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Kinetic isotope effects and mechanism of biomimetic oxidation of methane and benzene on FeZSM-5 zeolite

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Abstract

Earlier, iron complexes stabilized in a ZSM-5 zeolite matrix have been shown to produce a new form of surface oxygen (called α-oxygen) upon decomposition of N_2O. α-Oxygen exhibits a very high reactivity typical for oxygen of mono-oxygenases (MO) and mimics its unique ability in selective oxidation of hydrocarbons at room temperature. Kinetic isotope effect (KIE) measurements reported here reveal additional similarities between MO and the model. Depending on the temperature, the value of KIE for oxidation of methane with α-oxygen ranges from 1.9 to 5.5. For the oxidation of benzene the value of KIE is 1.0. This indicates that both biological and chemical oxidation of methane involves a rate limiting C–H bond cleavage, whereas the reaction with benzene is probably limited by the formation of an epoxy-type intermediate. The assumed structure of the active sites as well as some features of the oxidation mechanism allow one to consider FeZSM-5–N_2O system as a new and successful model for methane monooxygenase.

Keywords: FeZSM-5; Oxidation of methane to methanol; Oxidation of benzene to phenol; Kinetic isotope effect; Biomimetic oxidation; Nitrous oxide

1. Introduction

Enzyme monooxygenases (MO) are capable of effecting selective oxygenation of a variety of hydrocarbons under ambient conditions. This ability is attributed to a unique activation of oxygen performed by Fe-containing centers of MO. Reactivity of oxygen atoms coordinated to these centers is so high that they can easily insert into non-activated C–H bonds of organic molecules [1,2].

Significant efforts are being directed towards creation of biomimetic systems capable of generating oxygen species similar in reactivity to the oxygen of MO. Along with O_2 a number of other oxygen sources are being used including peroxides, peracids and iodosylbenzene. One of the major accomplishments in this field are the catalytic systems which mimick cytochrome P-450 in olefin epoxidation [3]. Success in the

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oxidation of alkanes is much more modest, though some models mimicking MO activity in these reactions, including metal-containing zeolites, have been suggested [4–6]. Modeling of methane monooxygenases (MMO) is even more challenging. Active centers of MMO, incorporating two iron atoms, are capable of generating oxygen species active enough to oxidize methane to methanol at room temperature [7,8].

Efforts to create biomimetic systems capable of low temperature oxidation of methane to methanol have been futile for a long time. A considerable progress was achieved during the last years. In 1994, this reaction was performed with a substantial selectivity at temperature as low as 250–300°C over $FePO_4$ [9]. Recently, we reported chemical oxidation of methane to methanol at room temperature using iron complexes stabilized in a ZSM-5 matrix [10,11]. These complexes, which we called α-sites, give rise to a new form of surface oxygen that is being formed upon decomposition of nitrous oxide [12–14]:

$$N_2O + (\ )_\alpha = N_2 + (O)_\alpha \quad (1)$$

The reactivity of this α-oxygen is so high that it reacts even with methane at room temperature giving quantitative yield of methanol [10,11]:

$$CH_4 + (O)_\alpha = (CH_3OH)_\alpha \quad (2)$$

This allows one to consider iron complexes in a zeolite matrix as a successful biomimetic model imitating a unique ability of MMO to generate highly active oxygen species.

In this paper we report results of a kinetic isotope effect study of α-oxygen oxidation of methane and benzene, which reveals further mechanistic similarity of the model and MMO.

2. Experimental

The FeZSM-5 zeolite ($SiO_2/Al_2O_3 = 72$; 0.56 wt% Fe) studied in this work was prepared by hydrothermal synthesis with the introduction of iron in the form of $FeCl_3$ to the starting gel [15]. The zeolite was converted into the H-form by an exchange with an ammonia buffer and subsequent air calcination at 550°C. XRD crystallinity of the sample was over 95%, and specific surface area was 400 m^2/g. To increase the concentration of α-sites, air calcination was followed by activation in vacuum at 900°C for 1 h [16], and finally by treatment with O_2 (0.8 Torr) at 550°C.

N_2O decomposition and oxidation of methane and benzene were carried out in a static unit connected to a mass-spectrometer for analysis of the gas phase. A catalyst sample (0.5 g, particle size 0.5–1.0 mm) was loaded into the microreactor, with an isolated volume (5 cm^3) which was negligible compared to total reaction volume of the unit (620 cm^3). The use of such microreactor significantly enhances the accuracy of adsorption and kinetic measurements [17]. Before every experiment the sample was pretreated consecutively in vacuum and in oxygen (0.8 Torr) at 550°C.

The experiments were carried out in the following sequence:

1. loading of the zeolite surface with α-oxygen;
2. interaction of α-oxygen with methane or benzene;
3. extraction of the product;
4. chemical and isotopic analysis of the product.

α-Oxygen was loaded by N_2O decomposition according to Eq. (1) at 250°C and initial pressure of 0.8 Torr as described elsewhere [11,12]. The amount of α-oxygen was calculated to be 2.2×10^{19} O atoms/g based on both the amount of N_2 formed (equivalent to N_2O consumed) and results of isotope exchange with $^{18}O_2$. After loading of α-oxygen the microreactor was isolated, cooled to the desired temperature of the reaction, and the gas phase in the reaction volume was replaced with methane or benzene.

Intramolecular KIE for the interaction of methane with α-oxygen was studied using dideuteriomethane CH_2D_2. Oxidation of CH_2D_2 was carried out with an initial pressure of 0.6 Torr and at temperatures from -50 to $+100$°C.

The product methanol was extracted from the surface of the sample using 2 ml of 1:1 mixture of CD_3CN and D_2O for 15 min. The KIE value was calculated from the intensities of ^1H NMR signals at $\delta_1 = 3.30$ ppm and $\delta_2 = 3.32$ ppm (Bruker MSL 400), attributed to the protons in CHD_2OD and CH_2DOD molecules, respectively.

KIE for the oxidation of benzene was measured using 1,3,5-d_3 benzene (Aldrich, 98%). The reaction with α-oxygen was carried out at 25°C and an initial pressure of 15 Torr. The sample was then taken out of the reactor and extracted with 2 ml of 1:1 solution of CD_3OD and D_2O. The isotopic composition of the product phenol was determined using NMR and GC/MS methods.

3. Results

3.1. Oxidation of methane by α-oxygen

Frequently, KIE value is determined by an intermolecular method based on measurements of rate constants for H- and D-substrates. In our case, this method could not be used because the reaction of methane with α-oxygen occurred with an immeasurably high rate. At 25°C the reaction rate value exceeds 6×10^{17} molecules of $CH_4/g \cdot s$ and was limited by the diffusion of methane in the micropore space of the zeolite. Special experiments which is described in detail elsewhere [18] show that methane pressure must be reduced by two orders of magnitude and the temperature decreased down to -50°C to drive the reaction into the kinetic region

The most accurate values for KIE can be obtained using an intramolecular method when the isotope effect is being determined by the competition of C–H and C–D bonds within one molecule. For example, relatively low intermolecular KIE values ($k_H/k_D < 2$) are observed for hydroxylation by cytochrome P-450 [19]. In contrast, when the measurements are made for intramolecular KIE these values reach 7–14 [20]. Similar distinctions are also observed in the case of MMO oxidation. The values of intermolecular KIE for oxidation of *trans*-2-phenylmethylcyclopropane and cyclohexane are 1.0 [21] and 0.9 [22], respectively, whereas the value of intramolecular KIE was measured to be 5.1 for *trans*-2-phenylmethylcyclopropane [21], 4.2 for ethane [23] and equal or greater than 5.5 for norbornene [22]. In the case of methane oxidation by α-oxygen, using the intramolecular method enables one to avoid the influence of diffusion and thus to study KIE over a wide range of temperatures.

The oxidation of dideutero methane CH_2D_2 used in these experiments leads to two types of

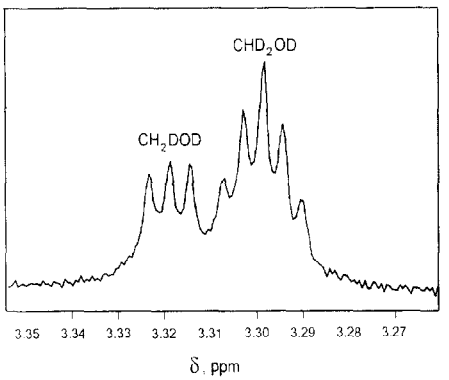


Fig. 1. Spectrum of methanol extracted after reaction of CH_2D_2 with α-oxygen at -10°C.

Table 1
Intramolecular KIE for oxidation of CH_2D_2 by α-oxygen (^1H NMR method)

Exp. #	T (°C)	CHD_2OD		CH_2DOD		KIE
		δ_1 (ppm)	I_1 (rel.units)	δ_2 (ppm)	I_2 (rel. units)	$I_1/2I_2$
1	100	3.3	56	3.32	58	1.9
2	25		68		42	3.2
3	−10		40		20	4.0
4 [a]	−10		63		33	3.8
5	−50		63		23	5.5

[a] In this experiment before extraction the sample was heated to 100°C and kept at this temperature for 30 min.

Table 2
Intramolecular KIE for oxidation of $C_6H_3D_3$ by α-oxygen (^1H NMR method)

Exp. #	$C_6H_2D_3OD$		$C_6H_3D_2OD$				KIE
	δ_1 (ppm)	I_1 (rel. units)	δ_2 (ppm)	I_2 (rel. units)	δ_3 (ppm)	I_3 (rel. units)	I_1/I_3
1	7.34	25	7.0	15	6.94	24	1.0
2	7.34	35	7.0	18	6.94	33	1.0

deuterated molecules of methanol (CHD_2OD and CH_2DOD) depending on which bond C–H or C–D participates in oxygen insertion. Fig. 1 shows an example of an NMR spectrum recorded for the product of CH_2D_2 reaction with α-oxygen at -10°C. The values of KIE calculated from the relative concentrations of CHD_2OD and CH_2DOD methanol molecules determined from the NMR spectra are given in Table 1. This Table shows that KIE for methane oxidation increases from 1.9 to 5.5 with the temperature decrease from $+100$°C to -50°C.

To verify these results and to confirm that H–D exchange exerts no influence on the KIE measurements, the following control experiment was carried out. After the reaction of CH_2D_2 with α-oxygen at -10°C, the sample was heated up to 100°C in an atmosphere of unreacted methane and was held under these conditions for 30 minutes. Mass-spectrometric analysis of methane in the gas phase revealed that there was no isotopic scrambling and the NMR spectrum of the product methanol turned out to be identical to the one shown in Fig. 1 for the standard experimental procedure.

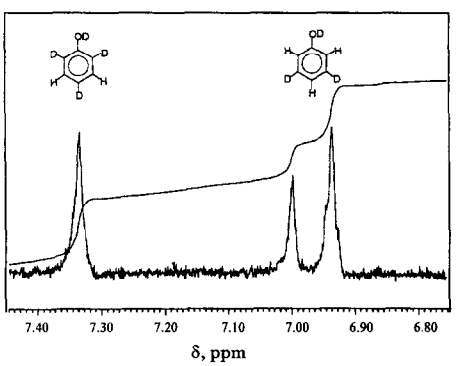


Fig. 2. Spectrum of phenol extracted after reaction of $C_6H_3D_3$ with α-oxygen at 25°C.

3.2. Oxidation of benzene by α-oxygen

In order to exclude diffusion-related complications, KIE for benzene was also measured by intramolecular method using 1,3,5-d_3-benzene. In this case benzene hydroxylation gives rise to the following deuterated homologs of phenol:

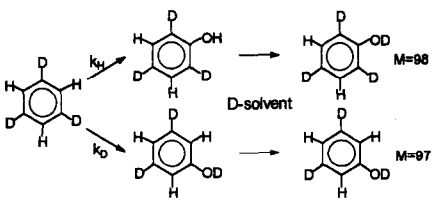


Fig. 2 shows NMR spectrum of phenol obtained in the reaction of $C_6H_3D_3$ with α-oxygen at 25°C. The value of KIE was calculated using signal intensities at $\delta_1 = 7.34$ and $\delta_2 = 6.94$ ppm assigned to protons in $C_6H_2D_3OD$ and $C_6H_3D_2OD$ molecules. As Table 2 shows, intramolecular KIE in the oxidation of benzene is close to unity. GC/MS analysis produced the same result. In the latter case KIE was determined from the relative intensities of peaks with m/e 98 and 97, which are proportional to concentrations of $C_6H_2D_3OD$ and $C_6H_3D_2OD$, respectively.

In summary, contrary to methane, there is no kinetic isotope effect in the case of benzene oxidation by α-oxygen.

4. Discussion

Experimental results for methane oxidation clearly show that with respect to reactivity and chemical properties, α-oxygen is similar to the active oxygen of methane monooxygenase. A characteristic feature of methane oxidation by MMO is relatively high KIE values. KIE were found to vary from 5 [24] to 11.8 [25]. Unusually large isotope effects (50–100) were observed for interaction of methane with the active intermediate of MMO (compound Q), where, most likely, there is a significant hydrogen tunneling [26]. Large KIE values indicate that the limiting step in oxidation of methane by MMO involves breaking of a C–H bond. The same conclusion can be made for CH_4 oxidation by α-oxygen which also has a large value of KIE.

In contrast to MMO, the system under study is thermally stable and allows one to perform reliable and reproducible experiments over a wide range of temperatures. Based on the data in Table 1, Fig. 3 shows temperature dependence of KIE plotted in the Arrhenius coordinates. This dependence is well described by a linear function whose inclination gives a difference between H and D activation energies equal to 5.0 ± 0.5 kJ/mol. This value is in a good agreement with the zero-point energy difference for C–H and C–D bonds, indicating little if any contribution of tunneling in methane oxidation by α-oxygen. Calculation of pre-exponential factor may be also used to decide on tunneling occurrence. But since the reaction rate is limited by diffusion this way is not valid in our case.

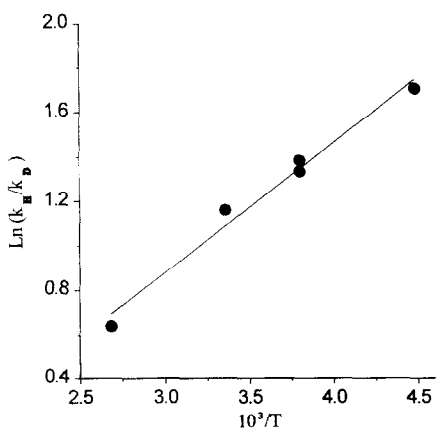


Fig. 3. Plot of intramolecular KIE for methane oxidation by α-oxygen.

An important feature of MMO compared to other monooxygenases is the binuclear structure of its active center. Our studies of the state of active iron in ZSM-5 matrix indicate that α-sites probably also have binuclear nature. One such indication is an excellent coincidence of Moessbauer spectra parameters of Fe in MMO and in ZSM-5 zeolite [11,27]. Recent quantum-mechanical calculations [28] also show that oxidation of CH_4 on FeZSM-5 surface apparently involves binuclear complexes in which Fe atoms are linked by (μ-oxo-) and (μ-hydroxo-) bridges. According to these calculations, such complexes can bind an oxygen atom from N_2O, and the resulting feroxo-complexes have high reactivity towards methane.

The current widely accepted mechanism of alkane hydroxylation by MMO [29] is mostly based on an analogy to the mechanism for cytochrome P-450. It is assumed that the interaction of an active feroxo-intermediate with alkanes follows an elimination-recombination scheme. However, direct insertion of an O atom into a C–H bond via pentacoordinated carbon intermediate is also contemplated [30]. The exact nature of the intermediates and details of the reaction mechanism are still not entirely clear and chemical mimicking monooxygenases can play an important role in resolving these problems.

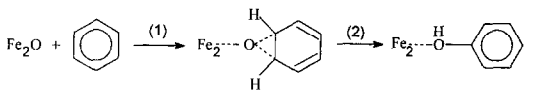
Along with the noted similarities between methane oxidation with participation of MMO and FeZSM-5, there are some differences, e.g. the lack of tunneling and lower values for KIE in the case of FeZSM-5. Despite these differences, we assume that the nature of the active sites and the reaction mechanism for both the enzyme and our inorganic model should have many similarities. The oxygen atom in the active center of FeZSM-5 can be stabilized between two atoms of iron in much the same way

as in the bis-μ-oxodiiron in the active intermediate suggested for MMO [31]. Recently, proof has been found for the existence of such intermediates in model chemical systems [32]. A redox equilibrium between Fe(IV) bis-μ-oxo and Fe(III) oxenic forms is possible for such an intermediate:

The differences observed between the enzyme and FeZSM-5 can be attributed to a softer ligand (imidazol) environment around Fe in MMO. This leads to stabilization of Fe(IV) and to shifting of the equilibrium to the left. In the case of a harder ligand environment of FeZSM-5, stabilization of Fe(IV) is not favored and the equilibrium is shifted toward the more reactive oxenic form. Different hydrophobicity of the environment can also play a role. In any case, the mechanism of methane oxidation by α-oxygen on iron complexes in ZSM-5 zeolites shows this system to be a successful functional model for active feroxo-intermediates effecting alkane hydroxylation in the MMO catalytic cycle.

It would be interesting to find out if the monooxygenase analogy holds for other reactions of α-oxygen, and for benzene oxidation in particular. It is known that for hydroxylation of aromatic compounds by cytochrome P-450 the observed KIE in most cases is close to unity [33]. A similar result has been obtained recently for oxidation of benzene by MMO [21]. For cytochrome P-450 the reaction was shown to proceed via initial formation of unstable areneoxides, which spontaneously isomerize into phenolic products [34,35]. In a number of cases these intermediates have been isolated. It is noteworthy that formation of such intermediates should have no isotope effect since there is no C–H bond breaking involved [33].

Similar to monooxygenases, oxidation of benzene by α-oxygen does not exhibit any KIE, which leads one to believe that the reaction on the FeZSM-5 zeolite surface follows a similar mechanism. This mechanism includes epoxidation of the aromatic ring with the formation of the adsorbed product:



The lack of KIE indicates that step (2) involving the breaking of the C–H bond should be fast, whereas step (1) is the rate limiting.

In summary, α-oxygen on the surface of FeZSM-5 zeolite is capable of selective hydroxylation of methane and benzene. The high reactivity of α-oxygen, the nature of the formed products and probable mechanisms of the oxidation reactions allow one to conclude that the chemistry of α-oxygen bears striking resemblance with that of the active oxygen of monooxygenases. This opens new possibilities for understanding the mechanism of biological oxidation and in the creation of new and efficient biomimetic systems.

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