J|A|C|S
COMMUNICATIONS

Published on Web 11/24/2006

Oxygen Isotope Effects upon Reversible O_2-Binding Reactions: Characterizing Mononuclear Superoxide and Peroxide Structures

Michael P. Lanci and Justine P. Roth*

Department of Chemistry, Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland 21218

Received September 26, 2006; E-mail: jproth@jhu.edu

The characterization of intermediates in oxidation reactions of transition metals is a common goal in biological and inorganic chemistry[1] needed to guide the development of new industrial catalysts that can use O_2 as a sacrificial oxidant. Such advances require improved capabilities for identifying metal−O_2 adducts as well as the mechanisms by which these species are formed. In this paper, we examine oxygen equilibrium isotope effects (^{18}O EIEs) on reversible reactions that give rise to peroxide (O_2^{2-}) and superoxide (O_2^{1-}) compounds. The EIEs reported here provide benchmarks for interpreting intermediates during transition-metal-mediated O_2 activation in a variety of natural and synthetic systems.[2−4]

Classic compounds with defined structures (Chart 1)[5] were chosen to examine how ^{18}O EIEs reflect the reduction of O_2 as well as the mode by which it coordinates to a metal center. The observation of O−O stretching frequencies, ν(O−O) = 800−930 cm^{-1} for side-on peroxide compounds and 1050−1200 cm^{-1} for end-on superoxide compounds, has typically served this purpose, although intermediate structures, such as those assigned to side-on superoxide species, have challenged this simple means of classification.[6] In principle, ^{18}O EIEs complement existing spectroscopic techniques by reporting on changes in O−O bonding together with the formation of new metal−O bonds.

In this work, ^{18}O EIEs were determined from the oxygen isotope composition of metal−O_2 adducts that had been pre-equilibrated with natural abundance O_2 from air. A detailed description of the high vacuum apparatus and methodology used for preparing samples has been published.[2,3b,7] Samples were analyzed by isotope ratio mass spectrometry (IRMS) which gives ^{18}O:^{16}O to precisions of ±0.0002. The ^{18}O EIEs were calculated according to eq 1 where R_t is the ^{18}O:^{16}O in the "total" O_2 isolated from air-saturated solutions containing the metal−O_2 adduct; R_u is the ^{18}O:^{16}O in the "unbound" O_2 from solutions containing only air and $1 - f$ is the fraction of metal-bound O_2 in the air-saturated solutions.

$$^{18}\text{O EIE} = \frac{K(^{16}\text{O}^{16}\text{O})}{K(^{18}\text{O}^{16}\text{O})} = \frac{1-f}{R_t/R_u - f} \qquad (1)$$

Reversibility of O_2 binding is a key requirement for accurate and reproducible determinations of ^{18}O EIEs. Spurious results occur when metal−O_2 adduct decomposition leads to irreversible consumption of O_2 on the time scale of sample collection. In most experiments, the recovery of O_2 was nearly quantitative at ≥22 °C; yields were determined by manometry and based on concentrations of the metal−O_2 adducts detected by multinuclear NMR and UV−vis spectroscopy.[7] Using the same methods, equilibrium constants for O_2 binding (K_{O_2}) under 1 atm of dry air were evaluated as a function of temperature in chlorobenzene (ClBz) or dimethylformamide (DMF) (Table 1).[7]

The metal−O_2 adducts in this study are derived from group IX transition metals. Binding of O_2 to square planar Rh^{I} or Ir^{I} precursors gives products with side-on peroxide ligands.[8] These structures are characterized by ^{18}O EIEs of 2−3% in DMF at 22 °C: 1.0199 ± 0.0017 (Rh), 1.0226 ± 0.0013 (Ir_{NCO}), and 1.0305 ± 0.0023 (Ir_{Cl}).

Chart 1. Structures and Abbreviations of the Compounds Examined

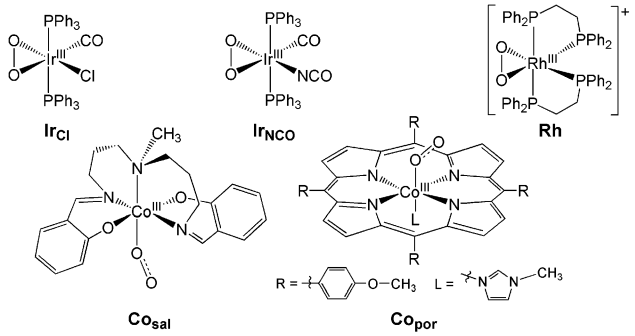

Table 1. Parameters Describing the Reversibility of O_2 Binding

		% yield O_2[a]	$K_{O_2} \times 10^{-3}$ (M^{-1})[a]	ΔH^e (kcal mol^{-1})	ΔS^e (e.u.)
Ir_{Cl}	DMF	82(13)	16(1.9)[b]	−8.4(0.5)	−9.3(3.3)
Ir_{NCO}	DMF	93(10)	1.3(0.30)	−7.3(0.5)	−10(2)
Rh	DMF	90(6)	0.47(0.11)	−15.1(0.8)	−37(3)
Co_{sal}	DMF	97(5)[c]	0.32(0.02)[c]	−13.1(1.0)	−39(7)
Co_{sal}	ClBz	110(19)[d]	0.26(0.05)[d]	−12.4(1.9)	−40(7)
Co_{por}	ClBz	94(14)[d]	0.63(0.21)[d]	−8.9(1.0)[f]	−26(4)[f]

[a] Measured at 22 ± 2 °C under 1 atm of dry air unless noted; ±1σ errors are in parentheses. [b] Estimated from ΔH and ΔS at 22 °C. [c] At −14 °C. [d] At −28 °C. [e] Determined over the following ranges: 40 to 70 °C (Ir_{Cl}), 30 to 60 °C (Ir_{NCO}), 15 to 40 °C (Rh), 0 to −28 °C (Co_{sal}). [f] From ref 5d with errors ±2σ; determined in toluene from −35 to −80 °C.

Binding of O_2 to five-coordinate Co^{II} precursors gives products with end-on superoxide ligands.[9] Here, lower temperatures were necessary to determine the ^{18}O EIEs, which are considerably smaller than those quoted above: 1.0041 ± 0.0011 (Co_{sal}) in DMF at −14 °C, 1.0053 ± 0.0017 (Co_{sal}) in ClBz at −28 °C, and 1.0066 ± 0.0013 (Co_{por}) in ClBz at −28 °C. Change in the ^{18}O EIE for Co_{sal} was undetectable from −28 to 0 °C.[7]

The results for the diverse compounds in solvents of widely varying polarity[10] provide strong evidence that ^{18}O EIEs are characteristic of the level of O_2 reduction together with the mode by which O_2 binds to the metal (Figure 1). The variation in the observed ^{18}O EIEs is large considering that the range of calculated ^{18}O EIEs is 1.00−1.05 for reactions (where O_2 is reduced to HO_2, H_2O_2, H_2O, O_2^{1-}, and O_2^{2-}).[11] Further, the distinctive ^{18}O EIEs for side-on peroxide and end-on superoxide structures are in contrast to the expectation of similar ^{18}O EIEs (∼1.01) based on an earlier model.[11] This model assumed analogous bonding within a metal superoxide species and HO_2 as well as within a metal peroxide species and H_2O_2.

The formalism of Bigeleisen and Goeppert-Mayer[12] is generally used to calculate heavy atom isotope effects in terms of the change in force constants in proceeding from a reactant to a product state. Using this approach, ^{18}O EIEs of 1.049 ($O_2 \rightarrow O_2^{2-}$) and 1.033 ($O_2 \rightarrow O_2^{1-}$) are predicted for the reduction of O_2 in the absence of concomitant bond formation (Figure 2). Here the size of the ^{18}O

10.1021/ja0669326 CCC: $33.50

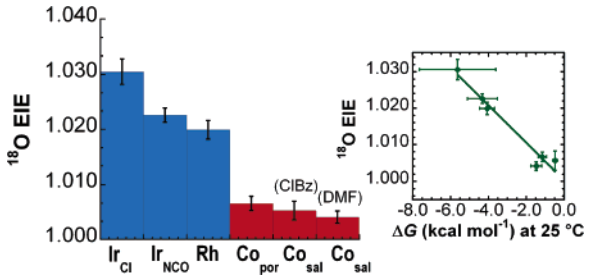

Figure 1. Left: ^{18}O equilibrium isotope effects upon forming the compounds in Chart 1. Right: ^{18}O EIE versus ΔG calculated at 25 °C.

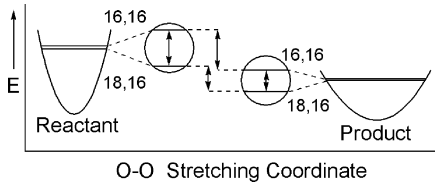

Figure 2. Oxygen isotope effect due to a change in O−O force constant; 16,16 and 18,16 designate zero-point energies of the oxygen isotopologues.

EIE is largely determined by the O−O force constant of the product relative to that of O_2.[2]

The ^{18}O EIEs measured for side-on peroxide compounds roughly agree with those calculated using stretching frequencies for the O−O and metal−O normal modes in the above-mentioned approach.[3] We have encountered more difficulty matching the experimental results for Co_{sal} and Co_{por}, where calculated ^{18}O EIEs are 1.006−1.017. The variations appear to reflect uncertainties in the low-frequency modes.[7] The observed ^{18}O EIEs are, however, close to values reported for end-on Fe^{III} superoxide species in heme proteins (1.0039−1.0056). In this original work, the small size of the ^{18}O EIEs was attributed to hydrogen bonding of the terminal oxygen to a nearby amino acid.[11] Such effects are unlikely in the present study since the ^{18}O EIEs for Co_{sal} and Co_{por} are indistinguishable in DMF and ClBz, yet only DMF has the ability to form hydrogen bonds.

^{18}O EIEs which characterize the metal−O_2 adducts are likely the result of competing enthalpic and entropic isotope effects,[13] making Figure 2 an oversimplified view. Weakening of the O−O bond contributes to a normal (>1) isotope effect upon ΔH. Loss of mass-dependent translational and rotational modes when O_2 coordinates to a metal contributes to a normal isotope effect upon ΔS. Offsetting these effects is the formation of new, low-frequency vibrational and rotational modes in the product. The large differences seen for side-on peroxide and end-on superoxide structures suggest that these new modes reduce the ^{18}O EIEs from the values estimated for O_2^{2-} and O_2^{1-} yet do not affect the difference due to the change in O−O force constant. This result would seem counterintuitive because the metal−O modes are also expected to influence the ^{18}O EIE.

The physical origin of ^{18}O EIEs as well as how they relate to ^{18}O kinetic isotope effects (KIEs) will be the subject of future investigations. At this stage, some insight may be gleaned from a comparison of the reactions examined here. If it is assumed that the ^{18}O EIEs for each of the cobalt compounds is the same at 25 °C and the lower experimental temperatures, a trend is observed where the ^{18}O EIE increases as ΔG for O_2 binding becomes more favorable (Figure 1). The result is in contrast to expectations based upon net bonding changes; the formation of two metal−O bonds stabilizes peroxide compounds relative to superoxide compounds. Instead, the trend seems to indicate that the magnitudes of the ^{18}O EIEs are largely determined by changes in the O−O force constant, that is, decreases in ν(O−O). Studies of O_2 adducts derived from different metals and having different bonding geometries are currently in progress to further address this interesting observation.

Insofar as ^{18}O EIEs can be taken as upper limits to ^{18}O KIEs upon unidirectional O_2 binding, the present results support previous studies of O_2 activation by group IX and X metal compounds.[3a] In this work, we reported ^{18}O KIEs of 1.0069−1.0268 on reactions leading to metal peroxide products. On the grounds that (i) KIEs decreased in proportion to the barriers to O_2 binding and (ii) no intermediate was detectable in any of the reactions, we proposed a single-step mechanism involving a transition state with peroxide rather than superoxide character. Assuming the above ^{18}O EIEs as boundary conditions, a KIE < 1.007 would be expected for a transition state leading to a superoxide intermediate and a KIE < 1.03 would be expected for a transition state leading to a peroxide product. Thus, the observed KIEs appear more consistent with a concerted $2e^-$ mechanism. Of course, a sequential mechanism involving the reorganization of a high-energy superoxide intermediate to a peroxide product in the rate-limiting step cannot be excluded.

In summary, oxygen isotope effects upon reversible O_2 binding to synthetic transition-metal compounds have been determined for the first time. Using defined systems, we have found that the isotope effect is distinctly different when O_2 is bound as a side-on peroxide ligand versus an end-on superoxide ligand to a group IX metal. We suggest the ranges of isotope effects for these compounds can serve as benchmarks for identifying transient metal−O_2 adducts. For example, in cases where outer-sphere electron transfer to O_2 can be ruled out, ^{18}O KIEs of ∼1% may signal the intermediacy of end-on superoxide species,[2,4] whereas values of 2−3% are consistent with peroxide intermediates. This type of analysis provides a new approach to characterizing intermediates in catalytic oxidation reactions.

Acknowledgment. We are grateful for support from NSF CAREER award 0449900 (to J.P.R.) and a Kilpatrick fellowship (to M.P.L.) awarded by the JHU Department of Chemistry.

Supporting Information Available: A description of the experiments and calculations. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) *Active Oxygen in Biochemistry*; Valentine, J. S., Foote, C. S., Greenberg, A., Liebman, J. F., Eds.; Chapman & Hall: New York, 1995. (b) *Biomimetic Oxidations Catalyzed by Transition Metal Complexes*; Meunier, B., Ed.; Imperial College Press: London, 2000.
(2) Roth, J. P.; Klinman, J. P. In *Isotope Effects in Chemistry and Biology*; Kohen, A., Limbach, H. H., Eds.; CRC Press: Boca Raton, FL, 2005.
(3) Lanci, M. P.; Brinkley, D. W.; Stone, K. L.; Smirnov, V. V.; Roth, J. P. *Angew. Chem., Int. Ed.* **2005**, *44*, 7273. (b) Smirnov, V. V.; Brinkley, D. W.; Lanci, M. P.; Karlin, K. D.; Roth, J. P. *J. Mol. Catal. A* **2006**, *251*, 100.
(4) (a) Smirnov, V. V.; Roth, J. P. *J. Am. Chem. Soc.* Accepted. (b) Smirnov, V. V.; Roth, J. P. *J. Am. Chem. Soc.* **2006**, *128*, 3683.
(5) (a) Vaska, L.; Chen, L. S.; Senoff, C. V. *Science* **1971**, *174*, 587. (b) McGinnety, J. A.; Payne, N.; Ibers, J. A. *J. Am. Chem. Soc.* **1969**, *91*, 6301. (c) Trovog, B. S.; Kitko, D. J.; Drago, R. S. *J. Am. Chem. Soc.* **1976**, *98*, 5144. (d) Walker, F. A. *J. Am. Chem. Soc.* **1973**, *95*, 1154.
(6) Cramer, C. J.; Tolman, W. B.; Theopold, K. H.; Rheingold, A. L. *Proc. Natl. Acad. Sci. U.S.A.* **2003**, *100*, 3635.
(7) See Supporting Information.
(8) (a) Vaska, L. *Science* **1963**, *140*, 809. (b) McGinnety, J. A.; Payne, N. C.; Ibers, J. A. *J. Am. Chem. Soc.* **1969**, *91*, 6301. (c) Reed, C. A.; Roper, W. R. *J. Chem. Soc., Dalton Trans.* **1973**, 1370.
(9) (a) Jones, R. D.; Summerville, D. A.; Basolo, F. *Chem. Rev.* **1979**, *79*, 140. (b) Cini, R.; Orioli, P. *J. Chem. Soc., Dalton Trans.* **1983**, 2564.
(10) Dielectric constants at 20 °C are $\epsilon = 36.7$ (DMF) and $\epsilon = 2.7$ (ClBz): Lide, D. R. *Handbook of Chemistry and Physics*, 74th ed.; CRC Press: Boca Raton, FL, 1993.
(11) Tian, G.; Klinman, J. P. *J. Am. Chem. Soc.* **1993**, *115*, 8891.
(12) Bigeleisen, J.; Goeppert-Mayer, M. *J. Chem. Phys.* **1947**, *15*, 26.
(13) This issue has been discussed extensively for the related reaction of $H_2 + Ir_{Cl}$. See: Janak, K. E.; Parkin, G. *J. Am. Chem. Soc.* **2003**, *125*, 13219 and references therein.

JA0669326