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# Friedel–Crafts Chemistry. A Mechanistic Study of the Reaction of 3-Chloro-4′-fluoro-2-methylpropiophenone with $AlCl_3$ and $AlCl_3$–$CH_3NO_2$

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*Received December 20, 1977*

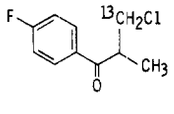
The mechanism of reaction of 3-chloro-4′-fluoro-2-methylpropiophenone (**1**) with $AlCl_3$ has been studied using both $^2H$- and $^{13}C$-labeled substrate. Analysis of kinetic isotope effects and of label location in the products as revealed in $^2H$ and $^{13}C$ NMR spectra allows definition of the major pathways involved. In cyclization to the 2-methylindanone **2**, an isotope rate effect supports ionization concerted with $C_2$–H migration as the rate-determining step. The skeletally rearranged products **3** and **4** form via initial methyl migration and not acyl migration. When the $AlCl_3$–$CH_3NO_2$ system is used as catalyst, no rearrangements transpire, and formation of **2** proceeds below the thermal threshold required with neat $AlCl_3$. This reaction occurs via enolization as a result of the protic nature of $AlCl_3$–$CH_3NO_2$ solutions. This same system possesses oxidizing power, and chloride is oxidized to chlorine which, in the enolizing medium, converts **2** to its α-chloro analogue **6**. When chloride concentration is low, competitive oxidation of **2** to isocoumarin **7** is also observed.

Reaction of 3-chloro-4′-fluoro-2-methylpropiophenone (**1**) with $AlCl_3$ was recently reported to give three products: 5-fluoro-2-methyl-1-indanone (**2**), 5-fluoro-3-methyl-1-indanone (**3**), and 2-(4′-fluorophenyl)-1-oxoniacyclopent-1-enyl cation (**4**).[2] Formation of each product was pictured, with some reservations, as having proceeded through carbenium ions which differed fundamentally from those cited in cyclialkylation of phenylalkyl halides[3] by the presence of a carbonyl group linking the aliphatic and aromatic moieties.

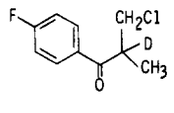
We have continued study of this reaction, and wish now to report the results of experiments using (a) both $^{13}C$- and $^2H$-labeled **1** and (b) nitromethane as solvent. The label studies amplify our understanding of some of the mechanistic pathways involved; the presence of nitromethane alters the outcome of the reaction entirely.

## Results

Carbon-13 labeled **1** (C-1) was made via methoxymethylation[4] with $H^{13}CHO$; $C_2$-deuterated **1** (D-1) came from the addition of deuterium chloride to 4′-fluoromethacrylophenone (**5**).



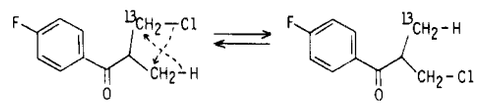

C-1




D-1

Products **2**, **3**, **4**, and "unreacted" starting material observed after reaction of C-1 with 2–3 equiv of $AlCl_3$ at 100 °C, neat, showed that scrambling had occurred in two and only two positions, as shown in Figure 1. Because this scrambling was also observed with C-1 at 70 °C, where *no* carbon–carbon bond reorganization could be discerned, the result was attributed to the equivalent of a 1,3-hydride shift in **1** as depicted in Scheme I.[5] (The $C_2$-attached H was not involved, as will be evident below from results with D-1.)

Scheme I[a]




[a] For clarity, complexation of $AlCl_3$ is not shown in this or the other schemes.

The reaction of D-1 was, overall, slower than unlabeled **1** under identical conditions. Dissection of the relative rates of the individual processes supported $C_2$–H (or $C_2$–D) bond breaking as rate determining in the formation of unrearranged indanone **2**, with $k_H/k_D = 2.5$. Negligible rate differences were seen in formation of **3** or **4**. Deuterium in $CH_2D$ and CHD groups of **2**, **3**, and **4** was located by $^{13}C$ NMR spectroscopy. Integration of the signals for $^2H$-split vs. solely $^1H$-bearing singlet $^{13}C$ signals provided a semiquantitative distribution. Proton NMR showed no detectable loss nor scrambling of $^2H$ in the recovered D-1. Overall $^2H$ content in each product was also assessed by mass spectroscopy; attempts to assign its distribution in **2** and **3**, methyl group vs. indanone ring, by means of mass fragmentography[6] were not in accord with the $^{13}C$ NMR results.

Mechanistic suggestions are proposed on the basis of the rates and products; unfortunately, the loss of some of the deuterium, and some of its incorporation into the aromatic nucleus as ultimately shown by $^2H$ NMR, precludes total definition of the reactions.

Reaction of 1 M solutions of **1** in nitromethane containing 2 equiv of $AlCl_3$ occurred slowly as low at 70 °C to produce **2** without detectable formation of **3** or **4**. The medium, however, supported further reaction of **2** along two parallel paths to its α-chlorinated derivative **6** and to the isocoumarin **7** (Scheme II). The isocoumarin was not observed when the experiment was conducted in sealed tubes. These unexpected transformations are ascribed to the nature of the modified catalytic system.

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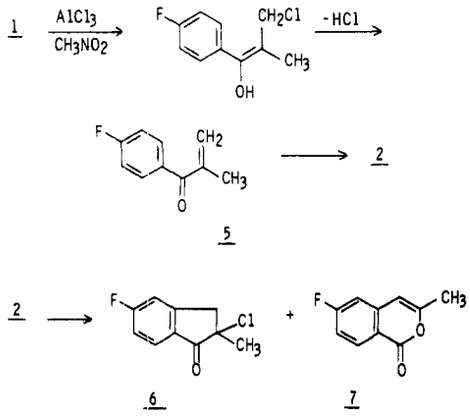
Scheme II



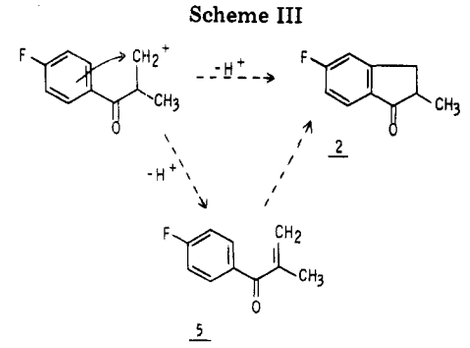
## Discussion

Certain aspects of the reaction of 1 with $AlCl_3$ could not be defined with our original experimental data.[2] For instance, it was suggested[2] that **2** might arise by direct intramolecular cyclization of 1 after ionization at $C_3$. "Intervention of [**5**] is neither necessary nor excluded . . ." (Scheme III). Nucleophilic $\pi$-assisted displacement of chloride concomitant with ring formation would be an allowable alternative. Likewise, the rearrangement products **3** and **4** were rationalized in terms of rapid alkyl and hydride migrations; however, the possibility of an aroyl migration as depicted in Scheme IV was not ruled out. Publications concerning similar rearrangements are becoming increasingly frequent.[7] It was our belief that these, and other aspects, might be clarified by working with isotopically labeled 1.

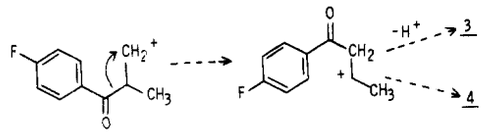
**A. The Question of Methyl and Hydride Migration vs. Acyl Migration to Give 3 and 4.** A clear choice between these two pathways can be made utilizing C-1. The latter mechanism, i.e., acyl migration (Scheme IV), would provide **3** and **4** possessing the label adjacent to the carbonyl functions, while product **2** would maintain skeletal integrity and keep its label at $C_3$. Moreover, the use of $^{13}C$ labeling would provide a highly sensitive probe; if even 1% of C-1 were to rearrange via acyl migration, the signal intensity for the $\alpha$ carbon would double, relative to unlabeled carbon atoms.

The products resulting from such an experiment (Figure 1) showed conclusively that acyl migration was not a contributory pathway in these rearrangements. Because of the unexpected scrambling, however, we studied the reaction under milder conditions. Nothing happened during 20 h at 50 °C. At 70 °C, the $^{13}C$ NMR signal for the methyl carbon grew

Scheme III



Scheme IV



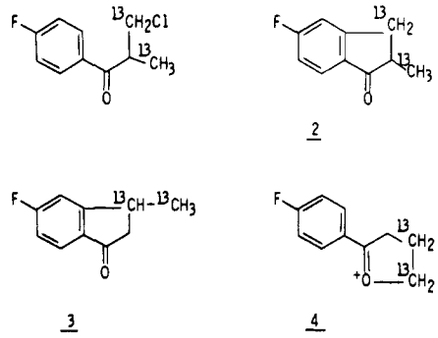


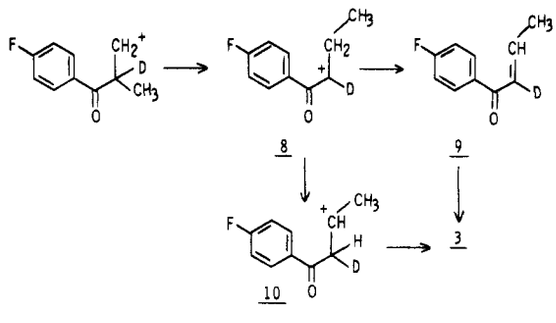
**Figure 1.** Labeling pattern found in products **2**, **3**, and **4**, and "unconverted" starting material after reaction of C-1 with $AlCl_3$ at 100 °C. Label was shared equally between the two positions indicated.

at the expense of the methylene signal without any indication of structural change. A 1,3-hydride–chloride shift, shown in Scheme I, accounts for these observations, and it can therefore be considered to precede any other step in the overall sequence.[5,8] The half-life for this label scrambling at 70 °C with 2.4 equiv of $AlCl_3$ was 21 h.

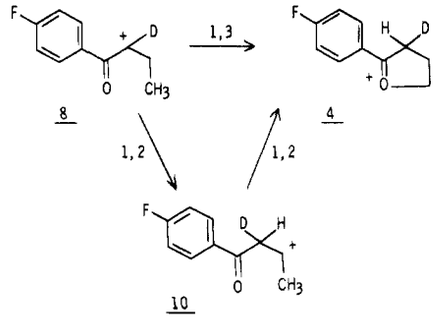
**B. Inferences from Kinetic Measurements of the Reaction of D-1.** Side-by-side comparison of 1 and D-1 showed the latter to react more slowly. The stability, noninterconvertibility, and hence independent formation of **2**, **3**, and **4** were verified. Reaction aliquots were examined with time and analyzed kinetically[10] in an experiment using 2.33 equiv of $AlCl_3$. In brief, half-lives of 3.2 and 5.6 h at 100 °C for 1 and D-1, respectively, were measured, equivalent to the first-order rate constants $\Sigma k_H = 0.22$ and $\Sigma k_D = 0.12$ $h^{-1}$. Relative rate constants $k_H/k_D$ for the individual products were calculated to be 2.5, 1.1, and 1.0 for **2**, **3**, and **4**, respectively.

In the formation of **3** and **4**, since there is no significant isotope effect and since acyl migration does not occur, methyl migration to form rearranged ion **8** (Scheme V) is the probable rate-determining step. The conversion of **8** to **3** can proceed via **9** or **10**, Scheme V. Support for **9** is its characterization in the product mixture.[2] The same ion, **8**, may serve as precursor to oxonium ion **4** by means of either a 1,3-hydride shift or two 1,2 shifts in concert with attack of carbonyl oxygen at the terminal carbon (Scheme VI). A stepwise procedure to a pri-

Scheme V



Scheme VI



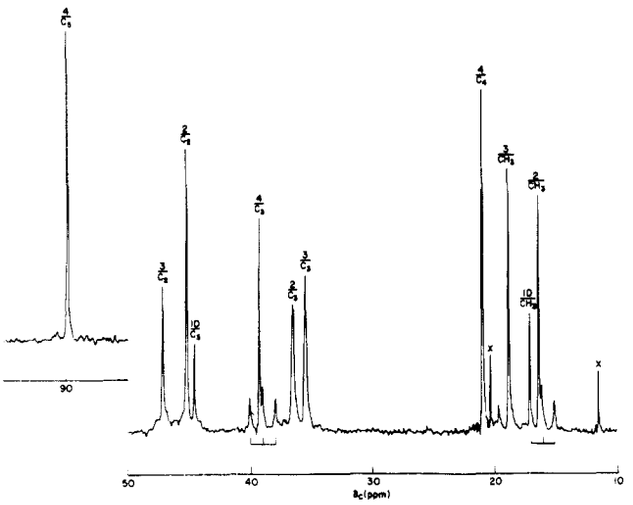


**Figure 2.** Partial $^{13}C$ NMR spectra of reaction of D-1 with neat $AlCl_3$ at 100 °C for 15.5 h. Deuterium-split triplets are indicated for the $CH_2D$ group of **2** (one leg of which coincides with the $CH_3$ of D-1) at 16.2 ppm and for $C_3$ ($C_\alpha$) of **4** at 39.1 ppm. The $C_4$ signal at 21 ppm is split due to a geminal deuterium isotope effect in the labeled molecules (cf. F. W. Wehrli and T. Wirthlin, "Interpretation of Carbon-13 NMR Spectra", Heyden & Son, Ltd., London, 1976, pp 107–110). Impurities from the nitromethane solvent used as diluent *after* reaction are marked "×" at 11.6 and 20.4 ppm.

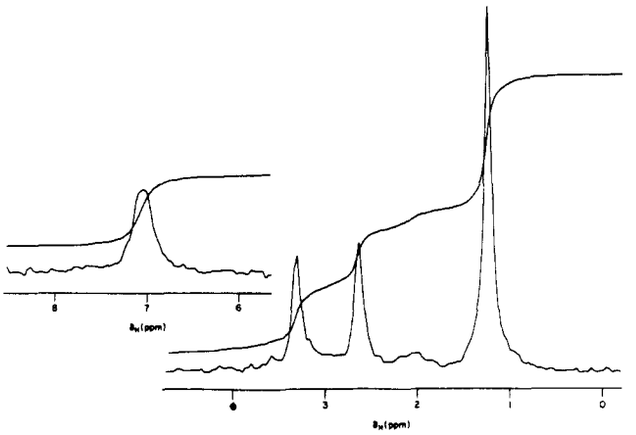


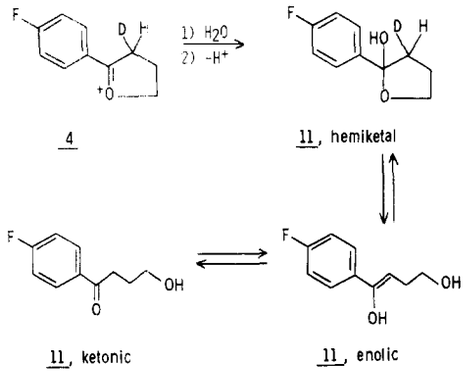
**Figure 3.** Deuterium NMR spectrum of **2** recovered from reaction of D-1. If $^2H$ were attached at $C_7$, its signal would be evident at ~7.7 ppm.

mary carbenium ion prior to cyclization on oxygen should be disfavored[11] even though formation of a primary carbenium ion has been recently postulated.[12] The proton-decoupled $^{13}C$ NMR spectrum of **4** formed from D-1 clearly shows a deuterium-coupled triplet for $C_\alpha$ at $\delta_C$ 39.03 ppm, with $J_{CD}$ = 20 Hz (Figure 2). The same spectrum shows no evidence for deuterium at other positions. Of the two paths (Scheme VI) for formation of **4**, we prefer the 1,3 shift.[14]

After quench, the 4′-fluoro-4-hydroxybutyrophenone (**11**) formed from **4** shows little or no aliphatically bound deuterium by $^1H$ or $^{13}C$ NMR or mass spectroscopic analysis. This lack of deuterium at $C_\alpha$ suggests that reaction of **4** proceeds by attack of water at the carbonyl carbon[16] and that the ring opens via enolic **11** (Scheme VII). If the deuterium were lost in **11** by a simple enolization exchange process during the quench, then we should expect similar exchange in the case of product **3**, contrary to our experimental observations. In some experiments, the NMR spectra of purified **11** have shown ketonic **11** exclusively;[2] in others, both the ketone and hemiketal have been observed.

**C. Does Methacrylophenone 5 Intervene in Reaction of 1 → 2?** Scheme III depicts the two a priori most likely paths for conversion of **1** to **2**. Studies with D-1 were expected to ease the choice. For example, direct cyclization of a carbenium ion formed by C–Cl heterolysis of **1** should occur without isotope rate effect from D-1 and should leave $C_\alpha$ deuterated. Conversely, if the same ion ejects $D^+$ to form **5**, which is clearly the intermediate from α-halo isomers of **1**,[2] then **2** would be devoid of aliphatic-bound D. In actuality, an isotope rate effect was observed, *and* deuterium was also found in **2** (0.6 atoms) by $^{13}C$ NMR in both the methyl and methylene groups, but not the methine. $CH_2D$ was favored 2:1 over CHD. Scheme VIII can account for these observations. Deuterium migration concerted[13] with ionization of the primary C–Cl bond generates the tertiary carbenium ion isotopic with one postulated from similar treatment of α-haloisobutyrophenones.[2] Proton loss to form methacrylophenone **5** leaves deuterium in either the methyl or methylene group. From **5a** is produced **2** containing label in the methylene; from **5b** comes the methyl-labeled indanone. Unlabeled **2** may arise from loss of $D^+$ here or during initial ionization.

Scheme VII

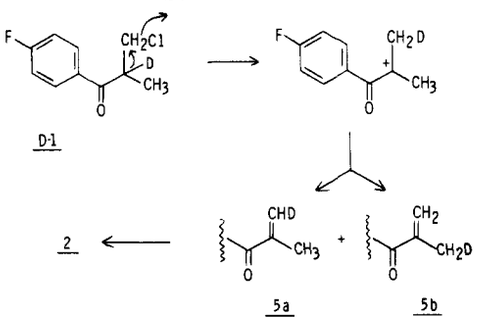



Deuterium migration parallels the methyl migration which was postulated above for the rearranged products (Scheme V). It follows that the 1,3-hydride–chloride interchange established with C-1 must occur with only minimal C–Cl separation. Once C–Cl ionization occurs to initiate the first 1,2 shifts of either Scheme V or VIII, reaction must continue irreversibly to product, since none of the recovered starting material, D-1, shows deuterium scrambling. This observation also rules out 1,2 shifts in the behavior of C-1 at 70 °C.[17]

**D. Other Aspects of the Overall Picture.** Additional observations, some of which are briefly implied above, are worth noting. While it is not apparent from either $^2H$ or $^{13}C$ NMR spectra, $^2H$ NMR conclusively shows the incorporation of deuterium into the aromatic ring of indanone **2** (and **3**) from D-1 to the extent of ca. 0.1 atom.[18,19] This is not random scrambling, since none appears at $C_7$ (Figure 3). It is best rationalized as an electrophilic substitution by DCl.

Finally, significant discrepancy was noted between NMR and mass spectroscopic analyses of the two indanones. Our[20] interpretation assumed that $M^+ - 15$ fragment ions for both

Scheme VIII



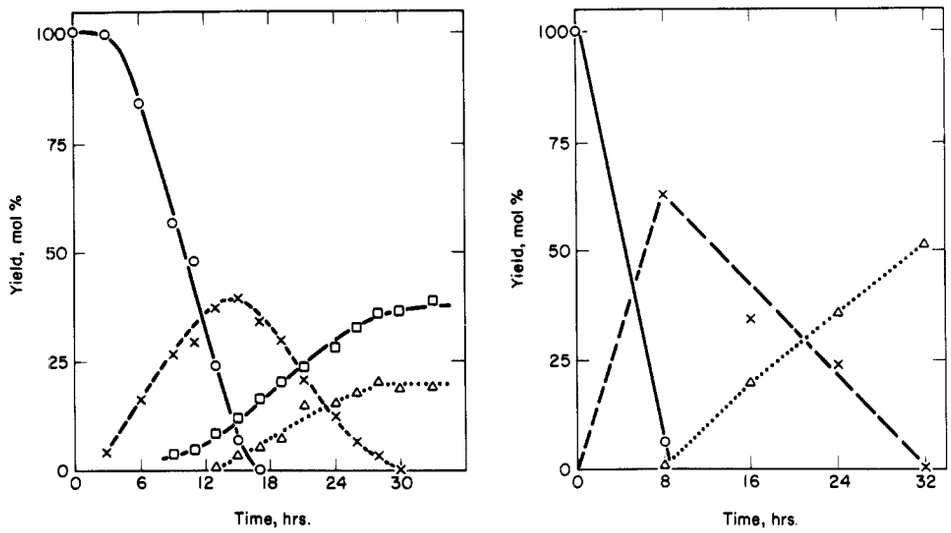



**Figure 4.** Transformation of 1 (○) to 2 (×), 6 (△), and 7 (□) by reaction with $AlCl_3$–$CH_3NO_2$ (see Experimental Section). Part A, left, represents reaction with escape of HCl; part B, right, represents reaction under autogenous HCl pressure.

2 and 3 reflect loss of the methyl group, which is likely, but nevertheless unproved. The more sensitive MS method suggests no deuterium loss from 3 in the $M^+ - 15$ ion whereas the $^2H$ NMR spectra show ca. 20–25% of the total $^2H$ on the methyl group. A lesser but real difference was also noted for 2.

The fragmentation pathway for neither 2 nor 3 has been studied in detail, and our assumption noted above may be in error. Scrambling under electron impact is also possible,[21] and it has recently been shown that the presence of deuterium in a substrate molecule completely changed its fragmentation from that of its proteo isotope.[22]

**E. The Reaction of 1 with $AlCl_3$–$CH_3NO_2$.** Prior studies including cyclialkylation of various phenylalkyl halides have shown that not only does nitromethane moderate the activity of $AlCl_3$, but it prevents reaction of ordinary primary alkyl halides unless there is participation by neighboring aryl and/or β-alkyl groups.[3a] More recently, we showed that some ω-halophenones, i.e., primary alkyl halides, would also react with participation of the carbonyl group in the same catalyst system to form oxonium ions.[15] Although some of these rearranged to thermodynamically more stable oxonium ions, they did not undergo carbon cyclialkylation (except with neat $AlCl_3$).

Despite the generally accepted belief that $AlCl_3$–$CH_3NO_2$ is milder than $AlCl_3$ as an alkylation catalyst,[23] 1 was transformed, albeit slowly, to indanone 2 at 70 °C, a temperature at which no detectable 2 formed in the presence of $AlCl_3$ alone! Furthermore, no 3-methylindanone 3 could be seen, even when C-1 was used as substrate, nor was scrambling observed in the unreacted starting material. Inescapably, hydride and alkyl shifts were suppressed while cyclialkylation took place. With time, 2 was transformed into α-chloroindanone 6 and the isocoumarin 7, albeit in modest yield. The reaction is pictured in Scheme II; a GLC study of the sequence may be seen in Figure 4. No other intermediates were detected spectroscopically nor from analysis of quenched aliquots. Both 2 and 6 were subjected to the same reaction conditions, and the results were found to be generally in accord with the data of Figure 4: 2 gave a mixture of 6 and 7; 6 proved not to be a precursor of 7.[24] In all cases, it was evident that higher molecular weight (i.e., nonvolatile, under our GLC conditions) by-products were also formed.

The very slow initiation of the reaction of 1 (note initial rate of its disappearance, Figure 4A) suggested either the intervention of an intermediate or that prior catalyst modification was involved. Paul, Kaushal, and Pahil[25] have noted the protic nature of nitromethane in the presence of Lewis acids, and they have isolated several solvent-derived salts in such systems, always with accompanying evolution of HCl. In such a modified Brønsted acid system, therefore, we may expect enolization of 1 to initiate cyclialkylation such as does $H_2SO_4$.[2] As for chlorination, Bauer and Foucault[26] have shown by polarography that $AlCl_3$–$CH_3NO_2$ exhibits a half-wave potential of 1.72 V vs. Ag–AgCl. Tables[27] of $E°$ show that 1.72 V is sufficiently high to oxidize $Cl^-$ to $\frac{1}{2}Cl_2$ ($E° = 1.36$), granting extrapolation from water to $CH_3NO_2$. In the enolizing medium[25] then, chlorine should attack 2 at $C_2$. If the $AlCl_3$ were behaving in its usual Lewis acid sense, we should anticipate aromatic chlorination according to Pearson's procedures,[28] rather than attack at the α position.

As for oxidation of 2 to an isocoumarin, similar transformations have been recorded[29] under different conditions with different oxidants. The formation of 7 here further demonstrates the oxidizing power of the $AlCl_3$–$CH_3NO_2$ reagent.

The reaction of 1 was repeated in sealed tubes, under which circumstances the HCl concentration and, hence, the rate of enolization would be increased. Under these conditions, the rate of reaction of 1 essentially doubled, as did the accumulation of 2, which reached peak concentrations in excess of 60 mol % (Figure 4B). The subsequent α-chlorination of 2 occurred this time to the exclusion of oxidation to isocoumarin 7, also attributable to higher HCl, and hence higher $H^+$ and $Cl_2$ concentrations. From this experiment we also concluded that oxidation of 2 to 7 is a significantly slower reaction than is chlorination.

## Summary

From the accumulated results of these experiments, we may assert that the conversion of 1 to 3 and 4 occurs by means of alkyl and hydride shifts and not by acyl migration. Preceding those or any other carbon bond reorganization is a degenerate 1,3-chloride–hydride transposition within the 1–$AlCl_3$ complex which is also the equivalent of a 1,3-hydride shift between methyl and methylene carbon atoms.

Once reaction begins, the sequence of alkyl and hydride shifts eludes total definition at the current state of the art; however, the label studies allow one to make inferences from which reasonable schemes have been proposed. The absence of isotope rate effects for 3 and 4 from D-1 implicate methyl migration as the rate-determining step. We believe it occurs concomitantly with irreversible C–Cl bond cleavage as the

initiating step. In the case of indanone **2**, the $k_H/k_D$ = 2.5 supports initiation by a completely analogous concerted hydride (deuteride) shift.[17] Both rate effects and label position in **2** argue against a mechanism involving $\pi$-assisted ionization of the C–Cl bond and/or direct cyclization.

Deuterium NMR revealed some $^2H$ exchange in the aromatic ring of **2** and **3** which was not noticed by $^1H$ or $^{13}C$ NMR spectroscopy. Indiscriminate scrambling was not its cause, since $C_7$–H, adjacent to carbonyl, was not exchanged.

The protic nature of $AlCl_3$–$NO_2$ has been invoked in order to explain its catalysis of cyclialkylation of **1** to **2** under milder conditions than those needed with $AlCl_3$ alone. Furthermore, the subsequent conversion of indanone **2** to chloroindanone **6** and isocoumarin **7** attests to the little recognized oxidizing power of that catalyst system.

## Experimental Section[30]

**C-1.** A solution of 474 mg of 20% $H^{13}CHO$ (90% $^{13}C$ label, MSD Canada, Ltd.), 501 mg of 4′-fluoropropiophenone (Aldrich), 36.5 mg of finely powdered potassium carbonate, and 1.9 mL of methanol was stirred at room temperature for 7 days, then concentrated in vacuo without heating.[4] It was taken up in ether, dried over sodium sulfate, then filtered into a glass Parr bomb liner. The system was closed, pressurized to 100 psig at room temperature with anhydrous HCl, then warmed 24 h at 40 °C. The residue remaining after removal of solvent was chromatographed on silica gel ($C_6H_6$: 0.5% MeOH) to give 475 mg of C-1 (78% overall): $^1H$ NMR ($CDCl_3$) $\delta$ 1.30 (t, $J$ = 6.5 Hz, 3, $CH_3$), 2.1–2.82 (m, 1, $\frac{1}{2}CH_2$), 3.82 (m, 1, CH), 4.68–5.37 (m, 1, $\frac{1}{2}CH_2$), 6.8–7.35 (m, 2, $H_{2',6'}$), 7.85–8.17 (m, 2, $H_{3',5'}$). Less pure fractions were held for rechromatography.

**D-1.** A 10% solution of 4′-fluoromethacrylophenone (**5**)[2] in ether was saturated with anhydrous DCl (MSD Canada, Ltd.) at 0–5 °C, then held at room temperature in the stoppered flask for 24 h. Chromatography (as with C-1) gave pure D-1 in near-quantitative yield: $^1H$ NMR ($CDCl_3$) $\delta$ 1.3 (s, 3, $CH_3$), 3.78 (ABq, 2, $CH_2$), 6.97–7.41 (m, 2, $H_{3',5'}$), 7.9–8.26 (m, 2, $H_{2',6'}$).

**Cyclialkylations** with neat $AlCl_3$ were performed as before.[2] The ongoing reactions, the crude product mixtures, and chromatographically purified samples were examined by $^1H$ and $^{13}C$ NMR and mass spectroscopy. Purified **2** and **3** from D-1 were also examined by $^2H$ NMR in $CHCl_3$ using a Varian XL-100, also used for $^1H$ and $^{13}C$ observations. Kinetic data were obtained from experiments at 100 °C using 2.33 ± 0.4 mol of $AlCl_3$ per mol of **1** or D-1 by the internal standard GLC method as previously reported.[2]

**2-Chloro-5-fluoro-2-methylindan-1-one (6).** Authentic **6** was prepared by chlorination of **2** with $SO_2Cl_2$ in carbon tetrachloride.[31] Recrystallized from hexane, it showed: mp 70–72 °C; $^1H$ NMR ($CDCl_3$) $\delta$ 1.8 (s, 3, $CH_3$), 3.55 (ABq, 2, $CH_2$), 6.97–7.35 (m, 2, $H_{4,6}$), 7.73–8.03 (m, 1, $H_7$); mass spectrum *m/e* (rel intensity) 200 ($M^+$, 5), 198 ($M^+$, 16), 163 (100), 135 (22), 133 (36), 115 (16), 109 (14), 107 (11), 94 (9), 57 (10). Anal. Calcd for $C_{10}H_8ClFO$: C, 60.47; H, 4.06; Cl, 17.85. Found C, 60.39; H, 4.12; Cl, 17.73.

**$AlCl_3$–$CH_3NO_2$ Cyclialkylations.** To a solution of 1.33 g (10 mmol) of $AlCl_3$ in 3 mL of $CH_3NO_2$ was added 1.0 g (5 mmol) of **1** and ca. 300 mg of *o*-nitrotoluene as an internal GLC standard. It was diluted with $CH_3NO_2$ to 5.0 mL, then heated at 85 ± 1 °C in a $N_2$ atmosphere under a reflux condenser with stirring. Samples were taken periodically, quenched into ice water and $CH_2Cl_2$, and worked up in standard fashion. Replicate GLC analyses were averaged and corrected for molar detector responses and yields were calculated. The data are plotted in Figure 4A.

Portions of an identical solution were sealed in capillary tubes, heated for specified periods, worked up, and analyzed as above. The (fewer) data points are plotted in Figure 4B.

An identical reaction run in a 5-mm NMR tube, but containing 15% of C-1 with **1**, was followed by $^{13}C$ NMR spectroscopy for 60 h at 70 °C. Label was observed only at $C_3$ in the **2** produced therefrom.

**Isolation of 2-Chloro-5-fluoro-2-methylindan-1-one (6) and 6-Fluoro-3-methylisocoumarin (7).** After the usual extractive workup of a reaction mixture run in $CH_3NO_2$, chromatography on silica gel using hexane, then benzene–hexane mixtures, gave **6**, identical to an authentic sample (see above) by TLC, $^1H$ NMR, GLC, and MS. Slightly more polar was **7**, which was crystallized from hexane containing a little ether: mp 90–92 °C; $^1H$ NMR ($CDCl_3$) $\delta$ 2.26 (br s, 3, $CH_3$), 6.21 (br s, 1, $H_4$), 6.87–7.28 (m, 2, $H_{5,7}$), 8.07–8.35 (m, 1, $H_8$); mass spectrum *m/e* (rel intensity) 178 ($M^+$, 54), 163 (25), 136 (22), 107 (100), 57 (29), 43 (98). Anal. Calcd for $C_{10}H_7FO_2$: C, 67.41; H, 3.96. Found: C, 67.61; H, 3.89.

**Registry No.**—**1**, 58472-46-1; C-**1**, 66483-26-9; D-**1**, 66483-25-8; **2**, 41201-58-5; $^{13}C$-labeled **2**, 66483-21-4; $^{13}C$-labeled **3**, 66483-22-5; $^{13}C$-labeled **4**, 66483-20-3; **5**, 58472-45-0; **6**, 66483-24-7; **7**, 66483-23-6; $H^{13}CHO$, 3228-27-1; 4′-fluoropropiophenone, 456-03-1; $AlCl_3$, 7446-70-0; $CH_3NO_2$, 75-52-5.

## References and Notes


(1) Part of this work was described during the Friedel–Crafts Symposium at the 173rd National Meeting of the Amercian Chemical Society, New Orleans, La., March 23–25, 1977.
(2) S. H. Pines and A. W. Douglas, *J. Am. Chem. Soc.*, **98**, 8119–8124 (1976).
(3) Recent reports include: (a) A. A. Khalaf, *Rev. Roum. Chim.*, **19**, 1361–1372 (1974); (b) R. M. Roberts, *Intra-Sci. Chem. Rep.*, **6**, 89–99 (1972); and (c) L. R. C. Barclay and E. C. Sanford, *Can. J. Chem.*, **46**, 3325–3331 (1968).
(4) S. H. Pines and A. W. Douglas, *J. Org. Chem.*, **42**, 2786–2787 (1977).
(5) As will be made clear later in this paper, we do not, in fact, consider that transposition of the Cl and H atoms of **1** occurs after discrete C–Cl ionization, as we have shown (for illustrative purposes) in Scheme I. Representation by valence bond pictures, or even dotted lines, leaves much to be desired.
(6) See: W. H. McFadden, "Techniques of Combined Gas Chromatography/Mass Spectrometry: Applications in Organic Chemistry", Wiley, New York, N.Y., 1973, pp 252–256, for a discussion of mass fragmentography.
(7) For some recent references to rearrangement of acyl groups to adjacent electron deficient centers, see (a) J. Kagan, D. A. Agdeppa, Jr., S. P. Singh, D. A. Mayers, C. Boyajian, C. Poorker, and B. E. Firth, *J. Am. Chem. Soc.*, **98**, 4581–4588 (1976); (b) J. M. Domagala, R. D. Bach, and J. Wemple, *ibid.*, **98**, 1975–1977 (1976); (c) J. N. Marx, J. C. Argyle, and L. R. Norman, *J. Am. Chem. Soc.*, **96**, 2121–2129 (1974); and references to older work found therein.
(8) A ring-protonated cyclopropyl ketone intermediate was ruled out earlier[2] on the basis of its reactivity. It should accumulate and be seen under these conditions. Now, an edge-protonated cyclopropane[9] may be eliminated from consideration. Such a species would have to be a special one, indeed. It would have to be present in concentrations too low to see, and it would require that the edge-attached proton not be permitted to exchange with the proton on $C_\alpha$ since D-**1** recovered from reaction at 100 °C is unscrambled.
(9) For useful reviews which discuss edge-protonated cyclopropanes, see: N. C. Deno in "Isotopes in Organic Chemistry", Vol. 1, E. Buncel and C. C. Lee, Ed., Elsevier, 1975, Chapter 1; J. L. Fry and G. J. Karabatsos in "Carbonium Ions", Vol. II, G. A. Olah and P. v. R. Schleyer, Ed., Wiley, 1970, p 530; and C. J. Collins, *Chem. Rev.*, **69**, 543–550 (1969).
(10) We are indebted to Dr. G. B. Smith of these laboratories for much of the kinetic analysis. The cited rate of constants and ratios represent averages from five time intervals convering a 13-h reaction span.
(11) G. J. Karabatsos and F. M. Vane, *J. Am. Chem. Soc.*, **85**, 729–732 (1963).
(12) G. A. Olah, R. J. Spear, and D. A. Forsyth, *J. Am. Chem. Soc.*, **98**, 6284–6289 (1976). Rearrangement from the ethylenebenzenium ion of this reference might also have been a process occurring in concert[13] with hydride migration such that a primary carbenium ion did not form.
(13) F. A. Carey and R. J. Sundberg, "Advanced Organic Chemistry", Part A, Plenum, New York, N.Y., 1977, p 237.
(14) Note that ion **10** was shown in Scheme V, also. We plan to examine the question of 1,3- vs. 1,2-hydride shifts in oxonium ion formation by use of properly labeled substrate. See also ref 15 for formation of oxonium ions under similar Friedel–Crafts conditions.
(15) S. H. Pines and A. W. Douglas, *Tetrahedron Lett.*, 1955–1958 (1976).
(16) For studies of hydrolysis of analogous oxonium ions and citation of the enolic form, see H. R. Ward and P. D. Sherman, Jr., *J. Am. Chem. Soc.*, **89**, 1962–63, 4222–24 (1967); **90**, 3812–3817 (1968); and D. J. Pasto and M. P. Serve, *J. Am. Chem. Soc.*, **87**, 1515–1521 (1965).
(17) A referee has postulated that **2** may arise by two paths jointly satisfying our kinetic and label data, one involving direct $D^+$ ejection to **5**, the other passing through a protonated cyclopropropyl ketone. "Olefin formation would of course provide DCl for scrambling purposes". Besides our earlier expressed views,[8] scrambling would require the residual labeling in methyl and methylene groups to be statistically equal. See also ref 18. The cyclopropyl route should also give $C_\alpha$-labeled **2**. We do not exclude some direct elimination of DCl to form unlabeled **2**.
(18) Lewis acid catalyzed labeling studies with toluene[19] show that essentially no label enters the aliphatic side chain. In ref 19, no exchange at all was noted with, e.g., acetophenone as substrate, presumably because the small amount of Lewis acid was completely coordinated as a salt. In the present case, we use excess $AlCl_3$.
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(20) We are indebted to Ms. P. C. Cala of these laboratories for the considerable mass spectral experiments, data, and discussion of them.
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(28) D. E. Pearson, H. W. Pope, W. W. Hargrove, and W. E. Stamper, *J. Org. Chem.*, **23**, 1412–1419 (1958).
(29) R. H. Carter (nee' Rayner), R. M. Colyer, R. A. Hill, and J. Staunton, *J. Chem. Soc., Perkin Trans. 1*, 1438–1441 (1976), and references cited therein. A new approach to these structures via π-olefin–metal complexes has recently been reported: D. E. Korte, L. S. Hegedus, and R. K. Wirth, *J. Org. Chem.*, **42**, 1329–1336 (1977).
(30) Melting points are uncorrected. Elemental analyses were performed under the direction of Mr. J. P. Gilbert of these laboratories. The "usual workup" involves aqueous washing of the organic solvent solutions followed by drying over sodium or magnesium sulfate then evaporation to dryness in vacuo.
(31) We thank Mr. W. E. Shearin for this preparation.

# Substituent Effects on Bromodecarboxylation Reactions

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*Received September 17, 1976*

The reaction of ring-substituted cinnamate and α-methylcinnamate ions with bromine in water or methanol was studied. Where strongly electron-donating substituents were present, the decarboxylation products, 1-bromo-2-phenylethene or 2-bromo-1-phenyl-1-propene, were predominant. With groups of indifferent electronic character, considerable β-lactone was observed. With electron-withdrawing groups (cinnamate ions) the predominant products result from solvent capture of the intermediate ion. The effects of temperature and bromide ion concentration are discussed. The stereochemistry of the conversion to lactone and olefin is interpreted in terms of the least motion of the intermediate ion to arrive at a conformation capable of forming products. An improved synthesis of cinnamic acids is given.

The problem of interest concerns the reactions of bromine with various substituted cinnamate ions (Scheme I). The reaction very likely proceeds through the intermediate cation (e.g., **2**, Scheme I) although contributions from an electron transfer, or a free-radical pathway, cannot be entirely ruled out.[1] Subsequent reactions of the intermediate carbonium ion **2** include two variations not possible in simple solvolyses,[2] namely decarboxylation and lactonization. Previous work on cinnamic acids includes the rates of halogenation studied by James and co-workers.[3] Tarbell and Bartlett apparently were the first to observe β-lactone formation from the treatment of α,β-unsaturated acids with bromine.[4] Berman and Price studied the reactions of the isomeric α-phenylcinnamate anions with bromine and concluded that the decarboxylation was stereospecific (retention).[5] Lactonization was considered but the importance of this intermediate or product was not clarified. More recently, Johnson and co-workers studied the chlorination of various α,β-unsaturated carbonyl compounds.[6] These workers postulated a concerted chlorodecarboxylation of *trans*-cinnamate ions or, alternatively, decarboxylation passing through a very short-lived intermediate analogous to **2**, since the olefin product was formed with high stereoselectivity, whereas the other reaction products were stereochemically mixed. Lactone was not reported. On the other hand, Berman and Price observed mixed isomeric olefins from treatment of *cis*-cinnamate with bromine.

In view of other work, the absence of β-lactone seems surprising.[4,7,8] The purpose of this work was to study the effects upon the yields and stereochemistry of decarboxylation product, lactone (if any), and solvent capture products as the following parameters are varied: (1) aromatic substituent X and vinyl substituent R; (2) bromide ion concentration; (3) temperature; and (4) solvent.

**α-Methylcinnamate Ions (1a); Products of Reaction.** Substrate **1a** (R = $CH_3$) reacts with bromine in the solvents water or methanol to form products **4, 5, 6, 10, 11**, and in certain cases **12** and **13** shown in Scheme I. Tables I and II list the yields of the major products.

For substrates with strongly electron donating groups X, the predominant reaction was decarboxylation to form the olefin **4**. The yield of **4** diminishes as X becomes progressively more electron withdrawing (90% **4** for X = *p*-$CH_3O$ to 2% for X = *p*-Cl in water as solvent). In methanol, the trend is similar.

For the same substituent change, the bromohydrin or bromo ether **6** is formed in progressively higher yields (8% for X = *p*-$CH_3O$ to 40% for X = *p*-Cl in water). Lactone **5** is definitely formed in many of these reactions. The yield of **5** is maximum for X = *p*-$CH_3$ in both solvents. The yields of **5** were rather variable in water, perhaps due to the lability of this product. No more than a trace of **5** is found where X = *p*-$CH_3O$, perhaps due to the facile reionization and subsequent decarboxylation (**5** → **2** → **4**).[9]

For compounds with electron-withdrawing groups, several additional products are observed by NMR (Figure 1), usually in very small yield. In two cases, the structure has been identified. For X = *p*-$NO_2$, an acidic product is formed in ca. 46% yield, whose NMR spectrum shows only methyl (δ 2.22) and aromatic absorptions. The olefinic structure **13** is assigned to this product which is also the product of solvolysis of **7** (free acid). For X = *p*-Cl and H, a second acidic product is formed, which shows methyl (δ 1.37), methoxyl (δ 3.49), and methine (δ 5.42) absorptions. The yield of this product is diminished by added bromide. The inverse addition structure **12** is assigned to this product, whose yield would be reduced by reaction of its precursor **3** with bromide. The appearance of **12** and **13** suggests that formation of ion **3** becomes competitive with formation of the benzylic ion **2**, as X becomes electron withdrawing. Solvolysis studies by Hughes and Ingold showed that ions of similar constitution as **3** (i.e., "α-lactones") enjoyed considerable stability, perhaps due to charge attraction in the zwitterion.[10,11] Reaction of the free acid of **1a** (various substituents) with bromine leads to **7** and the normal addition product **6** (no **13**), which suggests that **3** is stable as a zwitterion, but not as a simple cation.

In methanol, a sizable amount of a third material of unknown structure (labeled **6′** in Figure 1) is observed. The methyl chemical shift is very close to the bromohydrin **6** or to

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