Communication

A (Ni-SIr)_I model for [NiFe]hydrogenase

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Dedicated to Professor Georg Süss-Fink on the occasion of his 65th birthday.

ABSTRACT

We report the synthesis and characterization of a μ -hydroxo NiRu complex as a model for the active site of (Ni-SIr)_I of [NiFe]hydrogenase. This is the first example of the (Ni-SIr)_I model with a bridging hydroxo ligand between dimetal centers and an available coordination site on Ni center *cis* to the bridging hydroxo ligand. We have determined the structure of the (Ni-SIr)_I model complex by X-ray analysis and reported reversible switching between the catalytically inactive (Ni-SIr)_I and a catalytically active (Ni-SIr)_{II}.

Keywords: dihydrogen, hydrogenase, model

Introduction

[NiFe]hydrogenase ([NiFe]H₂ase) catalyzes reversible activation of H₂ into 2H⁺ and 2e⁻ *via* heterolytic cleavage of H₂ [1]. The active site of [NiFe]H₂ase provides two possible H₂-coordination sites, X and Y as shown in Fig. 1 [1g]. Which of these sites is responsible for binding to H₂, however, remains a matter of controversy [1].

Fig. 1. Possible coordination sites, X (blue-shaded area) and Y (red-shaded area), of active site of [NiFe]H₂ase (M = Fe, X = H₂O, OH⁻, or vacant coordination site and Y = vacant coordination site as shown in Fig. 2) and our models (M = Ru, X = H₂O or OH⁻ and Y = NO₃⁻).

Based on our previous model studies, we have proposed that the X position is the key site for H₂ activation [2,3]. The principle evidence for binding to the Y site comes from a crystal structure of [NiFe]H₂ase which bears a CO ligand at the Y position [4]. Since CO is known to deactivate [NiFe]H₂ase, it is thought that the coordinated CO ligand must therefore indicate the H₂ binding site.

The principle problem with this latter interpretation, however, is that (Ni-SIr)_I (EPR-silent ready state I) bears a vacant Y site but is catalytically inactive toward H₂ (Fig. 2) [1,5]. When the X site is made available by protonation of the OH⁻ ligand to a labile H₂O ligand {(Ni-SIr)_{II} (EPR-silent ready state II)}, H₂ activation is enabled [1,6]. The catalytically active (Ni-SIr)_{II} is an unobservable intermediate with two available coordination sites (H₂O and Y). The (Ni-SIr)_{II} releases H₂O to afford Ni-SIa (EPR-silent active

state). The Ni-SIa is reactive toward H₂, which has two available coordination sites (X and Y).

Fig. 2. Schematic representation of Ni-SIr (EPR-silent ready state), Ni-SIa (EPR-silent active state), and Ni-R (EPR-silent reduced state) of [NiFe]H₂ase. X (blue-shaded) and Y (red-shaded) = vacant coordination

sites. (Ni-SIr)_I is unreactive toward H₂, which has one available coordination site (Y). (Ni-SIr)_{II} is unobservable, which has two available coordination sites (H₂O and Y). Ni-SIa is reactive toward H₂, which has two available coordination sites (X and Y).

In view of this controversy, we felt it important to construct a structurally accurate model of (Ni-SIr)_I and investigate its properties. Here, we report a NiRu complex as the first example of a (Ni-SIr)_I model complex, [Ni^{II}L(NO₃)(μ-OH)Ru^{II}(η⁶-C₆Me₆)] (**1**, L = *N,N'*-dimethyl-3,7-diazanone-1,9-dithiolato), with a bridging OH⁻ ligand between dimetal centers and an available coordination site on Ni center *cis* to the OH⁻ ligand [7,8], and demonstrate which X or Y coordination sites is necessary for H₂ activation.

Results and discussion

μ-Hydroxo Ni^{II}Ru^{II} complex **1** as a model for (Ni-SIr)_I was produced from deprotonation of an aqua Ni^{II}Ru^{II} complex, [Ni^{II}LRu^{II}(H₂O)(η⁶-C₆Me₆)](NO₃)₂ [**2**](NO₃)₂ as a model for (Ni-SIr)_{II} [2b], in H₂O. The deprotonation process was followed by means of a titration experiment to establish the p*K*_a value of the H₂O ligand. Complex **2** was dissolved in H₂O and titrated with 100 mM NaOH/H₂O under an N₂ atmosphere (Fig. 3). This titration shows that the p*K*_a value is 8.5 ± 0.1 and the change is reversible [3b,9]. Although the p*K*_a value of (Ni-SIr)_I has been reported as 7.8 ± 0.1, it has not been conclusively established whether a bridging cysteine or OH⁻ is protonated at this pH [10].

Fig. 3. pH titration of **2** (5.0 mM, 1.0 mL) with 100 mM NaOH/H₂O in H₂O under an N₂ atmosphere.

The structure of **1** was characterized by X-ray analysis (Fig. 4) as well as electrospray ionization-mass spectrometry (ESI-MS) and X-ray photoelectron (XP) and EPR spectroscopy (Figs. S1–S3).

The framework of **1** is based around a NiS₂Ru butterfly core bridged by the OH⁻ ligand (Fig. 4). The Ni atom adopts distorted octahedral coordination that is drastically changed by deprotonation of the H₂O ligand of **2**. One of the *N*-donor of N₂S₂ ligand, previously occupying the equatorial plane, moved to an axial position. Notably, a NO₃⁻ ion was coordinated to the Ni center, this is important because the NO₃⁻ ion is so labile it can be regarded as a vacant coordination site.

The parameters around the Ni and Ru core are somewhat similar to those for Ni-B (ready state, see abbreviations in the supporting information), which is the one-electron oxidized state of (Ni-SIr)_I [11]. The Ni^{II}...Ru^{II} distance is 2.9428(16) Å, which is shorter than that for **2** {3.1611(6) Å} [2b] and longer than the

Ni^{III}...Fe^{II} distances of 2.69–2.81 Å for Ni-B [11a,b]. The Ni^{II}–S–Ru^{II} angles {Ni1–S1–Ru1 = 77.30(10)°, Ni1–S2–Ru1 = 75.54(8)°} are smaller than those for **2** {87.20(5)°, 86.81(4)°} [2b]. The Ru^{II}–OH bond distance {Ru1–O1 = 2.284(8) Å} is slightly longer than the Ru^{II}–OH₂ bond distance for **2** {2.154(3) Å} [2b].

Fig. 4. An ORTEP drawing of **1** with ellipsoids at 50% probability. The hydrogen atoms of the ligand L (*N,N'*-dimethyl-3,7-diazanone-1,9-dithiolato) and C₆Me₆ are omitted for clarity. Selected interatomic distances (l/Å) and angles (θ/°): Ni1...Ru1 = 2.9428(16), Ru1–S1 = 2.374(3), Ru1–S2 = 2.382(2), Ru1–O1 = 2.284(8), Ni1–O1 = 2.148(8), Ni1–O2 = 2.104(9), Ni1–S1 = 2.337(3), Ni1–S2 = 2.422(3), Ni1–N1 = 2.119(9), Ni1–N2 = 2.143(11), Ni1–O1–Ru1 = 83.1(3), Ni1–S1–Ru1 = 77.30(10), Ni1–S2–Ru1 = 75.54(8).

A positive-ion ESI mass spectrum of **1** exhibits a prominent signal at *m/z* 559.2 (relative intensity = 100% in the range of *m/z* 200–2000) (Fig. S1). The signal has a characteristic isotopic distribution that matches well with the calculated isotopic distribution for [**1** – NO₃]⁺, which shifts to *m/z* 560.2 by the use of [Ni^{II}L(NO₃)(μ-OD)Ru^{II}(η⁶-C₆Me₆)] (D-labeled **1**).

The oxidation and spin states of the metal centers were investigated by XP and EPR spectroscopy. The XP spectra of **1** show that the binding energies of Ni 2*p*_{3/2} and Ru 3*d*_{5/2} are 853.5 and 280.5 eV, respectively, comparable to those for the aqua Ni^{II}Ru^{II} complex **2**, and indicates that the oxidation states can be assigned as Ni^{II} and Ru^{II} (Fig. S2). The EPR spectrum of **1** in frozen H₂O at pH 10.5 at –150 °C indicates paramagnetism in **1**, which might be derived from a triplet (*S* = 1) Ni^{II} center (Fig. S3).

Having elucidated the structural properties of the model complex, we moved to investigate its catalytic properties, paying attention to the roles of the X and Y sites. We examined two cases: (i) X is occupied by a strongly coordinating OH⁻ ligand and Y is occupied by a labile NO₃⁻ ligand and (ii) X is occupied by a labile H₂O ligand and Y is occupied by a rigid *N*-donor of the supporting ligand L. The structural conformations of cases (i) and (ii) correspond to those of **1** and **2** (Fig. 5), respectively. We found that the μ-hydroxo Ni^{II}Ru^{II} complex **1** was unreactive toward H₂, while the aqua Ni^{II}Ru^{II} complex **2** was reactive toward H₂ to form a μ-hydrido Ni^{II}Ru^{II} complex [Ni^{II}L(H₂O)(μ-H)Ru^{II}(η⁶-C₆Me₆)](NO₃) [**3**](NO₃) as a model for Ni-R (EPR-silent reduced state) (Fig. 5) [2b,3]. These results demonstrate that a labile ligand is necessary at the X position for H₂ activation but a labile ligand at the Y position does not enable activation. These findings add weight to the proposition that X is the active site for H₂ activation on [NiFe]H₂ase.

Fig. 5. Reactivity of **1** and **2** toward H₂ [2b,3]. †: **A** was not observed by kinetic study of H₂ activation [9]. Blue- and red-shaded areas correspond to X and Y positions of [NiFe]H₂ase as shown in Fig. 1, respectively. **A** is not observed, which has one available coordination site (X). The (Ni-SIr)_{II} model is reactive toward H₂, which has one available coordination site (H₂O). The (Ni-SIr)_I model is unreactive toward H₂, which has one available coordination site (NO₃⁻).

Conclusions

In conclusion, we have synthesized an OH⁻ bridged Ni^{II}Ru^{II} complex with a highly labile NO₃⁻ ligand, corresponding to a vacant Y position of (Ni-SIr)_I. We have revealed that this model is unreactive toward H₂, as is (Ni-SIr)_I of [NiFe]H₂ase, but becomes reactive when the non-labile OH⁻ at the X site is protonated to a labile H₂O ligand. Our results suggest that H₂ activation by [NiFe]H₂ase requires a vacant bridging X site and not a vacant Y site.

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