Dihydrogen activation by sulfido-bridged dinuclear Ru/Ge complexes: insight into the [NiFe] hydrogenase unready state[†]

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A S/SH bridged hetero-dinuclear Ru/Ge complex cation reacted with H₂ to afford the μ -S/ μ -H complex. The reaction was considerably slower compared to that of the μ -S/ μ -OH complex. Thus, the μ -S/ μ -SH and μ -S/ μ -OH complexes might provide models for the unready and ready states, respectively, of [NiFe] hydrogenase.

[NiFe] hydrogenase, which catalyzes a reversible conversion of dihydrogen into protons and electrons, has been recognized as the key enzyme in hydrogen metabolism in nature.¹ In the inactive form, the active site contains a hetero-dinuclear Ni/Fe complex bridged by two cysteine thiolates and an O-donor ligand. The O-donor ligand disappears upon activation by H₂, and the nickel approaches the iron, either to form a direct Ni–Fe bond or a µ-hydride bridged metal pair. Recently, Ogo and co-workers have reported the conversion of a dinuclear Ni/Ru aqua complex to the Ni(µ-H)Ru complex upon treatment with H₂, modeling the activation of [NiFe] hydrogenase.² In the course of our [NiFe] hydrogenase model studies,³⁻⁵ we synthesized hetero-dinuclear Ru/Ge complexes having S/O bridges, $Dmp(Dep)Ge(\mu-S)(\mu-O)Ru(PR_3)$ (1a; R = Ph, 1b; R = Et), and S/OH bridges, $[Dmp(Dep)Ge(\mu-S)(\mu-OH)Ru(PR_3)](BAr^F_4)$ (2a; R = Ph, 2b; R = Et,⁴ and investigated the reaction of **1a** and **2a** with H₂ (Dmp = 2.6-dimesitylphenyl, Dep = 2.6-diethylphenyl, $Ar^{F} = 3.5 - (CF_3)_2 C_6 H_3$.⁵ Although this metal pair is not identical with that of the hydrogenase, we have obtained several important results that may provide insight into the reaction mechanism of [NiFe] hydrogenase; (i) both 1a and 2a activated H₂ heterolytically, but the reaction of 2a proceeded more readily under milder conditions, (ii) the reaction of 2a with H₂ afforded the μ -S/ μ -H complex, which could model the [NiFe] hydrogenase activation process, (iii) the reaction of H₂ and 2a was reversible, and that (iv) 2a cannot merely activate H₂ heterolytically, but further convert H₂ into two protons and electrons. In order to expand the scope of this study, we have examined the reactions of H₂ and Ru/Ge complexes having S/S bridges (3a,b) and S/SH bridges (4a,b) (Chart 1). This study may imply that the unready Ni-B' and Ni-'S' states of [NiFe] hydrogenase⁶ are oxidized forms having an S-donor

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ligand as a third bridge, states, as has been proposed as a possible structure for the inactive state.^{1b,7}

The μ -S/ μ -S complexes Dmp(Dep)Ge(μ -S)₂Ru(PR₃) (**3a**; R = Ph, **3b**; R = Et) were synthesized from Dmp(Dep)Ge(SH)₂, [RuCl₂(η^{6} -*p*-arene)], and the corresponding phosphines according to Scheme 1.⁴ Protonation of **3a** and **3b** upon treatment with H(OEt₂)₂BAr^F₄ gave the μ -S/ μ -SH complex cations [Dmp(Dep)Ge(μ -S)(μ -SH)Ru(PR₃)](BAr^F₄) (**4a**; R = Ph, **4b**; R = Et), respectively.⁴

As reported previously, the reaction of **3a** and H₂ resulted in the recovery of the starting materials even under 10 atm H₂ at 90 °C in benzene.^{5a} Unexpectedly, complex cation **4a** was also intact under 1–5 atm H₂ at 80–90 °C, while the μ -S/ μ -OH analogue **2a** smoothly reacted with 1 atm H₂ at rt within 7 h. On the other hand, the PEt₃ analogue **4b** was found to react with 1 atm H₂ gradually in refluxing benzene, and was converted to the μ -S/ μ -H complex **5b** in 83% yield in 3 days with concomitant formation of H₂S (Scheme 2).⁸ The enhanced reactivity of the PEt₃ adduct was also observed for the μ -S/ μ -OH complexes, so that the reaction of **2b** and 1 atm H₂ was completed within 5 min.⁹ The reaction of **4b** is considerably



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slower compared to that of **2b**. Thus sluggishness indicates the reverse reaction for **4b** is faster than for **2b**. Indeed, addition of 1.1 equiv. H_2S to **5b** gave **4b** quantitatively within 5 min at rt with concomitant formation of H_2 . Complex **5a**, synthesized by the reaction of **2a** and H_2 , was also converted to **4a** immediately upon a similar treatment with H_2S . Thus, in order to promote the forward H_2 activation reaction, the removal of H_2S is indispensable, and thus solvent-reflux conditions are required.

Interestingly, the μ -S/ μ -SH and μ -S/ μ -OH complexes were interconverted in the presence of H₂O or H₂S. When complex **4a** was treated with 20 equiv. H₂O in THF-d₁₀ at 293 K, complexes **4a** and **2a** were observed in a 98 : 2 ratio according to the ¹H NMR spectra, and thus the equilibrium constant K_{eq} for Scheme 3 can be estimated to be ~10⁻⁴. It is of note that interconversion was not observed between the μ -S/ μ -S complexes **3a,b** and the μ -S/ μ -O complexes **1a,b**, where protonation of μ -S or μ -O would be essential for these conversions.

Our detection of the $4a \leftrightarrow 2a$ equilibrium prompted us to re-examine the reaction of 4a and H_2 in the presence of H_2O . When a THF solution of 4a was refluxed under 1 atm H_2 with 10 equiv. H_2O for 1 day, the reaction proceeded as expected, and complex 5a was obtained in 68% yield. In this reaction, complex 2a was generated from 4a and H_2O *in situ*, which then reacted with H_2 .

It can be demonstrated that the μ -hydride of **5b** shows protonic behavior as observed for **5a**. Thus treatment of **5b** with tetraethylammonium hydroxide resulted in quantitative formation of Dmp(Dep)Ge(μ -S)Ru(PEt₃) (**6b**) (Scheme 4). Conversely, the protonation of **6b** by H(OEt₂)₂BAr^F₄ in toluene gave **5b**, quantitatively.

The molecular structures of **5b** and **6b**, determined by X-ray analysis, are shown in Fig. 1 and 2, respectively.‡ The structural properties and the metric parameters of **5b** and **6b** are quite similar to those of the previously reported PPh₃ analogues of **5a** and **6a**, respectively, irrespective of the different phosphines.^{5b} While their Ru–S and Ge–S bond distances are typical,^{4,10} the Ru(1)–H(1) distance of **5b** is elongated compared to terminal Ru–H bonds,^{5a} and is similar to those of μ -hydride complexes.¹¹ The Ge(1)–H(1) distance is even longer than the Ru(1)–H(1) bond, but is shorter than that of (depe)₂(CO)Mo(η^2 -H–GePh₂H) [2.08(6) Å],¹² indicating a weak bonding interaction between Ge and the hydride on Ru. The Ru(1)–Ge(1) distance of 2.5659(9) Å is also longer than those of the Ru–Ge σ -bonds of (C₆H₆)Ru(CO)(GeCl₃)₂ [2.408(2) Å] and *cis*-Ru(CO)₄(GeCl₃)₂ [2.481(5) Å].¹³ Upon deprotonation, the Ru–Ge distance of **6b** is





Fig. 1 ORTEP drawings of **5b**. Selected bond distances (Å) and angles (deg): Ru(1)-S(1) 2.4565(15), Ru(1)-P(1) 2.3176(12), Ge(1)-S(1) 2.1486(12), Ru(1)-Ge(1) 2.5659(9), Ru(1)-H(1) 1.67(5), Ge(1)-H(1) 1.97(6), Ru(1)-S(1)-Ge(1) 67.34(4), Ge(1)-H(1)-Ru(1) 90(2).



Fig. 2 ORTEP drawings of **6b**. Selected bond distances (Å) and angles (deg): Ru(1)-S(1) 2.4757(14), Ru(1)-P(1) 2.2952(15), Ge(1)-S(1) 2.1871(14), Ru(1)-Ge(1) 2.4157(6), Ru(1)-S(1)-Ge(1) 62.04(3), Ge(1)-Ru(1)-S(1) 53.10(3), Ru(1)-Ge(1)-S(1) 64.85(3).

shortened by 0.15 Å compared to **5b** becoming a common Ru–Ge σ -bond distance, and accordingly the bond angle around S(1) becomes smaller by 5.3° from that of **5b**.

In this study, we report that the μ -S/ μ -SH complex was converted to the μ -S/ μ -H complex upon treatment with H₂, as was observed for the μ -S/ μ -OH complex. This reaction was considerably slower compared to that of the μ -S/ μ -OH complex. However, in the presence of H₂O, the μ -S/ μ -SH complex equilibrates with the μ -S/ μ -OH complex, and then it appeared to react with H₂ more smoothly to form the μ -S/ μ -H complex, although it is still slower than the case of the μ -S/ μ -OH complex (Scheme 5). The different reactivity of the μ -S/ μ -OH and μ -S/ μ -SH complexes toward H₂ reminds us



of the ready states (Ni-B or Ni-SI_r) and the unready states (Ni-B', Ni-'S', Ni-A, or Ni-SU) of [NiFe] hydrogenase,⁶ in which the ready Ni-B state is easily activated within a few minutes under a hydrogen atmosphere, whereas the unready Ni-A state requires longer activation times of up to hours.¹ While the protein crystallographic analysis suggested that the Ni-A state contains μ -OOH as the third bridge, the Ni-B' or Ni-'S' states having a μ -SH⁶ may be important states showing a reactivity like the unready Ni-A state.^{1b,7} Considering that sulfate-reducing bacteria produce a large amount of H₂S in their metabolism, the active site may be converted by H₂S into the Ni-B' or Ni-'S' states having a μ -SH, similar to our results reported here, which show the μ -S/ μ -OH complexes **2a,b** and the μ -S/ μ -SH complexes **4a,b**.

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Notes and references

‡ Crystal data for **5b**: $C_{72}H_{66}BF_{24}GePRuS$; triclinic; $P\overline{1}$ (No. 2); a =12.057(3), b = 16.670(4), c = 20.047(3) Å; $\alpha = 68.826(12)$, $\beta = 70.639(11)$, $\gamma = 79.729(13)^\circ$, V = 3536.9(14) Å³; Z = 2; F(000) = 1650; $\mu = 7.955$ cm⁻¹; $\rho_{calc} = 1.534$ g cm⁻³; 29.042 reflections $(2\theta < 54.9^{\circ})$; 15512 unique ($R_{int} = 0.029$); $R_1 = 0.055$ $(I > 2\sigma(I))$, w $R_2 = 0.1597$ (all data), GoF = 1.085. For **6b**: $C_{40}H_{53}$ GePRuS; monoclinic; $P2_1/c$ (No. 14); a = 16.292(2), b =9.2011(14), c = 24.751(4) Å; $\beta = 91.198(2)^{\circ}$, V = 3709.4(9) Å³; Z =4; F(000) = 1600; $\mu = 13.43 \text{ cm}^{-1}$; $\rho_{\text{calc}} = 1.380 \text{ g cm}^{-3}$; 29413 reflections ($2\theta < 55.0^{\circ}$), 8474 independent ($R_{int} = 0.077$); $R_1 = 0.057$ $(I > 2\sigma(I))$, w $R_2 = 0.158$ (all data), GoF = 0.954. Single crystals were mounted on a loop using oil (CryoLoop, Paratone-N, HR2-643, Hampton Laboratories, Inc.). Diffraction data were collected at -100 °C under a cold nitrogen stream on a Rigaku AFC8 equipped with a Saturn 70 CCD area detector, equipped with a graphite monochromatized MoK α source ($\lambda = 0.71070$ Å). Data were collected for 720 images with an oscillation range of 0.5°, and were integrated and corrected for absorption using the Rigaku/MSC CrystalClear program package. The structures were solved by a direct method (SIR-97), and were refined by full-matrix least squares on F^2 using SHELXL-97¹⁴ in the Rigaku/MSC CrystalStructure program package. Anisotropic refinement was applied to all non-hydrogen atoms. The hydrogen atom H(1) of 5b was assigned from the Fourier map and refined isotropically. The other hydrogen atoms were put at the calculated positions.

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