

O-Atom Exchange between H₂O and CO₂ Mediated by a Bis(dithiolene)tungsten Complex

Junhyeok Seo and Eunsuk Kim*

Department of Chemistry, Brown University, Providence, Rhode Island 02912, United States

S Supporting Information

ABSTRACT: Inspired by the CO₂-reductase activity of tungsten-dependent formate dehydrogenases (W-FDHs), a reduced W-FDH model, [W^{IV}(OH)(S₂C₂Ph₂)₂][−], was prepared in situ through hydrolysis of [W^{IV}(OPh)(S₂C₂Ph₂)₂][−] (1) and its reactivity with CO₂ was investigated. The reaction between [W^{IV}(OH)(S₂C₂Ph₂)₂][−] and CO₂ at room temperature leads to the formation of [W^{IV}(O)(S₂C₂Ph₂)₂]^{2−} (2), which slowly oxidizes to [W^V(O)(S₂C₂Ph₂)₂][−] (3). Isotopic labeling experiments reveal that the O atom in CO₂ incorporates into 3. This implies that there is carbonic anhydrase like activity, in which carbonation and decarboxylation are mediated by a bis(dithiolene)tungsten complex.

Carbon dioxide (CO₂) has been implicated as one of the main causes for global warming,¹ thus, the transformation of CO₂ into environmentally friendly and valuable chemicals is of great interest. Among the various chemical transformations, the reduction of CO₂ is particularly significant because the reduced forms of CO₂ such as formic acid, methanol, or methane can be directly used as fuels, which establishes CO₂ as an abundant and inexpensive source for alternative energy.^{2,3} Conversion of CO₂ to formic acid can be achieved (electro)-chemically. The development of efficient catalysts for such a transformation comprises an active area of research.^{2–5} There have been continuing efforts in developing coordination complexes that can catalyze the reduction of CO₂ with H₂,⁴ insertion of CO₂ into an M–H bond,^{2,5} or electrochemical reduction of CO₂.³ Although these complexes show much promise, none has shown the comparable efficiency and selectivity of the CO₂-reducing enzymes found in nature.

Formate dehydrogenase (FDHs) are enzymes that catalyze the two-electron oxidation of formate (HCO₂[−]) to CO₂ coupled with the reduction of NAD(P)⁺ to NAD(P)H.⁶ In some prokaryotes, the FDHs contain molybdenum (Mo) or tungsten (W) cofactors, by which an efficient CO₂-reductase activity (reduction of CO₂ to formate) has been also observed.⁷ Recently, Hirst and co-workers have shown that a purified W-FDH can activate an electrode to reduce CO₂ to formate more efficiently than any of the known synthetic catalysts.⁸

The X-ray structures of several Mo- or W-containing FDHs are known.⁹ In the oxidized state, the active site contains a Mo^{VI} or W^{VI} ion in a trigonal-prism geometry with two pyranopterin molecules, one selenocysteine (SeCys), and a sixth –SH (or OH) ligand.^{9a–c} The coordination geometry of the reduced FDHs was first determined from *Escherichia coli*

Mo-FDH_H, in which Mo^{IV} was in a square-pyramidal geometry with two equatorial pyranopterins and a SeCys axial ligand.^{9a} However, the same crystallographic data have been reevaluated more recently,^{9d} revealing that the SeCys in the reduced state is no longer coordinated to the metal center. Instead, the –SH (or –OH) has been proposed for the axial ligand^{9d} (Figure 1).

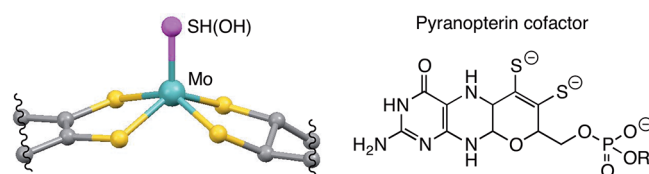


Figure 1. Active-site structures in the reduced Mo-FDH (*E. coli*).^{9d}

In light of the reexamined FDH structure^{9d} and the efficient electrocatalytic activity of W-FDH,⁸ here we report our studies on the CO₂ reactivity of a synthetic model complex of W-FDH.

Synthetic models for FDHs are limited,¹⁰ although a significant number of bis(dithiolene)molybdenum and -tungsten complexes are known.¹¹ Our own attempts to directly synthesize discrete HO- or HS-bound bis(dithiolene)tungsten analogues have not been successful. However, Holm and co-workers have previously reported¹² that a group of phenolate-bound tungsten or molybdenum bis(dithiolene) complexes undergo hydrolysis in the presence of excess H₂O to yield W^{IV}=O complexes via the formation of {W^{IV}OH} species. These reports inspired us to explore the CO₂ reactivity of [W^{IV}(OH)(S₂C₂Ph₂)₂][−], which can be prepared in situ through hydrolysis of [W^{IV}(OPh)(S₂C₂Ph₂)₂][−] (1) in the presence of H₂O.

We first sought a hydrolysis condition that can be achieved with the minimum amount of H₂O possible in order to favor the binding of CO₂ over H₂O to [W^{IV}(OH)(S₂C₂Ph₂)₂][−]. We found that a relatively small amount (10 equiv) of H₂O was sufficient enough to induce hydrolysis of 1^{12b} in acetonitrile to yield [W^{IV}(O)(S₂C₂Ph₂)₂]^{2−} (2). However, we noticed that 2 was not stable over 12 h in our reaction conditions, and it slowly converted into another well-known¹³ compound, [W^V(O)(S₂C₂Ph₂)₂][−] (3; Scheme 1), which is likely associated with the reduction of H⁺ to hydrogen (vide infra).

IR spectroscopy provides us with rich information that supports the generation of 3 as the final hydrolysis product as well as the released free phenol (Figure 2). The IR spectrum of

Received: May 3, 2012

Published: July 26, 2012



Scheme 1

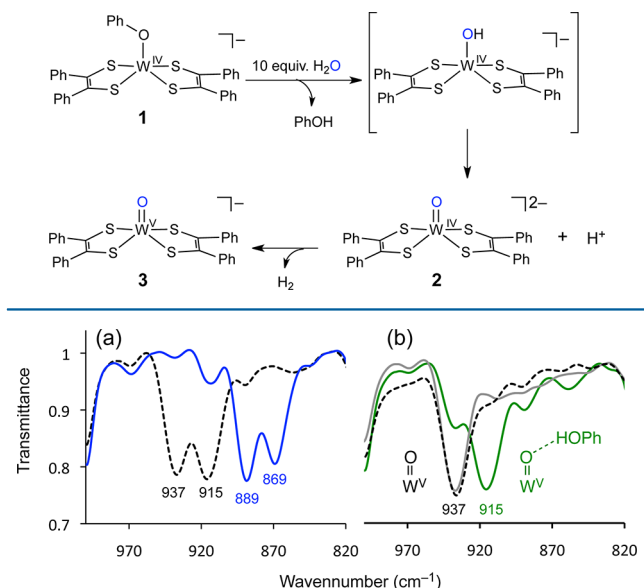


Figure 2. IR spectra (Nujol) of (a) the crude reaction products of 1 and 10 equiv of H₂O (black dotted line) and those of 1 and 10 equiv of H₂¹⁸O (blue solid line), (b) the isolated reaction product 3 (black dotted line), 3 in the presence of 2 equiv of externally added phenol (green solid line), and reisolated 3 after removal of phenol by precipitation (gray solid line).

the crude reaction products of 1/H₂O exhibits two strong W^V=O frequencies at 937 and 915 cm⁻¹, both of which shift to 889 and 869 cm⁻¹ when the reaction is carried out using H₂¹⁸O (Figure 2a). No such isotopic shifts were observed when independently synthesized 2 or 3 was treated with 10 equiv of H₂¹⁸O.¹⁴ This indicates that the O atoms in the reaction products originate from H₂O through hydrolysis of 1, during which the intermediate [W^{IV}(OH)(S₂C₂Ph₂)₂]⁻ must have been generated. The 937 cm⁻¹ peak from the crude reaction products is assigned to the stretching frequency of W^V=O in 3, consistent with the literature value.¹³ The presence of the additional peak at 915 cm⁻¹ is presumably due to the W^V=O moiety hydrogen-bonded to free phenol that is released from 1. Mass spectrometry further confirms the presence of free phenol in the reaction mixture. When 3 was isolated by precipitation with diethyl ether, only the 937 cm⁻¹ band was observed in the IR spectrum as expected. However, when the isolated 3 is redissolved in acetonitrile, followed by the addition of phenol, the 915 cm⁻¹ peak reappears (Figure 2b).¹⁵ The appearance of the 915 cm⁻¹ band is not observed when phenolate (PhO⁻) is added to a solution of 3, which supports the assignment of the 915 cm⁻¹ peak for the hydrogen-bonded W^V=O moiety. This cycle can be repeated multiple times without causing decomposition of 3.

To gain insight into the unexpected oxidation of 2 to 3 during hydrolysis, we studied the reactivity of independently synthesized 2 with a proton source. When 1 equiv of HBF₄ was added to an acetonitrile solution of 2 at room temperature, the absorption bands at 350, 449, and 527 nm from 2 decayed with a concomitant formation of 3 (λ_{max} = 720 nm) in the UV-vis spectrum.¹⁶ In addition, the H₂ evolution from the reaction was qualitatively detected from the headspace gas of the reaction flask with a commercial H₂ dosimeter.¹⁶

Because the formation of [W^{IV}(OH)(S₂C₂Ph₂)₂]⁻ was implied as an intermediate during our hydrolysis reaction, we studied the desired CO₂ reactivity of 1 in the presence of H₂O. An acetonitrile solution of 1 containing 10 equiv of H₂O was exposed to 1 atmospheric pressure of CO₂ at room temperature for 12 h.¹⁶ To our surprise, 3 was again identified as the final reaction product from the 1/H₂O/CO₂ reaction, with no indication of generating either the reduced CO₂ products (e.g., formate, CO, oxalate, etc.) or a hydrated product (HCO₃⁻).¹⁷ However, when we carry out the same reaction using 10 equiv of H₂¹⁸O, we observe that only ~32% of 3 contains the W=O¹⁸ moiety (889 and 869 cm⁻¹; Figure 3), suggesting that

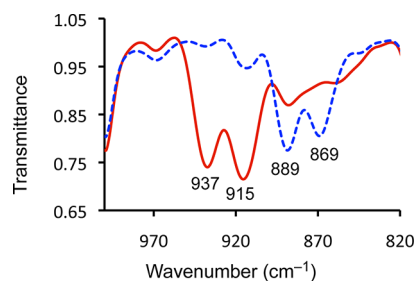
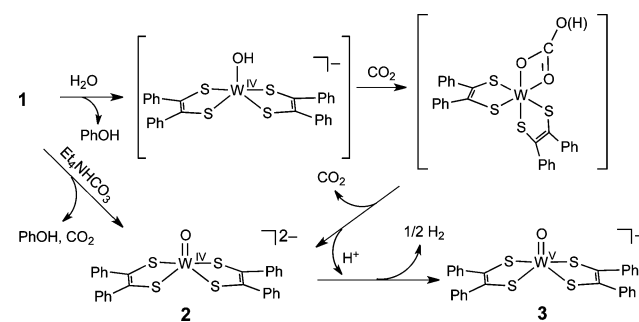


Figure 3. IR spectra (Nujol) of the crude reaction products of 1/H₂¹⁸O (10 equiv)/CO₂ (red solid line) and those of 1/H₂ (10 equiv) (blue dotted line).

H₂O is no longer the major source of oxygen in 3. Because CO₂ is the only other possible O-atom donor in the reaction mixture, the reaction was further evaluated by using C¹⁸O₂. When the reaction was carried out using ¹⁸O-enriched CO₂ (85% C¹⁸O₂) and H₂O, ~50% of W=O¹⁸ complexes were observed in the reaction products, confirming that the O atom in CO₂ incorporates into 3.¹⁶

Complex 1 does not react with CO₂ in dry solvent under the same experimental conditions, suggesting that the formation of the {W^{IV}OH} moiety is crucial to initiating reactivity with CO₂. This behavior along with the absence of any carbon-containing reaction products derived from CO₂ lead us to conclude that the reaction of 1/CO₂/H₂O does not exhibit the anticipated FDH activity. Instead, [W^{IV}(OH)(S₂C₂Ph₂)₂]⁻ reacts with CO₂ to form a presumable bicarbonato or carbonato intermediate, which immediately undergoes decarboxylation to generate [W^{IV}(O)(S₂C₂Ph₂)₂]⁻ (2) and CO₂ (Scheme 2). The formation of (bi)carbonato species from CO₂ with a metal hydroxide is common for many transition-metal complexes,¹⁸ and examples of tungsten(IV) carbonato complexes exist.¹⁹ In our reaction, however, the (bi)carbonato species does not appear to be stable probably because of the oxophilic character

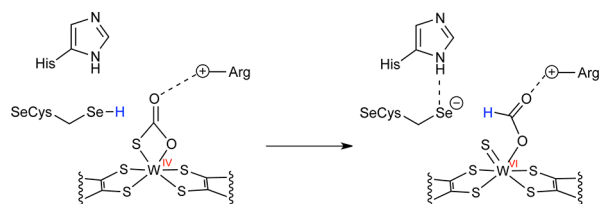
Scheme 2



of tungsten(IV) in a bis(dithiolene) ligand environment. In fact, with the only exception of FDHs, all other known bis(pyranopterin)-bound tungsten/molybdenum enzymes catalyze the O-atom-abstraction chemistry.⁶ In order to evaluate the prospect of the proposed (bi)carbonato intermediate during the reaction (Scheme 2), **1** was reacted with 1 equiv of Et₄NHCO₃. Upon the addition of bicarbonate to **1**, the oxo compound **2** formed immediately, as monitored by UV–vis spectroscopy.¹⁶ The result supports a notion that the O atom of CO₂ is inserted into **2** through a (bi)carbonate-bound tungsten intermediate.

The FDHs utilize a bis(dithiolene)-bound M^{IV} (M = Mo or W) ion to reduce CO₂ to formate. The use of higher-valent metal ions with noninnocent ligands by the enzyme is a strategy very different from that of most synthetic systems in which the metal ions in much lower valences, 0, 1+, and 2+, are utilized to activate CO₂.²⁰ Our current study shows that the presence of a nucleophilic ligand such as OH[−] is crucial to initiating CO₂ reactivity with a bis(dithiolene)tungsten(IV) species to likely form a tungsten (bi)carbonate intermediate. Indeed, a recent calculation study²¹ on the mechanism of Mo-FDH suggests that a Mo(IV) thiocarbonato intermediate forms during the oxidation cycle of formate to CO₂. With respect to the reverse reaction by W-FDH, one can expect the conversion of W(IV) thiocarbonate species to W(VI) formate (Scheme 3), similar to

Scheme 3



the typical O-atom-abstraction chemistry known for this class of enzyme.⁶ In our current synthetic model system, however, we were not able to imitate the reduction step. This may be due to the lack of a proton delivery channel near the metal active site, i.e., selenocysteine and histidine, that is strictly conserved in the FDH proteins.

In summary, we have studied the CO₂ reactivity of a structural analogue of W-FDH. A bis(dithiolene)tungsten complex **1** itself does not react with CO₂ at ambient temperature. However, an in situ generated hydrolysis product, [W^{IV}(OH)(S₂C₂Ph₂)₂][−], reacts with CO₂ and displays a carbonic anhydrase like activity. A tungsten (bi)carbonate species is presumed to form during the reaction. Future studies will focus on the factors critical to inducing an O-atom abstraction from a putative tungsten (bi)carbonate intermediate over the oxide (O^{2−}) abstraction chemistry observed in this study.

■ ASSOCIATED CONTENT

Supporting Information

Experimental details and UV–vis and IR spectra. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: Eunsuk_Kim@brown.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are grateful for support provided by the ACS-PRF (50840-DNI3) and Brown University.

■ REFERENCES

- (1) Crowley, T. J. *Science* **2000**, 289, 270–277.
- (2) Sakakura, T.; Choi, J. C.; Yasuda, H. *Chem. Rev.* **2007**, 107, 2365–2387.
- (3) (a) Benson, E. E.; Kubiak, C. P.; Sathrum, A. J.; Smieja, J. M. *Chem. Soc. Rev.* **2009**, 38, 89–99. (b) Rakowski DuBois, M.; DuBois, D. L. *Acc. Chem. Res.* **2009**, 42, 1974–1982.
- (4) Jessop, P. G.; Joo, F. *Coord. Chem. Rev.* **2004**, 248, 2425–2442.
- (5) Darensbourg, D. J. *Inorg. Chem.* **2010**, 49, 10765–10780.
- (6) (a) Hille, R. *Chem. Rev.* **1996**, 96, 2757–2816. (b) Moura, J. J.; Brondino, C. D.; Trincao, J.; Romao, M. J. *J. Biol. Inorg. Chem.* **2004**, 9, 791–799. (c) Andreesen, J. R.; Makdessi, K. *Ann. N.Y. Acad. Sci.* **2008**, 1125, 215–229.
- (7) (a) de Bok, F. A.; Hagedoorn, P. L.; Silva, P. J.; Hagen, W. R.; Schiltz, E.; Fritsche, K.; Stams, A. J. *Eur. J. Biochem.* **2003**, 270, 2476–2485. (b) Axley, M. J.; Grahame, D. A. *J. Biol. Chem.* **1991**, 266, 13731–13736. (c) Yamamoto, I.; Saiki, T.; Liu, S. M.; Ljungdahl, L. G. *J. Biol. Chem.* **1983**, 258, 1826–1832.
- (8) Reda, T.; Plugge, C. M.; Abram, N. J.; Hirst, J. *Proc. Natl. Acad. Sci. U.S.A.* **2008**, 105, 10654–10658.
- (9) (a) Boyington, J. C.; Gladyshev, V. N.; Khangulov, S. V.; Stadtman, T. C.; Sun, P. D. *Science* **1997**, 275, 1305–1308. (b) Jormakka, M.; Tornroth, S.; Byrne, B.; Iwata, S. *Science* **2002**, 295, 1863–1868. (c) Raaijmakers, H.; Macieira, S.; Dias, J. M.; Teixeira, S.; Bursakov, S.; Huber, R.; Moura, J. J.; Moura, I.; Romao, M. J. *Structure* **2002**, 10, 1261–1272. (d) Raaijmakers, H. C.; Romao, M. J. *J. Biol. Inorg. Chem.* **2006**, 11, 849–854.
- (10) (a) Groysman, S.; Holm, R. H. *Inorg. Chem.* **2007**, 46, 4090–4102. (b) Sarkar, S.; Das, S. K. *Proc.—Indian Acad. Sci., Chem. Sci.* **1992**, 104, 533–534.
- (11) (a) Enemark, J. H.; Cooney, J. J.; Wang, J. J.; Holm, R. H. *Chem. Rev.* **2004**, 104, 1175–1200. (b) Groysman, S.; Holm, R. H. *Biochemistry* **2009**, 48, 2310–2320.
- (12) (a) Lim, B. S.; Holm, R. H. *J. Am. Chem. Soc.* **2001**, 123, 1920–1930. (b) Sung, K. M.; Holm, R. H. *J. Am. Chem. Soc.* **2001**, 123, 1931–1943.
- (13) Goddard, C. A.; Holm, R. H. *Inorg. Chem.* **1999**, 38, 5389–5398.
- (14) Syntheses of **2** and **3** are known.¹³
- (15) The complete conversion of the 937 to 915 cm^{−1} peak requires at least 3 equiv of phenol.¹⁶ Upon substitution of phenol with *p*-nitrophenol, the 915 cm^{−1} peak further shifts to 910 cm^{−1}.¹⁶
- (16) See the Supporting Information.
- (17) The ¹³C NMR and IR spectra of the reaction mixtures of **1**/H₂O/¹³CO₂ did not display any signals for the CO₂-redrived products. The chemical detections for CO using Fe^{II}(TPP) and Cp*RuCl(PCy₃) were also negative.
- (18) Palmer, D. A.; Vaneldik, R. *Chem. Rev.* **1983**, 83, 651–731.
- (19) (a) Ito, T.; Sugimoto, S.; Ohki, T.; Nakano, T.; Osakada, K. *J. Organomet. Chem.* **1992**, 428, 69–83. (b) Alvarez, R.; Carmona, E.; Galindo, A.; Gutierrez, E.; Marin, J. M.; Monge, A.; Poveda, M. L.; Ruiz, C.; Savariault, J. M. *Organometallics* **1989**, 8, 2430–2439. (c) Green, M. L. H.; Parkin, G.; Ohare, D.; Wong, L. L.; Derome, A. E. *J. Organomet. Chem.* **1986**, 317, 61–68.
- (20) Gibson, D. H. *Chem. Rev.* **1996**, 96, 2063–2095.
- (21) Mota, C. S.; Rivas, M. G.; Brondino, C. D.; Moura, I.; Moura, J. J.; Gonzalez, P. J.; Cerqueira, N. M. *J. Biol. Inorg. Chem.* **2011**, 16, 1255–1268.