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Heterogeneous catalysis for the acetylation of benzo crown ethers

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Abstract

Heterogeneous catalytic acetylation of benzo-15-crown-5 was investigated using solid Lewis acids consisting of sulfated zirconia calcined at 625°C or K10 exchanged by Cu, Zn, Fe or Sn ions and treated at 250°C. The nature of the transition metal ions introduced in the mesoporous clay plays an important role in the activity of the catalysts. Sn-exchanged K10 shows the best catalytic properties and could suit for practical preparative purposes. 4′-Acetyl-benzo-15-crown-5 was produced with 90% yield under optimal conditions. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The acetylation of benzo-15-crown-5 (B15C5) crown ether yields 4′-acetyl-benzo-15-crown-5 (4′Ac-B15C5) (Scheme 1) which is a key intermediate for a variety of technological products including complexants for the separation of radioactive cations, ionophore antibiotics and phase transfer catalysts. The preparation of 4′Ac-B15C5 is then of practical importance. This acetylation can be performed in a Friedel–Crafts type reaction with the classical Lewis acid $AlCl_3$ with poor yield (only about 30%) in the presence of a very large excess of catalyst

([catalyst]/[substrate] about 5.5) [1] because of the formation of a stable $AlCl_3$–crown ether complex [2]. The acetylation can be carried out with P_2O_5 or polyphosphoric acid as catalysts [3,4], but these homogeneous catalytic reactions give rise to serious corrosion and environmental problems. Moreover, the separation of the products is difficult and the practical application of these reactions is therefore limited. The substitution of liquid acids by solids acids as catalysts in this process is therefore particularly attractive. Exchanged clays have been earlier proposed for Friedel–Crafts alkylation [5–9] and were possible candidates.

We reported recently that K10 acidic clay and its copper–ion exchanged form, Cu^{2+}-K10 could be applied as catalysts for this reaction [10]. However, the reaction had to be optimized,

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Scheme 1.

and we present here the comparison of different cation-exchanged clays. Sulfated zirconia is known to be a strong Lewis acid after calcination above 600°C [11–13] and was compared to exchanged clays in order to learn the role of the catalyst. An effort has also been done to clarify the mechanism of formation of the by-products, and investigate the possible recycling of the catalyst.

2. Experimental

2.1. Catalysts preparation

K10 clay, manufactured by high temperature acidic treatment of bavarian montmorillonite, was purchased from Süd Chemie (Germany) and used as received. Cation exchange was performed with the method of Rhodes et al. [14] by gradually adding 10 g K10 clay to 125 ml, 1 mol l^{-1} stirred solution of $CuCl_2$, $FeCl_3$, $ZnCl_2$ or $SnCl_2$ at room temperature and stirring the suspension for 24 h. After exchange, the suspensions were filtered and washed with deionised water. The resulting solids were dried, and calcined at 250°C.

Sulfated zirconia was prepared as follows [15]: 0.51 ml of sulfuric acid were added to the mixture of 20 ml of $Zr(OC_3H_7)_4$ and 26.6 ml of n-propanol and stirred for 30 min at room temperature. The hydrolysis and gelation were obtained by adding dropwise 3.2 ml of water. The gel was then dried at 120°C for 12 h. Finally, the solid was calcined at 625°C for 4 h under flowing air $(8 \ 1 \ h^{-1})$ in a quartz tube inside a tubular furnace. This sample shows an XRD spectrum of a pure tetragonal structure, contains 1.8% S after calcination and is iron-free.

The main characteristics of these solids are reported in Table 1.

2.2. General reaction conditions

The reactor was a three neck glass reactor, in which were introduced 15 ml 1,2-dichloroethane, 0.54 g B15C5 crown ether, 0.75 ml acetyl chloride (AcCl) and 0.3–1 g of catalyst. The reaction was performed at 83°C (boiling point of the solvent) and was monitored by HPLC (C18 reversed phase column, UV-detection — 254 nm, methanol/water = 50/50 (v/v) as eluent, 2,4-dinitrotoluene as internal standard).

Table 1
Metal content and textural characteristics of the catalysts

Catalyst	Specific surface area $(m^2 \ g^{-1})$	Surface area of micropores $(m^2 \ g^{-1})$	Fe content (wt.%)	Metal retained (wt.%)
K10	229	2.5	1.97	
Cu^{2+}-K10	236	–		$Cu^{2+} = 1.24$
Zn^{2+}-K10	213	–		$Zn^{2+} = 1.19$
Fe^{3+}-K10	239	10	2.92	$Fe^{3+} = 0.95$
Sn^{2+}-K10	240	23.6		$Sn^{2+} = 5.5$
SO_4–ZrO_2	122	–	< 1 ppm	

Table 2
Investigation of the reaction conditions for Cu^{2+}-K10 catalyst

B15C5 concentration (g/100 ml)	Component ratio (mol/mol)		4′Ac-B15C5% (time to reach the final level)	By-products (%)
	Cu^{2+}/B15C5	AcCl/B15C5		
0.18	0.2	20	42 (3 h)	traces
3.6	0.2	20	66 (1 h)	11
3.6	0.1	5	60 (2 h)	10
9	0.1	5	64 (1.5 h)	8

2.3. Recycling of the catalyst

At the end of the reaction, the catalyst was filtered, washed with 1,2-dichloroethane, dried at 130°C for 50 min, and re-used in another reaction.

3. Results

The former results [10] were obtained in a rather diluted reaction medium and a simple kinetic study was performed in order to define better conditions. The results reported in Table 2 show that a yield of about 66% can be reached in a short time using a concentration of crown ether of 3.5%–9% which would be acceptable in practice. The reaction conditions found good for Cu^{2+}-K10 (3.6 g B15C5/100 ml, 0.1 mol Me^{n+}/mol B15C5, 5 mol AcCl/mol B15C5) were also the optimum conditions for Fe^{3+}-K10 and were used for all solids.

3.1. Comparison of different cation-exchanged catalysts

The comparison of the activities is presented on Fig. 1, in which the yield of the acetylated product is plotted in function of time. The initial concentration C_0 of the solution is about 1.2×10^{-4} mol ml^{-1}, and the rate v estimated from the first experimental point at 30 min is at most 6×10^{-7} mol s^{-1} g^{-1} of catalyst. Since the catalyst is used as a powder of radius R about 0.01 cm, and the diffusion coefficient D_{eff} in
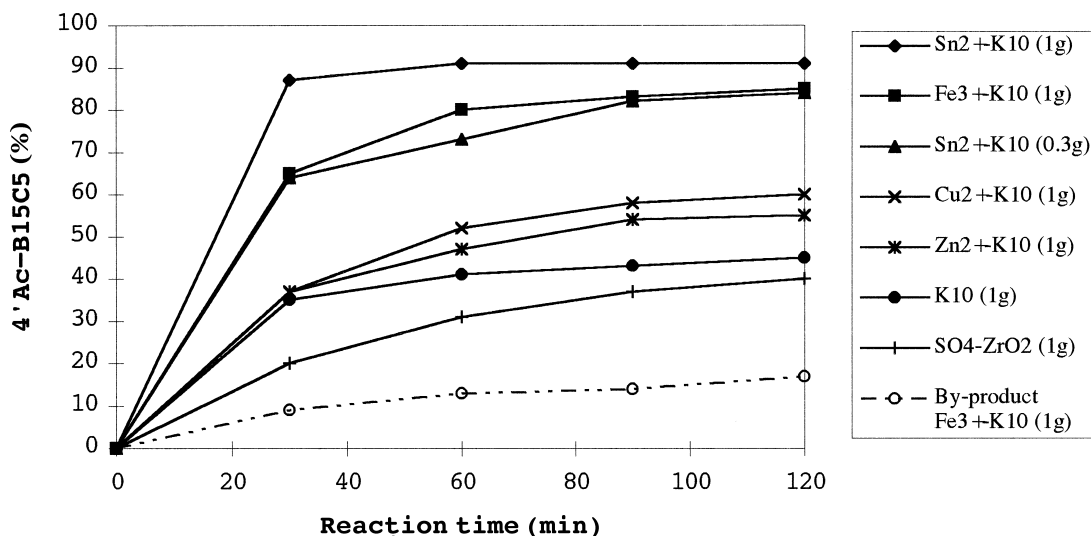

Fig. 1. Yield of acetylated crown ether as a function of time for different catalysts.

liquids is about 10^{-5} cm^2 s^{-1} [16], the Thiele modulus $\Phi = \upsilon R^2/(C_0 D_{\text{eff}})$ is close to 0.06, clearly below 0.1 and diffusion would not perturb the overall process even with Sn^{2+}-K10.

Sn^{2+}-K10 shows an outstanding activity since the reaction is practically completed within 30 min, even in the presence of a rather small amount of catalyst. Indeed the activity of Sn^{2+}-K10 is about three times higher than that of Fe^{3+}-K10 as evidenced on Fig. 1. It can be pointed out that sulfated zirconia calcined at 625°C shows a modest activity in spite of its strong Lewis acidity.

The selectivity also changes with the cation exchange in K10 catalysts as illustrated in Fig. 2, where the yield of the major product and the overall yield of by-products are compared. Sn^{2+}-exchanged K10 is the best catalyst, also in this aspect.

The acetylation reaction in all cases has reached rapidly the final conversion. It is also remarkable that the amount of the by-products was continuously growing, especially in case of Fe^{3+}-K10 when a decrease was observed in 4′Ac-B15C5 level (Fig. 1). These tendencies refer to a possible consecutive formation of the
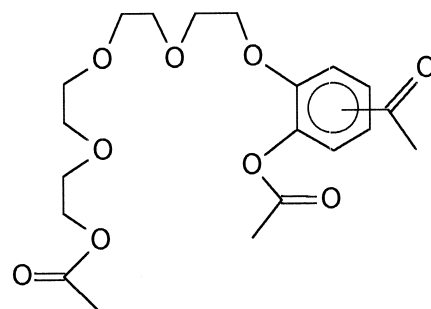

Fig. 3. Structure for the main by-product.

by-products. It was confirmed by the fact that neither the substrate B15C5 nor the desired product 4′Ac-B15C5 are converted on Fe^{3+}-K10 in the absence of the acetylating agent AcCl. On the other hand 4′Ac-B15C5 + AcCl in the presence of the catalyst produces quickly these by-products. By LC-MS technique an intensive $M^+ = 430$ molecular ion peak (containing $M^+ = 18$ NH$_4^+$ ionizating particles) could be detected for the most important by-product. This $M = 412$ molar mass, i.e., an increase of 102 compared to 4′Ac-B15C5, corresponds exactly to the molar mass of a triacetyl derivative shown in Fig. 3. Formation of this by-product is possi-
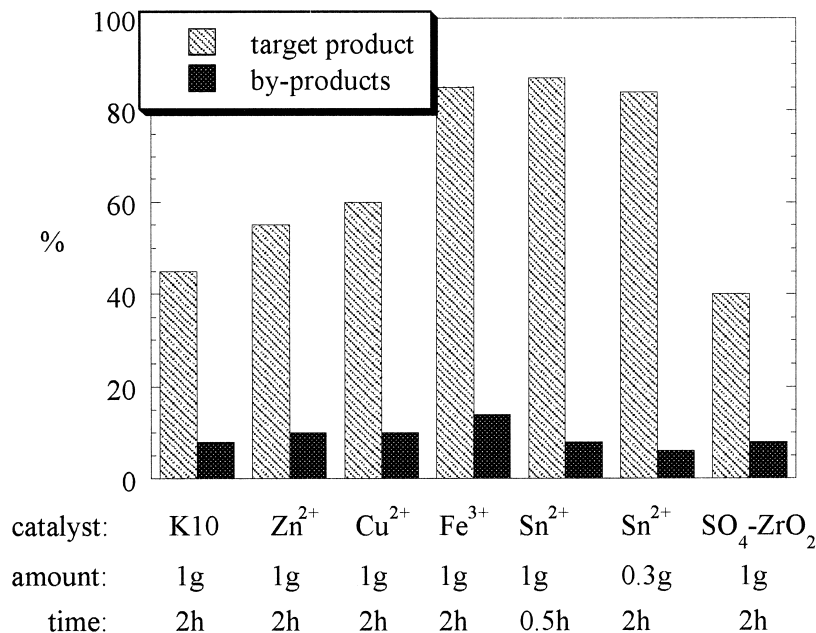

catalyst:	K10	Zn^{2+}	Cu^{2+}	Fe^{3+}	Sn^{2+}	Sn^{2+}	SO$_4$-ZrO$_2$
amount:	1g	1g	1g	1g	1g	0.3g	1g
time:	2h	2h	2h	2h	0.5h	2h	2h

Fig. 2. Selectivities of the different catalysts for acetylation.

Table 3
Recycling of the Fe^{3+}-K10 sample

	4'Ac-B15C5%		By-products (%)
	0.5 h	2 h	
First reaction	65	87	14
Second use	58	66	11
Third use	42	57	10

ble in a HCl-catalyzed aryl alkyl ether type splitting [17] of the crown ring followed by double acetylation. This proves that the major pathway of the formation of by-products proceeds via further acetylation of the primary acetylated product. Indeed this is confirmed by the observation that the lower part of the HPLC chromatogram (which contains the peaks of by-products) of the final reaction mixture of B15C5 + AcCl and that of the 4'Ac-B15C5 + AcCl on Fe^{3+}-K10 have exactly the same characteristics. It is then reasonable to conclude that the by-products formation proceeds via consecutive steps.

3.2. Recycling of the catalysts

The most important advantage of the heterogeneous Friedel–Crafts reaction catalysed by cation-exchanged K10 is the possibility of the recycling of the used catalysts. For testing this we have made some experiments with the Fe^{3+}-K10 sample and summarized in Table 3.
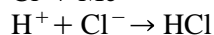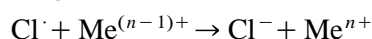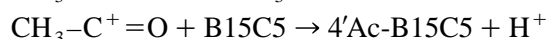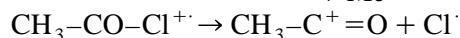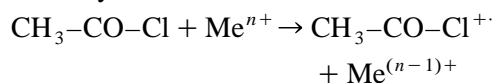
The reutilization of the used catalysts is possible with good conversion after simple washing and drying. The original conversion can be obtained by introducing a small additional amount of fresh catalysts.

4. Discussion

The Lewis and Bronsted acidities of these clay catalysts determined from pyridine adsorption have been reported before [9] and showed a change from a dominant Bronsted acidity after drying at 120°C to a dominant Lewis acidity after treatment at 500°C. The recent results by Brown and Rhodes [18] show that the maximum of Bronsted acidity is reached at 150°C, that of

Lewis acidity at 250°C–300°C and it is not significantly changed by thermal activation above this temperature. Our previous measurements of Lewis/Bronsted acidities on samples calcined at 500°C can therefore be used here for clays treated at 250°C. Concerning sulfated zirconia, previous work [11,12] shows that the solid is a strong Lewis acid after calcination above 500°C, but the comparison with clays requires to know the number of acid sites which has been determined by adsorption of ammonia. The number of sites for a Fe^{3+}-K10 sample calcined at 250°C is 0.22 mmol g^{-1} [18], while the total number of sites measured on the sample of sulfated zirconia used here was 0.38 mmol g^{-1}. It can be pointed out that the activity is significantly higher for the Fe^{3+}-exchanged clay showing a lower number of acid sites.

From the former measurements of acidity the pattern for Lewis acidity is Sn ≈ Zn > Cu > Fe, while the pattern for activities appears to be Sn > Fe > Cu ≈ Zn. The relative position of Fe and Zn is then reversed. Indeed calcination of the original Sn^{2+}-exchanged clay at 250°C most likely results in a partial oxidation to Sn^{4+} and the best catalysts appear then to be those which can be reduced. Pure K10 and Zn^{2+}-K10 also contain Fe and can also initiate redox processes. This observation and the fact that Fe-free sulfated zirconia in the Lewis form is a poor catalyst suggest that the redox mechanism earlier proposed for alkylation [9] could constitute an alternative pathway for the formation of carbocations. In this mechanism a charge transfer complex should be formed which loses a Cl radical and gives a carbocation. This can be formally written as:

$$CH_3-CO-Cl + Me^{n+} \rightarrow CH_3-CO-Cl^{+\cdot}$$
$$+ Me^{(n-1)+}$$
$$CH_3-CO-Cl^{+\cdot} \rightarrow CH_3-C^+=O + Cl^{\cdot}$$
$$CH_3-C^+=O + B15C5 \rightarrow 4'Ac\text{-}B15C5 + H^+$$
$$Cl^{\cdot} + Me^{(n-1)+} \rightarrow Cl^- + Me^{n+}$$
$$H^+ + Cl^- \rightarrow HCl$$

In conclusion, benzo crown ethers can be acetylated by acetyl chloride with good yields,

at low temperature using ion exchanged clays as catalysts. The best catalyst in this process is an Sn-exchanged clay, and the results reported here in the acetylation with acetyl chloride show the same behaviour previously reported for the alkylation of toluene by benzylchloride, suggesting that a redox mechanism could be envisaged in both cases.

Acknowledgements

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