1-1-2004

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Accepted version. *New Journal of Chemistry*, No. 28 (2004): 1568-1574. DOI. © 2004 The Royal Society of Chemistry and the Centre National de la Recherche Scientifique. Used with permission. Sergey V. Lindeman was affiliated with the University of Houston at the time of publication.
Structural Effects of Carbon Monoxide Coordination to Carbon Centers. \( \pi \) and \( \sigma \) Bindings in Aliphatic Acyl versus Aromatic Aroyl Cations

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Abstract:
The binding of carbon monoxide to carbon centers has been examined with two series of aromatic and aliphatic oxocarbonium ions that are successfully isolated as crystalline and highly reactive (hygroscopic) aroylium and acylium salts with poorly coordinating counteranions. X-ray crystallographic analyses at −150 °C afford precise structural parameters for the characteristic linear carbonyl bond ($r_{CO}$) and the bond to the carbon centers ($r_{C\alpha}$). The correlations of these structural parameters evaluated for alkyl (Me, Et and i-Pr) and aryl ($p$-Me, 2,4,6-trimethyl, $p$-MeO and $p$-fluorophenyl) oxocarbonium ions with the corresponding carbonyl stretching frequencies in the solid-state (reflectance) IR spectra yield valuable insight into the binding mode of carbon monoxide. Most noteworthy is the synergic ($\pi$–$\sigma$) bonding in aroylium structures in contrast to the mainly $\sigma$ bonding in acylium structures that are organic mimics for carbon monoxide bonding in classical and nonclassical metal carbonyls, respectively.

Introduction
Owing to the relevance of carbon monoxide to a wide variety of metal-catalyzed processes of industrial importance, including hydroformylation, Fischer–Tropsch, carboxylation, etc. various types of metal carbonyls $M$(CO)$_x$ have been isolated, synthesized and characterized as critical intermediates. Bonding among different metal carbonyls, especially of the transition series, is dominated by the classical model of synergic ($\sigma$–$\pi$) interactions of the CO base with different M-centered acids. Recently, a different type of metal–carbonyl binding in which the usual $\pi$ backbonding component is weak or nonexistent has been proposed for a new series of “nonclassical” metal carbonyls (the primary acid–base interaction deriving from a dominant metal $\sigma$ orbital). However, in metal–carbonyl bindings, the relative contributions of the $\sigma$ and $\pi$ components are difficult to assess quantitatively owing to the varying nature of the metal centers. It is thus noteworthy that there are a few examples from the organic literature in which CO is directly bonded only to carbon centers in the form of oxocarbonium moieties: of two basic types, that is, (A) aromatic arroyl, and (B) aliphatic acyl cations. The first member of the aromatic class is the benzoyl cation ($C_6H_5$–CO$^+$) that allows direct $\pi$ backbonding of the benzenoid ring to the $\sigma$-bonded CO substituent. Likewise, the first member of the aliphatic class is acetyl cation ($CH_3$–CO$^+$), in which the dominant $\sigma$ bond allows little or no possibility of direct $\pi$ conjugation. Importantly, both of these organic cations permit the effects of small (electronic) perturbations to be systematically examined by: (A) judicious placement of substituent groups on the phenyl ring, and (B) $\alpha$ branching at the methyl group, as depicted below:

![Structures](image)

(A) aroylium  \hspace{1cm} (B) acylium

Acetyl cation was first isolated by Olah et al. in their now classic studies on the reactive intermediates in Friedel–Crafts acylations, and the X-ray crystallographic analysis of their colorless crystals was later reported by Boer. The corresponding X-ray structure of benzoyl cation is unreported, but the close analogs, the $o$- and $p$-methyl derivatives, were successfully examined by Le Carpentier, Weiss et al. In both cases, diffraction data were only collected at room temperature. The resulting limited precision (accuracy) of 1–1.5 pm (e.s.d.) did allow the overall structure elucidation, but was clearly insufficient for any quantitative or comparative conclusions to be drawn among various structural types. Accordingly in this study, we minimized such imprecisions (arising largely from thermal motion) by the low temperature re-examination of these structures, together with preparation of a new (extended) series of other aroylium and acylium salts.
Results

Isolation and crystallization of pure aroylium and acylium salts suitable for X-ray crystallography posed serious experimental difficulties for two principal reasons. First, as cationic salts, the choice of the appropriate (complex) counteranion for solubility in anhydrous solvents was critical, and an anion suitable for a given oxocarbonium salt was not predictably applicable to a close relative. Second, all oxocarbonium salts were sensitive to traces of moisture in the solvent and glassware, being extremely hygroscopic. For these reasons, the entries in the following tables were largely dictated by what we were successfully able to isolate; but we believe their number and variety were sufficient to establish the unique structural patterns of π and σ bonding relevant to aromatic versus aliphatic oxocarbonium structures as follows.

I. Synthesis and isolation of oxocarbonium salts

Two synthetic methodologies were utilized in the preparation of crystalline oxocarbonium salts suitable for X-ray crystallography. The more direct approach (Method A) was based on Lewis acids such as antimony pentachloride and gallium trichloride applicable to Friedel–Crafts acylation with acid chlorides:

Method A: \( \text{RCOCl} + \text{GaCl}_3 \rightarrow \text{RCO}^{+}\text{GaCl}_4^- \) \hspace{1cm} (1)

in dichloromethane solution to generate the coordinatively saturated and low nucleophilic counteranions \( \text{SbCl}_6^- \) and \( \text{GaCl}_4^- \), respectively. The second method (Method B) was also found in Olah’s earlier studies, and employed silver(I):

Method B: \( \text{RCOCl} + \text{AgSbF}_6 \rightarrow \text{RCO}^{+}\text{SbF}_6^- + \text{AgCl} \) \hspace{1cm} (2)

This method depended on the careful separation of silver chloride even as a trace contaminant that could otherwise inhibit crystallization. Methods A and B were used interchangeably because optimum conditions for successful crystallinity and solubility were largely a matter of trial and error among numerous attempts.

II. X-Ray crystallography of pure oxocarbonium salts

In order to quantitatively evaluate electronic effects on structure, the X-ray crystallographic analyses of the various acylium and aroylium salts were consistently carried out at −150 °C to a uniform precision of (e.s.d) 0.3–0.5 pm. In each case, the X-ray structural data were supplemented by infrared (reflectance) analyses of the carbonyl stretching frequency (\( \nu_{\text{CO}} \)) in crystalline samples, as follows.

A. Aliphatic acylium cations. The low-temperature re-determination of the crystal structure of the acetyl salt \( \text{CH}_3\text{C} \equiv \text{O}^{+}\text{SbF}_6^- \) (earlier thought to be disordered) yielded the structural parameters in Table 1 with good precision. We were also able to improve the earlier (imprecise) data on the structure of \( \text{Et–C} \equiv \text{O}^{+}\text{GaCl}_4^- \), which together with the recent (low-temperature) determination of \( \text{i-Pr–C} \equiv \text{O}^{+}\text{SbCl}_6^- \) provided us with systematic observations on structure and electronic features of the aliphatic acylium cations in Table 1. Extension of the series to the highly branched pivaloyl cation was precluded owing to the reversible ready loss of carbon monoxide:

\( \text{(CH}_3\text{)}_3\text{C–CO}^+ \rightleftharpoons \text{(CH}_3\text{)}_3\text{C}^+ + \text{CO} \) \hspace{1cm} (3)
Table 1 Geometric and IR parameters of aliphatic acyl cations

<table>
<thead>
<tr>
<th>Cation</th>
<th>X</th>
<th>( a/\text{Å} )</th>
<th>( b/\text{Å} )</th>
<th>( \alpha/\text{deg} )</th>
<th>( \nu(\text{CO})/\text{cm}^{-1} )</th>
<th>Source (Method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Me–C≡O⁺ SbF₆⁻</td>
<td></td>
<td>1.108(4)</td>
<td>1.419(4)</td>
<td>179.2(3)</td>
<td>2302</td>
<td>This work (A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.11</td>
<td>1.39</td>
<td>177</td>
<td>2294</td>
<td>Ref. 3 Ref. 5</td>
</tr>
<tr>
<td>Et–C≡O⁺ GaCl₄⁻</td>
<td></td>
<td>1.102(5)</td>
<td>1.424(6)</td>
<td>178.6(5)</td>
<td>2282</td>
<td>This work (A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.07</td>
<td>1.43</td>
<td>177</td>
<td>—</td>
<td>Ref. 8b</td>
</tr>
<tr>
<td>( i )-Pr–C≡O⁺</td>
<td></td>
<td>1.101(4)</td>
<td>1.458(4)</td>
<td>177.4(3)</td>
<td>2257</td>
<td>Ref. 2</td>
</tr>
<tr>
<td>O⁺</td>
<td></td>
<td>1.12</td>
<td>1.44</td>
<td>176</td>
<td>—</td>
<td>Ref. 8b</td>
</tr>
</tbody>
</table>

\( a \) Reliable data used for the discussion are given in bold.

The ORTEP diagram of the ethyl derivative Et–CO⁺GaCl₄⁻ in Fig. 1(A) shows the linear coordination of CO in the basic 3 atom fragment C–C–O; and the (distorted) tetragonal disposition of chlorine from three GaCl₄⁻ anions about the cationic center (\( r_{C–Cl} 3.28–3.48 \text{ Å} \)) is identified by the unit-cell fragment in Fig. 1(B). Table 1 also includes the carbonyl stretching frequencies (last column) obtained from IR reflectance measurements on crystalline oxocarbonium salts (see Experimental).

Fig. 1 (A) ORTEP diagram (50% probability ellipsoids) of Et–CO⁺ showing the linear coordination of carbon monoxide. (B) Unit cell fragment showing the distorted tetragonal coordination of three GaCl₄⁻ about the cationic center.
B. Aromatic aryl cations. Since our initial attempts to obtain single crystals of benzoylium salts with various counteranions suffered badly from low solubilities, we re-determined the structure of the methyl derivative $p$-CH$_3$C$_6$H$_4$–CO$^+$SbCl$_6^-$ at $-150$ °C with superior resolution to that earlier reported by Le Carpentier, Weiss et al. In addition, the structural parameters are reported in Table 2 for the 2,4,6-trimethyl (Mes) and 2,3,4,5,6-pentamethyl (Me$_5$C$_6$) derivatives together with those of the $p$-fluoro- and $p$-methoxy-substituted analogs.

Table 2 Geometric and IR parameters of the aromatic aryl cations

<table>
<thead>
<tr>
<th>Cation-anion pair (method)</th>
<th>$a$/Å</th>
<th>$b$/Å</th>
<th>$\alpha$/deg</th>
<th>$c$/Å</th>
<th>$d$/Å</th>
<th>$e$/Å</th>
<th>$\nu$(CO)/cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-Me$_3$C$_6$H$_4$–C$\equiv$O$^+$SbCl$_6^-$ (A)</td>
<td>1.116(2)</td>
<td>1.391(2)</td>
<td>179.2(2)</td>
<td>1.405(2)</td>
<td>1.378(2)</td>
<td>1.400(2)</td>
<td>2220</td>
</tr>
<tr>
<td>$p$-Me$_3$C$_6$H$_4$–C$\equiv$O$^+$SbF$_6^-$ (B)</td>
<td>1.125(8)</td>
<td>1.375(9)</td>
<td>177.6(7)</td>
<td>1.410(9)</td>
<td>1.360(9)</td>
<td>1.396(9)</td>
<td>2215</td>
</tr>
<tr>
<td>Me$_5$C$_6$–C$\equiv$O$^+$SbCl$_6^-$ (A)</td>
<td>1.121(4)</td>
<td>1.375(4)</td>
<td>178.1(4)</td>
<td>1.420(3)</td>
<td>1.368(4)</td>
<td>1.397(4)</td>
<td>2203</td>
</tr>
<tr>
<td>Me$_5$C$_6$–C$\equiv$O$^+$SbF$_6^-$ (B)</td>
<td>1.135(5)</td>
<td>1.391(5)</td>
<td>178.9(5)</td>
<td>1.395(6)</td>
<td>1.366(6)</td>
<td>1.374(6)</td>
<td>2226</td>
</tr>
</tbody>
</table>

$\alpha$ Reliable data used for discussion are given in bold; the actual precision of geometric parameters for Mes–C$\equiv$O$^+$SbCl$_6^-$, $p$-MeOC$_6$H$_4$–C$\equiv$O$^+$SbF$_6^-$, and $p$-FC$_6$H$_4$–C$\equiv$O$^+$SbF$_6^-$ is higher because these are averaged over two symmetrically independent molecules. $b$ For the corresponding SbF$_6$ salt.

The structures of the $p$-methyl and 2,4,6-trimethylbenzoyl cations as well as the fluoro-substituted derivative were established to good experimental precision, whereas the permethylated and methoxy structures were affected by crystallographic disorder. The problem is especially pernicious in the case of the permethylated cation in which a small fraction (less than 10%) of the disk-shaped cations has the methyl and
carbonyl groups permuted. This disorder compromised the reliability of the structural parameters owing to the (effective) shift of the carbonyl carbon toward the oxygen and away from the benzene ring. Nevertheless, the crystallographic data in Table 2 provide sufficient structural information to discuss the principal structural and electronic features of aromatic aroyl carbocations.

Fig. 2 (A) ORTEP diagram (50% probability ellipsoids) of the p-fluorobezoyl cation showing the linear coordination of carbon monoxide. (B) Tetragonal coordination of SbF$_6^-$ anions about the cationic center.

The ORTEP diagram in Fig. 2(A) of the fluorobenzoyl moiety in p-FC$_6$H$_4$–CO$^+$ SbF$_6^-$ is a typical representation of the basic 3 atom fragment C=–C–O showing the linear coordination of CO to the aromatic (substituent) group; and Fig. 2(B) emphasizes the tetragonal disposition of SbF$_6^-$ anions ($r_{C\cdots F}$ 2.69–2.94 Å) about the cationic carbon center.

Discussion

I. Sigma binding of carbon monoxide in aliphatic acyl cations

The nature of the alkyl coordination in the series of acyl cations (Table 1) is revealed in the variation of two structural parameters: (i) the carbonyl bond length ($r_{CO}$) and (ii) the bonding distance to the alkyl group ($r_{C\alpha}$). As expected for a linear 3-center array, the variation of $r_{CO}$ runs counter to that in $r_{C\alpha}$, that is, the general trends in $r_{CO}$ and $r_{C\alpha}$ are opposed.

Furthermore, the correlation of the carbonyl bond length $r_{CO}$ with the carbonyl stretching frequency $\nu_{CO}$ has a qualitative trend which is opposite to expectations of the well-recognized bond-strength/bond-order interrelationship. Therefore, let us now normalize the structural parameters ($r$) to the bond orders ($n$) as described by Pauling.

In Table 3, the calculated carbonyl bond order encompasses a rather narrow range centered around $n_{CO} = 2.72$, whereas the alpha bond to the alkyl substituent is significantly more variant around $n_{C\alpha} = 1.22$. It is thus interesting to note that the total bond order ($\Sigma_n$) is rather close to 4 (required by the simple octet rule) with one exception, that is, $\Sigma_n$ for the isopropyl derivative is clearly less than 4. In other words, the Pauling approach alone does not adequately account for the electronic effects of the isopropyl group relative to those of either methyl or ethyl.
Table 3 Pauling bond orders for aliphatic acyl cations

<table>
<thead>
<tr>
<th>Alkyl–CO⁺</th>
<th>n CO</th>
<th>n Ca</th>
<th>Σn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Me–CO⁺</td>
<td>2.69(3)</td>
<td>1.32(2)</td>
<td>4.01(4)</td>
</tr>
<tr>
<td>Et–CO⁺</td>
<td>2.74(4)</td>
<td>1.29(4)</td>
<td>4.03(6)</td>
</tr>
<tr>
<td>i-Pr–CO⁺</td>
<td>2.75(3)</td>
<td>1.11(2)</td>
<td>3.86(4)</td>
</tr>
</tbody>
</table>

The inspection of Table 3 reveals that the bond order $n_{Ca}$ for isopropyl is unusually low and largely responsible for (a) the total bond order $\Sigma_n$ less than 4, and (b) the strong non-linear deviation of $r_{Ca}$. Since the Pauling paradigm of bond order in Table 3 is mainly focussed on the variation of the π component, the shortening of $r_{CO}$ in the isopropyl derivative is not adequately compensated in the (excess) lengthening of $r_{Ca}$. The discrepancy is seen in Table 3 for isopropyl with $\Sigma_n$ substantially less than 4, and this indicates that the π component alone is not sufficient to satisfy the octet requirement. Since earlier physical-organic studies indicated that the σ-donor property of the isopropyl group is enhanced relative to that of either methyl or ethyl, we suggest that the electron deficit (~0.3 e) is compensated by an inductive effect operating through the σ bond. Such a σ-inductive effect also accounts for the inverse order in the carbonyl stretching frequencies, and is in complete accord with the previous conclusions about the bonding in “nonclassical” metal carboxyls.

II. Pi binding of carbon monoxide in aromatic aroyl cations

In the substituent effect on the series of aroyl structures presented in Table 2, the general trend of the carbonyl bond length ($r_{CO}$) is opposed to the trend for aryl separation from CO ($r_{ar}$) which is consistent with the expectations of such compensating changes in bond lengths for the linear $C_\alpha$–C–O unit. However, both are opposite to the trends in $r_{CO}$ and $r_{Ca}$ for the aliphatic acyl cations as presented in Table 1. Most revealingly, the trend in the bond correlation for the aroyl cations is also opposed to that for acyl cations. Indeed, the inverse slope is the one expected for the Pauling analysis based on predominant π conjugation, and it is in accord with the π backbonding generally observed in transition metal carboxyls.

In aromatic aroyl cations, the electronically unsaturated (cationic) center adopts the linear sp-hybridized configuration as shown by all $\alpha$ values in Table 2 very close to 180°. Most importantly, the carbonyl bonds ($r_{CO}$) are 1–2 pm longer than those in the aliphatic acyl cations owing to π conjugation with the aromatic substituent; and this elongation is consistent with the reduced IR stretching frequency of the carbonyl group by $\Delta v_{CO} = 30–100$ cm⁻¹. Specifically in the $p$-methylbenzoyl cation, π conjugation achieves almost 100% efficiency as follows from the $\alpha$ bond length of $r_{Ca} = 1.391$ Å, which coincides with the standard value of 1.39 Å for the aromatic conjugated carbon–carbon π bond. Such a conjugation is accompanied by an elongation of the carbonyl bond by $\Delta r_{CO} = 0.7–1.3$ pm relative to that observed in the aliphatic acyl cations, as well as a significant quinonoidal distortion of the benzenoid ring. As expected, the presence of two additional methyl groups as in the mesitoyl cation further increases π conjugation by the bond length changes of $\Delta r_{CO} = 0.6$ pm and $\Delta r_{Ca} = 1.6$ pm, together with further quinonoidal distortion. The introduction of the strong π-donor substituent as in the anisoyl cation promotes the development of π conjugation since the Ar–CO bond of $r_{Ca} = 1.125$ Å is the longest and the quinonoidal distortion is the greatest. Remarkably, this structural change in MeOC₆H₄CO⁺ is not reflected in the decreased $v_{CO} = 2215$ cm⁻¹, and results in its poor correlation. At the other extreme, the introduction of fluorine as an electron-acceptor substituent in $p$-FC₆H₄CO⁺ results in the least π-conjugated carbocationic center with the shortest $r_{Ca} = 1.112$ Å (and with an increased stretching frequency of $v_{CO} = 2226$ cm⁻¹). The computation of the Pauling bond order in Table 4 shows that π conjugation is sufficient to complete the octet requirement with $\Sigma_n$ clearly equal to 4.0 for all the aromatic aroyl cations in contrast to the values of $\Sigma_n$ for the acyl cations listed in Table 3.
Table 4 Pauling bond orders for aromatic aroyl cations

<table>
<thead>
<tr>
<th>Ar–CO⁺</th>
<th>n ca</th>
<th>n co</th>
<th>Σn</th>
</tr>
</thead>
<tbody>
<tr>
<td>MeC₆H₄–CO⁺</td>
<td>2.62(2)</td>
<td>1.34(1)</td>
<td>3.97(2)</td>
</tr>
<tr>
<td>2,4,6-MeC₆H₄–CO⁺</td>
<td>2.58(3)</td>
<td>1.41(3)</td>
<td>3.99(4)</td>
</tr>
<tr>
<td>p-MeOC₆H₄–CO⁺</td>
<td>2.55(6)</td>
<td>1.41(6)</td>
<td>3.96(9)</td>
</tr>
<tr>
<td>p-FC₆H₄–CO⁺</td>
<td>2.65(4)</td>
<td>1.31(3)</td>
<td>3.96(5)</td>
</tr>
</tbody>
</table>

Summary and conclusions

Highly electrophilic oxocarbonium structures R–CO⁺ were synthesized from the corresponding acid halides (using strong Lewis acids or silver(I) salts) and isolated as crystalline solids in the presence of low-nucleophilic counteranions such as SbCl₆⁻, SbF₆⁻ or GaCl₄⁻. Precise low-temperature X-ray structural data were obtained for the aliphatic carbocations: CH₃–C=O+SbF₆⁻ and MeCH₂–C=O+GaCl₄⁻, which together with the latest literature data on Me₂CH–C=O+SbCl₆⁻ comprise the first reliable series of structural measurements on these important electronically unsaturated species as the key intermediates of Friedel–Crafts reaction. For the aromatic analogs, the structure of p-Me–C₆H₄–C=O+SbCl₆⁻ was re-determined with superior precision and its 2,4,6-trimethyl and 2,3,4,5,6-pentamethyl analogs were studied for the first time. The aromatic series was also extended to an even more electron-donor substituted benzoyl cation such as p-MeO–C₆H₄–C=O⁺ as well as electron-poor substituted p-F–C₆H₄–C=O⁺. Solid-state IR spectra were measured for the all carbocations investigated.

For both series of the oxocarbonium structures, the following general structural features are confirmed: (a) significant triple character of the carbonyl bond as follows from its length (1.10–1.11 Å for the aliphatic and 1.11–1.12 Å for the aromatic oxocarbonium structures) and from the enhanced IR stretching frequency (∼2300 cm⁻¹ for the aliphatic and ∼2200 cm⁻¹ for the aromatic series); (b) significant shortening of the adjacent single bond with r_Cα (up to 1.42 and 1.37 Å, in the aliphatic and the aromatic cations, respectively) due to electronic σ–π hyperconjugation of the aliphatic moiety and π–π conjugation of the aromatic moiety with the electronically deficient carbocationic center; (c) the sp¹-hybridized linear configuration of the carbocationic centers characterized by the α angle in Cα–C=O close to 180°.

In addition, for the aliphatic acyl cations, it was found that the σ–π hyperconjugation is not as strong as it was earlier deduced from less precise data. Nevertheless, hyperconjugation in CH₃–C=O⁺ and MeCH₂–C=O⁺ cations can be qualitatively estimated as 60% of the complete (1-electron benzenoid) conjugation that results in the shortest value of 1.42 Å for this bond type. The effectiveness of the σ–π hyperconjugation is significantly reduced in Me₂CH–C=O⁺, owing to the availability of only a single Cα–H bond. The geometry of the carbonyl group in acyl cations is almost unaffected by hyperconjugation, but shows significant bathochromic shifts in the IR spectra with the number of electron-donor groups at the β carbon center, that is, IR frequency of the carbonyl group decreases in the order: H₃C–C=O⁺ > MeCH₂–C=O⁺ > Me₂CH–C=O⁺, which is opposite to the degree of the hyperconjugation. This somewhat paradoxical spectroscopic behavior can be explained from the linear sp configuration of the carbocationic center in which the σ-bonding orbital of the single bond interacts with the σ-antibonding orbital of the carbonyl group.

Aromatic aroyl cations show π–π conjugation between the carbocationic center and the adjacent benzene ring, which increases progressively with the aryl donicity. The shortening of the single (conjugated) bond C–C of up to 1.37 Å with corresponding elongation of the triple bond C=O of up to 1.125 Å tracks the decreasing IR (ν_C=O) frequency. Conjugation also has a pronounced quinonoidal effect on the geometry of the benzene ring (which is less than that deduced earlier from less precise data). Interestingly, the electronegative methoxy oxygen has a significant enhancing effect on the IR frequency of the carbonyl group, apparently through the aforementioned σ–σ* inductive mechanism.
By contrast, the electron-accepting fluorosubstituent reduces the conjugation of the carbonyl group and raises the IR frequency to the most extreme values in the series.

Experimental

Materials
The acyl halides (acetyl chloride, acetyl fluoride, propionyl chloride, p-tolyl chloride, p-anisoyl chloride and p-fluorobenzoyl chloride) were from Aldrich. 2,4,6-Mesitoyl chloride and pentamethylbenzoyl chloride were prepared from the corresponding carboxylic acids (Aldrich) by treatment with oxalyl chloride (Aldrich). SbCl₅, SbF₅ and AgSbF₆ from Aldrich were used without additional purification. Dichloromethane, benzene and hexane were purified according to published procedures. 1,1,2-Trifluorotrichloroethane (Freon 113) from Aldrich was used without additional purification.

Synthesis of 2,4,6-trimethylbenzoyl chloride and pentamethylbenzoyl chloride

The corresponding 2,4,6-trimethylbenzoic (2 g or 12 mmol) or pentamethylbenzoic acid (10 mmol) were dissolved in 10 ml of benzene and a large excess (5 times) of oxalyl chloride was introduced (7.7 and 6.6 g, respectively) under stirring. The mixture was stirred under an argon atmosphere for 3 h. The solvent and the residual oxalyl chloride were removed under vacuum, and the remainder of the solution was distilled under reduced pressure (b.p. 121 and 140 °C at 20 mm Hg, respectively; yield 50–55%).

Syntheses of alkyl and aryloxocarbonium salts

The oxocarbonium salts were prepared using literature methods involving two general synthetic procedures described as methods (A) and (B) in eqns. (1) and (2). Method (A) was used for acyl and aroyl halides with either X = F and PF₅, BF₅, SbF₅, AsF₅ or X = Cl and AlCl₃, GaCl₃, SbF₅. Method B was used for acyl and aroyl chlorides and silver(I) PF₆⁻, BF₄⁻, SbF₆⁻, AsF₆⁻. It is important to mention that the target oxocarbonium salts are extremely sensitive to air. Their successful isolation required highly pure reagents and extreme precautions against moisture. The acid halides were always freshly distilled and anhydrous silver salts were carefully dried in vacuo (including cautious heating) prior to synthesis. The solvents were additionally passed through a column containing activated molecular sieves immediately prior to use. Generally, it is highly recommended to carry out all sample manipulations under an argon atmosphere in a rigorously water and air-free drybox.

Methyloxocarbonium hexachloroantimonate (method A). Freshly distilled acetyl chloride (0.785 g, 10 mmol) was dissolved in 10 ml of dry dichloromethane under an argon atmosphere, and the solution was cooled to 0 °C. Under careful stirring, a solution of 5.98 g of SbCl₅ (20 mmol) in 10 ml of dry dichloromethane was introduced. After 15 min of the continuous stirring, a white crystalline precipitate was collected, washed with cold CH₂Cl₂ and dried under vacuum. Single crystals suitable for X-ray analysis were obtained by slow cooling of the dry dichloromethane solution initially saturated at 40 °C.

Acetyl hexafluoroantimonate (method A). Freshly distilled acetyl fluoride (0.62 g, 10 mmol) was dissolved in 10 ml of Freon 113 under an argon atmosphere, and the solution was cooled to −20 °C. An equimolar amount of SbF₅ (2.17 g) was introduced with careful stirring. After 15 min of continuous stirring, a white crystalline precipitate was collected, washed with cold Freon and dried under vacuum. Single crystals suitable for X-ray analysis were obtained by slow evaporation of the Freon solution under an argon atmosphere.
Propionyl tetrachlorogallate (method A). Freshly distilled propionyl chloride (0.185 g, 2 mmol) was dissolved in 10 ml of dry dichloromethane under an argon atmosphere. 0.352 g of GaCl₃ (2 mmol) was added into the stirred solution which was then cooled to −40 °C. A white crystalline precipitate was collected, washed out with cold CH₂Cl₂ and dried under vacuum. Single crystals suitable for X-ray analysis were obtained by slow evaporation (2 h) of the dichloromethane solution.

4-Toluoyl hexachloroantimonate (method A). Freshly distilled p-toluyl chloride (0.46 g, 3 mmol) was dissolved in 15 ml of dry dichloromethane under an argon atmosphere. Under careful stirring, 5 ml of dichloromethane solution containing 0.89 g (3 mmol) of SbCl₅ were introduced. The solution was covered with a layer of dry n-hexane (15 ml) and allowed to stand at −40 °C. Well-formed crystals of the target oxocarbonium salt were collected at the solvent interface after 3 days.

2,4,6-Mesitoyl hexachloroantimonate (method A). Freshly prepared 2,4,6-trimethylbenzoyl chloride (90 mg, 0.5 mmol) were dissolved in 7 ml of dry dichloromethane under an argon atmosphere. Under careful stirring, 5 ml of dichloromethane solution containing 0.14 g (0.5 mmol) of SbCl₅ were introduced. The solution was covered with a layer of dry n-hexane (15 ml) and allowed to stand at −40 °C. Well-formed crystals of the target oxocarbonium salt were collected at the solvent interface after 2 days.

Syntheses of pentamethylbenzoyl, 4-methoxybenzoyl, and 4-fluorobenzoyl hexafluoroantimonates (method B). Anhydrous silver(I) salt AgSbF₆ (0.24 g, 0.7 mmol) were dissolved in 15 ml of dry dichloromethane. An equimolar amount of the corresponding aroyl halide (0.147, 0.120 and 0.111 g, respectively) was then added under stirring as a solution in a limited amount (∼5 ml) of dry dichloromethane. Stirring was continued for 10 min, then the AgCl precipitate was filtered off. Crystals suitable for X-ray study were obtained by slow evaporation of the filtrate (6–12 h) under an argon atmosphere.

Carbonyl stretching frequencies

Crystalline samples of the oxocarbonium salts were mounted directly on the germanium sampling plate of the single-reflection HATR (Smart Miracle, Pike Technology) under an argon atmosphere, and the infrared spectra (Fig. 3) were measured with a Nexus 470 FT-IR (Thermo Nicolet). Alternatively, crystals for X-ray crystallographic analysis suspended in mineral oil were used, and the mineral oil background digitally subtracted.
Fig. 3 Reflectance IR spectra (partial) of aroyl and acyl salts in the region of CO stretching vibrations.

X-Ray crystallography†

The intensity data for all the compounds were collected with a Siemens/Bruker SMART diffractometer equipped with an APEX CCD detector using MoKα radiation (λ = 0.710 73 Å), at −150 °C. In all cases, a semi-empirical absorption correction was applied. The structures were solved by direct methods and refined by full matrix least-squares procedure with IBM Pentium and SGI O2 computers. X-Ray structure details of the various salts are compiled in Table 5.
Table 5 Crystallographic parameters and the details of the structure refinements

<table>
<thead>
<tr>
<th>Compound</th>
<th>MeCO*SbF</th>
<th>EtCO*Gal</th>
<th>p-MesCO* SbCl p-TolCO*SbCl</th>
<th>p-MesCO* SbCl</th>
<th>p-MeOCl<em>HCO</em>SbCl</th>
<th>p-MeOC<em>HCO</em>SbCl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>C₂H₃F₆OSb</td>
<td>C₂H₅Cl₂Ga</td>
<td>C₄H₇Cl₂O₆Sb</td>
<td>C₅H₁₁Cl₆OSb</td>
<td>C₆H₁₇Cl₂F₆O₆Sb</td>
<td>C₆H₁₇F₆O₆Sb</td>
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<tr>
<td>M</td>
<td>278.79</td>
<td>268.59</td>
<td>453.59</td>
<td>481.64</td>
<td>495.92</td>
<td>370.89</td>
</tr>
<tr>
<td>Space group</td>
<td>P₂₁/m</td>
<td>P₂₁/c</td>
<td>P₂₁/c</td>
<td>P₂₁/c</td>
<td>P₂₁/c</td>
<td>C₂/c</td>
</tr>
<tr>
<td>a/Å</td>
<td>5.7299(7)</td>
<td>7.146(1)</td>
<td>11.7482(7)</td>
<td>9.2849(5)</td>
<td>7.6218(6)</td>
<td>19.061(1)</td>
</tr>
<tr>
<td>b/Å</td>
<td>7.7373(9)</td>
<td>9.487(2)</td>
<td>10.2038(6)</td>
<td>25.038(1)</td>
<td>12.7753(9)</td>
<td>10.4108(8)</td>
</tr>
<tr>
<td>c/Å</td>
<td>7.7479(9)</td>
<td>13.931(2)</td>
<td>12.4473(8)</td>
<td>14.9209(7)</td>
<td>18.242(1)</td>
<td>28.690(2)</td>
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<tr>
<td>β/°</td>
<td>100.187(2)</td>
<td>97.909(4)</td>
<td>93.428(1)</td>
<td>104.665(1)</td>
<td>90.641(1)</td>
<td>91.537(2)</td>
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<tr>
<td>U/Å³</td>
<td>338.08(7)</td>
<td>935.4(3)</td>
<td>1489.5(2)</td>
<td>3355.8(3)</td>
<td>1776.2(2)</td>
<td>5691.2(8)</td>
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<tr>
<td>Z</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>20</td>
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<td>Dₐ/g cm⁻³</td>
<td>2.739</td>
<td>1.907</td>
<td>2.023</td>
<td>1.907</td>
<td>1.855</td>
<td>2.164</td>
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<td>Nᵥₑᶠ (collecte d)</td>
<td>3629</td>
<td>8621</td>
<td>15992</td>
<td>36634</td>
<td>19127</td>
<td>31114</td>
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<tr>
<td>Rₑᶠ</td>
<td>0.0254</td>
<td>0.0485</td>
<td>0.0218</td>
<td>0.0219</td>
<td>0.0212</td>
<td>0.0342</td>
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<tr>
<td>Rₑᶠ (indep.)</td>
<td>1150</td>
<td>3008</td>
<td>4714</td>
<td>10746</td>
<td>5693</td>
<td>9116</td>
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<tr>
<td>Nₑᶠ [ &gt; 2σ(l)]</td>
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<td>1829</td>
<td>4366</td>
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<td>5180</td>
<td>7508</td>
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<td>R₁</td>
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<td>0.0202</td>
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<tr>
<td>wR₂</td>
<td>0.0502</td>
<td>0.0942</td>
<td>0.0496</td>
<td>0.0630</td>
<td>0.0723</td>
<td>0.1626</td>
</tr>
</tbody>
</table>

Acknowledgements
We thank the Robert A. Welch Foundation and the National Science Foundation for financial support.

References


6The isolation and X-ray crystallography of the resultant oxocarbonium hydrates (identified as α,α-dihydroxycarbonium ions) will be reported separately.

7Our attempts to obtain improved data on the molecular geometry of the Me–C–O=SbCl⁶⁻ salt (earlier studied by Le Carpentier and Weiss) was not quite successful because of the intrinsic racemic twinning of these crystals.

17. Fig. 1 and Fig. 2 locate the center of positive charge on the central (carbonyl) carbon atom. From a slightly different perspective, consider the linear cationic unit. Similarities in experimental conditions of these closely related cation salts minimize the systematic errors in the X-ray crystallography and thus the small differences in the bond lengths (Tables 1 and 2) are significant enough to reveal structural changes since we are not optimistic that more precise data on those highly reactive crystals will be forthcoming. As such, the qualitative trend is revealed by the extremes, which, in the case of acyl cations, is CH–CO⁺ compared to i-Pr–CO⁺ and in the case of aroyl extremes are p-FC₆H₄–CO⁺ compared to 2,4,6-Me₃C₆H₂–CO⁺ (with p-OMeC₆H₄–CO⁺ excepted). Note, however, the more compelling comparisons of bond orders for acyl and aroyl cations are given by  \( \Sigma_{\alpha} \) in Tables 3 and 4 (vide infra).

18. From a slightly different perspective, consider the linear cationic unit \((C–O)^+\) as a 3-center-6-electron assembly in which: (i) the carbonyl bond \( r_{CO} = 1.11 \, \text{Å} \) (ave.) is significantly shorter than the standard bond length of the carbonyl double bond \((C=O, 1.21 \, \text{Å})\); (ii) the alkyl–CO bond with \( r_{CO} = 1.42 \, \text{Å} \), for Me–CO⁺ and Et–CO⁺ in Table 1 is also among the shortest single bonds relative to 1.48 Å as the benchmark for \( C(sp^3)–C(sp^3) \) hybridized centers in (for example) methylacetylene; (iii) the computed (Pauling) bond orders for Me–CO⁺ and Et–CO⁺, Table 3, show that oxygen contributes an additional 1.4 e to promote the shortened \( r_{CO} \) (via the 2p lone pairs), and the Me(Et) group likewise contributes an additional 0.6 e to the shortened \( r_{CO} \) bond (via hyperconjugation). Basically, both of these added contributions invoke a π release mechanism to fulfill the “octet” requirement \((i.e. \, \Sigma_{\alpha} = 4.0)\) for the shortened \( r_{CO} \) and \( r_{CO} \) bonds. On the other hand, \( \Sigma_{\alpha} \) is only 3.86 for i-Pr–CO⁺, and the deficit of 0.3 e can be attributed to the diminished hyperconjugation of the i-propyl group, this deficiency being made up by its increased σ bonding characteristics. Fig. 1 and Fig. 2 locate the center of positive charge on the central (carbonyl) carbon atom.

19. The terminal oxygen 2p, and 2p- orbitals. Note also that the carbonyl bonds in Me–CO⁺ and Et–CO⁺ compare with \( r_{CO} = 1.07 \, \text{Å} \) in an authentic \((C \equiv O)\) triple bond; (b) Hyperconjugation is related to the number of α-hydrogens owing to the cylindrical symmetry of the linear carbonyl group. The observed lengths of the \( C(sp^3)–C(sp^3) \) bonds \((1.42 \, \text{Å}) \) are much shorter than the lengths of other hyperconjugated bonds, \( C(sp^3)–C(sp^3) = 1.44 \, \text{Å} \) observed in aliphatic carbocations. In fact, these are the shortest values for single C–C bonds including an sp³-hybridized carbon atom \((i.e. \, \text{in absence of } \pi \text{ conjugation})\). This remarkable shortening indicates an unusually high degree of hyperconjugation in the Me–CO⁺ and Et–CO⁺, which can be estimated at 60% (taking the degree of electronic conjugation in benzene ring for a 100% standard) according to Pauling’s formula. The \( C(sp^3)–C(sp^3) \) bonds in Me–CO⁺ and Et–CO⁺ are also remarkably shorter than the corresponding bond in i-Pr–CO⁺ measured in the accurate study by Strauss et al. \((1.458 \pm 0.004 \, \text{Å})\). This can be explained by the different number of C–H bonds available for the hyperconjugation in these cations. The most favorable configuration requires two σ orbitals of C–H bonds independently overlapping with two mutually orthogonal π orbitals of the triple bond. Therefore, the molecular structure of Et–CO⁺ cation is optimal for the hyperconjugation, and
the presence of an extra C–H bond in Me–CO+ analog cannot contribute more to the effect. At the opposite extreme, the availability of only one C–H σ orbital in i-Pr–CO+ cation greatly diminishes the efficiency of the hyperconjugation.

Considering the covalent radii of carbon and oxygen to be constant, extrapolation from standard values 1.54 and 1.43 Å for single bonds C–C and C–O, respectively, 1.32 and 1.21 Å for double bonds C=O (i.e. −0.22 Å each), respectively, and 1.18 Å for triple bond C≡C, gives 1.07 Å for C=O (i.e. −0.14 and −0.36 Å each, relative to the corresponding double and single bonds, respectively).


The decreasing strength of the carbonyl bond in acyl cations derives from the increased interaction in the order: i-Pr > Et > Me of the σ orbital of the alkyl substituent with the antibonding σ* orbital of carbonyl group as previously described by Strauss et al.

(a) Such a quinonoidal distortion is shown by the shortening of the endocyclic d (1.378 Å) as compared with c bonds (1.405 Å) and e bonds (1.408 Å) in Table 2; (b) For discussion of this type of quinonoidal distortion in cations, see: S. V. Lindeman, S. V. Rosokha, D. Sun and J. K. Kochi, J. Am. Chem. Soc., 2002, 124, 843; (c) Compare Le Carpentier et al. in refs. 4 and 8.

Quinonoidal distortion with the d bond of 1.368 Å; (b) Extension to the pentamethyl analog suffered from disorder. Nonetheless increased π conjugation is expected based on the decrease in νCO from 2220 and 2283 cm⁻¹ to 2197 cm⁻¹, from monomethyl and trimethyl to pentamethyl analogs; (c) Quinonoidal distortion with the shortest d bond = 1.360 Å.

We tentatively suggest that this “anomaly” may arise from the inductive effect of the methoxy group which acts as a σ acceptor to diminish the population of the σ* orbital of the carbonyl group much like that discussed with i-Pr–CO⁺ (vide supra).

However, the fluorine substituent also has a noticeable mesomeric effect on the benzenoid substituent that exhibits a rather pronounced quinonoidal distortion with the d bond of 1.366 Å.

The application of the Pauling relationships to aryl cations is based on rᵢ = 1.455 Å and K = 0.50.

G. M. Sheldrick, SADABS (Ver. 2.03) – Bruker/Siemens Area detector absorption and other corrections, Bruker Analytical X-ray Systems, Madison, WI, 2000.


Footnote

† CCDC reference numbers 239194–239200 and 249788. See http://www.rsc.org/suppdata/nj/b4/b407654k/ for crystallographic data in .cif or other electronic format.