Reaction Mechanisms

Establishing a Molecular Mechanism for the Beckmann Rearrangement of Oximes over Microporous Molecular Sieves**

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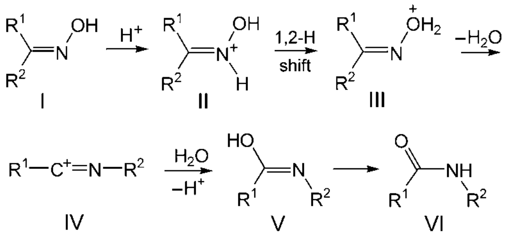
The Beckmann rearrangement constitutes a common route employed in organic chemistry to transform ketoximes into amides. One of the main industrial applications is the transformation of cyclohexanone oxime into ε-caprolactam, a raw material in the production of nylon 6. The conventional liquid-phase industrial process uses sulfuric acid or oleum as catalysts and is accompanied by the coproduction of large amounts of undesired ammonium sulfate.[1] To solve the problems derived from the use of concentrated sulfuric acid and the generation of this by-product, many solid-acid catalysts have been tested, including zeolites and zeotypes, mesoporous materials, and oxides.[2,3] Recently, Sumitomo Chemical Co. commercialized an environmentally friendly gas-phase heterogeneous process with a high-silica zeolite as the catalyst. The process has been in operation in a new production plant in Japan since 2003.[4]

Though catalytic performance over solids with acidity of a different nature and strength has been tested, the nature of the active sites in the catalysts for the Beckmann rearrangement is still a matter of controversy. In previous publications, strong Brønsted acid sites in zeolites were reported to catalyze the rearrangement.[5,6] Later, it was shown that these sites favor the formation of by-products, and that both the activity and selectivity of the amide is improved in the presence of high-silica zeolites with intermedium or weak Brønsted acid sites.[2,3,7] Finally, it has been suggested that weakly acidic or neutral silanol groups or silanol nests are active catalysts of the rearrangement reaction.[2,3,7,8] Discrepancies are also found in the location of the active sites, which have been proposed to be inside the micropores,[9,10] just at the aperture,[11] or at the zeolite surface.[2,3,7,8]

The reaction mechanism commonly assumed for the Beckmann rearrangement is described in Scheme 1.[5] This pathway initially involves the protonation of the oxime at the oxygen atom to give an oxonium cation III, followed by the migration of the alkyl group *anti* to the hydroxy group, the liberation of water, and the formation of a nitrilium cation IV. Cation IV is then hydrolyzed to give V, which finally tautomerizes to the corresponding amide VI. Ab initio molecular-orbital calculations on the isolated gas-phase system suggest that the first step is the N protonation of the oxime to give II, and that the rate-determining step is the 1,2-H shift to give the *O*-protonated oxime III.[12] More recently, quantum-chemical investigations suggested that the transfer of the alkyl group and simultaneous elimination of water to form the nitrilium ion IV is the rate-determining step when the gas-phase reaction occurs over oxide catalysts.[13] Nevertheless, despite numerous investigations, at present there is no experimental proof, and the Beckmann rearrangement reaction pathway is not yet well established.



Scheme 1. Generally accepted reaction mechanism for the Beckmann rearrangement.

Herein, we present experimental evidence on the identity of the intermediates formed in the initial stages of the Beckmann rearrangement, through a combination of solid-state NMR spectroscopy and theoretical calculations. For this investigation we chose acetophenone oxime as the reactant (which is transformed into acetanilide) and two beta zeolites as catalysts: pure siliceous beta-D, and Al-containing H-beta-D with Brønsted acid sites. Zeolite beta has a three-dimensional 12-ring channel system with a pore aperture of 0.7 nm,[14] which is able to host acetophenone oxime. We show that the *N*-protonated oxime is formed over Brønsted acid centers, but not over weakly acidic silanol groups.

Scheme 2 shows the models that result from the interaction of a molecule of acetophenone oxime with the $Si(OSiH_3)_3OH$ and $Al(OSiH_3)_3(OH)SiH_3$ clusters, as models

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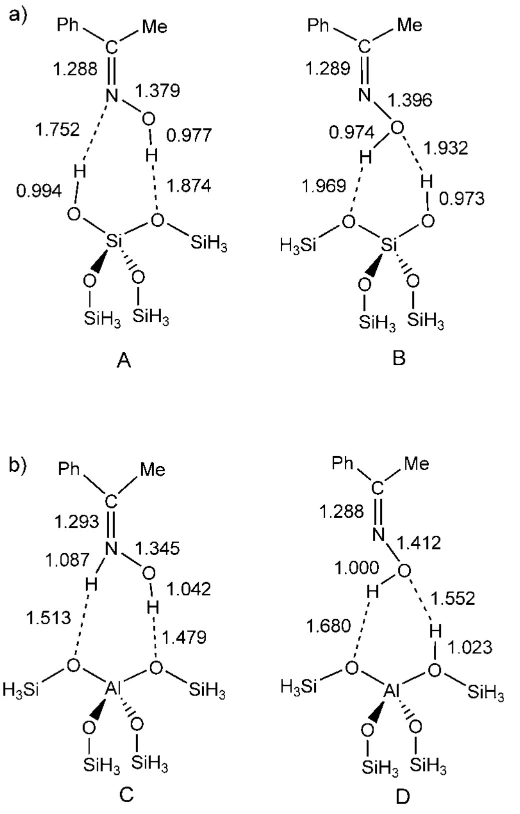

Scheme 2. Optimized structures of acetophenone oxime adsorbed on a) beta-D and b) H-beta-D cluster models. The oxime interacts with the zeolite hydrogen atoms through its nitrogen atom in A and C and through its oxygen atom in B and D. Interatomic distances are expressed in angstroms.

of the silanol-group and Brønsted acid sites, respectively, in the beta zeolites. Silanol defect groups are present in zeolites beta-D and H-beta-D, whereas Brønsted acid sites only exist in the Al-containing H-beta-D. The complexes in Scheme 2 are obtained by assuming that the hydrogen atom of the silanol (A, B) or Brønsted acid centers (C, D) of zeolite beta interacts with the nitrogen (A, C) or oxygen atom (B, D) of the acetophenone oxime molecule. The main distances obtained from the optimization of the geometry of the clusters by using the density functional B3PW91/6-31G(d,p) method are also indicated in Scheme 2. When silanol groups are considered (Scheme 2a), the distances between the H atom of the oxime hydroxy group and the oxygen atom of the zeolite framework are characteristic of hydrogen bonds. The same is true for the distances between the H atom of the zeolite Si–OH group and the nitrogen and oxygen atoms of the oxime in models A and B, respectively (Scheme 2a). Therefore, according to these calculations, no hydrogen-atom transfer occurs from the zeolite hydroxy group, and consequently the acetophenone oxime is not protonated at the N or O atoms. Table 1 summarizes the adsorption energies and the isotropic chemical shifts of the C=N group calculated for the oxime in both its isolated form and in complexes A and B (Scheme 2a). Only a small difference is observed in the energies of the two complexes: Model A, in which the zeolite hydroxy group forms a hydrogen bond with the N atom of the oxime, is slightly more stable. The calculated ^{13}C chemical shift of the carbon atom in the C=N bond is similar in both complexes, and shifted slightly downfield with respect to that of the free oxime. The ^{15}N chemical shift is displaced upfield in model A and downfield in model B relative to that of the oxime.

Table 1: Adsorption energies calculated for models A–D (Scheme 2) along with ^{13}C and ^{15}N NMR isotropic chemical shifts, $\delta(^{13}C)$ and $\delta(^{15}N)$, of the C=N group of acetophenone oxime, both isolated and in models A–D.

	E_{ads} [kcal mol^{-1}]	$\delta(^{15}N)_{calcd}$ [ppm][a],[b]	$\delta(^{13}C)_{calcd}$ [ppm][a],[c]	$\delta(^{15}N)_{exp}$ [ppm][b],[d]	$\delta(^{13}C)_{exp}$ [ppm][c],[d]
oxime		−36.7	157.8	−36.8	155.8
model A	−11.9	−51.9	160.3	−37.8	158.0
model B	−7.8	−26.2	160.4	−29.3	164.2
model C	−27.7	−138.6	165.7	−150.6	166.0
model D	−17.2	−31.2	166.9		

[a] Chemical shifts derived from theoretical calculations. [b] Chemical shifts are expressed in ppm relative to nitromethane. [c] Chemical shifts are expressed in ppm relative to tetramethylsilane. [d] Chemical shifts observed experimentally.

A different situation appears when acetophenone oxime is adsorbed over the Brønsted acid sites in zeolite beta (Scheme 2b). The complex resulting from the interaction of the oxime oxygen atom with the zeolite acid center (Scheme 2D) is similar to the equivalent complex with the zeolite silanol center (Scheme 2B), but with stronger, shorter hydrogen bonds and thus larger displacements of the ^{15}N and ^{13}C chemical shifts relative to those of the isolated oxime. However, a different result is obtained when the oxime interacts through the nitrogen atom (Scheme 2C). In this case, a very short distance to the acidic hydrogen atom of the zeolite emerges, typical of a N–H bond, thus indicating the complete transfer of the proton and formation of the *N*-protonated oxime. Inspection of the energies calculated for complexes C and D (Table 1) indicates that the former is more stable, and that the formation of the *N*-protonated oxime over the Brønsted acid sites is favored. According to theoretical calculations, the protonation results in a large upfield displacement of the ^{15}N chemical shift, whereas the ^{13}C resonance is shifted slightly downfield.

Figure 1 shows the ^{1}H-to-^{13}C (^{1}H/^{13}C) and ^{1}H-to-^{15}N (^{1}H/^{15}C) cross-polarization magic-angle spinning (CP MAS) NMR spectra of free acetophenone oxime, and acetophenone oxime on zeolites beta-D and H-beta-D. The ^{13}C and ^{15}N NMR spectra of the solid oxime (Figure 1a,a′) contain a peak at $\delta = 155.8$ and -36.8 ppm, respectively; these values are very close to those calculated theoretically (see Table 1). When acetophenone oxime is mixed with zeolite beta-D, the signals in the ^{13}C and ^{15}N NMR spectra become broader, and are displaced slightly, thus indicating that acetophenone oxime interacts effectively with the zeolite (Figure 1b,b′). After the system has been heated at 473 K, the spectra change considerably, with new signals appearing at $\delta = 172$ and -246 ppm in the ^{13}C and ^{15}N NMR spectra, respectively (Figure 1d,d′). The new signals are attributed to acetanilide, which is the product of the Beckmann rearrangement. Although the spectra are poorly resolved, at least two main

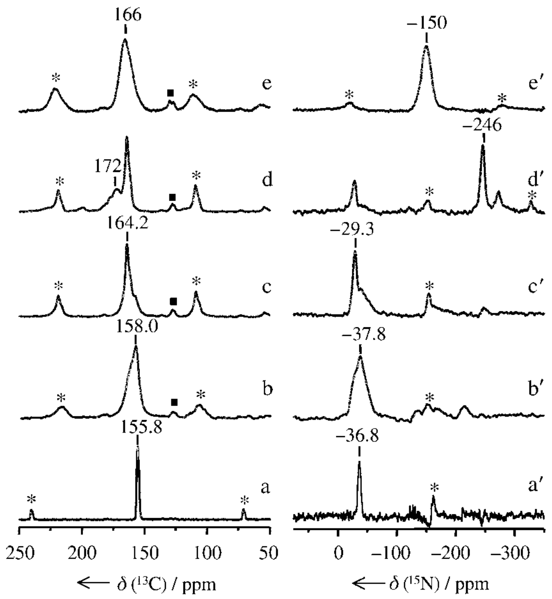

Figure 1. $^1H/^{13}C$ (a–d) and $^1H/^{15}N$ (a′–d′) CP MAS NMR spectra recorded at room temperature of (α-^{13}C,^{15}N)acetophenone oxime: pure (a, a′); over zeolite beta-D before (b, b′) and after heating the system at 423 K (c, c′) and 473 K (d, d′); over zeolite H-beta-D (e, e′). The asterisks indicate the spinning sidebands, and the squares the resonance of the aromatic carbon atoms.

components are apparent in the ^{13}C and ^{15}N spectra recorded both before (Figure 1 b,b′) and after (Figure 1 c,c′) heating the system at 423 K. The maximum of the main signal appears at $\delta = 158.0$ ppm in the ^{13}C NMR spectrum and $\delta = -37.8$ ppm in ^{15}N NMR spectrum recorded before treatment, and is displaced to $\delta = 164.2$ and -29.3 ppm, respectively, after the mixture has been heated at 423 K. The evolution of the signals in the spectra b,b′ and c,c′ in Figure 1, and comparison with the ^{13}C and ^{15}N chemical shifts calculated for complexes A and B (see Table 1), allows the assignment of the signals as given in Table 1. This assignment is mainly based on the variation of the ^{13}C, and in particular the ^{15}N, chemical shifts calculated for the acetophenone oxime in complexes A and B relative to those of the isolated oxime. The formation of oxime complexes hydrogen bonded through N has also been suggested previously on the basis of ^{15}N NMR spectroscopy for silicalite-1.[15]

The experimental spectra shown in Figure 1 a,a′,b,b′ can be interpreted as follows: The silanol hydroxy groups of the zeolite form hydrogen bonds with the nitrogen and oxygen atom of the acetophenone oxime to give complexes A and B (Scheme 2 a). Whereas the H bonding with the oxime occurs mainly through the nitrogen atom before treatment, interaction with the oxygen atom is preferred after heating. This interpretation is also consistent with the slightly higher stability calculated for the adsorption model A.

When acetophenone oxime is mixed with zeolite H-beta-D, the spectra in Figure 1 e,e′ are obtained. A dramatic upfield shift of the ^{15}N NMR signal relative to that of the free oxime is observed. The position of the signal is consistent with protonation of the oxime at the N atom.[15] This interpretation is further supported by the chemical shift calculated for complex C (see Table 1). Thus, the *N*-protonated oxime is formed immediately at the Brønsted acid sites at room temperature. This result is also coherent with the higher stability of complex C. No other species are observed in the NMR spectra of this system until the rearrangement starts at 373 K.

The results reported herein shed light on the reaction mechanism of the Beckmann rearrangement of oximes to amides on solid catalysts. As in the liquid phase, the *O*- and/or *N*-protonated oxime is usually assumed to be the initial reaction intermediate, whereby protonation at N is very favorable according to quantum-chemical calculations.[12] The theoretical calculations and the experimental results presented herein indicate that the silanol groups in zeolites are not acidic enough to protonate the oxime before its transformation into acetanilide (at 473 K), whereas the N protonation occurs readily over Brønsted acid sites at room temperature. As both sites are catalytically active, there are at least two possible reaction pathways for the Beckmann rearrangement, depending on the acid strength of the active center. We recognized the formation of the intermediates depicted in Scheme 2: complexes A and B over silanol groups and complex C over Brønsted acid sites in zeolites, and no other intermediate species were detected by NMR spectroscopy. Further investigations are now required to complete our understanding of the reaction pathways and to identify the rate-determining step of the Beckmann rearrangement over different active sites.

Experimental Section

Computational details: The structures of pure-silica zeolite beta and the nine different Al-substituted systems, obtained by introducing one Al atom at each of the nine crystallographically different T positions of beta zeolites, were optimized by molecular-mechanics techniques by using the GULP code[16] and the force field derived by Schröder and Sauer.[17] Two clusters of atoms were then cut out of the optimized structures of the pure-silica and T9-Al-substituted beta zeolites (the T9 site was found to be the most favorable substitution site); each cluster contained the T9 atom and two coordination spheres around it. The bonds that connected the clusters with the rest of the solid were saturated with H atoms at 1.49 Å from the Si atoms, and orientated toward the O atoms that occupied the next coordination sphere in the crystal. A silanol defect was created by substituting one siloxy ($OSiH_3$) group in the pure-silica cluster by one hydroxy (OH) group. The resulting $Si(OSiH_3)_3OH$ cluster is denoted as model beta-D. In a similar way, a Brønsted acid site was created by introducing one H atom into the Al-containing cluster. The resulting $Al(OSiH_3)_3(OH)SiH_3$ system is denoted as model H-beta-D. The geometries of the beta-D and H-beta-D clusters, of acetophenone oxime, and of the complexes formed by adsorption of the oxime on each cluster (structures A–D, Scheme 2) were optimized by using the density functional method B3PW91[18] and the standard 6-31G(d,p) basis set.[19] In these calculations, the coordinates of all atoms except the H atoms of the SiH_3 groups were fully optimized.

Isotropic absolute chemical-shielding constants σ were calculated with the B3PW91/6-31G(d,p) method on geometries optimized at the same level by using the gauge including atomic orbitals (GIAO) approach.[20,21] ^{15}N and ^{13}C NMR chemical shifts were calculated as $\delta = \sigma_{ref} - \sigma$ and corrected with the equations obtained from a preliminary study of the performance of B3PW91 functional. In this preliminary study, a least-squares fit of calculated against experimental chemical shifts for a set of 23 N-containing and a set of 30 Ccontaining molecules was performed. The root-mean-square errors obtained were 4.6 and 0.7 ppm for $\delta(^{15}N)$ and $\delta(^{13}C)$, respectively. For comparison with the experimental data, the references chosen were nitromethane for the ^{15}N NMR and tetramethylsilane for the ^{13}C NMR spectra; the calculated absolute chemical-shielding constants are $\sigma(^{15}N) = -108.381$ ppm and $\sigma(^{13}C) = 194.893$ ppm.

All calculations in this work were performed by using the Gaussian98 computer program.[22]

Solid-state NMR spectroscopy: Zeolite H-beta-D with Si/Al = 12.5 is commercially available (zeolyst CP811); zeolite beta-D was synthesized hydrothermally by the procedure described previously.[10] Acetophenone oxime was synthesized from (α-^{13}C)acetophenone (99%) and hydroxyl(^{15}N)amine hydrochloride (98%; both from Cambridge Isotope Laboratories) in a mixture of ethanol and sodium acetate at 368 K. The oxime was recrystallized from ethanol before use and identified by NMR spectroscopy. The zeolite (300 mg) was degassed at 723 K and mixed with acetophenone oxime CH_3-$(C_6H_5)^{13}C{=}^{15}N{-}OH$ (25 mg), a solid at room temperature, under an inert atmosphere. A portion of the mixture was introduced into a glass insert, which was sealed after a second degasification at room temperature. The NMR spectra were recorded at room temperature on a Bruker AV 400 WB spectrometer with a BL7 probe, with the samples spinning (MAS) at a rate of approximately 5 kHz. The ^{1}H-to-^{13}C (^{1}H/^{13}C) cross-polarization spectra were acquired by using a 90° pulse for ^{1}H of 5 μs, a contact time of 5 ms, and a recycle delay of 3 s. The ^{1}H-to-^{15}N (^{1}H/^{15}N) cross-polarization spectra were recorded with a 90° pulse for ^{1}H of 5 μs, a contact time of 5 ms and a recycle delay of 3 s.

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[1] *Encyclopedia of Chemical Technology*, 4th ed., Wiley, New York, **1992**, 827 – 838.

[2] G. Dalhhoff, J. P. M. Niederer, W. F. Hölderich, *Catal. Rev.-Sci. Eng.* **2001**, *43*, 381 – 441.

[3] T. Tatsumi in *Fine Chemicals through Heterogeneous Catalysis* (Eds.: R. A. Sheldon, H. van Bekkum), Wiley-VCH, **2001**, 185 – 204.

[4] H. Ichihashi, M. Kitamura, *Catal. Today* **2002**, *73*, 23 – 28.

[5] P. S. Landis, P. B. Venuto, *J. Catal.* **1966**, *6*, 245 – 252.

[6] A. Aucejo, M. C. Burguet, A. Corma, V. Fornés, *Appl. Catal.* **1986**, *22*, 187 – 200.

[7] H. Sato, *Catal. Rev.-Sci. Eng.* **1997**, *39*, 395 – 424.

[8] W. F. Hölderich, *Stud. Surf. Sci. Catal.* **1989**, *46*, 193 – 209.

[9] H. Kath, R. Gläser, J. Weitkamp, *Chem. Eng. Technol.* **2001**, *24*, 150 – 153.

[10] M. A. Camblor, A. Corma, H. García, V. Semmer-Herlédan, S. Valencia, *J. Catal.* **1998**, *177*, 267 – 272.

[11] H. Ichihashi, M. Ishida, A. Shiga, M. Kitamura, T. Suzuki, K. Suenobu, K. Sugita, *Catal. Surv. Asia* **2003**, *7*, 261 – 269.

[12] M. T. Nguyen, G. Raspoet, L. G. Vanquickenborne, *J. Am. Chem. Soc.* **1997**, *119*, 2552 – 2562.

[13] Y. Shinohara, S. Mae, D. Shouro, T. Nakajima, *J. Mol. Struct.* **2000**, *497*, 1 – 9.

[14] M. Newsam, M. M. J. Treacy, W. T. Koetsier, C. B. de Gruyter, *Proc. R. Soc. London A* **1988**, *420*, 375 – 405.

[15] W. O. N. Parker, *Magn. Reson. Chem.* **1999**, *37*, 433 – 436.

[16] J. D. Gale, *J. Chem. Soc. Faraday Trans.* **1997**, *93*, 629 – 637.

[17] K. P. Schröder, J. Sauer, *J. Phys. Chem.* **1996**, *100*, 11043 – 11049.

[18] a) A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648 – 5652; b) J. P. Perdew, Y. Wang, *Phys. Rev. B* **1992**, *45*, 13244 – 13249.

[19] P. C. Hariharan, J. A. Pople, *Theor. Chim. Acta* **1973**, *28*, 213 – 222.

[20] R. Ditchfield, *Mol. Phys.* **1974**, *27*, 789 – 807.

[21] K. Wolinski, J. F. Hinton, P. Pulay, *J. Am. Chem. Soc.* **1990**, *112*, 8251 – 8260.

[22] Gaussian 98 (Revision A.7), M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. A. Montgomery, R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. G. Johnson, W. Chen, M. W. Wong, J. L. Andres, M. Head-Gordon, E. S. Replogle, J. A. Pople, Gaussian, Inc., Pittsburgh, PA, **1998**..