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Enzyme Models

Synthesis and Reactivity of Mononuclear Iron Models of [Fe]-Hydrogenase that Contain an Acylmethylpyridinol Ligand

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Abstract: [Fe]-hydrogenase has a single iron-containing active site that features an acylmethylpyridinol ligand. This unique ligand environment had yet to be reproduced in synthetic models; however the synthesis and reactivity of a new class of small molecule mimics of [Fe]-hydrogenase in which a mono-iron center is ligated by an acylmethylpyridinol ligand has now been achieved. Key to the preparation of these model compounds is the successful C–O cleavage of an alkyl ether moiety to form the desired pyridinol ligand. Reaction of solvated complex $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_2(CH_3CN)_2]^+(BF_4)^-$ with thiols or thiophenols in the presence of NEt_3 yielded 5-coordinate iron thiolate complexes. Further derivation produced complexes $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_2(SCH_2CH_2OH)]$ and $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_2(CH_3COO)]$, which can be regarded as models of FeGP cofactors of [Fe]-hydrogenase extracted by 2-mercaptoethanol and acetic acid, respectively. When the derivative complexes were treated with $HBF_4{\cdot}Et_2O$, the solvated complex was regenerated by protonation of the thiolate ligands. The reactivity of several models with CO, isocyanide, cyanide, and H_2 was also investigated.

Introduction

Hydrogenases are enzymes that catalyze the production or consumption of H_2. Based on the metal atoms in the active site, hydrogenases are classified in three types, namely [FeFe]-, [NiFe]-, and [Fe]-hydrogenases.[1–5] Unlike the other two types of hydrogenases, [Fe]-hydrogenase, which is also called H_2-forming methylene-tetrahydromethanopterin dehydrogenase (Hmd), does not contain a redox-active site and a $[Fe_4S_4]$ cluster, and can only activate H_2 in the presence of methenyltetrahydromethanopterin (methenyl-H_4MPT^+).[1,2]

In the active site of [Fe]-hydrogenase, a Fe^{II} center is coordinated with two *cis*-CO, a cysteine sulfur atom (Cys 176), and a bidentate acylmethylpyridinol ligand. The sixth position, which is regarded as the H_2-binding position, is probably occupied by a labile water molecule (Figure 1).[6–8]

The iron guanylylpyridinol (FeGP) cofactor of [Fe]-hydrogenase can be extracted by denaturation of the enzyme in the presence of 2-mercaptoethanol or acetic acid.[9–13] If the FeGP cofactor is mixed with the apoenzyme, an active [Fe]-hydrogenase would be reconstituted. The structures of the protein-free cofactors were proposed accordingly as in Figure 2, and they were confirmed by mass spectrometry.[12,13]

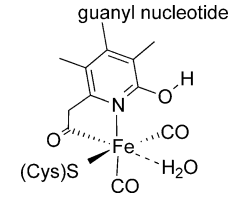

Figure 1. The active site of [Fe]-hydrogenase.

Since the elucidation of the structure of [Fe]-hydrogenase, a number of model complexes have been reported.[14–35] Recently we synthesized some five-coordinate mononuclear iron complexes with a 2-acylmethyl-6-methoxy-pyridyl ligand, which was a mimic to the acylmethylpyridinol ligand in the enzyme. However, the hydroxy group of the pyridinol ligand in the enzyme might carry a crucial function for H_2 activation.[36,37] The faithful reproduction of such secondary ligand environment in a model complex is therefore a desirable goal in biomimetic chemistry. However, only a dinuclear iron complex with an acylmethylpyridinol ligand has been reported; such a complex does not mimic the mononu-

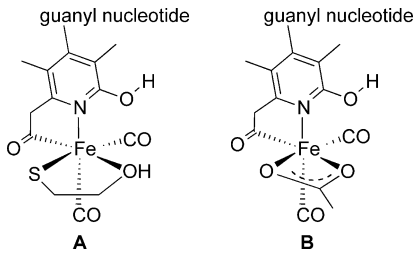

Figure 2. The proposed structure of the FeGP cofactor extracted with 2-mercaptoethanol (**A**) and extracted with acetic acid (**B**).

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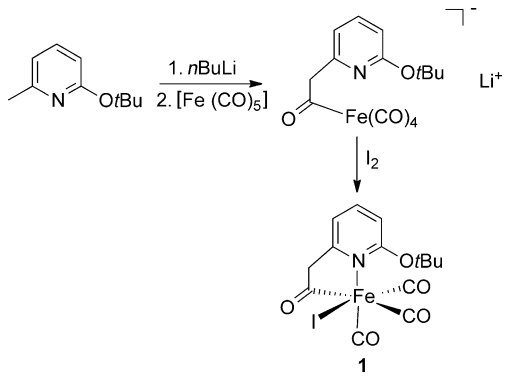
clear nature of [Fe]-hydrogenase and is not suitable for further reactivity study.[35] Herein, we report the synthesis and reactivity of the first mononuclear model complexes of [Fe]-hydrogenase that contain the previously elusive acylmethylpyridinol ligand.

Results and Discussion

Iron complexes with a 2-acylmethyl-6-*tert*-butoxy-pyridyl ligand

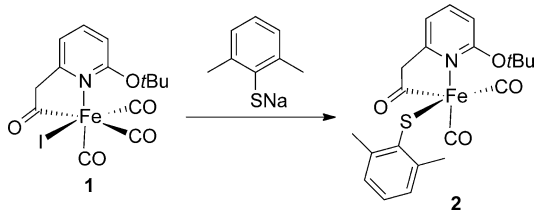
To install a pyridinol ligand, we first decided to incorporate a pyridyl alkoxyl group from which the alkyl ether moiety might be cleaved at a later stage. To this end, [(2-CH_2CO-6-tBuOC_5H_3N)Fe$(CO)_3$I] (**1**) was prepared by dropwise addition of lithiated 2-*tert*-butoxy-6-methylpyridine to [Fe$(CO)_5$], followed by treatment of I_2 (Scheme 1). The ^{1}H NMR spectrum of **1** in



Scheme 1. Synthesis of complex **1**.

$CDCl_3$ exhibits three signals at $\delta = 7.73$, 7.11, and 6.99 ppm for the pyridyl rings, two doublets at $\delta = 5.42$ and 4.29 ppm for the diastereotopic methylene hydrogen atoms, and one singlet at $\delta = 1.70$ ppm for the *tert*-butoxy group.[38] The results indicate a single isomer in the solution. The IR spectrum of **1** shows three ν(CO) absorptions in CH_2Cl_2; in the solid state, **1** displays five absorptions,[38] which might be caused by interactions between molecules in the solid lattice. Similar phenomenon has been found in complex [Fe$(S_2C_2H_4)(CO)_2(PMe_3)_2$].[39]

Reaction of **1** with NaS(2,6-$Me_2C_6H_3$) gave a five-coordinate complex [2-CH_2CO-6-tBuOC_5H_3N)Fe$(CO)_2${S-(2,6-Me_2-C_6H_3)}] (**2**) (Scheme 2), which was characterized by X-ray crystallography (Figure 3). The structure of **2** is similar to that of complex [2-



Scheme 2. Synthesis of complex **2**.

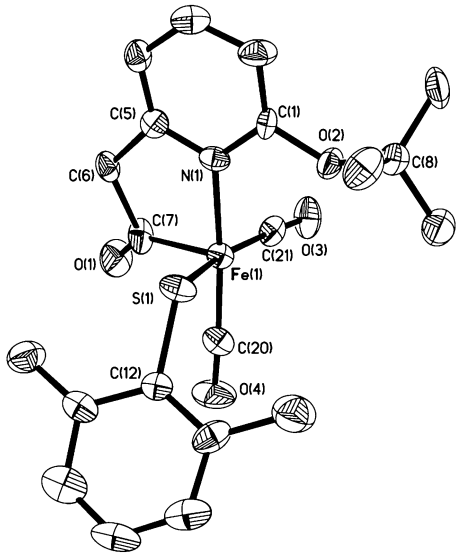


Figure 3. Solid-state structure of **2**.[41] Ellipsoids are set at 30% probability; hydrogen atoms are omitted for clarity. Selected bond lengths [Å] and angles [°]: Fe1–N1 1.953(9), Fe1–S1 2.219(4), Fe1–C7 1.827(13), Fe1–C20 1.773(13), Fe1–C21 1.761(15), C20–O4 1.137(14), C21–O3 1.156(16), C7–O1 1.220(15); C21-Fe1-C20 90.8(6), C20-Fe1-N1 175.5(5), C7-Fe1-N1 86.3(5), C21-Fe1-S1 163.5(4).

CH_2CO-6-MeOC_5H_3N)Fe$(CO)_2${S-(2,6-Me_2-C_6H_3)}].[28] The C21-Fe1-S1 angle is 163.5(4)°, and the C20-Fe1-N1 angle is 175.5(5)°. Thus, the coordination geometry of the Fe ion is best described as distorted square-pyramidal. The bidentate acylmethylpyridyl ligand coordinates with Fe by the pyridyl nitrogen and acyl carbon donors. The two CO and the acyl ligands are all mutually *cis*. The sulfur ligand is *cis* to the acyl and pyridyl ligands, and the position *trans* to the acyl ligand is unoccupied. The IR spectrum of **2** shows two equally intense ν(CO) absorptions at 2013 and 1948 cm^{-1} in the solid state, which is consistent with the existence of two *cis*-CO ligands (Table 1).

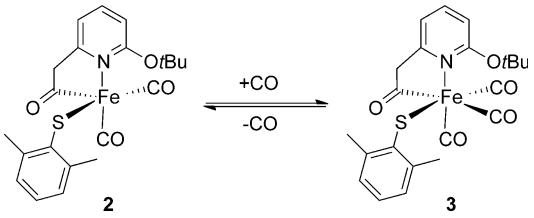
The ^{1}H NMR spectrum of **2** in CD_3CN exhibits four signals at $\delta = 7.97$, 7.24–7.20, 7.07, and 6.96 ppm for the pyridyl and phenyl rings, two doublets at $\delta = 4.44$ and 4.04 ppm for the diastereotopic methylene hydrogen atoms, one singlet at $\delta =$ 2.30 ppm for the methyl group, and one singlet at $\delta =$ 1.58 ppm for the *tert*-butoxy group.[38] No reactivity with H_2 was detected by monitoring with ^{1}H NMR spectroscopy. However, CO could occupy the open position in complex **2**, giving a tricarbonyl complex [2-CH_2CO-6-tBuOC_5H_3N)Fe$(CO)_3${S-(2,6-Me_2-C_6H_3)}] (**3**) (Scheme 2). Compound **3** was characterized by ^{1}H NMR, ^{13}C NMR, and IR spectroscopy. The ^{1}H NMR spectrum exhibits two doublets at $\delta = 5.18$ and 4.05 ppm for the diastereotopic methylene hydrogen atoms, and the ^{13}C NMR spectrum shows one signal at $\delta = 260.9$ ppm for the acyl carbon and three signals at $\delta = 210.3$, 208.3, and 205.8 ppm for terminal carbonyl carbon atoms. The IR spectrum of **3** shows three intense ν(CO) absorption bands (Table 1). The third CO ligand in **3** is labile. When a solution of **3** was purged with N_2, complex **2** was regenerated (Scheme 3).

Attempts to remove the *t*Bu group in **2** with Me_3SiI were unsuccessful, and some unidentified species were formed. Com-

Table 1. Selected IR spectroscopy data.

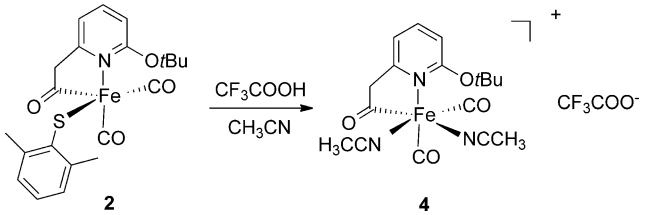
Complex	ν(CO) [cm^{-1}]	Complex	ν(CO) [cm^{-1}]
2[a]	2013, 1948	**9a**[b]	2074, 2020, 1989
3[b]	2078, 2027, 2001	**10**[b]	2017, 1956
4[a]	2047, 1988	**11**[b]	2008, 1947
6[a]	2057, 1999	**12**[b]	2006, 1937
6[b]	2065, 2010	**13**[a]	2042, 1972
7[b]	2011, 1944	**13** in CH_2Cl_2	2051, 1986
7a[b]	2063, 2011, 1983	Hmd[c]	1996, 1928
8[a]	2014, 1953	Hmd[d]	2011, 1944
8[b]	2013, 1953	CO-inhibited Hmd[d]	2074, 2020, 1981
9[a]	2024, 1960	Mercaptoethnol-FeGP cofactor[e]	2004, 1934
9[b]	2020, 1956	Mercaptoethnol-FeGP cofactor[d]	2031, 1972
9 in CH_2Cl_2	2022, 1958	Acetic acid-FeGP cofactor[e]	2029, 1957

[a] Spectrum of a solid sample on KBr disk. [b] Spectrum of a sample dissolved in CH_3CN. [c] Spectrum of a solid sample; data from Ref. [7]. [d] Spectrum of a sample dissolved in water; data from Ref. [40]. [e] Spectrum of a solid sample; data from Ref. [13].



Scheme 3. Reversible reaction of **2** with CO.

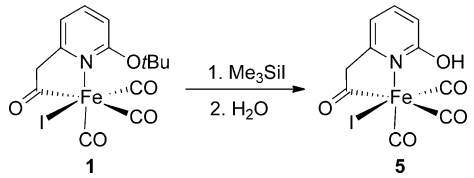
pound **2** was also treated with CF_3COOH/CH_3CN, but only an ionic product $[(2\text{-}CH_2CO\text{-}6\text{-}t\text{BuOC}_5H_3N)Fe(CO)_2(CH_3CN)_2]^+(CF_3COO)^-$ (**4**) was generated in a quantitative yield in CH_3CN (Scheme 4). Complex **4** is not stable in other solvents such as CH_2Cl_2 and THF. The IR spectrum of **4** in the solid state shows two intense ν(CO) absorption bands at 2047 and 1988 cm^{-1} (Table 1), which are comparable with the known ionic complex $[(2\text{-}CH_2CO\text{-}6\text{-}MeOC_5H_3N)Fe(CO)_2(CH_3CN)_2]^+(BF_4)^-$,[30] and much higher than that of **2** and [Fe]-hydrogenase. The structure of **4** was further confirmed by a ^{1}H NMR spectrum and elemental analysis.



Scheme 4. Reaction of **2** with CF_3COOH.

Iron complexes with an acylmethylpyridinol ligand

The difficulty in the deprotection of the *t*Bu group in complex **2** might be due to the instability of the targeted complex, so we next attempted to deprotect the *t*Bu group in the more stable complex **1**. This proved successful. Reaction of **1** with an excess of Me_3SiI (3.5 equiv) followed by addition of H_2O yielded $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_3I]$ (**5**) (Scheme 5). In CH_3CN, the IR



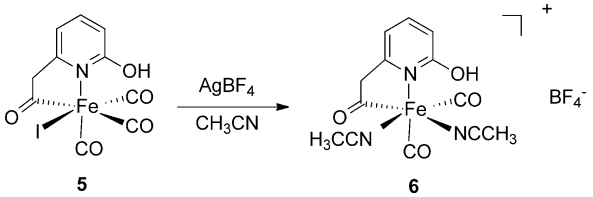
Scheme 5. Synthesis of complex **5**.

spectrum of **5** exhibits three ν(CO) absorptions, which is consistent with its structure.[38] In the solid state, its IR spectrum shows four ν(CO) absorptions, which is probably due to the same reason proposed for complex **1** (see above).

The ^{1}H NMR spectrum of **5** in CD_3CN exhibits one singlet at $\delta = 10.17$ ppm for the hydroxy group, three signals at $\delta = 7.81$, 7.08, and 6.87 ppm for the pyridyl ring, and two doublets at $\delta = 4.46$ and 4.08 ppm for the CH_2 group. No *t*Bu group is shown, which is in agreement with the cleavage of the *t*Bu group.[38]

After the synthesis of **5**, we set out to install a thiolate ligand on the Fe center. Reactions of **5** with PhSNa, 2,6-$Me_2C_6H_3SNa$, 4-NO_2-C_6H_4SNa, and C_6F_5SNa did not yield isolable complexes.

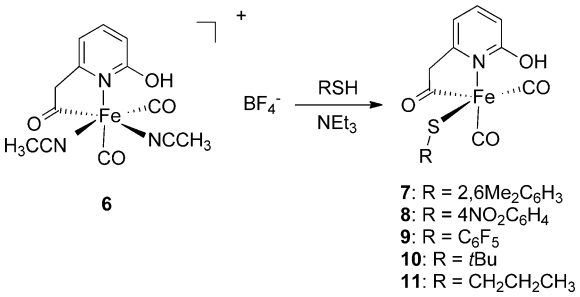
An alternative route was developed to synthesize the desired iron thiolate model complexes. Complex **5** was treated with $AgBF_4$ in CH_3CN, giving $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_2(CH_3CN)_2]^+(BF_4)^-$ (**6**) (Scheme 6). The two intense ν(CO) absorp-



Scheme 6. Synthesis of complex **6**.

tion bands in its IR spectra (2057 and 1999 cm^{-1} in the solid state; 2065 and 2010 cm^{-1} in CH_3CN) are comparable to that of **4**, and confirm its ionic nature (Table 1). Compound **6** was treated with a series of thiols and thiophenols in the presence of NEt_3 at $-30\,^\circ$C to give the targeted thiolate complexes (Scheme 7).

Complexes $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_2\{S\text{-}(2,6\text{-}Me_2\text{-}C_6H_3)\}]$ (**7**) and $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_2\{S\text{-}(4\text{-}NO_2\text{-}C_6H_4)\}]$ (**8**) are highly unstable, and they decomposed completely in 10 min in the dark at $-30\,^\circ$C. The instability made it impossible to obtain



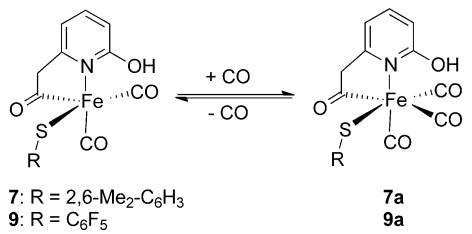
Scheme 7. Synthesis of thiolate iron complexes.

satisfying ^{1}H NMR spectra of these complexes. Their IR spectra in CH_3CN and in the solid state show two intense ν(CO) absorption bands, indicating their existence as monomers both in solution and in the solid state (Table 1).

The complex [(2-CH_2CO-6-HOC_5H_3N)Fe(CO)$_2${S-(C_6F_5)}] (**9**) is much more stable. It has a lifetime of about 1 h at room temperature in the dark. Ambient light accelerates its decomposition (lifetime of about 30 min). From the reaction of **6** with C_6F_5SNa, the ^{1}H NMR spectrum of **9** could be obtained, although the resolution was not high owing to the existence of some paramagnetic impurities. The two characteristic doublets of the diastereotopic methylene hydrogen atoms at $\delta = 4.66$ and 3.91 ppm were evident. The reaction of **9** with H_2 (1 atmosphere) was monitored by ^{1}H NMR spectroscopy; however, no reaction was found. The result is consistent with the essential role of methenyl-H_4MPT^+ for H_2 activation by [Fe]-hydrogenase. It also suggests that replacing the methoxyl group in **2** and its analogues by a hydroxy group as in **9** does not result in a dramatic change in the reactivity towards H_2.

Like **7** and **8**, complexes [(2-CH_2CO-6-HOC_5H_3N)Fe(CO)$_2$(S-*t*Bu)] (**10**) and [(2-CH_2CO-6-HOC_5H_3N)Fe(CO)$_2$($SCH_2CH_2CH_3$)] (**11**) could only be identified by IR spectroscopy owing to their high instability. From the two intense absorptions (2017 and 1956 cm^{-1} for **10**; 2008 and 1947 cm^{-1} for **11**) (Table 1), both **10** and **11** exist as monomers in CH_3CN. The lifetime of **10** and **11** is only about 3 min at −30 °C.

Compounds **7** and **9** were further selected to study the reactivity with CO. Unexpectedly, upon exposure to CO, the conversion into tricarbonyl products [(2-CH_2CO-6-HOC_5H_3N)Fe(CO)$_3${S-(2,6-Me_2-C_6H_3)}] (**7a**) and [(2-CH_2CO-6-HOC_5H_3N)Fe(CO)$_3${S-(C_6F_5)}] (**9a**) was not complete (33% for **7** and 38% for **9**) (Scheme 8).[38] This behavior is different from that of **2** and [Fe]-hydrogenase, which could be completely converted into the tris(carbonyl) complexes.[40] It is worth noting that both the ν(CO) absorption bands of **7a** and **9a** are close to those of CO-inhibited [Fe]-hydrogenase (Table 1).

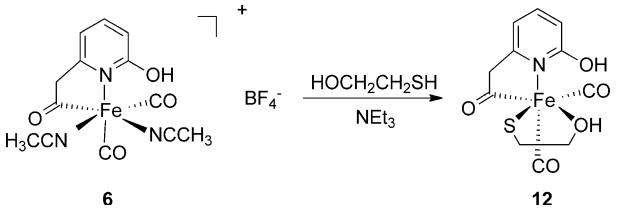


Scheme 8. Reversible reactions of **7** and **9** with CO.

One of the decomposition products of **7** was identified as the tricarbonyl complex **7a** (Supporting Information, Figure S12).[38] This decomposition pathway was earlier found for complex [(2-CH_2CO-6-$MeOC_5H_3N$)Fe(CO)$_2${S-(4-NO_2-C_6H_4)}]$_2$.[33] After 2 min at −30 °C, two new peaks at 2063 and 1983 cm^{-1} appeared, which were attributed to **7a**. After about 10 min, the decomposition of **7** was complete.[38]

The decomposition reaction of **9** was similar to that of **7**, and **9a** was also formed (Supporting Information, Figure S19).[38]

To model the isocyanide- and cyanide-inhibited [Fe]-hydrogenase,[37,40] the reactions of **9** with *p*-toluenesulfonylmethylisocyanide and [NEt_4]CN were explored. Treatment of **9** with *p*-toluenesulfonylmethylisocyanide gave an unstable dicarbonyl product.[38] Treatment of **9** with [NEt_4]CN gave unidentified products. Installation of a 2-mercaptoethanol ligand onto the Fe center was also attempted to model the protein-free FeGP cofactor extracted with 2-mercaptoethanol. When **6** was treated with 2-mercaptoethanol in the presence of NEt_3, [(2-CH_2CO-6-HOC_5H_3N)Fe(CO)$_2$(SCH_2CH_2OH)] (**12**) was produced (Scheme 9). The IR spectrum of **12** shows two absorptions at



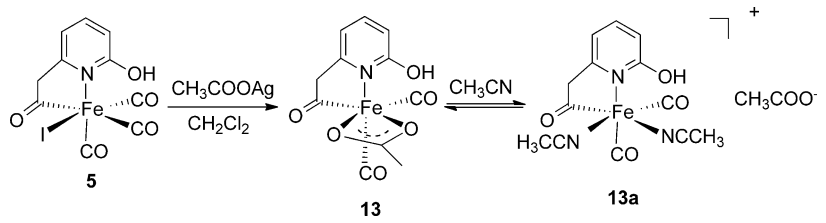
Scheme 9. Synthesis of complex **12**.

2006 and 1937 cm^{-1} in CH_3CN, within several cm^{-1} of those of 2-mercaptoethanol extracted FeGP cofactor in the solid state (Table 1). In contrast to the five-coordinate models **7** and **9**, compound **12** did not react with CO, which is similar to the FeGP cofactor extracted with 2-mercaptoethanol.[40] This suggests that **12** is a six-coordinate complex, with OH group of 2-mercaptoethanol coordinating to Fe.

Unlike the dinuclear complexes [(2-CH_2CO-6-$MeOC_5H_3N$)Fe(CO)$_2${S-(4-NO_2-C_6H_4)}]$_2$[33] and [(2-CH_2CO-6-$MeOC_5H_3N$)Fe(CO)$_2${SCH_2CH_2OH)}]$_2$,[31] **7**–**12** all exist as monomers (Table 1). The results demonstrate that the 6-hydroxy group in the pyridyl ring has certain influences over their structures and possibly activities.

To model the acetic acid extracted FeGP cofactor, acetate ligand was also installed by reacting **5** with CH_3COOAg in CH_2Cl_2 (Scheme 10).

The ^{1}H NMR spectrum of the product in $CDCl_3$ exhibits three signals at $\delta = 7.67$, 6.86, and 6.68 ppm for the pyridinol ring, two doublets at $\delta = 4.01$ and 3.92 ppm for the $-CH_2$ group, and one singlet at $\delta = 2.41$ ppm for the acetate group. The IR spectrum displays two intense ν(CO) absorptions both in the



Scheme 10. Reaction of **5** with CH_3COOAg.

solid state and in CH_2Cl_2 (Table 1).[38] The ESI-MS (negative mode) shows an intense peak at 305.9706. All the data are consistent with the formulation of the product as [(2-CH_2CO-6-HOC_5H_3N)$Fe(CO)_2(CH_3COO)$] (**13**) (calculated mass: 305.9701).

Interestingly, two species with a ratio of about 2:1 were detected when **13** was dissolved in CH_3CN, according to the four characteristic peaks in the 1H NMR spectrum at $\delta = 4.20$, 4.05, 3.85, and 3.82 ppm for the CH_2 groups in CD_3CN. The IR spectrum is also consistent with the ^{1}H NMR result, and shows four ν(CO) absorption bands.[38] We propose that a second species formed when **13** is dissolved in CH_3CN, and this species is $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_2(CH_3CN)_2]^+(CH_3COO)^-$ (**13a**) (Scheme 10).

Complex **13** could react with C_6F_5SH/NEt_3 to generate **9**. When CH_2Cl_2 was used as the solvent for this reaction, two intense ν(CO) absorptions at 2022 and 1958 cm^{-1} were observed in the IR spectrum of the product, nearly identical to those of **9** produced according to Scheme 7 (Table 1).[38] The reaction of **9** produced from **13** with CH_3CN (20 equiv) was monitored in CH_2Cl_2, but no reaction was found. This result indicates that **9** is five-coordinate and CH_3CN does not coordinate to Fe, as proposed in Scheme 7.

Similar to $[2\text{-}CH_2CO\text{-}6\text{-}MeOC_5H_3N)Fe(CO)_2\{S\text{-}(2,6\text{-}Me_2\text{-}C_6H_3)\}]$,[30] complexes **7**–**12** reacted with $HBF_4{\cdot}Et_2O/CH_3CN$ to form **6**. This reactivity again suggests that the Cys176 thiolate ligand in [Fe]-hydrogenase might serve as a proton acceptor after H_2 splitting.[30]

Conclusion

In summary, two mononuclear iron complexes with acylmethylpyridinol ligand (**5** and **6**) were synthesized and fully characterized by ^{1}H NMR and IR spectroscopy and elemental analysis. Starting from **6**, a series of iron thiolate complexes (**7**–**12**) were generated and identified by IR and/or ^{1}H NMR (**9**) spectroscopy. These complexes are the first mononuclear iron models of [Fe]-hydrogenase that contain an acylmethylpyridinol ligand. In contrast to the known complexes with a 2-acylmethyl-6-methoxy-pyridyl ligand,[31,33] **7**–**12** always exist as monomers and are not subject to dimerization. This is evidence that the 6-hydroxy group in the pyridyl ring can influence the structures and probably the activity of the model complexes. Compounds **7**–**12** reacted with HBF_4 to generate **6**, which is consistent with the Cys176 thiolate ligand in [Fe]-hydrogenase being a possible proton acceptor after H_2 splitting. An acetate ligand was installed in complex **13**, which serves as a model of the acetic acid extracted FeGP cofactor. The lack of reactivity of these new models towards H_2 echoes that of [Fe]-hydrogenase, and suggests that methenyl-H_4MPT^+ and the enzymatic environment are essential for H_2 activation.

Experimental Section

Synthesis of $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_3I]$ (5)

Me_3SiI (610.0 mg, 3.05 mmol) was added into a solution of **1** (400.0 mg, 0.871 mmol) in CH_2Cl_2 (10 mL) under stirring at room temperature. After 12 h, H_2O (20 mL) was added into the mixture. The water phase was washed with CH_2Cl_2 (3×20 mL) and ether (10 mL), respectively. The combined organic phase was washed with H_2O (20 mL). After drying the organic phase over Na_2SO_4 and evaporation of the solvent, the residue was extracted with ether (10 mL), and the filtrate was dried in vacuum. The residue was washed with hexane (40 mL) and CH_2Cl_2 (1 mL), respectively. The solid residue was then extracted with ether (10 mL) again, and the filtrate was dried in vacuum. The residue was washed with hexane (20 mL) and recrystallized from ether/hexane to afford **5** (110.0 mg, 0.273 mmol; yield: 31%) as a red solid.

^{1}H NMR (400.13 MHz, CD_3CN): 10.17 (s, 1H), 7.81 (t, $J = 8.0$ Hz, 1H), 7.08 (d, $J = 8.0$ Hz, 1H), 6.87 (d, $J = 8.0$ Hz, 1H), 4.46 (d, $J = 20.0$ Hz, 1H), 4.08 ppm (d, $J = 20.0$ Hz, 1H); IR (ν_{CO}, KBr):$\tilde{\nu} = 2102$ (s), 2048 (s), 2023 (s), 2014 cm^{-1} (s); IR (ν_{CO}, CH_3CN): $\tilde{\nu} = 2068$ (s), 2050 (s), 1996 cm^{-1} (s); elemental analysis calcd (%) for $C_{10}H_6FeNO_5I$: C 29.8, H 1.5, N 3.5; found: C 30.1, H 1.5, N 3.8.

Synthesis of $[(2\text{-}CH_2CO\text{-}6\text{-}HOC_5H_3N)Fe(CO)_2(CH_3CN)_2]^+(BF_4)^-$ (6)

$AgBF_4$ (48.1 mg, 0.248 mmol) was added into a solution of **5** (100.0 mg, 0.248 mmol) in CH_3CN (5 mL) under stirring. Gas (CO) was formed immediately. After 1 min, the mixture was filtered and the filtrate was dried in vacuum. The residue was washed with ether (10 mL) and dried in vacuum to afford **6** (101.0 mg, 0.242 mmol; 98%) as a light yellow oily solid.

^{1}H NMR (400.13 MHz, CD_3CN): 9.33 (s, 1H), 7.83 (t, $J = 8.0$ Hz, 1H), 7.10 (d, $J = 8.0$ Hz, 1H), 6.88 (d, $J = 8.0$ Hz, 1H), 4.66 (d, $J = 20.0$ Hz, 1H), 3.89 (d, $J = 20.0$ Hz, 1H), 1.96 ppm (s, 6H); IR (ν_{CO}, KBr): $\tilde{\nu} =$ 2057 (s), 1999 cm^{-1} (s); IR (ν_{CO}, CH_3CN): $\tilde{\nu} = 2065$ (s), 2010 cm^{-1} (s); elemental analysis calcd (%) for $C_{13}H_{12}BF_4FeN_3O_4$: C 37.5, H 2.9, N 10.1; found: C 37.7, H 3.0, N 9.9.

General procedure of the synthesis of thiolate complexes 7–12

Thiol or thiophenol (0.048–0.096 mmol, 1–2 equiv) was added into a solution of **6** (20.0 mg, 0.048 mmol) in CH_3CN (5 mL) under stirring. NEt_3 (0.048–0.096 mmol, 1–2 equiv) was added into the mixture at −30 °C. The IR spectrum was recorded immediately. If $HBF_4{\cdot}Et_2O$ (0.048–0.14 mmol, 1–3 equiv) was added quickly after the formation of the thiolate product, **6** was regenerated.

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[1] S. Shima, R. K. Thauer, *Chem. Rec.* **2007**, *7*, 37 – 46.
[2] S. Shima, R. K. Thauer, U. Ermler, *Met. Ions Life Sci.* **2009**, *6*, 219 – 240.
[3] F. Gloaguen, T. B. Rauchfuss, *Chem. Soc. Rev.* **2009**, *38*, 100 – 108.
[4] M. Y. Darensbourg, *Comments Inorg. Chem.* **2010**, *31*, 144 – 152.
[5] M. T. Stiebritz, M. Reiher, *Chem. Sci.* **2012**, *3*, 1739 – 1751.
[6] S. Shima, O. Pilak, S. Vogt, M. Schick, M. S. Stagni, W. Meyer-Klaucke, E. Warkentin, R. K. Thauer, U. Ermler, *Science* **2008**, *321*, 572 – 575.
[7] T. Hiromoto, K. Ataka, O. Pilak, S. Vogt, M. S. Stagni, W. Meyer-Klaucke, E. Warkentin, R. K. Thauer, S. Shima, U. Ermler, *FEBS Lett.* **2009**, *583*, 585 – 590.
[8] T. Hiromoto, E. Warkentin, J. Moll, U. Ermler, S. Shima, *Angew. Chem.* **2009**, *121*, 6579 – 6582; *Angew. Chem. Int. Ed.* **2009**, *48*, 6457 – 6460.
[9] E. J. Lyon, S. Shima, G. Buurman, S. Chowdhuri, A. Batschauer, K. Steinbach, R. K. Thauer, *Eur. J. Biochem.* **2004**, *271*, 195 – 204.
[10] S. Shima, E. J. Lyon, M. S. Sordel-Klippert, M. Kauss, J. Kahnt, R. K. Thauer, K. Steinbach, X. L. Xie, L. Verdier, C. Griesinger, *Angew. Chem.* **2004**, *116*, 2601 – 2605; *Angew. Chem. Int. Ed.* **2004**, *43*, 2547 – 2551.
[11] S. Shima, U. Ermler, *Eur. J. Inorg. Chem.* **2011**, 963 – 972.
[12] M. Schick, X. Xie, K. Ataka, J. Kahnt, U. Linne, S. Shima, *J. Am. Chem. Soc.* **2012**, *134*, 3271 – 3280.
[13] S. Shima, M. Schick, J. Kahnt, K. Ataka, K. Steinbach, U. Linne, *Dalton Trans.* **2012**, *41*, 767 – 771.
[14] C. Tard, C. J. Pickett, *Chem. Rev.* **2009**, *109*, 2245 – 2274.
[15] J. A. Wright, P. J. Turrell, C. J. Pickett, *Organometallics* **2010**, *29*, 6146 – 6156.
[16] M. J. Corr, J. A. Murphy, *Chem. Soc. Rev.* **2011**, *40*, 2279 – 2292.
[17] S. Dey, P. K. Das, A. Dey, *Coord. Chem. Rev.* **2013**, *257*, 42 – 63.
[18] K. M. Schultz, D. Chen, X. Hu, *Chem. Asian J.* **2013**, *8*, 1068 – 1075.
[19] A. M. Royer, T. B. Rauchfuss, D. L. Gray, *Organometallics* **2009**, *28*, 3618 – 3620.
[20] B. V. Obrist, D. Chen, A. Ahrens, V. Schunemann, R. Scopelliti, X. Hu, *Inorg. Chem.* **2009**, *48*, 3514 – 3516.
[21] B. Li, T. Liu, C. V. Popescu, A. Bilko, M. Y. Darensbourg, *Inorg. Chem.* **2009**, *48*, 11283 – 11289.
[22] T. B. Liu, B. Li, C. V. Popescu, A. Bilko, L. M. Perez, M. B. Hall, M. Y. Darensbourg, *Chem. Eur. J.* **2010**, *16*, 3083 – 3089.
[23] S. Tanino, Y. Ohki, K. Tatsumi, *Chem. Asian J.* **2010**, *5*, 1962 – 1964.
[24] P. J. Turrell, J. A. Wright, J. N. T. Peck, V. S. Oganesyan, C. J. Pickett, *Angew. Chem.* **2010**, *122*, 7670 – 7673; *Angew. Chem. Int. Ed.* **2010**, *49*, 7508 – 7511.
[25] A. M. Royer, M. Salomone-Stagni, T. B. Rauchfuss, W. Meyer-Klaucke, *J. Am. Chem. Soc.* **2010**, *132*, 16997 – 17003.
[26] D. Chen, R. Scopelliti, X. Hu, *J. Am. Chem. Soc.* **2010**, *132*, 928 – 929.
[27] D. Chen, R. Scopelliti, X. Hu, *Angew. Chem.* **2010**, *122*, 7674 – 7677; *Angew. Chem. Int. Ed.* **2010**, *49*, 7512 – 7515.
[28] D. Chen, R. Scopelliti, X. Hu, *Angew. Chem.* **2011**, *123*, 5789 – 5791; *Angew. Chem. Int. Ed.* **2011**, *50*, 5671 – 5673.
[29] D. Chen, A. Ahrens-Botzong, V. Schuemann, R. Scopelliti, X. Hu, *Inorg. Chem.* **2011**, *50*, 5249 – 5257.
[30] D. Chen, R. Scopelliti, X. Hu, *Angew. Chem.* **2012**, *124*, 1955 – 1957; *Angew. Chem. Int. Ed.* **2012**, *51*, 1919 – 1921.
[31] B. Hu, D. Chen, X. Hu, *Chem. Eur. J.* **2012**, *18*, 11528 – 11530.
[32] L.-C. Song, Z.-J. Xie, M.-M. Wang, G.-Y. Zhao, H.-B. Song, *Inorg. Chem.* **2012**, *51*, 7466 – 7468.
[33] B. Hu, D. Chen, X. Hu, *Chem. Eur. J.* **2013**, *19*, 6221 – 6224.
[34] P. J. Turrell, A. D. Hill, S. K. Ibrahim, J. A. Wright, C. J. Pickett, *Dalton Trans.* **2013**, *42*, 8140 – 8146.
[35] L.-C. Song, G.-Y. Zhao, Z.-J. Xie, J.-W. Zhang, *Organometallics* **2013**, *32*, 2509 – 2512.
[36] X. Yang, M. B. Hall, *J. Am. Chem. Soc.* **2009**, *131*, 10901 – 10908.
[37] H. Tamura, M. Salomone-Stagni, T. Fujishiro, E. Warkentin, W. Meyer-Klaucke, U. Ermler, S. Shima, *Angew. Chem.* **2013**, *125*, 9838 – 9841; *Angew. Chem. Int. Ed.* **2013**, *52*, 9656 – 9659.
[38] See the Supporting Information.
[39] Y. Guo, H. Wang, Y. Xiao, S. Vogt, R. K. Thauer, S. Shima, P. I. Volkers, T. B. Rauchfuss, V. Pelmenschikov, D. A. Case, E. E. Alp, W. Sturhahn, Y. Yoda, S. P. Cramer, *Inorg. Chem.* **2008**, *47*, 3969 – 3977.
[40] E. J. Lyon, S. Shima, R. Boecher, R. K. Thauer, F. W. Grevels, E. Bill, W. Roseboom, S. P. J. Albracht, *J. Am. Chem. Soc.* **2004**, *126*, 14239 – 14248.
[41] CCDC-963961 (**2**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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