Studies on Catalytic Aerobic Oxidation of Organic Molecules:
Development in Activation of Molecular Oxygen and Substrates

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2011
Preface

Chemical industry is essentially built on transformations of hydrocarbon-based feedstocks derived from petroleum, natural gas, coals, biomass, etc into high-value added products. Within the broad domain of organic molecule, oxygenated products such as alcohols, aldehydes, carboxylic acids, and epoxides are often used as essential building blocks in nearly all branches of industrial chemistry, ranging from polymer synthesis to medicinal chemistry. In this context, oxidation chemistry handling incorporation of oxygen into hydrocarbon and subsequent oxidative conversions, has performed a crucial function and role in industrial chemistry from the last century to today.

In most oxidation processes, an oxidizing agent plays a significant role because the efficiency and selectivity strongly depend on the choice of oxidant. Conventionally, a variety of oxidizing agent such as K$_2$Cr$_2$O$_7$, pyridinium chlorochromate and HNO$_3$ have been used for selective oxidations. Such oxidants, however, not only are toxic, corrosive, and expensive, but also yield equimolar amounts of environmentally-unfriendly wastes. Hydroperoxides such as cumenehydroperoxide and t-butylhydroperoxide are used in the field of epoxidation as less harmful oxidants due to production of alcohols as byproducts. Utilizing H$_2$O$_2$ as an oxidant is much more environmentally-benign process because it only produces water. But the use of these peroxide species inherently involves a risk of explosion. Moreover, a general problem of the aforementioned oxidants is that they are all manufactured via the oxidation of a precursor with oxygen. Ultimately, therefore, it is always O$_2$, which takes up the stoichiometric number of electrons. Utilizing molecular oxygen as a sole oxidant would, in contrast, not only reduce the cost but also eliminate many environmental problems, which also meets the criterion from the viewpoint of green chemistry. However, the perspective of the use of molecular oxygen as an oxidant is not still satisfactory and realizing the effective use of molecular oxygen is even now challenging. The main reason may be that the reactions between molecular oxygen and hydrocarbons are usually very slow due to the fact that they are spin forbidden, or that nonselective radical oxidation often proceeds by reduced active oxygen species. Therefore, appropriate activation of molecular oxygen using a catalyst and successful inhibition of the nonselective radical oxidation are required for efficient aerobic oxidation.
Generally speaking, chemical transformation processes including oxidation consist of two different styles, homogeneous and heterogeneous systems. In homogeneous systems, relatively small molecules such as transition metal complexes, polyoxometalates, and organic compounds which can be dissolved in the reaction medium have been employed as catalysts. Among them, transition metal complexes have been most commonly used due to the variety of choices for metal element and the flexibility of molecular design to dictate the catalytic performance. Unfortunately, molecular catalysts, however, essentially have difficulty in separation of the catalyst from the reaction medium containing products. Moreover, high temperature is not permitted owing to solvent evaporation and thermal stability of catalysts. In heterogeneous systems, on the other hand, insoluble materials such as metal oxides, zeolites, and highly dispersed transition metals on support have been used as catalysts. These materials have practical advantages of not only separability and thermal stability but also reusability. But they have some disadvantages like difficulty in detailed structural design and construction of an active site and in elucidation of reaction mechanism of the catalysis. To develop more effective catalyst, it is significant to appropriately modify the structure of the catalyst and/or to understand the catalytic cycle in detail in both of homogeneous and heterogeneous systems.

In this context, the author developed two type of catalytic aerobic oxidation systems in the present study; homogeneous one using Fe(II) complexes and heterogeneous one based on Nb$_2$O$_5$ photocatalyst. In the former, activation of molecular oxygen was investigated from the viewpoints of electronic structure and coordination environment of Fe(II) center of the complex, so that aerobic oxidation of hydrocarbons without any reductant is established. Fine tuning of the electronic structures of the Fe(II) complexes and the effect on the catalytic activity were also studied. In the latter, enhancement in the photocatalytic activity and the selectivity was performed by the consideration of the kinetic aspect and by inhibition of the formation of active oxygen species, respectively. Furthermore, a comprehensive photoactivation mechanism in the photocatalysis of Nb$_2$O$_5$ was proposed and discussed in detail.

The studies presented in this thesis were performed at Department of Molecular Engineering, Graduate School of Engineering, Kyoto University from 2006 to 2011 under the supervision of Professor Tsunehiro Tanaka. The author wishes to express his sincere gratitude to Professor
Tsunehiro Tanaka for his exact guidance, fruitful discussions, insightful suggestions and valuable comments, throughout this study. The author makes grateful acknowledgements to Professor Tetsuya Shishido for his instructive discussions, warmhearted advices, and continual encouragement. The author’s heartfelt appreciation goes to Professor Yutaka Hitomi at Doshisha University for his precise insight, beneficial suggestions, and helpful supports. The author thanks sincerely from his heart to Lecturer Kentaro Teramura for his valuable suggestions, informative advice, and cheerful messages. Special thanks are made to Professor Sakae Takenaka at Kyushu University for his helpful guidance and kind supports, especially in the measurement of XAFS. The author is deeply grateful to Professor Hiromi Yamashita at Osaka University and Professor Hisao Yoshida at Nagoya University for their fruitful suggestions and kind encouragement. A lot of thanks are dedicated to Dr. Seiji Yamazoe at Ryukoku University, Dr. Junya Ohyama at Nagoya University, and Mr. Toshiaki Miyatake, who were seniors of the laboratory the author belongs to, for their helpful discussions and advices. The author is grateful to Dr. Saburo Hosokawa, Professor Kenji Wada, and Professor Masashi Inoue for their aid in the measuring of X-ray photoelectron spectra. The author shows gratitude to the staffs of Photon Factory at KEK in Ibaraki Prefecture and Spring-8 in Hyogo Prefecture for their technical supports in XAFS measurement. In addition, a great acknowledgement should be shown to JSPS for a grant that made it possible to develop this study.

The author is indebted to Mses. Ayaka Tamura and Manami Satani and Messrs. Daisuke Tsukio and Yasuhiro Ohno for their collaborations and discussions on the studies of the selective photocatalytic oxidation based on Nb$_2$O$_5$ described in Part II. The author owes an important debt to Secretary Ms. Ayako Tanaka for her kind official support. The author is grateful to all the members of the group of catalysis research led by Professor Tanaka.

Finally, the author sincerely thanks his parents Taizo and Kayo for their understanding and cheering. The author also would like to express his deepest appreciation to his wife Yuko for her enduring supports, cheerful encouragement, and complete confidence.

Shinya Furukawa

Kyoto,

October, 2011
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Part I

Homogeneous Oxidation Using
Mononuclear Non-Heme Fe(II) Complexes
**Introduction of Part I**

In nature, a variety of oxidation processes using molecular oxygen such as, hydroxylation of hydrocarbons\(^1\), oxidative cleavage of aromatic rings\(^2,3\), or DNA chains\(^2,4\) are performed under mild conditions by iron-containing enzymes or natural products. For instance, Rieske oxygenases and catechol dioxygenases\(^2\), which are mononuclear non-heme iron enzymes, catalyze hydroxylation of several substrates and oxidative cleavage of catechol aromatic rings in metabolic routes, respectively. A natural enzyme, however, generally has a huge molecular weight and can function only in aqueous conditions, which are bottlenecks in view of industrial application or fundamental research. Therefore, a lot of functional model complexes consisted of metal centers and tailor-made ligands which are soluble in organic solvent have been synthesized and investigated in this context\(^3,5,6\). For example, mononuclear iron complex bearing a tripodal N\(_4\) ligand TPA (Tris(pyrid-2-ylmethyl)amine) and a catecholate is known to be a good functional model of the catechol dioxygenase\(^7,8\). Among the researches based on model complexes, much attention has been focused on how to activate molecular oxygen or how to control the reactivity of active species.

**Activation of Molecular Oxygen**

Generally, molecular oxygen is reductively activated by a ferrous ion to generate superoxide and ferric ion or to form an Fe(III)-superoxo adduct, whereas a ferric ion does not react with molecular oxygen. In the system of an extradiol catechol dioxygenase, the resulting Fe(III)-superoxo species attacks the chelating catecholate followed by oxidative cleavage\(^2\). In other systems, the Fe(III)-superoxo species is further transformed into Fe(III)-hydroperoxo, Fe(III)-\(\mu\)-peroxo dimer, or Fe(IV)-oxo species in a stepwise manner as shown scheme 1\(^5,9,10\). High-valent oxo-iron species act as electrophilic oxidants and are active for O-transfer reaction such as sulfoxidation\(^9\) or olefin epoxidation\(^11\). To be active for the reduction of molecular oxygen, iron centers of the most enzymes and model complexes in the resting-state are indeed in ferrous state\(^2\). Cytochrome P450\(^1\) and intradiol catechol dioxygenase\(^2\) have ferric iron centers in their resting-states. But in the former case, the ferric ion is reduced when substrate comes close to the iron center because of increase in the redox potential of Fe(III)/Fe(II) couple caused by desorption of weakly coordinated water molecule.\(^1\)
In the latter case, the chelation of chatecholate to the ferric center provides an Fe(II)-semiquinonate character which allows to react with molecular oxygen.\textsuperscript{2,12,13} Reactivity of the model complex toward molecular oxygen has been systematically investigated in the light of electronic structure of the iron center. Fukuzumi et al. reported that the reduction potential of ferrous center was a key factor to activate molecular oxygen.\textsuperscript{14} Higuchi et al. studied the correlation between the reactivity and spin state of the iron center.\textsuperscript{12,13} A series of Fe(III)-catecholate complexes bearing TPA ligand with various substituents (MeO, H, Cl, NO\textsubscript{2}) they employed shows spin crossover phenomenon; the fraction of high-spin species increased with increase in electron-donating ability of the substituent group. In addition, the rate of reaction between the complex and molecular oxygen increased as the fraction of high-spin species increased. This result emphasizes a significance of spin state in the process of dioxygen activation by iron complex.

**Scheme 1.** Activation of molecular oxygen and formation of active oxygen complexes.

**Correlation between the Reactivity of Active Species and Its Electronic State**

The reactivity of an iron complex toward substrate also strongly depends on the electronic state of the active oxidizing species. High-valent oxo-iron species are active oxidizing species for not only O-transfer reaction but also H-abstraction reaction. Actually in cyclohexene oxidation by Fe(IV)-oxo porphyrinato complexes,\textsuperscript{15} catalytic activity and selectivity to O-transfer product (cyclohexene oxide) or H-abstraction product (2-cyclohexene-1-ol and 2-cyclohexene-1-one) vary
with electron density of the iron center; the more iron porphyrin was electron deficient, the more selectivity to cyclohexene oxide was obtained. The different selectivity of epoxidation versus allylic oxidation was explained by the preference of two-electron reduction process (epoxidation) over one-electron reduction process (allylic oxidation), depending the electronic nature of iron porphyrin complexes. Thus in heme iron systems, the effect of electronic state of iron complex on the reactivity has been deeply investigated. In non-heme iron systems, on the other hand, such studies have been limited. Que et al. synthesized several Fe(II)—TPA complexes having a variety of functional groups at pyridyl moieties of the TPA ligand, and investigated their electronic states and the catalytic activities in alkane hydroxylation.\textsuperscript{16} But, the positions of substituent groups they chose were mainly 5- and 6- position of pyridyl ring, which are close to the iron center. Therefore, involvement of steric effect of the substituent in the electronic states did not allow revealing a good correlation between their electronic states and catalytic activities.

**Survey of Part 1**

Although Fe(III)—TPA catecholate complexes conduct aerobic oxidative cleavage of catechol aromatic ring, this system does not respond to oxidation of other substrates. However, the activation of molecular oxygen and the formation of Fe(III)-superoxo species in this system implies the possibility of oxidation of other substrate such as hydrocarbon, if the chelating catecholate ligand is absent. In chapter 1, in this context, the author developed aerobic oxidation of hydrocarbons by using a series of high-spin Fe(II)—TPA complexes. The spin states of the Fe(II)—TPA complexes were controlled by modification of coordination environment such as counter anions and solvents. The author investigated the reaction mechanism of aerobic hydrocarbon oxidation by Fe(II)—TPA complexes and discussed the desired condition of the coordination environment.

In chapter 2, the author synthesized a series of mononuclear nonheme iron(II) complexes supported by TPA and its derivatives that have one to three nitro-groups at 4-position of the pyridine ligand, and evaluated the effect of the nitro-groups on the catalytic oxidation activity of these complexes. In this case, nitro-substitution at 4-position of the pyridine ligand seems to minimize the steric effect to the iron center and to enable a stepwise variation in the electronic state of the catalyst.
The spin crossover phenomenon observed with a series of Fe(III)–TPA catecholate complexes is counterintuitive in the light of coordination chemistry because introduction of electron-withdrawing groups generally makes high-spin state more favorable due to the weaker ligand field.\textsuperscript{17,18} But, an exact evaluation of the substitution effect was prevented by participation of spin crossover and a significant amount of Fe(II)-semiquinonate character of the Fe(III)-catecholate complex. In this context, it seems to be a promising approach to employ Fe(II)–TPA complex and its nitro derivatives which are predominantly in low-spin state. In chapter 3, the author investigated the effects of nitro-substitution to the Fe(II)–TPA complex on the electronic structure in more detail from both experimental and theoretical aspects.

References


Chapter 1

Aerobic Oxidation of Hydrocarbons by

High-Spin Fe(II)–TPA Complexes Without Any Reductant

Abstract

Fe(II)tris(2-pyridylmethyl)amine complexes, Fe(II)–TPA, having different co-existing anions, [Fe(TPA)(MeCN)2](ClO4)2 (1), [Fe(TPA)(MeCN)2](CF3SO3)2 (2) and [Fe(TPA)Cl2] (3), were prepared. Effective magnetic moments (evaluated by the Evans method) revealed that while 1–3 in acetone and 3 in acetonitrile (MeCN) have a high-spin Fe(II) ion at 298 K, the Fe(II) ions of 1 and 2 are in the low-spin state in MeCN. The aerobic oxidation of 1–3 was monitored by UV–Vis spectral changes in acetone or MeCN under air at 298 K. Only the high-spin Fe(II)–TPA complexes were oxidized with rate constants of $k_{obs} = 0.1–1.3$ h$^{-1}$, while 1 and 2 were stable in MeCN. The aerobic oxidation of 1 or 2 in acetone was greatly accelerated in the presence of pure, peroxide-free cyclohexene (1000 equiv.) and yielded a large amount of oxidized products; 2-cyclohexene-1-ol (A) and 2-cyclohexene-1-one (K) (A+K: 23940% yield based on Fe; A/K = 0.3), and cyclohexene oxide (810%). Besides cyclohexene, aerobic oxidation of norbornene, cyclooctene, ethylbenzene, and cumene proceeded in the presence of 1 in acetone at 348 K without any reductant. Essential factors in the reaction are high-spin Fe(II) ion and labile coordination sites, both of which are required to generate Fe(II)-superoxo species as active species for the H-atom abstraction of hydrocarbons.
Introduction

The catalytic oxidation of hydrocarbons such as alkanes, alkenes and aromatic compounds to oxygen-containing materials is one of the most important chemical transformations in industrial chemistry.\(^1\) For economic and environmental reasons, the use of dioxygen as sole oxidant is highly desirable.\(^2\) Since it reacts slowly with hydrocarbons owing to its triplet ground state, appropriate activation of dioxygen is required for efficient oxidation of hydrocarbons using dioxygen. In nature, such dioxygen activation is performed by iron- and/or copper-dependent enzymes such as cytochrome P450,\(^3\) methane monooxygenase,\(^4\) tyrosinase,\(^5\) dopamine \(\beta\)-monooxygenase\(^6\) and various types of mononuclear nonheme iron dioxygenases,\(^7\) where dioxygen is reductively activated via the Cu(I) or Fe(II) ion(s). It is noteworthy that a high-spin Fe(II) center activates dioxygen in heme and nonheme iron-dependent enzymes\(^8\) and model complexes.\(^9\)–\(^11\)

Previously, we reported that low spin Fe(III)–TPA catecholate complexes (TPA: tris(2-pyridylmethyl)amine, Figure 1) have a lower dioxygen reactivity than the high-spin species, even though the former has a much higher Fe(II)-semiquinolate character.\(^12\) This result motivated us to examine the spin-state dependency on the dioxygen activation ability of simple Fe(II)–TPA complexes. Diebold and Hagen reported that the spin state of the Fe(II)–TPA complex is different depending on its counter anions.\(^13\) Therefore, we prepared three Fe(II)–TPA complexes; [Fe(TPA)(MeCN)\(_2\)](ClO\(_4\))\(_2\) (1), [Fe(TPA)(MeCN)\(_2\)](CF\(_3\)SO\(_3\))\(_2\) (2) and [Fe(TPA)Cl\(_2\)] (3), and examined their spin states and dioxygen activation ability. We also examined the aerobic oxidation of hydrocarbons in the presence of the Fe(II)–TPA complexes.

![Figure 1. Structure of the tpa ligand.](image-url)
Experimental

Materials

The TPA ligand was synthesized according to published procedures. All other reagents and dehydrated solvents were purchased from commercial sources. All dehydrated solvents were deoxygenated by N₂ bubbling prior to use. Treatment of the TPA ligand with Fe(ClO₄)₂, Fe(OTf)₂ and FeCl₂ in MeCN gave the corresponding complexes 1–3 as crystalline solids in high yield.

\[
\text{[Fe(TPA)(MeCN)₂](ClO}_4\text{)₂ (1): ESI-MS calcd. (found): } m/z 193.6 (193.5) ([\text{Fe}^{II}(\text{TPA})(\text{MeCN})]^2+) \]

\[
\text{[Fe(TPA)(MeCN)₂](OTf)₂ (2): ESI-MS calcd. (found): } m/z 193.6 (193.5) ([\text{Fe}^{II}(\text{TPA})(\text{MeCN})]^2+) \]

\[
\text{[Fe(TPA)Cl₂ (3): ESI-MS calcd. (found): } m/z 381.1 (381.4) ([\text{Fe}^{II}(\text{TPA})\text{Cl}])^+) \]

Physical methods

Electrospray ionization mass spectrometry (ESI-MS) spectra were recorded on a PE SCIEX API 2000 mass spectrometer. \(^1\)H and \(^{19}\)F NMR spectra were recorded on a JEOL ECX400P spectrometer; chemical shifts for \(^1\)H and \(^{19}\)F NMR are referenced to tetramethylsilane and trifluoroacetic acid, respectively. UV–Vis spectra were recorded on a Hitachi UV-3000 spectrophotometer.

Aerobic oxidation of hydrocarbons

Oxygen was bubbled for 1 min into 5 ml of 1.0 mM Fe(II)–TPA complex solution containing 1000 equiv. of hydrocarbon as substrate, followed by vigorous stirring under 1 atm O₂ in a batch reactor tube equipped with an O₂ balloon. Organic products were analyzed by FID–GC (Shimadzu GC-14B) and GC–MS (Shimadzu GC-MS QP5050). Prior to use, substrates were dried over molecular sieves 4 A and deoxygenated by N₂ bubbling. 2-Butanone was used instead of acetone for the reaction at 348 K to avoid boiling.
Results and discussion

Characterizations of Fe(II)−TPA complexes

The effective magnetic moments of complexes 1−3 were measured in acetonitrile (MeCN) and acetone by the Evans NMR method. The \( \mu_{\text{eff}} \) values, listed in Table 1, indicate that 1 and 2 possess mainly a low spin Fe(II) ion in MeCN, whereas 3 is in the high-spin state in MeCN. The spin states of Fe(II)−TPA type complexes in MeCN have been widely investigated. The present results in MeCN are well consistent with the reported data. In contrast, all the Fe(II) ions of 1−3 were in the high-spin states in acetone. The complexes 1 and 2 are known to be in the low spin state in the solid state. Therefore, the high spin state in acetone suggests the dissociation of coordinated π-accepting ligand MeCN. Then, we conducted \(^{19}\text{F}\) and \(^{1}\text{H}\) NMR study to clarify the coordination environment of the Fe(II) complex in acetone. The chemical shift of the fluorine atom of triflate anion with paramagnetic Fe(II) complex widely varies based on the chemical environment; ca. +60 (bridging triflate), ca. −10 (terminal) and ca. −80 ppm (free triflate). The \(^{19}\text{F}\) NMR spectrum of 2 in acetone-\( \text{d}_6 \) exhibited a single broad peak at −41.4 ppm (Figure 2, \( \nu_{1/2} = 1036 \text{ Hz} \)), which suggest that the triflate anions weakly coordinated to Fe(II) and they are equivalent. The observed line broadening indicates a fast exchange between coordinated and free triflate anions. In addition, the \(^{1}\text{H}\) NMR spectrum of 2 in acetone-\( \text{d}_6 \) shows that the all three pyridylmethyl moieties are equivalent (Figure 3), suggesting a fast exchange between a six-coordinate and a five-coordinate conformation as proposed with the similar Fe(II) complexes by Britovsek et al., which is shown in Scheme 1a. The electronic states of 1−3 in solution were also investigated by UV-Visible absorption spectroscopy (Table 1). Intense MLCT bands were observed for 1 and 2 in MeCN, but the MLCT bands for 1 and 2 in acetone were weaker in intensity. The MLCT bands of 3 were weak in intensity in both MeCN and acetone, similar to those observed for 1 and 2 in acetone. Thus, the intensity of the MLCT band was higher with low-spin Fe(II)−TPA complexes than with the high-spin. The similar correlation between intensity of the MLCT band and spin states of Fe(II) complexes has been reported by Britovsek et al. without rationale. The correlation suggests that the low spin complex
has the stronger interactions between dπ and pyridine π* orbitals compared with the high-spin complexes.

The preferential high spin state of 1 and 2 in acetone can be rationalized by coordination of the counter anions to the Fe(II) ion in acetone. On the other hand, the solvent-independent high spin state of 3 suggests that the two coordinated chloride ions of 3 are not exchanged by MeCN or acetone and result in the Fe(II) ion being in a high spin state.21

Table 1. UV-visible absorption properties, effective magnetic moments, rate constant of oxygen activation (k_{obs}) and catalytic activity of cyclohexene oxidation (TON) of Fe(II)-tpa complexes 1–3 in solution states.

<table>
<thead>
<tr>
<th>entry</th>
<th>solvent</th>
<th>complex</th>
<th>λ_{max} (ε)(^a)</th>
<th>(μ_{\text{eff}}(\mu_B))</th>
<th>(k_{\text{obs}}(\text{h}^{-1}))</th>
<th>TON(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>368 sh, 398 (6379), 506 (150)</td>
<td>0.740</td>
<td>0(^c)</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>acetone</td>
<td>2</td>
<td>368 sh, 398 (6608), 521 (141)</td>
<td>0.834</td>
<td>0(^c)</td>
<td>8.8</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>426 (1468)</td>
<td></td>
<td>5.29</td>
<td>0.529</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>362 (1268)</td>
<td></td>
<td>5.07</td>
<td>1.28</td>
<td>239</td>
</tr>
<tr>
<td>5</td>
<td>acetone</td>
<td>2</td>
<td>364 (1476)</td>
<td>5.33</td>
<td>0.118</td>
<td>253</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>470 (1331)</td>
<td></td>
<td>5.46</td>
<td>0.311</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\(^a\) Units of M\(^-1\)cm\(^-1\). \(^b\) TON was defined as mol of products (2-cyclohexene-1-ol and 2-cyclohexene-1-one)/mol of complex (5 µmol) after 24 h. \(^c\) No spectral change was observed after 24 h. In the absence of the catalyst, only a small amount of product was evolved (15 µmol in acetone after 24 h).
Figure 2. $^{19}$F NMR spectrum of 2 in acetone-d$_6$. 

Figure 3. $^1$H NMR spectrum of 2 in acetone-d$_6$. 

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Reaction with dioxygen

The reactions of 1–3 with dioxygen were examined by UV-visible spectroscopy. In MeCN, only 3 showed a spectral change upon reaction with O\textsubscript{2} (Figure 4), while 1 and 2 did not show any spectral changes for at least one day. The MLCT band of 3 disappeared in a first-order decay fashion with an isosbestic point at 413 nm over several hours. The observed first-order rate constant $k_{\text{obs}}$ is comparable with the reported value (0.68 h\textsuperscript{-1}) by Thallaj et al. (Table 1).\textsuperscript{17} In acetone, in contrast to MeCN, all complexes reacted with dioxygen (Table 1). These results clearly show the higher dioxygen reactivity of high spin Fe(II)–TPA complexes rather than low spin. Mandon and his co-workers has proposed that Fe(II)–TPA chloride complex (here in 3) reacts with dioxygen in a dissociative fashion.\textsuperscript{17,22,23} Our NMR study also supports the possible coordination of dioxygen to Fe(II) in five-coordinate (Scheme 1b). Interestingly, the $k_{\text{obs}}$ value of 2 in acetone is smaller than that of 3 in acetone or MeCN, which is contrary to the order of binding strength of the counter anion. This may be due to the difference in steric hindrance between bulky triflate and chloride. The fact that 1, which has the most weakly coordinating counter anions, showed the fastest oxidation reaction rate indicates that 1 was oxidized preferentially through the formation of a dioxygen adduct of the Fe(II) complex, that is, an Fe(III)-superoxo species (Scheme 1b).\textsuperscript{9,11,24,25} The Fe(III)-superoxo might convert to Fe(III) and superoxide in the presence of a nucleophile such as chloride (Scheme 1c), as found for the autooxidation of oxymyoglobin and oxyhemoglobin.\textsuperscript{26}

Aerobic oxidation of alkenes in the presence of the Fe(II) complexes

To examine the effect of the Fe(III)-superoxo species on the aerobic oxidation of alkenes, we first chose cyclohexene as a substrate with weak allylic C-H bonds; bond dissociation energy (BDE) = 81 kJ/mol.\textsuperscript{27} The aerobic oxidation of cyclohexene was carried out in the presence of 1–3 (0.1 mol%) both in MeCN and acetone. Gas chromatography analysis of the products revealed that 1 and 2 are capable of promoting aerobic oxidation of cyclohexene in acetone but not in MeCN (Table 1). Thus, these results clearly indicate that the high-spin Fe(II)–TPA complex can be a good promoter in the aerobic oxidation of cyclohexene. Complex 1 gave allylic oxidation products of cyclohexene, 2-cyclohexen-1-ol and 2-cyclohexene-1-one, (y. 23940% based on Fe), and cyclohexene oxide (y. 810%) in acetone after 24 h. The alcohol/ketone (A/K) ratio was ca. 1.0 at the beginning and
Figure 4. UV-visible spectral changes of 3 in MeCN upon the reaction with $O_2$. Inset: change in absorbance with time at 430 nm and fitted curve.

Scheme 1. Reaction of dioxygen with the Fe(II) centre via dissociative mechanism; (a) fast ligand exchange, (b) coordination of dioxygen and (c) release of superoxide.
decreased to 0.3 as the reaction proceeded (Figure 5). The decrease in A/K ratio from 1.0 indicates that the allylic oxidation occurs via a radical auto-oxidation process, followed by over-oxidation of the alcohol to ketone by radicals or other oxidants. Production of cyclohexene oxide, however, implies that metal-based oxidants are also formed during the oxidation reaction. Interestingly, 3 is virtually ineffective in initiating the aerobic oxidation of cyclohexene in both MeCN and acetone (Table 1). Thus, these results suggest that labile coordination sites on the high-spin Fe(II) center are a requisite for efficient aerobic oxidation of cyclohexene. In the presence of 1, oxidation of other alkenes and alkanes with weak or moderate C–H BDE (81−97 kJ/mol) were also examined, whose results are listed in Table 2. At 298 K, cumene (BDE: 83 kJ/mol)\(^{28}\) was oxidized; however, hydrocarbons with C–H BDE of more than 85 kJ/mol such as cyclooctene (85 kJ/mol),\(^{27}\) ethylbenzene (86 kJ/mol)\(^{27}\) and norbornene (97 kJ/mol)\(^{29}\) were intact under these conditions. The latter hydrocarbons were oxidized when the temperature was elevated to 348 K in 2-butanone. The product yield in the oxidation of cumene was effectively enhanced with increase in temperature. These results clearly show that the C–H activation of hydrocarbon is the key step in the catalytic system.

**Reaction mechanism**

Next, we monitored UV-visible absorption spectral changes of 1 in the presence of cyclohexene in acetone. The abundance fraction of Fe(II) species estimated by intensity of the MLCT band is plotted against reaction time in Figure 6. The Fe(II) species disappeared within 5 s with a small induction period in the presence of cyclohexene, which is significantly faster than the oxidation rate of 1 in the absence of cyclohexene (ca. 2 min). These results indicate that cyclohexene-derived radicals induce the oxidation of Fe(II) species. We propose that H-atom abstraction from cyclohexene by an Fe(III)-superoxo species is the key step in producing cyclohexene-derived radicals, which quickly oxidize Fe(II) species (Scheme 2). The radicals generated would propagate the radical chain oxidation of cyclohexene. Thus, the observed induction period corresponds to the initial dioxygen activation step. The fact that 3 was aerobically oxidized but did not initiate the aerobic oxidation of cyclohexene implies that Fe(III)-superoxo species immediately converts to Fe(III) and superoxide by nucleophilic attack of the chloride anion as discussed above.
Figure 5. Time course of (a) product yield based on Fe and (b) A/K ratios in the oxidation of cyclohexene with 1 (filled symbols) and 2 (open symbols) in acetone.
Table 2. Product yields in the aerobic oxidation of hydrocarbons in the presence of 1.

<table>
<thead>
<tr>
<th>substrate</th>
<th>solvent</th>
<th>T / K</th>
<th>product</th>
<th>yield (%)$^a$</th>
<th>sel. (%)</th>
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<tr>
<td>norbornene$^b$</td>
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<td>norbornene oxide</td>
<td>18340</td>
<td>51$^c$</td>
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<td>cyclooctanone</td>
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<td>cyclohexene oxide</td>
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<td>cumylalcohol</td>
<td>130</td>
<td>50</td>
</tr>
</tbody>
</table>

$^a$ Based on Fe (5 µmol) after 24 h of reaction. $^b$ 2100 equiv. of norbornene used. $^c$ Several byproducts also detected.
Figure 6. Change in fraction of Fe(II) species with time during oxidation of 1 in acetone in the presence (filled circle) or absence (open circle) of cyclohexene upon the reaction with O₂. The fraction of Fe(II) species was calculated from the MLCT band intensity. Inset shows the initial phase.

Scheme 2. Proposed reaction paths in the initial phase of oxidation of 1 in the presence of cyclohexene.
Superoxide has been reported to perform H-atom abstraction only from weak N–H and O–H bonds. The Fe(III)-superoxo species is also likely to generate a µ-peroxo dimer, followed by formation of a µ-oxo dimer as widely invoked in aerobic oxidation of heme and non-heme Fe(II) complexes. The formation of stable µ-oxo dimer can finally lead to deactivation of the catalysis.

Que and his co-workers have been studying hydrocarbon oxidation catalyzed by the Fe(II)–TPA complex and its derivatives with H₂O₂ or tBuOOH as oxidant. Recently, they reported that Fe(III)-hydroperoxo and -alkylperoxo species supported by the TPA ligand were transformed to Fe(IV)-oxo species in acetone. Production of cyclohexene oxide supports the generation of Fe(IV)-oxo species in our system, although the aerobic oxidation mainly proceeds via radical chain oxidation, as shown by the A/K ratio.

The reactivity of metal-superoxo species involved in hydrocarbon oxidation reactions has attracted much attention recently in the field of bioinorganic chemistry, since Cu(II)-superoxide species have been postulated to initiate H-atom abstraction from substrates in the catalytic cycles of copper-dependent enzymes such as dopamine ß-monooxygenase and peptidylglycine α-hydroxylating monooxygenase (PHM), and the Fe(III)-superoxo species have been proposed as active species in a di-iron-dependent enzyme, myo-inositol oxygenase. It has been reported by using model complexes that Cu(II)-superoxo species can perform H-atom abstraction from weak O–H and N–H bonds. Recently, Itoh and co-workers synthesized a series of Cu(II) end-on superoxo species which mimic a tetrahedral geometry in the X-ray structure of oxy-PHM reported by Amzel and co-workers, and demonstrated that this species also mimics the H-atom abstraction from aliphatic C–H bonds. H-atom abstraction by Fe(III)-superoxo species had been reported rarely, but recently, Fukuzumi and Nam et al. reported that Fe(III)-superoxo species generated in the reaction of the mononuclear nonheme Fe(II) complex with dioxygen performs H-atom abstraction from cycloalkenes. We believe that the same mechanism should be operative in the aerobic oxidation reaction promoted by 1 in acetone.
Conclusions

We found that aerobic oxidation of alkenes was efficiently promoted by the Fe(II)–TPA complex, when the Fe center was in the high-spin state. It is noteworthy that the aerobic oxidation proceeded without any reductants, since most of the aerobic oxidation systems catalyzed by heme or nonheme iron complexes require stoichiometric co-reductants such as aldehydes and Zn/AcOH.\(^5\) We propose that an Fe(III)-superoxo species is a key intermediate in the efficient aerobic oxidation of alkenes. The essential factor in the reaction is the presence of labile coordination sites that provides stable coordination of dioxygen, giving Fe(III)-superoxo species active for the H-atom abstraction; the strong interaction of MeCN with the low-spin iron(II) center would prevent the formation of the Fe(III)-superoxo species, and chloride ion may shorten the life-time of the Fe(III)-superoxo species probably through nucleophilic attack. Thus, the ligand-exchange chemistry including dioxygen should be of important in the performance of the efficient aerobic oxidation.\(^5\) Consequently, high-spin Fe(II)–TPA complexes except for the chloride complex effectively initiated aerobic oxidation of hydrocarbons. We will further study the relationship between spin state and dioxygen activation ability.

References


Chapter 2

Alkane Oxidation Catalyzed by Fe(II)–TPA Complex
and Its Nitro-Substituted Derivatives

Abstract

We have prepared a series of mononuclear nonheme iron(II) complexes supported by TPA (TPA= tris(2-pyridylmethyl)amine) and its derivatives that have one to three nitro-groups at 4-position of the pyridine ligand, and evaluated the effect of the nitro-groups on the catalytic oxidation activity of these complexes. The introduction of nitro-group to the TPA ligand proved to decrease the product yield of cyclohexane oxidation with hydrogen peroxide as well as the product ratio of alcohol to ketone. During the catalytic reaction, a significant amount of Fe(II) species exists in cases of nitro-substituted complexes, while the parent Fe–TPA complex was rapidly oxidized to Fe(III) state. These results suggest that the introduction of nitro-groups prevents from the generation of cis-oxo-hydroxo-iron(V) species, but induces homolysis of the Fe O bond of Fe(III)OOH species to initiate radical oxidation of cyclohexane.
Introduction

Mononuclear nonheme iron enzymes catalyze the selective oxidation of unactivated organic substrate under ambient conditions,\(^1\) most of which are still rather difficult tasks for man-made catalysts. For example, naphthalene dioxygenase is able to perform \textit{cis}-dihydroxylation of the aromatic ring of naphthalene,\(^2\) but such a type of oxidation reactions has never been archived by any catalysts and oxidants. To mimic the oxidation ability of these enzymes, a number of nonheme iron complexes have been synthesized and examined as catalysts for oxidation reactions.\(^3\)–\(^5\) One of intriguing successes is \textit{cis}-dihydroxylation of alkenes catalyzed by Fe–TPA complex (TPA=tris(2-pyridylmethyl)amine), which was discovered by Que and co-workers in 1999.\(^6\) Their mechanistic and theoretical studies indicated the involvement of \textit{cis}-oxohydroxo-iron(V) species as an oxidant for \textit{cis}-dihydroxylation.\(^7\)–\(^11\) The same system, i.e., the reaction with hydrogen peroxide catalyzed by Fe–TPA complex, was also applied for alkane hydroxylation.\(^12\)–\(^14\) Although the turnover number was moderate, the reaction took place through hydrogen atom abstraction by a metal based oxidant, \textit{cis}-oxo-hydroxo-iron(V) species. In this study, we focused on the effect of substituent groups on the TPA ligand on the catalytic alkane hydroxylation, since modification of the electronic structure of \textit{cis}-oxo-hydroxo-iron(V) species should make a great impact on the catalytic activity in alkane hydroxylation. Very recently, a theoretical study, that supports our idea, was reported by Ma and Balubuena.\(^15\) In this report, they have proposed that the reactivity of \textit{cis}-oxo-hydroxo-iron(V) species for the hydrogen atom abstraction could be enhanced by introducing electron-withdrawing groups to the aromatic rings of TPA. Enhancement of oxidation power of the active species might enable us to oxidize substrates otherwise difficult to be oxidized, such as methane. Herein, we have synthesized a series of iron(II) complexes (Figure 1, 1–4) supported by TPA and nitro-substituted TPA ligands, and evaluated how the introduction of nitro-groups to TPA ligand affects the catalytic activity of 1–4 in cyclohexane oxidation with hydrogen peroxide. The introduction of nitro-groups at 4-position of the pyridine ligand of TPA has an advantage in being able to modulate only electronic, but not steric factors that should control the reactivity of metal complexes.\(^16\)–\(^21\)
Experimental

Synthesis of tris(4-nitro-pyridin-2-ylmethyl)amine

To a stirred mixture of 2-chloromethyl-4-nitropyridine (0.66 g, 3.8 mmol) and 2-aminomethyl-4-nitropyridine dihydrochloride (0.54 g, 1.9 mmol) in water (1mL) was slowly added 5.0 N NaOH (2.0 mL, 10 mmol). The reaction mixture was stirred at 0 °C for 4 days. The organic layer was separated, and the aqueous layer was extracted with CH$_2$Cl$_2$ several times. The combined organic layers were dried over Na$_2$SO$_4$, and volatile components were removed. Purification of the product on an alumina column (8:1 CH$_2$Cl$_2$/AcOEt) gave a yellow solid of tris(4-nitro-pyridin-2-ylmethyl)amine (0.26 g, yield 32%); $^1$H NMR (400 MHz, CDCl$_3$): 8.78 (3H, d, $J$ = 5.5 Hz), 8.22 (3H, d, $J$ = 1.8 Hz), 7.85 (3H, dd, $J$ = 5.4 Hz, $J'$ = 2.3 Hz), 4.11 (6H, s); $^{13}$C NMR (CDCl$_3$, 99.5 MHz): 163.7, 155.5, 152.4, 116.6, 115.7 and 60.9.

Figure 1. Structure of the complexes 1–4.
Synthesis of Fe–TPA and nitro-derivatives

Typical procedure: to a stirred solution of Fe(ClO$_4$)$_2$·$n$H$_2$O (0.109 g, 0.30 mmol) in MeCN was added a solution of TPA or TPA derivatives (0.3 mmol) in MeCN under N$_2$. The reaction mixture was stirred for 30 min. The solid was obtained by diffusion of diethyl ether into the MeCN solution.

[Fe(TPA)(MeCN)$_2$](ClO$_4$)$_2$ (1):

$^1$H NMR (400 MHz, CD$_3$CN): 11.19 (3H, s, H$_{\alpha}$ (Py)), 8.66 (3H, s, H$_{\beta/\beta'}$ (Py)), 8.57 (3H, s, H$_{\beta/\beta'}$ (Py)), 7.26 (3H, t, $J = 7.7$ Hz, H$_{\gamma}$ (Py)), 6.57 (6H, s, H$_{Me}$). ESI-MS: m/z 193.5 ([Fe$^{II}$(TPA)(CH$_3$CN)]$^{2+}$).

[Fe(monoNO$_2$-$\alpha$TPA)(MeCN)$_2$](ClO$_4$)$_2$ (2):

$^1$H NMR (400 MHz, CD$_3$CN): 10.41 (1H, br s, H$_{\alpha(NO2-Py)}$), 10.02 (2H, br s, H$_{\alpha(Py)}$), 8.63 (1H, s, H$_{\beta/\beta' (NO2-Py)}$), 8.55 (1H, br s, H$_{\beta/\beta (NO2-Py)}$), 8.02–8.00 (4H, br m, H$_{\beta+\beta' (Py)}$), 7.54 (2H, t, $J = 7.7$ Hz, H$_{\gamma (Py)}$), 5.76 (2H, s, H$_{NO2-Me}$), 5.70 (2H, d, $J = 16.6$ Hz, H$_{Me}$), 5.40 (2H, d, $J = 16.6$ Hz, H$_{Me}$). ESI-MS: m/z 216.6 ([Fe(monoNO$_2$-$\alpha$TPA)(CH$_3$CN)]$^{2+}$).

[Fe(diNO$_2$-$\alpha$TPA)(MeCN)$_2$](ClO$_4$)$_2$ (3):

$^1$H NMR (400 MHz, CD$_3$CN): 9.93 (2H, br d, $J = 4.0$ Hz, H$_{\alpha(NO2-Py)}$), 9.95 (1H, br s, H$_{\alpha(Py)}$), 8.40 (2H, s, H$_{\beta/\beta (NO2-Py)}$), 8.35 (2H, br d, $J = 4.0$ Hz, H$_{\beta/\beta (NO2-Py)}$), 7.77–7.78 (2H, br m, H$_{\beta+\beta (Py)}$), 7.68 (1H, t, $J = 7.7$ Hz, H$_{\gamma (Py)}$), 5.43 (2H, d, $J = 17.4$ Hz, H$_{Me}$), 5.20 (2H, d, $J = 17.4$ Hz, H$_{Me}$), 5.18 (2H, s, H$_{NO2-Me}$). ESI-MS: m/z 259.2 ([Fe(diNO$_2$-$\alpha$TPA)(MeCN)$_2$]$^{2+}$).

[Fe(triNO$_2$-$\alpha$TPA)(MeCN)$_2$](ClO$_4$)$_2$ (4):

$^1$H NMR (400 MHz, CD$_3$CN): 9.68 (3H, br d, $J = 5.1$ Hz, H$_{\alpha(NO2-Py)}$), 9.95 (3H, br s, H$_{\alpha(Py)}$), 8.30 (3H, s, H$_{\beta/\beta (NO2-Py)}$), 8.26 (3H, br d, $J = 4.0$ Hz, H$_{\beta/\beta (NO2-Py)}$), 5.20 (3H, d, $J = 17.4$ Hz, H$_{NO2-Me}$). ESI-MS: m/z 281.9 ([Fe(triNO$_2$-$\alpha$TPA)(MeCN)$_2$]$^{2+}$).
Results and Discussion

Characterization of a series of iron(II) complexes

TPA and TPA derivatives with one and two nitro-groups were synthesized according to published procedures.\cite{17} Tris(4-nitro-pyridin-2-ylmethyl)amine was readily obtained by coupling 2-(chloromethyl)-4-nitropyridine and 2-(aminomethyl)-4-nitropyridine. Complexation of the ligand with Fe(ClO$_4$)$_2$ in MeCN gave the corresponding complexes 1–4 as a crystalline solid in high yield. These complexes can be formulated as [Fe$^{II}$L(CH$_3$CN)$_2$(ClO$_4$)$_2$]. The NMR spectra of 1–4 in MeCN-d$_3$ at 298K show proton signals at a range of 4–12, indicating that these complexes predominantly have a diamagnetic low spin ferrous ion (Figure 1).\cite{18}

![Figure 1. $^1$H NMR spectra of 1–4 in MeCN-d$_3$ at 298 K.](image-url)
UV–Vis spectra of 2 and 3 in MeCN show two intense broad bands, while one intense broad band was observed for 1 and 4 (Figure 2). As listed in Table 1, the broad bands could be categorized into two classes; lower energy band at around 490 nm and higher energy at around 350 nm. The former is due to charge transfer from iron(II) to a low-lying π* orbital of 4-nitropyridine ligand, and the latter is assignable to the charge transfer from iron(II) to a low-lying π* orbital of pyridine ligand, which has been observed for other iron(II) complexes supported by pyridine-based ligands.22–27 Cyclic voltammetry shows a reversible oxidation corresponding to the Fe$^{II}$/Fe$^{III}$ couple for complexes 1–4. The oxidation potentials successively increased on going from 1 to 4 (1: 1.00V; 2: 1.12V; 3: 1.22 V; 4: 1.32V vs. NHE in MeCN).

![Figure 2](image)

**Figure 2.** UV-Vis spectra of 1–4 in acetonitrile at 298 K: Solid line (1); dotted line (2); dashed line (3); chain line (4).

**Table 1.** MLCT bands of 1–4 in MeCN at 298 K.$^a$

<table>
<thead>
<tr>
<th>Complex</th>
<th>higher energy MLCT band / nm</th>
<th>lower energy MLCT band / nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>398 (7040), 370 sh (6350)</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>359 (4431)</td>
<td>493 (3972)</td>
</tr>
<tr>
<td>3</td>
<td>336 (2828)</td>
<td>489 (7389)</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>486 (9656)</td>
</tr>
</tbody>
</table>

$^a$ In parentheses, molar absorption coefficient is expressed in M$^{-1}$ cm$^{-1}$.
Catalytic oxidation

The catalytic activities of 1–4 in cyclohexane oxidation was evaluated by the following procedure: to a vigorously stirred solution containing the ferrous complex and 1000 equiv. of cyclohexane in MeCN was slowly supplied 30 equiv. of hydrogen peroxide by using a syringe pump over 90 min at room temperature. Samples for GC analysis were taken periodically to determine the time course of the oxidation of cyclohexane. In all the cases, an induction period was observed up to 10 min, and the oxidized products then increased almost linearly until 90 min, at which time the supply of hydrogen peroxide was ended (Figure 3). The reaction mixture contained considerable amounts of the corresponding alcohol and ketone, but the total yields were decreased on going from 1 to 4. Table 2 shows the yields of cyclohexanol and cyclohexanone with respect to hydrogen peroxide at 90 min. Interestingly, the alcohol/ketone (A/K) ratios shows the highest value of 11 for 2, which is rather higher even compared with ever reported mononuclear nonheme iron catalysts, while 3 and 4 show the A/K values close to 1. The results indicate the involvement of radical oxidants for the cyclohexane oxidation in the presence of 3 and 4.

To gain more insights into the catalytic oxidation, we monitored the UV–Vis spectral changes of 1–4 under the aforementioned catalytic conditions. Figure 4a shows the UV–Vis spectral changes of 1. The Fe(II)-to-pyridine MLCT band at 398 nm rapidly disappeared, and the spectrum of 1 was converted to that of Fe(III)–TPA species. The spectral change clearly demonstrated that an oxidation from Fe(II) to Fe(III) took place within 3 min, which corresponds to the observed induction period of product formation. In contrast to complex 1, complexes 2–4 showed only a slight to moderate decrease of the corresponding MLCT bands (Figure 4b–d), whose extent became larger as the number of nitro groups increased. Thus, 2–4 retained the Fe(II) state even during the catalytic reaction. Since the iron(III) species is prerequisite to the formation of cis-oxo-hydroxo-iron(V) oxidizing species, it is conclusive that the decrease in the product yields on going from 1 to 4 should be caused mainly by the ineffective conversion to the iron(III) species. The preference of the iron(II) state of nitro-substituted complexes is in agreement with their high oxidation potentials.
Table 2. Product yields and A/K ratios in cyclohexane oxidation catalyzed by 1–4.

<table>
<thead>
<tr>
<th>Complex</th>
<th>Cyclohexane (%) a</th>
<th>Cyclohexanol (%) a</th>
<th>A/K ratio</th>
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<tr>
<td>1</td>
<td>32</td>
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<td>4</td>
<td>4.6</td>
<td>2.6</td>
<td>1.8</td>
</tr>
</tbody>
</table>

a Yield at 90 min, with respect to the total hydrogen peroxide.
Proposed reaction cycle

There are two possible mechanisms that can account for the ineffective formation of iron(III) species during the oxidation reaction catalyzed by 2–4: one is slow-down of the reaction rate of Fe(II) complex with hydrogen peroxide due to the high oxidation potentials of 2–4. As shown in Figure 2, however, the oxidation reaction was ceased as the supply of hydrogen peroxide was stopped in all the cases. This result suggests that complexes 2–4 have a considerable reactivity with hydrogen peroxide, like complex 1. The other possible mechanism is regeneration of Fe(II) species by

Figure 4. UV–vis spectral changes of 1–4 during the catalytic reaction: (a) 1, (b) 2, (c) 3 and (d) 4.
hydrogen peroxide. To explore this possibility, we added hydrogen peroxide to the solution of 4 after the catalytic reaction, and observed a growth of the MLCT band at around 490 nm, indicating regeneration of ferrous complex 4 (Figure 5). ESI–mass measurements verified the formation of ferrous complex 4 as major species, together with a small amount of Fe(III)-OOH species (Figure 6). The formation of ferrous complex 4 might be through homolytic dissociation of the Fe O bond of Fe(III)-OOH species, which should also produce hydroperoxo radical. Such reduction of metal center by hydrogen peroxide was observed for Cu(II) complexes, especially when the metal center is supported by ligands that stabilize Cu(I) state.\textsuperscript{30,31} Scheme 1 depicted a possible catalytic reaction cycle of complex 4, together with that for 1.\textsuperscript{29,32,33} The OH radical in the cycle for 4 would give an explanation for the observed A/K ratio close to 1.

![Image](image-url)

**Figure 5.** UV–vis spectral changes upon addition of 10 equiv. of hydrogen peroxide to the solution of 4 after the catalytic reaction.
Figure 6. Electron ionization mass spectrum upon addition of 10 equiv. of hydrogen peroxide to the solution of 4 after the catalytic reaction was ended. (a) [Fe(triNO$_2$-TPA)(MeCN)]$^{2+}$ m/z 261.3, (b) [Fe(triNO$_2$-TPA)(MeCN)(OOH)]$^{2+}$ m/z 277.3, (c) [Fe(triNO$_2$-TPA)(MeCN)$_2$]$^{2+}$ m/z 281.6.

Scheme 1. Proposed catalytic cycles of cyclohexane oxidation catalyzed by 1 (a) and 4 (b).
Conclusions

A number of mononuclear nonheme iron complexes have been prepared and examined as catalysts for alkane hydroxylation with hydrogen peroxide, but there is no systematic exploration on the effects of the electronic structures of these catalysts on their catalytic oxidation activity. In this study, we have prepared a series of mononuclear nonheme iron(II) complexes supported by TPA and its nitro-derivatives, and evaluated the effect of the nitro-groups on the catalytic oxidation activity. The introduction of nitro-group to the TPA ligand proved to lower the product yields as well as A/K ratio. During the catalytic oxidation, a significant amount of Fe(II) species is present in the cases of nitro-substituted complexes, while the unsubstituted Fe–TPA complex was rapidly oxidized to Fe(III) state. Theoretical calculations predicted that introducing nitro-groups should facilitate H-atom abstraction from alkane by cis-oxo-hydroxo-iron(V) species, but our experimental study demonstrated that such energetically unfavorable species cannot be obtained by the reaction with hydrogen peroxide. In fact, it induces homolysis of the Fe-O bond of Fe(III)OOH to afford Fe(II) and hydroperoxide radical. The A/K ratio of 3 and 4 decreases dramatically to reach 1, which should be caused by the radical.

References


Chapter 3

Theoretical Study on Electronic Structure of Fe(II)–TPA Complex and Its Nitro-Substituted Derivatives

Abstract

The electronic and geometric structures of a series of iron(II) complexes supported by tetridentate tris(pyrid-2-ylmethyl)amine-type ligands with different number of 4-nitropyridine groups, [(PyCH$_2$)$_{3-n}$(4-NO$_2$PyCH$_2$)$_n$N] (n = 0–3), were examined by X-ray absorption fine-structure and variable-temperature $^1$H NMR spectroscopies and theoretical calculations in order to reveal how low-spin state is stabilized through $\pi$ back-bonding interactions between iron(II) and 4-nitropyridine donor group(s).
Introduction

Transition metal complexes with d⁴–d⁷ electronic configurations are capable of exhibiting two spin states (high spin or low spin) depending on the strength of the ligand field. In special cases, the high-and low-spin states are in thermal equilibrium, which can be shifted to either a high-spin or low-spin state by external perturbations such as light, heat, or pressure. Since the change in spin states is accompanied by changes in magnetic moment, color, and molecular geometry, such spin-crossover compounds have attracted much attention for technological applications such as in display devices and data storage.¹ The spin-crossover phenomena have been frequently observed in iron(III) and iron(II) complexes,²–⁵ and the factors that control this behavior have therefore been extensively studied with iron complexes that have a wide variety of supporting ligands.⁶–¹¹ The introduction of substituent groups expected to show steric or electronic effects was traditionally employed as a strategy.¹²–²⁰ The incorporation of either sterically demanding substituents close to the donor atoms¹⁴,¹⁵ or electron-withdrawing ones¹²,¹³ generally reduces the ligand field strength and makes the high-spin configuration more favorable. For example, M. Enamullah and W. Linert studied the substituent effects of iron(II)-4-X-2,6-bis-(benzimidazol-2′-yl)pyridine complexes (X = H, OH, and Cl) on their spin-crossover phenomena, in which electron-withdrawing substituents made the high spin more favorable.¹³

In previous research,²¹ we prepared a series of iron(III)-catecholate complexes supported by tris(pyrid-2-ylmethyl)amine (TPA)-type ligands having various substituent groups at the 4-position of the pyridine donor groups, in order to obtain insights into the reaction mechanism of mononuclear nonheme iron(III)-dependent catechol dioxygenases, and found that the iron(III)-catecholate complexes undergo the high-spin/low-spin crossover and that electron-withdrawing substituents make the low-spin state more favorable. This counterintuitive result indicated that pyridine ligands with electron-withdrawing substituents stabilize the dπ orbitals of iron, probably through π back-bonding interactions of iron dπ orbitals and π* orbitals of the pyridine ligands. At that time, however, an evaluation of the contribution of π back-bonding interactions was prevented by a significant amount of iron(II)-semiquinonate
character of the iron(III)-catecholate complex. Recently, we prepared a series of iron(II) complexes supported by TPA-type ligands with different number of 4-nitropyridine groups, \([\text{PyCH}_2]_{3-n}(4\text{-NO}_2\text{PyCH}_2)_n\text{N} \) \((n = 0–3) \) \((1–4)\) shown in Figure 1b, and carried out the catalytic oxidation of cyclohexane with hydrogen peroxide using \(1–4\) as catalysts.\(^{22}\) UV–Vis and \(^1\)H NMR spectroscopic and electrochemical measurements revealed that the electronic structures of \(1–4\) changed as the number of 4-nitropyridine groups increases, which explained well the difference in their catalytic activities of \(1–4\). Interestingly, the dominant low-spin state became more favorable as the number of 4-nitropyridine donor groups was increased. This result suggests that \(d\pi\) orbitals should be stabilized through \(\pi\) back-bonding interactions between iron(II) and 4-nitropyridine donor group(s), as suggested for the iron(III)-catecholate complexes. Herein, we discuss how low-spin state is stabilized through \(\pi\) back-bonding interactions between iron(II) and 4-nitropyridine donor group(s) in light of theoretical calculations.

**Figure 1.** TPA-type ligands used in this study (a) and calculated structures \(1–4\) (b).
Experimental

Synthesis of a series of iron(II) complexes

[Fe(TPA)(MeCN)₂](ClO₄)₂ (1), [Fe(4-NO₂-TPA)(MeCN)₂](ClO₄)₂ (2), [Fe(di-4-NO₂-TPA)(MeCN)₂](ClO₄)₂ (3), and [Fe(tri-4-NO₂-TPA)(MeCN)₂](ClO₄)₂ (4) were prepared according to published procedures (Figure 1a).²¹,²² Variable temperature ¹H NMR spectra of these complexes in MeCN-d₃ were recorded on a JEOL ECX400P spectrometer.

X-ray absorption

The X-ray absorption experiments were carried out on the beam line 7C at Photon Factory (Tsukuba, Japan). The ring energy was 2.5 GeV, and the stored current was 340–370 mA. The Fe K-edge (7.1 keV) XAFS spectra of 1–4 in MeCN (10 mM) were recorded in a fluorescence mode with a Si(111) two-crystal monochromator at room temperature. The EXAFS analysis was performed by a Rigaku REX2000 program. For a curve fitting analysis, the backscattering amplitude and the phase shift functions of an Fe–N pair was obtained from a theoretical reference generated by using the code FEFF 8.²³ A complex consisted of an Fe center and octahedrally coordinated six N atoms with 1.96 Å of Fe–N distances was used as a model for the theoretical reference. The Fe–N distance of 1.96 Å was referenced from the crystal structure of [Fe(bpy)₃]²⁺ (bpy = bipyridine).²⁴ The Fourier transformation and inverse Fourier transformation of the EXAFS signals were performed in the k-range of ca 2.5–12 Å⁻¹ and R-range of ca 1–2 Å, respectively.

Computational details

We used computational methods based on density functional theory²⁵ as implemented in the ORCA 2.6 of computer programs.²⁶ Fe(II) complexes 1–4 with two possible stereoisomers of 2 and 3 were calculated (Figure 1b). Spin quantum numbers of S = 0 and S = 2 were applied for the calculation of low-spin and high-spin configurations, respectively. The calculation made use of BP86 and B3LYP functionals for geometry optimization and single point energy calculations, respectively. All
calculations employed Ahlrichs triple-ζ valence basis set with some sets of first polarization functions; one set for H atom, two sets for C and N atoms and three sets for Fe atom. Tight SCF convergence \(10^{-8}\) au was used for all calculations. The solvent effect (MeCN) was considered by using the conductor like screening model (COSMO). All reported values for orbital correspond to the B3LYP single point calculations. Vibrational frequency calculations at 298.15 K were performed on Gaussian03 \(^\text{27}\) using BLYP, B3LYP, B3LYP* functionals, and LanL2DZ basis set to estimate thermal energies of the Fe(II) complexes.

**Results and Discussion**

**Variable temperature \(^1\)H NMR study**

We already reported the proton NMR spectra of \(1–4\) in MeCN-\(d_3\) at 298 K.\(^{22}\) Here, we report the proton NMR spectral change at a range from 233 to 298 K in order to address the spin-crossover behaviors of \(1–4\) in solution state (Figure 2). The proton signals appearing at a range of 4–12 ppm were shifted upfield and reached constant values as the temperature decreased to 233 K. This result indicates that a trace fraction of high-spin species exists at 298 K and disappears at 233 K in case of all the complexes \(1–4\).\(^{28}\) Spin-crossover behaviors for \(1–4\) can be clearly seen in the Curie plots of Figure 3. All the signals moved toward diamagnetic values as the temperature was lowered from 298 K to 233 K. The slopes became milder as the number of nitro groups increased. This result clearly indicates that 4 should have the highest fraction of low-spin state among \(1–4\) at the same temperature. Interestingly, the signals of axial and equatorial pyridine ligands could not be distinguished and appeared as averaged broad signals even at 233 K, which is in sharp contrast to the case of Ru(II)–TPA complex.\(^{29}\) These results indicate the rapid exchange of axial and equatorial pyridine ligands of Fe(II)–TPA complexes at a rate close to but faster than the NMR timescale, probably through a five-coordinated species as proposed by Birtovsek et al.\(^{30}\)

**Fe K-edge EXAFS studies**

Fe K-edge EXAFS spectra of the ferrous complexes \(1–4\) in MeCN and their Fourier transforms
Figure 2. $^1$H NMR spectra of (a) 1, (b) 2, (c) 3, and (d) 4 in MeCN-d$_3$ at various temperatures (298 K to 233 K)
are shown in Figures 4 and 5, respectively. The peaks at about 1.5 Å in Figure 5 are assigned to Fe–N scatterings. The EXAFS analysis indicated Fe–N distances of 1.940–1.958 Å (Table 1; Fourier filtering and curve fitting were shown in Figure 6), whose values are comparable to those typically found in low-spin Fe(II) complexes such as [Fe(phen)$_3$]$_{2}^{2+}$ (1.97 Å),$^{31}$ [Fe(bpy)$_3$]$^{2+}$ (1.96 Å)$^{24}$ and [Fe(bpca)$_2$]$^{2+}$ (1.94 Å)$^{32}$ (where phen = 1,10-phenanthroline; bpy = bipyridine; bpca = N-(2-pyridinylcarbonyl)- 2-pyridinecarboximidate monoanion). The estimated Fe–N bond length decreased by nitro-substitution, even though the standard deviation are rather large (1: 1.958(4) Å; 2: 1.957(6) Å; 3: 1.950(6) Å; 4: 1.940(6) Å), indicating stronger ligation to iron(II) by 4-nitropyridine than by 4-unsubstituted pyridine ligand and/or the decrease of a trace fraction of

\[ \delta_{\text{Fe-N}} = 1.940 - 1.958 \text{ Å} \]

Figure 3. Curie plots for some signals of 1–4: 1 (○), 2 (△), 3 (□), 4 (■), : (A) α-H (Py), (B) β-H (Py), (C) H of CH$_2$, (D) α-H (nitroPy), (E) β-H (nitroPy) and (F) H of nitroCH$_2$. 

- 45 -
high spin species whose Fe–N bond length is ca. 2.1 Å.

The former reason is more probable because the iron(II) center of 1–4 are predominantly in low spin state at room temperature.

Figure 4. $k^3$-Weighted K-edge EXAFS spectra of ferrous complexes 1–4 in MeCN.

Figure 5. Fourier transformed $k^3$-weighted Fe K-edge EXAFS spectra of 1–4 in MeCN.
Table 1. EXAFS curve-fitting results for the Fe–N shells of compounds 1–4.

<table>
<thead>
<tr>
<th>complex</th>
<th>r (Å)</th>
<th>$\sigma^2$ (Å$^2$)</th>
<th>R (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.958(4)</td>
<td>0.004</td>
<td>1.20</td>
</tr>
<tr>
<td>2</td>
<td>1.957(6)</td>
<td>0.004</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>1.950(6)</td>
<td>0.004</td>
<td>4.31</td>
</tr>
<tr>
<td>4</td>
<td>1.940(6)</td>
<td>0.004</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Figure 6. Fourier filtered EXAFS oscillations (solid curve) and the curve fit (circle) for complexes 1–4.
high-spin species whose Fe–N bond length is ca. 2.10 Å.\textsuperscript{20} The former reason is more probable because the iron(II) center of 1–4 are predominantly in low-spin state at room temperature.

**Calculated orbital energies**

A theoretical approach based on DFT calculations is very useful and has been used for investigation of electronic structures of Fe\textsuperscript{33–35} or Ru complexes\textsuperscript{34,36} including π back-bonding interactions. In this study, we performed DFT calculation for low-spin Fe(II) complexes 1–4 with two possible isomers of 2 and 3 (Figure 1b). The so-called frontier orbitals of 1–4 are shown in Figure 7, which includes the two isomers of 2 and 3, where the frontier orbitals can be seen to stabilize as the number of nitro groups increases. Two dσ-like Kohn-Sham orbitals (KSOs) are found at −0.5 to −1.0 eV, and three dπ-like KSOs are located at −6.4 to −7.2 eV. The stabilization by introduction of nitro groups is ca. 0.1 eV per one nitro group, which is in good agreement with the difference in oxidation potential (1: 1.00 V; 2: 1.12 V; 3: 1.22 V; 4: 1.32 V vs. NHE in MeCN).\textsuperscript{22} Although both dσ and dπ orbitals are incrementally stabilized by introducing one nitro group into the TPA ligand, dπ orbitals are stabilized more than dσ orbitals. For example, dσ and dπ orbitals of 4 are lowered in energy by 0.44 and 0.54 eV, respectively, compared with those of 1 (Table 2). As a result, the energy gap between dσ and dπ orbitals, which correspond to the ligand field strength, is increased by the introduction of nitro groups. These results are in agreement with the observation that a low-spin state became more favorable on going from 1 to 4.

The lower-lying unoccupied π*-like orbitals of pyridyl ligands are located at −2 to −1 eV, and the lower-lying unoccupied π*-like orbitals of 4-nitropyridyl ligands were found at around −3.5 eV. Thus, π*-like orbitals of 4-nitropyridine ligands are located lower in energy by ca. 1.6 eV than those of 4-unsubstituted pyridyl ligands. We already reported that the metal-to-ligand charge transfer (MLCT) transition of 1–4 can be classified in two classes; the MLCT band from dπ(Fe) to π*(Py) appearing in ca. 3.4 eV and the band from dπ(Fe) to π*(NO\textsubscript{2}-Py) in ca. 2.5 eV. The energy difference of the two types of MLCT bands should be related to the energy difference of π*-like orbitals of 4-nitropyridine and 4-unsubstituted pyridyl ligands.\textsuperscript{22}
Table 2. Energy levels of d orbitals of 1–4.

<table>
<thead>
<tr>
<th>complex</th>
<th>orbital energy / eV&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dσ</td>
</tr>
<tr>
<td>1</td>
<td>-0.577</td>
</tr>
<tr>
<td>2a</td>
<td>-0.740</td>
</tr>
<tr>
<td>2b</td>
<td>-0.737</td>
</tr>
<tr>
<td>3a</td>
<td>-0.879</td>
</tr>
<tr>
<td>3b</td>
<td>-0.879</td>
</tr>
<tr>
<td>4</td>
<td>-1.021</td>
</tr>
</tbody>
</table>

<sup>a</sup> Energies of the highest dπ orbitals and the lowest dσ ones are listed.
π Back-bonding interactions

The Fe–N distances in the optimized structures of 1–4 (S = 0) are listed in Table 3. The averaged Fe–N lengths (N¹–N⁶) of 1–4 (ca. 1.95 Å) agree with those estimated by EXAFS analyses. Clearly, 4-nitropyridine ligands interact with the low-spin iron(II) center than 4-unsubstituted pyridine ligands. For the axial pyridine ligation, the Fe–N² bonds of 2a, 3b and 4 (1.939–1.952 Å) are shorter than those of 1, 2b and 3a (1.962–1.967 Å). For the equatorial pyridine ligation, the Fe–N bonds involving 4-nitropyridine (1.949–1.970 Å) are shorter than those involving 4-unsubstituted pyridine (1.978–1.986 Å). Interestingly, conformer 2a has the shortest Fe–N(4-nitropyridine) bond (1.939 Å) and the longest Fe–N(pyridine) bond (1.985 Å). While the average bond length of Fe–N(pyridine) becomes shorter on going from 1 to 4, the average bond length of Fe–N(MeCN) slightly increases, and the Fe–N(amine) bond distance shows almost no difference among 1–4. Thus, nitro-substitution shortens corresponding Fe–N(pyridine) length. The averaged Fe–N length (N¹–N⁶) also slightly decreases by introduction of nitro groups, which is consistent with the trend obtained from the EXAFS study.

Table 3. Fe–N distances in the optimized structures of low-spin ferrous complexes 1–4.

<table>
<thead>
<tr>
<th>N atom</th>
<th>1</th>
<th>2a</th>
<th>2b</th>
<th>3a</th>
<th>3b</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>N¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R = H</td>
<td>1.978</td>
<td>1.985</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R = NO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R = H</td>
<td>1.962</td>
<td>1.964</td>
<td>1.967</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R = NO₂</td>
<td>1.939</td>
<td></td>
<td>1.947</td>
<td>1.952</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R = H</td>
<td>1.978</td>
<td>1.982</td>
<td>1.983</td>
<td>1.986</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R = NO₂</td>
<td>1.964</td>
<td></td>
<td>1.964</td>
<td>1.969</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ave. of N¹-N³</td>
<td>1.973</td>
<td>1.968</td>
<td>1.965</td>
<td>1.965</td>
<td>1.966</td>
<td>1.963</td>
</tr>
<tr>
<td>N⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.003</td>
<td>1.999</td>
<td>2.000</td>
<td>2.001</td>
<td>1.998</td>
<td>1.998</td>
<td></td>
</tr>
<tr>
<td>N⁵</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.895</td>
<td>1.902</td>
<td>1.902</td>
<td>1.904</td>
<td>1.906</td>
<td>1.908</td>
<td></td>
</tr>
<tr>
<td>N⁶</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.916</td>
<td>1.924</td>
<td>1.922</td>
<td>1.927</td>
<td>1.926</td>
<td>1.928</td>
<td></td>
</tr>
<tr>
<td>Ave. of N¹-N⁶</td>
<td>1.956</td>
<td>1.955</td>
<td>1.953</td>
<td>1.955</td>
<td>1.955</td>
<td>1.954</td>
</tr>
</tbody>
</table>
The natural bond order (NBO) analysis also revealed that the bond orders of Fe–N(4-nitropyridine) are higher than those of Fe–N(pyridine) (Table 4). On the other hand, the N–C bond length of the pyridine ring became longer by introducing nitro groups as shown in Table 5. These results strongly indicate the higher π-acceptability of 4-nitropyridine ligand than 4-unsubstituted pyridine ligand.

**Table 4.** Bond orders of Fe–N bonds of low-spin ferrous complexes 1–4 estimated by natural bond analysis.

<table>
<thead>
<tr>
<th>N atom</th>
<th>1</th>
<th>2a</th>
<th>2b</th>
<th>3a</th>
<th>3b</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>N^1</td>
<td>R^1 = H</td>
<td>0.568</td>
<td>0.566</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R^1 = NO_2</td>
<td>0.581</td>
<td>0.574</td>
<td>0.572</td>
<td>0.569</td>
<td></td>
</tr>
<tr>
<td>N^2</td>
<td>R^2 = H</td>
<td>0.589</td>
<td>0.592</td>
<td>0.598</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R^2 = NO_2</td>
<td>0.602</td>
<td>0.599</td>
<td>0.598</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N^3</td>
<td>R^3 = H</td>
<td>0.567</td>
<td>0.574</td>
<td>0.564</td>
<td>0.575</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R^3 = NO_2</td>
<td>0.574</td>
<td>0.577</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N^4</td>
<td></td>
<td>0.556</td>
<td>0.563</td>
<td>0.561</td>
<td>0.564</td>
<td>0.566</td>
</tr>
<tr>
<td>N^5</td>
<td></td>
<td>0.626</td>
<td>0.619</td>
<td>0.616</td>
<td>0.620</td>
<td>0.617</td>
</tr>
<tr>
<td>N^6</td>
<td></td>
<td>0.613</td>
<td>0.606</td>
<td>0.608</td>
<td>0.609</td>
<td>0.608</td>
</tr>
</tbody>
</table>

**Table 5.** Selected N–C distances in pyridyl moieties of low-spin ferrous complexes 1–4. ^a

<table>
<thead>
<tr>
<th>N atom</th>
<th>1</th>
<th>2a</th>
<th>2b</th>
<th>3a</th>
<th>3b</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>N^1</td>
<td>R^1 = H</td>
<td>1.364</td>
<td>1.363</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R^1 = NO_2</td>
<td>1.367</td>
<td>1.365</td>
<td>1.366</td>
<td>1.365</td>
<td></td>
</tr>
<tr>
<td>N^2</td>
<td>R^2 = H</td>
<td>1.357</td>
<td>1.357</td>
<td>1.356</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R^2 = NO_2</td>
<td>1.363</td>
<td>1.361</td>
<td>1.360</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N^3</td>
<td>R^3 = H</td>
<td>1.364</td>
<td>1.362</td>
<td>1.363</td>
<td>1.362</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R^3 = NO_2</td>
<td>1.365</td>
<td>1.364</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^a^ The α-carbon atoms close to amine N atom (N^4^) are selected.
The compositions of the frontier orbitals in terms of contributions from Fe, the pyridyl ligands, the 4-nitropyridyl ligands, and acetonitrile are listed in Table 6. HOKS, HOKS–1, and HOKS–2 have a large contribution of iron (~84%) and also contain some fraction of pyridyl and/or 4-nitropyridyl moieties. The sum of contribution of pyridyl and 4-nitropyridyl moieties reaches ca. 16–17% in HOKS (Fe d$_{xy}$). On the other hand, HOKS–1 (Fe d$_{yz}$) and HOKS–2 (Fe d$_{zx}$) contain the fraction of MeCN, but not the fraction of pyridyl and/or 4-nitropyridyl moieties. Interestingly, the fraction of 4-nitropyridine π* orbitals in HOKS increases from 0 to 6, 11, and 17 on going from 1 to 4. In addition, LUKS of 2, LUKS+1 of 3, and LUKS+2 of 4 have large fractions of 4-nitropyridyl moieties as well as some contribution of the Fe d$_{xy}$ orbital. In contrast, the total fraction of MeCN π* orbitals to HOKS–1 and HOKS–2 does not change regardless of the number of nitro groups (1: 18.6%, 2a: 18.4%, 3a: 18.5%, 4: 18.6%). Thus, these results demonstrate that π back-bonding interactions between the Fe d$_{xy}$ orbital and the π* orbitals of the pyridine moiety become stronger in a stepwise manner as the number of nitro groups increases.

Then, we investigated in detail how the nitro-substitution stabilized the orbitals of pyridyl moiety by comparing the KSOs of pyridine and 4-nitropyridine molecules. Figure 5 shows the frontier orbitals of pyridine and 4-nitropyridine. The π and π* orbitals of 4-nitropyridine are located in lower energy than those of pyridine. Particularly, the LUKS of 4-nitropyridine is located by 2.3 eV lower energy than that of pyridine, which well accounts the enhanced π-acceptability of 4-nitropyridine ligands. In both cases of 4-nitropyridine and pyridine, the phase of the LUKS is allowed to interact with d$_{xy}$(Fe) orbital (HOKS in the iron complexes) when the pyridine is coordinated to Fe(II). Indeed, the π back-bonding interactions between d$_{xy}$(Fe) and π*(NO$_2$-Py) are clearly observed in LUKS, LUKS+1, and LUKS+2 of 2–4, as shown in Figure 6.

**Ligand field of the complex in high-spin configuration**

To understand how the π back-bonding affects the spin-crossover behaviors of 1–4, the effect of the π back-bonding on the ligand field strength should be investigated not only in the low-spin state (S = 0) but also in high-spin state (S = 2). In this context, we optimized the structures of 1–4 in high-spin configuration (1$^*$–4$^*$) and calculated their KSOs in low-spin configuration (S = 0).
Table 6. Orbital energies and atomic orbital contributions for frontier orbitals from HOKS–2 to LUKS+2 of the low-spin ferrous complexes 1–4.

<table>
<thead>
<tr>
<th>complex</th>
<th>KSO</th>
<th>E (eV)</th>
<th>%Fe</th>
<th>%Py</th>
<th>%NO$_2$-Py</th>
<th>%MeCN</th>
<th>symmetry $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUKS+2</td>
<td>–1.711</td>
<td>1.0</td>
<td>95.0</td>
<td>–</td>
<td>–</td>
<td>0.9</td>
<td>$\pi^*$($\text{Py}$) – $d_{xy}$</td>
</tr>
<tr>
<td>LUKS+1</td>
<td>–1.828</td>
<td>4.9</td>
<td>94.0</td>
<td>–</td>
<td>–</td>
<td>0.1</td>
<td>$\pi^*$($\text{Py}$) – $d_{xy}$</td>
</tr>
<tr>
<td>LUKS</td>
<td>–1.987</td>
<td>0.9</td>
<td>93.5</td>
<td>–</td>
<td>–</td>
<td>0.3</td>
<td>$\pi^*$($\text{Py}$)</td>
</tr>
<tr>
<td>HOKS</td>
<td>–6.414</td>
<td>79.1</td>
<td>15.8</td>
<td>–</td>
<td>–</td>
<td>4.7</td>
<td>$d_{xy} – \pi(\text{Py})$</td>
</tr>
<tr>
<td>HOKS–1</td>
<td>–6.647</td>
<td>87.4</td>
<td>4.3</td>
<td>–</td>
<td>–</td>
<td>7.2</td>
<td>$d_{yz} – \pi(\text{MeCN})$</td>
</tr>
<tr>
<td>HOKS–2</td>
<td>–6.680</td>
<td>85.0</td>
<td>1.8</td>
<td>–</td>
<td>–</td>
<td>11.4</td>
<td>$d_{xz} – \pi(\text{MeCN})$</td>
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<th>complex</th>
<th>KSO</th>
<th>E (eV)</th>
<th>%Fe</th>
<th>%Py</th>
<th>%NO$_2$-Py</th>
<th>%MeCN</th>
<th>symmetry $^a$</th>
</tr>
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<tr>
<td>LUKS+2</td>
<td>–1.892</td>
<td>2.5</td>
<td>54.9</td>
<td>39.0</td>
<td>–</td>
<td>0.2</td>
<td>$\pi^*($Py$)$ – $d_{xy}$</td>
</tr>
<tr>
<td>LUKS+1</td>
<td>–2.068</td>
<td>0.8</td>
<td>84.9</td>
<td>7.8</td>
<td>–</td>
<td>0.3</td>
<td>$\pi^*($Py$)$</td>
</tr>
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<td>–3.657</td>
<td>2.3</td>
<td>10.6</td>
<td>86.5</td>
<td>–</td>
<td>0.2</td>
<td>$\pi^*($NO$<em>2$-Py$)$ – $d</em>{xy}$</td>
</tr>
<tr>
<td>HOKS</td>
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<td>78.1</td>
<td>11.2</td>
<td>6.0</td>
<td>–</td>
<td>4.3</td>
<td>$d_{xy} – \pi($Py$) – \pi($NO$_2$-Py$)$</td>
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<td>HOKS–1</td>
<td>–6.830</td>
<td>87.2</td>
<td>3.5</td>
<td>0.6</td>
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<td>1.2</td>
<td>1.0</td>
<td>–</td>
<td>11.0</td>
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<table>
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<tr>
<th>complex</th>
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<th>E (eV)</th>
<th>%Fe</th>
<th>%Py</th>
<th>%NO$_2$-Py</th>
<th>%MeCN</th>
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<td>–1.925</td>
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<tr>
<td>LUKS+1</td>
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<td>96.0</td>
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<td>0.0</td>
<td>$\pi^*($NO$<em>2$-Py$)$ – $d</em>{xy}$</td>
</tr>
<tr>
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<td>0.2</td>
<td>98.8</td>
<td>–</td>
<td>0.1</td>
<td>$\pi^*($NO$_2$-Py$)$</td>
</tr>
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<td>5.8</td>
<td>11.1</td>
<td>–</td>
<td>4.8</td>
<td>$d_{xy} – \pi($NO$_2$-Py$)$ – $\pi($Py$)$</td>
</tr>
<tr>
<td>HOKS–1</td>
<td>–7.008</td>
<td>85.5</td>
<td>1.2</td>
<td>0.9</td>
<td>–</td>
<td>10.9</td>
<td>$d_{yz} – \pi($MeCN$)$</td>
</tr>
<tr>
<td>HOKS–2</td>
<td>–7.008</td>
<td>87.1</td>
<td>0.8</td>
<td>3.2</td>
<td>–</td>
<td>7.6</td>
<td>$d_{xz} – \pi($MeCN$)$</td>
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</tbody>
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<table>
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<tr>
<th>complex</th>
<th>KSO</th>
<th>E (eV)</th>
<th>%Fe</th>
<th>%Py</th>
<th>%NO$_2$-Py</th>
<th>%MeCN</th>
<th>symmetry $^a$</th>
</tr>
</thead>
<tbody>
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<td>LUKS+2</td>
<td>–3.636</td>
<td>3.0</td>
<td>–</td>
<td>–</td>
<td>96.5</td>
<td>0.0</td>
<td>$\pi^*($NO$<em>2$-Py$)$ – $d</em>{xy}$</td>
</tr>
<tr>
<td>LUKS+1</td>
<td>–3.685</td>
<td>1.7</td>
<td>–</td>
<td>–</td>
<td>97.9</td>
<td>0.2</td>
<td>$\pi^*($NO$<em>2$-Py$)$ – $d</em>{xy}$</td>
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<tr>
<td>LUKS</td>
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<td>0.6</td>
<td>–</td>
<td>–</td>
<td>98.4</td>
<td>0.1</td>
<td>$\pi^*($NO$_2$-Py$)$</td>
</tr>
<tr>
<td>HOKS</td>
<td>–6.952</td>
<td>78.0</td>
<td>–</td>
<td>–</td>
<td>16.9</td>
<td>4.6</td>
<td>$d_{xy} – \pi($NO$_2$-Py$)$</td>
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<tr>
<td>HOKS–1</td>
<td>–7.158</td>
<td>86.8</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td>HOKS–2</td>
<td>–7.181</td>
<td>85.9</td>
<td>–</td>
<td>–</td>
<td>2.4</td>
<td>10.2</td>
<td>$d_{xz}$</td>
</tr>
</tbody>
</table>

$^a$ N$_{\text{Py}}$-Fe-N$_{\text{Py}}$ is the x axis, N$_{\text{MeCN}}$-Fe-N$_{\text{py}}$ is the y axis.
Figure 8. Energy diagrams and schematic illustrations of frontier orbitals of pyridine and 4-nitropyridine molecules. The value of each isocontour surface is 0.03 au.

Figure 9. Schematic illustrations of frontier orbitals of low-spin ferrous complexes 1–4. The value of each isocontour surface is 0.03 au.
The Fe–N distances of 1’–4’ are about 2.2 Å (Table 7), which show good agreements with those typically found in high-spin Fe(II) complexes such as [Fe(6-Me3-TPA)(CH3CN)2]2+ (2.18–2.25 Å), [Fe(BQPA)(H2O)(ClO4)]2+ (2.17–2.20 Å) and [Fe(5-Me2-BPME)(CH3CN)2]2+ (2.16–2.23 Å) (where BQPA = bis(2-quinolylmethyl)(2-pyridylmethyl)amine; BPMEN = N,N’-dimethyl-N,N’-bis(2-pyridylmethyl)-1,2-diamino-ethane). Contrary to the low-spin structures, there is no systematic change in Fe–N bond length of the high spin structures on going from 1’ to 4’. The KSO diagrams of singlet 1’–4’ are significantly different from those of singlet 1–4 (Figure 7 vs. Figure 10). For examples, dσ like orbitals are located in lower energy than π*(Py) like orbitals. The d-d splittings of 1’–4’ are smaller than those of 1–4, which clearly describes that the high-spin structures have weaker ligand fields than the low-spin ones. This result should be caused by the longer Fe–N distances of high-spin structures. The dσ and dπ orbitals of 4’ are stabilized by 0.38 and 0.44 eV than those of 1’, respectively, which are smaller than the case of the low-spin structures. Moreover, the contribution of π*(Py) orbital to dπ like HOKS in 1’–4’ (1; 9.0%, 2a; 8.6%, 3a; 8.6%, 4; 7.3%) is lower than that in 1–4 (1; 15.8%, 2a; 17.2%, 3a; 16.9%, 4; 16.9%). These results strongly suggest that the π back-bonding interactions of 1’–4’ are smaller than those of 1–4. Thus, the high-spin structure has smaller ligand field and is less sensitive toward nitro-substitution than the low-spin one. Stabilization of dπ orbitals (especially dxy orbital) corresponding to the highest occupied KSOs seems to stabilize total electronic energy of the complex and to make the low-spin state more preferable.

**Table 7.** Fe–N distances in the optimized structures of 1’–4’.

<table>
<thead>
<tr>
<th>N atom</th>
<th>1’</th>
<th>2a’</th>
<th>2b’</th>
<th>3a’</th>
<th>3b’</th>
<th>4’</th>
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<tbody>
<tr>
<td>N1 R¹ H</td>
<td>2.179</td>
<td>2.179</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R¹ NO₂</td>
<td></td>
<td></td>
<td>2.154</td>
<td>2.185</td>
<td>2.156</td>
<td>2.183</td>
</tr>
<tr>
<td>N² R² H</td>
<td>2.175</td>
<td>2.176</td>
<td>2.174</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>R² NO₂</td>
<td></td>
<td></td>
<td></td>
<td>2.189</td>
<td>2.172</td>
<td></td>
</tr>
<tr>
<td>N³ R³ H</td>
<td>2.180</td>
<td>2.163</td>
<td>2.171</td>
<td>2.178</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R³ NO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.143</td>
<td>2.155</td>
</tr>
<tr>
<td>N⁴</td>
<td>2.269</td>
<td>2.247</td>
<td>2.250</td>
<td>2.240</td>
<td>2.253</td>
<td>2.237</td>
</tr>
<tr>
<td>N⁵</td>
<td>2.090</td>
<td>2.102</td>
<td>2.108</td>
<td>2.105</td>
<td>2.104</td>
<td>2.106</td>
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<tr>
<td>N⁶</td>
<td>2.167</td>
<td>2.158</td>
<td>2.159</td>
<td>2.155</td>
<td>2.143</td>
<td>2.145</td>
</tr>
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</table>
Figure 10. Energy diagrams of frontier orbitals of high-spin ferrous complexes $1'$–$4'$.

Then, in order to estimate the thermal energies, we carried out vibrational frequency calculations with using some functionals such as BLYP, B3LYP, and B3LYP* for 1 and 4 in low-spin configuration ($S = 0$) and $1'$ and $4'$ in high-spin one ($S = 2$) as listed in Table 8. Reiher et al. reported that B3LYP* functional, B3LYP analogue of which exact exchange admixture parameter was modified from 20% to 15%, could well reproduce low-spin/high-spin energy splittings of Fe(II) complexes.\textsuperscript{39,40} The calculated low-spin/high-spin splittings in enthalpy ($\Delta H_{LS-HS}$) are negative, and the $\Delta H_{LS-HS}$ value for trinitro-substituted complex is more negative than that of unsubstituted one, regardless of functionals. This result supports that the low-spin state becomes more thermodynamically preferable by introduction of nitro groups. Although the calculated values based on B3LYP functional are close to zero, BLYP and B3LYP* functionals give values which are consistent with the experimental results that the low-spin species are dominant at 298 K.
Table 8. Calculated gap in enthalpy ($\Delta H_{\text{LS-HS}}$/ kcal·mol$^{-1}$) between low-spin and high-spin complexes using several functionals. $^a$

<table>
<thead>
<tr>
<th>complex</th>
<th>functional</th>
<th>BLPY</th>
<th>B3LYP</th>
<th>B3LYP$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (1')</td>
<td></td>
<td>−19.6</td>
<td>−0.08</td>
<td>−5.5</td>
</tr>
<tr>
<td>4 (4')</td>
<td></td>
<td>−20.2</td>
<td>−0.12</td>
<td>−6.8</td>
</tr>
</tbody>
</table>

$^a\Delta H_{\text{LS-HS}} = H_{\text{LS}} - H_{\text{HS}}$. LS; low-spin, HS; high-spin.

Conclusions

In this study, we investigated the effect of the nitro groups on the electronic and geometric structures of iron(II) complexes supported by TPA-type ligands. The introduction of nitro groups on the tpa-type ligand stabilizes the low-spin state of the ferrous complex, which is caused by significant $\pi$ back-bonding interactions between iron(II) and 4-nitropyridine ligand. The DFT calculation revealed that introducing the nitro groups stabilizes $d\pi$ orbitals more than $d\sigma$ orbitals, which is more prominent with the low-spin state than with the high-spin. Thus, our study demonstrates that a 4-nitropyridine donor group can work as a good $\pi$-acceptor and favor a low-spin ferrous iron state by stabilizing the iron $d\pi$ orbitals.

References

(1) Kahn, O.; Martinez, C. J. Science 1998, 279, 44.


Part II

Selective Oxidation Using Heterogeneous Nb$_2$O$_5$-Based Photocatalysts
Introduction of Part II

In industrial chemistry, organic molecules including C=O\(^1\) or C=N\(^2\) moiety (carbonyl compounds or imine derivatives) have been used as important building blocks of higher-valued product such as polymers, fine chemicals, and pharmaceutical compounds. These products are usually synthesized by oxidative dehydrogenation of alcohols and amines or by oxygenation of hydrocarbons. However, non-catalytic methods with stoichiometric, toxic, corrosive, and expensive oxidants such as dichromate and permanganate, which produce a large amount of heavy metal waste, under stringent conditions of high pressure and/or temperature have been widely used.\(^3\) Therefore, in the last few years, much attention has been paid to the development of heterogeneous catalytic systems that use clean and atom efficient oxidants like molecular oxygen or H\(_2\)O\(_2\).\(^4,5\) Recently, several heterogeneous catalysts employing transition metals that can function with molecular oxygen were reported. Ru species supported by hydroxyapatite,\(^6,7\) Al\(_2\)O\(_3\),\(^8-10\) Au nanoparticles supported by CeO\(_2\),\(^11-13\) and graphite\(^14,15\) are known to be highly active for oxidative dehydrogenation of both of alcohols and amines. Pd-based catalysts such as Pd/hydrotalcite,\(^16,17\) Pd/hydroxyapatite,\(^18,19\) and Pd/Al\(_2\)O\(_3\)\(^20\) are also effective for aerobic oxidation of alcohols. But in these systems, expensive precious metals are employed and relative high temperature (mostly >373 K) is required. In addition, use of solvent such as benzene, trifluorotoluene is necessary in the case of most of these systems.

Aerobic Oxidation Using TiO\(_2\)-based Photocatalysts

Utilizing semiconductor photocatalysts for aerobic oxidation of organic molecules has practical advantages of economical efficiency, environmental-friendliness, reusability, and durability. Up to now, various semiconductor materials have been tested as oxidation photocatalysts, and it is generally accepted that the anatase TiO\(_2\) is the most reliable material owing to its low cost, high photostability, and high photocatalytic activity. When a semiconductor material is irradiated with photons equal to or greater than the band gap energy (e. g. \(h\nu \geq 3.2\) eV for anatase TiO\(_2\)), electrons are excited in the conduction band and remaining holes are generated in the valence band (charge separation, eq 1).\(^21\) The excited electrons and positive holes can recombine on the surface or in the bulk of the particle in a few nano seconds and the energy dissipates as heat (recombination, eq 2).\(^21\)
\[
\begin{align*}
\text{(TiO}_2\text{)} & \ + \ h\nu \ \rightarrow \ h^+ \ + \ e^- \quad (1) \\
h^+ \ + \ e^- \ \rightarrow \ \Delta (heat) \quad (2)
\end{align*}
\]

Since photocatalytic activity strongly depends on the efficiency of charge separation, it is a significant factor to inhibit recombination of the charge carriers. Addition of electron acceptors such as transition metals has been commonly employed in this context.\(^22\) Indeed, a series of various transition-metal loaded TiO\(_2\) (M/TiO\(_2\); M = Pt,\(^{23-28}\) Rh,\(^{29}\) Ru,\(^{30}\) Ni,\(^{31}\) Cu,\(^{32-34}\) and Ag\(^{35}\)) shows improved photocatalytic activity. Excited electrons in the conduction band and positive holes in the valence band can be also trapped by Ti\(^{4+}\) to form Ti\(^{3+}\) (eq 3) and O\(^2-\) (lattice oxygen) to form O\(^-\) (eq 4), respectively.\(^36\)

\[
\begin{align*}
e^- & \ + \ \text{Ti}^{4+} \ \rightarrow \ \text{Ti}^{3+} \quad (3) \\
h^+ & \ + \ \text{O}^{2-} \ \rightarrow \ \text{O}^- \quad (4)
\end{align*}
\]

The valence band of anatase TiO\(_2\) composed of O 2p orbital has a considerably positive potential (ca. +3.0 V vs. NHE).\(^21\) The trapped hole (O\(^-\)) is, therefore, able to oxidize most organic compounds. However, as partial oxidation products are generally more easily to be oxidized than parent substrate, over-oxidation to CO\(_2\) is essentially associated with photocatalytic oxidation with TiO\(_2\) due to the strong oxidizing ability. Moreover, photocatalytic system of anatase TiO\(_2\) in aerobic condition generally produces various active oxygen species other than O\(^-\) as represented in eqs 5–9.\(^21,28,36-38\)

\[
\begin{align*}
\text{Ti}^{3+} & \ + \ \text{O}_2 \ \rightarrow \ \text{Ti}^{4+} \ + \ \text{O}_2^- \quad (5) \\
\text{O}_2^- & \ + \ H^+ \ \rightarrow \ \bullet\text{OOH} \quad (6) \\
h^+ & \ + \ \text{–OH} \ \rightarrow \ \bullet\text{OH} \quad (7) \\
\text{O}^- & \ + \ \text{H}_2\text{O} \ \rightarrow \ \text{–OH} \ + \ \bullet\text{OH} \quad (8) \\
\text{O}^- & \ + \ \text{O}_2 \ \rightarrow \ \text{O}_3^- \quad (9)
\end{align*}
\]

where –OH represents surface hydroxyl group of TiO\(_2\). These active oxygen species are also highly oxidizing and trigger non-selective oxidation. Particularly in aqueous condition, formation of hydroxyl radical becomes dominant. With this background, most researchers have focused on application of TiO\(_2\) to degradation reactions such as mineralization of volatile organic compounds (VOC) and water purification.\(^39\) In this context, application of TiO\(_2\) to selective catalytic oxidation
has been challenging.

Recently, a few efforts have been devoted to developing TiO$_2$ as a selective catalyst in the oxidation of various types of organic molecules such as alkanes, arenes, and alcohols. The strategies employed are based on optimizing the solvent, the reaction conditions, or the preparation method of TiO$_2$. However, over-oxidation to CO$_2$ or non-selective oxidation is inevitably associated even with these systems. To establish a selective photocatalytic oxidation system, one should focus on fundamental approaches to remove the undesired oxidation process caused by the active oxygen species.

### Selective Photooxidation of Alcohols over Nb$_2$O$_5$

In 2007, Ohuchi et al. reported that solvent-free aerobic oxidation of alcohol photocatalytically proceeded over niobium oxide (Nb$_2$O$_5$), and Nb$_2$O$_5$ showed higher selectivity to partial oxidation products than TiO$_2$ at a comparable conversion level (Figure 1). In this case, the highest photocatalytic activity is obtained when the calcination temperature of niobic acid hydrate as a catalyst precursor is 773 K. The photocatalytic activity correlates to the surface area and crystallinity which are decreases and increases with increase in calcination temperature, respectively.

![Figure 1. Photooxidation of 1-pentanol over various metal oxides. Reaction condition: pentanal (10 ml), catalyst (100 mg), O$_2$ flow (2 ml·min$^{-1}$) irradiation time (24 h). $^a$irradiation time (84 h).](image)
The mechanistic study\textsuperscript{50} revealed that alcohol photooxidation over Nb\textsubscript{2}O\textsubscript{5} was oxidative dehydrogenation via photoactivation of surface complex consisted of dissociatively adsorbed alcohol (alkoxide) and Nb\textsubscript{2}O\textsubscript{5} as shown scheme 1: (a) dissociative adsorption of alcohol, (b) photoactivation of Nb\textsubscript{2}O\textsubscript{5}-alkoxide surface complex, (c) conversion of photogenerated carbon radical to carbonyl compound, (d) desorption of product, and (e) reoxidation of reduced Nb\textsuperscript{4+} sites by molecular oxygen. Moreover, although Nb\textsubscript{2}O\textsubscript{5} catalyst is not able to absorb light at wavelengths longer than 390 nm, the photooxidation of 1-pentanol proceeds under irradiation up to ca. 480 nm. This phenomenon has been rationalized by generation of donor levels within the forbidden band of Nb\textsubscript{2}O\textsubscript{5} due to the formation of alkoxide species. Thus, the mechanism they proposed is entirely different from classical electron transfer mechanism found in semiconductor photocatalysis; the formation of an excited electron in the conduction band and a positive hole in the valence band which trigger reduction and oxidation, respectively.

\textbf{Survey of Part II}

As mentioned above, Nb\textsubscript{2}O\textsubscript{5} shows selective photocatalysis and unique photoactivation mechanism in the system of alcohol oxidation. But the photocatalytic activity of Nb\textsubscript{2}O\textsubscript{5} is much lower than that of TiO\textsubscript{2}. One of particular interest is whether the properties of Nb\textsubscript{2}O\textsubscript{5} are also observed for substrates other than alcohol. In this context in chapter 4 and 5, the author applied Nb\textsubscript{2}O\textsubscript{5} to aerobic photooxidation of amines and hydrocarbons, evaluated the photocatalytic performance, and investigated their reaction mechanisms in detail. The rationale for the higher selectivity observed for Nb\textsubscript{2}O\textsubscript{5} than that for TiO\textsubscript{2} was also discussed and clarified.

The other interest is the methodologies to improve the photocatalytic performance of existing materials, in other words, how to increase the photocatalytic activity of Nb\textsubscript{2}O\textsubscript{5} or to enhance the selectivity for TiO\textsubscript{2}. In chapter 6, the author prepared a variety of metal loaded Nb\textsubscript{2}O\textsubscript{5} photocatalysts
(M/Nb$_2$O$_5$; M = Pt, Rh, Ru, Ni, Cu, and Ag) for the purpose of increase in the photocatalytic activity in 1-pentanol oxidation due to promotion of charge separation. In addition, the Cu/Nb$_2$O$_5$ catalyst which showed much higher activity than bare Nb$_2$O$_5$ was applied to a wide scope of alcohols. In this case, however, no promotion effect was observed through the addition of Pt, Rh, Ru, Ni and Ag. This result strongly suggests that the role of Cu cannot be explained by the simple charge promotion mechanism. In chapter 7, the mechanism of alcohol photooxidation over Cu/Nb$_2$O$_5$ was investigated in detail to understand the role of Cu in enhancement of the photocatalytic activity in alcohol oxidation. In chapter 8, the author modified the electronic state of Cu on Cu/Nb$_2$O$_5$ by pretreatment to optimize the positive role of Cu revealed in the previous chapter. Correlation between photocatalytic activity of the modified Cu/Nb$_2$O$_5$ catalysts in alcohol photooxidation and the state of Cu on Cu/Nb$_2$O$_5$ was also studied by means of X-ray absorption fine structure (XAFS) spectroscopy. On the other hand, to develop a selective photocatalytic system using TiO$_2$-based material, one should inhibit non-selective oxidation caused by active oxygen species. In chapter 9, the author demonstrated a selectivity enhancement in alcohol photooxidation using TiO$_2$ covered with Nb$_2$O$_5$. Correlation between the selectivity and amount of photogenerated oxygen anion radical species was also discussed.

References

(15) So, M. H.; Liu, Y. G.; Ho, C. M.; Che, C. M. Chem. Asian J. 2009, 4, 1551.
Chapter 4

Selective Photooxidation of Amines Using Nb$_2$O$_5$

Abstract

Niobium oxide (Nb$_2$O$_5$) can function as a photocatalyst for selective oxidation of benzylamine rather than other semiconductor metal oxides such as TiO$_2$, ZnO and WO$_3$. Various amines including primary, secondary and cyclic amines are also photocatalytically converted to corresponding imines in excellent yields by using Nb$_2$O$_5$ in atmospheric pressure of O$_2$. Nb$_2$O$_5$ exhibits a catalytic activity with high selectivity even under visible light ($\lambda > 390$ nm) irradiation, although Nb$_2$O$_5$ does not absorb visible light. Mechanistic study revealed that the photooxidation of amine over Nb$_2$O$_5$ was oxidative dehydrogenation of amine to corresponding imine via photoactivation of surface complex consisted of dissociatively adsorbed amine (amide) and Nb$_2$O$_5$. When the substrate is a primary amine, the produced primary imine is immediately hydrolyzed and converted into dimerized imine. DFT calculations revealed that 1) the surface donor level derived from the adsorbed amide species was located in the forbidden band, 2) direct electron excitation from the surface donor level to the conduction band takes place by absorbing a photon, 3) the excitation energy from surface donor level to the Nb 4d conduction band is lower than that from the O 2p valence band to Nb 4d.
Introduction

Oxidation of amine to imine is an important chemical transformation because of the versatile applications of imines as synthetic intermediates of medicines or biologically active nitrogen containing organic compounds.\textsuperscript{1} Several oxidation procedures using stoichiometric oxidants such as 2-iodoxybenzoic acid\textsuperscript{2,3} or $N$-tert-butylphenylsulfinimidoyl chloride\textsuperscript{4} have been reported. However, a catalytic system using molecular oxygen as a sole oxidant has been desired in view of green chemistry.\textsuperscript{5,6} In this context, a number of transition-metal catalyzed aerobic oxidation systems have been developed. Ru-based catalysts such as RuCl$_3$\textsuperscript{7} $[\text{RuCl}_2(\text{RCH}_2\text{NH}_2)(\text{PPh}_3)_2]$\textsuperscript{8,9} Ru-porphyrin\textsuperscript{10} Ru-hydroxyapatite\textsuperscript{11} Ru$_2$(OAc)$_3$Cl\textsuperscript{12} and Ru/Al$_2$O$_3$\textsuperscript{13} are known to be effective for aerobic oxidation of amines. Au nanoparticles supported on Al$_2$O$_3$\textsuperscript{14,15} CeO$_2$\textsuperscript{14,15} graphite\textsuperscript{16} and hydroxyapatite\textsuperscript{16} are also found to be good catalysts for amine oxidation. But in these systems, expensive precious metals are employed and relative high temperature (mostly $> 373$ K) is required.

Utilizing semiconductor photocatalysts for aerobic oxidation of organic molecules has practical advantages of economical efficiency, environmental-friendliness, reusability, and durability. In addition, to effectively utilize solar energy, it is necessary to develop a material that will function under visible light.\textsuperscript{17} Very recently, Su and co-workers reported that mesoporous graphite carbon nitride (mpg-C$_3$N$_4$) can work as effective photocatalyst to activate O$_2$ for the selective oxidations of benzylic alcohols and amines with visible light\textsuperscript{18,19} Although this material exhibits excellent catalytic performance under visible light irradiation, high oxygen pressure (0.5 MPa) and trifluorotoluene as solvent are necessary to obtain good yields. Zhao et al. reported that photooxidation of amines using TiO$_2$ with UV light gave a high selectivity to imines under a diluted condition.\textsuperscript{20} We recently reported that photocatalytic oxidation of various alcohols proceeded selectively over niobium oxide (Nb$_2$O$_5$) under a mild condition.\textsuperscript{21,22} Nb$_2$O$_5$ showed higher selectivities to partial oxidation products; therefore it can be thought that Nb$_2$O$_5$ is more suitable for selective oxidation than TiO$_2$. Moreover, we found that Nb$_2$O$_5$ can catalyze the selective photooxidation of alcohols even under visible light irradiation up to 450 nm, although the band gap of Nb$_2$O$_5$ is at 390 nm (3.2 eV).

In the present study, we report that photocatalytic aerobic oxidations of various amines to
imines take place over Nb$_2$O$_5$ with high yields at room temperature and atmospheric pressure. Nb$_2$O$_5$ exhibits a catalytic activity in high selectivity even under visible light irradiation as well as alcohol oxidation. Mechanistic study was also carried out to understand the catalysis and the mechanism of visible response.

**Experimental**

**Preparation**

Niobium oxide hydrate (Nb$_2$O$_5$·$n$H$_2$O, HY-340) was kindly supplied from CBMM. Niobium oxide (Nb$_2$O$_5$) catalyst was prepared by calcinations of niobium oxide hydrate in a dry air flow at 773 K for 5 h (BET surface area: 48 m$^2$·g$^{-1}$). BET surface areas of catalysts were determined using N$_2$ adsorption isotherm at 77 K measured by a BELSORP 28SA (BEL Japan Corp.). TiO$_2$, ZrO$_2$ and CeO$_2$ samples used in this study were supplied from Japan Catalysis Society and were calcined at 773 K for 5 h (JRC-TIO-4, equivalent to Degussa. P-25; rutile/anatase = 3/7; BET surface area = 49 m$^2$·g$^{-1}$, JRC-ZRO-1 and JRC-CEO-1). MoO$_3$ and WO$_3$ were prepared by calcination (773 K, 5 h) of ammonium paratungstate ((NH$_4$)$_{10}$(H$_2$W$_{12}$O$_{42}$)·4H$_2$O) and molybdic acid (H$_2$MoO$_4$), respectively. V$_2$O$_5$, Ta$_2$O$_5$ and ZnO were purchased from Wako Pure Chemical Industries, Ltd and were calcined at 773 K for 5 h. All catalysts were ground into powder under 100 mesh (0.15 mm) after calcination. All reagents (substrate and solvent) were of reagent grade and were obtained from Aldrich Chemical Co., Tokyo Kasei Kogyo Co., Ltd and Wako Pure Chemical Industries, Ltd. According to the literature,$^{23}$ $N$-deuterated benzylamine (benzylamine-$N$-$d_2$) was prepared by washing of benzylamine (3 g) in CH$_2$Cl$_2$ (5 ml) with D$_2$O (3 ml) three times, followed by separation, evaporation of CH$_2$Cl$_2$, and distillation. An $^1$H NMR spectrum indicated >90% deuterium content at the $\alpha$ positions by comparison of the $\alpha$ signals’ integral with that of the benzylic position.

**Reaction Conditions of Photooxidation of Amine**

The photocatalytic oxidation of amines was carried out in a batch system under atmospheric oxygen. Nb$_2$O$_5$ (100 mg), amine (5 mmol), benzene as a solvent (10 ml), and a stirring bar were
introduced to the Pyrex glass reactor. The substrate was used without further purification. The suspension was stirred vigorously at room temperature and irradiated through the flat bottom of the reactor by reflection from a cold mirror with a 500 W ultra-high pressure Hg lamp (USHIO Denki Co.). The organic products were identified by GC-MS (Shimadzu GC-MS QP5050) and $^1$H-NMR (JEOL ECX400) and quantified by FID-GC (Shimadzu GC-14B) using chlorobenzene as an internal standard. For kinetic analysis, benzylamine or dibenzylamine was used as a substrate. Substrate concentration and oxygen pressure were balanced by using benzene and nitrogen when required, respectively. The light intensity was controlled using a metal mesh. To measure an action spectrum, the reaction was carried out in a batch reactor with Nb$_2$O$_5$ (200 mg) and benzylamine (4 mmol) and benzene as a solvent (5 ml) using a monochromatic irradiator (JASCO CRM-FA Spectro Irradiator) as light source.

**UV-Vis spectra**

Diffuse reflectance spectra (1 nm resolution) were obtained with a UV-Vis spectrometer (JASCO UV570). A slurry of the mixture of benzylamine (0.8 ml) and Nb$_2$O$_5$ (500 mg) was used as the sample of benzylamine adsorbed on Nb$_2$O$_5$.

**FT-IR spectra**

FT-IR spectra of the sample before and during photo irradiation were recorded with a Perkin-Elmer SPECTRUM ONE Fourier transform infrared spectrometer. The resolution of the spectra was 4 cm$^{-1}$. A Nb$_2$O$_5$ sample was cast into a pellet with diameter 12 mm. The molded sample was introduced into an in situ IR cell equipped with BaF$_2$ windows. Prior to the measurements, the sample was pretreated with 6.7 kPa of O$_2$ for 1 h and evacuated at 673 K for 0.5 h. A 200 W Hg-Xe lamp (SAN-EI ELECTRIC SUPERCURE-204S) was used as light source. An L-42 cutoff filter was used for visible light irradiation (> 390 nm). 6.7 kPa of O$_2$ was introduced onto the Nb$_2$O$_5$ with adsorbed amine before photo-irradiation.
ESR spectra

ESR measurements were carried out using an X-band ESR spectrometer (JEOL JES-SRE2X) with in situ quartz cell. Prior to the measurements, the sample was pretreated with 6.7 kPa of O₂ for 1 h and evacuated at 673 K for 0.5 h. The g value of the radical species was determined using a Mn(II) marker. The ESR spectra of Nb₂O₅ with adsorbed amine were recorded before and after photo-irradiation. A 500 W ultra-high pressure Hg lamp was used as light source. An L-42 cutoff filter was used for visible light irradiation (> 390 nm). ESR spectral simulations were performed using the Win-EPR SimFonia software package from Bruker, software version 1.25, 1996.

Surface models and DFT calculation method

Quantum chemical calculations using the DFT method as implemented in Gaussian 03 were carried out to investigate the electronic structure and excitation energy of the Nb₂O₅ and Nb₂O₅-amide complex. We used the neutral Nb₁₂O₄₃H₂₆ cluster (1) in this study which was obtained from the structure of H-Nb₂O₅ by saturating the peripheral oxygen atoms with hydrogen atoms. The Nb₁₂O₄₂H₂₅(NHCH₃) cluster (2) as a model of the Nb₂O₅-amide complex was obtained by substitution of one OH group of the Nb₁₂O₄₃H₂₆ cluster. The calculation made use of Becke’s three parameter hybrid (B3LYP) method involving Lee et al.’s correlation function and the LanL2DZ basis set for a single point energy calculation. One-electron excitation energies of model clusters were also obtained by time-dependent (TD) calculations with singlet spin multiplicity.

Results and Discussion

Photooxidation of Benzylamine over Various Metal Oxides

Photocatalytic activity and selectivity in the aerobic oxidation of benzylamine over various metal oxides were examined as summarized in Table 1. TiO₂, ZnO, and Nb₂O₅ show much higher yields of N-benzylidene benzylamine than other oxides (Table 1, entry 1–3). Nb₂O₅ showed the highest yield per mole of catalyst (Table 1, entry 3). TiO₂, which is an extensively used photocatalyst, also exhibited higher yield than Nb₂O₅ and ZnO. However the selectivity to N-benzylidene benzylamine was comparatively low because benzaldehyde was formed as a byproduct (Table 1,
entry 1). The highest selectivity was obtained with Nb$_2$O$_5$ among the metal oxides tested. When benzylamine was photoirradiated in the absence of any catalyst, a very low yield was observed (Table 1, entry 11). The evolution of photogenerated products over Nb$_2$O$_5$ responded to illumination. Moreover, no product was detected in the dark with the Nb$_2$O$_5$ catalyst (Table 1, entry 4). These indicate that that photooxidation over the Nb$_2$O$_5$ catalyst was due entirely to a photocatalytic reaction.

**Table 1. Oxidation of benzylamine over various metal oxides.**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Yield (µmol)</th>
<th>Yield (µmol / mmol cat)$^b$</th>
<th>Selectivity (%)$^c$</th>
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<tr>
<td>1</td>
<td>TiO$_2$</td>
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<td>708</td>
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<td>ZnO</td>
<td>790</td>
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<td>94</td>
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<td>Nb$_2$O$_5$</td>
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<td>915</td>
<td>98</td>
</tr>
<tr>
<td>4$^d$</td>
<td>Nb$_2$O$_5$</td>
<td>n. d.</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
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<td>472</td>
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<td>none</td>
<td>199</td>
<td>–</td>
<td>81</td>
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$^a$ Reaction conditions: catalyst (100 mg), benzylamine (5 mmol), benzene as a solvent (10 ml), irradiation time (5 h), oxygen pressure (1 atm), $^b$ amount of $N$-benzilidene benzylamine per mole of catalyst. $^c$ selectivity to $N$-benzylidene benzylamine. Benzaldehyde was yielded as a main by-product except entry 10. $^d$ In the dark. $^e$ Benzylamine-$N$-carbaldehyde was formed as a main by-product.
The oxidation of various amines including primary, secondary and bicycloamine derivatives were examined by using the Nb$_2$O$_5$ photocatalyst (Table 2). Primary benzylamine derivatives bearing various functional groups (OMe, Me, H, Cl, and CF$_3$) were converted to corresponding coupled imines with excellent yields (Table 2, entries 1–7). Electron-rich benzylamines (OMe and Me derivatives) were oxidized faster than electron-deficient ones (Cl and CF$_3$ derivatives) (Table 2, entries 2–5). The reaction rate of the regioisomer increased in the order of $\text{orth} < \text{meta} < \text{para}$ isomer, indicating the presence of a steric effect (Table 2, entries 2, 6, and 7). A primary aliphatic amine was also converted to the corresponding coupled imine, but the selectivity was lower than those of benzylic homologues (Table 2, entry 8). Secondary N-alkylbenzylamines (alkyl = Bn, Ph, iPr, and tBu) were also oxidized to dehydrogenated imines. (Table 2, entries 9–12). Relative high yields were observed within 20 h in the oxidations of N-isopropylbenzylamine and dibenzylamine. On the other hand, N-phenyl and N-tert-butyl derivatives were oxidized very slowly. The order of reaction rates corresponding to the bulkiness of the alkyl moiety ($iPr > \text{Bn} >> tBu > \text{Ph}$) indicates that steric hindrance around the nitrogen atom is a key factor for the reaction rate. Benzaldehyde was formed as a byproduct in the oxidations of these secondary benzylic amines. The formation of benzaldehyde is attributed to the oxidative cleavage of the C–N bond. In addition, a small amount of N-benzylidene benzylamine was also yielded in these cases. This indicates an involvement of the C–N bond cleavage, followed by coupling of the fragments. 1,2,3,4-Tetrahydroisoquinoline was smoothly converted to mono-dehydrogenated 3,4-dihydroisoquinoline with high yield (Table 2, entry 13). In contrast, the rate of oxidation of 1,2,3,4-tetrahydroquinoline to aromatized quinoline was much slower than the $\text{iso}$-isomer (Table 2, entry 14). In this case, a small amount of mono-dehydrogenated 3,4-dihydroquinoline as an intermediate product was also detected. The significant difference of the reaction rate between the tetrahydroquinoline isomers is generally observed in various catalytic systems. Indole was yielded with moderate selectivity in the oxidation of indoline. The Nb$_2$O$_5$ photocatalyst was reusable and showed the same conversion and selectivity without any pretreatment as the catalyst as prepared. The amine oxidations over Nb$_2$O$_5$ took place even under visible light (> 390 nm) irradiation (Table 2, entries 1′–15′). Although the reaction rates were lower than that under UV (> 300 nm) irradiation, comparable selectivities were obtained. In the absence of Nb$_2$O$_5$, oxidation of benzylamine did not proceed under visible irradiation.
Table 2. Aerobic oxidation of various amines to corresponding imines using Nb$_2$O$_5$. $^a$

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>T / h</th>
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<th>Sel. (%)</th>
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$^a$ Reaction condition: Nb$_2$O$_5$ (100 mg), substrate (5 mmol), benzene as a solvent (10 ml), $\lambda > 300$ nm (entries 1–15) or $\lambda > 390$ nm (entries 1'–15'), oxygen pressure (1 atm).
FT-IR Measurement for Adsorbed Species

In order to understand the reaction mechanism of amine photooxidation over Nb$_2$O$_5$, the adsorbed species on Nb$_2$O$_5$ before and during photoirradiation were characterized in detail by FT-IR. Figure 1 shows FT-IR spectra obtained when benzylamine was adsorbed on Nb$_2$O$_5$. Although two bands assigned to NH$_2$ bending vibration ($\delta_{\text{NH}_2}$)$^{32}$ were observed at 1620 and 1583 cm$^{-1}$ upon the introduction of benzylamine, the band at 1583 cm$^{-1}$ grew with increase in the introduction time (Figure 1B, form a–e). After evacuation at room temperature, the band at 1620 cm$^{-1}$ disappeared whereas the band at 1583 cm$^{-1}$ remained (Figure 1B, e and f). These results indicate that the bands at 1620 and 1583 cm$^{-1}$ correspond to physisorbed and chemisorbed species, respectively. A similar behavior was also observed for the bands assigned to C–N stretching vibration ($\nu_{\text{C-N}}$)$^{32}$ at 1129, 1071, and 1035 cm$^{-1}$ (the former two correspond to chemisorption). In contrast, other bands due to CH$_2$ bending vibrations ($\omega_{\text{CH}_2}$; 1380 cm$^{-1}$, $\delta_{\text{CH}_2}$; 1456 cm$^{-1}$)$^{32}$ and C–C stretching vibrations of aromatic ring ($\nu_{\text{C-C}}$; 1499 and 1525 cm$^{-1}$)$^{32}$ showed continuous growths. In the region of >3100 cm$^{-1}$, the band at 3442 and 3245 cm$^{-1}$ corresponding to $\nu_{\text{O-H}}$ and $\nu_{\text{N-H}}$ developed with time (Figure 1A). The corresponding bands for $\nu_{\text{O-D}}$ and $\nu_{\text{N-D}}$ were observed at 2544 and 2400 cm$^{-1}$ with use of benzylamine-N-d$_2$ (Figure 2, a–d). The experimental ratios of $\nu_{\text{O-H}}/\nu_{\text{O-D}}$ and $\nu_{\text{N-H}}/\nu_{\text{N-D}}$ are both 1.35, in good agreement with the theoretical ratio of 1.37 expected for H–D isotopic exchange. These strongly suggest that the appearance of O–H(D) bond is due to dissociative adsorption of benzylamine at N–H(D) moiety. The band at 3734 cm$^{-1}$ assigned to $\nu_{\text{O-H}}$ of surface hydroxyl groups, on the other hand, decreased immediately after the introduction of benzylamine. This band was recovered after evacuation (Figure 1A, e and f), indicating an interaction between the surface hydroxyl groups and physisorbed benzylamine. The corresponding band for $\nu_{\text{O-D}}$ was observed at 2700 cm$^{-1}$ in addition to the band at 2545 cm$^{-1}$ upon exposure to D$_2$O (Figure 2, e–g). The experimental ratio of $\nu_{\text{O-H}}/\nu_{\text{O-D}}$ (1.38; 3734 cm$^{-1}$ / 2545 cm$^{-1}$) shows a good agreement with the theoretical ratio of 1.37. On the basis of these results, the adsorption fashion of benzylamine on Nb$_2$O$_5$ can be summarized as shown in scheme 1. The introduced benzylamine weakly interacts with an isolated surface hydroxyl group as a physisorbed species at first. Dissociative adsorption of benzylamine occurs to form an amide species as a chemisorbed species and a bridging hydroxyl group. These two hydroxyl groups are also generated by heterolytic adsorption of water.
Figure 1. FT-IR spectra obtained when Nb$_2$O$_5$ was exposed to 0.6µmol of benzylamine for (a) 1, (b) 10, (c) 20, (d) 30, and (e) 40 min, (f) followed by evacuation. The regions of (A) 3100–3900 cm$^{-1}$ and (B) 1000–1800 cm$^{-1}$ are shown.

Figure 2. FT-IR spectra obtained when (a) 0.45, (b) 0.98, (c) 1.6, and (d) 2.8 µmol of benzylamine-$N$-$d_2$ was introduced or Nb$_2$O$_5$ was exposed to (e) 0.04, (f) 0.17, and (g) 0.28 kPa of D$_2$O, respectively.
After the evacuation, the sample containing the chemisorbed species was exposed to illumination of visible light ($h\nu > 390$ nm). Figure 3 shows the changes in FT-IR spectra during the irradiation. As irradiation time increased, the bands for $\nu_{\text{C-N}}$ (1071 and 1129 cm$^{-1}$), $\omega_{\text{CH}_2}$ (1363 cm$^{-1}$), $\delta_{\text{sCH}_2}$ (1456 cm$^{-1}$), $\delta_{\text{sNH}_2}$ (1583 cm$^{-1}$), and $\nu_{\text{N-H}}$ (3260 cm$^{-1}$) which belonged to the amide species decreased (Figure 3, blue arrows). In contrast, several bands were newly observed in the whole region. The peak positions of the developed bands within 1200–1800 cm$^{-1}$ are in good agreements with those of authentic benzaldehyde adsorbed on Nb$_2$O$_5$ (Figure 3, red arrows). The prominent bands at 1648, 1547, and 1410 cm$^{-1}$ are assigned to $\nu_{\text{C=O}}$, $\nu_{\text{C-C}}$ (aromatic), and $\delta_{\text{sCHO}}$, respectively. The band around 1049 cm$^{-1}$ and the broad feature in the region of 2800–3600 cm$^{-1}$ were absent in the spectrum of authentic benzaldehyde. These features are in accordance with those of ammonia adsorbed on Nb$_2$O$_5$ (Figure 3, green arrows). The broad feature within 2800–3600 cm$^{-1}$ can be assigned to an ensemble of various modes such as symmetric and asymmetric stretching vibrations ($\nu_{\text{N-H}}$ and $\nu_{\text{asN-H}}$) or overtone of asymmetric bending of NH$_3$ ($\delta_{\text{asNH}_3}$). Other bands characteristic to the adsorbed ammonia ($\delta_{\text{sNH}_2}$; 1199 and 1431 cm$^{-1}$, $\delta_{\text{asNH}_3}$; 1602 cm$^{-1}$) seem to be overlapped with those for benzaldehyde in the spectra during irradiation. These results clearly show that the adsorbed amide species was converted into benzaldehyde and ammonia, which was triggered by visible light. In the cases of secondary alcohols, corresponding dehydrogenated imines were yielded.
as mentioned above, whereas, no evidence for the dehydrogenated primary imine was obtained by FT-IR at room temperature. This indicates that hydrolysis of the primary imine to aldehyde immediately takes place.

**Figure 3.** FT-IR spectra of (a) benzaldehyde and (b) ammonia adsorbed on Nb$_2$O$_5$ after evacuation and differential FT-IR spectra before and after irradiation of visible light ($h\nu > 390$ nm) to benzylamine chemisorbed on Nb$_2$O$_5$ for (b) 1, (c) 10, (d) 30, (e) 60, (f) 120, and (g) 180 min. The regions of (A) 2600–3600 cm$^{-1}$ and (B) 1000–1800 cm$^{-1}$ are shown.

**Wavelength Dependence on the Apparent Quantum Yield**

Figure 4 shows the apparent quantum yield of the benzylamine photooxidation over Nb$_2$O$_5$ as a function of the wavelength of the incident light (action spectrum). UV-Vis spectra of Nb$_2$O$_5$ before and after the adsorption of benzylamine on Nb$_2$O$_5$, and difference spectrum were also described. Nb$_2$O$_5$ shows an intense broad band at 300 nm due to band gap excitation, but no absorption in the region of $\lambda > 390$ nm (Figure 4A, trace 1). As mentioned above, oxidation of various amines
proceeded over Nb$_2$O$_5$ under visible irradiation ($h\nu >$390 nm). The action spectrum indeed does not agree with the UV-Vis spectrum of Nb$_2$O$_5$, and the reaction is responsive to light up to 460 nm (Figure 4B, plot 4). Figure 4A, trace 2 shows UV-Vis spectrum obtained when benzylamine was added to Nb$_2$O$_5$. The absorption band at 300 nm extended to higher wavelength region and the differential spectrum before and after the adsorption of benzylamine showed a new absorption band at ca. 350 nm which was overlapped with the region of >390 nm (Figure 4B, trace 3). Since benzylamine itself exhibits no absorption in the region of >300 nm, the new absorption can be ascribed to a surface species derived from adsorbed amine. This surface species corresponds to an Nb$_2$O$_5$-amide surface complex according to the results of FT-IR study, as shown in Scheme 2b. Moreover, the differential spectrum shows a good agreement with the action spectrum, which strongly suggest that the amine oxidation is triggered by light absorption by the surface complex. On the basis of these results we proposed a possible rationale for the visible-response photooxidation; generation of surface donor levels within the forbidden band of Nb$_2$O$_5$ owing to the formation of the surface complex, and direct electron excitation from the donor level to the conduction band of Nb$_2$O$_5$.

**Figure 4.** (A) UV-Vis spectra of (1) Nb$_2$O$_5$, and (2) Nb$_2$O$_5$ with adsorbed benzylamine. (B) (3) Differential UV-Vis spectrum of (2) – (1) and (4) action spectrum of benzylamine photooxidation over Nb$_2$O$_5$. 

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DFT Calculations for Excitation Mechanism

To demonstrate theoretically the proposed photoactivation mechanism, the electronic structures of Nb$_2$O$_5$ and Nb$_2$O$_5$-amide surface complex were estimated and compared by DFT calculations using model clusters. Figure 5a shows the model cluster of Nb$_2$O$_5$ (Nb$_{12}$O$_{43}$H$_{26}$; 1) and that of amide adsorbed on Nb$_2$O$_5$ [Nb$_{12}$O$_{42}$H$_{25}$(NHCH$_3$); 2]. In the cluster 2, one of the hydroxyl groups is substituted with a methylamide. The occupied and the unoccupied Kohn-Sham orbitals (KS) of these model clusters dominantly consist of delocalized O 2p orbitals and Nb 4d orbitals, respectively (Figure 6). These compositions are consistent with the band structure of Nb$_2$O$_5$.

![Figure 5](image)

**Figure 5.** (A) Model cluster of Nb$_2$O$_5$ (Nb$_{12}$O$_{43}$H$_{26}$; 1) and that of amide adsorbed on Nb$_2$O$_5$ [Nb$_{12}$O$_{42}$H$_{25}$(NHCH$_3$); 2]. (B) Graphical illustrations of LUKS and HOKS of 1 and 2.
Figure 6. Graphical illustrations of occupied and unoccupied KSOs of 1 and 2.
Figure 5b shows schematic illustrations of the highest occupied and the lowest unoccupied Kohn-Sham orbitals (HOKS and LUKS) of 1 and 2. The cluster 2 exhibits quite a different electronic structure of HOKS from the cluster 1; HOKS of 1 is composed by delocalized O 2p orbitals, whereas that of 2 is made up of N 2p orbital localized on the amide nitrogen atom. Moreover, the energy level of HOKS of 2 is higher than that of HOKS of 1, while those of LUKS–LUKS+4 are almost same whether 1 or 2 (Figure 7). These results clearly show that a donor level whose population is localized on the amide nitrogen is generated by formation of Nb₂O₅-amide surface complex. Indeed, the electron excitation energies of 1 and 2 calculated by TD-DFT revealed that lower energy transition takes place with 2 than with 1 (Table 3). Thus, the photooxidation of amine led by lower-energy light than the band gap of Nb₂O₅ can be explained by excitation of the surface complex, i.e., direct electron transition from N 2p orbital localized on amide nitrogen to Nb4d orbital composing conduction band of Nb₂O₅ (Scheme 2).

Figure 7. Energy diagram of the frontier KSOs of 1 and 2.
Table 3. Electron excitation energies of 1 and 2 estimated by TD-DFT calculations.

<table>
<thead>
<tr>
<th>entry</th>
<th>model</th>
<th>energy / eV</th>
<th>( f^a )</th>
<th>assignment ( ^b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2.82</td>
<td>0.0018</td>
<td>H‒6 → L+2 (43%)</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2.82</td>
<td>0.0001</td>
<td>H‒6 → L+1, L+3 (54%)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2.84</td>
<td>0.0003</td>
<td>H → L (63%)</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1.92</td>
<td>0.0008</td>
<td>H → L (65%)</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>1.95</td>
<td>0.0010</td>
<td>H → L+2 (51%)</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>2.01</td>
<td>0.0031</td>
<td>H → L+1, L+2 (98%)</td>
</tr>
</tbody>
</table>

\( ^a \) Oscillator strength. \( ^b \) Only the major parent one-electron excitations are reported. Their percentage contributions to wave functions of excited states are given in parentheses. H = HOKS. L = LUKS

Scheme 2. Schematic illustration of visible-light-induced direct electron transition from N 2p orbital localized on amide nitrogen atom to the conduction band of Nb₂O₅. Formation of an excited electron in the conduction band and a hole at amide nitrogen atom (amide radical) are described.
ESR Measurement of Intermediate Species

We then performed ESR measurement of intermediate species to understand the oxidation process in detail. Figure 8a shows ESR spectra of adsorbed amine on Nb$_2$O$_5$ under photo irradiation at 77 K. Visible-irradiation (> 390 nm) to butylamine adsorbed on bare Nb$_2$O$_5$ at 77 K resulted in the appearance of an ESR signal assigned to organic radical at $g = 2.005$. In addition to this organic radical, a broad feature owing to Nb(IV) was also observed at $g = 1.924$.\textsuperscript{36,37} But visible-irradiation to neat butylamine at 77 K showed no signal. Since Nb$_2$O$_5$ does not absorb visible light (> 390 nm), the formation of this organic radical can be attributed to photoactivation of the surface complex above mentioned. The DFT calculation indicated that photoactivation of Nb$_2$O$_5$-amide complex induced electron excitation from N 2p orbital localized on amide nitrogen to conduction band of Nb$_2$O$_5$ consisted of Nb 4d orbital. Therefore, the observed Nb(IV) and organic radical can be due to

![Figure 8](image)

(a) ESR spectrum obtained when butylamine adsorbed on Nb$_2$O$_5$ was exposed to illumination of visible light ($h\nu > 390$ nm) at 77 K. (b) Experimental spectrum after background subtraction (solid line) and simulated spectrum of the proposed amide radical (dotted line).
reduction of Nb(V) by excited electrons and resulting amide radical, respectively. Indeed, a simulated ESR spectrum assuming an axially symmetric amide radical with one amino- and two \( \alpha \)-protons showed a good agreement with the experimental spectrum (Figure 8b; estimated hyperfine coupling constants are listed in Table 4). This result strongly supports generation of the amide radical and the proposed photoactivation mechanism. In addition, this photoexcitation process does not involve change in the molecular backbone and is consistent with the Franck-Condon principle. On the basis of these results, we proposed a plausible electron transfer mechanism during the photooxidation process as shown in Scheme 3. At first, photo irradiation to the \( \text{Nb}_2\text{O}_5 \)-amide surface complex induces excitation from N 2p orbital localized on amide nitrogen to conduction band of \( \text{Nb}_2\text{O}_5 \), followed by reduction of Nb(V) to Nb(IV) by the excited electron and formation of resulting amide radical (Scheme 3, step a). This process can be triggered by lower-energy light (>390 nm) than the band gap of \( \text{Nb}_2\text{O}_5 \) because of the excitation from donor levels derived from amide species. Then, the resulting positive hole on the amide nitrogen corresponding to an amide radical triggers oxidation of \( \alpha \)-C–H bond to generate dehydrogenated imine and Nb(IV) (Scheme 3, step b).

**Table 4.** Condition of the ESR simulation assuming an amide radical.

<table>
<thead>
<tr>
<th>nuclei</th>
<th>( I )</th>
<th>number of nuclei</th>
<th>( A_{\parallel} / \text{mT} )</th>
<th>( A_{\perp} / \text{mT} )</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
<td>1.33</td>
<td>0.20</td>
</tr>
<tr>
<td>( ^{1}\text{H} )</td>
<td>1/2</td>
<td>1</td>
<td>3.30</td>
<td>1.40</td>
</tr>
<tr>
<td>( ^{1}\text{H} )</td>
<td>1/2</td>
<td>2</td>
<td>1.10</td>
<td>0.55</td>
</tr>
</tbody>
</table>

**Scheme 3.** Proposed electron transfer during photooxidation of amine over \( \text{Nb}_2\text{O}_5 \) based on the results of ESR: (a) electron excitation from amide nitrogen atom and reduction of Nb(V), (b) \( \alpha \)-C–H activation by positive hole generated on amide nitrogen atom (amide radical) to from dehydrogenated imine and Nb(IV).
Photocatalytic oxidation of benzylamine under N$_2$ atmosphere

The photooxidation of benzylamine over Nb$_2$O$_5$ was performed under N$_2$ atmosphere to investigate the role of molecular oxygen. As shown in Figure 9, although the reaction ceased within a few hours, a small amount of N-benzylidene benzylamine (36 µmol, 6 h) was evolved despite the absence of O$_2$. This amount is close to that of chemisorbed NH$_3$ on Nb$_2$O$_5$ (28 µmol / 100 mg·cat) determined in the previous study. In addition, the color of the catalyst turned dark blue during the reaction under N$_2$, which corresponds to accumulation of excited electrons$^{38,39}$ due to the absence of O$_2$ as an electron acceptor. These results suggest that complete reduction of the adsorption sites on the catalyst surface (Nb$^{5+}$ + e$^- \rightarrow$ Nb$^{4+}$) results in catalyst deactivation. After 6 h of the reaction, excess O$_2$ was flushed into the reactor. The color of the catalyst returned white and continuous evolution of N-benzylidene benzylamine was observed. This indicates that reoxidation of the reduced Nb$^{4+}$ sites by O$_2$ is required for catalytic oxidation of benzylamine.

![Figure 9. Change in product amount during photooxidation of benzylamine over Nb$_2$O$_5$ under 1 atm N$_2$ (0–6 h) or 1 atm O$_2$ (6–9 h). Reaction condition: Nb$_2$O$_5$ (100 mg), benzylamine (5 mmol), benzene (10 ml), $h\nu > 300$ nm. After 6 h of reaction, the reaction atmosphere was replaced with excess O$_2$. Total amount of benzylamine and N-benzylidene benzylamine is expressed as [(mol of benzylamine) + 2 x (mol of N-benzylidene benzylamine)].](image-url)
Proposed Reaction Mechanism

On the basis of the obtained results, a plausible reaction mechanism of photooxidation of amines over Nb$_2$O$_5$ is proposed as shown in Scheme 4. At first, the substrate amine is dissociatively adsorbed on Nb$_2$O$_5$ to form an amide species (step i). The Nb$_2$O$_5$-amide surface complex absorbs light of lower energy than the band gap of Nb$_2$O$_5$ (3.2 eV, 390 nm) and electron at the amide nitrogen atom is excited to the conduction band of Nb$_2$O$_5$. The excited electron is trapped by Nb(V) to generate Nb(IV) and a positive hole remains at amide nitrogen (step ii). The remaining hole at amide nitrogen (amide radical) oxidizes $\alpha$-C–H bond to generate corresponding dehydrogenated imine (step iii). In the case of a primary amine (R’ = H), the dehydrogenated primary imine is immediately hydrolyzed into an aldehyde and ammonia by the neighboring water molecule generated due to oxidative dehydrogenation (step iv). Then, the produced aldehyde and ammonia are desorbed (step vi). Condensation of the aldehyde and the substrate primary amine immediately takes place to generate dimerized imine (vii). In the case of a secondary amine (R’ ≠ H), the dehydrogenated secondary imine and water are desorbed (v). A part of the secondary imine may be hydrolyzed into an aldehyde and a primary amine (R’NH$_2$). Although this process can be reversible, the aldehyde eventually seems to remain as a by-product due to overoxidation of the fragmented amine. Finally, the reduced Nb(IV) site are reoxidized to Nb(V) by O$_2$. We have confirmed that the condensation of benzaldehyde and benzylamine to $N$-benzylidene benzylamine immediately and quantitatively proceeds when benzaldehyde is added to benzylamine in benzene solvent in the absence of Nb$_2$O$_5$ under the dark. Moreover, gaseous ammonia was indeed detected by TCD-GC in the reaction atmosphere of benzylamine photooxidation.

Kinetic Study to Determine the Rate-determining Step

We performed a kinetic analysis to verify the proposed mechanism shown in Scheme 4 and to determine the rate-determining step of the photooxidation of amine over Nb$_2$O$_5$. The dependencies of the concentrations of substrate and O$_2$ and light intensity on the reaction rate ($r$) of benzylamine photooxidation were obtained as expressed in eq 1.
Here, the rate constant, the O₂ pressure, the light intensity, and the substrate concentration are abbreviated to \( k \), \( P_{O_2} \), \( I \), and \([A]\), respectively. The obtained rate equations are compared with those derived from the proposed reaction mechanism employing steady-state approximation. Rate constants and equilibrium constants in each elementary step for the case of a primary amine are defined as shown in Scheme 5. As mentioned above, the condensation of benzaldehyde and
benzylamine immediately took place without catalyst and only a trace amount of benzaldehyde was yielded as a by-product in the photooxidation of benzylamine. These clearly indicate that the dimerization process (Scheme 5, step 6) does not correspond to the rate determining step. The rate equations for other steps were derived by assuming that the total number of adsorption sites is constant (eq 2) and that each step is a rate-determining step as follows (eqs 3–8):

\[
[S]_0 = [S] + [AS] + [BS^*] + [C'S**] + [D'S**] + [S**]
\]  \hspace{1cm} (2)
(step 1)

\[
\frac{k_1K_2K_3K_4K_5[\text{S}][\text{P}]_{0.5}I[A]}{K_2K_3K_4K_5K_6(K_7P_{0.5}+1)I[A]+[(K_3K_4+K_3+1)K_2+1][\text{NH}_3][\text{H}_2\text{O}][\text{E}]} \tag{3}
\]

(step 2)

\[
\frac{k_2K_3K_4K_5K_6K_7[\text{S}][\text{P}]_{0.5}I[A]}{K_1K_3K_4K_5K_6K_7P_{0.5}I[A]+K_3K_4K_5K_6(K_7P_{0.5}+1)[A]+(K_3K_4+K_3+1)[\text{NH}_3][\text{H}_2\text{O}][\text{E}]} \tag{4}
\]

(step 3)

\[
\frac{k_3K_1K_2K_3K_4K_5[\text{S}][\text{P}]_{0.5}I[A]}{K_1K_4K_5K_6K_7(K_2+1)P_{0.5}[A]+K_4K_5K_6(K_7P_{0.5}+1)[A]+(K_4+1)[\text{NH}_3][\text{H}_2\text{O}][\text{E}]} \tag{5}
\]

(step 4)

\[
\frac{k_4K_1K_2K_3K_4K_5[\text{S}][\text{P}]_{0.5}I[A]}{K_1K_2K_3K_4K_5K_6(K_2+1)P_{0.5}[A]+K_4K_5K_6(K_7P_{0.5}+1)[A]+(K_4+1)[\text{NH}_3][\text{H}_2\text{O}][\text{E}]} \tag{6}
\]

(step 5)

\[
\frac{k_5K_1K_2K_3K_4K_5[\text{S}][\text{P}]_{0.5}I[A]}{K_1K_2K_3K_4K_5K_6(K_2+1)P_{0.5}[A]+(K_4+1)[\text{NH}_3][\text{H}_2\text{O}][\text{E}]} \tag{7}
\]

(step 7)

\[
\frac{k_7K_1K_2K_3K_4K_5K_6[\text{S}][\text{P}]_{0.5}I[A]}{K_1K_2K_3K_4K_5K_6I[A]+[(K_3K_4+K_3+1)K_2+1][\text{NH}_3][\text{H}_2\text{O}][\text{E}][A]+[\text{NH}_3][\text{H}_2\text{O}][\text{E}]} \tag{8}
\]

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The reaction orders of the substrate concentration, the light intensity, and the pressure of the oxygen in steps 1, 2, and 7 are not compatible with the experimental data. As a consequence, step 3 (conversion of amide radical into primary imine), step 4 (hydrolysis of primary imine to aldehyde), or step 5 (desorption of products) is the rate-determining step of the photooxidation of primary amine over Nb2O5. The amide radical species could be observed at 77 K, but was not detected at room temperature. The primary imine was also not observed by FT-IR at room temperature in contrast to the aldehyde. These suggests that step 3 and 4 are much faster than step 5. On the basis of these results, we conclude that the desorption of the aldehyde and ammonia is the rate-determining step of the photooxidation of primary amine over Nb2O5.

Conclusion

In this study, the photocatalytic performance of Nb2O5 in photooxidation of amine was compared with other metal oxides and the substrate scope was investigated. Nb2O5 showed higher selectivity than TiO2, ZnO, and other metal oxides. Various amines including primary, secondary, and bicycloamine derivatives were selectively oxidized in the presence of Nb2O5. Secondary amines were oxidized into corresponding dehydrogenated imines, whereas primary amines were converted into dimerized imines. The mechanistic study revealed that the photooxidation of amine over Nb2O5 was oxidative dehydrogenation of amine via photoexcitation of the Nb2O5-amide surface complex, which consisted of dissociatively adsorbed amine (amide) and Nb2O5. In the case of primary amine, the dehydrogenated primary imine was immediately hydrolyzed into aldehyde and ammonia, followed by condensation of the aldehyde and substrate amine to dimerized imine. The reaction took place not only under UV light (> 300 nm) but also visible light (390 nm), although the band gap of Nb2O5 is ca. 3.2 eV (390 nm). DFT calculations revealed that 1) the surface donor level derived from adsorbed amide species is located in the forbidden band, 2) direct electron transition from the surface donor level to the conduction band takes place by absorbing a photon, 3) the excitation energy from surface donor level to Nb 4d is lower than that from O 2p valence band to Nb 4d. The effective wavelength is shifted to a longer wavelength by the formation of a donor level derived from the adsorbed molecule during a chemical reaction, which can be expressed as “in-situ doping” effect.
The photoactivation mechanism and the outline of the photooxidation of amine over Nb$_2$O$_5$ is essentially the same as that for alcohol, except that the hydrolysis of primary imine and the subsequent dimerization take place.

**References**


Chapter 5

Mechanism of Photooxidation of Hydrocarbons over Nb$_2$O$_5$

Abstract

Selective aerobic photooxidation of hydrocarbons to oxidized products, mainly ketones, was conducted over Nb$_2$O$_5$ in the absence of solvent. For the oxidation of cyclohexane and ethylbenzene, Nb$_2$O$_5$ shows significantly higher selectivity to partial oxidation products than does TiO$_2$. In the oxidation of cyclohexane, Nb$_2$O$_5$ gave a much higher ketone/alcohol ratio than TiO$_2$. On the basis of spectroscopic and kinetic studies, the following mechanism is proposed. Both hydrocarbon and dioxygen adsorb on Nb$_2$O$_5$. The C–H bond of the hydrocarbon is activated to produce an alkyl radical by a photogenerated positive hole, and adsorbed oxygen is reduced by a photogenerated electron. The alkyl radical reacts with superoxide to produce a hydroperoxide. Then, the hydroperoxide is converted to a ketone, which subsequently desorbs from Nb$_2$O$_5$. This proposed mechanism is a typical Langmuir–Hinshelwood mechanism, including the formation of the hydroperoxide species as an intermediate. A linear correlation between logarithms of the reaction rates and bond dissociation enthalpies of several hydrocarbons indicates that the rate-determining step is C–H bond activation. ESR study suggests that the higher selectivity of Nb$_2$O$_5$ for partial oxidation products than TiO$_2$ is due to the absence of O$_3^-$, which is highly active for the complete oxidation of hydrocarbons.
**Introduction**

Heterogeneous photocatalysts have potential application in the aerobic oxidation of organic molecules.\(^1\)-\(^3\) Up to now, various semiconductor materials have been tested as oxidation photocatalysts, and it is generally accepted that the anatase TiO\(_2\) is the most reliable material, owing to its low cost and high photostability. Significant effort has been devoted to developing TiO\(_2\) as a selective catalyst in the oxidation of various types of organic molecules such as alkanes,\(^4\)-\(^9\) arenes,\(^10\) and alcohols.\(^11\)-\(^13\) However, the undesired over-oxidation to CO\(_x\) (CO and CO\(_2\)) is essentially associated with photocatalytic oxidation using TiO\(_2\) owing to the strong oxidation ability of a hole generated in the valence band of TiO\(_2\).\(^14\) To achieve selective oxidation, a variety of catalytic systems based on TiO\(_2\) have been devised with a view of optimizing the solvent,\(^7,8\) the reaction conditions,\(^11\) or the preparation method of TiO\(_2\).\(^13\) On the other hand, we have developed a series of selective photocatalytic systems as alternatives to TiO\(_2\), e.g., hydrocarbon oxidation over alumina-supported vanadium oxide (V\(_2\)O\(_5\)/Al\(_2\)O\(_3\))\(^15\)-\(^18\) and alcohol oxidation over niobium oxide (Nb\(_2\)O\(_5\)).\(^19\)-\(^21\) The mechanisms of photoactivation of these systems are entirely different from those of classical photoactivation, which involves the formation of an excited electron in the conduction band and a positive hole in the valence band, followed by the activation of the substrate by the positive hole or the excited electron. In the case of V\(_2\)O\(_5\)/Al\(_2\)O\(_3\), orthovanadate-like (V=O) O\(_3\) species in the triplet excited state activate adsorbed alkanes.\(^17,18\) In the case of Nb\(_2\)O\(_5\), an alcohol is dehydrogenated to the corresponding carbonyl compound via photoexcitation of a surface complex consisting of adsorbed alkoxide species and Nb\(_2\)O\(_5\).\(^20\),\(^21\) Moreover, these photocatalysts show high selectivities to partial oxidation products.

In this study, the photocatalytic activity of Nb\(_2\)O\(_5\) and its selectivity to partial oxidation products in hydrocarbon oxidation are investigated and compared with those of anatase TiO\(_2\). Herein, we report that Nb\(_2\)O\(_5\) shows higher selectivities in the aerobic oxidation of various hydrocarbons than TiO\(_2\). We also carried out a mechanistic study by FT-IR, ESR spectroscopy, and a kinetic study to understand the reaction mechanism and rationalize the observed difference in the selectivities of Nb\(_2\)O\(_5\) and TiO\(_2\).
Experimental Section

Catalyst Preparation

Niobic acid, niobium oxide hydrate (Nb$_2$O$_5$·$n$H$_2$O, AD/2872, HY-340) was kindly supplied from CBMM. Niobium oxide catalyst was prepared by calcination of niobic acid in a dry air flow at 773 K for 5 h. A TT-Nb$_2$O$_5$ phase with a pseudohexagonal structure was obtained from the XRD pattern and Raman spectral data.\textsuperscript{19} The specific surface area of this Nb$_2$O$_5$ sample, which was evaluated by the Brunauer–Emmett–Teller (BET) method using the N$_2$ adsorption isotherm at 77 K, was 48 m$^2$·g$^{-1}$.\textsuperscript{19} TiO$_2$ used in this research was JRC-TIO-11, supplied by the Catalysis Society of Japan as a standard TiO$_2$ sample. This TiO$_2$ sample was hydrated in distilled water at 353 K for 2 h, followed by evaporation, drying, and calcination at 773 K for 5 h in a dry air flow. JRC-TIO-11 consists of anatase (91%) and rutile (9%) phases, and its specific surface area was evaluated to be 78 m$^2$·g$^{-1}$. After calcinations, the catalysts were ground into powders under 100 mesh (0.15 mm).

Reaction Conditions

The photocatalytic oxidation of the hydrocarbon was carried out in a quasi-flowing batch system (Figure 1) under atmospheric oxygen at room temperature. The substrate was used without further purification. The catalyst (100 mg), hydrocarbon substrate (10 mL), and a stirring bar were added into a Pyrex glass reactor in the absence of solvent. The suspension was vigorously stirred at room temperature and irradiated from the flat bottom of the reactor using a 500 W ultrahigh-pressure Hg lamp via reflection through a cold mirror (USHIO Denki Co.). Oxygen was introduced into the reactor at 2 mL·min$^{-1}$. The organic oxidation products were analyzed by GC-FID (Shimadzu GC-14B) and GC-MS (Shimadzu GC-MS QP5050). At the downstream of the flow reactor, a saturated barium hydroxide solution (Ba(OH)$_2$) was used to determine the quantity of carbon dioxide by the formation of barium carbonate (BaCO$_3$). The total amount of the products formed in the reaction is used to define the reaction rate ($r$) in units of mmol·h$^{-1}$. The relative reaction rate ($r_{\text{rel}}$) considering the frequency factor is further defined by dividing $r$ by the number of C–H bonds involved in the reaction ($n_{\text{C–H}}$: cyclooctene, 16; toluene, 3; ethylbenzene, 2; diphenylmethane, 2). In the kinetic study, benzene and nitrogen were used as diluents to modify the concentration of the substrate and oxygen pressure, respectively. Light intensity was controlled using a metal mesh.
ESR Spectra

ESR measurements were conducted using an X-band ESR spectrometer (JEOL JES-SRE2X) with an in situ quartz cell. Prior to ESR measurements, the sample (Nb$_2$O$_5$ or TiO$_2$) was pretreated with 6.7 kPa of O$_2$ at 673 K for 1 h, followed by evacuation for 0.5 h at 673 K. After pretreatment, the sample was exposed to 0.5 kPa of $^{16}$O$_2$ or degassed ethylbenzene at room temperature. Subsequently, the sample was cooled to 77 K and irradiated. ESR spectra were recorded before and after photoirradiation. When isotopically enriched oxygen (20% $^{17}$O) was used, 4.0 kPa of oxygen was introduced. The g values of the radical species were determined using a Mn marker. A 500 W ultrahigh-pressure mercury lamp was used as the light source.
FT-IR Spectra

FT-IR spectra of the samples after photoirradiation were recorded with a Perkin-Elmer SPECTRUM ONE Fourier transform infrared spectrometer. The spectral resolution was 4 cm\(^{-1}\). The Nb\(_2\)O\(_5\) sample was pressed into a pellet (diameter: 12 mm). The molded sample was introduced into an in situ IR cell equipped with BaF\(_2\) windows. Prior to measurements, the sample was pretreated with 6.7 kPa of O\(_2\) for 1 h at 673 K, followed by evacuation for 0.5 h at 673 K. The pretreated sample was exposed to 16.1 kPa of degassed cyclohexane for 15 min, followed by evacuation for an additional 10 min. Before photoirradiation, 1.6 kPa of O\(_2\) was introduced to the sample cell. A 200 W Hg–Xe lamp (SUN-EI ELECTRIC SUPERCURE-204S) was used as a light source.

Results

Photocatalytic Oxidation of Alkanes over Nb\(_2\)O\(_5\) and TiO\(_2\)

Table 1 shows the yields of the partial oxidation products and carbon dioxide (CO\(_2\)) in liquid-phase photooxidations of ethylbenzene and cyclohexane over Nb\(_2\)O\(_5\) and TiO\(_2\). Acetophenone and a small amount of 1-phenylethanol were obtained as partial oxidation products in the ethylbenzene oxidation. In addition, cyclohexanone was mainly produced as a partial oxidation product in the cyclohexane oxidation. Oxidation of cyclohexane is an important chemical process for the production of caprolactam, which is a monomer used for the synthesis of nylon-6. A higher ketone/alcohol ratio (K/A ratio) is preferred for caprolactam production because the following step of cyclohexanol overoxidation to cyclohexanone requires additional cost and energy. It is therefore noteworthy that a much higher K/A ratio was obtained in the cyclohexane photooxidation over Nb\(_2\)O\(_5\) (>999) than that obtained over TiO\(_2\) (47). The photocatalytic activity of Nb\(_2\)O\(_5\) is lower than TiO\(_2\) in the oxidation of cyclohexane but is higher in the oxidation of ethylbenzene. In both cases, Nb\(_2\)O\(_5\) exhibited higher selectivities to partial oxidation products than TiO\(_2\).

We previously reported that alcohol oxidation over Nb\(_2\)O\(_5\) occurred even under irradiation by visible light (\(\lambda > 390\) nm).\(^{20}\) A mechanistic study using UV–Vis, action spectra, and DFT calculation revealed that this is caused by direct electron transition from a donor level derived from adsorbed alkoxide species. However, oxidation of cyclohexane over Nb\(_2\)O\(_5\) did not proceed under visible light.
irradiation (\(\lambda > 390\ \text{nm}\)) or in the dark. Oxidation of ethylbenzene also barely occurred under the same conditions. These results are different from those obtained from alcohol oxidation and indicate that the oxidation of the hydrocarbon is triggered by band gap excitation of \(\text{Nb}_2\text{O}_5\) (\(<390\ \text{nm}\)),\(^\text{20}\) as is the case for oxidation over \(\text{TiO}_2\) (\(<390\ \text{nm}\)).

**Table 1.** Evolutions of partial oxidation products and carbon dioxide in photooxidation of cyclohexane and ethylbenzene.\(^a\)

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Catalyst</th>
<th>Alcohol / µmol (^b)</th>
<th>Ketone / µmol</th>
<th>Dimer / µmol</th>
<th>(1/n) CO(_2)</th>
<th>Conv. (%)</th>
<th>Sel. (%) (^c)</th>
<th>K/A ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Cyclohexane</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{Nb}_2\text{O}_5)</td>
<td>n. d.</td>
<td>572</td>
<td>n. d.</td>
<td>160</td>
<td>0.76</td>
<td>78</td>
<td>&gt; 999</td>
</tr>
<tr>
<td></td>
<td>(\text{Nb}_2\text{O}_5) (^d)</td>
<td>n. d.</td>
<td>n. d.</td>
<td>n. d.</td>
<td>n. d.</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(\text{Nb}_2\text{O}_5) (^e)</td>
<td>n. d.</td>
<td>n. d.</td>
<td>n. d.</td>
<td>n. d.</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(\text{TiO}_2) (^f)</td>
<td>17</td>
<td>796</td>
<td>n. d.</td>
<td>714.6</td>
<td>1.39</td>
<td>57</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>(\text{TiO}_2)</td>
<td>54</td>
<td>1828</td>
<td>n. d.</td>
<td>1711</td>
<td>3.7</td>
<td>52</td>
<td>34</td>
</tr>
<tr>
<td><strong>Ethylbenzene</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{Nb}_2\text{O}_5)</td>
<td>1469</td>
<td>7831</td>
<td>n. d.</td>
<td>272</td>
<td>11.7</td>
<td>98</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>(\text{Nb}_2\text{O}_5) (^e)</td>
<td>n. d.</td>
<td>287</td>
<td>n. d.</td>
<td>n. d.</td>
<td>0.35</td>
<td>&gt; 99</td>
<td>&gt; 999</td>
</tr>
<tr>
<td></td>
<td>(\text{Nb}_2\text{O}_5) (^g)</td>
<td>2</td>
<td>3</td>
<td>65</td>
<td>n. d.</td>
<td>0.09</td>
<td>&gt; 99</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(\text{TiO}_2)</td>
<td>905</td>
<td>5044</td>
<td>n. d.</td>
<td>562</td>
<td>7.9</td>
<td>91</td>
<td>5.6</td>
</tr>
</tbody>
</table>

\(^a\) Reaction conditions: catalyst; 100 mg, substrate 10 ml, O\(_2\) flow; 2 ml·mim\(^{-1}\), photo irradiation time; 24 h. \(^b\) For cyclohexane, cyclohexanol (alcohol) and cyclohexanone (ketone); for ethylbenzene, 1-phenylethanol (alcohol), acetophenone (ketone), and 2,3-diphenylbutane (dimer); \(n\) represents the number of carbon atoms included in the substrate. \(^c\) Selectivity to partial oxidation products. \(^d\) Under the dark. \(^e\) \(\lambda > 390\ \text{nm}\). \(^f\) Photo irradiation time; 6 h. \(^g\) Photo irradiation time; 12 h, under 1 atm N\(_2\).
The photooxidation of ethylbenzene over Nb$_2$O$_5$ under 1 atm N$_2$ resulted in the formation of 2,3-diphenylbutane, a dimer coupled at the benzylic position of ethylbenzene, almost as the sole product. Likewise, a similar coupled dimer, 1,2-diphenylethane, was exclusively formed in the photooxidation of toluene under an N$_2$ atmosphere. The formation of such dimers strongly suggests the generation of a radical with an unpaired electron at the benzylic position, followed by radical coupling. Moreover, the absence of oxygenated products (1-phenylethanol and/or acetophenone for ethylbenzene, benzaldehyde, and/or benzoic acid for toluene) suggests that molecular oxygen participates in oxygenation of the substrate. Figure 2 shows the time course of the product yield and K/A ratio in the oxidation of ethylbenzene. Although the ketone was predominantly produced, the K/A ratio decreased as the reaction proceeded. If the ketone is produced via overoxidation of the alcohol as a primary product, the K/A ratio should increase with reaction time. Therefore, this change in K/A ratios indicates that the ketone was not formed by the overoxidation of the alcohol but directly from the hydrocarbon.

![Figure 2](image)

**Figure 2.** Time course of the product yields and K/A ratio of photooxidation of ethylbenzene over Nb$_2$O$_5$. 
The oxidation of hydrocarbons with various C–H bond dissociation energies (C–H BDE), such as cyclooctane (92.0 kcal·mol\(^{-1}\)),\(^{22}\) toluene (87.5 kcal·mol\(^{-1}\)),\(^{23}\) ethylbenzene (84.5 kcal·mol\(^{-1}\)),\(^{23}\) and diphenylmethane (82.0 kcal·mol\(^{-1}\))\(^{24}\) were also carried out. Figure 3 shows the correlation between the relative reaction rates (\(r_{\text{rel}}\)) and C–H BDE. The logarithm of \(r_{\text{rel}}\) linearly correlated with C–H BDE values of the substrates, giving a slope of approximately –0.3. Thus, the reaction rates of the photocatalytic oxidations of hydrocarbons over Nb\(_2\)O\(_5\) decreased with the increase of the C–H BDE of substrates. This linear relationship clearly shows that C–H activation of the hydrocarbon is the rate-determining step of the reaction.\(^{25-29}\)

**Figure 3.** Plot of logarithm of \(r_{\text{rel}}\) against C–H BDE of substrates (Ph\(_2\)CHH, diphenylmethane; PhCH\(_2\)CH\(_3\), ethylbenzene; PhCH\(_3\), toluene; \(c\)-C\(_8\)H\(_{16}\), cyclooctane).
ESR Study of Oxygen Anion Radicals and Alkyl Radical

We conducted ESR measurements to characterize the photogenerated reaction intermediate species. Figure 4 shows the ESR spectra observed when TiO$_2$ or Nb$_2$O$_5$ was irradiated under an O$_2$ atmosphere at 77 K. Photoirradiation of TiO$_2$ gave intense signals consisting of two sets of rhombic g values assigned to O$_2^-$ ($g_{1a} = 2.018$, $g_{2a} = 2.010$, and $g_{3a} = 2.003$) and O$_3^-$ ($g_{1b} = 2.013$, $g_{2b} = 2.007$, and $g_{3b} = 2.001$). The generation of O$_2^-$ and O$_3^-$ is attributed to the reduction of adsorbed O$_2$ by excited electrons and the combination of positive holes trapped on surface lattice oxygen (equivalent to O$^-$) and adsorbed O$_2$, respectively. On the other hand, only a tiny signal consisting of one set of rhombic g values ($g_1 = 2.036$, $g_2 = 2.003$, and $g_3 = 1.986$) was observed when Nb$_2$O$_5$ was irradiated.

![ESR Spectra](image)

**Figure 4.** ESR spectra of (A) anatase-TiO$_2$ and (B) Nb$_2$O$_5$ irradiated in the presence of $^{16}$O$_2$ (0.5 kPa) at 77 K.
To obtain further information about this species, a similar experiment with $^{17}$O-enriched oxygen was performed. As shown in Figure 5, six lines due to hyperfine interaction with one $^{17}$O nuclei ($I = 5/2$) along the $g_2$ direction were confirmed. This hyperfine structure strongly suggests the generation of $^{16}$O$^{17}$O$^{-}$ and that the two oxygen nuclei are equivalent. The equivalent hyperfine interactions also suggest that the O$_2^-$ ion is adsorbed in a side-on fashion on the Nb$_2$O$_5$ surface, with its internuclear axis parallel to the plane of the surface, as commonly observed in other metal oxides. Eleven lines corresponding to two $^{17}$O nuclei ($^{17}$O$^{17}$O$^{-}$, $I = 5$) that were expected were not apparently observed, probably because of inadequate enrichment of $^{17}$O (20%).

Figure 5. ESR spectrum of Nb$_2$O$_5$ irradiated in the presence of $^{17}$O-enriched oxygen (4.0 kPa) at 77 K. $A$ refers to the $^{17}$O hyperfine structures.
Figure 6 shows the ESR spectrum obtained when ethylbenzene adsorbed on Nb$_2$O$_5$ was exposed to irradiation at 77 K. Irradiation of this sample resulted in the appearance of an intense signal with fine structure around $g = 2.0$. This fine structure can be assigned to the ethylbenzyl radical ($g = 2.003$, $A_{H1} = 6.0$ mT, $A_{H2} = 2.0$ mT) overlapped with the signal of electrons trapped at an oxygen vacancy (F center).$^{35-37}$ In addition, a broad signal assigned to Nb(IV) ($g = 1.933$)$^{38,39}$ was concomitantly observed with the ethylbenzyl radical. These results strongly support the oxidation of the benzylic C–H bond of ethylbenzene by the photogenerated hole and the reduction of Nb(V) to Nb(IV) by the excited electron. Subsequently, this sample was exposed to O$_2$ under photoirradiation at 77 K. A signal assigned to O$_2^−$ appeared and the fine structure of the ethylbenzyl radical vanished (Figure 7). This suggests that the ethylbenzyl radical reacted with excess O$_2^−$ to form a diamagnetic alkyl peroxide anion (ROO$^−$) or hydroperoxide (ROOH).

![Figure 6. ESR spectrum of ethylbenzene adsorbed on Nb$_2$O$_5$ irradiated at 77 K.](image)
FT-IR Measurement for Adsorbed Species

Figure 8 shows the FT-IR spectrum obtained after 10 min of photoirradiation of cyclohexane adsorbed on Nb$_2$O$_5$ in the presence of O$_2$. After photoirradiation, the bands assigned to $\nu$(C=O) (1666 cm$^{-1}$) and $\nu$(carbonate) (1567 cm$^{-1}$) appeared. These changes indicate generation of cyclohexanone and the subsequent photodecomposition of cyclohexanone into carbonate species. This photodecomposition is due to the $n$$\rightarrow$$\pi^*$ transition at the carbonyl moiety of cyclohexanone, known as the Norrish I type reaction.$^{40,41}$ In the $\nu$(O–H) region, a negative peak at 3673 cm$^{-1}$ and a broad feature in the 3200–3500 cm$^{-1}$ range were observed. These bands are assigned to isolated surface hydroxyl groups and hydrogen-bonded surface hydroxyl groups and/or water molecules, respectively. The negative peak may be due to the loss of isolated surface hydroxyl groups by hydrogen bonding or oxidative consumption by photogenerated holes, producing hydroxyl radicals.

A small band assigned to $\nu$(C–O) appeared at 1192 cm$^{-1}$. We previously reported that the IR spectra of cyclohexanol adsorbed on Nb$_2$O$_5$ exhibited characteristic peaks at 1068 cm$^{-1}$ (nondissociative adsorption) and 1091 cm$^{-1}$ (dissociative adsorption).$^{20}$ The position of the peak
observed at 1192 cm\(^{-1}\) is significantly different from those of the adsorbed cyclohexanol species. Therefore, this suggests that a certain species containing the C–O bond, which can be distinguished from cyclohexanol, is formed to some extent on the Nb\(_2\)O\(_5\) surface. According to the literature, alkyl hydroperoxide species exhibit absorption due to \(\nu(CCO)\) in the range of 1198–1176 cm\(^{-1}\).\(^{42}\) Moreover, it has been reported that authentic cyclohexyl hydroperoxide introduced on TiO\(_2\) exhibits characteristic bands at 1367 cm\(^{-1}\) corresponding to \(\omega(CH_2)\).\(^{43}\) Similar peaks are also observed in this study (1192 cm\(^{-1}\) and 1367 cm\(^{-1}\)). On this basis, we can consider that cyclohexyl hydroperoxide is generated in the photooxidation of cyclohexane over Nb\(_2\)O\(_5\). The evolution of water molecules could be rationalized by decomposition of this hydroperoxide to ketone and water and/or C–H activation by hydroxyl radicals.

**Figure 8.** FT-IR spectrum after 10 min of photo irradiation to cyclohexane adsorbed on Nb\(_2\)O\(_5\) in the presence of O\(_2\). Differential spectrum between before and after irradiation is shown. Inset shows a close-up of the 1400–1000 cm\(^{-1}\) region.
Discussion

On the basis of these results, the reaction mechanism is proposed as shown in Scheme 1. The hydrocarbon and molecular oxygen are competitively adsorbed on the Nb$_2$O$_5$ surface (steps i and ii, respectively). Photoirradiation of Nb$_2$O$_5$ results in the reduction of Nb(V) to Nb(IV) by an excited electron and the formation of a positive hole on lattice oxygen (step iii). Molecular oxygen is reduced to superoxide by an excited electron (step iv), and a C–H bond of the substrate is oxidized to produce an alkyl radical by a positive hole (step v, rate-determining step). Furthermore, C–H activation is possibly caused by a hydroxyl radical as commonly suggested. However, the generation of a hydroxyl radical should result in the formation of oxygenated products even under N$_2$ atmosphere, as shown in eqs 1 and 2.

\[
R + \cdot OH \rightarrow R\cdot + H_2O \quad (1)
\]

\[
R\cdot + \cdot OH \rightarrow ROH \quad (2)
\]

In fact, the oxygenated products (1-phenylethanol and acetophenone) did not form in the photooxidation of ethylbenzene under N$_2$. Subsequently, the alkyl radical is oxidized to alkyl hydroperoxide by the reaction with superoxide, followed by protonation (step vi). The alkyl hydroperoxide is decomposed to ketone and water (step vii), followed by desorption (step viii). Such decomposition of alkyl hydroperoxide to ketone or alcohol has frequently been proposed in various systems where the aerobic oxidation of cyclohexane is performed using materials such as metal-containing molecular sieves,\textsuperscript{44} O$_2$-loaded Na–Y zeolite\textsuperscript{45}, and TiO$_2$ photocatalyst.\textsuperscript{46} It has also been proposed that the ketone is formed by heterolytic decomposition, whereas the alcohol is formed by homolytic decomposition.\textsuperscript{44} The proposed mechanism is essentially similar to that of the photooxidation of cyclohexane over TiO$_2$ reported by Mul and co-workers.\textsuperscript{46} However, in the present study, a principal difference was observed in the amount and type of oxygen anion radical species (O$_2^-$ or O$_3^-$) formed in the reaction over TiO$_2$ and in that formed in the reaction over Nb$_2$O$_5$. The amount of oxygen anion radical formed on Nb$_2$O$_5$ was much lower than that formed on TiO$_2$. 

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Moreover, in contrast to the reaction over TiO$_2$, O$_3^-$ was not generated in that over Nb$_2$O$_5$. Such surface oxygen species are known to be active for the complete oxidation of various hydrocarbons.\textsuperscript{47-51} However, Lunsford et al. reported that O$_2^-$ was stable up to ca. 423 K.\textsuperscript{50} In contrast, O$_3^-$ was active even at room temperature.\textsuperscript{49,51} On this basis, the higher selectivity to partial oxidation products that was observed for Nb$_2$O$_5$ than for TiO$_2$ may be due to the lack of O$_3^-$. 

Scheme 1. Proposed mechanism of photooxidation of hydrocarbon over Nb$_2$O$_5$: (i) adsorption of hydrocarbon, (ii) adsorption of O$_2$, (iii) charge separation, (iv) reduction of O$_2$, (v) C–H activation, (vi) oxygenation of alkyl radical, (vii) heterolytic decomposition of hydroperoxide and (viii) desorption of ketone.
On the basis of the proposed mechanism, kinetic analysis was then carried out. The rate constants and equilibrium constants of these elemental steps are defined as shown in Scheme 2. The overall reaction rate $r$ is represented as the rate of step v (eq 3). This rate equation is converted to a function of substrate concentration ([A]), oxygen pressure ($P_{O2}$), and light intensity (I) (eq 4) by considering the following conditions: steady-state approximation, charge conservation (eq 5), and by the total number of adsorption sites being constant (eq 6). Equation 4 can be simplified into a single function of [A], $P_{O2}$, or I, (eqs 7–9, respectively).

\begin{align*}
\text{(i)} & \quad \text{A} + \text{S} \underset{k_1}{\overset{k_i}{\rightleftharpoons}} \text{SA} & K_1 \\
\text{(ii)} & \quad \text{O}_2 + \text{S} \underset{k_2}{\overset{k_i}{\rightleftharpoons}} \text{SO}_2 & K_2 \\
\text{(iii)} & \quad h\nu \overset{k_3}{\underset{k_i}{\rightleftharpoons}} \text{e}^- + \text{h}^+ & K_3 \\
\text{(iv)} & \quad \text{SO}_2 + \text{e}^- \overset{k_4}{\underset{k_i}{\rightleftharpoons}} \text{SO}_2^* & K_4 \\
\text{(v)} & \quad \text{SA} + \text{h}^+ \overset{k_5}{\underset{k_i}{\rightleftharpoons}} \text{SA}^* & K_5 \\
\text{(vi)} & \quad \text{SA}^* + \text{SO}_2^* \overset{k_6}{\underset{k_i}{\rightleftharpoons}} \text{SB} + \text{S} & K_6 \\
\text{(vii)} & \quad \text{SB} \overset{k_7}{\underset{k_i}{\rightleftharpoons}} \text{SC} + \text{H}_2\text{O} & K_7 \\
\text{(viii)} & \quad \text{SC} \overset{k_8}{\underset{k_i}{\rightleftharpoons}} \text{C} + \text{S} & K_8
\end{align*}

\[ r = k_5[SA][h^+] \]  

\[ r = \frac{k_5K_1K_2K_3K_4K_6K_7K_8[S]_0[A]P_{O2}I}{K_2^2K_3^2K_4^2K_7K_8P_{O2}^2I + K_2K_3^{0.5}K_4K_8P_{O2}(K_1K_7K_8[A])} \]  

\[ [e^-] = [h^+] \]  

\[ [S]_0 = [S] + [SA] + [SA^*] + [SO_2^2] + [SO_2^*] + [SB] + [SC] \]  

\[ \frac{1}{r} = a_1 \frac{1}{[A]} + b_1 \]  

\[ \frac{P_{O2}}{r} = a_2P_{O2}^2 + b_2P_{O2} + c_2 \]  

\[ \frac{1}{r} = a_3(1^{0.5})^2 + b_3(1^{0.5}) + c_3 \]  

The experimental reaction rate of the photooxidation of ethylbenzene over Nb_2O_5 (\( r / \text{mmol·h}^{-1} \)) was obtained as a function of [A], P_{O2}, and I (Figure 9). A positive correlation was observed in the \( r \) vs. [A] and \( r \) vs. I plots, whereas a negative correlation was observed in the \( r \) vs. P_{O2} plot, suggesting competitive adsorption of the substrate and molecular oxygen. We then plotted reciprocals of the reaction rates (1/r) versus the reciprocal of the substrate concentration (1/[A]), as shown in Figure 10a. A linear correlation was obtained between 1/r and 1/[A]. This correlation can be expressed as eq 10, corresponding with eq 7. Likewise, a good quadratic correlation was found in the P_{O2}/r vs. P_{O2}, and I/r vs. \( r^{0.5} \) plots (Figure 10b and c, respectively). These correlations are described as eqs 11 and 12, corresponding with eqs 8 and 9, respectively. Thus, the kinetic model derived from the proposed mechanism is satisfactorily consistent with the experimental data.
\[
\frac{1}{r} = 14.2 \frac{1}{[A]} + 2.41
\]  \tag{10}

\[
\frac{P_{O_2}}{r} = 2.05 P_{O_2}^2 + 0.770 P_{O_2} + 0.0365
\]  \tag{11}

\[
\frac{1}{r} = -15.5(I^{0.5})^2 + 29.6(I^{0.5}) - 9.7
\]  \tag{12}

Figure 9. Reaction rates of ethylbenzene photooxidation over Nb$_2$O$_5$ under conditions of (a) various concentrations of ethylbenzene in benzene as a solvent; [A], (b) O$_2$ diluted by N$_2$ in the gas phase; P$_{O_2}$ and (c) different light intensity; I.

Figure 10. Plots of (a) $1/r$ against $1/[A]$, (b) $P_{O_2}/r$ against $P_{O_2}$ and (c) $I/r$ against $r^{0.5}$. 
Conclusions

The photooxidation of various undiluted hydrocarbons in liquid phase was conducted over Nb$_2$O$_5$ at room temperature. Nb$_2$O$_5$ exhibited higher selectivities to partial oxidation products than did TiO$_2$. A much higher K/A ratio was obtained in the photooxidation of cyclohexane over Nb$_2$O$_5$ than in that over TiO$_2$. The mechanistic study revealed that the photooxidation of hydrocarbon over Nb$_2$O$_5$ proceeds via a typical Langmuir–Hinshelwood mechanism as follows. Substrate and dioxygen are adsorbed on the Nb$_2$O$_5$ surface. Photoirradiation of Nb$_2$O$_5$ resulted in the reduction of Nb(V) to Nb(IV) by an excited electron and the formation of a positive hole on lattice oxygen. Dioxygen is reduced to superoxide by an excited electron, and a C–H bond of the substrate is oxidized by a positive hole to produce an alkyl radical. The alkyl radical is oxygenated to alkyl hydroperoxide by reaction with superoxide, followed by protonation. Finally, the alkyl hydroperoxide is decomposed to ketone and water. This mechanism is essentially the same as that of the photooxidation of cyclohexane over TiO$_2$. However, ESR measurements revealed that the strongly oxidizing species O$_3^-$ was not formed in the reaction over Nb$_2$O$_5$, in contrast to that conducted over TiO$_2$. These results lead us to the conclusion that the absence of O$_3^-$ is the key factor for the high selectivity to partial oxidation that is achieved in the photooxidation of hydrocarbon over Nb$_2$O$_5$. Moreover, this reaction mechanism does not involve the photoactivation of an adsorbed species, as is found in the alcohol photooxidation over Nb$_2$O$_5$; that is, excitation from an O 2p orbital localized on adsorbed alkoxide species to a conduction band consisting of Nb 4d orbital. This implies that the strong interaction between a substrate and surface (e.g., dissociative adsorption) is a key factor in the photoactivation of the adsorbed species.

References


(34) To the best of our knowledge, there has been no literature that characterizes surface oxygen species on Nb$_2$O$_5$.


Chapter 6

Solvent-free aerobic alcohol oxidation using Cu/Nb$_2$O$_5$: 
Green and highly selective photocatalytic system

Abstract

Photooxidation of alcohols without organic solvents in the presence of O$_2$ took place at the atmospheric pressure and room temperature over Nb$_2$O$_5$ and Cu/Nb$_2$O$_5$, avoiding the cost, toxicity, and purification problems associated with transition-metal systems. Loading of a small amount of copper on Nb$_2$O$_5$ significantly enhanced activity without lowering selectivity. On the other hand, loading of Pt, Ni, Rh, Ru, and Ag showed no promotion effect. The selectivities of the photooxidation of aliphatic, aromatic and heteroatom-containing alcohols over Cu/Nb$_2$O$_5$ were in the range of 80–99%. Cu/Nb$_2$O$_5$ was easily separated from the reaction mixture and was reusable without reducing the catalytic performance.
Introduction

Alcohol oxidation to corresponding carbonyl compounds is one of the most useful and the simplest transformations in organic and industrial chemistry. Non-catalytic methods with stoichiometric, toxic, corrosive and expensive oxidants such as ClO\textsuperscript{-}, dichromate, permanganate, and peroxy acids under stringent conditions of high pressure and/or temperature have been widely used for alcohol oxidations.\textsuperscript{1-4} In addition, these reactions are often carried out with high concentration of bases and environmentally unfriendly organic solvents. Therefore, much attention has been paid to the development of heterogeneous catalytic systems that use clean and atom efficient oxidants like molecular oxygen or H\textsubscript{2}O\textsubscript{2} without organic solvents.\textsuperscript{5-16} Therefore, the development of catalytic systems for alcohol oxidation has been one of the most pursued targets in last decade, due to substituting them with heterogeneous catalytic oxidation using clean and atom-efficient oxidants such as molecular oxygen without organic solvents.

Recently, the aerobic alcohol oxidation was successfully carried out by using heterogeneous catalysts such as tetrapropylammonium perruthenate (TPAP)/MCM-41,\textsuperscript{8} Ru/CeO\textsubscript{2},\textsuperscript{9} Ru-hydrotalcite,\textsuperscript{10} Ru/hydroxyapatite (Ru-HAP),\textsuperscript{11,12} [RuCl\textsubscript{2}(p-cymene)]/activated carbon,\textsuperscript{13} Ru/Al\textsubscript{2}O\textsubscript{3},\textsuperscript{14} Pd-hydrotalcite which requires the addition of pyridine,\textsuperscript{15} and Pt on activated carbon.\textsuperscript{16} These systems require the use of organic solvents like toluene and trifluorotoluene. Solvent-free aerobic oxidation of alcohols by Pd/Al\textsubscript{2}O\textsubscript{3} was also reported,\textsuperscript{17} however, the use of the noble metal Pd is essentially required.

In this respect, photoreactions are promising processes and the development of photocatalysts is a subject that is now receiving noticeable attention. TiO\textsubscript{2} has been identified as one example of a practical and useful photocatalysts,\textsuperscript{18-22} and widely used in degradation of organic pollutants in air and water. In the most part of these reports, TiO\textsubscript{2} is used in vapor phase oxidations at high temperatures,\textsuperscript{18} oxidation of only lower alcohols,\textsuperscript{19-21} oxidation using solvents such as benzene\textsuperscript{22} and a low selectivity to partial oxidized products due to excess photo-activation of target products which leads to deep oxidation. Zhao et al.\textsuperscript{23,24} reported that the photooxidation of alcohols on TiO\textsubscript{2} could be dramatically accelerated without any loss of selectivity by adsorption of Brønsted acid and this effect by Brønsted acid results from the
decomposition of the relatively stable side-on peroxyde promoted by the protons, which effectively clean the catalytic Ti–OH\textsubscript{2} sites. Recently, Su and co-workers reported that mesoporous graphite carbon nitride (mpg-C\textsubscript{3}N\textsubscript{4}) can work as effective photocatalyst for the selective oxidations of benzylic alcohols with visible light. However, these systems require the use of benzotrifluoride as a solvent.

Here, we report that Nb\textsubscript{2}O\textsubscript{5} and Cu/Nb\textsubscript{2}O\textsubscript{5} catalyze photooxidation of various aliphatic and aromatic alcohols without solvents in the presence of O\textsubscript{2} at the atmospheric pressure and room temperature. We found that loading of a small amount of copper on Nb\textsubscript{2}O\textsubscript{5} significantly enhanced activity without lowering selectivity, whereas loading of Pt, Ni, Rh, Ru, and Ag showed no promotion effect. This strongly suggests that the role of Cu on Nb\textsubscript{2}O\textsubscript{5} is different from those of precious metals such as Pt and Rh on TiO\textsubscript{2} photocatalyst, in other words, the promotion of charge separation.

**Experimental**

**Preparation**

Niobic acid, niobium oxide hydrate (Nb\textsubscript{2}O\textsubscript{5} \cdot nH\textsubscript{2}O, AD/2872, HY-340) was kindly supplied from CBMM. Other chemicals used were of reagent grade and were obtained from Aldrich Chemical Co., Tokyo Kasei Kogyo Co., Ltd and Wako Pure Chemical Industries, Ltd. All reagents were used without further purification.

Niobium oxide (Nb\textsubscript{2}O\textsubscript{5}) catalyst was prepared by calcination of niobic acid in a dry air flow at 773 K for 5 h (BET surface area: 48 m\textsuperscript{2}g\textsuperscript{-1}). A series of niobium oxide supported metal catalysts (M/Nb\textsubscript{2}O\textsubscript{5}; M = Ru, Rh, Ni, Pt, Cu, and Ag) was prepared by impregnation of niobic acid with an aqueous solutions of metal salts (RuCl\textsubscript{2}, RhCl\textsubscript{3}, Ni(NO\textsubscript{3})\textsubscript{2}, H\textsubscript{2}PtCl\textsubscript{4}, Cu(NO\textsubscript{3})\textsubscript{2} and Ag(NO\textsubscript{3})) at 353 K, followed by evaporation, drying and calcination at 773 K in a stream of dry air for 5 h. After calcination, the catalysts were ground into powder under 100 mesh (0.15 mm). M/Nb\textsubscript{2}O\textsubscript{5} catalysts were reduced under 5% H\textsubscript{2}/N\textsubscript{2} flow at 20 cm\textsuperscript{3}min\textsuperscript{-1} for 0.5 h at 673 K prior to use.
Characterization

BET surface areas of catalysts were determined using N\textsubscript{2} adsorption isotherm at 77 K measured by a BELSORP 28SA (BEL Japan Corp.). Crystal phase of each catalyst was determined by X-ray diffraction technique (XRD) under ambient conditions at room temperature using a Shimadzu XD-D1 X-ray diffractometer with Cu K\textalpha radiation (\(\lambda = 1.5418\) Å).

Photooxidation of alcohols

The photocatalytic oxidation of alcohol was carried out in a quasi-flowing batch system (see Chapter 5, Figure 1). Catalyst (100 mg) and a stirring bar were introduced to the Pyrex glass reactor (cut-off light below 300 nm). An alcohol as a substrate (10 ml) without solvent was introduced into the reactor. The suspension was vigorously stirred at room temperature and irradiated from the flat bottom of the reactor through a reflection by a cold mirror with a 500 W ultra-high-pressure Hg lamp (USHIO Denki Co.). Oxygen was flowed into the reactor at 2 cm\textsuperscript{3} min\textsuperscript{-1} (0.1 MPa). At the down stream of the flow reactor, a saturated barium hydroxide solution (Ba(OH)\textsubscript{2}) was equipped to determine the quantity of carbon dioxide (CO\textsubscript{2}) as barium carbonate (BaCO\textsubscript{3}). Products were analyzed and quantified by FID–GC (Shimadzu GC14B) and GC–MS (Shimadzu QP-5050).

Results and Discussion

Solvent-Free Photooxidation of 1-Pentanol over M/Nb\textsubscript{2}O\textsubscript{5}

Table 1 shows the results of photooxidation of 1-pentanol over Nb\textsubscript{2}O\textsubscript{5} and M/Nb\textsubscript{2}O\textsubscript{5} (M = Ru, Rh, Ni, Pt, Cu, and Ag) with molecular oxygen under irradiation at 323 K. The photogenerated products were pentanal (RCHO) as a main product, and a small amount of pentanoic acid (RCOOH) and carbon dioxide (CO\textsubscript{2}). Control experiments revealed that catalyst, oxygen and photo irradiation are necessary for the reaction (entries 12–14). The evolution of photogenerated products occurred in response to illumination. These results indicate that photooxidation of 1-pentanol over Nb\textsubscript{2}O\textsubscript{5} and M/Nb\textsubscript{2}O\textsubscript{5} was due entirely to a photocatalytic reaction. We have already reported that Nb\textsubscript{2}O\textsubscript{5} shows higher selectivity to pentanal than TiO\textsubscript{2} at
the same conversion level although TiO$_2$ shows higher activity than Nb$_2$O$_5$. Cu/Nb$_2$O$_5$ showed much higher activity than that of bare Nb$_2$O$_5$ (entries 1 and 7–11). On the other hand, when Ru, Rh, Ni, Pt, and Ag were supported on Nb$_2$O$_5$, the yields were almost similar to or slightly lower than that of bare Nb$_2$O$_5$ (entries 1–6).

**Table 1.** Photocatalytic activities of M/Nb$_2$O$_5$ (M = Ru, Rh, Ni, Pt, Cu, and Ag) in solvent-free photooxidation of 1-pentanol. $^a$

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Loading (mol%)</th>
<th>Yield / $\mu$mol $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nb$_2$O$_5$</td>
<td>–</td>
<td>355</td>
</tr>
<tr>
<td>2</td>
<td>Ru/Nb$_2$O$_5$</td>
<td>2.6</td>
<td>315</td>
</tr>
<tr>
<td>3</td>
<td>Rh/Nb$_2$O$_5$</td>
<td>2.6</td>
<td>305</td>
</tr>
<tr>
<td>4</td>
<td>Ni/Nb$_2$O$_5$</td>
<td>2.6</td>
<td>220</td>
</tr>
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<td>5</td>
<td>Pt/Nb$_2$O$_5$</td>
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<td>340</td>
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<td>445</td>
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<tr>
<td>7</td>
<td>Cu/Nb$_2$O$_5$</td>
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<td>780</td>
</tr>
<tr>
<td>8</td>
<td>Cu/Nb$_2$O$_5$</td>
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<td>1145</td>
</tr>
<tr>
<td>9</td>
<td>Cu/Nb$_2$O$_5$</td>
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<td>1285</td>
</tr>
<tr>
<td>10</td>
<td>Cu/Nb$_2$O$_5$</td>
<td>2.6</td>
<td>1125</td>
</tr>
<tr>
<td>11</td>
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<td>880</td>
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<tr>
<td>12 $^c$</td>
<td>Cu/Nb$_2$O$_5$</td>
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<td>36</td>
</tr>
<tr>
<td>13 $^d$</td>
<td>Cu/Nb$_2$O$_5$</td>
<td>1.9</td>
<td>n. d.</td>
</tr>
<tr>
<td>14</td>
<td>none</td>
<td>–</td>
<td>n. d.</td>
</tr>
</tbody>
</table>

$^a$ Reaction condition: catalyst (100 mg), 1-pentanol (10 ml), oxygen flow (2 cm$^3$min$^{-1}$), $\lambda$ > 300 nm, irradiation time, 5 h. $^b$ Amount of pentanal produced. $^c$ Under 1 atm N$_2$. $^d$ In the dark.
XRD patterns of Nb$_2$O$_5$ and M/Nb$_2$O$_5$ showed diffraction lines assignable to TT-phase Nb$_2$O$_5$ with a pseudohexagonal structure (Figure 1). No diffraction line due to these metal species was detected, indicating that these metal species were highly dispersed or with amorphous. It has been reported that modification with a small amount of highly dispersed metal species like Pt$^{20,22,26}$, Rh$^{27}$ and Ni$^{28}$ improves the photocatalytic activity of TiO$_2$.

Usually, it is thought that these metal species supported on TiO$_2$ act as an electron acceptor, resulting in inhibiting the recombination of photoactivated electrons and positive holes (charge separation mechanism). Therefore, above results of photooxidation over Nb$_2$O$_5$ and M/Nb$_2$O$_5$ suggest that the role of Cu supported on Nb$_2$O$_5$ is different from that of metal species on TiO$_2$, i.e., electron acceptor in charge separation mechanism. Hashimoto and co-workers reported that Cu(II) species grafted on TiO$_2$ promotes the oxidative decomposition of 2-propanol even under visible light (>450 nm) irradiation.$^{29,30}$ They also proposed that visible light initiates interfacial charge transfer (IFCT),$^{31-33}$ in other words, electron in the valence band of TiO$_2$ are directly transferred to Cu(II) and form Cu(I). In the IFCT mechanism, Cu(II) acts as an electron acceptor.

Figure 1. XRD patterns of M/Nb$_2$O$_5$: M = (a) Ru, (b) Rh, (c) Ni, (d) Pt, (e) Cu and (f) TT-Nb$_2$O$_5$.
Recently, we found that the photooxidation of 1-pentanol over Nb$_2$O$_5$ took place under visible light irradiation up to 480 nm, although the band gap of Nb$_2$O$_5$ is 390 nm (3.2 eV). This observation indicates that the photo-activation mechanism of alcohol over Nb$_2$O$_5$ is different from the classical electron transfer mechanism found in semiconductor photocatalysis (the formation of an excited electron in the conduction band and the positive hole in the valence band). By means of UV–Vis, ESR, FT-IR with the aid of DFT calculations, the detailed reaction mechanism of photooxidation of alcohol over revealed and unique photo-activation mechanism by “in situ doping” (the direct electron transfer from the O 2p orbital derived from adsorbed alcoholate species to the conduction band consisting of Nb 4d orbitals) was proposed.

Moreover, kinetic analysis revealed that the rate-determining step of the photooxidation of alcohol over Nb$_2$O$_5$ is desorption of products. These results suggest that copper on Nb$_2$O$_5$ acts as an accelerator of the product desorption in addition to the promoter of charge separation. The detailed reaction mechanism and the role of copper of Cu/Nb$_2$O$_5$ are now under investigation and will be reported in the near future.

**Photooxidation of Alcohols over Cu/Nb$_2$O$_5$**

The catalytic activities and selectivities for the solvent-free photooxidation of several aliphatic and aromatic alcohols over Nb$_2$O$_5$ and Cu/Nb$_2$O$_5$ with molecular oxygen at atmospheric pressure are summarized in Table 2 (entries 1–6). These aliphatic and aromatic alcohols were selectively oxidized to corresponding carbonyl compounds. The selectivity to cyclohexanone was slightly low (entry 4) among aliphatic alcohols tested. This may be due to autooxidation by the formation of radical species by the photo-activation (Norrish Type I reaction) of the produced cyclohexanone. In the case of aliphatic primary and secondary alcohols except for cyclohexanol (entry 4), the catalytic activities were significantly increased by loading of Cu. The conversions and selectivities in oxidation of aromatic alcohols were higher than those of aliphatic alcohols (entries 5 and 6). This tendency is similar to the conventional thermal catalyst. Primary alcohols were easier to be oxidized than secondary ones in the case of both of aliphatic and aromatic ones. This result is in contrast to the photooxidation of alcohol over TiO$_2$ film.
Table 2. Photooxidations of various alcohols catalyzed by Cu/Nb$_2$O$_5$ and Nb$_2$O$_5$. $^a$

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Products</th>
<th>Time / h</th>
<th>Cu/Nb$_2$O$_5$</th>
<th>Nb$_2$O$_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C (%)</td>
<td>S (%)</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>48</td>
<td>33</td>
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<tr>
<td>2</td>
<td></td>
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<td>48</td>
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</tr>
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<td>3</td>
<td></td>
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<td>4</td>
<td></td>
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<td>24</td>
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<td>99</td>
</tr>
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<td>6</td>
<td></td>
<td></td>
<td>24</td>
<td>24</td>
<td>98</td>
</tr>
<tr>
<td>7 $^b$</td>
<td></td>
<td></td>
<td>48</td>
<td>94</td>
<td>91</td>
</tr>
<tr>
<td>8a $^b$</td>
<td></td>
<td></td>
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<td>59</td>
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<tr>
<td>8b $^{b,c}$</td>
<td></td>
<td></td>
<td>48</td>
<td>40</td>
<td>64</td>
</tr>
<tr>
<td>9a $^b$</td>
<td></td>
<td></td>
<td>48</td>
<td>96</td>
<td>21</td>
</tr>
<tr>
<td>9b $^{b,c}$</td>
<td></td>
<td></td>
<td>48$^c$</td>
<td>51</td>
<td>49</td>
</tr>
</tbody>
</table>

$^a$ Reaction condition: catalyst (100 mg), alcohol (10 ml), oxygen flow (2 cm$^3$ min$^{-1}$), $h\nu > 300$ nm, C; conversion of alcohol, S; selectivity to partial oxidation products. $^b$ Catalyst (100 mg), alcohol (1 mmol), benzene (10 ml), oxygen pressure (0.1 MPa), $h\nu > 300$ nm. To avoid solvent evaporation, the oxidation was carried out in a closed system. $^c$ $h\nu > 390$ nm (using L42 cut-filter). BET surface areas of Nb$_2$O$_5$ and Cu/Nb$_2$O$_5$ are 48 and 59 m$^2$g$^{-1}$. 

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Figure 2 shows the time course of photooxidation of 1-phenylethanol over Nb$_2$O$_5$ and Cu/Nb$_2$O$_5$. The conversion increased with irradiation time. On the other hand, the selectivity to acetophenone was almost constant. The formation rate of acetophenone over Cu/Nb$_2$O$_5$ was higher than that of Nb$_2$O$_5$. Furthermore, in the case of Cu/Nb$_2$O$_5$, 1-phenylethanol was almost stoichiometrically oxidized after 192 h of photo irradiation even under solvent-free condition (96% yield; entry 6). Up to now, attempts to use photocatalyst for selective solvent-free aerobic oxidation of alcohols have met with very limited success. Fukuzumi et al. reported that 9-phenyl-10-methylacridium acts as an effective photocatalyst for solvent-free selective photocatalytic oxidation of benzyl alcohol under visible light irradiation via efficient photoinduced electron transfer from benzyl alcohol to the singlet excited state of the acridium ion. However, turnover number (TON) of their system is quite small. To the best of our knowledge, our system (Cu/Nb$_2$O$_5$) is the first example that aerobic photooxidation of alcohol proceeded quantitatively even under solvent-free condition.

![Figure 2](image_url)

**Figure 2.** Time course of conversions and selectivities in photooxidation of 1-phenylethanol over Cu/Nb$_2$O$_5$ and Nb$_2$O$_5$. Filled circle and triangle are the conversion and selectivity over Cu/Nb$_2$O$_5$ and unfilled circle and triangle are those over Nb$_2$O$_5$. 

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Leaching of active metal species into solution is an important point to consider the stability of catalyst. After 5 h of photooxidation of 1-pentanol, Cu/Nb$_2$O$_5$ catalysts could be easily separated by filtration. Further irradiation to the solid-free solution did not give any products. Moreover, the separated Cu/Nb$_2$O$_5$ was successfully reused with no reduction in the activity and selectivity as well as the separated Nb$_2$O$_5$. These results strongly suggest that the photooxidation takes place on the surface of the Cu/Nb$_2$O$_5$ catalyst.

In the cases of photooxidations of $\alpha$-methyl-2-pyridine methanol, $\alpha$-cyclopropylbenzyl alcohol, and cinnamyl alcohol, benzene was used as a solvent (Table 2, entries 7–9). In the case of Pd catalysts, alcohols having heteroatom, such as (3-pyridyl)methanol, (2-aminophenyl)methanol and (3-thiophenyl)methanol did not proceed due to the complexation of Pd with the heteroatom. However, by using Cu/Nb$_2$O$_5$, $\alpha$-methyl-2-pyridine methanol was converted to the corresponding ketone in high yield. On the other hand, the photooxidations of $\alpha$-cyclopropylbenzyl alcohol, and cinnamyl alcohol did not give the corresponding ketone and $\alpha,\beta$-unsaturated aldehyde in high yields. In these cases, benzaldehyde was mainly produced as by-product, indicating that C–C or C=C bond was cleaved at $\alpha$-position in each case. Interestingly, the selectivities to corresponding ketone and $\alpha,\beta$-unsaturated aldehyde moderately increased by the addition of Cu to Nb$_2$O$_5$. To confirm the contribution of photoreaction of $\alpha$-cyclopropylbenzyl alcohol and cinnamyl alcohol, these alcohols were irradiated in the absence of catalyst. The conversions of $\alpha$-cyclopropylbenzyl alcohol and cinnamyl alcohol were 71 and 99 % after 48 h of irradiation, respectively. This result indicates that a part of benzaldehyde formation was due to the photoreaction of these alcohols independently of the photo-activation by photocatalyst. On the other hand, the photoreaction of these alcohols in the absence of catalyst did not take place under visible light irradiation (> 390 nm). The photooxidation of these alcohols with Nb$_2$O$_5$ or Cu/Nb$_2$O$_5$ catalysts were tested under visible light irradiation. Although the band gap of Nb$_2$O$_5$ is 390 nm, the photooxidations proceeded over Nb$_2$O$_5$ and Cu/Nb$_2$O$_5$, and the selectivities to corresponding ketone and $\alpha,\beta$-unsaturated aldehyde improved (entries 8b and 9b). Moreover, Cu/Nb$_2$O$_5$ showed higher selectivities than those over Nb$_2$O$_5$. However, these selectivities are not still sufficiently high and admit of improvement. In our previous work, we proposed unique photo-activation mechanism by “in situ doping” (the direct electron transfer from the electron
donor level derived from adsorbed alcohohate species to the conduction band of photocatalyst).\textsuperscript{34,35} The fact that the photooxidation of \(\alpha\)-cyclopropylbenzyl alcohol and cinnamyl alcohol proceeded even under visible light irradiation supports that the photooxidation of alcohols over Nb\(_2\)O\(_5\) and Cu/Nb\(_2\)O\(_5\) took place by this “\textit{in situ doping}” mechanism. In our proposed mechanism, the radical species was formed by the direct electron transfer from the electron donor level to the conduction band under photo-irradiation, and then radical species was converted to corresponding carbonyl compound. We already confirmed that a radical intermediate with an unpaired electron located on \(\alpha\)-carbon is generated by photoexcitation of the chemisorbed alcohol.\textsuperscript{34,36,37} It is well known that a radical adjacent to the cyclopropyl or allyl moiety is unstable to easily rearrange. Therefore, it is likely that C–C and C=C bonds cleavage accompanied with the radical rearrangement occurs in the cases of photooxidation of \(\alpha\)-cyclopropylbenzyl alcohol and cinnamyl alcohol. This undesired radical rearrangement probably results in the decrease of the selectivity to the desired product.

\textbf{Conclusions}

Solvent-free aerobic photooxidations of various alcohols over Cu/Nb\(_2\)O\(_5\) and Nb\(_2\)O\(_5\) were examined. Several alcohols were selectively oxidized into corresponding carbonyl compounds at room temperature under atmospheric pressure. The photocatalytic activities were remarkably enhanced by addition of a small amount of Cu to Nb\(_2\)O\(_5\) without lowering selectivities. 1-penylethanol was quantitively oxidized to acetophenone by using Cu/Nb\(_2\)O\(_5\) even under solvent-free condition. A heteroatom-containing alcohol, \(\alpha\)-methyl-2-pyridine methanol was selectively oxidized by using Cu/Nb\(_2\)O\(_5\) and Nb\(_2\)O\(_5\). On the other hand, Nb\(_2\)O\(_5\) and Cu/Nb\(_2\)O\(_5\) gave moderate selectivities in the photooxidation of an allylic alcohol (cinnamyl alcohol) or \(\alpha\)-cyclopropylbenzyl alcohol. By the addition of a small amount of Cu to Nb\(_2\)O\(_5\), the selectivities to the corresponding carbonyl compounds improved. Cu/Nb\(_2\)O\(_5\) was easily separated from the reaction mixture and was reusable without reducing the catalytic performance.
References


Chapter 7

Reaction Mechanism of Alcohol Photooxidation over Cu/Nb$_2$O$_5$:

Roles of Cu in Enhancement of Photocatalytic Activity

Abstract

Reaction mechanism of photooxidation of alcohol over Cu/Nb$_2$O$_5$ and the role of Cu in enhancement of photocatalytic activity was elucidated. Alcohol was adsorbed on the Lewis acid site (Nb(V)) to form an alkoxide species. Photo-generated holes and electrons on Cu/Nb$_2$O$_5$ were trapped by the adsorbed alkoxide and Cu(II) species to form the alkoxide carbon radical and Cu(I) species. The formed alkoxide carbon radical was converted to a carbonyl compound and then desorbed. Finally, the reduced Cu(I) sites were re-oxidized by reaction with O$_2$. The alcohol photooxidation over Nb$_2$O$_5$ takes place under not only UV-irradiation but also visible light irradiation up to 450 nm, although the band gap of Nb$_2$O$_5$ is 390 nm (3.2 eV). DFT calculations revealed that 1) the surface donor level derived from the adsorbed alkoxide species is located in the forbidden band, 2) direct electron transition from the surface donor level to the conduction band takes place by absorbing a photon, 3) the excitation energy from surface donor level to the Nb 4d conduction band is lower than that from the O 2p valence band to Nb 4d. The kinetic study and FT-IR spectra suggest that Cu(I) acts as an effective desorption site for the products. Based on these results, we conclude that copper functions as an effective redox promoter and desorption site for the product.
**Introduction**

We have reported that the aerobic photooxidation of alcohols without organic solvents in the presence of O$_2$ under mild conditions (at atmospheric pressure and room temperature) proceeded over niobium oxide (Nb$_2$O$_5$) with excellent selectivity to carbonyl compounds.$^{1-2}$ In the previous study, we proposed the reaction mechanism of the photooxidation of alcohols over Nb$_2$O$_5$ as follows (Scheme 1): alcohol adsorbed on a Lewis acid site (Nb(V)) over Nb$_2$O$_5$ surface. The adsorbed alcohol was excited under photo-irradiation to generate an alkoxide carbon radical by trapping a photo-formed hole. At the same time, Nb(V) was reduced to Nb(IV) by trapping an excited electron. The formed alkoxide carbon radical was converted to a carbonyl compound. The product desorbed and the reduced Nb(IV) sites were re-oxidized by reaction with molecular oxygen. A kinetic study revealed that the rate-determining step of the photooxidation of alcohol over Nb$_2$O$_5$ is desorption of the formed carbonyl compounds. In this mechanism, the direct electron transition from the donor level derived from the adsorbed molecule to the conduction band of the photocatalyst plays an important role in the photo-activation step.

It is well known that the photocatalytic activity of TiO$_2$ is enhanced by the addition of a small amount of metal species such as Pt,$^{3-7}$ Rh,$^8$ Ru,$^9$ Ni,$^{10}$ Cu$^{11-13}$ and Ag.$^{14}$ Many researchers claimed that this enhancement of activity by metal species was based on the promotion of charge separation, that is, inhibition of recombination of excited electrons and positive holes generated by photo-irradiation.$^{4-6}$ Recently, we investigated the effect of various metals on the activity of the photooxidation of alcohols over Nb$_2$O$_5$. No promotion effect was observed through the addition of Pt, Rh, Ru, Ni and Ag. On the other hand, we found that loading of a small amount of copper significantly enhanced the catalytic activities of the photooxidation of various alcohols.$^{15}$ Although this result strongly suggests that the role of copper can not be explained by the simple charge separation mechanism, the role of copper over Nb$_2$O$_5$ in the photooxidation of alcohols still remains unclear. In this study, to clarify the role of copper, we investigated the reaction mechanism of the photooxidation of alcohol over Cu/Nb$_2$O$_5$ in detail through the action spectrum, kinetic analysis, DFT calculations, and several spectroscopic techniques (Cu K-edge XAFS, FT-IR, UV-Vis, and ESR).
Preparation

Niobic acid, niobium oxide hydrate (Nb$_2$O$_5$·nH$_2$O, AD/2872, HY-340) were kindly supplied by CBMM. The niobium oxide catalyst was prepared by calcination of niobic acid in dry air flow at 773 K for 5 h. After calcination, the catalyst was ground into powder below 100 mesh (0.15 mm). The TT-Nb$_2$O$_5$ phase with pseudohexagonal structure$^{16}$ was obtained according to the XRD pattern and Raman spectral data.$^1$ A niobium oxide-supported copper catalyst (Cu/Nb$_2$O$_5$) was prepared by impregnation of niobic acid with an aqueous solution of Cu(NO$_3$)$_2$ at 353 K, followed by evaporation, drying and calcination in dry air flow at 773 K for 5 h. The amount of Cu loaded was fixed at 1.9 mol%. After calcination, the catalysts were ground into powder below 100 mesh (0.15 mm).

Photocatalytic Activity Measurements

The photocatalytic oxidation of alcohols was carried out in a quasi-flowing batch system under atmospheric oxygen. Catalyst (100 mg), 1-pentanol (10 ml), and a stirring bar were introduced...
to the Pyrex glass reactor. The substrate was used without further purification. The suspension was stirred vigorously at RT and irradiated through the flat bottom of the reactor by reflection from a cold mirror with a 500 W ultra-high pressure Hg lamp (USHIO Denki Co.). Oxygen was passed into the reactor at 2 cm$^3$ min$^{-1}$. The organic products were analyzed by FID–GC (Shimadzu GC-14B) and GC–MS (Shimadzu GC–MS QP5050). The quantity of carbon dioxide (CO$_2$) was determined as barium carbonate (BaCO$_3$) using a saturated barium hydroxide solution (Ba(OH)$_2$) trap placed downstream of the flow reactor. For kinetic analysis, 1-pentanol was used as a substrate. We confirmed that no product was detected in the dark with a Cu/Nb$_2$O$_5$ catalyst and the evolution of photogenerated products responded to illumination. Substrate concentration and oxygen pressure were balanced by using benzene and nitrogen when required, respectively. The light intensity was controlled using a metal mesh.

To measure an action spectrum, the reaction was carried out in a batch reactor with Cu/Nb$_2$O$_5$ (200 mg) and 1-pentanol (4 ml) and using a monochromatic irradiator (JASCO CRM-FA Spectro Irradiator) as light source.

**Cu K-edge X-ray absorption spectra**

Cu K-edge X-ray absorption spectra were measured on the beam line BL01B1 at SPring-8 of the Japan Synchrotron Radiation Research Institute (Proposal No. 2007B1123 and 2008A1147), Japan in transmission mode at RT using two ion chambers. The storage ring was operated at 8 GeV with injection currents of 100 mA. An Si (111) two crystal monochromator was used to obtain a monochromatic X-ray beam. The photon energy was calibrated with Cu foil. The samples were sealed in polyethylene bags under dry nitrogen atmosphere. Data were analyzed using the REX2000 program (Version: 2.5.9; Rigaku Corp.). The oscillation was normalized using the edge height around 70–100 eV higher than the threshold.

**UV-Vis spectra**

Diffuse reflectance spectra (1 nm resolution) were obtained with a UV-Vis spectrometer (JASCO UV570). A slurry of the mixture of 1-pentanol (0.2 ml) and Cu/Nb$_2$O$_5$ (100 mg) was used as the sample of 1-pentanol adsorbed on Cu/Nb$_2$O$_5$. 

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FT-IR spectra

FT-IR spectra of the sample before and during photo irradiation were recorded with a Perkin-Elmer SPECTRUM ONE Fourier transform infrared spectrometer. The resolution of the spectra was 4 cm$^{-1}$. A Cu/Nb$_2$O$_5$ sample was cast into a pellet with diameter 12 mm. The molded sample was introduced into an in situ IR cell equipped with BaF$_2$ windows. Prior to the measurements, the sample was pretreated with 15.6 kPa of O$_2$ for 1 h and evacuated at 773 K for 0.5 h. A 300 W Xe lamp (Perkin-Elmer CERAMAX PE300BF) was used as light source. An L-42 cutoff filter was used for visible light irradiation (> 390 nm). 13.3 kPa of O$_2$ was introduced onto the Cu/Nb$_2$O$_5$ with adsorbed alcohol before photo-irradiation.

ESR spectra

ESR measurements were carried out using an X-band ESR spectrometer (JEOL JES-SRE2X) with in situ quartz cell. The g value of the radical species was determined using a Mn(II) marker. The ESR spectra of Nb$_2$O$_5$ or 1.9 mol% Cu/Nb$_2$O$_5$ with adsorbed alcohols were recorded before and after photo-irradiation. A 500 W ultra-high pressure mercury lamp was used as light source.

Surface models and DFT calculation method

Quantum chemical calculations using the DFT method as implemented in Gaussian 03$^{17}$ were carried out to investigate the electronic structure and excitation energy of the Nb$_2$O$_5$ and Nb$_2$O$_5$-alkoxide complex. We used the neutral Nb$_{12}$O$_{43}$H$_{26}$ cluster in this study which was obtained from the structure of H-Nb$_2$O$_5$ by saturating the peripheral oxygen atoms with hydrogen atoms. The Nb$_{12}$O$_{42}$H$_{25}$(OCH$_3$) cluster as a model of the Nb$_2$O$_5$-alkoxide complex was obtained by substitution of one OH group of the Nb$_{12}$O$_{43}$H$_{26}$ cluster.

The calculation made use of Becke’s three parameter hybrid (B3LYP) method involving Lee et al.’s correlation function$^{18-19}$ and the LanL2DZ basis set for a single point energy calculation. One-electron excitation energies of model clusters were also obtained by time-dependent (TD)$^{20-22}$ calculations with singlet spin multiplicity.
Results

Redox Behavior and Local Structure of Cu over Nb₂O₅

Cu K-edge XANES spectra were measured to investigate the change in copper valency under the photooxidation of alcohol. Figure 1 shows the Cu K-edge XANES spectra and first derivatives of several reference compounds (Cu foil, Cu₂O, CuO and Cu(OH)₂) and Cu/Nb₂O₅. It is well known that Cu K-edge XANES spectra strongly reflect the chemical state and local symmetry of Cu species. The XANES spectrum of Cu₂O exhibited a single strong peak owing to the 1s → 4pπ transition around 8982 eV, characteristic of Cu(I). A small pre-edge peak around 8977.5 eV owing to Cu(II) 1s → 3d transition appeared in the XANES spectrum of Cu(II) (d⁹). This transition is formally dipole-forbidden, however, the dipole forbidden transition partially allows for distortion of the octahedral environment, which brings about the absence of a centre of inversion symmetry and the mixing of p orbitals with d orbitals. Therefore, it becomes more intense as the symmetry distorts from that of a regular octahedron. The coordination of copper in CuO: 4 atoms O at 1.94 Å + 2 atoms O at 2.78 Å and in Cu(OH)₂: 4 atoms O at 1.96 Å + 2 atoms O at 2.63 Å, is similar but the CuO₆ unit is much more distorted in Cu(OH)₂. As a result, the peak intensity owing to the Cu(II) 1s → 3d transition of Cu(OH)₂ (distorted O₆h) is more intense than that of CuO (D₄h). The absorption edge varied with copper oxidation state in the following order: Cu(0) < Cu(I) < Cu(II) (D₄h) < Cu(II) (O₆h). The peak position of Cu/Nb₂O₅ oxidized at 298 K was similar to that of Cu(OH)₂, and higher than that of CuO. A small pre-edge peak appeared around 8977.5 eV. These results indicate that Cu(II) is present in the octahedral symmetry. In the case of Cu/Nb₂O₅ reduced at 673 K, the Cu K-edge XANES spectrum clearly showed that copper had a zero valence. After photooxidation, a similar XANES spectrum was obtained in spite of the pretreatment (Figure 1, c and d). A small pre-edge peak owing to the Cu(II) 1s → 3d transition was observed; the intensity of the pre-edge peak was similar to that of CuO. Peaks owing to the Cu(II) 1s → 4pₓ and the Cu(II) 1s → 4pᵧ transitions were also observed at 8987 and 8997 eV, respectively. The first derivatives of XANES spectra gave a shoulder peak at 8981 eV assigned to the 1s → 4pₓ* transition. This peak is assigned to Cu(I). On the basis of these results, we conclude that the copper forms oxide species and the state of copper during photo-irradiation was a mixture of the dominant divalent cation with a small...
amount of the monovalent cation. This result suggests that redox of copper (between Cu(II) and Cu(I)) was involved in the catalytic cycle of photooxidation of 1-pentanol over Cu/Nb₂O₅.

Figure 1. (A) Cu K-edge XANES spectra and (B) their first derivatives of Cu/Nb₂O₅ catalyst and the reference compounds: (a) oxidized at 298 K for 24 h, (b) reduced at 673 K for 2 h, (c) oxidized at 298 K for 24 h followed by 6 h of photooxidation, (d) reduced at 673 K for 2 h followed by 6 h of photooxidation, (e) Cu(OH)₂, (f) CuO, (g) Cu₂O and (h) Cu foil. The inset shows a magnified view of the pre-edge region.
**FT-IR measurement for adsorbed species**

Figure 2 shows FT-IR spectra of adsorbed cyclohexanol on Cu/Nb$_2$O$_5$. The bands at 1467 and 1452 cm$^{-1}$ was assigned to $\delta$(CH$_2$). The peaks at 1364 cm$^{-1}$ were assigned to $\omega$(CH$_2$). Formation of the alkoxide species by the chemisorption of alcohol is usually accompanied by a shift of the stretching mode of the C–O bond to a higher wavenumber. Pure cyclohexanol had a band at 1068 cm$^{-1}$, which is assignable to the stretching mode of a C–O bond. This band was similar to that of the physisorbed cyclohexanol (Figure 2, c). After adsorption on Cu/Nb$_2$O$_5$, the bands at 1093 and 1130 cm$^{-1}$ appeared, and these were assigned to the stretching mode of a C–O bond in the alkoxide species on Cu/Nb$_2$O$_5$. These results correspond to FT-IR spectra of adsorbed cyclohexanol on bare Nb$_2$O$_5$.$^2$ Furthermore, the positions of these bands were consistent with those of the niobium alkoxide complex Nb(OC$_6$H$_{11}$)$_5$.$^{32}$ This result indicates that the alkoxide species was generated on an Nb(V) site.

![Figure 2. FT-IR spectra of cyclohexanol adsorbed on Cu/Nb$_2$O$_5$: (a) cyclohexanol exposed to Nb$_2$O$_5$ for 1.0 h (physisorption + chemisorption), (b) evacuated for 0.2 h (chemisorption), (c) difference spectrum (a-b: physisorption). Cu/Nb$_2$O$_5$ was oxidized at 673 K with 10.7 kPa of O$_2$ then evacuated at 298 K for 0.5 h before FT-IR measurements.](image-url)
Figure 3A shows the change in FT-IR spectra during visible light irradiation (> 400 nm) of the alkoxide species adsorbed on Cu/Nb$_2$O$_5$. The intensity of the bands assigned to $\nu$(C–O) (around 1090 cm$^{-1}$), $\delta$(CH$_2$) (1467 cm$^{-1}$) and $\omega$(CH$_2$) (1364 cm$^{-1}$) decreased as the light irradiation time increased, whereas the bands assigned to $\nu$(C=O) (1705 and 1721 cm$^{-1}$) and the asymmetric and symmetric stretches of the carboxylic acid anion (1551 and 1412 cm$^{-1}$) grew gradually. This result clearly indicates that the surface complex consisting of adsorbed cyclohexanol (i.e. alkoxide species)

![Figure 3A](image)

**Figure 3.** (A) FT-IR spectra of (A) cyclohexanol adsorbed Cu/Nb$_2$O$_5$ under visible light irradiation. Differential spectra between before and after photo irradiation are shown (irradiation time; (a) 5 min, (b) 10 min, (c) 15 min, (d) 30 min, (e) 60 min, (f) 120 min, (g) 180 min and (h) 240 min). (B) FT-IR spectra in the region of C=O stretching vibrations; (a) after 240 min of photo irradiation to the adsorbed cyclohexanol on Cu/Nb$_2$O$_5$, (b) cyclohexanone introduced on Cu/Nb$_2$O$_5$, (c) after photo irradiation to the adsorbed cyclohexanol on Nb$_2$O$_5$, (d) cyclohexanone introduced on CuO, (e) Cu$_2$O, (f) Cu metal and (g) gaseous cyclohexanone.
and metal oxide was excited by photons and oxidized to carbonyl compounds by visible light irradiation. In the region of the C=O stretching vibration (around 1710 cm$^{-1}$), first the band at 1705 cm$^{-1}$ grew, then the band at 1721 cm$^{-1}$ appeared.

When cyclohexanone was introduced onto Cu/Nb$_2$O$_5$, these two bands were observed (Figure 3B, b). On the other hand, the band at 1705 cm$^{-1}$ appeared after photo-irradiation of the adsorbed cyclohexanol on bare Nb$_2$O$_5$, whereas the band at 1721 cm$^{-1}$ was not observed (Figure 3B, c). This suggests that the band at 1721 cm$^{-1}$ arises from cyclohexanone adsorbed on a Cu site. The band at 1721 cm$^{-1}$ was also observed when Cu$_2$O was exposed to cyclohexanone (Figure 4B, e). In addition, the band at 1721 cm$^{-1}$ was not observed when Cu metal and CuO were exposed to cyclohexanone (Figure 3B, d and f), indicating that both CuO (Cu(II)) and Cu metal (Cu(0)) have no interaction with cyclohexanone. These results suggest that the photogenerated carbonyl compounds adsorbed on the Nb sites and Cu(I) sites over Cu/Nb$_2$O$_5$. The position of the band owing to $\nu$(C=O) of the photogenerated cyclohexanone on the Cu(I) site was lower than that for pure cyclohexanone, but higher than on the Nb site (Figure 3B, g). This indicates that the photogenerated cyclohexanone on the Cu(I) sites has a weaker interaction with the Cu(I) sites than the Nb(V) site.

**Wavelength dependence on the apparent quantum yield**

Figure 4 shows the apparent quantum yield of the 1-pentanol photooxidation over Cu/Nb$_2$O$_5$ as a function of the wavelength of the incident light (action spectrum). UV-Vis spectra of Cu/Nb$_2$O$_5$ before and after the adsorption of 1-pentanol on Cu/Nb$_2$O$_5$, and difference spectrum were also described. Cu/Nb$_2$O$_5$ exhibited an intense absorption band around 275 nm corresponding to the interband transition of the Nb$_2$O$_5$ support. The band gap energy of Cu/Nb$_2$O$_5$ was estimated as 3.2 eV (the photoexcitation wavelength was 390 nm) and was similar to bare Nb$_2$O$_5$ (390 nm). When 1-pentanol was adsorbed on Cu/Nb$_2$O$_5$, a slight increase in absorption around 300–350 nm was observed. The difference spectrum showed an absorption band at 340 nm. Since 1-pentanol has no absorption at wavelengths longer than 300 nm,$^{33}$ it seems that the band around 340 nm is attributed to absorption by a surface complex consisting of adsorbed species and Nb$_2$O$_5$.

In the case of typical semiconductor photocatalysis, an interband transition takes place by photo-irradiation and forms an excited electron in the conduction band and a positive hole in the
valence band. Then the excited electron or hole triggers the reaction. In this case, the action spectrum agrees with the absorption band corresponding to the interband transition. However, the photooxidation of 1-pentanol over Cu/Nb$_2$O$_5$ proceeded under irradiation up to ca. 460 nm, although the band gap of Cu/Nb$_2$O$_5$ is at 390 nm (3.2 eV). This indicates that the photo-activation mechanism of alcohol over Cu/Nb$_2$O$_5$ is different from the interband transition in typical semiconductor photocatalysis. The action spectrum of 1-pentanol photooxidation over Cu/Nb$_2$O$_5$ shows agreement with the difference spectrum. These results suggest strongly that the absorption by a surface complex consisting of adsorbed species and Nb$_2$O$_5$ support would be involved in the photo-activation process.

Interestingly, the apparent quantum yield was improved remarkably by addition of a small amount of copper to Nb$_2$O$_5$ (from 7% to 30% at 340 nm). This value (30%) is much higher than those for general semiconductor photocatalysts.}

Figure 4. Action spectrum of 1-pentanol photooxidation over Cu/Nb$_2$O$_5$, UV-Vis spectra of Cu/Nb$_2$O$_5$ and 1-pentanol adsorbed on Cu/Nb$_2$O$_5$, and difference spectrum between them.
Investigation of excitation mechanism by DFT calculations

The electronic structure of the model of the Nb$_2$O$_5$-alkoxide complex was compared to that of Nb$_2$O$_5$ by DFT calculations. Figure 5A shows the model cluster of the H-phase Nb$_2$O$_5$ (1; Nb$_{12}$O$_{43}$H$_{26}$) and that of the dissociative adsorption of methanol onto the H-phase Nb$_2$O$_5$ (100) surface (2; Nb$_{12}$O$_{42}$H$_{25}$(OCH$_3$)). In cluster 2, one terminal hydroxyl group was substituted with methoxy one. The occupied and virtual Kohn-Sham orbitals (KSOs) of these model clusters consisted of O 2p orbitals and Nb 4d orbitals, respectively (Figure 6). Figure 5B shows selected frontier orbitals of 1 and 2. Cluster 2 exhibits a different electronic state from cluster 1. Particularly with HOKS and HOKS–1 of 2, O 2p orbitals localize on the oxygen atom of the methoxy group.

![Figure 5](image.png)

**Figure 5.** (A) Model clusters of H-Nb$_2$O$_5$; Nb$_{12}$O$_{43}$H$_{26}$ (1) and alkoxide adsorbed on H-Nb$_2$O$_5$; Nb$_{12}$O$_{42}$H$_{25}$(OCH$_3$) (2). (B) Graphical illustrations of LUKS, HOKS, and HOKS–1 of 1 and 2.
Figure 6. Graphical illustrations of occupied and unoccupied KSOs of 1 and 2.
As shown in Figure 7, the energy levels of HOKS and HOKS–1 are higher than that of the HOKS of 1, whereas the energy levels of LUKS and other unoccupied orbitals of 1 and 2 are almost the same. These results clearly show that donor levels whose populations are localized on the alkoxide oxygen are generated by the formation of a surface complex (Nb₂O₅-alkoxide). Indeed, the electron excitation energies of 1 and 2 calculated by TD-DFT revealed that a lower energy transition takes place with 2 than with 1 (Table 1). Thus, the photooxidation of alcohols proceeding by lower-energy light than the band gap of Nb₂O₅ can be explained by excitation of the surface complex, i.e., direct electron excitation from the O 2p orbital localized on the alkoxide oxygen to the conduction band of Nb₂O₅ consisting of a Nb 4d orbital (Scheme 2a).

![Energy diagram of the frontier KSOs of 1 and 2.](image)

**Figure 7.** Energy diagram of the frontier KSOs of 1 and 2.
**Table 1.** Electron excitation energies of 1 and 2 estimated by TD-DFT calculations.

<table>
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<th>assignment $^b$</th>
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<td>0.0018</td>
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<td>0.0001</td>
<td>H‒6 → L+1, L+3 (54%)</td>
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<tr>
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<td></td>
<td>2.46</td>
<td>0.0010</td>
<td>H → L+1, L+2 (97%)</td>
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</table>

$^a$Oscillator strength. $^b$Only the major parent one-electron excitations are reported. Their percentage contributions to wave functions of excited states are given in parentheses. H = HOKS. L = LUKS.

**Scheme 2.** Schematic illustration of (a) photo excitation from O 2p orbital localized on alkoxide oxygen atom to Nb 4d orbital and (b) reduction of Cu(II) oxide by excited electron. Applied potentials are vs. NHE.
ESR Measurement for Intermediate Species

Figure 8 shows the ESR spectra of adsorbed alcohols on Nb₂O₅ or Cu/Nb₂O₅ under photo-irradiation at 77 K. UV-irradiation to 1-pentanol adsorbed on bare Nb₂O₅ resulted in the appearance of an ESR signal assigned to the corresponding alkoxide carbon radical\(^2\) at 77 K (Figure 8a). In the case of 1-pentanol adsorbed on Cu/Nb₂O₅, however, a broad signal assigned to the Cu(II) ion\(^3\) appeared, whereas no signal assignable to an organic radical was detected. On the other hand, when tertiary butyl alcohol adsorbed on Nb₂O₅ or Cu/Nb₂O₅ under UV-irradiation at 77K, an intense signal \((g = 2.003, A_H = 2.0 \text{ mT})\) assigned to the methyl radical\(^3\) was found predominantly regardless of the presence of copper (Figure 8c, d). As mentioned above, it is suggested that a direct electron transition takes place from the O 2p orbital localized on the oxygen atom of the alkoxide to a conduction band consisting of the Nb 4d orbital by light absorption regardless of the presence of copper. This transfer enables the remaining hole to be located on the oxygen atom of the alkoxide thereby forming an alkoxide radical (Scheme 2a). It seems that the observed methyl radicals are generated via C–C bond cleavage of the adsorbed tertiary butoxide by the hole as shown in Scheme 3a. Moreover, a weak signal was also observed, and this signal may be an alkoxide carbon radical\(^3\) formed by C–H bond cleavage of the adsorbed tertiary butoxide. These results suggest that the photoexcitation mechanism of adsorbed alcohol over Cu/Nb₂O₅ is almost similar to that over Nb₂O₅.

In the case of Nb₂O₅, the ESR signal owing to Nb(IV) was observed by exposure to excess alcohol under photo-irradiation.\(^2\) This indicates that a part of Nb(V) was reduced by excitation of an electron to Nb 4d orbitals (the conduction band of Nb₂O₅). On the other hand, when 1-pentanol adsorbed on Cu/Nb₂O₅ under photo-irradiation, no signal owing to Nb(IV) appeared as shown in Figure 7b. However, the intensity of the ESR signals owing to Cu(II) decreased by photo-irradiation. XANES and FT-IR analyses indicated the generation of Cu(I) oxide species during the photooxidation. Accordingly, the decrease of Cu(II) and increase of Cu(I) may be attributed to reduction of Cu(II) to Cu(I) by a photoexcited electron. This suggests that the photoexcited electron at the conduction band of Nb₂O₅ is trapped by Cu(II) to produce Cu(I) (Scheme 2b). The reduction potential of CuO to Cu₂O can be estimated as +0.099 V vs. NHE from reported values (CuO + 2H\(^+\) + 2e\(^-\) = Cu + H₂O; E\(^+/V\) = +0.570 vs. NHE, Cu₂O + 2H\(^+\) + 2e\(^-\) = 2Cu + H₂O; E\(^+/V\) = +0.471 vs.
NHE). This value is more positive than that of Nb$_2$O$_5$ to NbO$_2$ (Nb$_2$O$_5$ + 2H$^+$ + 2e$^-$ = 2NbO$_2$ + H$_2$O; E$^*/$V = –0.289 vs. NHE)$^{40}$, which supports our model.

Scheme 3b shows the proposed electron transfer mechanism in the photooxidation of a primary or secondary alcohol. The photogenerated radical intermediate seems to be oxidized to the product by transferring an electron to Nb(V) or Cu(II). This radical intermediate appeared on Nb$_2$O$_5$ whereas it disappeared on Cu/Nb$_2$O$_5$, suggesting that the intermediate was immediately converted to the product in the presence of copper, because Cu(II) may work as an electron acceptor.

**Figure 8.** ESR spectra of adsorbed alcohol species under photo irradiation at 77 K (solid line); 1-pentanol adsorbed on (a) Nb$_2$O$_5$, (b) Cu/Nb$_2$O$_5$, tert-butylalcohol adsorbed on (c) Nb$_2$O$_5$ and (d) Cu/Nb$_2$O$_5$. Dotted lines show spectra under the dark.
Discussion

Based on these results, the reaction mechanism shown in Scheme 4 is proposed. Alcohol is adsorbed on the Cu/Nb₂O₅ surface to generate an alkoxide species I (step i). The alkoxide adsorbed on Cu/Nb₂O₅ is excited under photo-irradiation by transferring an electron to copper thus reducing Cu(II) to Cu(I), and leaving a hole on the alkoxide (step ii). The radical intermediate II is oxidized and transferred to carbonyl compound III (step iii). A part of the carbonyl compound produced on Nb(V) migrates onto the Cu(I) site and then desorbs (step iv). Finally, the reduced Cu(I) sites are reoxidized by reaction with molecular oxygen (step v). The rate of photooxidation of alcohol may depend on the concentrations of alcohol and O₂, and light intensity. Figure 9 shows the formation rate of pentanal in the photooxidation of 1-pentanol over Cu/Nb₂O₅ under various concentrations of 1-pentanol and oxygen, and various light intensities. A slightly positive-correlation was observed for

Scheme 3. Plausible electron-transfer mechanism of alkoxide species with (a) tertiary butyl alcohol and (b) primary or secondary alcohol.
Scheme 4. The reaction mechanism of alcohol photooxidation over Cu/Nb$_2$O$_5$.

Figure 9. Formation rate of 1-pentanal in the photooxidation of 1-pentanol ($r$) under various condition of (a) 1-pentanol concentrations; [A], (b) oxygen pressures; P$_{O_2}$ and (c) relative light intensities; I.
the \( r-[A] \) and \( r-P_{O_2} \) plots. The \( r-I \) plot was linear from the origin and the reaction order of light intensity was estimated to be first order. Thus, the rate-determining step of the photooxidation of 1-pentanol over Cu/Nb\(_2\)O\(_5\) seems to be one photon absorption process, in other words, photoexcitation of the surface complex. Considering that the rate-determining step of the photooxidation of alcohol over Nb\(_2\)O\(_5\) was desorption of the product, a kinetic analysis of the photooxidation of 1-pentanol over Cu/Nb\(_2\)O\(_5\) and FT-IR spectra of adsorbed cyclohexanol on Cu/Nb\(_2\)O\(_5\) suggests that the Cu(I) site worked as an effective desorption site and accelerated desorption of the product. Based on the reaction mechanism shown in Scheme 4, elemental steps are described in the rate equation as shown in Scheme 5.

\[
\begin{align*}
(i) & \quad A + S \quad \underset{k_{-1}}{\xrightarrow{k_1}} \quad AS \quad K_1 \\
(ii) & \quad AS + h\nu \quad \underset{k_3}{\xrightarrow{k_2}} \quad BS^* \quad (r. \ d. \ s.) \\
(iii) & \quad BS^* \quad \underset{k_{-3}}{\xrightarrow{k_3}} \quad CS^* + H_2O \quad K_3 \\
(iv) & \quad CS^* \quad \underset{k_{-4}}{\xrightarrow{k_4}} \quad C + S^* \quad K_4 \\
(v) & \quad S^* + 1/2 O_2 \quad \underset{k_{-5}}{\xrightarrow{k_5}} \quad S \quad K_5
\end{align*}
\]

**Scheme 5.** Rate equations of the elementary steps in 1-pentanol photooxidation. S: vacant active site. AS: active site adsorbed 1-pentanol. B: alkoxide carbon radical. S*: reduced site. C: pentanal.

We derived the following rate equation by assuming that photoexcitation of the surface complex (step ii) is the rate-determining step (eq 1) using a steady-state approximation.

\[
r = \frac{k_2K_iK_3K_4KS_0[A]P_{O_2}^{0.5}I}{(K_i+1)K_3K_4K_5[A]P_{O_2}^{0.5} + K_3K_4 + K_5[C] + 1}
\]  

(1)
To verify our proposed reaction mechanism (Scheme 4), the obtained rate equation is compared with the rate equation derived from our proposed reaction mechanism (eq 1). Figure 10 shows plots of the reciprocals of the reaction rates \((r^{-1})\) against the reciprocal of the substrate concentration \([A]^{-1}\) and square root of oxygen pressure \(P_{O_2}^{-0.5}\) and these plots shows a linear correlation. This linear correlation indicates that the reaction mechanism is consistent with experimental kinetic data.

This mechanism is essentially the same as the case of Nb\(_2\)O\(_5\), whereas 1) redox of copper (Cu(II)/Cu(I)) takes place instead of the redox of niobium (Nb(V)/Nb(IV)), and 2) desorption of the product from Cu(I) sites is involved. On the basis of the results above, we conclude that Cu(II) acts as a promoter to accelerate step (iii), and Cu(I) promotes desorption of the product (step iv). This mechanism is different from the simple charge separation mechanism.

**Figure 10.** Reciprocals of the reaction rates of 1-pentanol photooxidation \((r^{-1})\) against the reciprocal of (a) 1-pentanol concentration; \([A]^{-1}\) and (b) square root of oxygen pressure; \(P_{O_2}^{-0.5}\).

**Conclusion**

Loading of a small amount of copper on Nb\(_2\)O\(_5\) significantly enhanced the activity of the photooxidation of alcohols without organic solvents in the presence of O\(_2\) at atmospheric pressure and room temperature. A mechanistic study revealed that the photooxidation of alcohols over Cu/Nb\(_2\)O\(_5\) proceeds as follows: alcohol was adsorbed on a Lewis acid site (Nb(V)) to form an
alkoxide species. Photo-generated holes and electrons on Cu/Nb$_2$O$_5$ were trapped by the adsorbed alkoxide and Cu(II) species, respectively, to form the alkoxide carbon radical and Cu(I) species. The formed alkoxide carbon radical was converted to a carbonyl compound and desorbed. Finally, the reduced Cu(I) sites are re-oxidized by reaction with molecular oxygen. It was concluded that the rate-determining step is the photoexcitation step, and that the role of copper are 1) as redox promoter and 2) to act as effective desorption site for the product.

DFT calculations revealed that 1) the surface donor level derived from adsorbed alkoxide species is located in the forbidden band, 2) direct electron transition from the surface donor level to the conduction band takes place by absorbing a photon, 3) the excitation energy from surface donor level to Nb 4d is lower than that from O 2p valence band to Nb 4d. The effective wavelength is shifted to a longer wavelength by the formation of a donor level derived from the adsorbed molecule during a chemical reaction, which can be expressed as “in-situ doping” effect. This unique photo-activation mechanism by direct electron transition from the surface donor level to the conduction band gives us attractive ways for removing the limit of band gap energy, and utilization of the visible light.

Reference


Chapter 8

XAFS Study of Cu/Nb₂O₅: Effects of Electronic States of Cu on Photocatalytic Activity in Alcohol photooxidation

Abstract

Correlation between photocatalytic activity of a series of Cu/Nb₂O₅ catalysts pretreated under various conditions in alcohol photooxidation and state of Cu on Cu/Nb₂O₅ is shown. Reduction of as-prepared Cu/Nb₂O₅ at 673 K enhances its photocatalytic activity. Subsequent oxidation of the reduced Cu/Nb₂O₅ at 348–393 K further improves the activity. But the catalysts oxidized above 393 K show lower activities than the reduced one. The highest activity observed for the catalyst oxidized at 393 K after the reduction is twice as high as the as-prepared catalyst. XANES study reveals that the change in photocatalytic activity corresponds to the fraction of Cu₂O which promotes the rate-determining step, desorption. EXAFS study indicates that Cu metal particles with ca. 4 nm diameter are oxidized to Cu₂O and CuO in a stepwise manner from outer layer of the particles with increase in the oxidation temperature.
Introduction

Heterogeneous photocatalysts have potential application in the aerobic oxidation of organic molecules.\textsuperscript{1–3} To the present, various semiconductor materials have been tested as oxidation photocatalysts, and it is generally accepted that the anatase TiO\textsubscript{2} is the most versatile and reliable material in view of cost, stability, and photocatalytic activity. Since photocatalytic oxidation of organic molecule over TiO\textsubscript{2} is caused by positive holes and/or hydroxyl radicals derived from band gap excitation of TiO\textsubscript{2}, the photocatalytic activity depends on efficiency of charge separation. In this context, various metal species such as Pt,\textsuperscript{4–8} Rh,\textsuperscript{9} Ru,\textsuperscript{10} Ni,\textsuperscript{11} Cu,\textsuperscript{12–14} and Ag\textsuperscript{15} have been often used as effective electron acceptors to promote charge separation in TiO\textsubscript{2}-based photocatalytic systems. On the other hand, we previously reported a photocatalytic system of alcohol photooxidation using niobium oxide (Nb\textsubscript{2}O\textsubscript{5}) of which photoactivation mechanism was different from that of TiO\textsubscript{2}:\textsuperscript{16–18} reduction by excited electron in the conduction band and oxidation by positive hole in valence band. The alcohol photooxidation over Nb\textsubscript{2}O\textsubscript{5} proceeds via photoactivation of surface complex consist of dissociatively adsorbed alcohol (alkoxide) and Nb\textsubscript{2}O\textsubscript{5}, followed by conversion of photogenerated radical intermediate to carbonyl compound.\textsuperscript{17,18} In this system, the photocatalytic activity is significantly enhanced by loading of Cu, although addition of various metals such as Pt, Rh, Ru, Ni, or Ag to Nb\textsubscript{2}O\textsubscript{5} shows no increase in the activity.\textsuperscript{19} This suggest that the positive effect of Cu is not promotion of charge separation. Recently, our mechanistic study indeed revealed that the roles of Cu were to accelerate the conversion of photogenerated radical intermediate to product by Cu(II) and to facilitate desorption of the product by Cu(I) (Scheme 1).\textsuperscript{20} In the former case, Cu(II) acts as an electron acceptor to promote electron transfer from the radical (Scheme 1c), and in the latter case, Cu(I) works as an effective desorption site (Scheme 1d). Thus, the concerted effect provided by two Cu species functions in this system, and they are constantly supplied due to the redox cycle of Cu(II)–Cu(I) couple. However, a XAFS (X-ray absorption fine structure) study showed that Cu on as-prepared Cu/Nb\textsubscript{2}O\textsubscript{5} catalyst was entirely Cu(II), and that large portion of Cu remained Cu(II) even during the reaction.\textsuperscript{20} This implies that some increase in Cu(I) fraction brings about further enhancement in the photocatalytic activity, hence there may be room for optimization of
the initial state of Cu on Cu/Nb₂O₅. In this study, the state of Cu on Cu/Nb₂O₅ was modified by reduction and subsequent oxidation treatment at various temperatures, and the photocatalytic activities of the pretreated catalysts in alcohol photooxidation were evaluated. We also investigated the correlation between the photocatalytic activity and the state of Cu on Cu/Nb₂O₅ which was closely characterized by XAFS analyses.

**Scheme 1.** Reaction mechanism of alcohol photooxidation over Cu/Nb₂O₅: (a) adsorption of alcohol, (b) photoactivation of adsorbed alcohol and reduction of Cu(II) by excited electron, (c) electron transfer from photogenerated radical intermediated to Cu(II) to form product, (d) desorption of the product, and (e) reoxidation of reduced Cu(I) to Cu(II) by molecular oxygen.
Experimental

Catalyst Preparation

Niobic acid, niobium oxide hydrate (\(\text{Nb}_2\text{O}_5 \cdot n\text{H}_2\text{O}\), AD/2872, HY-340) was kindly supplied from CBMM. Other chemicals used were of reagent grade and were obtained from Aldrich Chemical Co., Tokyo Kasei Kogyo Co., Ltd and Wako Pure Chemical Industries, Ltd. All reagents were used without further purification.

Niobium oxide supported Cu catalyst (Cu/Nb\(_2\text{O}_5\)) was prepared by impregnation of niobic acid with an aqueous solutions of Cu(NO\(_3\))\(_2\) at 353 K, followed by evaporation, drying and calcination at 773 K in a stream of dry air for 5 h. After calcination, the catalysts were ground into powder under 100 mesh (0.15 mm). Loading amount of Cu was fixed to 1.9 mol\% (0.46 wt\%) which was optimized in the previous study. Unfortunately, TEM images of as-prepared Cu/Nb\(_2\text{O}_5\) catalyst gave no information about Cu species probably due to low contrast between Nb and Cu.

Reaction Condition

The photocatalytic oxidation of alcohol was carried out in a quasi-flowing batch system\(^{19,21}\) under atmospheric oxygen. Cu/Nb\(_2\text{O}_5\) catalyst (100 mg) and a stirring bar were introduced to the Pyrex glass reactor (cut-off light below 300 nm). The Cu/Nb\(_2\text{O}_5\) catalyst was pretreated in the reactor under the following conditions: reduction under 5\% H\(_2\)/N\(_2\) flow at 20 mL\(\text{min}^{-1}\) for 0.5 h at 673 K followed by oxidation under O\(_2\) flow at 20 mL\(\text{min}^{-1}\) for 0.5 h at various temperatures as appropriate (348 K, 373 K, 393 K, 423 K, and 473 K). Reduced Cu/Nb\(_2\text{O}_5\) and oxidized Cu/Nb\(_2\text{O}_5\) after reduction are described as R673 and RO\(_T\), respectively; \(T\) indicates the oxidation temperature. After this pretreatment, 1-pentanol as a substrate (10 mL) without solvent was introduced into the reactor. The suspension was vigorously stirred at room temperature and irradiated from the flat bottom of the reactor through a reflection by a cold mirror with a 500 W ultra-high-pressure Hg lamp (USHIO Denki Co.). Oxygen was flowed into the reactor at 2 mL\(\text{min}^{-1}\) (0.1 MPa). Products were analyzed and quantified by FID-GC (Shimadzu GC14B) and GC-MS (Shimadzu QP-5050).
**XAFS Study**

X-ray adsorption experiments were carried out on the beam line BL12C at Photon Factory, of the High Energy Accelerator Research Organization (Tsukuba, Japan). The ring energy was 2.5 GeV, and the stored current was 450 mA. Cu/Nb$_2$O$_5$ catalysts were pretreated prior to measurement under the following conditions: reduction under 7.0 kPa of H$_2$ for 0.5 h at 673 K followed by oxidation under 7.0 kPa of O$_2$ for 0.5 h at various temperatures as appropriate (348 K, 373 K, 393 K, 423 K, and 473 K). The pretreated samples were then sealed into polyethylene bags under dry N$_2$ atmosphere. The Cu K-edge (8.98 keV) XAFS spectra of Cu/Nb$_2$O$_5$ were recorded in a fluorescence mode with a Si(111) two-crystal monochromator at room temperature. The XANES and EXAFS analyses were performed by a Rigaku REX2000 program. Pattern fittings of XANES spectra of Cu/Nb$_2$O$_5$ oxidized at 473 K were implemented using the spectra of reduced Cu/Nb$_2$O$_5$, Cu$_2$O, CuO, and Cu(OH)$_2$ in the energy range of 8950–9010 eV. Fittings for other samples were carried out without using the spectra of reduced Cu/Nb$_2$O$_5$, Cu$_2$O, and CuO, because the fitting with that of Cu(OH)$_2$ showed some negative fractions and worse R factors. The Fourier transformation and inverse Fourier transformation of the EXAFS signals were carried out in the $k$-range of 3.0–12.0 Å$^{-1}$ and R-range of 1.78–2.70 Å (Cu–Cu) or 1.14–1.81 Å (Cu–O), respectively. Curve-fitting analysis of the EXAFS spectra was performed for the inverse Fourier transforms on the Cu–Cu or Cu–O shells. Empirical parameters for Cu–Cu and Cu–O shells in the analysis were obtained from Cu foil and CuO, respectively.

**Results**

**Photocatalytic Activity of Cu/Nb$_2$O$_5$ as a Function of Pretreatment Temperature**

Figure 1 shows the results of photooxidation of 1-pentanol over Cu/Nb$_2$O$_5$ photocatalysts pretreated under various conditions. In each case, pentanal was evolved as a main oxidized product and the amount was almost linearly increased as the reaction time increased. But a small induction period was observed in the first 1 h for reduced Cu/Nb$_2$O$_5$ (R673) (Figure 2). Only a trace amount of pentanoic acid was observed in this conversion level. Figure 3 shows pentanal yield after 5 h as a function of oxidation temperature. Photocatalytic activity of R673 was 1.5
times as high as that of as-prepared catalyst. Cu/Nb$_2$O$_5$ catalyst oxidized at 348 K after the reduction (RO348) showed similar activity to R673. The photocatalytic activity increased as oxidation temperature elevated up to 393 K, however it drastically declined over 393 K. Finally, the activity decreased to the same level as untreated one when oxidation temperature reached to 393 K. The highest activity was obtained at 393 K of oxidation temperature (RO393). The photocatalytic activity of RO393 is 2- and 6.5-fold as high as those of as-prepared Cu/Nb$_2$O$_5$ and bare Nb$_2$O$_5$ catalysts, respectively. Thus, appropriate treatment to Cu/Nb$_2$O$_5$ provides further enhancement in photocatalytic activity in alcohol photooxidation.

Figure 1. Time course of produced pentanal in photooxidation of 1-pentanol over Cu/Nb$_2$O$_5$ catalysts pretreated under various conditions.
Figure 2. Time course of pentanal yield in photooxidation of 1-pentanol over R673 and RO393.

Figure 3. Pentanal yield in 5 h of photooxidation of 1-pentanol over the pretreated catalysts as a function of oxidation temperature. Pentanal yields for R673 and as-prepared Cu/Nb$_2$O$_5$ are represented as a dashed and a dotted lines, respectively.
XANES study of Cu/Nb₂O₅ for Cu valence

Figure 4a shows Cu K-edge XANES spectra of Cu/Nb₂O₅ catalysts pretreated under various conditions and reference compounds. The XANES spectrum of the reduced Cu/Nb₂O₅ (R673) is similar to that of Cu foil, showing that the loaded Cu is reduce to Cu(0). The XANES feature of the oxidized Cu/Nb₂O₅ gradually changed to that characteristic of CuO as oxidation temperature was elevated. This simply describes that oxidation of Cu(0) to Cu(II) proceeds more deeply at higher oxidation temperature. The XANES spectrum of Cu₂O exhibits an intense pre-edge peak due to the 1s → 4pπ transition around 8980 eV, characteristic of Cu(I). 22–24 This feature is also observed in the spectrum of Cu/Nb₂O₅ oxidized at 393 K or 423 K after reduction (RO393 or RO423), indicating the presence of Cu(I) species in these samples as an intermediate to Cu(II) species. As shown in Figure 4b, change in composition of Cu species are observed more clearly in the first derivatives of XANES spectra: 1) the peak at 8977.5 eV assignable to Cu(0) decreases with increasing of oxidation temperature; 2) the peak feature characteristic of Cu(I) at 8979 eV increases as oxidation temperature elevated up to 393 K, then it gradually decreases; 3) small features assigned to Cu(II) species grow over 393 K. These trends show stepwise oxidation of Cu(0) to Cu(I) and Cu(II) corresponding to the oxidation temperature. When the oxidation temperature was 473 K, formation of a small portion of Cu(II) species with Cu(OH)₂ like structure was observed. The fractions of Cu species in Cu/Nb₂O₅ were then estimated by pattern fittings of XANES spectra of them (Figure 5). Oxidation of metallic Cu to Cu₂O drastically occurred when oxidation temperature was elevated from 373 K to 393 K. The maximum fraction of Cu₂O in Cu/Nb₂O₅ reached 45% at 393 K of oxidation temperature. With increasing oxidation temperature over 393 K up to 473 K, the fraction of Cu₂O turned to decrease and that of CuO rose to 59%. Thus, the change in the fractions as a function of oxidation temperature well represents the stepwise oxidation of Cu species. The variation of the Cu₂O fraction with RO393 at the top agrees with the change in photocatalytic activity, indicating that the formation of Cu₂O is important to increase the photocatalytic activity, but not of CuO. As mentioned above, we have proposed that the roles of Cu in enhancement of photocatalytic activity are to accelerate conversion of radical intermediate to product by Cu(II) and to facilitate desorption of the product by Cu(I). The results in this study therefore clearly show that the second role of Cu, that is Cu(I),
Figure 4. Cu K-edge XANES spectra (a) and their first derivatives (b) of Cu/Nb$_2$O$_5$ catalysts pretreated under various conditions and reference compounds.

Figure 5. Fractions of Cu species in oxidized Cu/Nb$_2$O$_5$ estimated by pattern fittings of XANES spectra as a function of oxidation temperature. Figure in parenthesis shows factors (%) for fitting.
dominantly contribute to improving the photocatalytic activity, and are consistent with the fact that desorption is the rate-determining step in alcohol oxidation over Nb$_2$O$_5$. However, there are some unreasonable behavior: RO423 and RO473 exhibit lower activities than R673 despite higher fractions of Cu$_2$O, and R673 which does not contain Cu$_2$O shows higher activity than as-prepared Cu/Nb$_2$O$_5$. These suggest an involvement of another factor in the photocatalytic activity, such as structure of Cu species.

**EXAFS study for structure of Cu species on Cu/Nb$_2$O$_5$**

The structures of Cu species on Cu/Nb$_2$O$_5$ were then investigated on the basis of EXAFS analyses of them. Figure 6a shows $k^3$-weighted Cu K-edge EXAFS spectra of the pretreated Cu/Nb$_2$O$_5$ catalysts and reference compounds. The EXAFS spectra of R673, RO348, and RO373 show similar oscillation phases to that observed for Cu foil, while the spectra of RO393, RO423, and RO473 resemble that of CuO. As clearly shown in Fourier-transformed EXAFS (FT-EXAFS, Figure 6b), the height of band at 2.2 Å, assigned to the Cu–Cu scatterings of Metallic Cu, decreased with the oxidation temperature increased. In particular, a prominent fall of the height was observed between R373 and R393, and the Cu–Cu scattering almost disappeared with RO473. These changes are in accordance with the drawdown of the Cu(0) fraction represented in Figure 5. The band at 1.5 Å assigned to Cu–O scattering, on the other hand, grew upon increase of the oxidation temperature above 393 K. In addition to the amplitude, the distance of the Cu–O bond slightly increased on going from RO393 to RO473. The FT-EXAFS of reference compounds evidence that CuO or Cu(OH)$_2$ has larger amplitude and longer distance of Cu–O scattering than that of Cu$_2$O. Therefore, the increase in Cu–O bond length from RO393 to RO473 can be attributed to formation of CuO and/or Cu(OH)$_2$. On the basis of these results, a series of the changes in FT-EXAFS corresponds to participation of oxygen atoms into Cu metal particles to form Cu$_2$O and CuO. A Curve-fittings analysis was then performed for the Cu–Cu and Cu–O shells in the FT-EXAFS (Table 1). For RO423, the low amplitude of Cu-Cu scattering did not allow determination of appropriate structural parameters for the Cu-Cu shell by curve fitting. The coordination number (CN) of the Cu-Cu pair for R673 is 10.8, although the foil have a CN of 12. This suggests that the reduced Cu metal particles have ca. 4 nm diameter, assuming the
cuboctahedral structure. The CN of the Cu-Cu pair decreased along with increase of the oxidation temperature, implying that metallic moiety became reduced in size. But the estimated CN of the Cu-Cu pair of the sample containing Cu oxide species does not correctly indicate coordination number for metallic moiety, as the amplitude of EXAFS oscillation is normalized by total amount of Cu. We therefore defined \(<CN>\), namely CN divided by the fraction of metallic Cu, as an alternative which represents coordination number of the Cu-Cu pair just in metallic moiety (Table 1). The \(<CN>\) still became smaller on going from R673 to RO393, which supports the shrinkage of the metallic moiety upon increase in the oxidation temperature.

Figure 6. (a) Cu K-edge EXAFS spectra and (b) their Fourier-transformation of Cu/Nb$_2$O$_5$ catalysts pretreated under various conditions (top) and reference compounds (bottom), respectively.
Table 1. Curve-fitting results of Cu–Cu or Cu–O scattering of the Cu K-edge FT-EXAFS spectra.\textsuperscript{a}

<table>
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<tr>
<th>sample</th>
<th>shell</th>
<th>CN\textsuperscript{b}</th>
<th>&lt;CN&gt;\textsuperscript{c}</th>
<th>r / Å\textsuperscript{d}</th>
<th>σ / Å\textsuperscript{e}</th>
<th>R\textsubscript{f} (%)\textsuperscript{f}</th>
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<tr>
<td>R673</td>
<td>Cu–Cu</td>
<td>10.8(23)</td>
<td>10.8(23)</td>
<td>2.55(1)</td>
<td>0.06(3)</td>
<td>10</td>
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<tr>
<td>RO348</td>
<td>Cu–Cu</td>
<td>8.4(17)</td>
<td>9.7(19)</td>
<td>2.56(1)</td>
<td>0.06(3)</td>
<td>22</td>
</tr>
<tr>
<td>RO373</td>
<td>Cu–Cu</td>
<td>6.1(13)</td>
<td>9.0(18)</td>
<td>2.56(1)</td>
<td>0.05(3)</td>
<td>23</td>
</tr>
<tr>
<td>RO393</td>
<td>Cu–Cu</td>
<td>1.5(3)</td>
<td>5.5(10)</td>
<td>2.56(1)</td>
<td>0.04(3)</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Cu–O</td>
<td>1.9(3)</td>
<td>–</td>
<td>1.91(1)</td>
<td>0.05(3)</td>
<td>28</td>
</tr>
<tr>
<td>RO423</td>
<td>Cu–O</td>
<td>3.3(5)</td>
<td>–</td>
<td>1.91(1)</td>
<td>0.07(2)</td>
<td>33</td>
</tr>
<tr>
<td>RO473</td>
<td>Cu–O</td>
<td>3.6(7)</td>
<td>–</td>
<td>1.94(1)</td>
<td>0.06(3)</td>
<td>30</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Inverse Fourier range ∆R = 1.78–2.70 Å for Cu–Cu shell, ∆R = 1.14–1.81 Å for Cu–O shell, fitting range ∆k = 3.0–12.0 Å. \textsuperscript{b} CN: coordination number. \textsuperscript{c} <CN>: coordination number of the Cu–Cu pair in metallic moiety. \textsuperscript{d} r: interatomic distance. \textsuperscript{e} σ: Debye-Waller factor. \textsuperscript{f} So-called R factor.

**Discussion**

On the basis of the results from photocatalytic reaction and XAFS study of Cu/Nb$_2$O$_5$, we discuss the correlation between the state of Cu species on Cu/Nb$_2$O$_5$ and the photocatalytic activity. At first, metallic Cu particles on Cu/Nb$_2$O$_5$ are formed with ca. 4 nm diameters (Scheme 2a) by reduction of as-prepared Cu/Nb$_2$O$_5$ at 673 K. Cu$_2$O and CuO moieties are formed at outer layer of the Cu particles by oxidation treatment with the reduced Cu/Nb$_2$O$_5$. The Cu$_2$O moiety formed at the outermost layer acts as an effective desorption site of the product, enhancing the photocatalytic activity (Scheme 2b). When the fraction of Cu$_2$O reaches the maximum at 393 K of oxidation temperature, the highest activity is accordingly obtained. The Cu$_2$O fraction in the overall Cu species gradually decreases above 393 K. However, the outermost Cu$_2$O moiety, that is an effective desorption site, decreases more rapidly than inner one because oxidation proceeds from outside. Therefore, the activity drastically falls above 393 K. Finally, Cu$_2$O at the outermost layer is wholly converted to CuO at 473 K and in consequence, the activity of R473 becomes identical to that of as-prepared Cu/Nb$_2$O$_5$ (Scheme 2c).
We have already confirmed that metallic Cu on Cu/Nb$_2$O$_5$ was converted to CuO within 24 h upon exposure to 1 atm O$_2$ even at room temperature.$^{20}$ In the case of R673, therefore, Cu$_2$O and/or CuO moieties may be formed in the reaction atmosphere by molecular oxygen, which results in the higher activity of R673 than that of as-prepared Cu/Nb$_2$O$_5$. Indeed, the induction period observed for R673 (Figure 2) can be attributed to such an *in-situ* generation of Cu$_2$O.

Through a series of stepwise oxidation, metallic Cu core decreases in size by oxidation from outer layer. The shrinkage of metallic moiety is reflected in the change in $<\text{CN}>$ estimated by XAFS study as mentioned above. But the number of $<\text{CN}>$ for RO393, 5.5 is too small to assume the cubocathedral structure, because the diameter of ca. 1 nm derived from the $<\text{CN}>$ is too small to be consistent with the fraction of remaining metallic Cu, 27% (decrease in diameter of metallic Cu from 4 nm to 1 nm corresponds to ca. 95% of metallic Cu being oxidized). For such a small number of $<\text{CN}>$, it may be plausible to further assume that the metallic core has a flattened shape and/or that the particles are split into pieces upon the oxidation treatment.

**Scheme 2.** States of Cu particle on Cu/Nb$_2$O$_5$ after pretreatment in various conditions: (a) reduction at 673 K (R673), oxidation at (b) 393 K (RO393) and (c) 473 K (RO473) after the reduction.
Conclusions

In this study, we investigated the correlation between photocatalytic activity of alcohol photooxidation over Cu/Nb$_2$O$_5$ and the state of Cu on Cu/Nb$_2$O$_5$. Reduction of as-prepared Cu/Nb$_2$O$_5$ at 673 K enhanced its photocatalytic activity. Subsequent oxidation of the reduced Cu/Nb$_2$O$_5$ at 348–393 K further improved the activity. But the catalysts oxidized above 393 K showed lower activities than the reduced one. As a consequence, oxidation at 393 K after the reduction exhibited the highest activity which was twice as high as the as-prepared catalyst. Moreover, the highest activity is 6.5-fold as high as the activity of bare Nb$_2$O$_5$ photocatalyst. Cu K edge XANES study revealed that the change in photocatalytic activity corresponded to the fraction of Cu$_2$O which promoted the rate-determining step, desorption. EXAFS study indicated that Cu metal particles with ca. 4 nm diameter were oxidized to Cu$_2$O and CuO in a stepwise manner from outer layer of the particles with increase in the oxidation temperature. The obtained results also pointed that the presence of Cu$_2$O at the outermost layer of the Cu particle as an efficient desorption site was indispensable for the enhancement of the photocatalytic activity. Thus, appropriate modification of the state of Cu particle on Cu/Nb$_2$O$_5$ provides further enhancement in photocatalytic activity in alcohol photooxidation.

References


Chapter 9

Selective Photooxidation of Alcohol over TiO$_2$ Covered with Nb$_2$O$_5$

Abstract

A selectivity enhancement in alcohol photooxidation using TiO$_2$ covered with Nb$_2$O$_5$ is demonstrated. A series of TiO$_2$ covered with Nb$_2$O$_5$ catalysts (Nb$_2$O$_5$/TiO$_2$, loading of Nb$_2$O$_5$; 0–5 mol%) were prepared and characterized. XPS studies suggest that the TiO$_2$ surface was completely covered with Nb$_2$O$_5$ at a 3.5 mol% loading. UV-Vis spectra of TiO$_2$ and the Nb$_2$O$_5$/TiO$_2$ series revealed that the band gap energy of the catalyst was not changed upon addition of Nb$_2$O$_5$. The amounts of photogenerated oxygen anion radical species (O$_2^-$ and O$_3^-$) over the catalyst, as estimated by ESR, drastically decreased with increased loadings of Nb$_2$O$_5$. The O$_3^-$ anion, in particular, which can be formed on anatase TiO$_2$, completely disappeared at Nb$_2$O$_5$ loadings over 4 mol%. In the oxidations of several alcohols (1-pentanol, 2-pentanol, 3-pentanol and cyclohexanol), the Nb$_2$O$_5$/TiO$_2$ catalysts exhibited higher selectivities than TiO$_2$ with comparable conversion levels. Furthermore, the Nb$_2$O$_5$/TiO$_2$ system gave a higher photocatalytic activity compared to Nb$_2$O$_5$ without lowering the selectivity.
Introduction

Heterogeneous photocatalysis have a potential application in the aerobic oxidation of organic molecules.\textsuperscript{1–3} Numerous semiconductor-type metal oxides have been tested as photocatalysts for oxidation, but it is generally accepted that anatase TiO\textsubscript{2} is the most reliable material due to its low cost, high photostability and photocatalytic activity. Recently, a lot of effort has been devoted to the application of TiO\textsubscript{2} to the selective catalytic oxidation of various organic molecules, such as alkanes,\textsuperscript{4–9} arenes\textsuperscript{10} and alcohols.\textsuperscript{11–13} However, undesired over-oxidation to carbon dioxide (CO\textsubscript{2}) is essentially associated with the photocatalytic oxidation over TiO\textsubscript{2},\textsuperscript{14,15} due to the presence of highly oxidizing radical species; positive holes trapped by surface lattice oxygen (O\textsuperscript{−}),\textsuperscript{16,17} ozonide ion (O\textsubscript{3}−)\textsuperscript{18,19} or hydroxyl radical (HO\textcdot).\textsuperscript{2,15} It is generally accepted that O\textsubscript{3}− is formed upon the combination of O\textsuperscript{−} and O\textsubscript{2},\textsuperscript{18–20} and that HO\textcdot is released via the oxidation of a surface hydroxyl group by a hole.\textsuperscript{2,21} Tsukamoto et al. reported that TiO\textsubscript{2} partially coated with WO\textsubscript{3} showed higher activity and selectivity in the photooxidation of benzylic alcohols to aldehydes than TiO\textsubscript{2} under diluted conditions (5 mg of catalyst, 0.1 mmol of alcohol, and 5 mL of water as a solvent).\textsuperscript{22} They interpret that the phenomena that TiO\textsubscript{2} surface of the catalyst, which is active for oxidation, is partially coated with WO\textsubscript{3} layer (WO\textsubscript{3} loading: 7.6 wt%), which leads to a decrease in the amount of aldehyde adsorbed on TiO\textsubscript{2} surface. It appeared that the area of TiO\textsubscript{2} surface was decreased by WO\textsubscript{3} addition. However, not only the selectivity to aldehyde but also the rate of alcohol conversion increased. Therefore, it seems that WO\textsubscript{3} layer has another role in addition to adsorption site of photogenerated aldehyde.

We reported that the selective photooxidation of alcohols proceeded over niobium oxide (Nb\textsubscript{2}O\textsubscript{5}) and showed a higher selectivity than TiO\textsubscript{2} with a comparable conversion level.\textsuperscript{23} ESR studies suggested that this high selectivity was due to the absence of O\textsubscript{3}− over Nb\textsubscript{2}O\textsubscript{5}, in contrast to TiO\textsubscript{2} under photo irradiation.\textsuperscript{24} However, the photocatalytic activity of Nb\textsubscript{2}O\textsubscript{5} in the oxidation of alcohols was much lower than that of TiO\textsubscript{2}. To develop an effective photocatalyst that exhibits both high activity and selectivity in the aerobic oxidation of alcohols, there are two primary strategies: improve the photocatalytic activity of Nb\textsubscript{2}O\textsubscript{5} or enhance the selectivity of TiO\textsubscript{2}. In the first strategy, we have already achieved a remarkable increase in photocatalytic activity by addition of Cu to
In the oxidation of alcohols over Cu/Nb$_2$O$_5$, the Cu(I) site operates as a desorption site and successfully promotes the desorption of the produced carbonyl compound which is the rate-determining step. In the latter, attention should be focused on how the formation of the highly oxidizing species above mentioned is inhibited. In this context, a promising approach is to cover the surface of TiO$_2$ with Nb$_2$O$_5$ which inhibits the production of highly oxidizing O$_3^−$ (Scheme 1).

In this study, we have prepared a series of TiO$_2$ covered with Nb$_2$O$_5$ photocatalysts and their photocatalytic activities and selectivities have been compared with those of bare TiO$_2$ or Nb$_2$O$_5$ in the oxidation of alcohols. The correlation between the amount of photogenerated oxygen anion radicals and selectivity has also been investigated.

**Scheme 1.** Strategy for the selective photocatalytic oxidation of alcohols over Nb$_2$O$_5$/TiO$_2$.

The inhibition of O$_3^−$ generation by surface coverage of TiO$_2$ with Nb$_2$O$_5$ is shown.

**Experimental**

**Catalyst preparation**

Ammonium niobium oxalate (NH$_4$[NbO(C$_2$O$_4$)$_2$(H$_2$O)]·nH$_2$O), as a precursor of niobium oxide, and niobium oxide hydrate (Nb$_2$O$_5$·nH$_2$O, HY-340) were kindly supplied by CBMM. The
TiO<sub>2</sub> sample used in this study, JRC-TIO-4 (equivalent to Degussa. P-25; rutile/anatase = 3/7; BET surface area = 49 m<sup>2</sup>·g<sup>–1</sup>) was supplied by the Japan Catalysis Society. After the hydration of TiO<sub>2</sub> in distilled water for 2 h at 353 K and evaporation at 368 K, the sample was dried at 353 K overnight. The TiO<sub>2</sub> catalyst was then calcined in dry air at 773 K for 5 h. A series of TiO<sub>2</sub> supported niobium oxide catalysts (n mol% Nb<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub>; n = 1–5) were prepared by impregnation of the TiO<sub>2</sub> sample with aqueous solutions of ammonium niobium oxalate followed by calcination at 773 K for 5 h. Nb<sub>2</sub>O<sub>5</sub> catalyst (BET surface area = 48 m<sup>2</sup>·g<sup>–1</sup>) was prepared by calcination of niobium oxide hydrate in a dry air flow at 773 K for 5 h. All catalysts were ground into powders under a 100 mesh (0.15 mm) after calcination.

**Characterization**

A Rigaku MultiFlex DR Powder X-ray diffractometer (XRD) was used for the identification of compounds formed on the catalyst samples. Specific surface areas were evaluated using the BET method using liquid nitrogen with a BEL Japan BELSORP28 28A. UV-Vis diffuse reflectance spectra (1 nm resolution) were obtained with a JASCO UV570 spectrometer. X-ray photoelectron spectra (XPS) were acquired using an ULVAC PHI 5500MT. XPS samples were mounted on an indium foil and the spectra were measured using Mg Kα radiation (15 kV, 400 W) in a chamber with the base pressure of ca. 10<sup>–9</sup> Torr. The take-off angle was set at 45°. Binding energies were referenced to the O 1s level at 530.2 eV.

**ESR measurement of oxygen anion radicals**

ESR measurements were carried out using an X-band ESR spectrometer (JEOL JES-SRE2X) with an in situ quartz cell. Prior to ESR measurement, the sample was pretreated with 6.7 kPa O<sub>2</sub> at 673 K for 1 h, followed by evacuation for 0.5 h at 673 K. After pre-treatment, the sample was exposed to 0.5 kPa O<sub>2</sub> at room temperature. The sample was then cooled to 123 K and irradiated. ESR spectra were recorded before and after photoirradiation at 123 K. The g values and the amounts of yielded radical species were determined using a certain amount of Mn/MgO marker. The radical amounts of the Mn/MgO marker were determined using 4-Hydroxy-2,2,6,6-tetramethylpiperidine-
1-oxyl (TEMPOL; radical density 97%, purchased from Wako). A 500 W ultra-high-pressure mercury lamp was used as a light source.

**Reaction conditions**

The photocatalytic oxidations of alcohols were carried out in a quasi-flowing batch system under atmospheric oxygen. Catalyst (100 mg), alcohol (10 mL) and a stirrer bar were introduced to a Pyrex glass reactor. No solvent was used. Substrate was used without further purification. The suspension was vigorously stirred at room temperature and irradiated from the flat bottom of the reactor via reflection using a cold mirror with a 500 W ultra-high-pressure Hg lamp (USHIO Denki Co.). Oxygen was flowed into the reactor at 2 cm$^3$·min$^{-1}$. Organic products were analyzed by FID-GC (Shimadzu GC-14B) and GC-MS (Shimadzu GC-MS QP5050). At the downstream of the flow reactor, a saturated barium hydroxide solution (Ba(OH)$_2$) was set-up to determine the quantities of carbon dioxide (CO$_2$) formed as barium carbonate (BaCO$_3$). The partial oxidation product selectivities are defined as yields (mmol) of aldehyde and acid (partial oxidation products) per yield (mmol) of aldehyde, acid and 1/n CO$_2$ (n = the number of carbon atoms of the substrate).

**Results and Discussion**

**Characterization of catalysts**

The valences of niobium and titanium cations on Nb$_2$O$_5$/TiO$_2$ catalyst surface were evaluated using XPS. The binding energies of the Nb 3d and Ti 2p peaks of Nb$_2$O$_5$/TiO$_2$ did not change regardless of Nb$_2$O$_5$ loading (Figure 1). These Nb 3d (207.1 eV for 3d$_{5/2}$ and 209.8 eV for 3d$_{3/2}$) and Ti 2p (464.5 eV for 2p$_{3/2}$ and 458.8 eV for 2p$_{1/2}$) peaks can be assigned to Nb$^{5+}$ and Ti$^{4+}$, respectively. The surface Nb/Ti ratios for the Nb$_2$O$_5$/TiO$_2$ catalysts were estimated from the areas of Nb 3d and Ti 2p XPS, as shown in Figure 2. The surface Nb/Ti ratio increases linearly with increasing Nb$_2$O$_5$ loading up to 3.5 mol% (equivalent to 10 wt%). It then becomes more gradual. The linear relationship indicates the formation of a two-dimensional niobium oxide overlayer, and the change in the slope can be attributed to the transition from a two-dimensional overlayer to three dimensional particles (monolayer coverage) at loadings over 3.5 mol% Nb$_2$O$_5$.27
Figure 1. XPS of (A) Nb 3d and (B) Ti 2p regions of Nb$_2$O$_5$/TiO$_2$ catalysts with various loadings; (a) 1 mol%, (b) 2 mol%, (c) 3 mol%, (d) 4 mol% and (e) 5 mol%.

Figure 2. Changes in surface Nb/Ti ratio with Nb$_2$O$_5$ loading.
The XRD patterns of a series of Nb$_2$O$_5$/TiO$_2$ catalysts were compared with those of TiO$_2$ and Nb$_2$O$_5$, as shown in Figure 2. The patterns for 1–4 mol% Nb$_2$O$_5$/TiO$_2$ samples indicate no changes in the crystallinity of the TiO$_2$ support (anatase and rutile) and no formation of a niobium oxide crystallite. On the other hand, the 5 mol% Nb$_2$O$_5$/TiO$_2$ exhibits a small feature assignable to TT-Nb$_2$O$_5^{28-31}$, which is associated with TiO$_2$. Similar diffraction patterns have also been reported for 7.7$^{32}$ or 11$^{33}$ mol% Nb$_2$O$_5$/TiO$_2$ samples. The formation of a niobium oxide crystallite at loadings over 3.5 mol% is consistent with the results from the XPS study.

Figure 3. XRD patterns of (a) TiO$_2$, (b) 1 mol%, (c) 2 mol%, (d) 3 mol%, (e) 4 mol%, (f) 5 mol% Nb$_2$O$_5$/TiO$_2$ and (g) Nb$_2$O$_5$. 
UV-Vis spectra of the 1–5 mol% Nb$_2$O$_5$/TiO$_2$ catalysts were also identical to that of TiO$_2$ (Figure 4), whose band gap energy was estimated as 3.10 eV. The Nb$_2$O$_5$ catalyst possesses similar spectral features to TiO$_2$ and the band gap energy was estimated as 3.16 eV. Thus, the surface coverage of TiO$_2$ with Nb$_2$O$_5$ does not influence the crystallinity of the TiO$_2$ support and does not change the optical properties of the catalysts. The BET surface area measurements revealed that the surface area of TiO$_2$ (49 m$^2$·g$^{-1}$) was maintained after the addition of Nb$_2$O$_5$ ($S_{BET}$ of 1, 2, 3, 4, and 5 mol% Nb$_2$O$_5$/TiO$_2$ are 54, 47, 47, 51, 40 m$^2$·g$^{-1}$, respectively).

**Figure 4.** UV-Vis spectra of (a) Nb$_2$O$_5$, (b) TiO$_2$ and Nb$_2$O$_5$/TiO$_2$ catalysts with various loadings; (c) 1 mol%, (d) 2 mol%, (e) 3 mol%, (f) 4 mol% and (g) 5 mol%. The spectra are vertically offset for clarity. Inset shows spectra without offset.
ESR measurements of photogenerated oxygen anion radicals

We characterized the photogenerated oxygen anion radical species over TiO$_2$, Nb$_2$O$_5$/TiO$_2$ and Nb$_2$O$_5$ using ESR and estimated the amounts of the radical species. Figure 5 shows the ESR spectra obtained when the catalysts were irradiated in the presence of oxygen at 123 K. An intense signal consisting of two sets of rhombic $g$ values were observed over TiO$_2$, which can be assigned to superoxide (O$_2^-$: $g_1 = 2.024$, $g_2 = 2.009$, $g_3 = 2.003$)$^{34-36}$ and ozonide (O$_3^-$: $g_1 = 2.019$, $g_2 = 2.006$, $g_3 = 2.000$)$^{35-38}$ Such radical species over TiO$_2$ are well known and have been widely characterized. Generally, it is proposed that the O$_2^-$ is generated via the reduction of adsorbed O$_2$ by excited electrons. The O$_3^-$ is formed from the combination of a positive hole captured by surface lattice oxygen (equivalent to O$^-$) and O$_2$.$^{20,35,39,40}$ In contrast, only a small broad signal was observed over Nb$_2$O$_5$. In this case, using $^{17}$O-enriched O$_2$ (20%) instead of $^{16}$O$_2$, a signal appeared with hyperfine splitting, as derived from the $^{17}$O nuclei (I = 5/2) (Figure 6). This hyperfine structure indicates the generation of $^{16}$O$^{17}$O$^-$ and suggests that the two oxygen nuclei are equivalent. The equivalent hyperfine interactions are also consistent with the O$_2^-$ ion being adsorbed in a side-on fashion onto the Nb$_2$O$_5$ surface, with its internuclear axis parallel to the plane of the surface. This type of adsorption is commonly observed with other metal oxides.$^{20}$ Eleven lines corresponding to the two $^{17}$O nuclei ($^{17}$O$^{17}$O$^-$, I = 5) were expected, but not observed apparently, which is likely due to an inadequate enrichment of $^{17}$O (20%).

The intensities of the ESR signals for the oxygen anion radicals were dramatically decreased with increasing of Nb$_2$O$_5$ loading. Although the signals assigned to O$_2^-$ remained at a 5 mol% loading, the signal assigned to O$_3^-$ completely disappeared at loadings over 4 mol%. This result strongly indicates that the TiO$_2$ surface, which can produce O$_3^-$, is completely covered at loadings over 4 mol%. It is also consistent with a monolayer coverage at 3.5 mol% loading, as estimated from the XPS study. The amounts of photogenerated oxygen anion radical species are shown in Figure 7. The amount of the radical species drastically decreases on going from 0 to 4 mol% Nb$_2$O$_5$ loading. This change becomes gradual at loadings over 4 mol%. Thus, these results demonstrate that the surface coverage of TiO$_2$ with Nb$_2$O$_5$ effectively inhibits the formation of oxygen anion radicals. In particular, the generation of O$_3^-$ was completely inhibited by full coverage (Scheme 2). The $g$ values
of the ESR signal assigned to $O_2^-$, as generated on 5 mol% Nb$_2$O$_5$/TiO$_2$, are different from those on TT-Nb$_2$O$_5$. This may be due to the differences in crystallinity of Nb$_2$O$_5$ (amorphous or TT-phase). The ESR spectrum of the oxygen anion radicals formed on 5 mol% Nb$_2$O$_5$/TiO$_2$ has a shoulder feature in the region of $g = 2.003–2.008$. This is in good agreement with the peak features of $O_2^-$, formed on TT-Nb$_2$O$_5$ in the same region (Figure 6), which implies the formation of $O_2^-$ on TT-Nb$_2$O$_5$ (Scheme 2).

![Figure 5](image-url)

**Figure 5.** ESR spectra of the photogenerated oxygen anion radical at 77 K over TiO$_2$, $n$ mol% Nb$_2$O$_5$/TiO$_2$ (abbreviated as $n$NbTi; $n = 1, 3, 5$) and Nb$_2$O$_5$. 
Figure 6. ESR spectra obtained when Nb₂O₅ was irradiated in the presence of 4.0 kPa of (a) oxygen and (b) isotopically enriched oxygen (20% ¹⁷O). Hyper fine derived from ¹⁷O¹⁶O was not apparently observed due to low ¹⁷O concentration.
Figure 7. Changes in the amount of photogenerated oxygen anion radical species ($\text{O}_2^- + \text{O}_3^-$) over Nb$_2$O$_5$/TiO$_2$ catalyst with Nb$_2$O$_5$ loading. The dotted line shows the radical amount over Nb$_2$O$_5$.

Scheme 2. Plausible surface species on the Nb$_2$O$_5$/TiO$_2$: (a) below 3 mol% Nb$_2$O$_5$ loading and (b) over the monolayer.
In addition to the signals of the oxygen anion radicals, small signals were also observed in the region of $g < 2.000$. These can be assigned to excited electrons trapped by the Ti$^{4+}$ sites (equivalent to Ti$^{3+}$) and are composed of two distinct signals (Ti$^{3+}$ (i) and (ii)). The $g$ values of Ti$^{3+}$ (i) ($g_1 = 1.982$, $g_2 = 1.977$, $g_3 = 1.971$) are similar to those for bulk and surface Ti$^{3+}$ in TiO$_2$. The $g$ values and the signal intensity do not depend on the loading amount of Nb$_2$O$_5$. These suggest that the Ti$^{3+}$ (i) corresponds to the bulk Ti$^{3+}$ site. On the other hand, the signals assigned to Ti$^{3+}$ (ii) are only observed with a large surface coverage of TiO$_2$ (> 3 mol%). The $g$ values of Ti$^{3+}$ (ii) ($g_\perp = 1.990$, $g_\parallel = 1.962$) are almost identical to those obtained from Nb-doped anatase TiO$_2$, and are attributed to the interstitial Ti$^{3+}$ ion. Based on this, the Ti$^{3+}$ (ii) is assignable to the interfacial Ti$^{3+}$ sites adjacent to loaded Nb$_2$O$_5$ (Scheme 2).

**Photocatalytic activity and selectivity**

The photocatalytic activities and selectivities of the TiO$_2$, Nb$_2$O$_5$/TiO$_2$ and Nb$_2$O$_5$ catalysts were evaluated using the photooxidation of 1-pentanol as shown in Figure 8. Although the photocatalytic activity gradually decreases as the loading of Nb$_2$O$_5$ is increased, 5mol% Nb$_2$O$_5$/TiO$_2$, which seems to be fully covered with Nb$_2$O$_5$, still exhibits a higher activity than Nb$_2$O$_5$. The selectivity to partial oxidation products became higher on going from 1 to 5mol% loading, and reached 97%, which is as high as that obtained with Nb$_2$O$_5$ (Figure 8a). The higher selectivities of the Nb$_2$O$_5$/TiO$_2$ catalysts, as compared to the TiO$_2$ are maintained at a same conversion level (Figure 8b). Thus, the surface coverage of TiO$_2$ with Nb$_2$O$_5$ effectively enhances the selectivity of the photooxidation of 1-pentanol. The selectivity at comparable conversion levels increased with increasing Nb$_2$O$_5$ loading up to 3 mol%. As mentioned above, the ESR study revealed that coverage of the TiO$_2$ surface with Nb$_2$O$_5$ inhibits the generation of O$_3^-$, which is highly active towards the complete oxidation of organic molecules. In fact, O$_3^-$ is known to be active even at room temperature, while O$_2^-$ is stable up to ca. 423 K. Based on this, the change in selectivity on going from 0 to 3 mol% Nb$_2$O$_5$ loading agrees with the results from the ESR study. However, 5 mol% Nb$_2$O$_5$/TiO$_2$ and Nb$_2$O$_5$ showed lower selectivities compared to 3 mol%. In this case, higher yields of pentanoic acid are obtained than the lower loading homologues. This indicates that over-oxidation of the products to CO$_2$ takes place more severely for 5 mol% Nb$_2$O$_5$/TiO$_2$ and Nb$_2$O$_5$, due to the much longer reaction.
Figure 8. Product yields in the photooxidation of 1-pentanol over TiO$_2$, $n$ mol% Nb$_2$O$_5$/TiO$_2$ (abbreviated as $n$NbTi; $n$ = 1, 2, 3 and 5) and Nb$_2$O$_5$; (a) after 5 h of photo irradiation, (b) at a comparable conversion level (TiO$_2$; 5h, 1NbTi; 5.5 h, 2NbTi; 6 h, 3NbTi; 7.5 h, 5NbTi; 13 h and Nb$_2$O$_5$; 20 h).
times. Figure 9 shows the relationship between selectivity and conversion in the photooxidation of 1-pentanol over 3 mol% Nb$_2$O$_5$/TiO$_2$ and TiO$_2$. At the higher the conversion level, 3 mol% Nb$_2$O$_5$/TiO$_2$ catalyst exhibited a much higher selectivity than TiO$_2$. The 3 mol% Nb$_2$O$_5$/TiO$_2$ catalyst maintained more than 85% selectivity, even at 20% conversion. However, the selectivity fell below 75% at 15% conversion when TiO$_2$ was used.

![Figure 9. Selectivity-conversion plots for the photooxidation of 1-pentanol over 3 mol% Nb$_2$O$_5$/TiO$_2$ and TiO$_2$.](image-url)
We went on to apply 3 mol% Nb$_2$O$_5$/TiO$_2$ to the oxidation of various alcohols. The activities and selectivities were compared with those of TiO$_2$ and Nb$_2$O$_5$ (Figure 10). The oxidation of several secondary alcohols (2-pentanol, 3-pentanol, cyclohexanol) gave the corresponding ketones and certain amounts of CO$_2$. In each case, the 3 mol% Nb$_2$O$_5$/TiO$_2$ catalyst showed not only a much higher activity than Nb$_2$O$_5$ without lowering selectivity, but also a higher selectivity than TiO$_2$ at a comparable conversion level. Thus, the surface coverage of TiO$_2$ with Nb$_2$O$_5$ enhanced the selective partial oxidation of various alcohols, including primary and secondary alcohols.

Figure 10. Product yields and Selectivities to partial oxidation product(s) in photocatalytic oxidation of various alcohols over TiO$_2$ (Ti), 3 mol% Nb$_2$O$_5$/TiO$_2$ (3NbTi) and Nb$_2$O$_5$ (Nb). Reaction condition: catalyst (100 mg), alcohol (10 ml), O$_2$ flow (2 ml·min$^{-1}$), $h\nu$ (> 300 nm), reaction time (3 h for TiO$_2$, 5 h for 3NbTi and Nb). □: partial oxidation product(s); aldehyde + acid for primary alcohol or ketone for secondary one, ■: 1/n CO$_2$ (n indicates the number of carbon atoms of substrate).
Conclusions

In this study, we prepared a series of TiO$_2$ supported Nb$_2$O$_5$ catalysts (Nb$_2$O$_5$/TiO$_2$, with loadings of Nb$_2$O$_5$ between 0–5 mol%) for the selective photooxidation of alcohols. XPS studies suggested that the TiO$_2$ surface was completely covered with Nb$_2$O$_5$ at loadings over 3.5 mol%. UV-Vis spectra of TiO$_2$ and a series of Nb$_2$O$_5$/TiO$_2$ samples revealed that the absorption band of the catalyst remained unchanged by the addition of Nb$_2$O$_5$. However, the amounts of photogenerated O$_2^-$ and O$_3^-$ over the catalyst were estimated by ESR to be drastically decreased with increased loadings of Nb$_2$O$_5$. In particular, O$_3^-$ which can be formed on anatase TiO$_2$ completely disappeared at loadings over 4 mol%. We also investigated the photocatalytic activities and selectivities of these catalysts in the oxidation of 1-pentanol. Although the photocatalytic activity gradually decreased with increasing of Nb$_2$O$_5$ loading, the selectivity was enhanced. At a comparable conversion level, the maximum selectivity was obtained with a 3 mol% Nb$_2$O$_5$ loading. Similarly, 3 mol% Nb$_2$O$_5$/TiO$_2$ exhibited higher selectivities than TiO$_2$ in the oxidation of secondary alcohols (2-pentanol, 3-pentanal and cyclohexanol). Thus, the surface coverage of TiO$_2$ with Nb$_2$O$_5$ effectively enhanced the selectivity to partial oxidation product(s) in alcohol photooxidation, due to inhibition of O$_3^-$ formation.

References


Summary

The author developed two different types of effective aerobic oxidation system in this thesis; one is the homogeneous system using mononuclear non-heme Fe complexes and the other is the heterogeneous system based on Nb₂O₅ photocatalyst.

In Part I, aerobic oxidation of hydrocarbon using Fe(II)–TPA complexes was established by controlling of spin state and coordination environment. Moreover, effects of nitro-substitution to the Fe(II)–TPA complex on its catalytic activity in oxidation of hydrocarbon and detailed electronic structure were investigated and discussed.

In Chapter 1, aerobic oxidation of hydrocarbons without any reductant using Fe(II)–TPA complexes was achieved by modifying spin state and coordination environment of the complex. The author found that aerobic oxidation of hydrocarbons was efficiently promoted by the Fe(II)–TPA complex, when the Fe center was in the high-spin state. It is noteworthy that the aerobic oxidation proceeded without any reductant, since most of the aerobic oxidation systems catalyzed by heme or nonheme iron complexes require stoichiometric co-reductants. The essential factor in the reaction is the presence of labile coordination sites that provides stable coordination of dioxygen, giving Fe(III)-superoxo species active for the H-atom abstraction; the strong interaction of MeCN with the low-spin iron(II) center would prevent the formation of the Fe(III)-superoxo species, and chloride ion may shorten the life-time of the Fe(III)-superoxo species probably through nucleophilic attack.

In Chapter 2, the author synthesized a series of Fe(II)–TPA complex and its derivatives that have one to three nitro-groups at 4-position of the pyridine ligand, and evaluated the effect of the nitro-groups on their catalytic activity in alkane hydroxylation. The introduction of nitro-group proved to lower the product yields. During the catalytic oxidation, a significant amount of Fe(II) species is present in the cases of nitro-substituted complexes, while the unsubstituted Fe–TPA complex was rapidly oxidized to Fe(III) state. Although theoretical calculations predicted that introducing nitro-groups should facilitate H-atom abstraction from alkane by cis-oxo-hydroxo-iron(V) species, the present experimental study demonstrated that such energetically unfavorable species cannot be obtained in the reaction condition.
In Chapter 3, the author investigated the effects of nitro-substitution to the Fe(II)–TPA complex on the electronic structure in more detail from both experimental and theoretical aspects. The introduction of nitro groups on the TPA-type ligand stabilizes the low-spin state of the ferrous complex, which is caused by significant \( \pi \) back-bonding interactions between iron(II) and 4-nitropyridine ligand. The DFT calculation revealed that introducing the nitro groups stabilizes \( d\pi \) orbitals more than \( d\sigma \) orbitals, which is more prominent with the low-spin state than with the high-spin state.

In summary of Part I, the author studied two important factors during aerobic oxidation processes; activation of molecular oxygen and hydrocarbon by Fe(II)–TPA and active intermediate derived Fe(II)–TPA, respectively. The results obtained in Part I also points out that 1) it is necessary for effective catalysis not only to active molecular oxygen but also to successfully generate an active intermediate, and that 2) ease of formation of the active intermediate plays a significant role rather than reactivity of the active intermediate.

In Part II, the enhancement in the photocatalytic activity and the selectivity was developed using \( \text{Nb}_2\text{O}_5 \)-based photocatalysts from the aspect of kinetics and by inhibition of the formation of active oxygen species, respectively. In addition, a specific photoactivation mechanism discovered in the photocatalysis of \( \text{Nb}_2\text{O}_5 \) was advanced and discussed in detail.

In Chapter 4, the author demonstrated that selective photooxidation of amines to imines proceeded over \( \text{Nb}_2\text{O}_5 \) through a similar reaction mechanism to that of alcohol over \( \text{Nb}_2\text{O}_5 \); oxidative dehydrogenation of amine to corresponding imine via photoactivation of the surface complex consisted of dissociatively adsorbed amine (amide species) and \( \text{Nb}_2\text{O}_5 \). The substrate screening revealed that a variety of amines including primary, secondary, and bicycloamine derivatives were also oxidized to imine. In contrast to alcohol oxidation, a primary imine produced by dehydrogenation of the corresponding primary amine is immediately hydrolyzed into aldehyde and converted to a dimerized imine.

In Chapter 5, it was found that aerobic photooxidation of hydrocarbon proceeded over \( \text{Nb}_2\text{O}_5 \) with higher selectivity than that over \( \text{TiO}_2 \). However, mechanistic study revealed that the photoactivation mechanism of hydrocarbon over \( \text{Nb}_2\text{O}_5 \) was different from that for alcohol and
amine involving photoactivation of surface complex. The proposed mechanism is typical Langmuir-Hinshelwood mechanism including C–H activation by positive holes and O₂ reduction by excited electrons, followed by combination of the resulting alkyl radical and superoxide. ESR study suggests that the higher selectivity of Nb₂O₅ for partial oxidation products than TiO₂ is due to the absence of O₃⁻, which is highly active for the complete oxidation of hydrocarbons.

In Chapter 6, the author prepared a variety of metal loaded Nb₂O₅ photocatalysts (M/Nb₂O₅; M = Pt, Rh, Ru, Ni, Cu, and Ag) and discovered the positive but counterintuitive effect of Cu on photocatalytic activity in alcohol oxidation in contrast to other metals. The author demonstrated that Cu/Nb₂O₅ catalyst exhibited higher activity than bare Nb₂O₅ without lowering selectivity toward a wide scope of alcohols including primary, secondary, aliphatic and aromatic ones. In particular, 1-phenylethanol was almost quantitatively converted to acetophenone in a solvent-free condition. This is the first example that aerobic photooxidation of alcohol proceeded quantitatively even under solvent-free condition.

In Chapter 7, the author investigated the mechanism of alcohol photooxidation over Cu/Nb₂O₅ in detail and elucidated the role of Cu in enhancement of the photocatalytic activity in alcohol oxidation. The reaction mechanism for Cu/Nb₂O₅ is essentially the same as that for bare Nb₂O₅, except that redox of Cu(II)–Cu(I) is involved instead of that of Nb(V)–Nb(IV). The roles of Cu were found to be an effective desorption site (Cu(I)) to promote desorption of the product and a redox promoter to accelerate the conversion from radical intermediate to the product (Cu(II)). The proposed photoactivation mechanism was supported by DFT calculations in a similar fashion to the case of amine oxidation.

In Chapter 8, the author modified the composition of Cu species on Cu/Nb₂O₅ by pretreatment in order to optimize the positive role of Cu in alcohol photooxidation. Photocatalytic activity twice as high as that of as-prepared Cu/Nb₂O₅ was obtained by optimized pretreatment; oxidation at 393 K after the reduction. The photocatalytic activity in alcohol oxidation varied according to the fraction of Cu₂O species estimated by XAFS spectroscopy. The obtained result suggested that the presence of Cu₂O at the outermost layer of the Cu particle as an efficient desorption site was the crucial factor in enhancement of the photocatalytic activity.

In Chapter 9, a series of TiO₂ catalysts covered with Nb₂O₅ (Nb₂O₅/TiO₂, loading of Nb₂O₅;
0–5 mol%) was prepared to inhibit formation of the highly oxidizing oxygen anion radical, \( \text{O}_3^- \) for selective photocatalytic oxidation. The author demonstrated that selectivity in alcohol photooxidation was enhanced with increase in surface coverage of TiO\(_2\) with Nb\(_2\)O\(_5\). ESR study supported that formation of \( \text{O}_3^- \) was successfully inhibit upon Nb\(_2\)O\(_5\) coating and \( \text{O}_3^- \) completely disappeared over monolayer coverage (3.5 mol% Nb\(_2\)O\(_5\) loading). 3 mol% Nb\(_2\)O\(_5\)/TiO\(_2\) exhibited higher selectivities than TiO\(_2\) at a comparable conversion level in the oxidation of not only 1-pentanol but also other secondary alcohols such as 2-pentanol, 3-pentanol, cyclohexanol.

As an overview of Part II, the selective photocatalytic oxidation of alcohols, amines, and hydrocarbons using Nb\(_2\)O\(_5\)-based photocatalysts was established. Among these systems, molecular oxygen plays different two roles. For oxygenation of hydrocarbon, molecular oxygen literally acts as an oxygen source to be incorporated into substrate. But, for oxidative dehydrogenation of alcohol and amine, molecular oxygen is virtually employed as an acceptor of electrons and protons taken up from substrate. In both cases, however, the achieved high selectivities owe a great deal to the lack of \( \text{O}_3^- \) over the Nb\(_2\)O\(_5\)-based photocatalysts. The result obtained in Part II proves the strategy to inhibit the formation of active oxygen species effective and provides a new promising basis for selective photooxidation. In addition, the photocatalysis of Nb\(_2\)O\(_5\) shows some specific photocatalytic properties; the effect of Cu and in-situ doping. The role of Cu discovered and elucidated in this study, promotion of desorption, points out that one should focus attention on not only promotion of charge separation, but also acceleration of a rate-determining process among the overall catalytic cycle even from the viewpoint of photocatalysis. The in-situ doping effect occurs for oxidation of alcohol or amine, whereas the photooxidation of hydrocarbon proceeds only via band gap excitation of Nb\(_2\)O\(_5\).

The crucial difference between these two photoactivation systems is whether the substrate is dissociatively adsorbed. This unique photo-activation mechanism by direct electron transition from the surface donor level provides us attractive ways for removing the limit of band gap energy, and utilization of the visible light.
List of Publications

Part I

Chapter 1.

1. Efficient Aerobic Oxidation of Hydrocarbons Promoted by High-Spin Nonheme Fe(II) Complexes Without Any Reductant
Shinya Furukawa, Yutaka Hitomi, Tetsuya Shishido, and Tsunehiro Tanaka

Chapter 2.

2. Alkane Hydroxylation Catalyzed by a Series of Mononuclear Non-Heme Iron Complexes Containing 4-Nitropyridine Ligands.
Yutaka Hitomi, Shinya Furukawa, Masakazu Higuchi, Tetsuya Shishido, and Tsunehiro Tanaka
*Journal of Molecular Catalysis A: Chemical, 2008, 288, 83.*

Chapter 3.

3. π Back-Bonding of Iron(II) Complexes Supported by Tris(pyrid-2-ylmethyl)amine and Its Nitro-Substituted Derivatives
Shinya Furukawa, Yutaka Hitomi, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka
*The Journal of Physical Chemistry A, 2011, 115, 13589*
Part II

Chapter 4.

4. Selective Amine Oxidation Using Nb$_2$O$_5$ Photocatalyst and O$_2$
Shinya Furukawa, Yasuhiro Ohno, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka
*ACS Catalysis*, **2011**, *1*, 1150.

5. Mechanistic Study on Selective Photooxidation of Amines over Nb$_2$O$_5$: Direct Electron Transfer from Adsorbed Species to Conduction Band
Shinya Furukawa, Yasuhiro Ohno, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka
To be submitted.

Chapter 5.

6. Reaction Mechanism of Selective Photooxidation of Hydrocarbons over Nb$_2$O$_5$
Shinya Furukawa, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka

Chapter 6.

7. Solvent-free Aerobic Alcohol Oxidation Using Cu/Nb$_2$O$_5$: Green and Highly Selective Photocatalytic System
Shinya Furukawa, Ayaka Tamura, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka
*Applied Catalysis B: Environmental*, **2011**, *110*, 216.
Chapter 7

8. Reaction Mechanism and the Role of Copper in the Photooxidation of Alcohol over Cu/Nb₂O₅
Shinya Furukawa, Yasuhiro Ohno, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka

Chapter 8

9. XAFS Study of Cu/Nb₂O₅ as a Photocatalyst for Alcohol Photooxidation: Correlation between Oxidation State of Cu and Photocatalytic Activity
Shinya Furukawa, Daisuke Tsukio, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka
To be submitted.

Chapter 9

10. Photocatalytic Oxidation of Alcohols over TiO₂ covered with Nb₂O₅
Shinya Furukawa, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka
*ACS Catalysis*, in revision.
Publications not Included in the Present Thesis

11. Alkane Metathesis by Tandem Catalytic System: Dehydrogenation and Hydrogenation over PtSn/Al₂O₃, and Metathesis over Re₂O₇/Al₂O₃
Shinya Furukawa, Tetsuya Shishido, Kentaro Teramura, and Tsunehiro Tanaka
Submitted.