693	−0.179	1.6	11.5
2,6-Dimethyl	6	94	0.946	...	15.7	...
p-CH_3	63	37	0.809	−0.311	0.6	15.7
m-CH_3	23	77	1.16	−0.066	3.4	1.9
o-CH_3	21	79	0.798	...	3.8	...
H	50	50	1.00	0	1.0	1.0
p-CO_2CH_3	80	20	0.574	0.489	0.25	...
p-Br	>99	<1	1.09	0.150	<0.01	0.7
p-F	>99	<1	0.938	−0.073	<0.01	...
p-CN	>99	<1	1.16	0.659	<0.01	...
p-NO_2	>99	<1	0.561	0.790	<0.01	...

[a] This ratio was found to be the same at 70, 15, and 12 ev within experimental error. [b] See ref 15b. [c] Acid-catalyzed rearrangement. [d] See ref 43.

by aryl (XVI → ga) and phenyl (XVI → gb) migration as determined by ^{18}O labeling is shown in Table II. In 12 out of 15 examples, the over-all rate of decarboxylation decreases upon introduction of either electron-withdrawing or electron-releasing substituents, and is at a maximum when X = H.

This observation can be rationalized on the basis of charge distribution[16] in the molecular ion, and by taking account of the relative basicities[42] of the aryl groups concerned. In an unsymmetrical aryl phenyl carbonate molecular ion (*e.g.*, that of II), the positive charge will be unsymmetrically partitioned on either side of the carbonyl group. The direction and magnitude of this charge asymmetry will depend on the electronic character of the substituent X. The relative contributions of resonance forms IIa (preferred for electron-attracting groups X) and IIb (preferred for electron-donating substituents) provide an approximate description of the situation.



IIa IIb

Thus simply on charge localization grounds, aryl migration to the most electrophilic center might be predicted to preponderate (see arrows in IIa) for X = +σ groups, and phenyl migration (see arrows in IIb) for X = −σ substituents. In fact, the reverse situation obtains (Table II), indicating that the nucleophilicity of the migrating group is critical. The more nucleophilic entity is preferentially itinerant (arrows, IIb) when X = +σ substituents (*e.g.*, p-NO_2, p-CN, p-F, p-Br, p-CO_2CH_3, o-OCH_3), although the rate of migration is lower than in diphenyl carbonate (II, X = H) itself, since IIb is a higher energy resonance form of the molecular ion. Conversely, when X = −σ groups (*e.g.*, CH_3, p-C_6H_5, m- and p-OCH_3), migration of the more basic aryl moiety (arrows, IIa) is preferred, again at a lower rate than when X = H, since IIa is now a higher energy resonance contributor.

Charge localization and nucleophilicity, therefore, oppose each other in determining the over-all migratory propensities of aryl groups in this particular system. The more basic aryl groups, with electron-releasing substituents, excel at both charge localization and migration. Conversely, the less nucleophilic aryl groups, with electron-withdrawing substituents, are poorer at both charge localization and migration, and the relative migratory aptitudes tend to be leveled by internal compensation of these two effects.

The resulting aryl group migratory aptitudes (Table II, column 6) for the electron impact induced decarboxylation reaction (1,3 migration) are to be compared with those for acid-catalyzed rearrangement of substituted benzpinacols[43] (1,2 migration) (Table II, column 7). It can be seen that the electron impact process migration propensities follow only in an extremely qualitative sense those observed for the carbonium ion process in solution.[44] Further studies are in progress to determine the relative migratory aptitudes of both aryl and alkyl groups in other mass spectral rearrangement reactions.

Experimental Section

Mass Spectra. The low-resolution mass spectra of the aryl methyl carbonates I were obtained by Drs. A. M. Duffield and J. K. MacLeod, using an Atlas CH-4 instrument and operating under the following conditions: ionizing voltage 70, 15, and 12 ev, inlet temperature 70°, AN-4 ion source at 180°. Low-resolution spectra of the aryl phenyl carbonates II were recorded by Mr. N. S. Garcia, employing a CEC 21-103 machine equipped with an all-glass heated inlet system at 200° and ion source temperature 250°. All high-resolution mass measurements were secured by Mr. R. G. Ross, with an AEI MS-9 double-focusing mass spectrometer of apparent resolution 1 part in 15,000, and fitted with an all-glass heated inlet system at 200°, and ion source temperature 250°.

For quantitative relative abundance measurements, the spectra of each series of compounds I and II were run sequentially under identical operating conditions. At least duplicate determinations were made for each individual compounds, and it was found that peak heights were reproducible to within ±1%.

The ALGOL computer program for least-squares treatment of the Hammett plot data was kindly supplied by Dr. J. I. Brauman.

Preparation of Carbonates. Unlabeled aryl methyl carbonates and aryl phenyl carbonates were prepared as before,[8] from methyl and phenyl chloroformates, respectively. ^{18}O-Labeled aryl methyl

Table III. Melting Points of Solid Carbonate Esters

$CH_3OCOOC_6H_4X$ X	Mp, °C	$C_6H_5OCOOC_6H_4X$ X	Mp, °C
p-NO_2	114–115	p-NO_2	130–131
m-NO_2	74–75	p-CN	88–90
p-CN	89–90	p-F	79–80
m-CN	62–63	p-Br	104–105
p-CO_2CH_3	70–71	p-Cl	103–104
m-CO_2CH_3	49–50	p-CO_2CH_3	94–95
p-$COCH_3$	88–89	p-C_6H_5	195–197
p-C_6H_5	83–84	p-OCH_3	92–94

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(42) As for example toward electrophilic substitution.[15b]

(43) W. E. Bachmann and J. W. Ferguson, *J. Am. Chem. Soc.*, **56**, 2081 (1934).

(44) In a study of aryl group migratory aptitudes in the Baeyer-Villiger rearrangement (1,2 migration to oxygen) of substituted acetophenones, M. F. Hawthorne and W. D. Emmons, *ibid.*, **80**, 6398 (1958), report the relative rate sequence p-CH_3 > H > p-Cl > p-Br > m-NO_2 > p-NO_2, with $\rho = -1.45$ (acetonitrile, 29.8°).

carbonates (VI, X = H, CN, OCH_3) were made by converting methanol-^{18}O (55.5% enriched)[45] to the chloroformate, which was then treated with the appropriate phenol in pyridine.[8] ^{18}O-Labeled methyl phenyl carbonate (V) and all ^{18}O-labeled aryl phenyl carbonates XII were prepared by transforming ^{18}O-phenol[45] (diluted to 37.5% enrichment) to the chloroformate, and then adding methanol or the appropriate substituted phenol, respectively.[8] The carbonate esters were purified as before,[8] using gas–liquid chromatography and several injection–collection cycles for liquids, and recrystallization to constant melting point for solids.

Identity and purity of all unlabled carbonates were determined by elemental combustion analysis, gas–liquid or thin layer chromatography, and infrared and low-resolution mass spectra. The retention times or R_f values, infrared and mass spectra, and melting points (Table III) of the labeled carbonates were critically compared with those of the corresponding unlabeled materials.

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[45] Supplied by Yeda Research and Development Co. Ltd., Rehovoth, Israel.

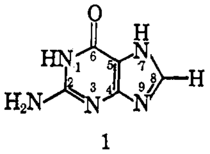
Mass Spectra of Nucleic Acid Derivatives. II. Guanine, Adenine, and Related Compounds[1a]

Jerry M. Rice[1b] and Gerald O. Dudek[1c]

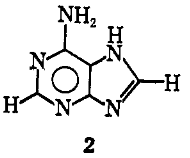
Contribution from the National Cancer Institute, National Institutes of Health, Bethesda, Maryland 20014, and the Department of Chemistry, Harvard University, Cambridge, Massachusetts 02138. *Received November 17, 1966*

Abstract: The mass spectra of guanine, its 1-, 3-, and 7-methyl derivatives, and of isocytosine, hypoxanthine, adenine, and 6-methylaminopurine have been analyzed with the aid of high-resolution mass measurements, metastable peaks, and deuterium labeling. The major electron-impact fragmentation pattern exhibited by guanine and its mono-N-methyl derivatives consists of initial expulsion of a cyanamide fragment, which contains N-1, C-2, and the amino nitrogen atom, followed by decarbonylation. This sequence thus involves all the guanine atoms which take part in the Watson–Crick pattern of hydrogen bonding in polynucleotides. In contrast, the initial fragment expelled from the adenine molecular ion originates uniquely from a single site only when the amino group is methylated.

Guanine (2-amino-6-oxypurine; the prevailing 1H tautomer is shown as **1**) and adenine (6-aminopurine, **2**) comprise the major purine components of both ribo- and deoxyribonucleic acids, and of a variety of coenzymes and biosynthetic intermediates as well.[2] Most of the minor purine constituents of both transfer RNA[3,4] and of DNA[5] consist of mono- and dimethyl derivatives of **1** and **2**.



1



2

It has recently been demonstrated that adenine also is the principal component of a number of alkaloids, including the cytokinins, which under certain conditions are powerful stimulators of plant cell division. The naturally occurring compounds in this series include zeatin, 6-(4-hydroxy-3-methyl-2-butenyl)aminopurine, isolated as the free base[6] and possibly as a nucleoside and nucleotide[7] from maize, and its deoxy derivative, 6-(3-methyl-2-butenyl)aminopurine.[8,9] The latter compound has been isolated both from a bacterium[10] and, in the form of its ribonucleoside, as a minor component of transfer RNA in yeast[8,11] and in calf liver.[8] The isomeric 6-amino-3-(3-methyl-2-butenyl)purine, which is devoid of cytokinin activity, has been identified as the alkaloid triacanthine.[12]

Mass spectrometry played a significant but limited role in the elucidation of the structures of these substituted adenine derivatives, and has also been applied in studies of the mechanism of biological methylation of transfer RNA,[13] but to date no systematic study of the mass spectra of the parent compounds has been published. The mass spectra of purine nucleosides, in which the fragmentation patterns of the purine moieties have received relatively little attention, have been used in studies both of nucleic acid components[13,14] and of certain antibiotics.[15,16] We present here the mass spectra of guanine, adenine, and some of

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[1] (a) Part I of this series: J. M. Rice, G. O. Dudek, and M. Barber, *J. Am. Chem. Soc.*, **87**, 4569 (1965). (b) National Cancer Institute. (c) To whom inquiries should be addressed at Harvard University.

[2] The 7(9) protropic tautomerism of purines unsubstituted in the imidazole ring is ignored in these studies; the imidazole proton is generally represented arbitrarily as residing on N-7.

[3] Abbreviations and notation used in this paper: RNA, ribonucleic acid; DNA, deoxyribonucleic acid; M, molecular (parent) ion; $M - n$, the m/e value of a fragment ion formed by loss of n mass units from the molecular ion.

[4] L. R. Mandel and E. Borek, *Biochemistry*, **2**, 555 (1963).

[5] D. B. Dunn and J. D. Smith, *Nature*, **175**, 336 (1955).

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[8] R. H. Hall, M. J. Robins, L. Stasiuk, and R. Thedford, *J. Am. Chem. Soc.*, 88, 2614 (1966).

[9] K. Biemann, *et al.*, *Angew. Chem.*, **78**, 600 (1966).

[10] D. Klambt, G. Thies, and F. Skoog, *Proc. Natl. Acad. Sci. U. S.*, **56**, 52 (1966); J. P. Helgeson and N. J. Leonard, *ibid.*, **56**, 60 (1966).

[11] H. G. Zachau, D. Dutting, and H. Feldmann, *Angew. Chem.*, **78**, 392 (1966).

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[13] B. E. Tropp, J. H. Law, and J. M. Hayes, *Biochemistry*, **3**, 1837 (1964); B. E. Tropp, Doctoral Dissertation, Harvard University, July 1965.

[14] K. Biemann and J. A. McCloskey, *J. Am. Chem. Soc.*, **84**, 2005 (1962).

[15] S. Hanessian, D. C. DeJongh, J. A. McCloskey, *Biochim. Biophys. Acta*, **117**, 480 (1966).

[16] S. H. Eggers, S. I. Biedron, and A. O. Hawtrey, *Tetrahedron Letters*, 3271 (1966).