SYNTHESIS OF ZR-BETA ZEOLITE IN FLUORIDE MEDIUM
AND ITS APPLICATIONS IN CATALYTIC LIQUID-PHASE
REACTIONS

BY

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Summary

Zeolite beta is one of the few large-pore high-silica zeolites with a three-dimensional pore structure containing 12-membered apertures, which makes it a very suitable and regenerable catalyst for the production of fine chemicals in liquid phase reactions. The objective of this study is to study the synthesis and characterization of Al-free Zr-beta in fluoride medium, and to apply the as-made Zr-beta zeolite in catalytic liquid phase reactions.

Al-free Zr-beta zeolite has been synthesized for the first time in the presence of F⁻ and TEA⁺ at near neutral pH. The incorporation of zirconium into the framework of zeolite beta greatly prolonged the crystallization time. In the presence of dealuminated beta seeds, pure and well crystallized samples of zeolite beta could be obtained with Si/Zr ratio in the range from 84 to infinity, whereas in the unseeded synthesis the lowest Si/Zr ratio was 102. The size of the crystals of Zr-beta zeolite was greatly influenced by the seeds. Bigger crystal size was obtained in the unseeded system. Characterization of the materials with XRD, IR and ²⁹Si MAS NMR showed an increased resolution of the patterns when decreasing the zirconium content. This is due to the absence of connectivity defects and also to the higher degree of order in the absence of zirconium. The incorporation of zirconium into the framework also induced the preference for the stacking sequence of polymorph B as observed in the XRD patterns. IR spectra of adsorbed pyridine showed that Lewis acidity was predominant in Zr-beta zeolite samples.

Zr-beta zeolite was found to be a regioselective catalyst for the Meerwein-Ponndorf-Verley (MPV) reduction of 4-tert-butylcyclohexanone to cis-4-tert-butylcyclohexanol.
The excellent performance of Zr-beta zeolite in this reaction is due to an appropriate Lewis acidity and the ease of ligand exchange at the Zr active sites within the zeolite beta pore channels. The observed high selectivity (\textit{cis:trans}>99\%) to the thermodynamically less stable \textit{cis}-alcohol is suggested to result from transition-state selectivity. Another prominent feature of Zr-beta zeolite catalyst is its ability to maintain activity even in the presence of rather significant amounts of water, up to 9 wt %. The activity was slightly affected by the presence of pyridine, but was decreased by added acids. However, the poisoning effect could be easily reversed by washing.

Zr-beta zeolite was also found to be a chemoselective catalyst for the MPV reduction of cinnamaldehyde to cinnamyl alcohol. The active sites were again considered to be the Lewis acid zirconium sites which are located in the micropores of the zeolite. For Al-free Zr-beta zeolite samples, excellent conversion was always paired with high selectivity. In contrast, Al-containing Zr-beta samples were not as active as Al-free Zr-beta samples. High chemoselectivity was also observed in the Oppenauer oxidation of cinnamyl alcohol to cinnamaldehyde over Zr-beta zeolite.

Zr-beta zeolite showed high stereoselectivity in the cyclisation of citronellal to isopulegol. The diastereoselectivity, up to 93\%, obtained in this study is perhaps the highest among all heterogeneous catalysts reported for this reaction. The influence of solvents and temperature on the activity of Zr-beta zeolite was studied. A tentative reaction mechanism for the cyclisation of citronellal to isopulegol was proposed.

In the last part of this thesis, several metal-substituted beta zeolites were studied as heterogeneous racemization catalyst. Zr-beta was found to be the best for (S)-1-phenylethanol racemization. The coupling of Zr-beta zeolite catalyzed racemization with
the enzyme catalyzed resolution of 1-phenylethanol was possible in one pot. Under optimized conditions, more than 93% conversion with an $ee$ value of 83% was achieved at 60 ºC with toluene as solvent. While the $ee$ value is not yet fully satisfactory, the outcomes demonstrate the validity of the concept of a one-pot dynamic resolution over a cheap and robust racemising agent.
List of Publications

Journal papers

1. Supported zirconium propoxide—a versatile heterogeneous catalyst for the Meerwein–Ponndorf–Verley reduction
   
   Y. Z. Zhu, S. Jaenicke, and G. K. Chuah


2. Al-free Zr-zeolite beta as a regioselective catalyst in the Meerwein–Ponndorf–Verley reaction
   
   Y. Z. Zhu, G. K. Chuah, and S. Jaenicke


3. Chemo- and regioselective Meerwein-Ponndorf-Verley and Oppenauer reactions catalysed by Al-Free Zr-zeolite beta
   
   Y. Z. Zhu, G. K. Chuah, and S. Jaenicke

   *J. Catal.* 227 (2004) 1

4. Zirconia catalysts in Meerwein-Ponndorf-Verley reduction of citral
   
   Y. Z. Zhu, S. H. Liu, S. Jaenicke, and G. K. Chuah


5. Process intensification with biocatalysts: dynamic kinetic resolution and fluorous phase switch with continuous extraction
   

6. Cyclisation of Citronellal over Zirconium Zeolite Beta – A Highly Diastereoselective Catalyst to (∓)-Isopulegol

Y.Z. Zhu, Y.T. Nie, G. K. Chuah, and S. Jaenicke


Conference papers

1. Zirconium propoxide grafted SBA-15 catalysts for chemo-selective reductions

Y. Z. Zhu and S. Jaenicke


2. Hydrous zirconia as a selective catalyst for the Meerwein-Ponndorf-Verley reduction

S. H. Liu, Y. Z. Zhu, and G. K. Chuah


3. Catalytic Meerwein-Ponndorf-Verley reduction of cinnamaldehyde and Oppenauer oxidation of cinnamyl alcohol by Zr-beta zeolite

Y. Z. Zhu, G. K. Chuah, and S. Jaenicke

(Poster at the Singapore International Chemical Conference-3 (SICC-3), P27, Dec., 2003, Singapore)
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<tr>
<td>BET</td>
<td>Brunauer-Emmett-Teller</td>
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<td>BJH</td>
<td>Barrett-Joyner-Halenda</td>
</tr>
<tr>
<td>CALB</td>
<td><em>Candida Antarctica</em> lipase B</td>
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<tr>
<td>CTR</td>
<td>Cathode ray tube</td>
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<tr>
<td>CP</td>
<td>Cross-polarization</td>
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<tr>
<td>DABCO</td>
<td>1,4-Diazabicyclo [2,2,2] octane</td>
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<tr>
<td>DBDMA</td>
<td>Dibenzyldimethylammonium</td>
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<td>DKR</td>
<td>Dynamic kinetic resolution</td>
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<td>ee</td>
<td>enantiomeric excess</td>
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<td>ESCA</td>
<td>Electron spectroscopy for chemical analysis</td>
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<td>FID</td>
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<td>FTIR</td>
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Chapter 1

Introduction

1.1 General introduction

Zeolites are crystalline aluminosilicates whose lattice consists of a network of SiO$_4^{4-}$ and AlO$_4^{5-}$ tetrahedra with Si or Al atoms (collectively denoted T atoms) at the centers and oxygen atoms in each corner [1]. A network of SiO$_4^{4-}$ tetrahedra is neutral while each AlO$_4^{5-}$ tetrahedron in the framework bears a net negative charge which is balanced by a cation (Na$^+$, K$^+$, or NH$_4^+$) that resides in the interstice of the framework. Zeolite crystals are porous at the molecular level. Their framework structure contains channels and voids with dimensions between 4 and 14 Å, which is similar to the size of small organic molecules. Typical zeolite pore size using oxygen-packing models are shown in Figure 1-1. They include small pore zeolites with 8-ring pores with free diameters of 3-4.5 Å, e.g., zeolite A; medium pore zeolites with 10-ring pores, 4.5-6.0 Å, e.g., zeolite ZSM-5; large pore zeolites with 12-ring pores with 6-8 Å, e.g., zeolite X and Y; and extra-large pore zeolites with 14-ring pores, e.g., zeolite UTD-1. The chemical properties of zeolites combined with their structural architecture have led to many applications in catalysis, ion exchange, and gas adsorption. It is possible to say that zeolites are the most widely used heterogeneous catalysts in industry.

Compared to the successful use of zeolites in hydrocarbon processing, their use in the synthesis of organic intermediates and fine chemicals is in a relatively early state of development. Two main reasons for this are: 1) many organic intermediates and fine chemicals are too bulky to be built in or to desorb from the zeolite pore systems; 2) the
average synthetic organic chemist is not sufficiently acquainted with zeolites, their handling and tuning and their potential, other than their use as drying agent.

In the last decades it has been recognized that zeolite beta is one of the few large pore high-silica zeolites with a three-dimentional pore structure containing 12-membered ring apertures [2-4]. This makes zeolite beta a very suitable and regenerable catalyst in organic reactions, where high thermal and hydrothermal stability and low steric restrictions can be of paramount importance. Therefore, the study of using zeolite beta in the production of organic intermediates and fine chemicals would be significant.

1.2 Synthesis of zeolite beta

1.2.1 Synthesis of zeolite beta in basic medium

Zeolite Beta was first synthesized by Wadlinger et al. in 1967 [5]. In their pioneering work, zeolite beta was prepared from basic media (without F\textsuperscript{-}) in the presence of Na\textsuperscript{+} and TEA\textsuperscript{+} cations as the template. Amorphous silica or silica sol was employed as silica sources and metallic aluminum or sodium aluminate as aluminum sources. The crystallization was carried out at 150°C in an autoclave under static conditions for 3-6 days. The molar ratios of Si/Al in the recovered product were in the range 5-100. Later on, the use of other templating agents such as 1,4-diazabicyclo [2,2,2] octane (DABCO) [6] or dibenzylidimethylammonium cation [7] was also reported.

In general, the synthesis of zeolite beta with Si/Al ratio higher than 100 is rather difficult in the basic medium. Nevertheless, the preparation of all-silica zeolite beta in basic medium has been achieved by van der Waal et al. [8] in the presence of dibenzylidimethylammonium cation as structure-directing agent, although the use of dealumminated zeolite beta as seeds is required. At the low Si/Al side, the minimum Si/Al
ratio attained so far is 5 using TEA$^+$ as the template. Gusnet et al. [9] reported that a substantial amount of non-framework aluminium in the low Si/Al materials may be present. However, the natural beta analogue Tschernichite possesses a Si/Al ratio of 3. The mineral’s composition is $\text{Ca}_{0.97}\text{Na}_{0.05}\text{Mg}_{0.08}\text{Al}_{2.0}\text{Fe}_{0.02}\text{Si}_{5.95}\text{O}_{16.00}$. This suggests that nature used divalent cations ($\text{Ca}^{2+}$) as the template, offering potential new routes to zeolite beta.

1.2.2 Synthesis of zeolite beta in fluoride medium

The use of fluoride as a flux component for the crystal growth from a melt is well known. On the other hand the mineralizing role of fluoride in hydrothermal synthesis was known already to the ancient mineralogists and chemists, but until the end of the seventies fluoride ions were never applied in the synthesis of microporous materials. The first clear example of the use of fluoride was for crystallization of silicalite-1 in slightly alkaline media by Flanigen and Patton [10]. After that, the fluoride route has been extensively investigated, and many zeolites have been successfully synthesized in fluoride medium.

The fluoride route has been applied to the synthesis of zeolite beta. Caullet et al. [11] reported the synthesis of zeolite beta in fluoride medium using DABCO and methylamine as templates. However, the method restricted the Si/Al ratio to a very narrow range (Si/Al=9-22) and the presence of seeds was necessary to obtain a fully crystallized material. It was also reported there that no zeolite beta was obtained using other templates apart from DABCO in the fluoride medium. It could later be shown that DABCO is not the only template to induce crystallization of zeolite beta. Camblor et al. [12] carried out a detailed study on the synthesis of zeolite beta in a fluoride medium in
the presence of TEA cation at near neutral pH. They obtained a very wide range of Si/Al ratios, ranging from Si/Al=6.5 to almost pure silica materials. Al incorporation in the material has been characterized by different techniques. It seems that there exists an upper limit of about 6 Al/u.c. to form the zeolite beta structure. In the same report, they found that increasing the Al content led to a longer crystallization time. Moreover, a decrease in the amount of fluoride anions incorporated in the solid has also been observed when increasing the Al content until 4-5 Al/u.c. Above that value, some TEA oxofluoroaluminated complexes may be present in the samples.

As we mentioned above, the synthesis of zeolite beta with Si/Al ratios higher than 100 is rather difficult in the basic medium. In the fluoride medium, it seems relatively easy to increase the Si/Al ratio, even without addition of zeolite seeds. A few groups have succeeded in preparing pure silica zeolite beta. Camblor et al. [13] were the first to report the synthesis of pure silica zeolite beta using TEA cation as template in fluoride medium. They found that pure silica beta showed much better resolution of the diffraction peaks both in powder X-ray diffraction pattern and in $^{29}$Si MAS NMR spectra, and ascribed this to its large crystals and its defect–free nature. They also observed that pure silica beta was thermally very stable. Calcination up to 1000 °C did not result in a loss of crystallinity, while the same treatment completely destroyed the structure of conventional zeolite beta.

1.2.3 Incorporation of other metal elements to zeolite beta

The aluminium atom is not the only non-siliceous metal that can be incorporated in the beta framework. The isomorphous substitution of aluminium in the zeolite beta framework by other trivalent elements such as iron [14], boron [8, 15-18], indium [19] or
gallium [20, 21] has been achieved by direct synthesis from alkaline reaction media. Compared to the numerous studies on isomorphous substitution of aluminium by other trivalent elements, studies on isomorphous substitution of aluminium by tetravalent elements such as titanium, zirconium, and tin were relatively few because the crystallization of zeolite beta was considered impossible without Al or another trivalent element. Nevertheless, by partial substitution of aluminium, [Al, Ti]-beta [22, 23], [Al, Zr]-beta [24], and [Al, Sn]-beta [25] were successfully synthesized in the alkaline medium. Recently, Camblor et al. [26] also reported the successful synthesis of practically Al-free Ti-beta with tetraethylammonium in basic media with Si/Al ratios up to 5000 or above in the final material, but this required the use of dealuminated zeolite beta seeds.

Isomorphous substitution of aluminum in the zeolite beta framework by other elements has also been studied in the fluoride medium. Kallus et al. [27] prepared boron zeolite beta using the fluoride route from gels containing DABCO and methylamine as the templates. In comparison with the [Si, Al] system, the [Si, B] system appeared less active and generally much longer crystallization time was needed. Moreover, the products obtained displayed a narrower range of compositions than those obtained with the [Si, Al] system. Only boron-rich (Si/B=2) and fluoride-poor media (F/Si=2) led to well-crystallized samples of zeolite beta. They ascribed this to a stronger complexation of boron by the fluoride anions.

Hazm et al. [28] investigated the synthesis of gallium beta zeolite from fluoride-containing media. It was found that the morphology and the size of the crystals of zeolite beta were greatly influenced by the Si/Ga ratios. The largest crystals with a bipyramidal
morphology and a size up to 10 µm were obtained from the Si-rich mixtures. Pure and fully crystallized beta samples could only be obtained from the gels with Si/Ga ratios higher than or equal to 20. Gallium atoms were found to remain almost totally in tetrahedral coordination, even for the gallium-richest samples.

Compared to the synthesis of pure zeolite beta and isomorphous substitution of aluminum by trivalent elements in the fluoride media, the isomorphous substitution of aluminium by tetravalent elements is extremely difficult. Prior to this work, only titanium and tin substituted zeolite beta have been synthesized in the fluoride media.

Corma et al. [29] investigated the synthesis of Al-free titanium beta zeolite in the presence of fluoride. They found that at near neutral pH the incorporation of Ti into the framework appeared to present an upper limit of ca. 2.3 Ti/u.c. After calcination, Ti incorporation in the framework was characterized by an increase in the unit cell volume. By $^{29}$Si MAS NMR, $^1$H-$^{29}$Si CP MAS NMR, and infrared spectroscopies, they concluded that upon contact with ambient humidity there was no hydrolysis of Si-O-Ti bonds in Ti-beta zeolites prepared by the fluoride route, while this was probably a major feature of those synthesized in OH-medium. The more hydrophobic character of Ti-beta-F (synthesized in the fluoride media) compared to conventional Ti-beta-OH (synthesized in the hydroxide media) gives Ti-beta-F attractive properties in oxidation reactions. However, the paramount importance of the hydrophobic/hydrophilic character of Ti-beta in selective oxidation reactions needs to be further studied.

Recently, Al-free Sn-beta zeolite was successfully synthesized in fluoride medium. [30]. It has proved to be a very efficient catalyst for Baeyer-Villiger oxidation and
Meerwein-Ponndorf-Verley (MPV) reduction. This will be discussed in the application section of this chapter.

1.2.4 Synthesis mechanism of zeolite beta

In order to elucidate the synthesis mechanism of zeolite beta, Perez-Pariente et al. [31-34] carried out detailed mechanistic studies on the nucleation and crystal growth of zeolite beta. They used tetraethylorthosilicate (TEOS), sodium aluminate, TEAOH, NaOH or KOH, or a mixture of KOH and NaOH as starting materials. The standard procedure consisted of TEOS hydrolysis in an aqueous solution containing other reaction mixtures. It was found that from the resulting gel, zeolite beta nuclei were formed via a liquid-phase synthesis mechanism and that Al was an essential element for its formation. Both the crystallization rate and crystal size of zeolite beta depend on the alkali content and the molar fraction of each cation in Na- and K-containing gels. No zeolite can be obtained in the absence of alkali cations, and an optimum value of (Na+K)/SiO₂ ratio seems to exist.

The liquid-phase crystallization mechanism seems to govern zeolite syntheses which start from clear solutions. However, when an amorphous solid is present in the starting reaction mixture, other alternatives are also possible. Serrano et al. [35] studied the crystallization mechanism of Al-Ti-beta zeolite synthesized from amorphous wetness impregnated xerogels. They observed that the crystals were formed by aggregation, densification and zeolitization of amorphous primary particles. They also found that the increase in the Al content accelerated the nucleation of zeolite beta from the amorphous solid gel. These findings, however, are inconsistent with the conventional crystallization mechanism, which postulates that the zeolite synthesis proceeds through two main steps:
nucleation (formation of the first very small crystalline entities) and crystal growth around these nuclei by progressive incorporation of soluble species. It seems therefore that the crystallization of zeolite beta can also proceed by a solid-solid transformation mechanism, especially when amorphous xerogels, wet impregnated with the template solution, are used as raw materials for the synthesis.

Serrano [36] also studied the crystallization mechanism of all-silica zeolite beta in fluoride medium. Through the characterization of samples obtained at different synthesis times, they concluded that the crystallization of pure silica zeolite beta took place via a solid-solid transformation mechanism. They also proposed that the low solubility of silica at the near-neutral pH during the synthesis may be one of the major reasons for the development of a solid-solid transformation.

1.2.5 Structure of zeolite beta

The structure of zeolite beta is very complex. It therefore could only be solved 20 years after the synthesis, using a combination of high-resolution electron microscopy, electron diffraction, computer-assisted modeling and powder X-ray diffraction [2-4].

The structure of zeolite beta is accepted as a highly faulted intergrowth of two distinct, but closely related structures that both have fully three-dimensional pore systems with 12-rings as the minimum constricting apertures [2]. One end member, polymorph A, forms an enantiomorphic pair, space group symmetries P4₁22 and P4₂22. The other end member, polymorph B, is achiral with space group symmetry C2/c. The structure of polymorph A and polymorph B are shown in Figure 1-2. Generally, the ratio of Polymorph A to B in zeolite beta is 60:40. However, it has been proposed that a third
polymorph (polymorph C) also exist in zeolite beta and zeolite beta composed of pure polymorph C has been synthesized by using germanium as stabilizer [37].

Zeolite beta has a three-dimensional intersecting channel system [2-4]. Two mutually perpendicular straight channels, each with a cross section of 7.6 x 6.4 Å, run in the \( a \)- and \( b \)-directions (Figure 1-3 a). These channels are unaffected by any changes in the layer stacking sequence. A sinusoidal channel of 5.5 x 5.5 runs parallel to the \( c \)-direction and is nonlinear (Figure 1-3 b). Its shape in disordered zeolite beta is somewhat irregular depending on the nature of the layer stacking sequence.

1.3 Modification of zeolite

The properties of zeolite and thus their catalytic behavior can be influenced with certain limits by modifying the zeolite either during or after the actual synthesis. They may be modified in many ways; they can be tuned over a wide range of acidity, and hydrophyllicity and hydrophobicity, many cations can be introduced by ion-exchange, and isomorphous substitution is possible which allows one to introduce isolated redox centers in the lattice. Moreover, metal crystallites and metal complexes can be entrapped within the microporous environment.

1.3.1 Tuning hydrophilic/hydrophobic property of zeolite

The high Si/Al ratio of zeolite beta, typically around 10, makes it inherently hydrophobic. Changing the Si/Al ratio of zeolite beta has, however, a marked influence on the hydrophobicity. The increased hydrophobicity of silica-rich zeolite beta has been demonstrated by competitive adsorption of toluene and water. The so-called hydrophobicity index [38], the amount of toluene adsorbed divided by the amount of
water adsorbed at 25 °C amounts to 2.3 for a Si/Al=10 sample, and increases to 10.8 for an all-silica beta (Table 1-1).

It is well known that plenty of connectivity defects (Si-O⁻ or Si-OH groups) exist in beta zeolite synthesized in OH- media. The presence of connectivity defects can affect the sorption and hydrophilic/hydrophobic properties of zeolites. The high concentration of defects leads to a lower thermal stability of this material compared with other high-silica zeolites, and is also responsible for its hydrophilic character. However, beta zeolite synthesized in fluoride medium is almost free of connectivity defects because organic cations are counterbalanced by occluded F⁻. Therefore, the hydrophobicity of zeolite beta can be greatly increased simply by synthesizing it in the fluoride medium.

1.3.2 Introduction of Brønsted and Lewis acidity

Like many other zeolites, zeolite beta has both Brønsted and Lewis acid sites. Pure silica zeolite containing only SiO₄⁴⁻ tetrahedra would be electrically neutral, and no acidity could be developed on its surface. Brønsted acid sites are developed when Si⁴⁺ atoms are isomorphically substituted by trivalent metal cations, for instance Al³⁺, and a negative charge is created in the lattice, which is compensated by a proton. The proton is attached to the oxygen atom connecting neighboring silicon and aluminum atoms, resulting in the so-called bridged hydroxyl group, which is the site responsible for the Brønsted acidity of zeolites (Figure 1-4)

In as-synthesized zeolites, the negative charge present on the Al-substituted framework is compensated by organic and inorganic alkaline cations rather than by H⁺, and such zeolites show no Brønsted acidity. Brønsted acidity is generated upon decomposition of organic cations by thermal treatment or by ion-exchange of the
synthesis cations by protons, or NH$_4^+$ and di- or trivalent cations followed by calcination. Theoretically, one proton should be introduced for each framework Al$^{3+}$, and therefore, the larger the number of framework aluminum atoms, the higher the potential number of acid sites would be in a given zeolite. Thus, it is clear that the total number of Brønsted acid sites present in a zeolite catalyst will depend on the framework Si/Al ratio.

The acid strength of a given acid site in zeolite could be affected by the Si/T ratio, the type of T-atom, and the zeolite structure. The acid strength of the proton at the aluminum site is strongly dependent on Si/Al ratio. For example, it was found that the acid strength of zeolite HY increases with decreasing Al content. Maximum acidity was, however, obtained for Si/Al rations above 7 [39]. The acidity of the well-studied ZSM-5 zeolites is known to fall according to the T-atom sequence Al>Ga>Fe>>B [40]. In this way, the acid strength increases from the mildly acidic borosilicates to the strongly acidic sites in alumino- and gallosilicates. Zeolite geometry also plays a role in determining the acid strength of zeolites. It is claimed that the distances and bond angles in the Al-OH-Si group can affect the acidity of the hydroxyl group [41], and strongly acidic zeolites have a range of T-O-T angles (ZSM-5, 137-177º; mordenite, 143-180º), which is generally larger than that of other less acidic zeolites (HY, 138-147º).

Zeolites also contain Lewis sites [42]; these were attributed to tricoordinated Al centers. However, this type of Al has not been detected by $^{27}$Al MAS NMR. Instead, samples exhibiting Lewis acidity have octahedrally coordinated Al centers, suggesting that extraframework Al species, generated during steaming or calcination of hydrated zeolites, are responsible for the Lewis acidity. In a recent infrared study, Bortnovsky et al. [43] identified three types of Al-related Lewis sites in zeolite H-beta: framework Lewis
sites, partly framework Lewis sites, and extraframework Lewis sites. The majority of framework Lewis sites consists of framework Al with a distorted coordination environment. In IR spectra of H-beta zeolite, the OH band at 3780 cm$^{-1}$ and the T–O–T vibration at 882 cm$^{-1}$ is considered to be related to a partly skeletal Al cation bearing an OH group. The T–O–T band at 901 cm$^{-1}$ reflects perturbation of the framework as a result of the presence of extraframework AlO$_x$ complex counterions coordinated to the cationic site. These extraframework AlO$_x$ related Lewis sites were claimed to be responsible for the activity of H-beta zeolite for MPV reduction [43]. Using $^{27}$Al MAS NMR, Fajula [44] demonstrated that the Al in zeolite beta has a dynamic character and is able to cycle between the tetrahedral full-lattice configuration and octahedral and tetrahedral lattice-grafted forms.

The acidity of zeolites can be determined by temperature programmed adsorption/desorption methods using probe molecules such as NH$_3$ or CO$_2$ [45]. The pyridine adsorption/desorption method can specifically probes acid sites in solids by IR [84]; characteristic absorption bands for protonated pyridinium ion (1550 cm$^{-1}$) and for a Lewis adduct (1450 cm$^{-1}$) allow the separate determination of Brønsted and Lewis sites in a single measurement. Acid sites on the external surface of pentasil zeolites can be probed by adsorbing a bulky base, such as 2,4-di-tert-butylpyridine [46].

1.3.3 Introduction of metal and metal complexes

Zeolites are crystalline, highly porous materials. Their large surface area and their cage-like pores also make them good candidates as metal particle support. Very small metal particles with the same dimensions of the zeolite channel or cage can be prepared in the inner pore of zeolite. Due to the small size of the metal particles, usually 5-15 Å,
they can exhibit different catalytic properties compared with the bulk metal. These supported metal particles may activate C-H bond and may serve as catalyst in hydrogenation/dehydrogenation, aromatization and oxidation reactions. They also exert a stabilizing effect in several reactions and catalyze oxidative reactivation of used zeolites.

Introduction of metal particles is done via a two step method. Firstly, the metal is introduced in the pores of the zeolite by ion exchange with an aqueous solution of a cationic metal-ammine complex (Pt(NH$_3$)$_4^{2+}$ or Pd(NH$_3$)$_4^{2+}$). Special caution has to be taken during this ion exchange step to attain a homogeneous dispersion of the cations over the zeolite crystal [47, 48]. Careful reduction or oxidation/reduction of the metal cations in the pores of a zeolite yields finely dispersed, nano-sized metal particles.

1.3.4 High temperature treatment

The calcination of zeolites serves in the first place to create the H-form by decomposition of the ammonium-form or by removing organic template molecules incorporated into the zeolite framework during the synthesis. At temperatures exceeding 400 °C, dehydration may occur, leading to transformation of Brønsted acid sites into Lewis acid centers. Since this means that the catalytic properties are affected, it is necessary to carry out the thermal treatment under carefully controlled conditions.

The tempering of zeolites in the presence of water is a well-known method for preparing thermally stable zeolites with a long active lifetime. This so-called steaming brings about dealumination (alumina migrates out of the zeolite framework into the cages) with partial curing of the lattice structure by insertion of Si. The well know ultrastable zeolite USY is obtained in this way. Kunkeler et al. [49] found that the activity of H-beta
for the Meerwein-Ponndorf-Verley reduction can be increased by several orders of magnitude by a mild steam treatment.

1.3.5 Inertization of external surface of zeolites

The active centers located at the outer surface of zeolites do not display any shape selective behaviors, and often lead to some decrease of selectivity towards the desired product. Therefore, these external active sites should be reduced. This can be achieved either by lowering drastically the Al concentration in the reaction solution towards the end of the zeolite synthesis, resulting in the formation of a SiO₂ coating [50-52] or alternatively, by neutralizing or poisoning the acid centers of the outer surface subsequent to the synthesis. Bulky nitrogen bases such as 4-methylquinoline [53] or silanes bearing bulky substituents such as triphenylchlorosilane [54, 55] are suitable for the latter purpose. Covering by a thin silica layer may also be achieved by post-synthesis treatment with tetraethyl orthosilicate [56].

The relative amount of external surface sites can also be reduced if relatively large zeolite crystals are synthesized. However, the activity generally decreases with increasing crystal size due to intracrystalline diffusion problems.

1.4 Applications of zeolite beta in organic reactions

Zeolite beta is a high-silica zeolite possessing a three-dimensional system of large rings (rings of 12 oxygen atoms as the minimum constricting apertures). This gives zeolite beta interesting potential applications in catalytic reactions where high thermal and hydrothermal stability and low steric restrictions can be of paramount importance. We will in this section briefly review some of the most important applications of zeolite beta in liquid-phase reactions.
1.4.1 Alkylation.

In the field of benzene alkylation with lower olefins (ethene, propene), zeolite-based processes are predominant now. For the bulk product ethylbenzene, the original AlCl₃-catalyzed alkylation of benzene with ethene has given way to processes which employ zeolite-based catalysts. Various zeolites such as ZSM-5, USY, beta and MCM-22 can be used to catalyze this reaction. Comparison of zeolite beta with other zeolites (ZSM-5, USY and MCM-22) [57, 58] has shown that zeolite beta seems to be the most active catalyst, whereas MCM-22 sometimes shows the best overall properties combining good activity with excellent stability. In the zeolite-based cumene processes, zeolite beta has been selected for use in the process developed by Enichem [59].

In the fine-chemicals area, the alkylation of biphenyl and naphthalene is of considerable interest, owing to the importance of \( p,p' \)-difunctionalized biphenyls, 2,6-dialkynaphthalenes, and their derivatives obtained by oxidation of the alkyl groups, as intermediates for specialty polymers. In the \( \text{iso-propylation} \) of naphthalene, for example, conventional catalysts such as AlCl₃ give the 2,6-isomer in the thermodynamic 1:1 ratio with the undesired 2,7-isomer (Scheme 1). Chu and Chen [60] found that zeolites beta gave higher 2,6-isomer selectivity than non-microporous catalysts, but H-ZSM-5 with smaller pores gave a low 2,6/2,7-isomer ratio as a result of non-shape-selective reaction at the external surface.

The Fajula group [61] also recently studied the alkylation of naphthalene with \( \text{tert} \)-butanol. Over zeolite beta, 2-\( \text{tert} \)-butynaphthalene was obtained as the main product together with relatively small amounts of the di-\( \text{tert} \)-butynaphthalene. Over HY, 2,6- and
2.7-di-tert-butylnapthalene were the major products, which is due to the more spacious pore system of HY.

1.4.2 Acylation

Another application of zeolite beta in Friedel–Crafts reactions is the acylation of aromatics. Aromatic acylation processes are widely applied in the fine chemical industry as reaction steps in the synthesis of pharmaceuticals and fragrances. Present industrial synthesis generally involves acid chlorides as the acylating agent. However, more than stochiometric amounts of the metal chloride are required due to the strong coordination of the product ketone to the Lewis-acid catalyst (AlCl₃, FeCl₃, and TiCl₄). Other acylating agents, like anhydrides, exhibit similar disadvantages. Moreover, the hydrochloric acid formed during work-up of the reaction generates highly corrosive media. A direct and truly catalytic route involving the free carboxylic acid or even the anhydride as the acylating agent would be most attractive. Zeolite catalysts such as H-beta show great promise in this respect.

Andy et al. [62] studied the industrially relevant acetylation of iso-butylbenzene with acetic anhydride over H-beta samples at 100°C in 1,2-dichloroethane as the solvent. Low catalyst activity together with high (>99%) para-selectivity was observed. The acetic acid formed may have acted as an inhibitor in this case by selective adsorption in the zeolite pores. A patent to Uetikon [63] claims for the same reaction a yield of 80% with 96% para-selectivity when operating a H-beta catalyst at 140°C.

Spagnol et al. [64] systematically investigated the acylation of anisole and veratrole with acetic anhydride (Scheme 1-2). They developed a solvent-free process where both reactants pass a fixed bed of H-beta. This new process for para-acetylanisole is clean and
also brings along a substantial process simplification with respect to the conventional AlCl₃-catalyzed process, which used 1,2-dichloroethane as the solvent and involved a hydrolysis step, several washing and separation steps, and requires recycling of water and solvents.

Compared to the above successful reactions, the selective acylation of 2-methoxynaphthalene in the 6-position, which produces a precursor for the drug Naproxene, is in a much earlier state of development. Here the kinetically favored substitution is at the 1-position while the desired product is substituted at the 6-position. Zeolite beta was found to be active for this reaction [65]. However, the desired 6-position substituted 2-methoxynaphthalene was obtained only after a long reaction time by an intermolecular irreversible isomerization process (Scheme 1-3).

1.4.3 The Fries Rearrangement

The Fries rearrangement is the acid-catalyzed transformation of aryl esters into hydroxyarylketones. This reaction plays an important role in the production of hydroxyarylketones by acylation of phenols with carboxylic acids, anhydrides, or acyl chlorides. As in the acylation reactions, the ketone produced forms a 1:1 adduct with AlCl₃. Therefore, the conventional process again requires more than stoichiometric amounts of catalyst. Heterogeneous catalysts, zeolite in particular, have been suggested as possible alternative catalysts for this reaction. Most of the studies so far concentrated on the synthesis of hydroxyacetophenones either by Fries rearrangement of the phenyl ester or by acetylation of phenol with the acetic acid or the anhydride. [66] H-beta gives particularly good results in this reaction with o/p hydroxy-acetophenone ratios up to 4.7 [67].
With resorcinol as the starting material, the regioselectivity was greatly enhanced and excellent results have been obtained in the benzolation towards 2,4-dihydroxybenzophenone, [68] a precursor of a well-known sunscreen agent (Scheme 1-4). With H-beta as the catalyst and benzoic acid as the acylating agent, yields of almost 90% have been achieved in the liquid phase. The present industrial process involves the reaction of benzoic acid (PhCCl₃) with resorcinol in the presence of FeCl₃.

The limited space inside the H-beta pores becomes apparent when 2-methyl and 2,6-dimethylbenzoic acid are used for the reaction with resorcinol and compared with benzoic acid. With 2-methylbenzoic acid, the conversion to the benzophenone is accelerated due to an electronic effect; with 2,6-dimethylbenzoic acid, the reaction slows down because the intermediate ester is too bulky to be formed inside in the pores [68, 69].

1.4.4 Meerwein-Ponndorf-Verley (MPV) reduction and Oppenauer oxidation

The Meerwein-Ponndorf-Verley (MPV) reduction of carbonyl compounds and the Oppenauer oxidation of alcohols, together denoted as MPVO reactions, are highly selective reactions that can be performed under mild conditions [70]. This reaction is usually catalyzed by metal alkoxides such as Al(OPrᵢ)₃ in the homogeneous phase. The catalytic activity of metal alkoxides is related to their Lewis acidic character in combination with ligand exchangeability. One major drawback of the use of metal alkoxide as catalyst in the MPV reaction is that stoichiometric amounts of catalyst are often needed. Moreover, the homogenous metal alkoxide catalysts are usually hard to separate and are not reusable. To overcome these problems, heterogeneously performed MPV reactions have been studied. Zeolite beta proves to be a promising catalyst for this reaction.
An elegant example of zeolite-induced shape-selectivity is provided by the MPV reduction of 4-tert-butylcyclohexanone over zeolite Beta. It was discovered by Creyghton et al. [71, 72] that this catalyst yielded cis-4-tert-butylcyclohexanol as almost the sole isomeric form, whereas other zeolites gave predominantly the thermodynamically favoured trans-isomer (Scheme 1-5a).

A very high stereoselectivity was observed in the reduction of 4-tert-butylcyclohexone to the cis-isomer (>95), which is a commercially desired product. The observed high selectivity to the thermodynamically unfavorable cis-isomer was explained by a restricted transition-state for the formation of the trans-isomer within the pores of the zeolites (Scheme 5b). This reaction was found not only to be catalyzed by Al-beta, but also by Al-free Ti-beta. Van der Waal et al. [73] reported the catalytic activity of Al-free Ti-beta in the same reaction. Again, a very high selectivity to the cis-isomer was observed, indicating similar steric restrictions on the mechanism. Kinetically restricted product distributions were also reported for the reduction of 2-, 3- and 4-methylecyclohexanones, the cis-, trans-, and cis-isomers being the major products, respectively. In this case, the tetrahedrally coordinated Ti-atom was assumed to behave as the Lewis acid metal center.

More recently, Corma et al. [30] performed MPV reductions using an Al-free Sn-Beta zeolite, which was synthesized in fluoride medium, as catalyst. The results obtained were compared with those obtained over optimized Al- and Ti-Beta zeolites. Sn-Beta showed much higher activity with better selectivity than any of the solid catalysts reported before. The high activity and selectivity was ascribed to the introduction of adequate Lewis acidity in the catalyst because Sn has a higher electronegativity than Ti, and may produce
the right polarization of the carbonyl group while coordinating both the alcohol and the ketone. This makes Sn more adequate for coordinating both reactants than Ti or extraframework Al species.

1.4.5 Oxidation reactions

1.4.5.1 Titanium containing zeolite beta

The discovery of the remarkable activity of TS-1, a titanium-containing silicalite-1, as a catalyst for a variety of synthetically useful oxidations with aqueous hydrogen peroxide constituted a major breakthrough in oxidation catalysis [74, 75]. However, the pore size of TS-1 (5.6 x 5.3 Å) is too small for most organic molecules, and for the application of organic hydroperoxides as oxidizing agents. The large pore apertures and high silica nature of zeolite beta made it an appropriate candidate for titanium incorporation.

[Ti,Al]-beta was first synthesized and used as an epoxidation catalyst by Camblor et al. [23]. Its activity and selectivity was less than TS-1 for small substrates like 1-hexene, but it was capable of converting larger molecules like cyclododecene. The lower selectivity was attributed to the presence of aluminum. Also, it was observed that aluminum has a negative effect on activity [76], which was later recognized to be related to the hydrophilicity of the acid site. The bifunctional nature of [Ti,Al]-beta was utilized by Corma et al. in the epoxidation/rearrangement of α-terpineol to cineol alcohol, and in the formation of furans from linalool [77, 78]. Similarly, van Klaveren et al. [79] applied [Ti,Al]-beta in the one-pot conversion of styrene to phenyl acetaldehyde. Sato et al. [80] solved the problem of the unwanted acid catalyzed side reaction by neutralizing the acid site by ion exchange with alkali metals. Corma et al. [81] observed that acetonitrile was very effective at suppressing epoxide solvolysis/hydrolysis reactions in [Ti,Al]-beta
without causing any loss of activity, presumably by successfully competing with epoxide molecules for coordination to the acidic proton. Nevertheless, the bifunctionality restricts the use of this catalyst to a limited number of reactions.

With the success of synthesis of Al-free Ti-beta zeolite [26, 82, 83], and even defect-free hydrophobic Al-free Ti-beta in the fluoride medium [29, 84], the epoxidation selectivity could be greatly improved and the difference between Ti-beta and TS-1 were not as large as they had been perceived to be earlier [83]. Whereas TS-1 is not capable of epoxidizing cyclohexene, Ti-beta has no problem with a wide range of cyclic alkenes, bulky olefin or terpenes [85].

1.4.5.2 Al-Free Sn-beta as Baeyer-Villiger oxidation Catalyst

Baeyer-Villiger oxidation is a versatile reaction which has been widely used to convert ketones into more complex and valuable esters and lactones [86]. Traditional oxidizing agents include peracids such as trifluoroperacetic acid, perbenzoic acid and m-chloroperbenzoic acid. These reagents, however, have some disadvantages; notably, they have to be prepared from highly concentrated hydrogen peroxide, which has been removed from commercial production recently because of the dangers involved in transport and handling. To avoid the use of peracids for the Baeyer-Villiger reaction, methods have been developed involving catalysts that are able to activate hydrogen peroxide, $\text{H}_2\text{O}_2$. Heterogeneous catalysis of the Baeyer-Villier oxidation with easily available 30% hydrogen peroxide is possible in the presence of zeolite catalysts. Acid zeolites such as H-beta and USY can activate hydrogen peroxide for the Baeyer-Villiger oxidation, but show selectivity of less than 70% [87].
Recently, Corma et al. [30] performed the Baeyer-Villier oxidation with hydrogen peroxide over Al-free Sn-beta synthesized in fluoride media. They found that Al-free Sn-beta acted as an efficient and stable heterogeneous catalyst for the Baeyer-Villiger oxidation of saturated as well as unsaturated ketones with hydrogen peroxide, with the desired lactones forming more than 98% of the reaction products. They ascribed the high selectivity to the direct activation of the ketone group, whereas other catalysts first activate hydrogen peroxide, which can then interact with the ketone group as well as other functional groups. They also proposed a reaction mechanism which is shown in Figure 1-5.

1.5 Aims of the present study

As reviewed above, zeolite beta can be synthesized either in basic media or in fluoride media. Its large, three-dimensional micropore structure combined with its acidic properties makes it a promising selective catalyst for liquid-phase organic reactions. We have seen that zeolite beta is very active in liquid phase reactions like Friedel–Crafts reaction, Fries rearrangement, and MPV reduction, and frequently with good selectivity. We have also seen that isomorphous substituted beta zeolites, such as Ti-beta or Sn-beta, are efficient Lewis acid catalysts for MPV reduction and some oxidation reactions. Due to the difficulty in isomorphous substitution of aluminum with other transition metals, presently, catalysts for these reactions that needed to be catalyzed by pure Lewis acid sites were limited to Ti-beta and Sn-beta.

Zirconium has been used in catalysis due to both its moderate acidity and oxidizing capabilities. Like most pure or supported metal oxides, Zirconium oxide is limited by its low surface area (<50m$^2$/g) and the absence of size-selectivity. Incorporation of
zirconium into zeolite beta may increase its surface area on one hand and improve its size-selectivity on the other hand. The substitution of Al by Zr in the framework of zeolite beta has already been attempted [24]. However, the synthesis of Zr zeolite beta is very difficult in a conventional basic media and requires the presence of aluminum. The present study focused on the following aspects:

1. Synthesis of Al-free Zr-beta in a fluoride medium and investigation of the physical and chemical parameters that may influence the synthesis of Al-free zeolite beta.

2. Characterization of as-made and calcined samples employing various characterization techniques such as power X-ray diffraction (XRD), infrared spectroscopy (IR), scanning electron microscopy (SEM), solid state nuclear magnetic resonance (NMR), thermogravimetric analysis (TGA) and N₂ adsorption.

3. Investigation of the catalytic activity and regio- and chemo-selectivity of Al-free Zr-beta zeolite in the MPV reduction of some ketones and some α, β unsaturated aldehydes, as well as comparison of catalytic activity of Zr-beta with that of other active zeolite beta such as H-beta, Ti-beta, and, Sn-beta. 

4. Study of the catalytic ability and stereoselectivity of Al-free Zr-beta in the cyclisation of citronellal to isopulegol.

5. Application of combining Zr-beta catalyzed racemization with enzyme catalyzed resolution for the dynamic kinetic resolution (DKR) of secondary alcohols.
Reference:


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Table 1-1. Hydrophobicity index for zeolite beta with various Si/Al ratios [38].

<table>
<thead>
<tr>
<th>Si/Al ratio</th>
<th>Hydrophobicity Index</th>
</tr>
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<tbody>
<tr>
<td>5</td>
<td>0.8</td>
</tr>
<tr>
<td>10</td>
<td>2.3</td>
</tr>
<tr>
<td>45</td>
<td>4.8</td>
</tr>
<tr>
<td>100</td>
<td>5.4</td>
</tr>
<tr>
<td>infinity</td>
<td>10.8</td>
</tr>
</tbody>
</table>
Scheme 1-1. Isopropylation of naphthalene.

Scheme 1-2. Acylation of anisole and veratrole.

Scheme 1-3. H-beta catalyzed acylation of 2-methoxynaphthalene.
Scheme 1-4. Synthesis of 2,4-dihydroxybenzophenone through Fries rearrangement

Scheme 1-5. MPV reduction of 4-tert-butylcyclohexone: proposed transition states for cis- and trans- 4-tert-butylcyclohexanol
Figure 1-1. Typical zeolite pore sizes illustrated with oxygen packing models.
Figure 1-2. Projections along principal crystallographic directions of zeolite beta structures: (a) polymorph A and (b) Polymorph B. The unit cell outlines are indicated by the dashed lines.

Figure 1-3. Pore sizes of zeolite beta: (a) 12-ring viewed along [100] and (b) 12-ring viewed along [001].
Figure 1-4. Brønsted acid site in zeolite framework with a proton on a bridging Al-O-Si.

Figure 1-5. Proposed mechanism for Baeyer-Villiger oxidation with hydrogen peroxide over Al-free Sn beta.
Chapter 2

Experimental

2.1 Materials

2.1.1 Preparation of zeolite beta seeds

Nanocrystalline zeolite beta seeds were synthesized following the procedure described in literature [1]. Typically, 0.216 g of Al (Goodfellow, >99.99%) was dissolved in 41.23 g of tetraethylammonium hydroxide (TEAOH, Aldrich, 40 wt% aqueous solution). Then 29.26 g of deionized water and 12 g of fumed silica (Degussa, Aerosil 200) was added and stirred for 2 hours. The molar composition of the final gel mixture was 1.0 SiO₂:0.56TEAOH: 0.02 Al₂O₃: 15 H₂O. The mixture was placed in a Teflon-lined stainless steel autoclave and kept at 140 °C for 72 h under autogeneous pressure. The product was separated by centrifugation, washed with deionized water, and dried in air at 100 °C.

Zeolite beta was dealuminated by treating 1 g of the as-made sample with 50ml of HNO₃ (60%) at 80 °C for 24 hours. The solid was recovered by centrifugation, washed with deionzed water, and dried at 100 °C. The Si/Al ratio of the resulting dealuminated beta zeolite was higher than 500 according to ICP analysis.

2.1.2 Synthesis of Al-free Zr-beta zeolite

Al-free Zr-beta zeolite was synthesized in fluoride medium. Typically, 10.42 g of Tetraethylorthosilicate (TEOS, Fluka, >98%) was mixed with 10.31 g of tetraethylammonium hydroxide (TEAOH, Aldrich, 40 wt% aqueous solution) and hydrolyzed under stirring. After 2 hours, a solution containing the calculated amount of ZrOCl₂·8H₂O (Merck, 99%) in 1.37 g water was added, and the mixture was stirred until
the ethanol formed upon hydrolysis of TEOS was evaporated. 1.014 ml of HF (Aldrich, 48%) was added to the gel-like solution obtained, and a thick paste was formed. Finally, 0.105 g dealuminated nanocrystalline zeolite beta seeds (~50 nm) in 1 g of water were added. The final gel composition was as follows: 1.0 SiO$_2$:0.005-0.02 ZrO$_2$:0.56 TEAOH: 6-10 H$_2$O: 0.56HF. The crystallization was carried out in a Teflon-lined stainless steel autoclave at 140 °C for 20 days. The solid product obtained was filtered, washed with deionized water, dried at 100 °C and activated at 580 °C for 4h. The samples are designated Zr$n$ where $n$ = Si/Zr of 75, 100 150, and 200. When no seeds are added, the samples are designated Zr$n$N where $n$=75, 100, and 200. Si/Zr ratios in the calcined samples were determined by ICP

2.1.3 Synthesis of Al-containing Zr-beta zeolite

Two Al-containing Zr-beta samples ZrAl100 (Si/Zr≈104, Si/Al≈103) and ZrAl25 (Si/Zr≈105, Si/Al≈27) were synthesized in an analogue way to the synthesis of Al-free Zr-beta. After hydrolyzing tetraethylorthosilicate (TEOS) with tetraethylammonium hydroxide (TEAOH), a solution of ZrOCl$_2$·8H$_2$O (Merck, 99%) and Al(NO$_3$)$_3$·9H$_2$O (Merck, 99%) in water was added and the mixture was stirred until all ethanol formed by the hydrolysis of TEOS was evaporated. HF and seed crystals were added as described before. The final gel composition was 1.0 SiO$_2$: 0.01 ZrO$_2$: x Al$_2$O$_3$: 0.56 TEAOH: 7.5 H$_2$O: 0.56 HF, where x was 0.005 and 0.02. Crystallization and activation procedures were same as described for Al-free Zr-beta zeolite.

2.1.4 Synthesis of Ti-beta zeolite

Ti-beta (Si/Ti≈100) was prepared following the procedure described by Blasco et al. [2]. For a typical synthesis, 0.12 ml titanium ethoxide (Fluka, TEOT,>95%) was added to
10.42 g Tetraethylorthosilicate (TEOS, >98%) and then 10.31 g tetraethylammonium hydroxide (TEAOH, 40% aqueous solution) was added dropwise with stirring. To facilitate the dissolution of TEOT, 1.93 ml H$_2$O$_2$ (30 % w/w) was added. The resulting mixture was stirred until the ethanol formed upon hydrolysis of TEOS and TEOT was completely evaporated. 1.014 ml of HF (Aldrich, 48%) was added to the cloudy solution and a thick paste was formed. 0.105 g of dealuminated nanocrystalline zeolite beta seeds (~50nm) in 2.4 g of water was added. The crystallization was carried out in a Teflon-lined stainless steel autoclave at 140°C for 10 days. The solid product obtained was filtered, washed with deionized water, dried at 100 °C and activated at 580 °C for 4h. ICP analysis showed a Si/Ti molar ratio of 100.

2.1.5 Synthesis of Al- and Sn-beta zeolites

Al-beta (Si/Al≈100) and Sn-beta (Si/Sn≈125) zeolites were synthesized in a similar way to the synthesis of Al-free Zr-beta. The only difference here was that Al(NO$_3$)$_3$·9H$_2$O (Merck, 99%) was used as aluminum source for Al-beta and SnCl$_4$·5H$_2$O (Merck, 99%) as tin source for Sn-beta. Other procedures were the same as described for Al-free Zr-beta zeolite.

2.1.6 Synthesis of Al-beta sample in basic medium

An Al-beta (Si/Al=12.5) zeolite sample with extraframework aluminum was synthesized according to Wadlinger and Kerr [3]. 1.31 g NaAlO$_2$ (Riedel, Technical) was dissolved in 26.60 g water and added to a mixture of 12 g fumed silica (Degussa, Aerosil 200) and 45.65 g of 40% tetraethylammonium hydroxide (TEAOH, 40% aqueous solution). The reaction mixture was charged to an autoclave and crystallized at 140 °C for 6 days. After crystallization, the solid product obtained was separated by centrifugation,
washed with deionized water, and dried in air at 100 °C. Calcination of the parent material to remove the organic template was performed at 540 °C for 10 hours. The heating rate was 1 °C/min.

The H-form of Al-beta zeolite was obtained by ion exchange with 1 M aqueous ammonium nitrate at 80 °C for 24 hours.

2.1.7 Synthesis of Zr-SBA-15

A Zr-SBA-15 sample with approximately 10% of Zr was prepared by a post-synthesis method, as described below:

Pure silica SBA-15 was synthesized according to the procedure described in Ref. [4]. Typically, 2 g of amphiphilic triblock copolymer, poly(ethylene glycol)-block-poly(propylene glycol)-block-poly(ethylene glycol) (Pluronic P123, Aldrich, average molecular weight 5800) was added to 75 cm³ of 1.6 M HCl solution. The mixture was stirred at 40 ºC for 3 h until all P123 had dissolved. Next, 4.25 g of TEOS was added and the mixture was stirred for another 24 h. The final composition of the mixture was 1.0 TEOS: 5.71 HCl: 158 H₂O. The resulting gel was placed in a Teflon-lined autoclave and heated at 100 °C for 24 h. The solid product obtained was filtered, washed, dried at 100 °C, and calcined at 550 °C for 12 h.

In a second step, zirconium 1-propoxide (Alfa, 70% in n-propanol) was grafted to SBA-15 following Ref. [5]. In a typical procedure, 1 g of pre-dried SBA-15 was added to a solution of zirconium 1-propoxide (0.87g) in dry hexane (30 mL). The suspension was refluxed at 69 °C for 12 h. After filtering in inert atmosphere, samples were washed with hexane and dried under vacuum.
2.2 Characterization

Many different experimental techniques can be used to characterize zeolites. In this thesis, the main characterization techniques utilized include powder X-ray diffraction (XRD), infrared spectroscopy (IR), scanning electron microscope (SEM), solid state nuclear magnetic resonance (NMR), thermogravimetric analysis (TGA) and N₂ adsorption.

2.2.1 X-ray diffraction (XRD)

For determining the long-range order and the phase purity of zeolites, X-ray diffraction is the most frequently used technique. Most zeolite materials are polycrystalline and their crystal sizes are not big enough for X-ray single crystal structure determination. Therefore, only powder X-ray diffraction techniques will be covered here. In polycrystalline materials (such as zeolites) each reflection observed at a given angle \( 2\theta \) in a powder X-ray diffraction pattern, measured at the wavelength \( \lambda \), is related to lattice planes with a distance \( d \) and an orientation indicated by the Millers indices \( hkl \) as described by the Bragg’s law:

\[
n\lambda = 2d_{hkl} \sin \theta
\]

where \( n \) is an integer, \( d \) the interplaner spacing, \( \theta \) the angle of diffraction, and \( \lambda \) the wavelength.

For crystals with cubic symmetry (e.g. faujasite) the size of the use cells \( a \) can be determined from the angular positions of the reflections:

\[
a = \frac{\lambda \sqrt{h^2 + k^2 + l^2}}{2 \sin \theta}
\]
The unique structure of the different zeolites, in terms of atom positions and unit cell dimensions, is reflected in characteristic positions and relative intensities of the peaks observed in XRD patterns. Therefore, XRD can be used to deduce information about crystal structure, crystallite size, location and concentration of exchanged cations and crystallinity of a zeolite sample.

In this thesis, the crystallinity and phase purity of the zeolite samples were determined by powder X-ray diffraction (XRD) in a Siemens D5005 diffractometer with Cu-K$_\alpha$ radiation. XRD diffraction patterns were recorded from 5° to 50° (2$\theta$) with a resolution of 0.02° and a count time of 1 s at each point. The relative crystallinity was evaluated by comparing the area of the characteristic peak at 20 close to 22.5° of the solid product with that of the reference sample Zr200. Mesoporous SBA-15 samples show characteristic peaks at very low diffraction angles because of their large pore size of the repeat unit. The crystalline structure of SBA-15 was therefore determined with a Bruker D8 GADDS at a sample-to-detector distance of 30 cm, using Cu radiation.

2.2.2 Infrared spectroscopy (IR)

Fourier transform infrared (FT-IR) spectroscopy is a characterization method by which infrared radiation is passed through a sample [6]. FT-IR techniques may be used for qualitative observations or quantitative measurements if used in conjunction with the Beer-Lambert relationship.

Vibrations of the frameworks of zeolites give rise to typical bands in the mid and far infrared range [7]. Moreover, Hydroxyl groups attached to zeolite structures may also be detected and characterized by IR spectroscopy. Therefore, FT-IR techniques are used to characterize zeolite samples synthesized in this thesis.
Infrared spectra of the framework vibrations (2000-400 cm\(^{-1}\)) were obtained in a Bruker Equinox 55 spectrometer using KBr pellet technique. Spectra in the hydroxyl stretching region (4000-3000 cm\(^{-1}\)) were recorded using self-supported wafers of 8~10mg in a special sample cell. The sample had been evaluated at 300 °C and 10\(^{-3}\) mbar for 4 hours before measurement.

2.2.3 Pyridine-adsorption IR

IR spectroscopy of adsorbed pyridine is widely used to investigate the nature of solid acid sites [8, 9]. Pyridine can adsorb on the solid acid sites in a number of ways. The adsorption of pyridine at Brønsted acid sites gives the pyridinium ion which shows adsorption bands at 1485-1500 cm\(^{-1}\), 1540 cm\(^{-1}\) as well as at ~1620 cm\(^{-1}\) and ~1640 cm\(^{-1}\). Hydrogen-bonded pyridine shows strong absorption bands at 1440-1447 cm\(^{-1}\) and at 1485-1490 and 1580-1600 cm cm\(^{-1}\). Pyridine coordinately bonded to Lewis acid sites has absorption bands at 1447-1460 cm\(^{-1}\), 1488-1503 cm\(^{-1}\), ~1580 cm\(^{-1}\), and 1600-1633 cm\(^{-1}\) (Table 2-1). Therefore, it is possible to use the band at 1540 cm\(^{-1}\) along with the band near 1640 cm\(^{-1}\) and the very intense band at 1485 cm\(^{-1}\) to indicate Brønsted acidity, while a band in the 1440-1465 cm\(^{-1}\) region indicates Lewis acidity, with a rough indication of the strength of the acidity being given by the frequency of the band.

IR spectra were recorded on a Bruker Equinox 55 spectrometer with a resolution of 2 cm\(^{-1}\). Typically, samples were pressed into self-supported wafers of 8-10 mg. The wafer was mounted in a Pyrex IR cell with NaCl windows and dried under vacuum (~ 10\(^{-3}\) mbar) for 2 hours at 300 °C. After cooling down to room temperature, a background spectrum was recorded. Subsequently, the sample was exposed to pyridine at 22 mbar for 15 minutes. The pyridine was pumped off and the sample was evacuated under vacuum (~
10^{-3} \text{ mbar}) for 1 hour before an IR spectrum was recorded. The sample was then heated to 100 °C for 1 h under vacuum, cooled down to room temperature and an IR spectrum was recorded. Another measurement was done after heating to 200 °C.

2.2.4 4-Methylcyclohexanone-adsorption IR

IR spectroscopy was employed to study the interaction of a ketone with a Lewis acid site, on the basis that the carbonyl band in the IR region is very strong and therefore allows the detection of small amounts of adsorbed 4-Methylcyclohexanone. 4-Methylcyclohexanone adsorption IR spectra were recorded on a Bruker Equinox 55 spectrometer with a resolution of 2 cm\(^{-1}\). Similar to pyridine adsorption, self-supported sample wafer (8-10mg) was mounted in a Pyrex IR cell with NaCl windows and dried under vacuum (~ 10^{-3} \text{ mbar}) for 2 hours at 300 °C. After cooling down to room temperature, a background spectrum was recorded. For adsorption, the sample was exposed to the probe molecule, 4-methylcyclohexanone, in the vapor phase for 10 min at room temperature. Subsequently, excess 4-methylcyclohexanone was pumped off and the sample was evacuated under vacuum (~ 10^{-3} \text{ mbar}) for 1 hour before an IR spectrum was recorded. Additional measurements were taken after partial desorption of the probe molecules at 50, 100, and 200 °C. All IR spectra of adsorbed 4-methylcyclohexanone were recorded at 25 °C.

2.2.5 Solid state nuclear magnetic resonance (NMR) spectroscopy

NMR spectroscopy is one of the most powerful tools for investigating the structure and dynamics of molecular systems [10]. NMR spectroscopy relies on the fact that transitions can be induced between magnetic spin energy levels of certain atomic nuclei in a magnetic field. The main application of NMR in chemistry is based on the early
observation that the transition frequency measured in the NMR spectrum of an atomic nucleus in a particular chemical or structural environment is a very sensitive probe of that environment. Provided that the distinct “chemically shifted” transitions of nuclei of the same element residing in different surroundings can be resolved in the NMR spectrum, unique information on the structure, conformation and dynamics of the system can be obtained.

Initially, the application of NMR spectroscopy in chemistry was more or less restricted to liquids, since the straightforward application of the conventional NMR techniques to solids yields, in general, spectra with very broad and almost featureless resonance lines, masking any differences in the transition frequencies of resonance atoms in distinct structural environments. However the development of novel sophisticated NMR techniques in the early 1970’s opened the possibility of measuring NMR spectra of solids with comparable spectral resolution to those of liquids. Subsequently, high-resolution solid-state NMR spectroscopy has developed rapidly into an effective and widely used means for elucidating subtle details of the structural properties of a wide range of different kinds of solid materials. Since high-resolution solid-state NMR spectroscopy gives, in general, information on the local order of the structure and can be applied to crystalline, microcrystalline and amorphous products, it is a valuable complement to X-ray and other diffraction techniques which probe the long-range order of crystalline materials.

$^{29}$Si MAS NMR spectra of the samples were measured on a Bruker DRX-400 wide-bore solid state spectrometer operating at a resonance frequency of 79.46 MHz with a
spinning rate of 12 kHz, pulse length of 3 µs and a recycle time of 20 s. 4 mm rotors were used and the $^{29}$Si chemical shifts are reported relative to TMS.

The $^{27}$Al MAS NMR spectra were obtained at 104.26 MHz with an excitation pulse of 1.7 µs and a recycle delay of 5 s. The $^{27}$Al chemical shifts were measured relative to aqueous Al(NO$_3$)$_3$.

The $^{13}$C CP MAS NMR spectra were acquired at 100.6 MHz, with a pulse width of 5 µs, 4 s repetition time, 5 ms contact time, and a spinning rate of 8 kHz.

2.2.6 N$_2$ adsorption

The textural properties (specific surface area, pore volume and pore size distribution) of solid samples were obtained from nitrogen adsorption-desorption isotherms measured at 77K with a Quantachrome NOVA 2000 porosimeter. Surface areas were calculated by the Brunauer-Emmett-Teller (BET) method. The Barrett-Joyner-Halenda (BJH) method was used for measuring the pore size distribution. The micropore surface area and micropore volume were estimated using the t-plot method.

For each measurement, about 30 mg sample was weighed into the sample cell and thoroughly degassed under a nitrogen flow for 4 hours in a Quantachrome Flow Degasser before being transferred to the nitrogen adsorption apparatus. After degassing, the sample was cooled down and weighed again to obtain the exact weight. The cell was put into a bath of liquid nitrogen for adsorption. The point-wise registration of the entire isotherm was under computer control. Depending on the surface area, an isotherm measurement (adsorption and desorption branch) may need about 5 hours for completion.
2.2.7 Thermogravimetric analysis (TGA)

Thermal Analysis is a well-established set of techniques for obtaining qualitative and quantitative information about the effects of various heat treatments on materials of all kinds, including new chemical compounds, plastics, ceramics, alloys, construction materials, minerals, foods and medicines. Heating is performed under strictly controlled conditions and the record of the sample weight (TGA) can reveal changes in structure and other important properties of the material being studied.

The thermogravimetric analysis (TGA) of as-made zeolite samples was performed on a Dupont SDT 2960 analyzer. In TG analysis, about 10 mg sample was heated in a flow of air (100 ml/min) from room temperature to 700 ºC at a rate of 10 ºC /min.

2.2.8 Scanning electron microscopy (SEM)

The scanning electron microscope (SEM) is an instrument that produces a largely magnified image by using electrons instead of light to form an image. In the SEM, an electron beam is focused into a fine probe and subsequently raster scanned over a small rectangular area of a sample. As the beam interacts with the sample, it creates various signals (secondary electrons, internal currents, photon emissions, etc.), all of which can be appropriately detected. The origin of these signals is localized to the area directly under the probe beam. By using these signals to modulate the brightness of a cathode ray tube (CTR), which is raster scanned in synchronism with the electron beam, an image is formed on the screen. The magnification of the displayed image is defined as the ratio of the size of the image on the CTR to the size of the travel of the electron beam scanning the specimen surface. The type of information obtained can be changed by switching the
signal. In this way, a specific desired characteristic of the specimen surface can be seen on the CRT in a magnified scale.

In this study, the SEM was used to study the topography and morphology of the zeolite samples. The SEM images were obtained on a JEOL JSM-5200 microscope using 15 KV electron beam.

2.2.9 X-ray photoelectron spectroscopy (XPS)

X-ray Photoelectron Spectroscopy, known as XPS or ESCA (Electron Spectroscopy for Chemical Analysis) is one of the most extensively used techniques in surface analysis [11]. It consists of ionizing the atoms of a solid sample with X-ray photons and analyzing the energy of core level electrons emitted from approximately the top 30 Å of the sample. The basis of the technique lies in Einstein’s explanation of the photoelectric effect, whereby photons can induce electron emission from a solid provided the photon energy \((h\nu)\) is greater than the work function. The kinetic binding energy of the photoelectron \((E_{\text{kin}})\) as measured by the analyzer is given by:

\[
E_{\text{kin}} = h\nu - E_B - w
\]

Where, \(h\) is Plank’s constant; \(\nu\) the X-ray photon frequency; \(w\) the work function of the analyzer.

The binding energies are characteristic of for each chemical element. Therefore, XPS can be used to analyze the composition of the sample. The most powerful aspect of XPS lies in its ability to measure the binding energy at a high resolution, determining the chemical states of an element being investigated. Any change in the chemical environment of the element will involve a spatial redistribution of its valence electron density, resulting in a different potential as seen by a core electron. This change will be
reflected in a binding energy shift, usually called “chemical shift”, in photoelectron spectroscopy.

In this study, XPS was used to determine the oxidation state of zirconium oxides in zeolite. XPS investigation was conducted on an AXIS-His 165 Ultra (Kratos Analysis) spectrometer using an Al Kα X-ray source (1486.71eV, 400W) at the constant analyzer pass energy of 20.0 eV. Curve-fitting was carried out using a nonlinear (Shirley type) least-squares fitting software (XPS-PEAK 41) to separate the overlapping peaks. Due to the charging problem of the insulating samples, the binding energy values were referenced to the C 1s line at 284.6eV (arising from the inadvertent carbon contamination).

2.3 Catalytic experiments

2.3.1 Meerwein-Ponndorf-Verley (MPV) reduction

\[ \text{R}_1\text{R}_2\text{O} + \text{OH} \xrightleftharpoons{\text{Lewis acid}} \text{R}_1\text{OH} + \text{R}_2\text{O} \]

The MPV reduction was carried out in 25-ml round-bottomed flasks equipped with septum port, reflux condenser, and a guard tube. Typically, the reaction mixture containing 1.3 mmol of substrate (ketone or aldehyde) and 5 g (83 mmol) of 2-propanol as solvent and proton donor was placed in the flask and heated to the reflux temperature of 2-propanol (82 °C). Then 100mg of catalyst was added to the reaction mixture (time 0). Aliquots were removed at different reaction times and the products were analyzed by a HP 6890 GC equipped with a HP-5 capillary column (250 µm x 0.25 µm x 30m) and FID detector. The identity of the products was verified by comparing the retention times and GC/MS spectra with authentic samples. In the case where no authentic samples were available, \(^1\)H NMR analysis was performed. Besides 2-propanol, other secondary
alcohols such as 2-butanol, 2-pentanol, cyclopentanol, cyclohexanol and 4-methyl-2-pentanol were also used as hydrogen donor.

To test the stability and activity of the catalyst with water in the reaction media, different amounts of water, from 0.6 wt% to 9.1 wt%, were added to the reaction mixture. Poisoning by acids and bases was investigated by adding 0.37 – 0.52 mmol of acetic acid, benzoic acid and pyridine to the reaction mixture.

2.3.2 Oppenauer oxidation

\[
\begin{align*}
\text{OH} & \quad \text{Lewis acid catalyst} & & \quad \text{Toluene, } 110 \degree C \\
\text{R}_1 \text{R}_2 & \quad \text{CHO} & & \quad \text{R}_1 \text{R}_2 \\
\text{O} & \quad \text{O} & & \quad \text{R}_1 \text{R}_2 \quad \text{O} \quad \text{CH}_2 \text{OH}
\end{align*}
\]

Similar to the MPV experiments, all Oppenauer oxidations were carried out in a 25-ml round-bottomed flask equipped with a septum port, reflux condenser, and a guard tube.

Typically, the reaction mixture containing 1.3 mmol substrate, 7.8 mmol oxidant, 10 ml toluene was placed in the flask and heated to reflux temperature of toluene (110 ºC). Then 100 mg of catalyst was added to the reaction mixture (time 0). Aliquots were removed at different reaction times and the products were analyzed by a HP 6890 GC equipped with a HP-5 capillary column (250 µm x 0.25 µm x 30m) and FID detector. The identity of the products was verified by comparing the retention times and GC/MS spectra with authentic samples. The oxidants used were furfural, benzaldehyde, cyclohexanone, and 2-butanone. Parameters have been modified as required if the catalysts and substrates were particularly reactive, or unusually unreactive.

The Oppenauer oxidation of 4-tert-butylcyclohexanol \((cis:trans \approx 27:73)\) was carried out using 2-butanone as oxidant. 1.3 mmol of 4-tert-butylcyclohexanol and 83 mmol of 2-butanone were reacted at 80 ºC in the presence of 100 mg Zr-beta zeolite catalyst.
2.3.3 Catalytic cyclisation of citronellal

Catalytic cyclisation of citronellal were carried out in a 25-ml two-necked round-bottomed flask equipped with a septum port, reflux condenser, and a guard tube. (±)-citronellal (Fluka, ~90%) and various solvents were commercial analytical grade products and were used as received. Typically, the reaction mixture containing 4 mmol (±)-citronellal and 5 ml solvent was placed in the flask and heated to reaction temperature (25-80 ºC). Then 50 mg of catalyst was added to the reaction mixture (time 0). Aliquot were removed at different reaction times and the products were analyzed by a HP 6890 GC equipped with a HP-5 capillary column (250 µm x 0.25 µm x 30m) and FID detector. The conversion of citronellal was corrected for the isopulegol originally present. The different isomers were identified by GC-MS and \(^1\)H NMR using a Bruker AMX500 (500MHz) spectrometer.

2.3.4 Synthesis of (S)-1-phenylethanol and (R)-1-phenylethyl acetate.

Racemic 1-phenylethanol (1.22 g, 10 mmol) and isopropenyl acetate (2 g, 20 mmol) were dissolved in TBME (10 ml). Then 150mg Novozym 435 was added. The suspension was stirred at 55 ºC until the enantiomeric excess (ee) of 1-phenylethanol was more than 99.5% (after about 30 hours). The reaction mixture was filtered and separated by HPLC
(Et$_2$O/n-hexane 5:95) to yield (S)-1-phenylethanol (0.42g, ee>99.5%, yield≈70%) and
(R)-1-phenylethyl acetate (0.60g, ee>99.5%, yield≈73%). The separated products were
used for the racemization experiments without further purification.

Novozym 435 (2.5 U/mg), an immobilized Candida Antarctica lipase B (CALB), was
bought from Fluka.

The ee of (S)-1-phenylethanol and (R)-1-phenylethyl acetate was determined by gas
chromatography on an Agilent 6890N GC equipped with a Supelco Beta Dex 325 chiral
capillary column (250 µm x 0.25 µm x 25m) and FID detector.

2.3.5 Racemization of (S)-1-phenylethanol

\[
\begin{align*}
\text{Catalyst} & \quad \text{Toluene, 60 °C} \\
\text{OH} & \quad \text{OH}
\end{align*}
\]

The racemization of (S)-1-phenylethanol was carried out in a two-necked round-
bottomed flask equipped with a septum port, a reflux condenser, and a guard tube.
Typically, 0.25mmol (S)-1-phenylethanol was dissolved in 5ml toluene and heated to 60
°C. Then 100 mg of catalyst was added to the reaction mixture (time 0). The reaction
progress and ee was monitored by an Agilent 6890N GC equipped with a Supelco Beta
Dex 325 chiral capillary column (250 µm x 0.25 µm x 25m) and FID detector.

2.3.6 General procedure for the dynamic kinetic resolution of 1-phenylethanol

\[
\begin{align*}
\text{enzyme} & \quad \text{acyl donor} \\
\text{OH} & \quad \text{OH}
\end{align*}
\]

Zr-beta catalyzed racemisation

theoretical yield 100%
1 mmol racemic 1-phenylethanol was dissolved in the selected solvent and mixed together with 30mg Novozym 435 and 400mg Zr-beta zeolite. The reaction slurry was stirred vigorously and heated to the desired reaction temperature. Then 2 mmol isopropenyl acetate was added to the reaction mixture (time 0). The reaction process and ee was monitored by an Agilent 6890N GC equipped with a Supelco Beta Dex 325 chiral capillary column (250 µm x 0.25 µm x 25m) and FID detector.

The identity of the products was verified by comparing the retention times and GC/MS spectra with authentic samples.
Reference


Table 2-1 Infrared bands of pyridine on acid solids in the 1400-1700 cm\(^{-1}\) region\(^a\).

<table>
<thead>
<tr>
<th>Hydrogen bonded pyridine</th>
<th>Coordinately bonded pyridine</th>
<th>Pyridinium ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1440-1447 cm(^{-1}) (v.s.)</td>
<td><strong>1447-1460 cm(^{-1}) (v.s.)</strong></td>
<td></td>
</tr>
<tr>
<td>1485-1490 cm(^{-1}) (w)</td>
<td>1488-1503 cm(^{-1}) (v)</td>
<td>1485-1500 cm(^{-1}) (v.s.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>1540 cm(^{-1}) (s)</strong></td>
</tr>
<tr>
<td>1580-1600 cm(^{-1}) (s)</td>
<td>~1580 cm(^{-1}) (v)</td>
<td>1600-1633 cm(^{-1}) (s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~1620 cm(^{-1}) (s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~1640 cm(^{-1}) (s)</td>
</tr>
</tbody>
</table>

\(^a\) Band intensities: v.s.—very strong; s—strong; w—weak; v—variable.
Chapter 3

Synthesis and characterization of Zr-beta zeolite in fluoride medium

3.1 Introduction

Zeolite beta is a large-pore and high-silica microporous material which was first synthesized by Wadlinger et al. [1] in 1967 from basic aqueous aluminosilicate gels with sodium and tetraethylammonium cations as the structure directing agents (SDA). Because of the high complexity of its framework, the structure of zeolite beta has been only resolved 30 years after its synthesis using a combination of high-resolution electron microscopy, model building, and powder pattern simulation [2-4]. Zeolite beta was reported to be an intergrowth of two or more polymorphs comprising a three-dimensional system of 12-membered ring channels. It is one of the few high-silica zeolites possessing a three-dimensional system of large rings (rings of 12 oxygen atoms as the minimum constricting apertures). This gives zeolite beta interesting potential applications in acid-catalyzed reactions where high thermal and hydrothermal stability and low steric restrictions can be of paramount importance. Because one of the polymorphs that compose zeolite beta is chiral, therefore, another reason for the interest in zeolite beta is the possibility of synthesizing a chiral, enantiomerically pure zeolite and the potential applications of such a catalyst in enantioselective reactions.

The Si/Al molar ratio for zeolite beta described in the original patent is in the range 5-100. Later, various parameters that influence the synthesis of zeolite beta have been investigated. These parameters include the alkali cation concentration, the type of cation used [5-7], the hydroxide concentration [5, 7, 8], the nature and the amount of the organic template [1, 5-7, 9, 10], the temperature and the type of silica source used [5, 11]. The
isomorphous substitution of aluminum in the zeolite beta framework by other element such as iron [12, 13], boron [9], indium [14], and gallium [15, 16] has also been achieved by direct synthesis from alkaline reaction media or by a dry-gel conversion technique. However, for almost 30 years, it seemed to be not possible to obtain zeolite beta without Al or another trivalent element.

Only recently, the introduction of seed-assisted synthesis made the synthesis of zeolite beta with Si/Al ratio of more than 100 and the isomorphous substitution of aluminum by other than trivalent element possible. Van der Waal et al. [9] reported the synthesis of pure silica zeolite beta by using dimethyldibenzylammonium as the structure-directing agent. In their synthesis, deboronated borosilicate zeolite beta was used as seeds. Camblor et al. [17], employing dealuminated zeolite beta as seeds, successfully synthesized Zeolite Ti-beta with tetraethyl ammonium salts in basic media with Si/Al ratios up to 5000. In a similar way, Al free Sn-beta [18] was synthesized in basic media, again using the tetraethylammonium cation as structure directing agent.

By using a near-neutral non-alkaline medium, where hydroxide anions are replaced by fluoride anions as the mineralizing agent, the Al- and B-beta zeolites were prepared in the presence of 1, 4-diazabicyclo [2.2.2] octane and methylamine as the templates [19, 20]. From similar almost neutral fluoride-containing media, the synthesis of pure silica [21, 22], Al-[23], Ga-[24], Ti-[25, 26] and Sn-beta [27] zeolites was also reported in the presence of tetraethylammonium cations as the structuring agent. Zeolites synthesized in fluoride medium are usually defect-free, and they generally exhibit low density, and can be grown into relatively large crystals. Moreover, the protonic form of the zeolite can be
obtained directly by calcination of the as-made solid. All these properties make the fluoride route a promising one, especially for the synthesis of high silica zeolites.

Zirconium-base catalysts have been widely used in many reactions due to their moderate acidity and oxidizing capability [28]. However, low surface areas of these materials restrict their industrial applications. Therefore, attempts are being made to perform isomorphous substitution of Si by Zr in zeolite and zeolite-like materials. This has led to the synthesis of microporous zirconium silicates with MFI [29], MEL [30], and AFI [31] topology and mesoporous zirconium silicates with HMS [32, 33], MCM-41 [34, 35], and MCM-48 [36] structure.

The substitution of Al by Zr in the framework of zeolite beta has also been attempted [37]. However, the synthesis of Zr-beta zeolite is very difficult in a conventional basic media and requires the presence of aluminum. In this chapter, the synthesis of Al-free Zr-beta zeolite in the presence of tetraethylammonium cations and fluoride anions at near neutral pH was investigated. The materials obtained have been characterized by powder X-ray diffraction (XRD), $^{29}$Si MAS NMR, IR, XPS, and TG.
3.2 Results and discussions

3.2.1 Synthesis of Zr-beta zeolite in fluoride medium

The possibility to synthesize the Al-free zeolite beta in fluoride medium using TEAOH or dibenzyldimethylammonium (DBDMA+) as template opened the way for the isomorphous substitution of Si by metals other than trivalent element. In this study, Zr-beta zeolite was synthesized by using TEAOH as structure-directing agent and HF as mineralizer at near neutral pH. The most representative syntheses results are presented in Table 3-1.

As can be seen, pure and highly crystalline Zr-beta zeolite was obtained in a range of initial Si/Zr ratios between $\infty$ and 75 with dealuminated zeolite beta as seeds. In this range, no impurities were detected, so it can be concluded that under our synthesis conditions, Al-free Zr-beta can be easily obtained in the fluoride medium at near neutral pH. Aluminum is not necessary for the synthesis of Zr-beta zeolite in fluoride medium; in contrast, it is impossible to obtain Zr-beta zeolite in a conventional basic medium without the presence of an aluminum source [37]. Zr-beta zeolite could also be synthesized in the absence of seed crystals. However in this case, an extremely long synthesis time was needed and in our synthesis conditions Zr-beta zeolite was obtained only with Si/Zr ratios greater than 100.

The data in Table 3-1 show that the Si/Zr ratio in the solid was quite similar to that in the synthesis mixture. However, the incorporated Zr percentage decreased slightly as the total Zr concentration increases. This is possibly because at nearly neutral fluoride medium, when Zr content increases, the soluble Zr complexes with F⁻ maintain a significant portion of Zr in solution and limit the incorporation of Zr to the zeolite.
To study the effect of the initial Si/Zr ratio on the formation of zeolite Zr-beta in the fluoride medium, the crystallization kinetics were studied with the initial Si/Zr from 200 to 75. The crystallization of zeolite Zr-beta was carried out in static conditions at 140 ºC with synthesis times in the range 5-25 days. Crystallinity was determined by XRD as mentioned in 2.2.2 of Chapter 2. As can be seen in Figure 3-1, the crystallization time needed to obtain Zr-beta zeolite increased considerably when the Si/Zr ratio in the synthesis mixture decreased. Actually, there was a steady and strong increase in the “induction period” (time before any crystallinity is observed) as the Si/Zr ratio decreases. This observation indicates that the introduction of zirconium in the synthesis mixture seems to slow down the crystallization rate. A similar dependence of the crystallization time on the metal content had already been observed for zeolite beta synthesized both in basic medium in the absence of alkali metals [38] and in fluoride medium [23].

An interesting feature of this synthesis procedure is that the yield of crystalline solids is always more than 95%. This is a significant improvement compared to the conventional synthesis in basic medium where the yield of zeolite beta is always less than 50%, and decreases as the Si/Al ratio increases due to a decreased efficiency of Si incorporation. It is also remarkable that the materials obtained with this method are highly stable at the synthesis conditions, and once the maximum crystallinity has been reached, the zeolite yield and crystallinity are maintained for at least 10 additional days.

3.2.2 Powder X-ray diffraction

Figure 3-2 displays the X-ray diffraction patterns of the as-made and calcined Zr-beta samples Zr100. These patterns show the typical features of zeolite beta with both sharp and broad reflections, which indicate a highly faulted structure. It is remarkable that no
other crystalline phases were observed competing with beta, and all samples exhibit very high crystallinity compared with alumina zeolite beta synthesized in basic medium (less than 80%, not shown here). The enhanced crystallinity of these samples could be attributed to the relatively large crystal size (~1µm) and also to the decrease in connectivity defects (will be discussed below). It has to be pointed out that the resolution of the X-ray diffraction patterns improves as the Si/Zr ratio increases, which has been shown in Table 3-1. The decrease of the resolution is possibly due to Zr incorporation in the framework which reduces the degree of zeolite lattice order because the bond length of tetrahedral Zr-O (2.00 Å) is much longer than that of the tetrahedral Si-O (1.59 Å).

On close examination of the broad peaks in the low 2θ angle region of pure Si-beta and Zr-beta samples (Figure 3-3), we found that the fault plane, as defined by Newsam et al. [2], was dependent on the Si/Zr molar ratio. In pure Si-beta, the bigger peak at 2θ ≈7.8º relative to the shoulder at 7.2º indicates that the fault probability may be nearer to polymorph A than in standard zeolite beta samples. This observation is in line with the results reported by Camblor et al. [21]. However, as the Zr content increases, the bigger peak splits into two peaks: one at 2θ ≈7.5º and the other at 2θ ≈8.2º. If we compare our experimental powder X-ray diffraction patterns with that of the simulated patterns of zeolite beta in the low angle region (Figure 3-4), it is very clear that the stacking probability of polymorph B is more than 60% in Zr-beta samples. The change in line profile with increasing Zr-substitution may be interpreted as a Zr-induced preference for the stacking sequence of polymorph B.

XRD technology was also used to evaluate the thermal stability of zeolite Zr-beta samples synthesized in fluoride medium. The powder XRD patterns of zeolite Zr-beta
sample Zr100 calcined at 580 °C, 750 °C, and 900 °C for 2 h, respectively are shown in Figure 3-5. The XRD peak intensity of the sample calcined at 900 °C was nearly the same as the one calcined at 580 °C. This result indicates zeolite Zr-beta synthesized in fluoride medium is much more thermally stable than the conventional zeolite beta because the crystallinity of the latter is destroyed upon calcination at 750 °C.

It is well known that plenty of connectivity defects (Si-O’ or Si-OH groups) exist in beta zeolite synthesized in OH- media [9]. The presence of connectivity defects can affect the sorption and hydrophilic/hydrophobic properties of zeolites while usually causing a relatively poor thermal stability. However, beta zeolite synthesized in fluoride medium is almost free of connectivity defects because organic cations are counterbalanced by occluded F-. Therefore, we can conclude that the high thermal stability of Zr-beta synthesized in fluoride medium is due to the absence of connectivity defects.

3.2.3 $^{29}$Si MAS NMR spectroscopy

$^{29}$Si MAS NMR was used to study the coordination and chemical environment of Si species in the calcined zeolite Zr-beta samples. It has been reported that there were two resonances in the $^{29}$Si MAS NMR spectra of beta zeolite synthesized in basic media, one of which located at about –110.9ppm assigned to $Q^4$ (Si with four O-Si connectivities) and the other appearing at –101.6 ppm assigned to $Q^3$ [9, 40]. The formation of $Q^3$ was assumed to derive from structural defects of connectivity (Si-O- or Si-OH groups). However, for pure siliceous beta zeolite synthesized in fluoride medium, only the resonance lines corresponding to $Q^4$ species occupying different crystallographic sites was detected in $^{29}$Si MAS NMR spectrum [21].
As can be seen in Figure 3-6, in our synthesis conditions, the spectrum of the pure Si-beta is similar to the spectrum reported by Camblor et al. [21]. When Zr is incorporated to Al-free zeolite beta by the route described here, a broadening of the peaks is apparent in the $^{29}$Si MAS NMR spectrum. This broadening, which increases as the Zr content increases, causes a major loss of resolution, and only three broad resonances are evident at ca. -112, -113.0 and -115.8 ppm (all these resonances are assigned to $Q^4$ species). A similar broadening was observed in Al-beta, Ti-beta samples synthesized in both basic and fluoride media. The reason for this is most likely a decreased local order due to the distortion of the framework caused by the incorporation of Zr atoms and the presence of overlapping Si(OSi)$_4$ and Si(OSi)$_3$OZr resonances unspecifically occupying different crystallographic sites. However, these lines could still be assigned to the Si(OSi)$_4$ species occupying different crystallographic non-equivalent tetrahedral sites because all these resonances appear at a chemical shift more negative than -109 ppm.

In conclusion, $^{29}$Si MAS NMR analysis ascertains the absence of connectivity defects in our zeolite Zr-beta samples synthesized in the fluoride medium.

3.2.4 FTIR spectroscopy

3.2.4.1 Framework Vibration Region

The IR spectra of the as-made material in the framework vibration region are shown in Figure 3-7. In the 500-650 cm$^{-1}$ region, characteristic vibrations of the zeolite beta appear in zeolite Zr-beta, but there are some differences compared with that of a H-beta zeolite synthesized in basic medium. The vibrations in the Zr-beta samples are more complicated; 4 additional peaks at 498 cm$^{-1}$, 558 cm$^{-1}$, 723 cm$^{-1}$, and 766 cm$^{-1}$ appear in these samples. We attribute these extra vibration bands to the incorporation of F$^{-1}$ in the
zeolite. This can influence the vibrations of the T atoms, as F\(^{-1}\) is usually located in the small cages within the zeolite framework, possibly modifying T-O-T angles. Furthermore, coordination of F\(^{-1}\) to framework Si, giving rise to pentacoordinated [SiO\(_{4/2}\)F\(^{-1}\)], has been recently demonstrated [41, 42], and could be a general feature of zeolites synthesized in fluoride media. The presence of these species would certainly affect the IR framework vibrations.

The IR spectra of the calcined samples in the framework vibration region are shown in Figure 3-8. In contrast to the observation in the as-made samples, Zr-beta showed an IR spectrum very similar, though better resolved, to the Al-beta zeolite. This is because the F\(^{-}\) anion and TEA\(^{+}\) cation in the as-made samples are removed during calcination. This observation further confirms our conclusion on the effect of F\(^{-}\) on the IR spectrum. An interesting observation is that the intensity of the peaks at 475 cm\(^{-1}\), 644 cm\(^{-1}\), and 745 cm\(^{-1}\) decreases as the Zr content increases. This shows that the incorporation of Zr into beta framework decreases the number of some oscillators located in different vibration environments. Another remarkable feature is the lack of a band at about 960 cm\(^{-1}\). This band is frequently observed in zeolites when Si is partially substituted by other metals (such as Ti, Sn, V, Cr…). It is generally assigned to a Si-O stretching vibration in Si-O-T (T= Ti, Sn, V, Cr…) groups. However, this band also appears in high silica zeolites containing a high concentration of connectivity defects. Thus it is also assigned to the Si-O\(^{-}\) groups in these defects. Rakshe et al. [29] observed the band at 960 cm\(^{-1}\) in Zr-Sil-1 synthesized in basic medium. However, they did not observe this band when Zr-Sil-1 was synthesized in fluoride medium. Therefore, this band may be mainly due to the Si-O\(^{-}\) in connectivity defects (at least in zirconium containing zeolites). The absence of
this band therefore further confirms the absence of connectivity defects in Zr-beta zeolite synthesized in the fluoride medium.

3.2.4.2 OH stretching region

IR spectra in the OH stretching region for samples with different Si/Zr ratios after being evacuated at 300 °C for 4h are shown in Figure 3-9. In the 3650-3750 cm\(^{-1}\) range, only a very small broad band appears in the IR spectrum of pure Si-beta zeolite. This shows the hydrophobic nature of the pure Si-beta zeolite synthesized in fluoride medium. In contrast, an extremely strong broad band (3200-3750 cm\(^{-1}\)) is formed in the spectrum of Al-beta sample synthesized in basic medium. Camblor et al. [43] studied the OH stretching of the as-made H-beta zeolite sample employing FTIR spectroscopy. They found two vibration bands; one is at around 3745 cm\(^{-1}\), the other at around 3615 cm\(^{-1}\). The former was assigned to OH in silanol groups. The latter was assigned to OH in Si-(OH)-Al groups in the framework. In our calcined H-beta sample, these two bands are not well resolved. This is perhaps due to residual adsorbed water, because of the relatively poor vacuum during drying and sample measurements (~10\(^{-3}\) mbar).

In the case of Zr-beta samples, a very broad band appeared at ca. 3670 cm\(^{-1}\), and its intensity increases as the Zr content increases. The hydroxyl groups on ZrO\(_2\) have been extensively studied [44-47]. The IR spectra of isolated OH groups on pure ZrO\(_2\) phases exhibit one or two structured bands. Their intensity ratio and their intensity distribution within each of the bands are unequivocally related to the surface phase composition and the local surface structure, respectively. However, the two pure ZrO\(_2\) phases both exhibit a band centered around 3670 cm\(^{-1}\), which is related to the tetrahedrally coordinated bulk oxygen which is present in monoclinic and tetragonal ZrO\(_2\). In our zeolite Zr-beta
samples, the Zr atom is isolated, and is connected via O to Si atom. The broad band at about 3670 cm$^{-1}$ could be assigned to the terminal Zr-OH group. Though the terminal Si-OH groups may also contribute to this band, the synthesis method we used prevented the formation of Si-OH groups. This conclusion could be confirmed by our $^{29}$Si MAS NMR results.

3.2.4.3 Pyridine adsorption

The infrared spectra of pyridine adsorption at 25 ºC and desorption at 25 ºC, 100 ºC, and 200 ºC on calcined Zr100 are given in Fig. 3-10. The spectra showed medium strong bands at 1600 cm$^{-1}$ and 1450 cm$^{-1}$ due to pyridine coordinately bound to Lewis acid sites (νs modes) [48]. The band at 1600 cm$^{-1}$ shifts to 1608 cm$^{-1}$ when the temperature during desorption was increased. A band of medium intensity at 1490 cm$^{-1}$ due to both the coordinated pyridine and pyridine chemisorbed on protonic acid sites is also observed. A very weak band at 1545 cm$^{-1}$ is assigned to the pyridine adsorbed on Brønsted acid sites. However, the desorption of pyridine with higher desorption temperature indicates preferential removal of pyridine bound to Brønsted relative to Lewis acid sites. From these observations, it is concluded that Lewis acidity is predominant in zeolite Zr-beta.

The pyridine adsorption spectra of zeolite Zr-beta were compared with Si-beta and an zeolite Al-beta synthesized in basic medium after evacuation at 100 ºC (Figure 3-11). Al-beta zeolite exhibits both strong Lewis and strong Brønsted acidity. This is line with the reported results. It was also found that pure Si-beta possesses some very weak Lewis acid sites. The acidity of Zr-beta is much weaker than H-beta zeolite but stronger than pure Si-beta. Moreover, it increases along with Zr content in beta zeolite. These observations
indicate that the Lewis acidity of Zr-beta is related to the zirconium species incorporation in the zeolite lattice.

3.2.5 Scanning Electron Microscopy (SEM)

Zeolite beta synthesized in basic medium typically yields small crystallites, usually <1 µm and, when the synthesis is carried out in the absence of alkali cations, nanocrystals as small as 10 nm can be obtained. On the other side, syntheses carried out in F⁻ medium typically produce bigger crystal. This has been related to the lower mineralizing power of F⁻ as compared to OH⁻, causing lower supersaturation and therefore smaller nucleation rates. The few nuclei formed can therefore grow to bigger crystals. The slower crystal growth results in higher crystallinity and less defects. This is in agreement with the absence of connectivity defects inferred from framework IR measurements (see 3.2.4.1)

SEM images of pure Si-beta and Zr-beta samples synthesized without seeding are shown in Figure 3-12 (a-c). The crystals show the truncated square bipyramidal morphology typical of zeolite beta. Moreover, the crystal size is quite uniform and unusually large, exceeding 10 µm. However, the synthesis time needed to crystallize Zr-beta zeolite is extremely long without seeding. From catalytic point of view, small crystal sizes are usually preferred in order to eliminate internal diffusion limitations. Considering all of these, we performed syntheses of the material using zeolite beta seed crystals with very small crystal size (about 50 nm). The SEM images of the zeolite Zr-beta synthesized with seeding are presented in Figure 3-12 (d-e). The seeded samples give zeolite Zr-beta with an average crystal size around 1 µm. The crystal size distributions are quite uniform and also show the truncated square bipyramidal morphology typical of zeolite beta. The seeding effect is obvious because both crystallization time and crystal size decrease.
3.2.6 N\textsubscript{2} adsorption

Textural properties of calcined zeolite Zr-bera samples were measured using N\textsubscript{2} adsorption isotherms at -196 °C, and the results are displayed in Table 2. The BET surface area and total pore volume were found to be quite similar for all samples within experimental error. The external surface area constitutes less than 6% of the total, which indicates the existence of some mesopores in the samples. The micropore volume in zeolites is calculated in the literature by different procedures: from the t-plot, from the adsorbed volume at a given relative pressure (normally P/P\textsubscript{0}=0.3) and from the extrapolation to P/P\textsubscript{0}=0.3 of the slope of the isotherm in the plateau. Micropore volume of zeolite Zr-beta was found to be in the range of 0.21-0.23 cm\textsuperscript{3}/g using the t-plot method.

3.2.7 X-ray photoelectron spectroscopy (XPS)

X-ray photoelectron spectroscopy (XPS) was used to obtain information on the oxidation state and the co-ordination of the Zr in the framework. The experimental X-ray photoelectron spectrum of zeolite Zr-beta sample Zr100, resolved using a Gaussian fit is shown in Figure 3-14. The observed binding energy of Zr 3d5/2 (183 eV) is significantly higher than that of ZrO\textsubscript{2} (182.2 eV), but close to that of Zr in ZrSiO\textsubscript{4} (183.3 eV). The position of the lines is very similar to that observed for Zr in the MFI structure, where it had been shown that the Zr is incorporated into the framework of the zeolite structure. In our study, the Zr 3d3/2 and 3d5/2 peaks are better resolved, and the full width at half maximum of the peaks is narrower (1.6 eV), indicating less spread in the nature of the chemical environment around the Zr\textsuperscript{4+} ions.
3.2.8 $^{13}$C CP MAS NMR and thermogravimetric analysis

$^{13}$C CP MAS NMR and thermogravimetric analysis were performed to determine the chemical state of organic materials filling the pores. The $^{13}$C CP MAS NMR spectrum of the as-synthesized Zr100 is given in Figure 3-15. Two peaks were observed, one at 51.9 ppm assigned to the methylene groups and the other at 6.5 ppm due to the methyl groups of the TEA cations. A comparison of the chemical shifts with those of aqueous TEAOH confirms the presence of TEA cations in the zeolite pores. The TGA curves for Zr-zeolite beta show three main weight losses occurring in the following temperature ranges: (i) 185-320 °C, (ii) 320-380 °C, (iii) 380-500 °C (Fig. 3-14). A similar decomposition pattern has been observed by zeolite beta synthesized in fluoride media [18, 24]. The first two weight losses can be attributed to the degradation of TEA$^+$ balancing the F$^-$ ions and the oxidation of the organic materials. The third weight loss can be assigned to TEA$^+$ balancing framework Zr charges. Indeed, it was found that as the Zr content increased, the weight loss at the high temperature range also increased proportionally.
3.3 Conclusions

The synthesis of Al-free Zr-beta zeolite has been achieved in a fluoride medium at near neutral pH. In the presence of dealuminated beta seeds, pure and well crystallized samples of zeolite beta could be obtained with Si/Zr ratio in the range from infinity to about 84, whereas in the unseeded synthesis the lowest Si/Zr was 102. The size of the crystals of zeolite Zr-beta was greatly influenced by the seeds. Bigger crystal size was obtained in the unseeded system. Increasing the Zr content required very much longer crystallization time. Because no alkaline metal was used during the synthesis, the H-form of zeolite beta can be directly obtained thought this synthesis route.

Characterization of the materials with powder X-ray diffraction and $^{29}$Si MAS NMR showed an increased resolution of the pattern when decreasing the zirconium content. This is due to the absence of connectivity defects and also to the higher degree of order in the absence of zirconium. The XPS spectrum is consistent with zirconium incorporated in the framework of the zeolite structure. The incorporation of zirconium into framework induced the preference for the stacking sequence of polymorph B as observed in the XRD patterns. IR spectra of the adsorbed pyridine showed that Lewis acidity was predominant in zeolite Zr-beta samples.
References


Table 3-1. Synthesis of Zr-beta zeolite in fluoride medium.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Seeding&lt;sup&gt;a&lt;/sup&gt; (wt %)</th>
<th>Time (d)</th>
<th>Temp. (°C)</th>
<th>Yield&lt;sup&gt;b&lt;/sup&gt; (%)</th>
<th>Crystalinity (%)</th>
<th>Si/Zr molar ratio Gel product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-beta</td>
<td>-</td>
<td>10</td>
<td>140</td>
<td>102</td>
<td>129</td>
<td>∞</td>
</tr>
<tr>
<td>Zr200</td>
<td>3.5</td>
<td>20</td>
<td>140</td>
<td>96</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Zr150</td>
<td>3.5</td>
<td>20</td>
<td>140</td>
<td>97</td>
<td>98</td>
<td>150</td>
</tr>
<tr>
<td>Zr100</td>
<td>3.5</td>
<td>20</td>
<td>140</td>
<td>95</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>Zr75</td>
<td>3.5</td>
<td>25</td>
<td>140</td>
<td>95</td>
<td>89</td>
<td>75</td>
</tr>
<tr>
<td>Zr50</td>
<td>3.5</td>
<td>30</td>
<td>140</td>
<td>-</td>
<td>amorphous</td>
<td>50</td>
</tr>
<tr>
<td>Zr200N</td>
<td>-</td>
<td>25</td>
<td>140</td>
<td>99</td>
<td>87</td>
<td>200</td>
</tr>
<tr>
<td>Zr100N</td>
<td>-</td>
<td>30</td>
<td>140</td>
<td>100</td>
<td>81</td>
<td>100</td>
</tr>
<tr>
<td>Zr75N</td>
<td>-</td>
<td>40</td>
<td>140</td>
<td>-</td>
<td>amorphous</td>
<td>75</td>
</tr>
</tbody>
</table>

<sup>a</sup> dealuminated zeolite beta as seeds.<sup>b</sup> Calculated in calcined samples with respect to SiO<sub>2</sub>+ZrO<sub>2</sub> in the starting mixture. <sup>c</sup> As reference.

Table 2. Characteristic N<sub>2</sub> adsorption/desorption data for calcined zeolite Zr-beta samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>BET area (m&lt;sup&gt;2&lt;/sup&gt;/g)</th>
<th>Ext. surface area (m&lt;sup&gt;2&lt;/sup&gt;/g)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Total pore Vol. cm&lt;sup&gt;3&lt;/sup&gt;/g</th>
<th>Micropore Vol. cm&lt;sup&gt;3&lt;/sup&gt;/g&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-beta</td>
<td>487</td>
<td>30</td>
<td>0.264</td>
<td>0.225</td>
</tr>
<tr>
<td>Zr200</td>
<td>475</td>
<td>39</td>
<td>0.264</td>
<td>0.214</td>
</tr>
<tr>
<td>Zr150</td>
<td>474</td>
<td>33</td>
<td>0.264</td>
<td>0.216</td>
</tr>
<tr>
<td>Zr100</td>
<td>490</td>
<td>35</td>
<td>0.268</td>
<td>0.223</td>
</tr>
<tr>
<td>Zr75</td>
<td>499</td>
<td>30</td>
<td>0.269</td>
<td>0.230</td>
</tr>
</tbody>
</table>

<sup>a</sup> From the <i>t</i>-plot method.
Figure 3-1. Influence of Si/Zr ratio on the synthesis of Zr-beta. (●) Si/Zr=200, (■) Si/Zr=100, and (▲) Si/Zr=75.

Figure 3-2. X-ray diffraction patterns of as-made (a) and calcined (b) Zr-beta zeolite samples Zr100.
Figure 3-3. XRD diffraction pattern of calcined Zr-beta at low 2θ range: (a) Zr75, (b) Zr100, (c) Zr200, and (d) Si-beta.
Figure 3-4. Intensity of simulated powder X-ray diffraction patterns versus diffraction angle ($2\theta$) of the BEA-Polymorph B series in steps of 10% intergrowth. The stacking sequences number 2 and 4 (cf. Table 1) are disordered. The 100% BEA and 0% BEA patterns corresponds to pure Polymorph A and B [39].
Figure 3-5. X-ray diffraction patterns of zeolite Zr-beta sample Zr100 calcined at: (a) 580 °C, (b) 750°C, and (c) 900 °C.
Figure 3-6. $^{29}$Si MAS NMR of calcined zeolite Zr-beta and pure Si-beta samples: (a) Zr75, (b) Zr100, (c) Zr200, and (d) Si-beta.
Figure 3-7. Infrared spectra in the framework vibration region of as-made zeolite Zr-beta samples and one beta sample synthesized in basic medium: (a) Al-beta, (b) Zr200, (c) Zr150, (d) Zr100, and (e) Zr75.

Figure 3-8. Infrared spectra in the framework vibration region of calcined zeolite Zr-beta samples and one beta sample synthesized in basic medium: (a) Al-beta, (b) Zr200, (c) Zr150, (d) Zr100, and (e) Zr75.
Figure 3-9. Infrared spectra in the OH vibration region of calcined zeolite Zr-beta samples and one beta sample synthesized in basic medium: (a)Si-beta, (b)Zr200, (c)Zr100, (d) Zr75, and (e) Al-beta.

Figure 3-10. Infrared spectra of pyridine adsorption at 25 ºC and desorption at 25 ºC (a), 100 ºC (b), and 200 ºC (c) on calcined zeolite Zr-beta sample Zr100.
Figure 3-11. Infrared spectra of pyridine adsorption (at 25 ºC) and after desorption at 100 ºC over zeolite Zr-beta samples and one Al-beta sample: Si-beta (a), Zr200 (b), Zr100 (c), Zr75 (d), and Al-betaTi-beta (e).
Figure 3-12. SEM images of Zr-beta zeolite synthesized in the fluoride medium.
Figure 3-13. X-ray photoelectron spectroscopy of calcined zeolite Zr-beta sample Zr100.

Figure 3-14. $^{13}$C CP MAS NMR of uncalcined zeolite Zr-beta sample Zr100.
Figure 3-15. Thermogravimetric analysis of uncalcined zeolite Zr-beta samples: (a) Zr75, (b) Zr100, and (c) Zr200.
Chapter 4

Zr-beta zeolite as a regioselective catalyst in the Meerwein-Ponndorf-Verley reduction

4.1 Introduction

The Meerwein-Ponndorf-Verley (MPV) reduction of carbonyl compounds and the Oppenauer oxidation of alcohols, together denoted as MPVO reactions, are highly selective reactions and can be performed under mild reaction conditions [1]. One characteristic of the MPV reaction is that only carbonyl groups are reduced while other reducible groups such as C=C double bonds and C-halogen are not affected. In MPV reactions, a simple secondary alcohol (e.g. isopropanol) is used as the hydrogen donor while in Oppenauer oxidations, a ketone or aldehyde is the hydrogen acceptor. The generally accepted mechanism for MPVO reactions proceeds via a transition-state complex in which both carbonyl and alcohol are coordinated to a Lewis acid metal center, after which a hydride transfer from the alcohol to the carbonyl group occurs (Scheme 4-1) [1, 2].

In homogeneous phase, the MPV reduction is usually catalyzed by metal alkoxides such as Al(OPr')₃. Recently, a number of other aluminum complexes have been reported to be highly active for the MPV reduction of carbonyl substrates [3, 4]. In-situ generated alkoxides from precursors such as dimethylaluminum chloride or trimethylaluminum were shown to give superior yields in the reaction [5]. Besides aluminum complexes, the zirconium complex, bis(cyclopentadienyl)zirconium di-hydride, has also been reported to be active in the MPV reaction [6].
Although the homogenous performed MPVO reaction has many advantages, such as chemoselectivity, mild reaction conditions, and ready adaptation both in the laboratory and on a large scale, the need for large amounts of catalyst and separation problems limit their practical applications. To overcome these problems, heterogeneous catalysis of the MPV reaction has been studied on metal oxides, such as Al$_2$O$_3$ [7], hydrous ZrO$_2$ [8, 9] as well as magnesium oxides or phosphates [10, 11], grafted alkoxides or alkyl complexes [12-14].

Al-zeolite beta has been reported to be a highly active and regioselective catalyst for the reduction of 4-tert-butylcyclohexanone to the thermodynamically less stable cis-4-tert-butylcyclohexanol [15]. The high selectivity towards the thermodynamically less favoured cis-alcohol was explained by a restricted transition-state around a Lewis-acidic aluminum atom in the straight channels of the zeolite beta pore system. Later on, Ti-Beta [16, 17] and Sn-beta [2, 18] were also reported as excellent catalysts for MPVO reactions. In all these systems, Lewis acid sites in the zeolite were claimed to be the active center of the catalyst. With regards to activity and selectively, Al-free Sn-beta synthesized in fluoride medium was claimed to be the best. Sn-beta was even reported to have high activity in the presence of some water if its surface was hydrophobized in a post-synthesis silylation step.

Zirconium has been used as catalyst for many reactions due to both its moderate acidity and oxidizing capabilities [19]. However, the application of Zirconium-based catalysts is limited by its low surface area and the absence of shape selectivity. Incorporation of zirconium into zeolite beta may increase its surface area on one hand and may improve its size-selectivity on the other hand. In Chapter 3, we described the
successful synthesis of zeolite Zr-beta in fluoride medium and gave results on its characterization by different techniques such as XRD, IR TGA, NMR, SEM, and XPS. In this Chapter, we will first present the catalytic ability of zeolite Zr-beta in the MPV reaction, choosing 4-tert-butylcyclohexanone as probe molecule. After that, the influence of the structure of various alcohols and ketones was studied; finally the high activity and water resistant ability of Zr-beta in MPV reaction was explored through poisoning experiments.
4.2 Results and Discusses

4.2.1 Catalyst characterization

The physical properties of the catalysts used are summarized in Table 4-1. Except zirconium impregnated beta, all samples possess large specific surface area, > 450 m²/g. The crystal size of the unseeded pure Si-beta was in the range of 10-15 µm, while that of the seeded Zr-beta samples was much smaller (1-2 µm). Due to their small particle sizes and their aggregation, the crystal size of H-beta samples synthesized according to Wadlinger and Kerr [20] can not be determined by SEM.

XRD patterns of several metal substituted zeolite beta samples synthesized in fluoride medium and one H-beta sample synthesized in basic medium are shown in Figure 4-1. These patterns show the typical features of zeolite beta with sharp and broad reflections. The crystallinity of all samples synthesized in fluoride medium was higher than that of H-beta synthesized in basic medium. As we have discussed in Chapter 3, introduction of Zr into the zeolite beta framework induced preference for the stacking sequence of polymorph B. In contrast, the broad peak of other metal substituted beta zeolite was similar to that of H-beta zeolite. This observation suggests that the effect of other metals on the stacking sequence of zeolite beta is not obvious.

The acidic properties of different metal-substituted beta zeolites were determined by IR spectroscopy following adsorption of pyridine at room temperature and desorption at 100 ºC (Figure 4-2). The pyridine adsorption spectra showed the presence of only Lewis acid sites on Sn- and Ti-zeolite beta. Due to the very low metal content, the IR spectra of these zeolites were very similar to that of the pure silica beta. However, the band at ~1442 cm⁻¹, indicative of H-bonded and Lewis-acid bonded pyridine, was shifted to
higher wavenumber for Zr-beta as compared to Ti- and Sn-beta. In addition to the bands at 1445 cm\(^{-1}\) and 1490 cm\(^{-1}\), a small band at 1545 cm\(^{-1}\) indicates the presence of some Brønsted acid sites [22]. Compared with Zr-, Sn-, and Ti-beta samples synthesized in fluoride medium, H-beta contained a much larger concentration of Lewis and Brønsted acid sites.

**4.2.2 Catalytic activity of various metal substituted zeolite beta**

For the MPV reduction of 4-tert-butylcyclohexanone, results obtained over various metal substituted zeolites beta are presented in Table 4-2. In most cases, 4-tert-butylcyclohexanol was the only product formed. After 60 min, >95 % conversion was achieved over Zr75 and Zr100. Zeolite Sn-beta (Si/Sn=125) was also active with 70.6 % conversion. However, both Ti-beta (Si/Ti=100) and Al-beta (Si/Al=100) were rather inactive with conversions of 2.9 % and < 0.5 %, respectively. H-beta synthesized in basic medium with a higher Al content (Si/Al 12.5) was also not very active; the conversion being 16 % for the 500 °C-calcined sample and 65.4 % for the 700 °C sample. Of the two possible isomers for the product, the thermodynamically less favored cis-4-tert-butylcyclohexanol was formed with very high selectivity. Over Zr-beta, the cis:trans alcohol was 99:1 while over H-beta, the ratio was slightly lower. The high regioselectivity of the reduction proves that the reaction proceeds in the channels of the zeolite structure, where steric constraints force the reaction to proceed via the less bulky transition state, as proposed by Creighton et al. [15, 23] for Al-beta zeolite. It can be seen in Scheme 4-2, in an analogous way for Zr-beta, that the transition states leading to the cis- and trans-alcohol differ substantially in spatial requirements. The transition state leading to the cis-isomer is aligned with the zeolite channel while that leading to the
trans-alcohol occupies a much more equitorial position. Even with smaller alkyl groups than t-butyl or on other positions, selectivity to the axial alcohol product prevails. Thus in the reduction of 4-, 3- and 2-methylcyclohexanone the thermodynamically less favored products, the cis, trans- and cis-alcohol, respectively, always were the major products. This will be clearly shown in the later part of this chapter.

The presence of the metal atom is important as pure Si-beta was inactive for the reaction. Impregnation of the Si-beta with zirconium oxychloride to give Si/Zr=95 did not result in an active material, indicating that isolated Zr atoms in the framework of zeolite beta are important for activity. Further support for this hypothesis comes from a comparison of the activity of Zr-beta with that of Zr-SBA-15 with non-monomeric Zr species [24]. Despite the higher Zr loading, 10 wt %, of the grafted catalyst, 60 % conversion of 4-tert-butylcyclohexanone was only achieved after 30 min as compared to 5 min over Zr-zeolite beta. The pore size influence will be discussed further in the later part of this chapter.

Corma et al. reported [2] that Sn in the framework of the zeolite beta led to Lewis acidity, and they demonstrated that Sn-beta can coordinate ketones and polarize the carbonyl group by using cyclohexanone as probing molecular. To check the polarizing ability of Zr-beta, we performed a similar experiment utilizing 4-methylcyclohexanone as probing molecule. The IR spectra after adsorbing 4-methylcyclohexanone at room temperature and partially desorbing at different temperature over various beta zeolites are shown in Figure 4-3 and Figure 4-4. The IR spectra of adsorbed 4-methylcyclohexanone on Zr-beta revealed a strong interaction with the substrate. Besides the typical vibration of the carbonyl group at 1719 cm\(^{-1}\), a second signal appeared at 1675 cm\(^{-1}\). Upon
desorption at 200 °C, the former signal disappeared completely, whereas the latter still had substantial intensity, indicating a strong dative bond from the carbonyl oxygen to the Zr-centers in the zeolite. The shift of 45 cm$^{-1}$ is comparable to that reported for Sn-substituted zeolite beta [18] and larger than that observed for Ti-substituted zeolite. For Sn- and Ti-beta, both signals disappeared after desorption at 200 °C, indicating a weak interaction between the carbonyl group and the active sites in these catalysts. For Al-beta zeolite, various broad carbonyl bands in the IR spectra could be observed. This shows that various types of interactions between 4-methylcyclohexanone and aluminum centers existed in this material because both strong Lewis acid sites and Brøsted acid sites are present in this sample. These observations suggest that the interaction of the carbonyl group with the Zr center is stronger than with Sn and Ti, and more selective than with Al centers in H-beta zeolite.

4.2.3 Reuse of zeolite Zr-beta

Zeolite Zr-beta retained good activity over several rounds of catalytic testing (Table 4-3). The used catalyst was isolated from the reaction mixture by filtration and reactivated at 580 °C. The activity of the catalyst was slightly improved after reactivation, which can be explained by the exposure of some active sites originally being blocked by coke. An interesting finding was that Zr-beta catalyst could be regenerated just through washing with 2-propanol. The conversion to 4-tert-butylcyclohexanol was still as high as 95.6% after 8 recycle runs. It is considered that the drop of the activity is not due to the leaching of the zirconium active sites, but to the loss of the catalyst during washing process. ICP analysis of the used catalyst showed that Si/Zr was nearly same as the original catalyst. These results indicate that no zirconium is leached during reaction.
4.2.4 Influence of zeolite calcination temperature

In Chapter 3, we reported that zeolite Zr-beta synthesized in fluoride was thermally stable. The crystallinity was not affected even after being calcined at 900 ºC. In order to investigate the influence of activation temperature, Zr100 calcined at different temperatures was tested for the MPV reduction of 4-tert-butylcyclohexanone under identical reaction conditions. The plot of conversion against reaction time was nearly the same for three samples tested (Figure 4-5) and the reaction order was determined to be a first-order reaction with a rate constant of 0.0031 S\(^{-1}\). This shows that the activity of Zr-beta is not significantly affected by the activation temperature in the range of 580 ºC to 900 ºC, which confirms the high thermal stability of Zr-beta. In contrast, the activity of H-beta was reported to be greatly affected by the activation temperature [15].

4.2.5 Influence of crystal size of zeolite Zr-beta

For catalytic purposes, small crystal sizes are usually preferred in order to eliminate internal diffusion limitations. In Chapter 3, we have demonstrated that the crystal size of zeolite Zr-beta synthesized with seeds was much smaller than that of the one synthesized without seeds. In order to investigate the effect of crystal size, one seeded sample (crystal size\(\approx\)1 µm) and one unseeded sample (crystal size\(\approx\)15-20 µm) with nearly identical Si/Zr (~100) ratio were tested for MPV reduction of 4-tert-butylcyclohexanone. The results are shown in Figure 4-6. The initial rate of reaction after 5 min was much faster for the seeded sample, about 3.15 times that of the unseeded one. In both cases, the reaction rate followed first-order kinetics. The reaction rate of seeded sample (0.0031 s\(^{-1}\)) was about 3.9 times faster than that of unseeded sample (0.0008 s\(^{-1}\)). The product distribution was not affected and the cis/trans ratio was always higher than 99:1. These results confirm
that the MPV reaction takes place in the inside channel of zeolite Zr-beta. The bigger crystal size does cause additional diffusion limitations. This is easy to understand because if a reaction takes place in the inside of a zeolite, then the reactants have to be transported through the pores of the catalyst to reach the active sites, and the products formed have to diffuse out of the pores. Due to the small pores of zeolite Zr-beta, internal diffusion limitations must exist in liquid-phase MPV reactions in which case the pores of the zeolite are completely filled with reactants and solvent molecules. These limitations will increase as the zeolite crystal sizes increase.

**4.2.6 Influence of different reducing agents on the catalytic performance**

A series of sec-alcohols were tested as reducing agents for the MPV reduction of 4-tert-butylcyclohexanone over Zr100. Linear alcohols were more effective compared to branched or cyclic alcohols. As shown in Table 4-4, the rate of reaction was fastest using 2-propanol, followed by 2-butanol and 2-pentanol. In contrast, when cyclopentanol and cyclohexanol was used as hydrogen donor, the rate of reaction was slower. In the latter case, some cyclohexene, formed by dehydration of cyclohexanol, was detected. The lower activity achieved with bulkier alcohols such as cyclopentanol, cyclohexanol, and 4-methyl-2-pentanol may be due to hindered diffusion of these alcohols in the pores of the zeolite as well as steric hindrance in the formation of the transition state between 4-tert-butylcyclohexanone and the alcohol.

**4.2.7 Influence of the molecular structure of the substrate**

The position of the methyl substituent on cyclohexanone has considerable influence on the rate of the MPV reduction. The rate of reaction was fastest for cyclohexanone, followed by 4-methylcyclohexanone, 3-methylcyclohexanone, and 2-
methylcyclohexanone. Like Sn-beta [2], Zr-beta was able to catalyze the reduction of 2-methylcyclohexanone. However, when H-beta was used as catalyst, this reaction did not proceed [15]. This may be due to the bigger size of the Zr$^{4+}$ and Sn$^{4+}$ ions as compared to Al$^{3+}$ leading to higher “exposure” of these ions from the oxygen framework atoms. The variation in reaction rate with position of the methyl group on the cyclohexane ring may be explained by steric hindrance posed by the methyl group in the coordination of the carbonyl to the active site. One could expect that if the cyclohexanone has a smaller substituent group like methyl instead of tert-butyl, the pore constraints limiting the formation of the axially-oriented transition state will be reduced. However, the results showed that 4-methyl-cyclohexanone is also reduced almost exclusively to the cis-alcohol \((cis:trans > 99:1)\). This has been observed for Ti-beta [16] and Sn-zeolite beta [2]. The results suggest that the solvent may participate in the intracrystalline pore channels, restricting the volume so that the more aligned \(cis\)-transition state is favoured. The use of zeolite catalysts for liquid phase reactions leads to confinement of molecules in the intracrystalline volume, a subject that has been covered well by Derouane \textit{et al.} [25, 26].

The \(cis\)- and \(trans\)-isomers of 3-methylcyclohexanol could not be separated by gas chromatography. To ascertain if only one or both isomers were formed, $^1$H NMR spectra of the products were recorded. The results show that the \(trans\)-3-methylcyclohexanol was the major isomer with a \(cis:trans\) ratio of 29:71. \(Trans\)-3-methylcyclohexanol, with an axial hydroxyl, is more linear and can align better with the pore channels of zeolite beta than the 3-\(cis\) isomer. However, \(cis\)-3-methylcyclohexanol with both hydroxyl and methyl groups in equatorial position is the thermodynamically stable isomer. With 2-methylcyclohexanone, the rate of reaction was the slowest of all mono-methyl substituted
cyclohexanones, but more of the thermodynamically less stable \textit{cis}-alcohol was formed, with a \textit{cis}:\textit{trans} ratio of 55:45.

For comparison, the MPV reduction of methylcyclohexanones was carried out over a big pore Zr-SBA-15 catalyst containing 10 wt.% Zr. Details of this catalyst have been reported previously by us \cite{24}. The grafted Zr catalyst was less active than Zr-beta despite its higher Zr loading (Table 4-5). As the mean pore diameter in this catalyst is \textasciitilde 6.5 nm, the effect of pore constraints affecting the stereoselectivity of the products is expected to be small so that the thermodynamically stable isomer should be formed in each case. Indeed, the main isomer for the MPV reduction of 4-methylcyclohexanol over Zr-SBA-15 is the thermodynamically stable \textit{trans}-4-methylcyclohexanone with a \textit{cis}:\textit{trans} ratio of 19:81. The reduction of 3-methylcyclohexanone also led a higher proportion of the thermodynamically stable isomer, i.e., \textit{cis}-3-methycyclohexanol (\textit{cis}:\textit{trans} ratio of 75:25). Furthermore, in the MPV reduction of 2-methylcyclohexanone, slightly more \textit{trans}-2-methylocyclohexanol was formed than the \textit{cis}-alcohol when compared with Zr-beta.

In addition to alkyl-substituted cyclohexanones, a variety of other ketones were also tested over Zr-beta with 2-propanol as reducing agent (Table 4-6). Cyclopentanone is less easily reduced than cyclohexanone. Conjugation between the carbonyl bond and the C=C double bond in 2-cyclohexene-1-one and 2-cyclopenten-1-one makes these compounds more difficult to reduce than saturated ketones. An aryl substituent as in acetophenone slowed down the reduction compared to ketones with alkyl substituents. In benzyl methyl ketone, a CH$_2$ group separates the benzene ring from the carbonyl group; this substrate was more easily reduced than acetophenone. The increased flexibility leads to a reduction
of steric constraints around the carbonyl. Substituents in the aromatic ring have an effect on the conversion and selectivity of the reaction due to inductive and resonance effects. The incorporation of an electron-withdrawing group with lone pair electrons such as Cl in the benzene ring resulted in an enhanced rate of reaction compared to the unsubstituted acetophenone. The only product was the reduced alcohol, 1-(4-chlorophenyl)-ethanol. Although the rate of reduction of 4-methoxyacetophenone was similar to that for acetophenone, very little of the alcohol was detected and the major product was 1-(1-isopropoxylethyl)-4-methoxy benzene, which resulted from the etherification of the formed alcohol with 2-propanol. For the electron-donating methyl substituent, the rate of reaction was enhanced over acetophenone, but the selectivity to the alcohol was only 68 % with the other products being due to etherification of 1-(4-methylphenyl) ethanol and 2-propanol, and dehydration of the formed alcohol. The formation of ethers and dehydration products can be attributed to the more acidic nature of Zr-beta as similar products were not observed over Zr-SBA-15 catalyst [24]. The observation that the electron withdrawing group accelerated the reaction rate when located on the hydrogen acceptor (ketone) is due to the decreased electron density on the carbonyl carbon atom of the ketone. The more positively charged carbonyl carbon atom will be more sensitive to a hydride attack by an alcohol. Dihydrocarvone and benzoylcyclohexane were not reduced over Zr-zeolite beta which may be due to the rigid and bulky structure of the molecules posing steric hindrance in the formation of the transition state

4.2.8 Influence of acid, base and water on the catalyst activity

The activity of Zr-zeolite beta for the MPV reduction of 4-tert-butylcyclohexanone decreased by 30 % in the presence of benzoic acid, but was only slightly suppressed
when pyridine was added to the reaction medium (Figure 4-7). Acetic acid also decreased the activity of the catalyst. The activity of zeolite Zr-beta was less affected by pyridine. This is due to the facile ligand exchange at the Zr Lewis site and also to the strong coordination ability of 4-tert-butylcyclohexanone. As a carboxylate acid, benzoic acid may coordinate to Zr Lewis site through its carbonyl group. Therefore, a competition exists between substrate, 4-tert-butylcyclohexanone, and additive, benzoic acid. This competition led to the observed retarding effect. A similar effect has been observed over zirconium 1-propanol grafted on SBA-15, where the activity decreased to one-ninth that of the fresh catalyst [24]. However, unlike the grafted catalyst, the effect of poisoning was completely reversible over Zr-zeolite beta, and full activity was recovered after washing the catalyst with 2-propanol. In fact, the regenerated catalyst had a better activity than the fresh Zr-zeolite beta. This could be due to the removal of some carbon (remnants from template not removed by calcination) blocking the Zr-active sites by reaction with the acid. These results indicate that Zr-beta is very stable as neither base nor acid causes the leaching of zirconium active sites.

In addition, the Zr-zeolite beta was found to show good resistance to the presence of water (Figure 4-8 a) up to 9.1 wt %. Although the rate of reaction was decreased, the conversion of 4-tert-butylcyclohexanone was ~98% after 60 min. The turnover numbers calculated from the first 5 min of reaction showed that Zr-zeolite beta retained almost 50 % of its activity in the presence of as much as 9.1 % water. In contrast, Al- and Ti-beta were completely inactivated by the presence of water. The activity of Sn-beta (Si/Sn 125) was more adversely affected by the presence of water (Figure 4-8 b). With 9.1 wt % water in the reaction mixture, the conversion was ~10% after 60 min as compared to
over 95% under moisture-free conditions. This observation agrees with the result of Corma et al. [2] who found that the turnover number dropped from 109 to 3.8 upon exposure to about 10% water content. The authors reported that the water resistance of their Sn catalyst could be considerably improved by hydrophobizing the surface in a postsynthesis silylation step with hexamethyldisilazane. The activity of the modified material at 10% water content was 48 mol per mol·h, or about 45% of the activity under dry conditions. The Zr-zeolite beta synthesized for this study retained this level of activity in the presence of water, without requiring additional surface modification.

Zeolites synthesized in fluoride medium were reported to be relatively free of connectivity defects, making them more hydrophobic [2, 27, and 28]. Furthermore, the high water tolerance of Zr-beta may be due to the facile ligand exchange at the Zr active center within the zeolite framework. The retention of activity in the presence of water suggests that adsorbed water at the Zr centers can be exchanged for 2-propanol under reaction conditions so that the MPV activity is relatively unaffected. Water is not irreversibly adsorbed at the Lewis acidic Zr sites. Indeed, Liu et al. [29] have shown that hydroxyl groups in hydrous zirconia play an important role in its activity as an MPV catalyst. In contrast, aluminium-containing catalysts such as aluminum 2-propoxide, aluminum alkoxides grafted on MCM-41, and Al-zeolite beta are generally moisture sensitive. Even traces of water can dramatically reduce their activity. This feature limits their practical applicability. Sn-zeolite beta is water-resistant to some extent, indicating that the ligand exchange is not as facile as for Zr-zeolite beta. Zeolite Zr-beta is the most water-tolerance catalyst for the MPV reduction among all heterogeneous catalysts studied.
4.4 Conclusions

Zr-beta was found to be a regenerable, stereoselective catalyst for the Meerwein-Ponndorf-Verley reduction of 4-tert-butylcyclohexanone to cis-4-tert-butylcyclohexanol. The active sites of Zr-beta were proposed to be Lewis acid zirconium sites in the zeolite framework. The observed selectivity to the thermodynamically less stable cis-alcohol is suggested to result from transition-state selectivity.

The high catalytic activity shown by zeolite Zr-beta catalyst can be attributed to the presence of Lewis acid sites with appropriate acid strength and to the ease of ligand exchangeability of Zr. Zr-zeolite beta has predominantly Lewis acidity with higher Lewis acid strength than that of Ti- and Sn-zeolite beta. This appropriate medium Lewis acidity enables Zr-zeolite beta to bind the carbonyl group effectively. An insight into the ease of ligand exchangeability of Zr-beta may be drawn from the retention of activity with addition of acids, base or water. The sample showed good tolerance to the presence of water and pyridine. Its high activity and selectivity for MPV was only slightly affected even in the presence of ~9% H₂O. Regeneration of the catalyst after poisoning by benzoic acid can be achieved simply by washing with 2-propanol.
References


Table 4-1. Physical properties of zeolite beta samples tested in MPV reactions.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Si/Me ratio&lt;sup&gt;a&lt;/sup&gt;</th>
<th>BET surface area (m²/g)</th>
<th>Crystal size (µm)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Micropore volume (cm³/g)</th>
<th>Total pore volume (cm³/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-beta</td>
<td>–</td>
<td>487</td>
<td>10-15</td>
<td>0.23</td>
<td>0.26</td>
</tr>
<tr>
<td>Zr-beta (im)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>95</td>
<td>308</td>
<td>10-15</td>
<td>0.13</td>
<td>0.18</td>
</tr>
<tr>
<td>Zr75</td>
<td>84</td>
<td>499</td>
<td>~1</td>
<td>0.24</td>
<td>0.27</td>
</tr>
<tr>
<td>Zr100</td>
<td>107</td>
<td>490</td>
<td>~1</td>
<td>0.23</td>
<td>0.27</td>
</tr>
<tr>
<td>Zr200</td>
<td>194</td>
<td>474</td>
<td>1-2</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>Sn-beta</td>
<td>125</td>
<td>500</td>
<td>1-2</td>
<td>0.23</td>
<td>0.31</td>
</tr>
<tr>
<td>Al-beta</td>
<td>100</td>
<td>451</td>
<td>~1</td>
<td>0.22</td>
<td>0.24</td>
</tr>
<tr>
<td>Ti-beta</td>
<td>100</td>
<td>468</td>
<td>~1</td>
<td>0.22</td>
<td>0.25</td>
</tr>
<tr>
<td>H-beta-500&lt;sup&gt;d&lt;/sup&gt;</td>
<td>12.5</td>
<td>522</td>
<td>–</td>
<td>0.25</td>
<td>0.27</td>
</tr>
<tr>
<td>H-beta-700&lt;sup&gt;e&lt;/sup&gt;</td>
<td>12.5</td>
<td>508</td>
<td>–</td>
<td>0.25</td>
<td>0.27</td>
</tr>
</tbody>
</table>

<sup>a</sup> Determined by ICP. <sup>b</sup> Determined by SEM. <sup>c</sup> ZrOCl₂·8H₂O impregnated on pure Si-beta. <sup>d</sup> Activation temperature 500 ºC. <sup>e</sup> Activation temperature 700 ºC.
Table 4-2. MPV reduction of 4-tert-butylcyclohexanone over various zeolite beta catalysts.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Conversion(^a) (%)</th>
<th>Selectivity(^b) (%)</th>
<th>TOF(^c)</th>
<th>cis:trans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-beta</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Zr-beta (im)</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Zr75</td>
<td>97.3</td>
<td>&gt;99</td>
<td>551</td>
<td>99:1</td>
</tr>
<tr>
<td>Zr100</td>
<td>95.2</td>
<td>&gt;99</td>
<td>550</td>
<td>99:1</td>
</tr>
<tr>
<td>Zr200</td>
<td>72.8</td>
<td>&gt;99</td>
<td>575</td>
<td>98:2</td>
</tr>
<tr>
<td>Sn125</td>
<td>70.6</td>
<td>&gt;99</td>
<td>329</td>
<td>98:2</td>
</tr>
<tr>
<td>Ti100</td>
<td>2.9(^c)</td>
<td>&gt;99</td>
<td>-</td>
<td>100:0</td>
</tr>
<tr>
<td>Al100</td>
<td>&lt;0.5(^c)</td>
<td>–</td>
<td>-</td>
<td>–</td>
</tr>
<tr>
<td>Al-beta-500</td>
<td>16.0(^c)</td>
<td>98</td>
<td>-</td>
<td>84:16</td>
</tr>
<tr>
<td>Al-beta-700</td>
<td>65.4(^c)</td>
<td>&gt;99</td>
<td>-</td>
<td>89:11</td>
</tr>
</tbody>
</table>

Reaction conditions: 5.2 mmol 4-tert-butylcyclohexanone, 83 mmol 2-propanol, 100 mg catalyst, under reflux and stirring at 82 ºC. \(^a\) Conversion after 60 min. \(^b\) Selectivity to the corresponding alcohol. \(^c\) 1.3 mmol 4-tert-butylcyclohexanone used. \(^c\) Turnover frequency in mol.mol\(^{-1}\)Zr.h\(^{-1}\) calculated after 30min of reaction time.

Table 4-3. Zr-Beta Zeolite before and after MPV Reduction of 4-tert-butylcyclohexanone.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Si/Zr ratio</th>
<th>Conversion(^c) (%)</th>
<th>TOF(^d)</th>
<th>cis:trans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>After</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zr100</td>
<td>107</td>
<td>108</td>
<td>98.3</td>
<td>179</td>
</tr>
<tr>
<td>Zr100(^a)</td>
<td>108</td>
<td>110</td>
<td>99.0</td>
<td>180</td>
</tr>
<tr>
<td>Zr100(^b)</td>
<td>107</td>
<td>110</td>
<td>95.6</td>
<td>174</td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol 4-tert-butylcyclohexanone, 83 mmol 2-propanol, 50 mg catalyst, under reflux and stirring at 82 ºC. \(^a\) regenerated by calcination at 580 ºC. \(^b\) washed with 2-propanol and reused without calcination. \(^c\) Conversion after 60 min. \(^d\) Turnover frequency in mol.mol\(^{-1}\)Zr.h\(^{-1}\) calculated after 60min of reaction time.
Table 4-4. Reduction of 4-tert-butylcyclohexanone over Zr100 with various secondary alcohols

<table>
<thead>
<tr>
<th>Alcohol</th>
<th>Conversion (%)</th>
<th>Selectivity (%)</th>
<th>TOF</th>
<th>cis:trans</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-propanol</td>
<td>98.8</td>
<td>&gt;99</td>
<td>180</td>
<td>99:1</td>
</tr>
<tr>
<td>2-butanol</td>
<td>98.5</td>
<td>&gt;99</td>
<td>180</td>
<td>99:1</td>
</tr>
<tr>
<td>2-pentanol</td>
<td>90.5</td>
<td>&gt;99</td>
<td>165</td>
<td>99:1</td>
</tr>
<tr>
<td>Cyclopentanol</td>
<td>27.3</td>
<td>98.2</td>
<td>50</td>
<td>99:1</td>
</tr>
<tr>
<td>Cyclohexanol</td>
<td>32.4</td>
<td>82.8</td>
<td>59</td>
<td>100:0</td>
</tr>
<tr>
<td>4-methyl-2-pentanol</td>
<td>52.9</td>
<td>&gt;99</td>
<td>96</td>
<td>100:0</td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol 4-tert-butylcyclohexanone, 83 mmol alcohol, 100 mg catalyst, stirred at 82 °C. a after 30 min reaction. b Turnover frequency in mol.mol\(^{-1}\) Zr.h\(^{-1}\) calculated after 30min of reaction time.
Table 4-5. MPV reduction of alkyl cyclohexanones with 2-propanol over Zr100 and Zr-SBA-15.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Catalyst</th>
<th>Conversion (%</th>
<th>cis:trans&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclohexanone</td>
<td>Zr100</td>
<td>94.5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Zr-SBA-15</td>
<td>59.5</td>
<td>–</td>
</tr>
<tr>
<td>2-methylcyclohexanone</td>
<td>Zr100</td>
<td>6.1</td>
<td>55:45</td>
</tr>
<tr>
<td></td>
<td>Zr-SBA-15</td>
<td>3.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>42:58</td>
</tr>
<tr>
<td>3-methylcyclohexanone</td>
<td>Zr100</td>
<td>54.4</td>
<td>29:71</td>
</tr>
<tr>
<td></td>
<td>Zr-SBA-15</td>
<td>94.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>75:25</td>
</tr>
<tr>
<td>4-methylcyclohexanone</td>
<td>Zr100</td>
<td>81.7</td>
<td>99:1</td>
</tr>
<tr>
<td></td>
<td>Zr-SBA-15</td>
<td>98.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19:81</td>
</tr>
<tr>
<td>4-&lt;i&gt;tert&lt;/i&gt;-butylcyclohexanone</td>
<td>Zr100</td>
<td>98.8</td>
<td>99:1</td>
</tr>
<tr>
<td></td>
<td>Zr-SBA-15</td>
<td>59.8</td>
<td>16:84</td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol ketone, 83 mmol 2-propanol, 100 mg catalyst, stirred at 82 °C. <sup>a</sup> after 30 min reaction time. <sup>b</sup> after 360 min reaction time. <sup>c</sup>only product was corresponding alcohol.
Table 4-6. MPV reduction of different substrates over Zr100.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Time (h)</th>
<th>Conversion (%)</th>
<th>Selectivity&lt;sup&gt;a&lt;/sup&gt; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cyclopentanone</td>
<td>6</td>
<td>92.1</td>
<td>&gt;99</td>
</tr>
<tr>
<td>2</td>
<td>2-cyclopent-1-one</td>
<td>6</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Cyclohexanone</td>
<td>0.5</td>
<td>94.5</td>
<td>&gt;99</td>
</tr>
<tr>
<td>4</td>
<td>2-cyclohexen-1-one</td>
<td>6</td>
<td>31.2</td>
<td>56.5</td>
</tr>
<tr>
<td>5</td>
<td>4-tert-butylecyclohexanone</td>
<td>0.5</td>
<td>98.8</td>
<td>&gt;99</td>
</tr>
<tr>
<td>6</td>
<td>1,4-benzoquinone</td>
<td>6</td>
<td>90</td>
<td>&gt;99</td>
</tr>
<tr>
<td>8</td>
<td>Dihydro carvone</td>
<td>24</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Acetophenone</td>
<td>24</td>
<td>67.8</td>
<td>&gt;99</td>
</tr>
<tr>
<td>10</td>
<td>Benzyl methyl ketone</td>
<td>24</td>
<td>84.1</td>
<td>97.6</td>
</tr>
<tr>
<td>11</td>
<td>4-chloroacetophenone</td>
<td>24</td>
<td>89.1</td>
<td>&gt;99</td>
</tr>
<tr>
<td>12</td>
<td>4-methylacetophenone</td>
<td>24</td>
<td>81.2</td>
<td>66.9&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>13</td>
<td>4-methoxyacetophenone</td>
<td>24</td>
<td>63.1</td>
<td>&lt;1&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>14</td>
<td>Benzoylcyclohexane</td>
<td>24</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol substrate, 83 mmol 2-propanol, 100 mg catalyst, under reflux and stirring at 82 °C. <sup>a</sup>Selectivity to alcohol. <sup>b</sup>Corresponding isopropyl ether was the main by-product.
Scheme 4-1. Reaction mechanism for the MPVO reaction.

Scheme 4-2. Transition state for the formation of cis-4-t-butylcyclohexanol (left) and trans-4-t-butylcyclohexanol (right)
Figure 4-1. XRD patterns of the calcined catalysts. (a) Zr-beta (Si/Zr=107), (b) Sn-beta (Si/Sn=125), (c) Ti-beta (Si/Ti=100), (d) Al-beta (Si/Al=100), and H-beta (Si/Al=12.5).

Figure 4-2. IR spectra of pyridine adsorption (at 25 ºC) and desorption at 100 ºC over: (a) Si-beta, (b) Sn-beta (Si/Sn=125), (c) Ti-beta (Si/Ti=100), (d) Zr-beta (Si/Zr=107), and (e) H-beta (Si/Al=12.5).
Figure 4-3. IR Spectra of 4-methylcyclohexanone adsorption at 25 °C and desorption at 25, 50, 100, and 200 °C over Zr75 (a), Zr100 (b), Zr200 (c), and Si-beta (d).
Figure 4-4. IR Spectra of 4-methylcyclohexanone adsorption (at 25 °C) and desorption at 25, 50, 100, and 200 °C over Zr-beta (a), Sn-beta (b), Ti-beta (c), and H-beta (d).
Figure 4-5. Influence of zeolite calcination temperature on the MPV reduction of 4-tert-butylcyclohexanone. Reaction conditions: 1.3 mmol 4-tert-butylcyclohexanone, 83 mmol 2-propanol, 100 mg catalyst, under reflux and stirring at 82 ºC.

Figure 4-6. Influence of crystal size of Zr-beta on the MPV reduction of 4-tert-butylcyclohexanone. Reaction conditions: 1.3 mmol 4-tert-butylcyclohexanone, 83 mmol 2-propanol, 100 mg catalyst, under reflux and stirring at 82 ºC.
Figure 4-7. Conversion of 4-tert-butylcyclohexanone with added base and acids (●) pure reactants (○) 0.37 mmol pyridine (■) 0.52 mmol acetic acid (▲) 0.37 mmol benzoic acid and (△) after benzoic acid and washing with 2-propanol. Reaction conditions: 1.3 mmol substrate, 83 mmol 2-propanol, 100 mg catalyst, under reflux and stirring at 82 ºC.
Figure 4-8. Conversion of 4-tert-butylcyclohexanone over (a) Zr100 and (b) Sn125 – (○) without water and in the presence of added water: (■) 0.6 wt%, (▲) 2.9 wt%, and (●) 9.1 wt%. Reaction conditions: 1.3 mmol substrate, 83 mmol 2-propanol, 100 mg catalyst, under reflux and stirring at 82 ºC.
Chapter 5

Selective reduction of α,β-unsaturated aldehydes to the corresponding unsaturated alcohols over Zr-beta zeolite

5.1 Introduction

α,β-unsaturated alcohols are of industrial interest because many of them are important intermediates for production of pharmaceuticals, agrochemicals and fragrances. They may be produced by oxidation of olefins [1], or by alkylation of unsaturated aldehydes [2]. A more general route is the chemoselective reduction of unsaturated ketones and aldehydes. On the laboratory scale, stoichiometric reductions with borohydride, in combination with CeCl₃, or with oxazaborolidines, lead to satisfactory results, but cheaper reducing agents are desirable for larger scale reactions [3, 4]. In homogeneous catalysis, a major breakthrough was the discovery of the chemoselective reduction with H₂ and a Ru-phosphine-diamine catalyst [5, 6]. However, this catalyst requires extra base for its activation; it is not easily recovered from the reaction mixture, and in the recycling may lose its activity. To overcome these problems, the selective reduction of α,β-unsaturated aldehydes using heterogeneous catalysis has been the focus of many researchers.

Catalysts based on supported metals, such as osmium, iridium, ruthenium, rhodium, platinum, palladium, nickel, and cobalt have been extensively studied for the hydrogenation of α,β-unsaturated aldehydes [7-15]. The hydrogenation of α,β-unsaturated aldehydes into saturated carbonyls is comparatively easy to achieve. However, the selective hydrogenation of the C=O group is much more difficult in the presence of a C=C bond because the hydrogenation of the C=C bond is thermodynamically more
favored (Scheme 1). In order to hydrogenate C=O groups selectively, different approaches to modify the intrinsic catalytic properties of metal oxide catalysts have been adopted. The addition of promoters such as Fe(III), Sn(II), Ge(IV), and the selection of specific supports such as zeolites are found to be the most effective methods [7].

An alternative way to selectively reduce α,β-unsaturated aldehydes to the corresponding unsaturated alcohols is offered by the Meerwein-Ponndorf-Verley (MPV) hydrogen transfer reaction (Scheme 5-2). As we mentioned in Chapter 4, one characteristic of the MPV reaction is that only carbonyl groups are reduced, while other reducible groups such as C=C double bonds and C-halogen bonds are not affected. This feature makes it very appropriate for the production of α,β-unsaturated alcohols. In homogeneous phase, this method, however, is subject to some restrictions arising from the need to use stoichiometric amounts of catalyst and to subsequently neutralize the residual catalyst in the medium with a strong acid. Finally, because the process takes place in a homogeneous phase, isolating the products is very often a labor-intensive and time-consuming task.

To overcome these problems, MPV reaction has been investigated over different heterogeneous catalysts, including metal oxides [17], hydrous zirconia [18-20], hydrotalcites [21-26], zeolites [27-34] and even metal alkoxides immobilized on mesoporous materials [35-40]. Most of these catalysts have been applied in reactions of saturated ketones, e.g., substituted cyclohexanones, which are much easier to be reduced than unsaturated aldehydes. Only few heterogeneous catalysts were applied in the MPV reduction of α,β-unsaturated aldehydes. Liu et al. [20] reported that suitably pretreated hydrous zirconia was an active catalyst in the MPV reduction of an important α,β-
unsaturated aldehyde, cinnamaldehyde. The calcination temperature of the hydrous zirconia was found to be an important parameter because it affects the surface density of hydroxyl groups, which are necessary for ligand exchange with the reductant, 2-propanol. Aramendía et al. [26] found that Mg-Al mixed oxides could catalyze the MPV reduction of various α,β-unsaturated aldehydes, but only with moderate activity.

In the previous chapter, we demonstrated that Zr-beta zeolite was a very efficient catalyst for the reduction of alky and aryl saturated ketones. Lewis acid sites induced by incorporation of Zr into the zeolite framework were considered to be the active centers of the zeolite. In this chapter, we applied zeolite Zr-beta in the MPV reduction of α,β-unsaturated aldehydes. The effect of Al on the activity and selectivity of zeolite Zr-beta has been studied. The influence of water, acid, and base on the catalytic activity was discussed.
5.2 Results and discussions

5.2.1 Catalyst characterization

The Al-free zeolite Zr-beta samples, Zr75 to Zr200, have been described in detail in Chapters 3 and 4. Here, emphasis will be placed on a comparison of the properties of Al-free and Al-containing Zr-beta samples.

The chemical and textural properties of one Al-free Zr-beta sample, Zr100, and two Al-containing Zr-beta samples, ZrAl100 and ZrAl25, are shown in Table 5-1. The surface area of the Al-containing Zr-beta samples was a little larger than that of the Al-free Zr-beta sample. Compared with the Al-free sample, Al-containing samples have smaller crystal size. This may be due to the faster nucleation rate induced by the aluminum in the Al-containing samples.

XRD patterns of Zr100, ZrAl100, and ZrAl25 synthesized in fluoride medium are shown in Figure 5-1. These patterns showed the typical features of zeolite beta with sharp and broad reflections, indicative of stacking disorders. An obvious difference was observed in the lower broad peak range. In Al-free Zr100 and low Al content sample, ZrAl100, one big peak appeared at $2\theta \approx 7.5^\circ$ with a shoulder at $2\theta \approx 8.3^\circ$. However, in sample ZrAl25, only one broad peak could be observed at $2\theta \approx 8^\circ$. These results indicate that aluminum can influence the stacking sequence of Zr-beta zeolite. In Chapter 3, we demonstrated that incorporation of Zr in the zeolite beta framework could induce the formation of more polymorph B. In contrast, aluminum seems to induce the stacking sequence of polymorph A.

The acidic properties of Al-free and Al-containing Zr-beta samples were determined by IR spectroscopy following the adsorption of pyridine at room temperature and
desorption at 100 °C. The IR spectra obtained after pyridine desorption at 100 °C in the 1400-1700 cm\(^{-1}\) range are shown in Figure 5-2. The appearance of the band corresponding to Lewis acid sites in the IR spectra (1445 cm\(^{-1}\)) was clearly observed for all Zr-beta samples. The band corresponding to Brønsted acid sites in the IR spectra (1540 cm\(^{-1}\)) decreased with the decrease in the aluminum content of Zr-beta zeolite. This band almost completely disappeared in the Al-free Zr-beta. This observation indicates that Lewis acidity is predominant in the Al-free Zr-beta sample. In addition to the bands at 1445 cm\(^{-1}\) and 1550 cm\(^{-1}\), a band at 1490 cm\(^{-1}\) was also observed in the IR spectrum of all Zr-beta samples. Its intensity is clearly related to the aluminum content; the higher the aluminum content in zeolite Zr-beta samples, the stronger the band. This band is due to both coordinated pyridine and pyridine chemisorbed on protonic acid sites. Considering the bands at 1540 cm\(^{-1}\) and 1490 cm\(^{-1}\) and their relationship with the aluminum content, we can conclude that the Brønsted acid sites in Zr-beta are related to the aluminum content in the samples.

\(^{29}\)Si MAS NMR spectra of calcined Zr100, ZrAl100, and ZrAl25 are shown in Figure 5-3. Three bands at around δ -116, -113.4, and -111.7 ppm could be resolved in all three samples. A very small band at 104.9 ppm also appeared in sample ZrAl25. As we discussed in Chapter 3, the first three bands at around δ -116, -113.4, and -111.7 could be assigned to Si(4Si) species occupying different crystallographic sites. The extra band in sample ZrAl25 can be due to both Si(3Si, Al) and Si(3Si, OH) species according to Camblor et al. [41]

A loss of resolution was observed as the amount of Al in the Zr-beta samples increases. This decreased resolution in the spectra can be attributed to the presence of
connectivity defects generated by dealumination during calcination. This process will be more severe as the Al content increases. Another contribution to the line broadening is the decreased local order caused by the incorporation of Al.

$^{27}$Al MAS NMR spectra of calcined Zr100, ZrAl100, and ZrAl25 are shown in Figure 5-4. Not surprisingly, no signal related to Al could be detected in the Al-free Zr-beta sample. In the case of Al-containing samples, a well resolved band appeared at 55.4 ppm. This resonance band is generally assigned to Al in tetrahedral coordination environment, as expected for Al that is incorporated into the zeolite lattice. In the sample ZrAl25, which has a high Al content, a small band at -0.8 ppm was also observed, which could be assigned to an octahedral Al species. This extraframework Al species is frequently generated during calcination, and may contribute to the presence of the octahedral Al species; although it has also been proposed that a fraction of the Al can reversibly change its coordination form from tetrahedral to octahedral without leaving its framework sites [42].

5.2.2 MPV of cinnamaldehyde over Zr-beta

Cinnamaldehyde (3-phenyl-2-propenal, C9H8O) is an $\alpha,\beta$-unsaturated aldehyde which is used in the fragrance industry to give spicy and oriental notes [43]. It is also an important intermediate in the synthesis of cinnamyl alcohol and dihydrocinnamyl alcohol, both of which are also used in the perfume industry. The reduced unsaturated product cinnamyl alcohol is valuable in perfumery for its odor and fixative properties. It is also a starting material for cinnamyl esters, several of which are valuable fragrance compounds. In addition, cinnamyl alcohol finds applications in the formulation of animal repellent compositions and insect attractants, production of photosensitive polymers, and
multicolor ink formulations. Therefore, selective reduction of cinnamaldehyde to cinnamyl alcohol is important academically as well as industrially.

The selective reduction of cinnamaldehyde to cinnamyl alcohol via the MPV process was carried out at 82 °C over various catalysts with 2-propanol as reductant and solvent. Some results are listed in Table 5-2. As can be seen, Al-free Zr-beta (entries 1-4 in Table 5-2) was very selective for this reaction. The selectivity to the desired cinnamyl alcohol was more than 98%. The selectivity remained high during the whole reaction process. The only by-product detected was 1-cinnamyl 2-propyl ether (its formation will be discussed below). The rate of conversion of cinnamaldehyde over the Al-free Zr-beta zeolite was also very high, and was found to be related to the Si/Zr ratio (Figure 5-5). When the Si/Zr ratio decreases, conversion increases (note: low Si/Zr ratio means high Zr content). However, Zr100 exhibited the best activity. Nearly all cinnamaldehyde was reduced to cinnamyl alcohol after 4 hours of reaction time over Zr100. The TOF of Zr75 was the lowest amongst all Al-free Zr-beta samples though the loading of Zr in Zr75 is the highest. This observation indicates that Zr in zeolite beta is not equally efficient. At low Zr loading, Zr is incorporated in the zeolite framework. As the Zr loading increases, extra framework Zr species maybe formed. The extra framework Zr species may not as active as framework Zr species, which leads to the observed lower TOF over Zr75. A similar observation has been reported by Rena et al. in their studies on the Baeyer-Villiger oxidation over zeolite Sn-beta [44].

In the case of Al-containing samples (entry 5-6 in Table 5-2), both conversion and selectivity was greatly influenced by the Al content as shown in Figure 5-6. The conversion after 1 hour of reaction time dropped to 59.1% over ZrAl100 and 41.8% over
ZrAl25 respectively as compared with 80% over Zr100. The selectivity to the desired product, cinnamyl alcohol, was only 64.1% over ZrAl25, and it decreased further to less than 25% after 6 hours of reaction time. Beside the main by-product, 1-cinnamyl 2-propyl ether, two hydrogenated saturated products, 3-phenyl propanal and 3-phenyl 1-propanol, were also detected. The aldol condensation products were never observed in all our experiment. This is probably due to the high excess of 2-propanol used in our reaction.

That the presence of the metal atom is critical is proven by the fact that pure Si-beta was completely inactive for the reaction. Impregnation of the Si-beta with zirconium oxychloride to give Si/Zr 100 did not result in an active material either, which indicates that isolated Zr atoms in the framework of zeolite beta are important for activity.

A zirconium 1-propoxide grafted Zr-SBA-15 sample with about 10% of Zr was found to be active for the MPV reduction of cinnamaldehyde. This catalyst exhibited good selectivity and moderate activity. Its selectivity was close to 100%, but the TOF was only 2.4 mol.mol⁻¹Zr.h⁻¹ after 1 hour of reaction time. This result indicates that Zr in Zr-SBA-15 is not as efficient as in Zr-beta.

Ti-beta (Si/Ti=100) and Sn-beta (Si/Sn=125) was totally inactive for the MPV reduction of cinnamaldehyde. Even after 6 hours of reaction time, no corresponding MPV product was detected. This is surprising because these two catalysts are active for the MPV reduction of 4-tert-butylcyclohexanone. The poor performance of these catalysts may be caused by two reasons: 1) the Lewis acidity of Ti-beta and Sn-beta is too weak; 2) the conjugated carbonyl group in cinamaldehyde is not easy to be reduced.
Based on the catalytic results, in combination with the information obtained from the IR spectra of adsorbed pyridine and 4-methyl-cyclohexanone (see Chapter 4), a reaction pathway of MPV reduction of cinnamaldehyde over Zr-beta was proposed and is shown in Scheme 5-3. The desired product, cinnamyl alcohol, is formed via a six-membered transition state in which both cinnamaldehyde and 2-propanol are first coordinated to Lewis acid sites. The reaction proceeds by a hydride transfer from 2-propanol to the cinnamaldehyde. Lewis acidic Zr-sites are the active species. The formation of the main by-product, 3-cinnamyl 2-propyl ether, could be explained by the Brønsted acid catalyzed acetalization of cinnamaldehyde with 2-propanol, followed by dehydration. The formation of ethers during MPV reduction of a number of substituted cyclohexanones has been reported by Verhoef et al., who used MCM-22 as catalyst [45]. Because H-MCM-22 contains a large amount of Brønsted acid sites, the authors postulated that Brønsted acidity contributes to the formation of ethers. Our results seem to support this hypothesis. The appearance of two other by-products over Al-containing Zr-beta samples may also be related to the Brønsted acid sites induced by the incorporation of Al.

### 5.2.3 Poisoning test and catalyst stability

Aluminum-containing MPV catalysts, such as aluminum iso-propoxide, aluminum alkoxides grafted MCM-41, and H-beta, are generally moisture sensitive. Even trace amounts of water can dramatically decrease their activity. This, to some extent, limits their practical applications. Zeolites synthesized in fluoride medium are reported to be relatively free of connectivity defects, and hence are more hydrophobic [46]. Hydrophobic zeolites containing Lewis acids have been claimed to be more suitable for the MPVO reaction when water is present [33]. In Chapter 4, we discussed the influence
of water on the MPV reduction of 4-tert-butylcyclohexanone over various beta zeolites. Due to its high ligand exchangeability, Zr-beta was found to be the most water-resistant MPV catalyst. We also studied the influence of water on the MPV reduction of the unsaturated aldehyde, cinnamaldehyde, by adding different amounts of water to the reaction mixture. As shown in Table 5-3 and Figure 5-7, the activity of Zr-beta was only slightly influenced in the presence of 0.6 wt% of water, and nearly all cinnamaldehyde was converted after 6 hours of reaction time. However, in the presence of 3.0 wt% water, the activity dropped significantly. The conversion of cinnamaldehyde was less than 80% even after 6 hours of reaction time. Apparently, the higher amount of water in the reaction mixture reduced the activity of Zr-beta. The competitive adsorption of water and cinnamaldehyde on active sites may account for the observed results.

The activity of Zr-beta for the MPV reduction of cinnamaldehyde decreased significantly in the presence of pyridine but was only slightly suppressed when benzoic acid was added to the reaction medium (Figure 5-8). It has been reported that upon addition of pyridine, the activity of Al-beta and Ti-beta was reduced to zero in the MPV reduction of 4-tert-butylcyclohexanone. The deactivation was explained by the formation of a pyridinium cation by protonation of pyridine or the coordination of the amine directly onto Lewis acid sites [47]. In principle, the same reasoning applies to Zr-beta. However, the interaction between Zr-beta and pyridine is not as strong as in Al-beta. Some pyridine coordinated to Lewis acid sides in Zr-beta still can be displaced by 2-propanol. Therefore, the activity of Zr-beta is only partially suppressed by pyridine. In the case of benzoic acid, the activity of Zr-beta was only slightly affected. This observation is opposite to the result obtained in the MPV reduction of 4-tert-
butylcyclohexanone, where the activity of Zr-beta dropped significantly in the presence of benzoic acid. The high resistance of zeolite Zr-beta to acid poisoning in this study is likely to be due to the α,β-unsaturated nature of cinnamaldehyde. The presence of conjugated double bonds coupled to the benzene ring in cinnamaldehyde facilitates the coordination of the carbonyl group to Lewis acid centers. Therefore, its competitive binding is less affected by the presence of benzoic acid than that of 4-tert-butylcyclohexanone. Another reason is because the reaction rate of cinnamaldehyde is much slower than that of 4-tert-butylcyclohexanone. Thus, the poisoning effect is not obvious here. In conclusion, the activity of Zr-beta for the MPV reduction of cinnamaldehyde is not severely affected by the poisoning of water, base, and acid.

5.2.4 Catalyst deactivation and recycling

One of the advantages of heterogeneous catalysts over homogeneous catalysts is their potential reusability. In order to check whether Zr-beta could be reused, one Zr-beta catalyst, Zr100, was tested five times in the MPV reduction of cinnamaldehyde (Figure 5-9). After each test, the catalyst was filtered and washed with 2-propanol, and then submitted to a new reaction batch. Some loss in activity occurred during the reaction when the same catalyst is reused five times. The conversion was lowered to 75% after 5 cycles, but the selectivity was still as high as 95%. The loss of activity could be due to cinnamaldehyde or cinnamyl alcohol adsorbed on the catalyst after the reaction. Indeed, the originally white catalyst became a little yellow after reaction, indicative of something adsorbed on it. After five cycles, the used catalyst was recalcined, and this treatment almost restored the initial activity; in a subsequent run, the catalyst had again about 90% of its initial activity. These results indicate that Zr-beta is very stable and can be reused.
5.2.5 Selective reduction of other $\alpha,\beta$-unsaturated aldehydes

After discovery of the excellent catalytic performance of Zr-beta for the MPV reduction of cinnamaldehyde, a variety of other $\alpha,\beta$-unsaturated aldehydes were also tested over Zr-beta with 2-propanol as reducing agent. Typical results are summarized in Table 5-4. Linear substrates like crotonaldehyde, trans-2-hexenal, and trans-2-pentenal could be easily reduced to the corresponding $\alpha,\beta$-unsaturated alcohol with high conversion and selectivity. With branched substrates, however, the rate of reaction was somewhat slower; such was the case with 3-methylcrotonaldehyde and citral (entry 2 and 8 in Table 5-4). 2-furfural gave the highest TOF among all substrates tested. However, its selectivity dropped a little. The relative small size of molecule and the electronic effect derived from the oxygen atom in the cyclic ring could contribute to its high activity. The drop in its selectivity is due to the formation of a condensation by-product, 1,2-di(furan-2-yl)-2-hydroxyethanone. Two aryl-containing substrates were tested. Cinnamaldehyde reacted much faster than $\alpha$-amylcinnamaldehyde. Considering the bigger molecular size of $\alpha$-amylcinnamaldehyde, its slower rate of reaction is probably due to the steric hindrance effect. Indeed, when a zirconium 1-propoxide grafted Zr-SBA-15, which has big pores, was used as catalyst, up to 80% conversion after 24 hours was achieved for $\alpha$-amylcinnamaldehyde, which justifies the above hypothesis. Most importantly, except for citral where dehydration of the formed alcohols led to lower selectivity, all other substrates tested could be reduced with high selectivity to the unsaturated alcohol. The corresponding saturated products were never detected. All these results indicate that Zr-beta is an effective and chemoselective catalyst for the MPV reduction of $\alpha,\beta$-unsaturated aldehydes.
5.3 Conclusions

Zr-beta was found to be an active and chemoselective catalyst for the MPV reduction of cinnamaldehyde. High initial TOF between 50-80 mol.mol⁻¹ Zr.h⁻¹ was obtained over Al-free Zr-beta samples. Extremely high selectivity (>98%) for the desired cinnamyl alcohol was retained during the whole reaction process over these samples. The active sites for the MPV reduction were considered to be the Lewis acid zirconium sites which are located in the micropores of the zeolite. The formation of the major by-product, 3-cinnamyl 2-propyl ether, is related to the presence of the Brønsted acid sites. Brønsted acidity is related to the aluminum content in Al-containing Zr-beta samples; the essentially Al-free Zr-beta is therefore a particularly selective catalyst.

The addition of water and benzoic acid to the reaction medium had only a small effect on the activity of Zr-beta, but pyridine led to more severe deactivation. The deactivation is attributed to adsorption of pyridine at the Zr metal centers, which could be reversed on removal of the poison. Zeolite Zr-beta catalysts can be reused, though some loss of activity was observed after being recycled for 5 times. However, its activity could be recovered by calcination. This indicates that fouling by organic deposits is the dominant deactivation mechanism.

A variety of α,β-unsaturated aldehydes can be effectively reduced to allylic alcohols over Zr-beta via the MPV reaction. Excellent conversions were always paired with high selectivities. Therefore, Zr-beta zeolite is an promising heterogeneous catalyst for selective reduction of α,β-unsaturated aldehydes.
References


Table 5-1. Chemical and textural properties of zeolite Zr-beta samples tested in MPV reactions.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Si/Me ratio(^a)</th>
<th>Si/Zr</th>
<th>Si/Al</th>
<th>BET surface area (m(^2)/g)</th>
<th>Crystal size (µm)</th>
<th>Microporous pore volume (cm(^3)/g)</th>
<th>Total pore volume (cm(^3)/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr100</td>
<td>107</td>
<td>&gt;4000</td>
<td></td>
<td>490</td>
<td>~1</td>
<td>0.23</td>
<td>0.27</td>
</tr>
<tr>
<td>ZrAl100(^a)</td>
<td>104</td>
<td>103</td>
<td></td>
<td>510</td>
<td>0.5~1</td>
<td>0.23</td>
<td>0.31</td>
</tr>
<tr>
<td>ZrAl25(^a)</td>
<td>105</td>
<td>27</td>
<td></td>
<td>533</td>
<td>0.5~1</td>
<td>0.21</td>
<td>0.24</td>
</tr>
</tbody>
</table>

\(^a\) determined by ICP.

Table 5-2. MPV reduction of cinnamaldehyde over various catalysts.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Conv. (%)(^a)</th>
<th>TOF(^b)</th>
<th>Select. (%)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zr75</td>
<td>69.9</td>
<td>57.3</td>
<td>&gt;98</td>
</tr>
<tr>
<td>2</td>
<td>Zr100</td>
<td>80.6</td>
<td>74.7</td>
<td>&gt;98</td>
</tr>
<tr>
<td>3</td>
<td>Zr155</td>
<td>61.7</td>
<td>77.2</td>
<td>&gt;98</td>
</tr>
<tr>
<td>4</td>
<td>Zr200</td>
<td>40.5</td>
<td>67.7</td>
<td>&gt;98</td>
</tr>
<tr>
<td>5</td>
<td>ZrAl100</td>
<td>59.1</td>
<td>54.7(^c)</td>
<td>95.0</td>
</tr>
<tr>
<td>6</td>
<td>ZrAl25</td>
<td>41.8</td>
<td>38.8(^c)</td>
<td>64.1</td>
</tr>
<tr>
<td>7</td>
<td>Zr-SBA-15</td>
<td>20.3</td>
<td>2.4</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>Zr-beta (im)(^d)</td>
<td>No reaction</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Si-beta</td>
<td>No reaction</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>Ti100</td>
<td>No reaction</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Sn125</td>
<td>No reaction</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol cinnamaldehyde, 83 mmol 2-propanol, 100 mg catalyst, under reflux and stirring at 82 ºC. \(^a\) Conversion and selectivity after 1 hour. \(^b\) Turnover frequency in mol.mol\(^{-1}\)Zr.h\(^{-1}\) calculated after 1 hour of reaction time. \(^c\) Al was not considered when calculating TOF. \(^d\) ZrOCl\(_2\) impregnated on Si-beta.
Table 5-3. Influence of water, base, and acid on the catalytic activity of Zr-beta in the MPV reduction of cinnamaldehyde.

<table>
<thead>
<tr>
<th></th>
<th>Conv. (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>TOF&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Select. (%)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>No addition</td>
<td>80.6</td>
<td>74.7</td>
<td>&gt;98</td>
</tr>
<tr>
<td>Water (0.6 wt %)</td>
<td>63.3</td>
<td>58.6</td>
<td>&gt;98</td>
</tr>
<tr>
<td>Water (3.0 wt %)</td>
<td>25.6</td>
<td>23.7</td>
<td>&gt;98</td>
</tr>
<tr>
<td>Pyridine</td>
<td>28.0</td>
<td>25.9</td>
<td>&gt;98</td>
</tr>
<tr>
<td>(0.37mmol)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzoic acid</td>
<td>58.4</td>
<td>54.1</td>
<td>&gt;98</td>
</tr>
<tr>
<td>(0.37mmol)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol cinnamaldehyde, 83 mmol 2-propanol, 100 mg Zr100 (Si/Zr=107), under reflux and stirring at 82 °C. <sup>a</sup> Conversion and selectivity after 1 hour. <sup>b</sup> Turnover frequency in mol.mol<sup>-1</sup>Zr.h<sup>-1</sup> calculated after 1 hour of reaction time.
Table 5-4. MPV reduction of various $\alpha,\beta$-unsaturated aldehydes over Zr-beta

![Chemical reaction diagram](attachment:image.png)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Time (h)</th>
<th>Conv. (%)</th>
<th>Select. (%)</th>
<th>TOF$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crotonaldehyde</td>
<td>6</td>
<td>95.2</td>
<td>100</td>
<td>44.4</td>
</tr>
<tr>
<td>2</td>
<td>3-Methylcrotonaldehyde</td>
<td>6</td>
<td>87.7</td>
<td>93.7</td>
<td>29.0</td>
</tr>
<tr>
<td>3</td>
<td>trans-2-hexenal</td>
<td>4</td>
<td>99.1</td>
<td>100</td>
<td>68.9</td>
</tr>
<tr>
<td>4</td>
<td>trans-2-pentenal</td>
<td>6</td>
<td>97.4</td>
<td>100</td>
<td>53.8</td>
</tr>
<tr>
<td>5</td>
<td>2-furfural</td>
<td>1</td>
<td>96.3</td>
<td>93.4</td>
<td>89.2</td>
</tr>
<tr>
<td>6</td>
<td>cinnamaldehyde</td>
<td>3</td>
<td>98.4</td>
<td>&gt;98</td>
<td>74.7</td>
</tr>
<tr>
<td>7</td>
<td>$\alpha$-Amylcinnamaldehyde</td>
<td>24</td>
<td>33.2</td>
<td>&gt;98</td>
<td>2.6</td>
</tr>
<tr>
<td>8</td>
<td>Citral(E/Z)</td>
<td>6</td>
<td>92.8</td>
<td>72.4</td>
<td>53.2</td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol substrate, 83 mmol 2-propanol, 100 mg Zr100, under reflux and stirring at 82 ºC. $^a$ Turnover frequency in mol.mol$^{-1}$ Zr.h$^{-1}$ calculated after 1 hour of reaction time.
Scheme 1. The reaction pathways in the hydrogenation of α,β-unsaturated aldehydes.

Scheme 5-2. MPV reduction of α,β-unsaturated aldehydes [16].

Scheme 5-3. The reaction pathway for the MPV reduction of cinnamaldehyde over zeolite Zr-beta.
Figure 5-1. XRD patterns of calcined: (a) Zr100, (b) ZrAl100, and (c) ZrAl25.

Figure 5-2. IR spectra of pyridine adsorption at 25 °C and desorption at 100 °C over: (a) Zr100, (b) ZrAl100, and (c) ZrAl25.
Figure 5-3. $^{29}$Si MAS NMR of calcined: (a) Zr100, (b) ZrAl100, and (c) ZrAl25.

Figure 5-4. $^{27}$Al MAS NMR of calcined: (a) Zr100, (b) ZrAl100, and (c) ZrAl25.
Figure 5-5. MPV reduction of cinnamaldehyde over Al-free Zr-beta zeolite. (♦) Zr100 (Si/Al=107), (▲) Zr75 (Si/Zr=84), (●) Zr150 (Si/Zr=155), and (■) Zr200 (Si/Zr=194). Reaction conditions: 1.3 mmol cinnamaldehyde, 83 mmol 2-propanol, 100 mg catalyst, under reflux and stirring at 82 ºC.

Figure 5-6. MPV reduction of cinnamaldehyde over Al-containing Zr-beta zeolite (dashed lines and open symbols refer to selectivity). (●) Zr100 (Si/Al=107, Si/Al>4000), (▲) ZrAl100 (Si/Zr=104, Si/Al=102), and (■) ZrAl25 (Si/Zr=105, Si/Al=27). Reaction condition: same as in Figure 5-5.
Figure 5-7. Influence of water on the MPV reduction of cinnamaldehyde over Zr-beta. (●) without water, (■) 0.6 wt% of water, (▲) 3 wt% of water. Reaction conditions: 1.3 mmol cinnamaldehyde, 83 mmol 2-propanol, 100 mg Zr100 (Si/Zr=107), under reflux and stirring at 82 °C.

Figure 5-8. Influence of base and acid on the MPV reduction of cinnamaldehyde over Zr-beta. (●) No additive, (■) 0.37mmol of benzoic acid, (▲) 0.37mmol of pyridine. Reaction conditions: 1.3 mmol cinnamaldehyde, 83 mmol 2-propanol, 100 mg Zr100 (Si/Zr=107), under reflux and stirring at 82 °C.
Figure 5-9. Recycling tests of Zr-beta in the MPV reduction of cinnamaldehyde. Reaction conditions: 1.3 mmol cinnamaldehyde, 83 mmol 2-propanol, 100 mg Zr100 (Si/Zr=107), under reflux and stirring at 82 ºC. Reused catalyst was simply recovered by washing with 2-propanol.
Chapter 6

Liquid-phase Oppenauer oxidation of alcohols over Zr-beta zeolite

6.1 Introduction

In the Meerwein-Ponndorf-Verley (MPV) reduction, ketones and aldehydes are reduced with secondary alcohols by using a metal alkoxide as catalyst. The reverse reaction, which is known as Oppenauer oxidation, can be used for the oxidation of alcohols [1]. The Oppenauer oxidation is the best method for the preparation of aldehydes from primary alcohols, since further oxidation of the desired aldehyde to the carboxylic acid does not occur. Like the MPV reduction, Oppenauer oxidation proceeds via a complex in which both the oxidant and the reducing alcohol are bound to the Lewis metal center, and a hydride transfer occurs from the alcohol to the carbonyl group. The difference is that here the desired product is the ketone or aldehyde.

Several side reactions may occur during the Oppenauer oxidation [2]. The most important one is the aldol condensation, particularly when aldehydes are formed through oxidation of primary alcohols containing an α-hydrogen (Scheme 6-2). In most cases, the aldol condensation is followed by dehydration, and then the formed water deactivates the alkoxide catalyst. Aldehydes which lack an α-hydrogen, like benzaldehyde, may give rise to a Tishchenko reaction, yielding carboxylic esters (Scheme 6-3) [3]. These side reactions usually can be inhibited by diluting the reaction mixture with a solvent.

If only thermodynamics is considered, carbonyl compounds with high oxidation potentials, like aromatic and aliphatic aldehydes, should be especially suitable as oxidants in the Oppenauer oxidations [1]. Practically, however, other reasons, like separation problems and side reactions, should be considered. For example, although acetone has a
low oxidation potential, it is frequently used in the Oppenauer oxidation due to its low boiling point and cheaper price. The most commonly used oxidants for the Oppenauer oxidation are acetaldehyde, acrolein, benzaldehyde, furfural, acetone, butanone, cyclohexanone, acetophenone, p-benzoquinone, and benzophenone.

Aluminum alkoxides such as aluminum iso-propoxide and tert-butoxide are commonly used homogeneous catalysts in the Oppenauer oxidation because they are easy to prepare and show good solubility in alcohols and hydrocarbons. However, separation problems and the need for stoichiometric amounts of catalyst limit their practical applications.

Heterogeneous catalysts are also used in the Oppenauer oxidation. Magnesia [4] and aluminum oxide [5, 6] have been reported as catalysts for this reaction in the gas phase, while hydrous zirconium (IV) oxide [7, 8] was found to be an efficient solid catalyst both in the gas phase and in the liquid phase.

In the previous chapters, we have discussed the catalytic ability of zeolite Zr-beta for the Meerwein-Ponndorf-Verley (MPV) reduction. It was found that zeolite Zr-beta was not only very active for the MPV reduction but also exhibited high regioselectivity in the MPV reduction of 4-tert-butylcyclohexanone and high chemoselectivity in the MPV reduction of α,β-unsaturated aldehydes. In this chapter, the ability of zeolite Zr-beta to catalyze the Oppenauer oxidation in the liquid phase is described. Our studies were focused on the Oppenauer oxidation of cinnamyl alcohol to cinnamaldehyde, cyclohexanol to cyclohexanone, and 4-tert-butylcyclohexanol (mixture of cis- and trans-isomers) to 4-tert-butylcyclohexanone.
6.2 Results and discussions

6.2.1 Effect of the oxidants.

In order to choose an appropriate oxidant, the Oppenauer oxidation of cinnamyl alcohol with various ketones and aldehydes was carried out at 80 °C with Zr100 as catalyst. The results are listed in Table 6-1. Two ketones, 2-butanone and cyclohexanone, had moderate oxidation ability. After 6 hours of reaction time, the conversion of cinnamyl alcohol was 56.7% and 51.0% respectively. The highest turnover frequency (TOF), 38.7, was obtained with furfural as oxidant, while TOF was as low as 2.8 when benzaldehyde was used as oxidant. This result is surprising because the difference of oxidant potential between furfural and benzaldehyde is not so large. The microporous nature of zeolite Zr-beta is probably responsible for this difference. As we discussed in Chapter 4, the MPVO reactions proceed via a six-membered transition state in which both the reductant and the oxidant are coordinated to the Lewis zirconium metal center in the straight channels of the zeolite Zr-beta pore system. The six-membered ring of benzaldehyde is bulkier than the five-membered ring of furfural, and therefore makes it harder to form the transition-state in the small channels of zeolite Zr-beta. This explains why a slow reaction rate was obtained with benzaldehyde as oxidant. This hypothesis was confirmed through a separate experiment, in which it was confirmed that the rate of reaction with furfural was only slightly faster than with benzaldehyde if a big pore Zr-SBA-15 was used as catalyst for the Oppenauer oxidation of cinnamyl alcohol.

Furfural and benzaldehyde were also used as oxidants for the Oppenauer oxidation of cyclohexanol. The reaction was performed in the liquid phase using toluene as solvent and the reaction temperatures employed were 80 °C and 110 °C, respectively. As shown
in Figure 6-1, furfural presented very high oxidation ability. Equilibrium conversion was reached quickly at 110 ºC, but also at 80 ºC. In contrast, the use of benzaldehyde resulted in a much slower reaction rate. Even at 110 ºC, equilibrium was not approached after 6 hours of reaction time. The selectivity towards cyclohexanone was more than 95% when furfural was used as oxidant. In the case of benzaldehyde as oxidant, the selectivity was between 80-90%. The reaction environment under our reaction conditions is not totally oxygen free. The oxygen could be trapped in the condenser and could also be induced when we take samples for analysis. Zr-beta may catalyze air oxidation of benzaldehyde to perbenzoic acid which can serve as an oxidizing agent for the Baeyer-Villiger reaction. The further oxidation of cyclohexanone to ε-caprolactone has been confirmed by GC-MS analysis. To obtain high selectivity, an inert atmosphere has to be maintained, particularly when benzaldehyde is used as oxidant.

Based on these results, furfural was chosen as oxidant for further studies.

6.2.2 Effect of Si/Zr ratio in zeolite Zr-beta

Zeolite Zr-beta with different Si/Zr ratio was tested as catalyst for the Oppenauer oxidation of cinnamyl alcohol with furfural as oxidant. As shown in Figure 6-2, Zr100 was more active than any of the other two samples, Zr75 and Zr200. The lower activity of Zr200 is obviously due to the lower zirconium content in this zeolite. On the other hand, the lower activity of Zr75 can be ascribed to the existence of extra framework zirconium species in this sample, which have lower catalytic activity. Neither pure Si-beta nor zirconium oxychloride impregnated Si-beta was active for this reaction, which again indicates that isolated Zr atoms in the framework of zeolite beta are the catalytic active sites. The selectivity to the desired product, cinnamaldehyde, was always more than 95%.
By using furfural as oxidant and fixing the furfural/cyclohexanol ratio at 6:1, the effects of the Si/Zr ratio in zeolite Zr-beta was studied on the Oppenauer oxidation of cyclohexanol (Figure 6-3). All three zeolite Zr-beta samples tested were very active, and thermodynamic equilibrium could be obtained within 1 to 3 hours. Similar to the oxidation of cinnamyl alcohol, zeolite sample Zr100 was found to be the best catalyst.

6.2.3 Effect of ratio of furfural to substrate

Thermodynamically, the Oppenauer oxidation is a reversible reaction. Therefore, an increase in conversion can be realized by applying: 1) a stronger oxidant, giving a larger equilibrium constant; 2) a large excess of oxidant, which is often achieved by using the oxidant as the solvent; 3) selective removal of converted oxidant by evaporation [1]. In this study, different furfural/cinnamyl alcohol ratios were applied. As can be seen in Figure 6-4, the conversion of cinnamyl alcohol increased with the increasing ratio of furfural/cinnamyl alcohol. When the furfural/cinnamyl alcohol ratio was increased to 6:1, nearly all cinnamyl alcohol was converted after 5 hours of reaction time. In all cases, thermodynamic equilibrium seems to have been reached after 5 hours of reaction time. Even at a furfural/cinnamyl ratio of 1:1, a reasonably high conversion of 80% could be obtained, which shows that furfural is a strong oxidant.

The effect of ratio of furfural to cyclohexanol was also studied in the oxidation of cyclohexanol (Figure 6-5). Again, a similar trend was found as in the oxidation of cinnamyl alcohol. The higher the ratio, the higher the conversion of the cyclohexanol. The only difference is that here the reaction was much faster. This is can be explained
with the much smaller molecular size of cyclohexanol compared with that of cinnamyl alcohol.

6.2.4 Oppenauer oxidation of other alcohols with furfural

After it had been established that zeolite Zr-beta was a good catalyst for the Oppenauer oxidation of cinnamyl alcohol and cyclohexanol with furfural as oxidant, several other secondary alcohols were also tested. The results are summarized in Table 6-2. Except for diphenylmethanol, which cannot be oxidized due to its big molecular size, all tested alcohols were oxidized with high selectivities (more than 98%). Aldol condensation by-products were never detected. The acidic property of zeolite Zr-beta and the diluting effect of the solvent toluene may prohibit the formation of the bimolecular by-product.

1-cyclohexylethanol reacted very fast. Within 20 min, equilibrium was reached, and a conversion of 97% was obtained. In contrast, aryl substituted substrates reacted more slowly. The lower reactivity can be ascribed to the steric effect produced by the rigid aromatic ring. However, besides the above-mentioned steric restriction, the activity of alcohols containing aromatic groups can be influenced by other effects, such as resonance and inductive effects of the aromatic ring. We found that the substituent in the aromatic ring played an important role. 1-(4-chlorophenyl)-ethanol was reluctant to be oxidized, while 1-\textit{p}-tolyethanol and 1-(4-methoxyphenyl)-ethanol reacted faster than the unsubstituted phenylethanol, and a high conversion was obtained at the equilibrium point. These results indicate that electron withdrawing groups (such as chlorine) are slowing down the reaction rate while electron donating groups (such as methyl) are accelerating the rate when located on the hydrogen donor (alcohol). In the presence of an electron
withdrawing group, the electron density on the C-OH carbon atom is reduced. Therefore, the hydrogen donating ability of alcohol decreases. In contrast, an electron donating group enhances the electron density on the C-OH carbon atom; accordingly the hydrogen coordinated to this carbon atom is more easily donated. These observations excellently support the validity of the transition state shown in Scheme 6-1.

**6.2.5 Oppenauer oxidation of 4-tert-butylcyclohexanol with 2-butanone**

Zr-beta was also found to be an active and stereoselective catalyst in the Oppenauer oxidation of 4-tert-butylcyclohexanol to 4-tert-butylcyclohexanone (Scheme 6-4). As shown in Figure 6-6, when using a mixture of cis- and trans-4-tert-butylcyclohexanol (cis/trans≈27:73) as substrate and 2-butanone as oxidant, the cis- isomer was almost exclusively converted to the corresponding ketone within one hour, while the trans-isomer remained essentially unchanged after 2 hours. This is in agreement with what occurs when reducing the 4-tert-butylcyclohexanone and this again indicates that the pore size of Zr-beta hinders the formation of the transition state leading to the trans-isomer. The same result has also been observed by Creyghton et al. [9] and Corma et al. [10] in their Oppenauer oxidation of 4-tert-butylcyclohexanol catalyzed by zeolite Al-beta and Sn-beta, respectively.
6.3 Conclusions

Zeolite Zr-beta was found to be an excellent heterogeneous catalyst for the Oppenauer oxidation of alcohols. The isolated Zr atoms in the framework of zeolite beta were considered to be the catalytic active sites. The high selectivity obtained was explained by the favorable acidic property of zeolite Zr-beta and the diluting effect of toluene, which inhibit the formation of by-products.

The choice of the oxidant plays an important role in the Oppenauer oxidations over zeolite Zr-beta. Furfural was found to be the most efficient oxidant among all oxidants tested. High oxidation potential and a relatively small molecular size may contribute to its excellent performance. The ratio of oxidant to substrate also influences the final conversion of substrate.

Zeolite Zr-beta also showed regioselectivity in the Oppenauer oxidation of 4-tert-butylcyclohexanol with 2-butanone. Only cis-tert-butylcyclohexanol was oxidized, while trans-tert-butylcyclohexanol remained.
References


Table 6-1. Oppenauer oxidation of cinnamyl alcohol with various oxidants over zeolite Zr-beta sample Zr100.

![Catalyst](Catalyst.png)

<table>
<thead>
<tr>
<th>Oxidant</th>
<th>Conv. (%)(^a)</th>
<th>TOF(^b)</th>
<th>Select. (%)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-butanone</td>
<td>56.7</td>
<td>22.2</td>
<td>&gt;99</td>
</tr>
<tr>
<td>cyclohexanone</td>
<td>51.0</td>
<td>23.3</td>
<td>&gt;99</td>
</tr>
<tr>
<td>furfural</td>
<td>92.3</td>
<td>38.7</td>
<td>&gt;99</td>
</tr>
<tr>
<td>benzaldehyde</td>
<td>12.3</td>
<td>2.8</td>
<td>&gt;99</td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol cinnamyl alcohol, 7.8 mmol oxidant, 10 ml toluene, 100 mg Zr100 (Si/Zr=107) at 80 °C. \(^a\) Conversion and selectivity after 6 hours. \(^b\) Turnover frequency in mol·mol\(^{-1}\)Zr·h\(^{-1}\) calculated after 1 hour of reaction time.
Table 6-2. Oppenauer oxidation of various alcohols with furfural.

\[
\begin{align*}
\text{R}_1\text{R}_2\text{OH} & \quad \text{Zr-beta} \quad \text{Toluene, 110 oC} \\
& \quad \xrightarrow{} \\
\text{R}_1\text{R}_2\text{CHO} & \quad \text{R}_1\text{R}_2\text{OCH}_2\text{OH}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alcohol</th>
<th>Time (min)</th>
<th>Conv. (%)</th>
<th>Select. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\text{OH})</td>
<td>20</td>
<td>97</td>
<td>&gt;98</td>
</tr>
<tr>
<td>2</td>
<td>(\text{OH})</td>
<td>240</td>
<td>79</td>
<td>&gt;98</td>
</tr>
<tr>
<td>3</td>
<td>(\text{OH})</td>
<td>180</td>
<td>89</td>
<td>&gt;98</td>
</tr>
<tr>
<td>4</td>
<td>(\text{Cl})(\text{OH})</td>
<td>300</td>
<td>64</td>
<td>&gt;98</td>
</tr>
<tr>
<td>5</td>
<td>(\text{MeO})(\text{OH})</td>
<td>60</td>
<td>95</td>
<td>&gt;98</td>
</tr>
<tr>
<td>6</td>
<td>(\text{OH})</td>
<td>No reaction</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Reaction conditions: 1.3 mmol substrate, 7.8 mmol furfural, 10 ml toluene, 100 mg Zr100 at 110 ºC.
Scheme 6-1. Reaction mechanism of the Oppenauer oxidation.

Scheme 6-2. Aldol condensation of aldehydes containing α-hydrogen.

Scheme 6-3. Tishchenko reaction between two aldehydes without α-hydrogen.

Scheme 6-4. Oppenauer oxidation of 4-tert-butylcyclohexanol.
Figure 6-1. Effect of oxidants on the Oppenauer oxidation of cyclohexanol to cyclohexanone over zeolite Zr-beta: (●) furfural at 110 ºC, (○) furfural at 80 ºC, (■) benzaldehyde at 110 ºC, and (□) benzaldehyde at 80 ºC. Reaction conditions: 1.3 mmol cyclohexanol, 7.8 mmol oxidant, 10 ml toluene, 100 mg Zr100.

Figure 6-2. Oppenauer oxidation of cinnamyl alcohol over zeolite Zr-beta: (■) Zr100 (Si/Zr=107), (▲) Zr75 (Si/Zr=84), and (●) Zr200 (Si/Zr=194). Reaction conditions: 1.3 mmol cinnamyl alcohol, 2.6 mmol furfural, 10 ml toluene, 100 mg catalyst at 110ºC.
Figure 6-3. Oppenauer oxidation of cyclohexanol over zeolite Zr-beta: (■) Zr100 (Si/Zr=107), (▲) Zr75 (Si/Zr=84), and (●) Zr200 (Si/Zr=194). Reaction conditions: 1.3 mmol cyclohexanol, 7.8 mmol furfural, 10 ml toluene, 100 mg catalyst at 110 °C.

Figure 6-4. Oppenauer oxidation of cinnamyl alcohol over zeolite Zr-beta with different furfural/cinnamyl alcohol ratio: (■) 6:1, (●) 2:1, and (▲) 1:1. Reaction conditions: 1.3 mmol cinnamyl alcohol, 10 ml toluene, 100 mg Zr100 at 110 °C.
Figure 6-5. Oppenauer oxidation of cyclohexanol over zeolite Zr-beta with different furfural/cyclohexanol ratio: (■) 6:1, (●) 2:1, and (▲) 1:1. Reaction conditions: 1.3 mmol cyclohexanol, 10 ml toluene, 100 mg Zr100 at 110 °C.

Figure 6-6. Oppenauer oxidation of 4-tert-butylcyclohexanol with 2-butanone over Zr100: (▲) trans-4-tert-butylcyclohexanol, (■) cis-4-tert-butylcyclohexanol, and (●) 4-tert-butylcyclohexanone. Reaction conditions: 1.3 mmol 4-tert-butylcyclohexanol (mixture of cis- and trans- isomers, 83 mmol butanone, 100 mg Zr100 at 80 °C.
Chapter 7 Zr-beta Zeolite as diastereoselective heterogeneous Lewis-acid catalyst for Cyclisation of citronellal to isopulegol

7.1 Introduction

(-)-Menthol is one of the most important flavoring chemicals due to its characteristic peppermint odour and strong physiological cooling effect [1, 2]. It is used extensively in pharmaceuticals, cosmetics, toothpastes, chewing gum, and other toiletry goods as well as in cigarettes. Naturally, (-)-menthol is obtained by freezing the oil of Mentha arvensis to crystallize the menthol present. Synthetically, it can be produced by Lewis-acid catalyzed cyclization of (+)-citronellal with subsequent catalytic hydrogenation (Scheme 7-1).

In the cyclisation of citronellal to isopulegol, four different stereoisomers are formed as citronellal has one chiral and two prochiral carbons that become asymmetric centers in the product. Since only (-)-isopulegol is of commercial interest, diastereoselectivity towards (-)-isopulegol is critical in this reaction. Among many homogeneous catalysts, ZnBr₂ has been identified as the most suitable one for this reaction, providing a 94:6 diastereoselectivity [3]. Indeed, by using ZnBr₂ as catalyst, cyclisation of citronellal towards isopulegol has been commercialized with (-)-isopulegol yields up to 92% [4]. However, this catalyst has its own drawbacks including the requirement of a stoichiometric amount of ZnBr₂, difficulty in maintaining ZnBr₂ salt under anhydrous conditions, and reduced activity and selectivity when ZnBr₂ is employed in aqueous solution.

To overcome these drawbacks, several soluble metal complexes have been tested for cyclisation. The use of triethylaluminium and 2, 6-diphenylphenol with a molar ratio of
1:3 as catalyst gave an isopulegol yield of 95% [5]. Unfortunately, the catalyst has to be destroyed with NaOH after the reaction and cannot be recovered. Scandium trifluoromethanesulfonate has also been reported as an efficient catalyst for cyclisation of citronellal [6]. At -78 ºC, isopulegol yields up to 95% with a diastereoselectivity of 94:6 were obtained, while at room temperature, the yield was only 58% with a diastereoselectivity of 80:20 due to a consecutive reaction of the formed isopulegol with citronellal. Other soluble catalysts have also been used for performing the selective cyclisation of citronellal, but the yields obtained were lower than with ZnBr₂ [7].

Cyclisation of citronellal on solid acid catalysts has also been investigated. Fuentes et al. [8] studied the activities and selectivities of several zeolites with different pore sizes in the cyclisation of citronellal. They found zeolites with smaller channels have lower activity while bigger channels increased the formation of by-products, i.e. isopulegol ethers. In these studies, the activity could be correlated with the total amount of accessible Brøsted acid sites. The selectivity to the total isopulegol isomers was found in the range of 70-90% at 80% conversion level. But no data on the diastereoselectivity to isopulegol were given.

Ravasio et al. [9] studied the cyclisation of citronellal over some mixed oxides such as SiO₂-TiO₂, SiO₂-Al₂O₃, SiO₂-ZrO₂ and Cu supported on these mixed oxides. Lewis acid sites were found to be the most active and diastereoselective to isopulegol. The diastereoselectivity to isopulegol obtained on these oxides varied from 63 to 74%.

Sulfated ZrO₂ was reported active for the cyclisation of citronellal [10, 11]. However, the selectivity to isopulegol was low, and even when the sulfated ZrO₂ was coated with a carbon molecular sieve, the selectivity never exceeded 65%. Several zirconia-based
catalysts, including zirconium hydroxide, phosphated zirconia, and sulphated zirconia, were studied by Chuah et al. [12] for this reaction. Though good activity and high selectivity to isopulegol isomers were obtained, the diastereoselectivity towards isopulegol was only around 70%.

Noting the low diastereoselectivity of the heterogeneous catalysts studied previously for the cyclisation of citronellal, recently some researchers began to deal with the distribution of the stereoisomers formed during the reaction. Milone et al. [13, 14] compared the activity of impregnated ZnBr$_2$, ZnCl$_2$, Zn(NO$_3$)$_2$, FeCl$_3$ and SnCl$_2$ on commercial SiO$_2$ for the cyclisation of citronellal and found that ZnBr$_2$ was the most effective in terms of catalytic activity and selectivity. The maximum diastereoselectivity towards isopulegol obtained on supported ZnBr$_2$ was 86%. Corma and Renz [15] applied a zeolite Sn-beta as solid Lewis acid to the cyclisation of citronellal. High turnover numbers (TON, moles of substrate converted per mol of active sites) up to 1350 was obtained. The diastereoselectivity to isopulegol was in the range of 80-85%. Several polar solvent were tested, but the choice of solvent was found to have no effect on the diastereoselectivity. Zirconium-exchanged montmorillonite was reported to catalyze the cyclisation of citronellal [16]. High diastereoselectivity up to 90% to isopulegol was achieved after 24h in acetonitrile at 80 ºC. This was the highest diastereoselectivity reported over any heterogeneous catalyst. Furthermore, this catalyst could be recycled for at least 5 times without losing its original activity and selectivity.

The literature review indicates that Lewis acidity and pore structure are two important factors for cyclisation of citronellal to isopulegol. Zeolite Zr-beta has proved to be an excellent solid Lewis acid for the Meerwein-Ponndorf-Verley reduction and Oppenauer
oxidation. High regioselectivity and chemoselectivity was observed in the reduction of 4-tert-butylcyclohexanone and cinnamaldehyde respectively. In the following section, we report on the use of this catalyst for the carbonyl-ene reaction in the cyclisation of citronellal to isopulegol. The influence of various solvent was studied. In addition, some kinetic factors were also investigated.
7.2 Results and discussions

7.2.1 Cyclisation of citronellal over zeolite Zr-beta

We have shown in previous chapters that zeolite Zr-beta is an excellent Lewis acid for many transformations involving carbonyl functions. Its Lewis acidity should make it a good candidate for the cyclisation of citronellal, which is considered to be mainly catalyzed by Lewis acids. In order to verify this hypothesis, Zeolite Zr-beta with different Si/Zr ratio was applied to the cyclisation of citronellal with acetonitrile as solvent. Not surprisingly, Zr-beta was indeed found to be an efficient catalyst for this reaction (Table 7-1). Moreover, under the experimental conditions employed, citronellal was converted to isopulegol stereoisomers with more than 98% selectivity in all Zr-beta samples studied. The reaction products were: isopulegol, neoisopulegol and isoisopulegol. The less thermodynamically stable stereoisomer, neoisoisopulegol, was not formed under our reaction conditions. A remarkable result obtained was the high diastereoselectivity towards the desired isopulegol, which is more than 90%. This value almost matches that of the homogeneous ZnBr$_2$, and is perhaps the highest among all heterogeneous catalysts reported for this reaction at high conversions. The reason for the high diastereoselectivity towards isopulegol over Zr-beta will be discussed in the mechanism section.

The activity of zeolite Zr-beta was influenced by the Si/Zr ratio. As can be seen in Table 7-1, the conversion of citronellal increased with Zr content (note: the higher the ratio of Si/Zr, the lower the content of Zr in the zeolite), however the increase of activity was not linear with Zr content. Indeed, if we compare the TON of these samples, we found that Zr200 has the highest TON, though its Zr content was the lowest among all Zr-containing samples tested. The reasons for these results could be: 1) Zr in zeolite beta
is not equally active; 2) high loading of Zr in zeolite beta may give rise to some limitation
problems for reactants to absorb to and desorb from active sites. Corma and Renz [15]
have observed a similar trend for cyclisation of citronellal when using Sn-beta as catalyst.

7.2.2 Effect of metal substitution in zeolite beta catalysts

The catalytic results over various catalysts are summarized in Table 7-2. Zr-beta was
superior to other metal-substituted beta zeolites in terms of conversion and selectivity.
Sn-beta was active for the cyclisation of citronellal but was not as good as Zr-beta. Ti-
beta gave poor results. Only 17% conversion was reached after 1 hour. Additionally, the
diastereoselectivity with respect to the three other diastereomers was much lower for the
titanium-containing material, only 59%. Three commercial Al containing zeolites, H-Beta,
H-Y, and H-ZSM-5 were also studied for comparison purpose. However, all these
zeolites showed low conversion and poor activity under our reaction conditions. It is
worth to be note that HY gave very high activity when t-butanol instead of actonitrile was
used as solvent. In this case, more than 95% conversion could be obtained. But the
selectivity to isopulegol was still low due to the formation of isopulegol ethers and other
dehydrated by-products. This result indicates that the choice of the solvent plays an
important role in the cyclisation of citronellal. The solvent effect is discussed in the next
section.

7.2.3 Effect of solvent

The effects of various solvents on the activity and selectivity in the Zr-Beta catalyzed
cyclisation of citronellal was extensively investigated, since the co-adsorption of the
solvent into the micropore system of Zr-beta could greatly influence the intraporous
citronellal concentration. The solvent used may facilitate or retard the adsorption of the
reactant to the catalytic active sites. The hydrophobic nature of Zr-beta synthesized in fluoride medium will cause it to adsorb less polar molecules preferentially over more polar molecules. Apolar solvents are expected to be adsorbed strongly on Zr-beta, thus giving a low intraporous citronellal concentration and vice versa.

As can be seen in Table 7-3, the solvent employed has some impact on the activity and stability of the catalyst. When a non-polar solvent such as toluene and cyclohexane was used, a lower conversion was observed. Particularly, toluene gave a much reduced activity. In contrast, solvents with high relative polarity gave high conversion and high diastereoselectivity. One exception is 2-propanol. When 2-propanol was used, the selectivity to isopulegol stereoisomers was only 81%. This is because some of the citronellal was reduced to citonellol via the Meerwein-Ponndorf-Verley process. However, the cyclisation is faster than the reduction of citronellal. In our Zr-beta catalyzed cyclisation, high diastereoselectivity was obtained in all solvents studied, with its value a little higher in polar solvents than in apolar solvents. The best diastereoselectivity was obtained in t-butanol, more than 93%.

7.2.4 Effect of reaction temperature

To study the influence of the reaction temperature, zeolite Zr-beta catalyzed cyclisation of isopulegol was carried out at several temperatures between 25 and 80 ºC (Table 7-4). Aggarwal et al. [6] reported that the diastereoselectivity could be improved by lowering the reaction temperature when scandium trifluromethanesulfonate was used as catalyst. In our experiment, when the temperature was lowered from 80 ºC to 25 ºC, no improvement in selectivity was obtained, while the conversion was decreased
significantly. Obviously, the selectivity could not be improved by simply decreasing reaction temperature in our system.

The kinetics of cyclisation of citronellal to isopulegol was also studied.

Supposing this reaction follows simple first order kinetics over zeolite Zr-beta, the rate of reaction can be expressed as:

\[
 r_A = -\frac{dC_A}{dt} = kC_A 
\]  

(7-1)

The above equation can be integrated to get the following:

\[-\ln(1-X_A) = kt \]

(7-2)

Here \( C_A, t, X_A, \) and \( k \) represent the concentration of citronellal, the reaction time, the conversion of citronellal, and the rate constant. A plot of \(-\ln(1-X_A) \) vs \( t \) will be a straight line with the slope equal to \( k \). In our experiment, we found that the rate dependence could be roughly fitted with first order equation only when \( t \)-butanol was used as solvent. In the case of other solvents, the rate equation seemed more complex and didn’t follow the first-order reaction rate. This may be due to the solubility of isopulegol in the alcohol solvent, which makes desorption of isopulegol from the active sites much fast. Thus, the following discusses is limited to the solvent of \( t \)-butanol.

Figure 7-1 shows the plots of \(-\ln(1-X_A) \) vs \( t \) at different reaction temperatures. Four straight lines were obtained, and all these lines pass through the origin, which shows that the cyclisation of citronellal follows first order kinetics to a good approximation. With the rate constant obtained at different temperature, the Arrhenius plot of \( \ln k \) vs \( 1/T \) (\( T \) is the absolute temperature) was drawn and shown in Figure 7-2. Again a straight line was obtained. According to the Arrhenius equation, the slope of this line is equal to \(-E_a/R\).
From the slope of this line, an apparent activation energy of 35.9 kJ/mol can be calculated.

### 7.2.5 Effect of catalyst amount

To study the influence of the amount of catalyst, the cyclisation of citronellal was tested with different amounts of catalyst in *t*-butanol. As shown in Table 7-5, the conversion increased with catalyst amount, while the selectivity was not affected. In a first order reaction, the rate constant should be proportional to the amount of catalyst. To check this, the rate constant $k$ (determined from the slope of $-\ln(1-X_A)$ vs $t$) was plotted against catalyst amount (Figure 7-3). As expected, a straight line passing through the origin was obtained. This confirms that the reaction is first order in concentration of citronellal, and the rates of reactions are directly proportional to the catalyst amount.

### 7.2.6 Stability of Zr-beta catalyst

The effect of water on the activity was studied by adding different amounts of water to the reaction mixture. As shown in Table 7-6, Zr-beta lost little activity in the presence of 1 wt% water. Even in the presence of 3 wt% water, the activity of Zr-beta did not drop significantly. The low decrease of the activity of Zr-beta in the presence water can again be explained by the hydrophobic nature of this nearly all-silica zeolite synthesized in fluoride medium. This result indicates that Zr-beta is water-resistant and no special precautions are necessary in practical applications.

### 7.2.7 Reaction mechanism

The cyclisation of citronella in the presence of an acid catalyst is believed to involve the protonation of the carbonyl group of citronellal on an acidic site, followed by intramolecular rearrangement to form a more stable carbocation, and finally
deprotonation to give the final product, isopulegol. Fuentes et al. [8] observed a higher reaction rate and selectivity to isopulegol with polar solvents such as chloroform. Based on these findings, they suggested that the reaction takes place through carbocations at external sites of the zeolites. Ravasio et al. [9] used mixed oxides such as silica–titania, silica–zirconia, and silica–alumina and observed an increase in the stereoselectivity of the cyclisation reaction when strong Lewis acid sites were present. In contrast to the findings of Fuentes et al. [8], no enhancement of the reaction rate was observed when using chloroform instead of toluene, hence excluding a carbocation intermediate. Although the nature of the catalytic sites was not clear, the authors suggested that the possibility of a Lewis acid catalyzed mechanism is in agreement with the strong inhibition observed when dioxane was used as a solvent.

In this study, we found that the Lewis acid sites on the hydrophobic beta zeolites show good activity and selectivity for the cyclisation of isopulegol. Based on the catalytic results, in combination with the information obtained by the pyridine adsorption and 4-methylcyclohexanone adsorption FT-IR results (refer to chapter 4), the following Lewis acid catalyzed reaction mechanism is proposed. Firstly, the carbonyl group in citronellal is coordinated to a Lewis acid zirconium site and, thereby, the carbonyl group is activated (This has been confirmed by IR spectra of in-situ 4-methylcyclohexanone adsorption). This brings the citronellal in an orientation favorable for ring closure through an intramolecular carbon-carbon bond formation. The ring closure, then, induces an abstraction of a hydrogen atom from the isopropyl group by the oxygen connected the ring. Finally, the isopulegol formed desorbs from the Lewis acid center and completes the catalytic cycle.
Because the reaction proceeds in the inner channels of zeolite Zr-beta, the restriction of the pore size impedes the formation of bulkier stereoisomers, which leads to the high diastereoselectivity in the cyclisation of citronellal.
7.3 Conclusion

Zr-beta has been shown to be an effective heterogeneous catalyst for the cyclization of citronellal to isopulegol. The catalytic performance of Zr-beta with respect to conversion and diastereoselectivity was much higher than that of other metal substituted beta zeolites. The diastereoselectivity, up to 93%, obtained in this study is perhaps the highest among all heterogeneous catalysts reported for this reaction.

The activity of Zr-beta was found to be influenced by the choice of solvent. Better conversion was obtained in polar solvents, while in apolar solvents the reaction was a little slower. The presence of water did not impede the reaction, which means that this catalyst does not require the usual precautions against humidity needed for normal Lewis acids.

The cyclisation of citronellal over Zr-beta was found to follow first order kinetics. The activation energy was 35.9 kJ/mol in solvent t-butanol. A tentative reaction mechanism was proposed based on Lewis acid catalysis.
References


Table 7-1. Cyclisation of citronellal over zeolite Zr-beta.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Sample</th>
<th>Si/Zr ratio</th>
<th>Conv. (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Select. (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Diastereoselect. (%)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>TON&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Si-beta</td>
<td>0</td>
<td>n.r</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Zr75</td>
<td>84</td>
<td>86</td>
<td>&gt;98</td>
<td>92</td>
<td>402</td>
</tr>
<tr>
<td>3</td>
<td>Zr100</td>
<td>107</td>
<td>93</td>
<td>&gt;98</td>
<td>93</td>
<td>531</td>
</tr>
<tr>
<td>4</td>
<td>Zr150</td>
<td>155</td>
<td>83</td>
<td>&gt;98</td>
<td>92</td>
<td>640</td>
</tr>
<tr>
<td>5</td>
<td>Zr200</td>
<td>194</td>
<td>75</td>
<td>&gt;98</td>
<td>93</td>
<td>774</td>
</tr>
</tbody>
</table>

<sup>a</sup> Conversion after 1 h. <sup>b</sup> Selectivity to isopulegol isomers with respect to other products. <sup>c</sup> Selectivity to isopulegol with respect to other three diastereomers. <sup>d</sup> moles of citronellal converted per mol of Zr atoms. Reaction conditions: 4 mmol citronellal, 5 ml acetonitrile, 50 mg catalyst at 80 ºC.

Table 7-2. Cyclisation of citronellal to isopulegol over various catalysts.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Si/M ratio</th>
<th>Conv. (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Select. (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Diastereosel. (%)&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr-beta</td>
<td>107</td>
<td>93</td>
<td>&gt;98</td>
<td>93</td>
</tr>
<tr>
<td>Sn-beta</td>
<td>125</td>
<td>73</td>
<td>&gt;98</td>
<td>85</td>
</tr>
<tr>
<td>Ti-beta</td>
<td>100</td>
<td>17</td>
<td>84</td>
<td>59</td>
</tr>
<tr>
<td>H-beta&lt;sup&gt;d&lt;/sup&gt;</td>
<td>50</td>
<td>24</td>
<td>88</td>
<td>65</td>
</tr>
<tr>
<td>H-Y&lt;sup&gt;d&lt;/sup&gt;</td>
<td>60</td>
<td>20</td>
<td>89</td>
<td>67</td>
</tr>
<tr>
<td>H-ZSM-5&lt;sup&gt;d&lt;/sup&gt;</td>
<td>50</td>
<td>2</td>
<td>73</td>
<td>63</td>
</tr>
</tbody>
</table>

<sup>a</sup> Conversion after 1 h. <sup>b</sup> Selectivity to the four diastereomeric pulegols with respect to other products. <sup>c</sup> Selectivity to isopulegol with respect to the other three diastereomers. <sup>d</sup> Commercial material. Reaction conditions: 4 mmol citronellal, 5 ml acetonitrile, 50 mg catalyst at 80 ºC.
### Table 7-3. Effect of solvents on the cyclisation of citronellal to isopulegol over zeolite Zr-beta.

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Relative polarity</th>
<th>Conv. a (%)</th>
<th>Select. b (%)</th>
<th>Diastereosel. c (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-propanol</td>
<td>0.546</td>
<td>97</td>
<td>81</td>
<td>91</td>
</tr>
<tr>
<td>acetonitrile</td>
<td>0.46</td>
<td>93</td>
<td>&gt;98</td>
<td>92</td>
</tr>
<tr>
<td>tert-butanol</td>
<td>0.389</td>
<td>91</td>
<td>&gt;98</td>
<td>93</td>
</tr>
<tr>
<td>1,4-dioxane</td>
<td>0.164</td>
<td>93</td>
<td>&gt;98</td>
<td>92</td>
</tr>
<tr>
<td>cyclohexane</td>
<td>0.006</td>
<td>83</td>
<td>&gt;98</td>
<td>90</td>
</tr>
<tr>
<td>toluene</td>
<td>0.099</td>
<td>60</td>
<td>&gt;98</td>
<td>89</td>
</tr>
</tbody>
</table>

a Conversion after 1 h. b Selectivity to four diastereomeric isopulegols with respect to other products. c Selectivity to isopulegol with respect to other three diastereomers.

Reaction conditions: 4 mmol citronellal, 5 ml solvent, 50 mg Zr-beta (Si/Zr=107) at 80 ºC.

### Table 7-4. Effect of reaction temperature on the cyclisation of citronellal to isopulegol.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Temperature (ºC)</th>
<th>Conv. a (%)</th>
<th>Sele. b (%)</th>
<th>Diastereosel. c (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>14</td>
<td>&gt;98</td>
<td>92</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>34</td>
<td>&gt;98</td>
<td>92</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>57</td>
<td>&gt;98</td>
<td>92</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>79</td>
<td>&gt;98</td>
<td>93</td>
</tr>
</tbody>
</table>

a Conversion after 30min. b Selectivity to the four diastereomeric pulegols with respect to other products. c Selectivity to isopulegol with respect to the other three diastereomers.

Reaction conditions: 4 mmol citronellal, 5 ml t-butanol, 50 mg Zr-beta (Si/Zr=107).
Table 7-5. Effect of catalyst amount on the cyclisation of citronellal to isopulegol.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst amount (mg)</th>
<th>Conv.(^a) (%)</th>
<th>Sele.(^b) (%)</th>
<th>Diastereosel.(^c) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>55</td>
<td>&gt;98</td>
<td>93</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>79</td>
<td>&gt;98</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
<td>86</td>
<td>&gt;98</td>
<td>93</td>
</tr>
</tbody>
</table>

\(^a\) Conversion after 30min. \(^b\) Selectivity to the four diastereomeric pulegols with respect to other products. \(^c\) Selectivity to isopulegol with respect to the other three diastereomers.

Reaction conditions: 4 mmol citronellal, 5 ml \(t\)-butanol, 80 °C, Zr-beta (Si/Zr=107) as catalyst.

Table 7-6. Effect of water on the activity of Zr-beta.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Water added (wt %)</th>
<th>Conv.(^a) (%)</th>
<th>Sele.(^b) (%)</th>
<th>Diastereosel.(^c) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>91</td>
<td>&gt;98</td>
<td>93</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>87</td>
<td>&gt;98</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>81</td>
<td>&gt;98</td>
<td>93</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>78</td>
<td>&gt;98</td>
<td>93</td>
</tr>
</tbody>
</table>

\(^a\) Conversion after 1 hour. \(^b\) Selectivity to the four diastereomeric pulegols with respect to other products. \(^c\) Selectivity to isopulegol with respect to the other three diastereomers.

Reaction conditions: 4 mmol citronellal, 5 ml \(t\)-butanol, 80 °C, Zr-beta (Si/Zr=107) as catalyst.
Scheme 7-1. The production of (-)-menthol by Lewis-acid catalysed cyclisation of (+)-citronellal with subsequent catalytic hydrogenation.

Scheme 7-2. Proposed reaction mechanism for the cyclisation of citronellal to isopulegol.
Figure 7-1. Plots of $-\ln(1-X_A)$ again reaction time over Zr-beta (Si/Zr=107). (♦) 80 °C; (■) 60 °C; (▲) 40 °C; (●) 25 °C. Reaction conditions: 4 mmol citronellal, 5 ml t-butanol, 50 mg Zr-beta (Si/Zr=107).
Figure 7-2. Arrhenius plot of $\ln k$ vs $1/T$. Reaction conditions: 4 mmol citronellal, 5 ml $t$-butanol, 50 mg Zr-beta (Si/Zr=107).

$y = -4316.4x + 9.2912$

Figure 7-3. Plot of $k$ vs catalyst amount. Reaction conditions: 4 mmol citronellal, 5 ml $t$-butanol, 80 °C, Zr-beta (Si/Zr=107) as catalyst.
Chapter 8

Dynamic kinetic resolution of secondary alcohols combining enzyme-catalyzed transesterification with zeolite-catalyzed racemization

8.1 Introduction

Transformations based on enzymatic catalysis provide useful methods for the synthesis of chiral molecules with high optical purity [1, 2]. In particular, the kinetic resolution (KR) of racemic compounds by hydrolytic enzymes such as lipases and esterases has become the most important industrial approach to the synthesis of enantiomerically enriched molecules including alcohols, acids and their esters [3]. Kinetic resolution makes use of the fact that two enantiomers of a racemic mixture are transformed to products at different rates. Therefore, in an effective enzymatic resolution, one of the enantiomers is selectively transformed to a product, while the other is left behind (Scheme 8-1) [4].

However, a major drawback with KR is that the maximum theoretical yield is limited to 50%. To overcome this problem, three approaches can be used: using meso compounds or prochiral substrates [5], combining a KR with a stereoinversion [6], or applying a dynamic kinetic resolution (DKR) [3, 7-9]. DKR combines the resolution step of KR with an in situ racemization of the non-reactive enantiomer (Scheme 8-2). In this way, all of the substrate can be converted into a single product isomer with a 100% theoretical yield. Therefore, it is not surprising that DKR has attracted much attention academically and industrially.

Initially, DKR was applied to substrates that are prone to spontaneous racemization [10]. Recently, several groups have introduced the use of noble metal-based racemization
catalysts in combination with enzymes as the resolution catalyst for the DKR of chirally stable racemic compounds such as alcohols, esters, and amines. Williams et al. combined the palladium-catalyzed racemization of an allylic acetate [11] and a secondary alcohol [12] in the presence of stoichiometric quantities of ketone and base with the \textit{Pseudomonas fluorescens} lipase-catalyzed transesterification. At the same time, Reetz et al. [13] also showed that the use of palladium as a racemization catalyst is compatible with the lipase-catalyzed KR of amines. Although only moderate results were obtained in these early studies, they showed that the combination in one pot of both metal and enzyme catalysis is possible.

Bäckvall and co-workers [4, 14] developed an efficient system based on the use of \textit{p}-chlorophenylacetate as the acyl donor and a robust ruthenium catalyst for the racemization. In their DKR of 1-phenylethanol, (R)-1-phenylethyl acetate can be synthesized from the racemate in virtually quantitative yield and >99\% \textit{ee}. Furthermore no additional base is necessary and the reaction is considerably faster than with Williams’s catalyst. This system can also be applied to DKR of several other secondary alcohols. The drawback is that sometimes it is not easy to separate the \textit{p}-chlorophenylacetate from the product. In a recent review from the same group, it is mentioned that \textit{p}-chlorophenylacetate can be replaced by the more readily available isopropenyl acetate [8]. However, the use of an appropriate hydrogen source such as 2,4-dimethyl-3-pentanol is needed to prevent a drop in yield due to ketone formation.

Park and coworkers [15, 16] developed a particularly efficient ruthenium-based catalyst, aminocyclopentadienyl ruthenium chloride, which is able to racemize secondary alcohols at room temperature. When this racemization catalyst was combined with the
candida antarctica lipase B (CALB) catalyzed transesterification using isopropenyl acetate as acyl donor, an efficient DKR was obtained if sodium carbonate or molecular sieves are used as additives. This catalyst permits the use of more reactive acyl donors (e.g. vinyl acetate, isopropenyl acetate) and also extends the technique to lipases that are not thermostable. This group has also applied the DKR approach to the asymmetric transformation of acyloxyphenyl ketones by the use of multiple racemization/resolution pathways [17].

Finally, it should be mentioned that in 2002, a large scale industrial process for chemoenzymatic DKR of secondary alcohols was developed at DSM by Verzijl et al. where a modified Ru-Noyori type catalyst is used together with immobilized CALB [18].

In order to facilitate recycling of the expensive racemization catalyst, heterogeneous catalysts based on noble metals have been applied to DKR. Pd on carbon has a moderate catalytic activity for 1-phenylethylamine racemization under a hydrogen atmosphere [13]. Ru immobilized on hydroxyapatite was also reported recently to be an efficient heterogeneous catalyst for the racemization of some secondary alcohols [19]. Unfortunately, this catalyst lost its activity once it was coupled with lipase in the same pot for the resolution of alcohols. Acid polymers like Amberlyst® 15 [20] and Deloxan™ [21] are also reported to be active for benzylic alcohol racemization in aqueous media. Wuyts et al. [22] found that H-beta zeolite was an efficient heterogeneous catalyst for racemization of chiral 1-phenylethanol in water. They also claimed that H-beta zeolite catalyzed racemization could be combined with enzymatic kinetic resolution in a one-pot, two-phase procedure. However, because the racemization was carried out in aqueous phase, the hydrolysis of the acyl donor cannot be avoided.
From the literature review presented above, it is clear that the combination of transition metal catalyzed racemization with lipase-catalyzed enzymatic resolution of alcohols in one pot has already been very successful in homogeneous phase. In contrast, studies on DKR under heterogeneous conditions are rare, and the results obtained are not very good. This is due to the slow racemization rate or to incompatibility of the kinetic resolution and the racemization procedures. This chapter describes in the first part zeolite Zr-beta as a heterogeneous catalyst for the racemization of (S)-1-phenylethanol. In a later part, the coupling of Zr-beta catalyzed racemization with a lipase catalyzed resolution of racemic phenylethanol in one pot is reported.
8.2 Results and discussions

8.2.1 Racemization of (S)-1-phenylethanol

Wuyts et al. [22] found that some acid zeolites like H-beta were efficient heterogeneous catalysts for the racemization of benzylic alcohols in aqueous phase. But the use of water as solvent may cause some compatibility problems in DKR. In order to avoid these problems, we attempted to racemize benzylic alcohols in organic solvent by using some metal-substituted intrinsically hydrophobic beta zeolites as catalysts. (S)-1-phenylethanol was chosen as a model molecule for racemization and toluene as solvent. Some typical results are listed in Table 8-1.

Al-beta showed fast racemization ability. (S)-1-phenylethanol was nearly completely racemized after 2 hours. However, the yield to racemic 1-phenylethanol was only 58%, whereas the dehydration to styrene was a major side reaction. Indeed, styrene was the only product after 6 hours of reaction time. Sn-beta was not good at racemization of (S)-1-phenylethanol. After 6 hours, the enantiomeric excess of 1-phenylethanol was still as high as 95% (here a low ee is a good result). This indicates that almost no racemization took place.

In comparison with Al-beta, Zr-beta and Ti-beta gave moderate racemization rate. After 6 hours, the ee of 1-phenylethanol was 5% and 22% respectively. However, a much better yield, 72% for Zr-beta and 88% for Ti-beta, was obtained. These results show that Zr-beta and Ti-beta are suitable candidates for application in a dynamic kinetic resolution. Considering the racemization rate and yield of 1-phenylethanol, Zr-beta was finally chosen for further studies.
To test the stability of Zr-beta, several different additives were added to the reaction mixtures. In the presence of acetic acid and isopropenyl acetate, the racemization rate over Zr-beta was not significantly affected, which shows Zr-beta is very stable in acidic environment. Moreover, because isopropenyl acetate is the most frequently used acyl donor in enzymatic resolution, this result indicates that the chemical reagents are compatible with each other if we combine Zr-beta and enzyme catalysis for resolution of alcohols in one pot. In contrast, the activity of Zr-beta was completely inhibited by pyridine, which indicates that acidic sites are responsible for the racemization. The presence of water could suppress the formation of the by-product, styrene. However, water also decreased the racemization rate significantly.

Based on the racemization results, in combination with the information obtained from the pyridine adsorption experiments on various metal substituted beta zeolites (refer to chapter 4), a tentative reaction mechanism is proposed (Scheme 8-3). The first step is chemisorption of (S)-1-phenylethanol on a Lewis acid zirconium site. Then the racemization occurs on this active site. Finally the racemized product desorbs from the active site and completes the catalytic cycle. In the second step, the dehydration may occur, leading to the formation of styrene.

8.2.2 Dynamic kinetic resolution (DKR) of 1-phenylethanol in one pot

Based on these racemization results, the Zr-beta catalyzed racemization was combined with an enzyme-catalyzed transesterification for the DKR of 1-phenylethanol in one pot. Our basic idea is depicted in Scheme 8-4. It is expected that an enzyme could be used to selectively acylate one enantiomer of 1-phenylethanol. At the same time, Zr-beta can be employed to racemize the non-reacting enantiomer of 1-phenylethanol (but
not the product). Thus, all racemic 1-phenylethanol should ultimately be converted to the optical pure chiral product.

The enzyme used was *Candida antarctica* lipase B supported on an acrylic resin (commercially available under the trade name Novozym 435). This enzyme has been successfully employed in esterifications [23], transesterifications [24-28], and hydrolysis [29, 30], perhydrolysis [31], and aminolysis [32] of esters. It has been shown to possess a very high thermostability, tolerating temperatures as high as 70-80 °C, which makes this enzyme most suitable for our purposes. Indeed, Novozym 435 is one of the most frequently used enzymes for DKR of secondary alcohols.

Isopropenyl acetate was chosen as acyl donor because it was reported that it gave faster and more productive DKR [15]. Moreover, it is compatible with Zr-beta catalyzed racemisation (refer to 8.2).

The initial attempt for DKR of 1-phenylethanol combining enzyme Novozym 435 with Zr-beta catalysis was carried out in toluene at 60 °C. For 1 mmol of racemic 1-phenylethanol, 30 mg Novozym 435 and 100 mg Zr-beta (Si/Zr=107) was used. After 24 hours, the conversion of 1-phenylethanol was 60% with product ee about 94%. The rate-determining step is most likely the slow Zr-beta catalyzed racemisation step, since nearly 50% conversion was achieved after only 6 hours. Thought the reaction proceeded slowly, this initial result is encouraging because under the same reaction conditions, the conversion of 1-phenylethanol did not exceeded 50% even after 48 hours if racemization catalyst Zr-beta was not added.

To increase the racemisation rate, 400 mg Zr-beta was used instead, and the total reaction rate was subsequently improved. The reaction was monitored carefully by chiral
Two typical chromatograms are shown in Figure 8-1. After 48 hours, besides the acylated product, 1-phenylethyl acetate, two by-products were also detected; one is styrene and the other is acetophenone. Styrene forms by dehydration of 1-phenylethanol, which is catalyzed by Zr-beta. The selectivity to styrene was about 10%. Acetophenone is formed via Oppenauer oxidation of 1-phenylethanol, where acetone, the leaving group of isopropenyl acetate, is the oxidizing agent. Bäckvall and coworker [4] have reported the DKR of 1-phenylethanol using a dimeric Ru(II) complex as racemization catalyst. They found 28% of 1-phenylethanol was converted to acetophenone when isopropenyl acetate was used as acyl donor. In our experiment, the selectivity to acetophenone never exceeded 1%.

The ee of the product, 1-phenylethyl acetate, decreased as the reaction progressed (Figure 8-2). The drop of ee could be due to several reasons: 1) the kinetic resolution is not efficient enough, (S)-1-phenylethanol is also acylated; 2) Zr-beta catalyzes non-selective transesterification; and 3) Zr-beta racemizes the acylated product, (R)-1-phenylethyl acetate. The first reason could be ruled out because $k_R >> k_S$ when Novozym 435 is used for the resolution of 1-phenylethenol in toluene. In our studies on Zr-beta catalyzed racemisation of (S)-1-phenylethanol, a very small amount of 1-phenylethyl acetate was observed when adding isopropenyl acetate to the reaction mixture. This result indicates that Zr-beta can catalyze the acylation of 1-phenylethanol, though the reaction rate is very low. In a separate experiment, (R)-1-phenylethyl acetate was found to be slowly racemized by Zr-beta. In summary, both the Zr-beta catalyzed transesterification of 1-phenylethanol and racemization of 1-phenylethyl acetate take place, which explains the drop ee of the final product, especially after long reaction time.
Teo found that acetophenone could accelerate the racemisation rate of (S)-1-phenylethyl when using Zr grafted SBA-15 as racemisation catalyst [33]. Therefore, we also added acetophenone to the reaction mixture with the hope of improving the racemization rate and achieving higher ee. Contrary to our expectation, the conversion of 1-phenylethanol and ee of 1-phenylethyl acetate were nearly the same with or without acetophenone (Figure 8-3). In the presence of acetophenone, the racemization of (S)-1-phenylethyl was believed to be via the Meerwein-Ponndorf-Verley reduction/Oppenauer oxidation [33]. When Zr grafted SBA-15, a mesoporous material with large pore size (>50 Å), was used as catalyst, both acetophenone and 1-phenylethanol could be easily coordinated to the active zirconium center to form six-membered transition states which is necessary for MPVO reaction to occur. However, the pore size of Zr-beta (~7 Å) is too small to form six-membered transition state with both acetophenone and 1-phenylethyl coordinating to the active center. Therefore, the racmisation rate cannot be improved by adding acetophenone.

**8.2.3 Effect of solvents**

The solvent is an important parameter not only because of its influence on the lipase-catalyzed transesterification, but also because of its effect on the racemization rate. Therefore, the solvent effect on DKR of 1-phenylethanol was studied. As shown in Table 8-2, the non-polar solvent toluene was found to be the best among all the solvents studied. An ee value of 83.1% at 93.1% conversion was achieved after 48 hours. The performance of n-hexane was inferior only to toluene. 84.3% conversion and 81.6% ee was obtained after same reaction time. High ee was obtained in 1,4-dioxane and isopropyl ether solution. However, the conversion and yield were low due to the slow racemization rate.
The polar solvent acetonitrile gave the poorest result. The yield of 1-phenylethyl acetate was only 46.4% after 48 hours. Careful examination of the reaction process indicates that the catalytic activity of Zr-beta for the racemization reaction was completely inhibited by acetonitrile, and acetophenone was found to be the main by-product. Based on these results, toluene was finally chosen as the solvent for further studies.

### 8.2.4 Effect of temperature

The temperature is another important parameter which needs to be considered when performing a DKR. The racemization is usually faster at increased temperatures. However, the enzymes may undergo denaturation at high temperatures. Moreover, more side reactions may occur at elevated temperatures. To find the optimum reaction temperature for Zr-beta and enzyme CALB catalyzed DKR of 1-phenylethanol, the temperature effect was studied in the temperature range from 50 °C to 80 °C.

As can be seen in Table 8-3, at 50 °C the reaction preceded slowly, even after 48 hours, the conversion of 1-phenylethanol was less than 90%. Increasing reaction temperature led to higher reaction rate. The fastest rate was obtained at 80 °C. At this temperature, more than 95% of 1-phenylethanol was converted after 24 hours. Unfortunately, the \( ee \) of 1-phenylethanol acetate decreased to 75%.

Interestingly, a linear relationship was found to exist between the \( ee \) of (R)-1-phenylethanol acetate and the conversion 1-phenylethanol if we plot \( ee \) against conversion (Figure. 8-4). The lines at 50 °C, 60 °C, and 70 °C were nearly parallel while the slope of the line at 80 °C was a little steeper. Below 70 °C, the drop of \( ee \) was considered due to the Zr-beta catalyzed racemization of 1-phenylethanol acetate. At 80 °C,
a decrease of the enantioselectivity of the enzyme may also contribute to the dropping of $ee$. 60 ºC was found to be the optical reaction temperature in our reaction system.

### 8.2.5 Re-use of Zr-beta catalyst

Re-use of Zr-beta and enzyme Novozym 435 was found to be possible. After a first reaction cycle, the catalyst mixture was isolated from the reaction mixture by filtration and Zr-beta and Novozym 435 were manually separated. Zr-beta was reactivated by calcination at 500 ºC. The enzyme was recovered by washing with toluene for several times to remove residual substrate of the previous run as well as some attached fine Zr-beta particles. The enzyme was then dried under vaccum. Certain loss of activity was observed for the reused Zr-beta and Novozym 435, which can be seen in Figure 8-5. Fortunately, the conversion only dropped from 93.1% for fresh catalysts to 87.7% for reused catalysts after 48 hours. The $ee$ value of 1-phenylethyl acetate was also lower for reused catalysts after same reaction time. However, the $ee$ of 1-phenylethyl acetate was nearly same under both cases if we compare this value at same conversion level.

### 8.2.6 DKR of some other secondary alcohols

The combination of Zr-beta and Novozym 435 catalysis was also used to resolve several other secondary alcohols by using toluene as solvent at 60 ºC. The results are summarized in Table 8-4. In all cases, the corresponding (R)-acetates were the main enantiomers. 1-Cyclohexylethanol gave poor results in terms of conversion and $ee$. After 48 hours, 84 % of 1-cyclohexylethanol was transformed with an $ee$ value of 60 %. The main by-product was 1-cyclohexylethanone. 1-$p$-Tolylethanol reacted very fast; more than 98 % conversion was achieved after 6 hours and a moderate $ee$ value, 76 %, was obtained. The high conversion rate may be due to the electron donating effect of the
methyl group on the para position of aromatic ring. For 1-(4-chlorophenyl)ethanol, the reaction rate was a little higher than with 1-phenylethanol, but the ee was very low, only 46.3%. The electron withdrawing effect of the chloride group may contribute to the racemization of the acylated product.
8.3 Conclusions

Several metal-substituted beta zeolites were studied as heterogeneous racemization catalyst. Zr-beta was found to be the best for (S)-1-phenylethanol racemization. The racemization activity of Zr-beta was only slightly affected by acetic acid and isopropenyl acetate, while pyridine completely inhibited the activity of Zr-beta. Zirconium atoms in the framework of Zr-beta were considered to be the active racemization sites.

The coupling of the Zr-beta catalyzed racemization with the enzyme catalyzed resolution of 1-phenylethanol was possible in one pot. Under optimized conditions, more than 93% conversion with an $ee$ value of 83% was achieved at 60 ºC with toluene as solvent. While the $ee$ value is not yet fully satisfactory, the outcomes demonstrate the validity of the concept of a one-pot dynamic resolution over a cheap and robust racemising agent.
References


Table 8-1. Racemization of (S)-1-phenylethanol in toluene.

\[
\begin{align*}
\text{Entry} & \quad \text{Catalyst} & \quad \text{Si/Me} & \quad \text{Time (h)} & \quad \text{Yield (%)}^a & \quad \text{ee (%)}^b \\
1 & \text{Al-beta} & 100 & 2 & 58 & 1 \\
2 & \text{Sn-beta} & 125 & 6 & 99 & 95 \\
3 & \text{Ti-beta} & 100 & 6 & 88 & 22 \\
4 & \text{Zr-beta} & 107 & 6 & 72 & 5 \\
5 & \text{Zr-beta}^c & 107 & 6 & 75 & 8 \\
6 & \text{Zr-beta}^d & 107 & 6 & 78 & 21 \\
7 & \text{Zr-beta}^e & 107 & 6 & 99 & >99 \\
8 & \text{Zr-beta}^f & 107 & 6 & 95 & 59 \\
\end{align*}
\]

Reaction conditions: 0.25 mmol (S)-1-phenylethanol (ee>99.5%), 5 ml toluene, 60 ºC, 100 mg catalyst.  
\(^a\) Yield of racemic phenylethanol.  
\(^b\) \text{ee} of (S)-1-phenylethanol, determined by chiral GC,  
\(^c\) Addition of 0.25 mmol acetic acid.  
\(^d\) Addition of 0.25 mmol isopropenyl acetate.  
\(^e\) Addition of 0.25 mmol pyridine.  
\(^f\) Addition of 0.5 mmol water.
Table 8-2. Effect of solvents on the DKR of 1-phenylethanol.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent</th>
<th>Time (h)</th>
<th>Conv. (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Yield (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>ee (%)&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
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<tbody>
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<td></td>
<td>48</td>
<td>93.2</td>
<td>82.1</td>
<td>83.1</td>
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<td></td>
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<td>53.3</td>
<td>97.0</td>
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<td>48</td>
<td>63.7</td>
<td>46.4</td>
<td>&gt;99.5</td>
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Reaction conditions: 1 mmol racemic 1-phenylethanol, 5 ml solvent, 60 °C, 48 h, 30 mg Novozym 435, 400 mg Zr-beta (Si/Zr=107).<sup>a</sup> Conversion of racemic 1-phenylethanol. Yield of racemic 1-phenylethyl acetate,<sup>c</sup> ee of (R)-1-phenylethyl acetate.
Table 8-3. Effect of temperature on the DKR of 1-phenylethanol.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Temperature(ºC)</th>
<th>Time (h)</th>
<th>Conv. (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Yield (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>ee (%)&lt;sup&gt;c&lt;/sup&gt;</th>
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<td>24</td>
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<td>74.9</td>
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</table>

Reaction conditions: 1 mmol racemic 1-phenylethanol, 5 ml toluene, 30mg Novozym 435, 400 mg Zr-beta (Si/Zr=107). <sup>a</sup> Conversion of racemic 1-phenylthanol. <sup>b</sup> Yield of racemic 1-phenylethyl acetate, <sup>c</sup> ee of (R)-1-phenylethyl acetate.
Table 8-4. DKR of several other secondary alcohols.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Time</th>
<th>Conv. (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Yield (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>ee (%)&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
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<td>61.6</td>
<td>59.9</td>
<td>81.8</td>
</tr>
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<td>83.7</td>
<td>74.9</td>
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<td>48</td>
<td>96.5</td>
<td>85.3</td>
<td>46.3</td>
</tr>
</tbody>
</table>

Reaction conditions: 1 mmol substrate, 5 ml toluene, 60 ºC, 30mg Novozym 435, 400 mg Zr-beta (Si/Zr=107). <sup>a</sup> Conversion of substrate. <sup>b</sup> Yield of corresponding ester, <sup>c</sup> ee of corresponding (R)-acetate.
Scheme 8-1. Kinetic resolution of a secondary alcohol.

Scheme 8-2. Dynamic kinetic resolution of a racemic compound.
Scheme 8-3. Proposed mechanism for the racemization of (S)-1-phenylethanol over zeolite Zr-beta.

Scheme 8-4. Expected pathway for DKR of 1-phenylethanol.
Figure 8-1. Gas chromatograms of reaction mixture (a) after 1 hour and (b) after 48 hours. Column: a Supelco Beta Dex 325 chiral capillary column (250 µm x 0.25 µm x 25m); Oven temperature: 90 ºC (hold 2 min) to 200 ºC at 10 ºC /min; Carrier gas: Helium; Detector: FID detector.
Figure 8-2. Dynamic kinetic resolution of 1-phenylethanol in one pot. (♦) Conversion of 1-phenylethanol, (■) selectivity to 1-phenylethyl acetate, (▲) selectivity to styrene, and (○) ee of (R)-1-phenylethyl acetate. Reaction conditions: 1 mmol racemic 1-phenylethanol, 2 mmol isopropenyl acetate, 30 mg Novozym 435, 400 mg Zr-beta (Si/Zr=107), 5 ml toluene, 60 °C.
Figure 8-3. Influence of acetophenone on the DKR of 1-phenylethanol. (○) Conversion of 1-phenylethanol and (●) ee of 1-phenylethyl acetate without adding acetophenone. (■) Conversion of 1-phenylethanol and (□) ee of (R)-1-phenylethyl acetate with adding acetophenone. Reaction conditions: 1 mmol racemic 1-phenylethanol, 2 mmol isopropenyl acetate, 30 mg Novozym 435, 400 mg Zr-beta (Si/Zr=107), 5 ml toluene, 60 °C.
Figure 8-4. DKR of 1-phenylethanol at different temperatures: (●) 50 ºC, (▲) 60 ºC, (■) 70 ºC, and (♦) 80 ºC. Reaction conditions: 1 mmol racemic 1-phenylethanol, 2 mmol isopropenyl acetate, 5 ml toluene, 30 mg Novozym 435, 400 mg Zr-beta (Si/Zr=107).
Figure 8-5. Reuse of Zr-beta on the DKR of 1-phenylethanol. (■) Conversion of 1-phenylethanol and (□) ee of (R)-1-phenylethyl acetate over fresh Zr-beta. (●) Conversion of 1-phenylethanol and (○) ee of (R)-1-phenylethyl acetate over reused Zr-beta. Reaction conditions: 1 mmol racemic 1-phenylethanol, 2 mmol isopropenyl acetate, 5 ml toluene, 60 °C, 30mg Novozym 435, 400 mg Zr-beta (Si/Zr=107).