Acylating Friedel–Crafts Complexes: Multinuclear NMR Data and Chemical Reactivity

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^{13}C, ^{27}Al and ^{17}O NMR investigations about the nature of the 1:1 system $AlCl_3{\cdot}RCOCl$ (R = CH_3, CH_2Cl, $CHCl_2$, CCl_3) in CH_2Cl_2 show a donor–acceptor structure with the carbonyl oxygen involved in the metal co-ordination. The shift of the carbonyl group resonance ($\Delta\delta$) in ^{13}C and ^{17}O NMR spectra is strongly dependent on the electron-withdrawing power of the R group and shows a close connection with the reactivities of the different acyl complexes.

The simplest system in the Friedel–Crafts acylation reactions, *i.e.* the combination of aluminium chloride with acetyl chloride, has long been known,[1] but only recently have investigations made it possible to establish the nature of the interaction between the Lewis acid and the reagent.[2] Although an ion-pair structure for the solid was determined by X-ray diffraction,[2c] NMR studies[2a,e–h] showed that either the ion-pair or the donor–acceptor form may be present in solution, depending on the solvent system. In particular, the donor-acceptor form was deduced for the 1:1 $AlCl_3{\cdot}CH_3COCl$ complex in 1,2-dichloroethane from the ^{1}H NMR spectrum[2a] and in dichloromethane from ^{27}Al NMR data.[2f] More recently, Vol'pin and co-workers[2h] contributed further to the knowledge of these systems by showing, on the basis of ^{13}C, ^{17}O and ^{27}Al NMR evidence, that the addition of 1 mol of AlX_3 (X = Br, Cl) to the solid salt or to CH_2X_2 solution of the equimolar complex $AlX_3{\cdot}CH_3COX$, leads to the presence of both the acetylium salt and the donor–acceptor complex. Our interest in this field has come from the need to recognize the factors controlling the reactivity of metal phenolates towards acyl chlorides in order to obtain regiospecific attack on the *ortho* position. In previous papers[3] we have evidenced that highly co-ordinating metal phenolates, such as aluminium phenolates, react directly and selectively at the carbon in the *ortho* position with different classes of acyl chlorides bearing an electron-withdrawing group in the α position. The obtained results support the hypothesis of a co-ordinated Friedel–Crafts process controlled by the structure of the reacting complex as depicted in Fig. 1: the relative interactions between the aromatic substrate, metal and RCOCl, control and diversify the competitive reaction pathways toward *ortho*-acylation or oxygen esterification. In order to obtain more detailed information about the role of the Lewis acid–acyl chloride complexes in Friedel–Crafts reactions we have investigated the 1:1 system $AlCl_3{\cdot}RCOCl$ (R = CH_3, CH_2Cl, $CHCl_2$, CCl_3) in CD_2Cl_2 by ^{13}C, ^{27}Al and ^{17}O NMR spectroscopy (Table 1).[†] In spite of the attention of numerous authors towards the possible use of ^{13}C NMR spectroscopy as a tool for investigating the electron-density distribution in organic molecules,[4] no extensive and multinuclear investigations have been carried out on equimolar complexes between $AlCl_3$ and various acyl chlorides in the same solvent and in connection with synthetic results.[‡]

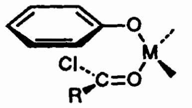

Fig. 1

Results and Discussion

This paper deals with the multinuclear NMR study of the complexes obtained by mixing in CD_2Cl_2 equimolar amounts of $AlCl_3$ and RCOCl. Direct evidence about the nature of these 1:1 complexes in dichloromethane comes from the ^{27}Al NMR spectra recorded at room temperature: chemical shift (δ) and linewidth ($\Delta\nu_{\frac{1}{2}}$) values indicate the presence of unsymmetrical tetraco-ordinated aluminium complexes, owing to a donor–acceptor structure with the oxygen involved in the metal co-ordination.[§]

Moreover, the upfield ^{17}O chemical shifts of the carbonyl oxygen, relative to the free acyl chloride, confirm a direct metal–oxygen interaction. Indeed, there is a correlation between C–O π bond order and chemical shift; carbonyl chemical shifts are displaced upfield when the π bond is weakened.[¶][6,7]

The δ values quoted in Table 1 for ^{13}C, ^{17}O and ^{27}Al NMR spectra are in accordance with the data reported in the literature[2f,h] for $AlCl_3{\cdot}CH_3COCl$ as a donor–acceptor complex and indicate the absence of acylium salts in all the cases we have examined.

Further, in the IR spectrum of a solution of $AlCl_3{\cdot}CH_3COCl$ in CH_2Cl_2 we have observed the complete absence of bands for the C≡O group.[2d]

Note that the shift of the carbonyl group resonance in the complex, relative to the free acyl chloride, $\Delta\delta$, is strongly dependent on the degree of α substitution, both in ^{13}C and ^{17}O NMR spectroscopy. In particular, there is a linear correlation between $\Delta\delta$ for the ^{13}C and ^{17}O nuclei [$\Delta\delta(^{17}O) = 6.30 + 3.26\ \Delta\delta(^{13}C)$; $R = 0.99$].

Increasing the electron-withdrawing inductive power of the R group by modulating the degree of α substitution from 0 to 3, we observed a reduction in $\Delta\delta$ of the carbonyl group owing to complex formation with the Lewis acid. The weaker interaction of the acyl chloride with $AlCl_3$ could account for this observation. Indeed, while acetyl chloride exothermically

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[†] We chose $AlCl_3$ as Lewis acid since aluminium phenolates, the closest model to the reaction system, reacted at the oxygen position with acetyl chloride even at low temperature.

[‡] A study on the species involved in the Friedel–Crafts benzoylation of acetanilide has just been published.[5]

[§] In order to confirm this hypothesis the NMR spectra of the pinacolone–$AlCl_3$ 1:1 complex and $Et_4N^+AlCl_4^-$ salt have been recorded (see Table 1); they gave reference spectra of aluminium co-ordinating a carbonyl oxygen (a donor–acceptor structure) and a fourth chloride (ion-pair structure), respectively.

[¶] The ^{17}O shielding observed for the pinacolone complex suggests that $AlCl_3$ co-ordination affects the decrease in carbon–oxygen π bond order less than protonation does.[7]

Table 1 ^{13}C, ^{27}Al and ^{17}O NMR data for the $AlCl_3{\cdot}RCOCl$ system in CD_2Cl_2 solution[a]

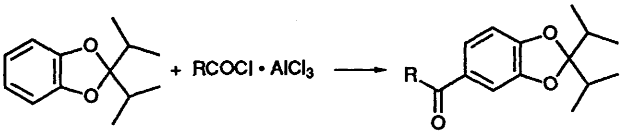
Compound	$\delta(^{13}C{=}O)$	$\delta^*(^{13}C{=}O)$[b]	$\Delta\delta(^{13}C{=}O)$[c]	$\delta(^{27}Al)$[d]	$\delta(^{17}O)$	$\Delta\delta(^{17}O)$[c]
$AlCl_3{\cdot}CH_3COCl$	207.6	170.6	37.0	96.9 (450)	388	−120
$AlCl_3{\cdot}ClCH_2COCl$	193.9	168.1	25.8	97.4 (600)	415	−93
$AlCl_3{\cdot}Cl_2CHCOCl$	189.4	165.9	23.5	98.7 (750)	420	−92
$AlCl_3{\cdot}Cl_3CCOCl$	169.4	163.7	5.7	97.1 (1300)	490	−20
$AlCl_3$–pinacolone[e]	246.9		33.7	94.9 (300)	391	−168
$Et_4N^+AlCl_4^-$[e]				102.2 (12)		

[a] ^{13}C shifts are referred to external Me_4Si; ^{17}Al shifts are referred to external $Al(H_2O)_6^{3+}$; ^{17}O shifts are referred to external H_2O. [b] δ^* is δ of free acyl chloride. We observed a 'reverse' polar effect, by which electron-withdrawing substituents shield the probe carbon. [c] $\Delta\delta = \delta$ (complex) − δ (free acyl chloride). [d] $\Delta\nu_{\frac{1}{2}}$/Hz in parentheses. [e] The data obtained are very close to those reported in ref. 2(*f*).

co-ordinates $AlCl_3$ dissolving it completely, trichloroacetyl chloride leaves some undissolved $AlCl_3$. So, in this case, the low value of $\Delta\delta$ is ascribable to the weak interaction as well as to the presence of uncomplexed ligand.*

We can consider $\Delta\delta$ of the carbonyl group as a useful measure for the interaction between different acyl chlorides and a specific Lewis acid, and for the polarization induced on the reactive carbonyl carbon.

The inductive effect of R and the degree of the Lewis acid induced polarization act competitively on the electron density of the carbonyl carbon, as the increase of the electron-withdrawing power of R results in a reduced interaction with $AlCl_3$. In order to examine the importance of the co-ordinative effect and consequently the possibility to assume carbonyl $\Delta\delta$ as a general index of reactivity of the different acyl complexes within a homogeneous series, we carried out some acylation experiments on 2,2-bis(1-methylethyl)-1,3-benzodioxole (**1**).† As expected, acetyl chloride is far more reactive than trichloroacetyl chloride (Scheme 1), being a better donor ligand for $AlCl_3$.‡ These results confirm the strong influence of the R group on the reactivity of the RCOCl complex.



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2a; $R = CH_3$
b; $R = CH_2Cl$
c; $R = CHCl_2$
d; $R = CCl_3$

3a; 100%[a]
b; 34%
c; 33%
d; 3%

Scheme 1 [a] This yield was reached after 10 min

In regard to the competitive acylation at the oxygen or at the *ortho* position of phenol salts, the results presented herein provide support for the suggested mechanism of a co-ordinated Friedel–Crafts process which is controlled by the structure of the reacting complex (Fig. 1):[3b,e] the relative interactions between the aromatic substrate, metal and RCOCl, control and diversify the competitive reaction pathways towards *ortho* acylation or oxygen esterification. The more the electron-withdrawing power of the R group increases the weaker the interaction of the reagent with the metal ion becomes, and consequently the metal ion strongly co-ordinates the phenolates, preventing the competitive attack at the oxygen.

Experimental

Physical Measurements.—^{13}C NMR spectra were recorded on a Bruker AC 100 spectrometer at 25.18 MHz with proton–noise decoupling: ^1H NMR spectra were recorded on the same instrument. ^{27}Al and ^{17}O NMR spectra were run on Bruker CXP 200 operating at 52.12 and 27.11 MHz, respectively, *J* values are given in Hz. IR spectra in CH_2Cl_2 solution were recorded on Nicolet 5PC FT spectrometer. Mass spectra were obtained on a Finnigan 1020 instrument at 70 eV.

Solutions for NMR measurements (*ca.* 1.5 mol dm^{-3}) were prepared in a dry nitrogen atmosphere under conditions excluding moisture. Samples were prepared by transferring quickly, in a glove box, some aluminium trichloride to an NMR sample tube. Having weighed the aluminium trichloride, dichloromethane was added to give a suspension. Then an equimolar amount of acyl chloride was transferred into the tube, and the molar ratio was deduced by weighing.

Materials.—Commercial $AlCl_3$ was sublimed twice before use. The acyl chlorides were all commercial products and were distilled and stored under nitrogen before use. 2,2-Bis(1-methylethyl)-1,3-benzodiazole (**1**) was prepared as described in the literature.[9]

Reaction of 2,2-*Bis*(1-*methylethyl*)-1,3-*benzodioxole* (**1**) *with Acyl Chloride*–$AlCl_3$ *Complexes* (**2a**–**d**).—*General procedure.* To a suspension of sublimed $AlCl_3$ (1.33 g, 10 mmol) in dry CH_2Cl_2 (20 cm^3) was added chloroacetyl chloride (1.13 g, 10 mmol) under nitrogen. After 30 min at room temperature the mixture was cooled to −20 °C, and a stoichiometric amount (2.06 g, 10 mmol) of **1** was added. After being stirred for 2 h the reaction was quenched with an NH_4Cl aqueous solution and upon reaching room temperature, it was extracted with CH_2Cl_2, dried (Na_2SO_4) and chromatographed on silica gel eluting with hexane–ethyl acetate (95:5). 1-[2,2-Bis(1-methylethyl)-1,3-benzodioxol-5-yl]-2-chloroethanone (**3b**) was isolated in the yield given in Scheme 1. The reactions with **2a**, **2c** and **2d** were carried out in the same way.

Compound **3a**.[9] n_D^{25} 1.527; ν_{max}/cm^{-1} 2976, 1772, 1678, 1614, 1600, 1496, 1441 and 1261; $\delta_H(CDCl_3; Me_4Si)$ 0.97 [12 H, d, *J* 6.8, $(CH_3)_2CH$], 2.31 [2 H, septet, *J* 6.8, $(CH_3)_2CH$], 2.54 (3 H, s, CH_3), 6.72 (1 H, d, *J* 8.1, 7-H), 7.31 (1 H, d, *J* 1.7, 4-H) and 7.48 (1 H, dd, *J* 8.1 and 1.7, 6-H) (Found: C, 72.2; H, 8.25. Calc. for $C_{15}H_{20}O_3$: C, 72.55; H, 8.1%); *m/z* 248 (M^+, 13%), 205 (100), 162 (13) and 55 (19).

Compound **3b**. n_D^{23} 1.548; ν_{max}/cm^{-1} 2977, 1694, 1614, 1602, 1498, 1448 and 1254; $\delta_H(CDCl_3; Me_4Si)$ 0.97 [12 H, d, *J* 6.8,

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* In the ^{13}C NMR spectrum of the freshly prepared system $AlCl_3{\cdot}2CH_3COCl$ at room temperature we have observed a coalescence signal due to the rapid exchange between free and complexed acetyl chloride; the same is expected to occur for trichloroacetyl chloride, that in the studied solution is found to be in excess.

† This aromatic substrate shows only one reactive position, avoiding in this way the competitive reaction observed for phenols, and gives ketone as a unique product with the different chloroacetyl chlorides, in contrast with benzene that reacts further;[8] moreover, it does not co-ordinate $AlCl_3$.[9]

‡ The carbonyl $\Delta\delta$ could be related to the electron-donating ability of the reagent towards a specific Lewis acid.[10]

$(CH_3)_2CH$], 2.32 [2 H, septet, *J* 6.8, $(CH_3)_2CH$], 4.63 (2 H, s, CH_2), 6.74 (1 H, dd, *J* 8.1 and 0.3, 7-H), 7.32 (1 H, dd, *J* 1.8 and 0.3, 4-H) and 7.47 (1 H, dd, *J* 8.1 and 1.8, 6-H) (Found: C, 64.1; H, 6.7. $C_{15}H_{19}ClO_3$ requires C, 63.7; H, 6.8%); *m/z* 282 (M^+, 24%), 241 (72), 239 (100), 162 (13) and 55 (36).

Compound **3c**. n_D^{25} 1.555; ν_{max}/cm^{-1} 2977, 1692, 1614, 1600, 1504, 1452 and 1255; δ_H($CDCl_3$; Me_4Si) 0.98 [12 H, d, *J* 6.8, $(CH_3)_2CH$], 2.33 [2 H, septet, *J* 6.8, $(CH_3)_2CH$], 6.64 (1 H, s, $CHCl_2$), 6.77 (1 H, d, *J* 8.2, 7-H), 7.41 (1 H, d, *J* 1.8, 4-H) and 7.63 (1 H, dd, *J* 8.2 and 1.8, 6-H) (Found: C, 56.6; H, 5.8. $C_{15}H_{18}Cl_2O_3$ requires C, 56.8; H, 5.7%); *m/z* 316 (M^+, 10%), 275 (100), 273 (100), 233 (35), 162 (26), 137 (14) and 55 (28).

Compound **3d**. n_D^{24} 1.552; ν_{max}/cm^{-1} 2977, 1698, 1611, 1601, 1492, 1440 and 1256; δ_H($CDCl_3$; Me_4Si), 0.99 [12 H, d, *J* 6.8, $(CH_3)_2CH$], 2.33 [2 H, septet, *J* 6.8, $(CH_3)_2CH$], 6.75 (1 H, d, *J* 8.4, 7-H), 7.58 (1 H, d, *J* 1.9, 4-H) and 7.88 (1 H, dd, *J* 8.4 and 1.9, 6-H) (Found: C, 51.4; H, 4.9. $C_{15}H_{17}Cl_3O_3$ requires C, 51.2; H, 4.9%); *m/z* 352 (M^+ + 2, 0.3%), 350 (M^+, 0.3), 306 (17), 273 (29), 233 (37), 206 (10), 163 (29) and 55 (100).

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