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Communication

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A Chromium(III)−Superoxo Complex in Oxygen Atom Transfer Reactions as a Chemical Model of Cysteine Dioxygenase

Jaeheung Cho,[§] Jaeyoung Woo,[§] and Wonwoo Nam*

Department of Bioinspired Science, Ewha Womans University, Seoul 120-750, Korea

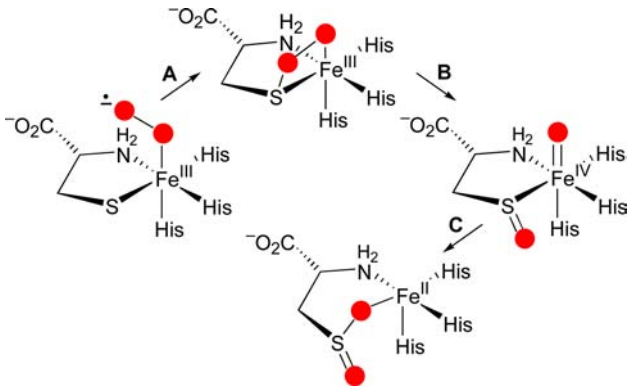
Supporting Information

ABSTRACT: Metal−superoxo species are believed to play key roles in oxygenation reactions by metalloenzymes. One example is cysteine dioxygenase (CDO) that catalyzes the oxidation of cysteine with O_2, and an iron(III)−superoxo species is proposed as an intermediate that effects the sulfoxidation reaction. We now report the first biomimetic example showing that a chromium(III)−superoxo complex bearing a macrocyclic TMC ligand, $[Cr^{III}(O_2)(TMC)(Cl)]^+$, is an active oxidant in oxygen atom transfer (OAT) reactions, such as the oxidation of phosphine and sulfides. The electrophilic character of the Cr(III)−superoxo complex is demonstrated unambiguously in the sulfoxidation of *para*-substituted thioanisoles. A Cr(IV)−oxo complex, $[Cr^{IV}(O)(TMC)(Cl)]^+$, formed in the OAT reactions by the chromium(III)−superoxo complex, is characterized by X-ray crystallography and various spectroscopic methods. The present results support the proposed oxidant and mechanism in CDO, such as an iron(III)−superoxo species is an active oxidant that attacks the sulfur atom of the cysteine ligand by the terminal oxygen atom of the superoxo group, followed by the formation of a sulfoxide and an iron(IV)−oxo species via an O−O bond cleavage.

Dioxygen activation at transition metal centers is of current interest in biological and catalytic oxidation reactions.[1] Oxygen-coordinating metal intermediates, such as metal−superoxo, −peroxo, −hydroperoxo, and −oxo species, are frequently invoked as plausible oxidants in the oxidation of organic substrates.[1] Among the metal−oxygen adducts, metal−superoxo species have attracted much attention recently, since the intermediates have been implicated as reactive species in the C−H bond activation of substrates by nonheme iron (e.g., isopenicillin *N* synthase and *myo*-inositol oxygenase)[2] and copper (e.g., dopamine β-monooxygenase and peptidylglycine-α-amidating monooxygenase)[3] enzymes. In biomimetic studies, iron(III)−superoxo species have been proposed as a potent oxidant in the C−H bond activation of hydrocarbons by mononuclear nonheme iron(II) complexes.[4] In the case of copper(II)−superoxo species, a number of synthetic copper(II)−superoxo complexes have shown reactivities in ligand oxidation and the oxidation of organic compounds with weak C−H, O−H, and N−H bonds.[5]

Cysteine dioxygenase (CDO), which is a mononuclear nonheme iron enzyme that contains an iron(II) center bound by three histidine groups in a facial orientation, catalyzes the oxidation of cysteine with O_2 to yield cysteine sulfinic acid (i.e., *S*-oxidation).[6] An iron(III)−superoxo intermediate is proposed as an active oxidant that attacks the sulfur atom of the ligand with the terminal oxygen atom of the superoxo group, followed by the O−O bond cleavage to form an iron(IV)−oxo species (Scheme 1).[6,7] As a chemical model of CDO, Limberg, Goldberg, de Visser, and their co-workers reported experimental and computational studies on the iron(II)-mediated *S*-oxidation by O_2,[8] in which iron(III)−superoxo species have been proposed as an active oxidant that effects the *S*-oxidation reactions. However, intermediacy of the iron(III)−superoxo species and the formation of an iron(IV)−oxo product in the *S*-oxidation reactions (Scheme 1) have never been observed in both enzymatic and biomimetic reactions.

Scheme 1



Mononuclear chromium(III)−superoxo complexes have been reported by Bakac and co-workers as chemical models of O_2 activating metalloenzymes and as active oxidants in the oxidation of substrates.[9] Very recently, we also reported the synthesis and characterization of an end-on chromium(III)−superoxo complex, $[Cr^{III}(O_2)(TMC)(Cl)]^+$ (**1**, TMC = 1,4,8,11-tetramethyl-1,4,8,11-tetraazacyclotetradecane), and highlighted its reactivity in hydrogen atom (H-atom) abstraction reactions.[10,11] This study provided the first direct experimental evidence that metal−superoxo species are able to abstract a H-atom from external substrates. However, to the best of our knowledge, metal−superoxo complexes have never been employed in oxygen atom transfer (OAT) reactions (e.g., *S*-oxidation). In this communication, we report that **1** is able to

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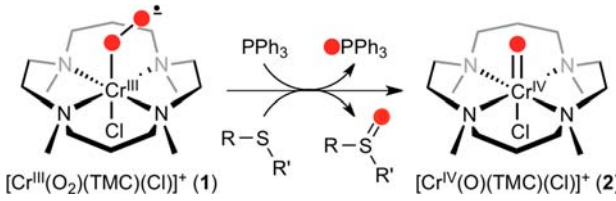
transfer its oxygen atom to organic substrates (e.g., PPh_3 and sulfides), yielding the corresponding oxygenated products and a chromium(IV)−oxo complex, $[Cr^{IV}(O)(TMC)(Cl)]^+$ (**2**), as shown in Scheme 2. An electrophilic character of **1** is also

Scheme 2



demonstrated in the oxidation of *para*-substituted thioanisoles. Thus, the present results report a chemical model of CDO and are discussed in light of the role of an iron(III)−superoxo intermediate in the oxidation of cysteine in CDO (see Schemes 1 and 2).

The Cr(III)−superoxo complex, $[Cr^{III}(O_2)(TMC)(Cl)]^+$ (**1**), was generated by bubbling O_2 through a solution of $[Cr^{II}(TMC)(Cl)]^+$ in CH_3CN at −10 °C, as reported previously.[10] The intermediate **1** was metastable so that it could be used in reactivity studies under stoichiometric conditions (e.g., ca. 5% decay for 1 h at −10 °C). Treating **1** with PPh_3 produced $OPPh_3$ in quantitative yield. The source of the oxygen incorporated into the product was determined to be the superoxo group by carrying out an isotope ^{18}O-labeling experiment; $^{18}OPPh_3$ was produced in the reaction of ^{18}O-labeled **1** (**1**-^{18}O) prepared using $^{18}O_2$ (Scheme 2; also see Supporting Information (SI), Experimental Section for reaction conditions and Figure S1). Kinetic studies of **1** with PPh_3 in CH_3CN at −10 °C exhibit a first-order decay profile (Figure 1a, inset), and pseudo-first-order rate constants increased proportionally with the PPh_3 concentration, giving a second-order rate constant (k_2) of 8.4×10^{-1} M^{-1} s^{-1} (Figure 1b). The rates were dependent on reaction temperature, from which a linear Eyring plot was obtained between 243 and 273 K to give the activation parameters of $\Delta H^{\ddagger} = 44$ kJ mol^{-1} and $\Delta S^{\ddagger} = -74$ J mol^{-1} K^{-1} (Figure 1c).

We then examined the reactivity of **1** in the oxidation of sulfides in CH_3CN at −10 °C. **1** disappeared upon addition of thioanisole with a first-order decay profile (Figure S2). The pseudo-first-order rate constants increased proportionally with the concentration of thioanisole ($k_2 = 5.2 \times 10^{-3}$ M^{-1} s^{-1}) (Figure 2a).[12] The reactivity of **1** was further investigated with *para*-substituted thioanisoles, *para*-X-Ph-SCH_3 (X = OH, CH_3, H, Cl), to investigate the electronic effect of *para*-substituents on the oxidation of thioanisoles by **1** (Figure 2a). A Hammett plot of the second-order rate constants vs σ_p^+ gave a ρ value of −3.3 (Figure 2b; Table S1). Such a negative ρ value indicates the electrophilic character of the superoxo group of **1** in OAT reactions, as frequently observed in the sulfoxidation of thioanisoles by high-valent metal−oxo complexes of heme and nonheme ligands.[13] In addition, we observed a good linear correlation when the rates were plotted against oxidation potentials (E_{ox}) of thioanisoles (Figure 2c; Table S1). Further mechanistic information needs to be obtained to clarify the mechanism of the oxygenation of sulfides by metal−superoxo species (e.g., direct oxygen atom transfer vs electron transfer followed by oxygen atom transfer).[13,14] The product analysis of the reaction solution of the oxidation of thioanisole by **1**

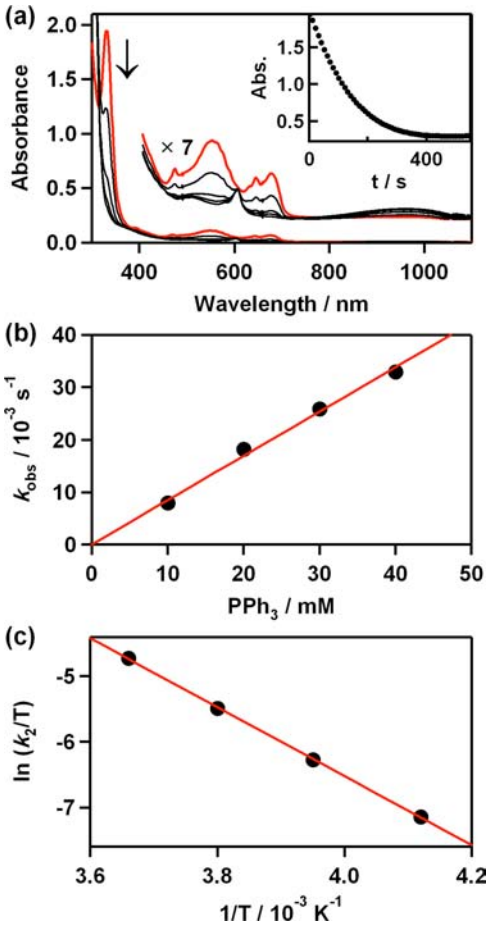


Figure 1. (a) UV−vis spectral changes of **1** (0.5 mM) obtained at 90 s intervals upon addition of PPh_3 (20 equiv to **1**, 10 mM) in CH_3CN at −10 °C. The upper inset shows the time course of the decay of **1** monitored at 331 nm. The lower inset is the expanded region of 400−1100 nm (×7). (b) Plot of k_{obs} against the concentration of PPh_3 to determine a second-order rate constant at −10 °C. (c) Plot of second-order rate constants against $1/T$ to determine activation parameters for the reaction of **1** and PPh_3.

revealed that methyl phenyl sulfoxide was produced with a high yield (~70% based on the amount of **1** used), and the source of oxygen in the sulfoxide product was found to be the superoxo ligand of **1** on the basis of an ^{18}O-labeling experiment performed with **1**-^{18}O (see SI, Experimental Section for reaction conditions and Figure S3).

Interestingly, we have observed the formation of a Cr(IV)=O complex, $[Cr^{IV}(O)(TMC)(Cl)]^+$ (**2**), as a product in the OAT reactions by **1** (see Scheme 2).[15] This intermediate was relatively stable in CH_3CN at −10 °C ($t_{1/2}$ ~40 min) and did not react with PPh_3 and sulfides under the conditions. Therefore, we were able to characterize **2** with various spectroscopic methods, such as UV−vis spectrophotometer, cold spray ionization mass spectrometry (CSI-MS), electron paramagnetic resonance (EPR) spectroscopy, and resonance Raman (rRaman) spectroscopy, and the structure of **2** was determined by X-ray crystallography. The UV−vis spectrum of **2** exhibits characteristic bands at 501 (ε = 60 M^{-1} cm^{-1}), 603 (ε = 90 M^{-1} cm^{-1}), and 960 nm (ε = 30 M^{-1} cm^{-1}) (Figure 3a). The CSI-MS of **2** shows a prominent ion peak at a mass-to-charge ratio (m/z) of 359.2 (Figure 3b), whose mass and isotope distribution pattern correspond to $[Cr^{IV}(O)(TMC)$-

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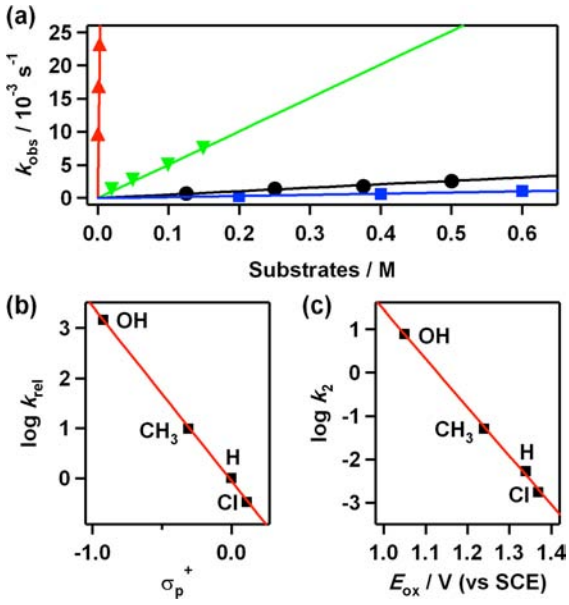

Figure 2. Reaction of **1** with para-substituted thioanisoles, *para*-X-Ph-SCH_3 (X = OH, CH_3, H, Cl), in CH_3CN at −10 °C. (a) Plots of k_{obs} against the concentration of *para*-X-Ph-SCH_3 (X = OH (red), CH_3 (green), H (black), Cl (blue)). (b) Hammett plot of log k_{rel} against σ_p^+ of *para*-substituted thioanisoles. The k_{rel} values were calculated by dividing k_2 of *para*-X-Ph-SCH_3 by k_2 of thioanisole. (c) Plot of log k_2 against E_{ox} for the oxidation of *para*-substituted thioanisoles.

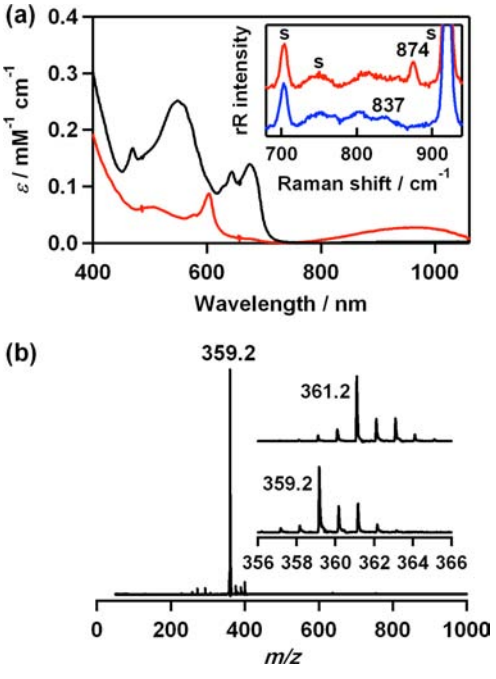

Figure 3. (a) UV−vis spectra of **2** (red line) and **1** (black line, for comparison) in CH_3CN at −10 °C. Inset shows rRaman spectra of **2**-^{16}O (red line) and **2**-^{18}O (blue line); solvent bands are labeled with "s". Similar but much more intense signals were obtained for **2** which was prepared by reacting $[Cr^{II}(TMC)(Cl)]^+$ with PhIO (see Figure S6). (b) CSI-MS of **2**. Inset shows isotope distribution patterns for **2**-^{16}O (lower) and **2**-^{18}O (upper).

$(Cl)]^+$ (**2**) (calculated *m*/*z* of 359.2). When the reaction was carried out with **1**-^{18}O (vide supra), a mass peak corresponding to $[Cr^{IV}(^{18}O)(TMC)(Cl)]^+$ (**2**-^{18}O) appeared at a *m*/*z* of 361.2 (calculated *m*/*z* of 361.2) (Figure 3b, inset). The shift in two mass units on substitution of ^{16}O with ^{18}O indicates that **2** contains one oxygen atom in it. **2** is EPR silent at 4.3 K, and the effective magnetic moment of **2** (μ_{eff} = 3.3 μ_B at −20 °C) indicates the spin state of S = 1 for the Cr^{IV} ion. The rRaman spectrum of **2**-^{16}O (32 mM), measured in CH_3CN/CH_2Cl_2 at −20 °C with 407 nm laser excitation, exhibits an isotopically sensitive band at 874 cm^{-1}, which shifted to 837 cm^{-1} in **2**-^{18}O (Figure 3a, inset). The observed isotopic shift of −37 cm^{-1} with ^{18}O-substitution is in good agreement with the calculated value ($\Delta\nu_{calc}$ = −38) for the Cr−O diatomic harmonic oscillator. The observed Cr−O frequency at 873 cm^{-1} is lower than those found in $[Cr^{IV}(O)(Tp^{tBu,Me})(pz'H)]^+$ (905 cm^{-1})[16] and $[Cr^{IV}(O)(TPP)]$ (1025 cm^{-1}).[17]

Single crystals of **2**-Cl·CH_3CN·H_2O were grown from CH_3CN/acetone/diethyl ether at −40 °C and contained two crystallographically independent but virtually identical cations in the asymmetric unit (denoted "A" and "B"). These two cations are mononuclear chromium−oxo complexes in a distorted octahedral geometry (Tables S2 and S3), as shown in Figure 4 for **2A**. Notably, the Cr1−O1 bond length of **2A**

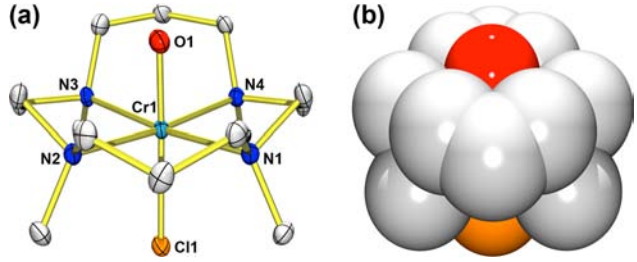

Figure 4. Molecular structure of one of crystallographically independent molecules of $[Cr(O)(TMC)(Cl)]^+$ (**2**). (a) ORTEP plot of **2A** with 30% probability thermal ellipsoid. Hydrogen atoms are omitted for clarity. (b) Space-filling representation of **2A**, derived from the single crystal structure determination. Selected bond lengths (Å) and angles (°): Cr1−O1 1.698(3), Cr1−Cl1 2.3830(11), O1−Cr1−Cl1 176.82(9).

(1.698(3) Å) is longer than those of other Cr(IV or V) complexes, such as $[Cr^{IV}(O)(Tp^{tBu,Me})(pz'H)]^+$ (1.602 Å),[16] $[Cr^{IV}(O)(TPP)]$ (1.572 Å),[17] $[Cr^{V}(O)(salen)]^+$ (1.545 Å),[18] and $[Cr^{V}(O)(TMC)(OCH_3)]^{2+}$ (1.604 Å).[11] The relatively long Cr−O bond distance of **2** is consistent with the low frequency of the Cr−O stretching vibration obtained in the rRaman measurement (vide supra). In addition, intermolecular hydrogen bonding interactions in crystalline environments are proposed to elongate the Cr−O bond distance (Figure S4), as observed in Fe−O(H) complexes using the secondary coordination sphere.[19] All four *N*-methyl groups of the TMC ligand in **2** point away from the oxo group, as observed in the crystal structures of $[Cr^{V}(O)(TMC)(OCH_3)]^{2+}$ and $[Fe^{IV}(O)(TMC)(CH_3CN)]^{2+}$.[11,20]

In conclusion, we have shown recently that a Cr(III)−superoxo complex, $[Cr^{III}(O_2)(TMC)(Cl)]^+$ (**1**), is a biomimetic oxidant for the metal−superoxo species proposed in C−H bond activation reactions by nonheme iron and copper enzymes. In the present study, we have demonstrated that **1** is able to conduct OAT reactions with an electrophilic character. We have also shown the formation of a chromium(IV)−oxo complex, $[Cr^{IV}(O)(TMC)(Cl)]^+$ (**2**), in the OAT reactions by **1**. Thus, the present study provides the first biomimetic example demonstrating that a metal(III)−superoxo complex possesses an electrophilic character and is able to conduct OAT

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reactions. In addition, a metal(IV)−oxo complex is formed as a product when the terminal oxygen atom of the superoxo group in the metal(III)−superoxo complex is transferred to organic substrates in the OAT reactions (see Schemes 1 and 2). Further studies, including density functional theory (DFT) calculations, will provide insights regarding the mechanism of the oxygen atom transfer from metal−superoxo species to organic substrates in enzymatic and biomimetic reactions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental Section, Tables S1−S3, and Figures S1−S6. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

wwnam@ewha.ac.kr

Author Contributions

[§]These authors contributed equally.

Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) (a) Ortiz de Montellano, P. R. *Chem. Rev.* **2010**, *110*, 932−948. (b) Green, M. T. *Curr. Opin. Chem. Biol.* **2009**, *13*, 84−88. (c) Krebs, C.; Fujimori, D. G.; Walsh, C. T.; Bollinger, J. M., Jr. *Acc. Chem. Res.* **2007**, *40*, 484−492. (d) Nam, W. *Acc. Chem. Res.* **2007**, *40*, 465 and review articles in the special issue. (e) Abu-Omar, M. M.; Loaiza, A.; Hontzeas, N. *Chem. Rev.* **2005**, *105*, 2227−2252. (f) Klotz, I. M.; Kurtz, D. M., Jr. *Chem. Rev.* **1994**, *94*, 567−568 and review articles in the special issue.

(2) (a) Bollinger, J. M., Jr.; Krebs, C. *Curr. Opin. Chem. Biol.* **2007**, *11*, 151−158. (b) van der Donk, W. A.; Krebs, C.; Bollinger, J. M., Jr. *Curr. Opin. Struct. Biol.* **2010**, *20*, 673−683.

(3) (a) Prigge, S. T.; Eipper, B. A.; Mains, R. E.; Amzel, L. M. *Science* **2004**, *304*, 864−867. (b) Chen, P.; Solomon, E. I. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 13105−13110. (c) Klinman, J. P. *J. Biol. Chem.* **2006**, *281*, 3013−3016. (d) Rolff, M.; Tuczek, F. *Angew. Chem., Int. Ed.* **2008**, *47*, 2344−2347.

(4) (a) Lee, Y.-M.; Hong, S.; Morimoto, Y.; Shin, W.; Fukuzumi, S.; Nam, W. *J. Am. Chem. Soc.* **2010**, *132*, 10668−10670. (b) Mukherjee, A.; Cranswick, M. A.; Chakrabarti, M.; Paine, T. K.; Fujisawa, K.; Münck, E.; Que., L., Jr. *Inorg. Chem.* **2010**, *49*, 3618−3628. (c) Chen, H.; Cho, K.-B.; Lai, W.; Nam, W.; Shaik, S. *J. Chem. Theory Comput.* **2012**, *8*, 915−926. (d) Chung, L. W.; Li, X.; Hirao, H.; Morokuma, K. *J. Am. Chem. Soc.* **2011**, *133*, 20076−20079.

(5) (a) Peterson, R. L.; Himes, R. A.; Kotani, H.; Suenobu, T.; Tian, L.; Siegler, M. A.; Solomon, E. I.; Fukuzumi, S.; Karlin, K. D. *J. Am. Chem. Soc.* **2011**, *133*, 1702−1705. (b) Kunishita, A.; Kubo, M.; Sugimoto, H.; Ogura, T.; Sato, K.; Takui, T.; Itoh, S. *J. Am. Chem. Soc.* **2009**, *131*, 2788−2789. (c) Maiti, D.; Lee, D.-H.; Gaoutchenova, K.; Würtele, C.; Holthausen, M. C.; Narducci Sarjeant, A. A.; Sundermeyer, J.; Schindler, S.; Karlin, K. D. *Angew. Chem., Int. Ed.* **2008**, *47*, 82−85. (d) Maiti, D.; Fry, H. C.; Woertink, J. S.; Vance, M. A.; Solomon, E. I.; Karlin, K. D. *J. Am. Chem. Soc.* **2007**, *129*, 264−265. (e) Cramer, C. J.; Tolman, W. B. *Acc. Chem. Res.* **2007**, *40*, 601−608. (f) Würtele, C.; Gaoutchenova, E.; Harms, K.; Holthausen, M. C.; Sundermeyer, J.; Schindler, S. *Angew. Chem., Int. Ed.* **2006**, *45*, 3867−3869. (g) Itoh, S. *Curr. Opin. Chem. Biol.* **2006**, *10*, 115−122.

(6) (a) McCoy, J. G.; Bailey, L. J.; Bitto, E.; Bingman, C. A.; Aceti, D. J.; Fox, B. G.; Phillips, G. N., Jr. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103*, 3084−3089. (b) Joseph, C. A.; Maroney, M. J. *Chem. Commun.* **2007**, 3338−3349. (c) de Visser, S. P.; Straganz, G. D. *J. Phys. Chem. A* **2009**, *113*, 1835−1846. (d) de Visser, S. P. *Coord. Chem. Rev.* **2009**, *253*, 754−768.

(7) (a) Crawford, J. A.; Li, W.; Pierce, B. S. *Biochemistry* **2011**, *50*, 10241−10253. (b) Kumar, D.; Thiel, W.; de Visser, S. P. *J. Am. Chem. Soc.* **2011**, *133*, 3869−3882. (c) Pierce, B. S.; Gardner, J. D.; Bailey, L. J.; Brunold, T. C.; Fox, B. G. *Biochemistry* **2007**, *46*, 8569−8578. (d) Aluri, S.; de Visser, S. P. *J. Am. Chem. Soc.* **2007**, *129*, 14846−14847.

(8) (a) Sallmann, M.; Siewert, I.; Fohlmeister, L.; Limberg, C.; Knispel, C. *Angew. Chem., Int. Ed.* **2012**, *51*, 2234−2237. (b) Badiei, Y. M.; Siegler, M. A.; Goldberg, D. P. *J. Am. Chem. Soc.* **2011**, *133*, 1274−1277. (c) Kumar, D.; Sastry, G. N.; Goldberg, D. P.; de Visser, S. P. *J. Phys. Chem. A* **2012**, *116*, 582−591. (d) Jiang, Y.; Widger, L. R.; Kasper, G. D.; Siegler, M. A.; Goldberg, D. P. *J. Am. Chem. Soc.* **2010**, *132*, 12214−12215. (e) McQuilken, A. C.; Jiang, Y.; Siegler, M. A.; Goldberg, D. P. *J. Am. Chem. Soc.* **2012**, *134*, 8758−8761.

(9) (a) Bakac, A.; Scott, S. L.; Espenson, J. H.; Rodgers, K. R. *J. Am. Chem. Soc.* **1995**, *117*, 6483−6488. (b) Bakac, A. *J. Am. Chem. Soc.* **1997**, *119*, 10726−10731. (c) Bakac, A. *Coord. Chem. Rev.* **2006**, *250*, 2046−2058.

(10) Cho, J.; Woo, J.; Nam, W. *J. Am. Chem. Soc.* **2010**, *132*, 5958−5959.

(11) Cho, J.; Woo, J.; Han, J. E.; Kubo, M.; Ogura, T.; Nam, W. *Chem. Sci.* **2011**, *2*, 2057−2062.

(12) We have reported the hydrogen atom transfer (HAT) reactivity of **1** in the C−H bond activation of substrates with weak bond dissociation energies such as 9,10-dihydroanthracene (k_2 = 1.7 × 10^{-1} M^{-1} s^{-1} at −10 °C) in ref 10. By comparing the rate of the oxidation of thioanisole by **1** (k_2 = 5.2 × 10^{-3} M^{-1} s^{-1} at −10 °C) to that of the HAT reaction, we found that the HAT reaction is faster than the OAT reaction.

(13) (a) Arias, J.; Newlands, C. R.; Abu-Omar, M. M. *Inorg. Chem.* **2001**, *40*, 2185−2192. (b) McPherson, L. D.; Drees, M.; Khan, S. I.; Strassner, T.; Abu-Omar, M. M. *Inorg. Chem.* **2004**, *43*, 4036−4050. (c) Sastri, C. V.; Seo, M. S.; Park, M. J.; Kim, K. M.; Nam, W. *Chem. Commun.* **2005**, 1405−1407. (d) Nam, W. *Acc. Chem. Res.* **2007**, *40*, 522−531.

(14) (a) Goto, Y.; Matsui, T.; Ozaki, S.; Watanabe, Y.; Fukuzumi, S. *J. Am. Chem. Soc.* **1999**, *121*, 9497−9502. (b) Taki, M.; Itoh, S.; Fukuzumi, S. *J. Am. Chem. Soc.* **2002**, *124*, 998−1002. (c) Kumar, A.; Goldberg, I.; Botoshansky, M.; Buchman, Y.; Gross, Z. *J. Am. Chem. Soc.* **2010**, *132*, 15233−15245. (d) Park, J.; Morimoto, Y.; Lee, Y.-M.; Nam, W.; Fukuzumi, S. *J. Am. Chem. Soc.* **2011**, *133*, 5236−5239.

(15) **2** was synthesized independently by reacting $[Cr^{II}(TMC)(Cl)]^+$ with 3.6 equiv of iodosylbenzene (PhIO) in CH_3CN at −10 °C, although this reaction afforded ca. 60% formation of **2** based on the UV−vis spectrum (Figure S5), and this species was further characterized with resonance Raman spectroscopy (Figure S6).

(16) Qin, K.; Incarvito, C. D.; Rheingold, A. L.; Theopold, K. H. *J. Am. Chem. Soc.* **2002**, *124*, 14008−14009.

(17) Groves, J. T.; Kruper, W. J., Jr.; Haushalter, R. C.; Butler, W. M. *Inorg. Chem.* **1982**, *21*, 1363−1368.

(18) Srinivasan, K.; Kochi, J. K. *Inorg. Chem.* **1985**, *24*, 4671−4679.

(19) (a) Shook, R. L.; Borovik, A. S. *Chem. Commun.* **2008**, 6095−6107. (b) Mukherjee, J.; Lucas, R. L.; Zart, M. K.; Powell, D. R.; Day, V. W.; Borovik, A. S. *Inorg. Chem.* **2008**, *47*, 5780−5786. (c) Conradie, J.; Tangen, E.; Ghosh, A. *J. Inorg. Biochem.* **2006**, *100*, 707−715.

(20) Rohde, J.-U.; In, J.-H.; Lim, M. H.; Brennessel, W. W.; Bukowski, M. R.; Stubna, A.; Münck, E.; Nam, W.; Que, L., Jr. *Science* **2003**, *229*, 1037−1039.