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Reaction mechanisms

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Identification of Active Surface Species for Friedel–Crafts Acylation and Koch Carbonylation Reactions by in situ Solid-State NMR Spectroscopy**

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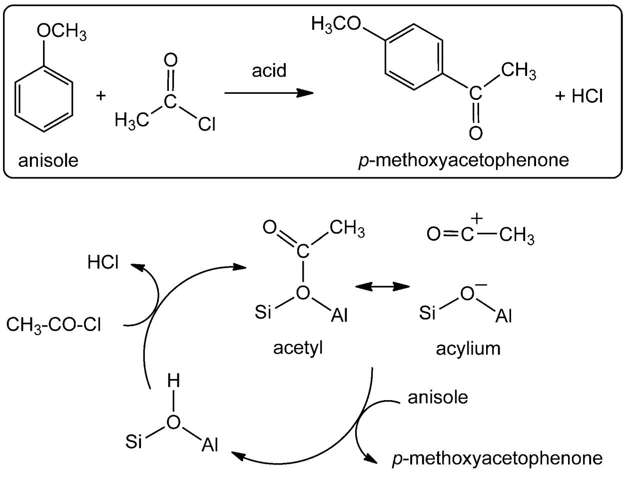
The acid-catalyzed Friedel–Crafts acylation reaction of aromatic rings with acylating agents yields aromatic ketones (Scheme 1) which are common intermediates for the production of fragrances, pesticides, and drugs.[1,2] The industrial process uses Lewis acids as catalysts, typically $AlCl_3$ and other metal halides, and is associated with the production of a large amount of waste. Thus, the development of new processes that satisfy global environmental regulations is imperative.

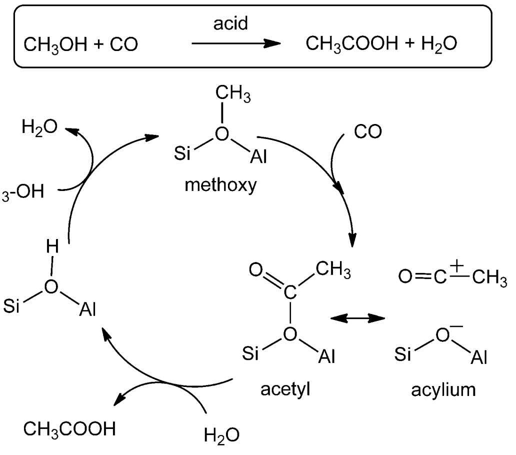


Scheme 1. Friedel–Crafts acylation of anisole over acid zeolites.

A variety of solids, such as micro- and mesoporous aluminosilicates, oxides, clays, and heteropolyacids, have been tested as catalysts in the Friedel–Crafts acylation of aromatic substrates with acyl chlorides, anhydrides, and carboxylic acids as acylating agents.[1,2] Among them, large-pore zeolites are the most promising candidates, because of the large variety of structures available and the possibility of tailoring the acidity, hydrophobic/hydrophilic properties, and selectivity for the *para*-substituted products.[1,2] Indeed, zeolites have already found industrial application as Friedel–Crafts acylation reaction catalysts,[3] although their universal use is still limited by low activity and selectivity, and by catalyst deactivation.

Scheme 1 illustrates the general mechanism of Friedel–Crafts acylation on solid acids for the reaction of anisole with acetyl chloride. It is usually assumed that the acylating agent reacts with the Brønsted acid site to form an acylium cation ($H_3C–C^+=O$), which then attacks the aromatic ring to give electrophilic substitution.[4] In situ magic angle spinning (MAS) NMR spectroscopy has shown that acetyl chloride adsorbed on the $AlCl_3$ Lewis acid catalyst gives rise to the formation of $H_3C–C^+=O$, which is characterized by two signals at $\delta\ ^{13}C = 152$ ppm and $\delta\ ^{13}C = 14$ ppm for the carbonyl and methyl groups, respectively.[5] On the other hand, the ^{13}C MAS NMR spectra of acetyl chloride adsorbed on a series of zeolites show a signal at $\delta\ ^{13}C\ (CO) = 180$ ppm, which is attributed to acetyl species covalently bound to a zeolite framework oxygen atom (Z-CO-CH_3),[6] whereas a second signal at $\delta\ ^{13}C$ (CO) ca. 160 ppm was tentatively assigned to free $H_3C–C^+=O$ species. However, the interpretation of the ^{13}C NMR spectra was not definitive and the issue of which was the reactive species was unclear.[6]

Aside from Friedel–Crafts acylation, other reactions on solid acid catalysts, such as the Koch carbonylation of alcohols or olefins with CO, are assumed to occur through acylium or acetyl species intermediates.[7–18] Scheme 2 shows the mechanism of methanol carbonylation on solid acids. Acylium/acetyl species are formed by insertion of CO into the methoxy



Scheme 2. Carbonylation of methanol with CO over acid zeolites.

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(or, more generally, alkoxy) species generated by the reaction of an alkene or alcohol molecule with a Brønsted acid site of the catalyst. The $H_3C{-}C^{+}{=}O$ or -CO-CH_3 species can be subsequently captured by water to produce acetic acid (Koch reaction), by methanol or dimethyl ether to give methyl acetate, or by ammonia to yield acetamide.[7–18] An acetyl species bound to an oxygen atom of the catalyst has been reported to be the intermediate in the carbonylation of methanol on 12-tungstophosphoric acid catalyst (12-$H_3PW_{12}O_{40}$), based on the appearance of ^{13}C MAS NMR signals at δ ^{13}C (CO) = 193 ppm, and δ ^{13}C (H_3C-) = 22 ppm attributed to CH_3-CO-(O-W-) species.[16] Similar surface acetyl groups, Z-CO-CH_3, have been hypothesized to be possible intermediates in the Koch carbonylation of methanol and dimethyl ether over H-mordenite,[10,11,13,18] and of methane over Zn-ZSM-5 catalysts.[19] However, other authors assume that, on acid zeolites, these reactions occur through the formation of $H_3C{-}C^{+}{=}O$ species as unstable intermediates too reactive to be detected by NMR spectroscopy.[7–9]

The aim of this work is to elucidate whether covalent H_3C-CO-Z or ionic $H_3C{-}C^{+}{=}O$ species are formed in zeolites by reaction of an acylating agent with a Brønsted acid site, and by carbonylation of an alkoxy group. For this purpose, we have combined theoretical calculations and in situ solid-state NMR spectroscopy to study the acylation of anisole over acidic H-Beta (Scheme 1) and the carbonylation of methanol over acidic H-Mordenite zeolite (Scheme 2). The results obtained provide direct experimental evidence of the formation acetyl species covalently bound to framework oxygen as the reactive intermediates in Friedel–Crafts acylation and Koch carbonylation reactions on acidic zeolites.

Figure 1 shows the calculated ^{13}C NMR isotropic chemical shifts (^{13}C δ) of the methyl and carbonyl groups of acetyl chloride adsorbed through hydrogen bonds onto the zeolite Brønsted acid site (Figure 1 a), and of the two possible species resulting from the subsequent reaction and release of hydrogen chloride: the covalent acetyl–zeolite (Figure 1 b) and the cationic acylium–zeolite (Figure 1 c) species. The ^{13}C NMR chemical shifts calculated for the acylium–zeolite complex shown in Figure 1 c agree fairly well with experimental values for this $H_3C{-}C^{+}{=}O$ species on $AlCl_3$, (carbonyl and methyl groups at $\delta = 152$ ppm and $\delta = 14$ ppm, respectively), which supports the validity of the theoretical models. Figure 1 d,e shows the ^{13}C NMR chemical shifts of *para*-methoxy acetophenone (PMAP) obtained by acylation of anisole, and of acetic acid produced by the carbonylation of methanol with CO, respectively, interacting with a zeolite Brønsted acid site. According to the theoretical chemical shifts shown in Figure 1, it should be possible to distinguish between the carbonyl groups of the two reaction intermediates (acetyl–zeolite at $\delta = 169.7$ ppm and acylium–zeolite at $\delta = 154.6$), as they are separated by more than 15 ppm and do not overlap with the reactants and products involved in the two reactions. As the ^{13}C NMR chemical shifts of the methyl group are less conclusive, for the sake of clarity we shall mostly focus on the carbonyl region of the ^{13}C NMR spectra.

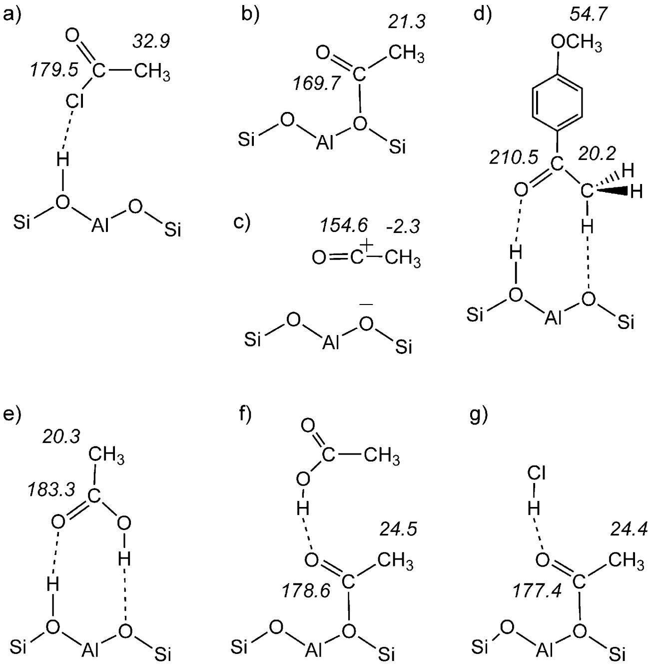

Figure 1. Calculated ^{13}C isotropic chemical shifts of a) acetyl chloride adsorbed on a Brønsted acid site, b) acetyl group covalently bound to a zeolite framework oxygen, c) cationic acylium–zeolite complex, d) *para*-methoxy acetophenone adsorbed on a Brønsted acid site, e) acetic acid adsorbed on a Brønsted acid site, f) covalently bound acetyl interacting with acetic acid, and g) covalently bound acetyl interacting with HCl. The numbers in italics are the calculated isotropic ^{13}C NMR chemical shifts of the associated carbon atoms.

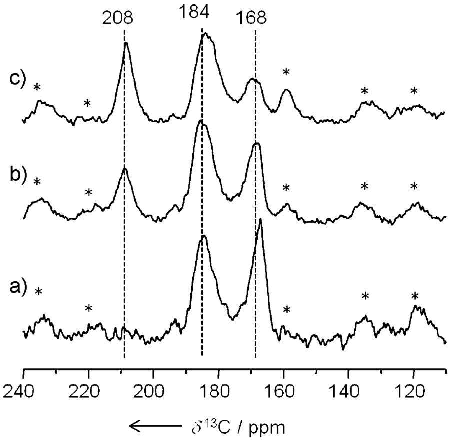

Figure 2. ^{13}C MAS NMR spectra of the $^{13}CH_3{}^{13}COCl$/anisole (molar ratio = 1:1) reaction mixture a) adsorbed at room temperature on H-Beta zeolite. The same sample was then heated at 363 K for b) 90 min and c) 300 min. Asterisks denote spinning side bands.

Figure 2 shows the carbonyl region of the ^{13}C MAS NMR spectra of the reaction mixture for the Friedel–Crafts acylation, $^{13}CH_3{}^{13}COCl$/anisole (1:1), adsorbed at room temperature on H-Beta zeolite (Figure 2 a) and after subsequent heating at 363 K for different periods of time (Figure 2 b,c). The spectrum of Figure 2 a, shows two carbonyl bands at $\delta = 184$ ppm and at $\delta = 168$ ppm. According to theoretical calculations, the band at 184 ppm with a methyl signal at δ $^{13}C = 32$ ppm (not shown) is assigned to $^{13}CH_3{}^{13}COCl$ adsorbed on a zeolite Brønsted acid sites

(Figure 1 a), and the band at 168 ppm must correspond to a covalently bound acetyl–zeolite group (Figure 1 b). Heating the sample at 363 K for 90 min provokes the appearance of a new signal at $\delta = 208$ ppm, which corresponds to *para*-methoxy(^{13}CO)-acetophenone (PMAP) adsorbed on the zeolite (Figure 1 d). We must note that adsorbed PMAP appears about 10 ppm high-field shifted with respect to the free compound ($\delta = 198$ ppm); this is indicative of strong adsorption on the zeolite, which can contribute to catalyst deactivation.[20] The spectrum of Figure 2 c shows that, at longer reaction times, the intensity of the signal of PMAP at 208 ppm progressively increases at the expense of the signal at 168 ppm, which indicates that the covalently bound acetyl–zeolite species is a reactive intermediate in the Friedel–Crafts acylation reaction. It is worth noting the absence of any signal at 150–160 ppm in Figure 2 that could be attributed to $H_3C{-}C^{+}{=}O$ (Figure 1 c), which suggests that this species is not formed.

The signal at δ $^{13}C = 32$ ppm (not shown), which is characteristic of the methyl groups of acetyl chloride (Figure 1), disappears in the spectra of Figure 2 b,c; thus indicating that this compound has reacted, and that the peak at δ $^{13}C = 180$ ppm must correspond to other species. According to the theoretical chemical shifts reported in Figure 1, this is most probably due to acetic acid (Figure 1 e) produced by partial hydrolysis of acetyl 1-2-^{13}C chloride (Figure 1 a) or of acetyl 1-2-^{13}C-zeolite (Figure 1 b) with residual water present in the reaction media. However, hydrogen bonded species such as those depicted in Figure 1 f,g, in which HCl or acetic acid are interacting with the carbonyl group of the acetyl–zeolite species, could also contribute to the signal at $\delta =$ 184 ppm. Indeed, this would explain the increase in the intensity of the signal at 168 ppm of acetyl–zeolite in the spectrum of Figure 3 b, recorded after degassing at 333 K, as compared to the spectrum of Figure 3 a, which was recorded without degassing.

To determine whether covalently bound acetyl–zeolite is also the intermediate species in carbonylation reactions, we studied the reaction of $^{13}CH_3OH$ with ^{13}CO over H-Mordenite zeolite. The carbonyl region of the ^{13}C NMR spectrum of the reaction mixture heated at 473 K on H-Mordenite (Figure 3 c) exhibits a band at 183 ppm that can be attributed to 1-2-^{13}C acetic acid or methyl acetate, and another one at 170 ppm that corresponds to the covalent Z-^{13}CO-$^{13}CH_3$ complex, which disappears at longer reaction times. A comparison of the spectra shown in Figure 3 makes evident the similarity of the intermediate species involved in the two reactions, Friedel–Crafts acylation and carbonylation, on acid zeolites.

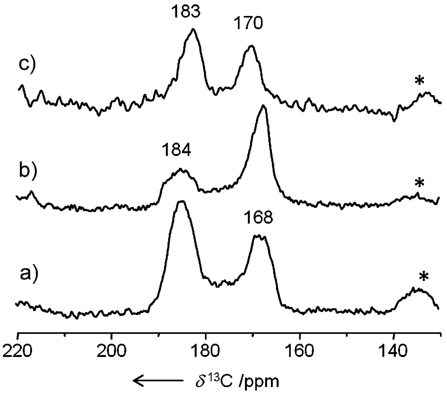

Figure 3. ^{13}C CP-MAS NMR spectra of $^{13}CH_3{}^{13}COCl$ adsorbed on H-Beta zeolite at room temperature and a) heated at 333 K for 2 h, before being b) outgassed at 333 K for 1 h. c) The reaction mixture $^{13}CO/^{13}CH_3OH$ (molar ratio = 3:1) on H-Mordenite zeolite heated at 473 K for 1 min. Asterisks denote spinning side bands.

In summary, in situ solid-state NMR spectroscopy combined with DFT calculations has demonstrated the formation of a covalent acetyl–zeolite complex as reactive intermediate species in both Friedel–Crafts acylation and Koch type carbonylation, while no signal that could be attributed to acylium cation, the usually assumed intermediate species, has been observed in any spectra.

Experimental Section

Acylation reaction: Before any adsorption, zeolite H-Beta (CP811, Zeolyst International) was introduced into a glass insert and dehydrated in a vacuum line at 673 K overnight to a final pressure of 10^{-5} mbar. Then, $^{13}CH_3{}^{13}COCl$(1000 μmol/g zeolite; ^{13}C, 99 %; provided by Isotec) corresponding to a molar ratio of $^{13}CH_3{}^{13}COCl/Al = 0.5$, was introduced onto the activated zeolite before heating the sample at 333 K for 2 h without degassing. The glass insert containing the sample was sealed and used for recording NMR spectra. A second sample was prepared in a similar way, but before being sealed it was heated for 1 h at 333 K under vacuum. To study the acylation reaction, a third sample was prepared in a similar way as the latter, but with a molar ratio of $^{3}CH_3{}^{13}COCl/anisole = 1$ added before sealing the glass insert. To follow the reaction, the sample was treated at 363 K outside of the NMR probe, progressively increasing the reaction time. In all cases, sealing was carried out with a torch while the glass insert was immersed in liquid nitrogen.

Koch reaction: H-Mordenite was obtained by calcination of a commercial mordenite (ammonium form) with a Si/Al = 10 (CBV20A, Zeolyst International) at 673 K over 2 h. Subsequently, $^{13}CH_3OH$ (730 μmol/g zeolite; ^{13}C, 99 %; Cambridge Isotope Laboratories) and then ^{13}CO (2200 μmol/g zeolite; ^{13}C, 99 %; Isotec) were admitted into the glass insert immersed into liquid nitrogen. The molar ratios used were $^{13}CH_3OH/Al = 1{:}2$ and $^{13}CO/^{13}CH_3OH =$ ca. 3:1. The glass inserts were sealed while they were immersed in liquid nitrogen. The NMR spectra were recorded after the sample was treated at 473 K outside of the NMR probe with progressively increasing reaction time.

Solid-state NMR spectra were recorded at room temperature on a Bruker AV 400 WB spectrometer. ^{13}C MAS NMR spectra were recorded with proton decoupling, a 90° pulse of 5 μs, and a recycle delay of 15 s. The ^{1}H to ^{13}C (^{1}H/^{13}C) CP-MAS spectra were recorded with a 90° pulse for ^{1}H of 5 μs, a contact time of 3.5 ms, and a recycle delay of 5 s.

Computational details: The Brønsted acid site was simulated by means of a $Al(OSiH_3)_3(OH)SiH_3$ cluster of atoms that was cut out from the periodic structure of a BEA zeolite, as described in previous work.[21] It consists of one Al atom, the four OSi groups in the first coordination sphere, the proton of the Brønsted acid site, and the H atoms that were used to saturate the dangling bonds that connected the cluster to the rest of the solid. The geometries of the acid site, isolated molecules, and complexes resulting from adsorption of reactants and products on the acid site were optimized using density functional theory at the B3PW91 level[22,23] with the standard 6-31G(d,p) basis set,[24] as implemented in the Gaussian 03 computer program.[25] In these calculations, the coordinates of all atoms were fully optimized, except for the terminal H atoms of the SiH_3 groups, which were kept fixed at their original positions to avoid unrealistic deformations. Isotropic absolute chemical shielding constants (σ) were calculated at the B3PW91/6-31G(d,p) level using the gauge including atomic orbitals (GIAO) approach,[26,27] and ^{13}C chemical shifts were calculated as $\delta = \sigma_{ref} - \sigma$, and corrected with equations obtained from a preliminary study of the performance of the B3PW91 functional.[21]

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