Quantitative Evaluation of Lewis Acidity of Zinc Ion with Tetradentate Tripodal Ligands in Formation of the Superoxide Complexes

Hideki Ohtsu and Shunichi Fukuzumi*
Department of Material and Life Science, Graduate School of Engineering, Osaka University, CREST, Japan Science and Technology Corporation, Suita, Osaka 565–0871

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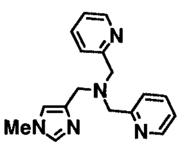
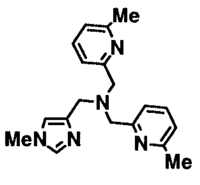
A series of Zn(II)–superoxide complexes containing tetradentate tripodal ligands are generated in the reactions between Zn(II) complexes and superoxide which is produced by the photoinduced reduction of dioxygen by dimeric 1-benzyl-1,4-dihydronicotinamide. The Zn(II)–superoxide complexes have been characterized spectroscopically in order to evaluate the Lewis acidity of Zn(II) ion depending on the ligands used as Cu,Zn–SOD models.

Copper–zinc superoxide dismutase (Cu,Zn–SOD) contains an imidazolate-bridged Cu(II)–Zn(II) heterodinuclear metal center in its active site.[1–10] This enzyme protects cells against oxidative damage by catalyzing the disproportionation (dismutation) of toxic superoxide ($O_2^{\bullet -}$) to dioxygen (O_2) and hydrogen peroxide (H_2O_2).[1] The Cu(II) form of the enzyme is reduced by $O_2^{\bullet -}$ to produce O_2 and the reduced Cu(I) enzyme which is oxidized by another $O_2^{\bullet -}$ molecule to yield H_2O_2.[1–10] The Cu(II) ion is coordinated to four imidazole N atoms of histidine residues and the Zn(II) ion located at a distance of 6.2 Å from the Cu(II) ion is coordinated to a carboxylato O atom of an aspartic acid residue and three imidazole N atoms of histidine residues.[1–4] However, it has yet to be understood why only the Zn(II) ion is coordinated to a carboxylato O atom of an aspartic acid residue.

We have recently reported that the Zn(II) ion in the SOD model complex is shown to play the essential role in facilitating the reduction of *p*-benzosemiquinone radical anion ($Q^{\bullet -}$) via coordination of $Q^{\bullet -}$ to the Zn(II) ion.[11] The coordination of $O_2^{\bullet -}$ to the Zn(II) ion may also play the essential role in the disproportionation of $O_2^{\bullet -}$ catalyzed by Cu,Zn–SOD.



MeIm(Py)₂



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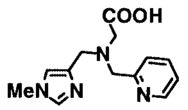

MeIm(Py)(COOH)

We report herein the detection and characterization of a series of Zn(II)–$O_2^{\bullet -}$ complexes generated by the reactions of $O_2^{\bullet -}$ with the Zn(II) complexes: $[Zn(MeIm(Py)_2)(CH_3CN)](ClO_4)_2$ (**1**), $[Zn(MeIm(Me)_2)(H_2O)](ClO_4)_2$ (**2**), $[Zn(MeIm(Py)(COO))(H_2O)](ClO_4)$ (**3**),[12] to evaluate the Lewis acidity of Zn(II) ion depending on the tetradentate tripodal ligands used as Cu,Zn–SOD models. The quantitative evaluation of the Lewis acidity of Zn(II) ion depending on the ligands is also made by the measurements of ^{19}F NMR spectra of the Zn(II) complexes which are coordinated to the fluoride ion (F^-).

Superoxide is produced by the photoinduced electron transfer reduction of O_2 with dimeric 1-benzyl-1,4-dihydronicotinamide $[(BNA)_2]$ in propionitrile (EtCN),[13] which can act as a unique two electron donor to produce two equivalents of one-electron reduced species.[14] When an oxygen-saturated EtCN solution containing $[(BNA)_2]$ was irradiated with a high pressure mercury lamp, $O_2^{\bullet -}$ formed photochemically is detected by the ESR spectrum in frozen EtCN at 133 K. The ESR spectrum shows a typical anisotropic signal with $g_{//} = 2.0900$ and $g_{\perp} = 2.0050$.[15]

The addition of Zn(II) complexes, **1**, **2**, and **3** to an EtCN solution of $O_2^{\bullet -}$ results in formation of the Zn(II)–$O_2^{\bullet -}$ complexes. Figure 1 shows a typical example of ESR spectrum of $[Zn(O_2^{\bullet -})(MeIm(Py)(COO))]$ measured in frozen EtCN at 133 K and the $g_{//}$-values of all the Zn(II)–$O_2^{\bullet -}$ complexes are listed in Table 1. The $g_{//}$ values of these Zn(II)–$O_2^{\bullet -}$ complexes are significantly smaller than the value of free $O_2^{\bullet -}$ due to the complexation of Zn(II) ion with $O_2^{\bullet -}$.[16]

The $g_{//}$-value gives valuable information concerning the binding strength of $O_2^{\bullet -}$ with metal ions.[17] The deviation of the

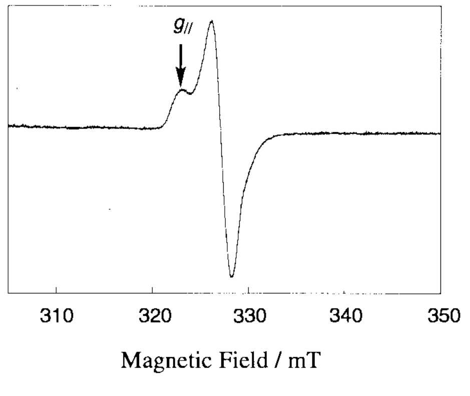

Figure 1. ESR spectrum of $[Zn(O_2^{\bullet -})(MeIm(Py)(COO))]$ in frozen EtCN at 133 K.

Table 1. The $g_{//}$-values and ΔE values of ESR spectra of Zn(II)–$O_2^{\bullet -}$ complexes

Complex	$g_{//}$	ΔE / eV[a]
$O_2^{\bullet -}$	2.0900	0.319
$[Zn(O_2^{\bullet -})(MeIm(Py)_2)]^+$	2.0351	0.854
$[Zn(O_2^{\bullet -})(MeIm(Me)_2)]^+$	2.0344	0.872
$[Zn(O_2^{\bullet -})(MeIm(Py)(COO))]$	2.0347	0.864

[a] The experimental error is ± 0.003 eV.

$g_{//}$-value from the free spin value (g_e = 2.0023) is caused by the spin–orbit interaction as given by eq 1,[18]

$$g_{//} = g_e + 2\sqrt{\frac{\lambda^2}{\lambda^2 + \Delta E^2}} \tag{1}$$

where λ is the spin–orbit coupling constant of oxygen which is known as 0.0140 eV,[19,20] and ΔE is the energy splitting of π_g levels due to the complex formation between $O_2^{\bullet -}$ and Zn(II) ion. Under the conditions that $\Delta E >> \lambda$, eq 1 is reduced to a simple relation, $g_{//} = g_e + 2\lambda/\Delta E$. Thus, the $g_{//}$-values can be used to determine the ΔE values since they are the most sensitive to the ΔE values.[17] The ΔE values of the Zn(II)–$O_2^{\bullet -}$ complexes are then evaluated from deviation of the $g_{//}$-values from the free spin value and they are listed in Table 1 with the $g_{//}$-values. The ΔE values of the $O_2^{\bullet -}$ complex with **1** (0.854 eV), **2** (0.872 eV), and **3** (0.864 eV) are significantly larger than those of $O_2^{\bullet -}$ complexes with other divalent metal ions (Mg(II) ion: 0.65 eV, Ca(II) ion: 0.58 eV, Sr(II) ion: 0.52 eV, and Ba(II) ion: 0.49 eV).[17] Such large ΔE values reflect the strong Lewis acidity of the Zn(II) complexes as compared to other divalent metal ions.[21] The ΔE values of $O_2^{\bullet -}$ complexes increase in the order **1** < **3** < **2**. The larger ΔE value of the $O_2^{\bullet -}$ complex with **2** (0.872 eV) than with **1** (0.854 eV) may be ascribed to the increased Lewis acidity of the Zn(II) ion in **2** due to the steric effect of the two *o*-methyl groups of pyridine moieties of **2**. In addition, the ΔE value (0.864 eV) of the $O_2^{\bullet -}$ complex with **3** which has the carboxylato O atom instead of the N atom of pyridine is larger than the value (0.854 eV) of $O_2^{\bullet -}$ complex with **1**.[22]

Further evidence of the coordinated ligand effect comes from ^{19}F NMR experiments of the fluoride ion complexes. The addition of one-equivalent of Bu_4NF to a CD_3CN solution of **1**, **2**, and **3** in the presence of an internal standard, trifluorotoluene (0 ppm), exhibited new signals at –157, –108, and –143 ppm, respectively, as shown in Figure 2.[23] The ^{19}F NMR signal of the fluoride ion complex with **2** at the lower magnetic field as compared with **1** and **3** indicates the Lewis acidity of Zn(II) ion increases in the order **1** < **3** < **2**.[24] This is consistent with the ΔE values (*vide supra*). The chemical shift of the fluoride ion is a good probe to determine the Lewis acidity of Zn(II) ion. These results from ESR and ^{19}F NMR measurements indicate that the carboxylato O atom is weaker donor than the N atom of pyridine. Thus, an important role of carboxylato O atom which is coordinated to Zn(II) ion in Cu,Zn–SOD may be to increase Lewis acidity of Zn(II) ion to accelerate the reduction of $O_2^{\bullet -}$ by the Cu(I) ion.

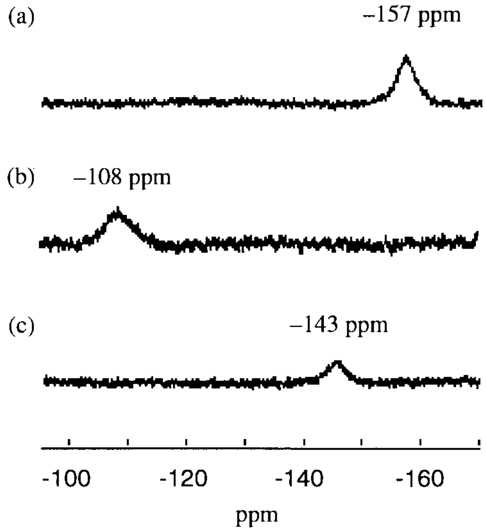

Figure 2. ^{19}F NMR spectra of (a) $[Zn(F^-)(MeIm(Py)_2)]^+$, (b) $[Zn(F^-)(MeIm(Me)_2)]^+$, and (c) $[Zn(F^-)(MeIm(Py)(COO))]$ in CD_3CN at 298 K.

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