

Hydrogen Evolution Catalyzed by Cobaloximes

JILLIAN L. DEMPSEY, BRUCE S. BRUNSCHWIG,*
JAY R. WINKLER,* AND HARRY B. GRAY*

Beckman Institute, California Institute of Technology, Pasadena, California 91125

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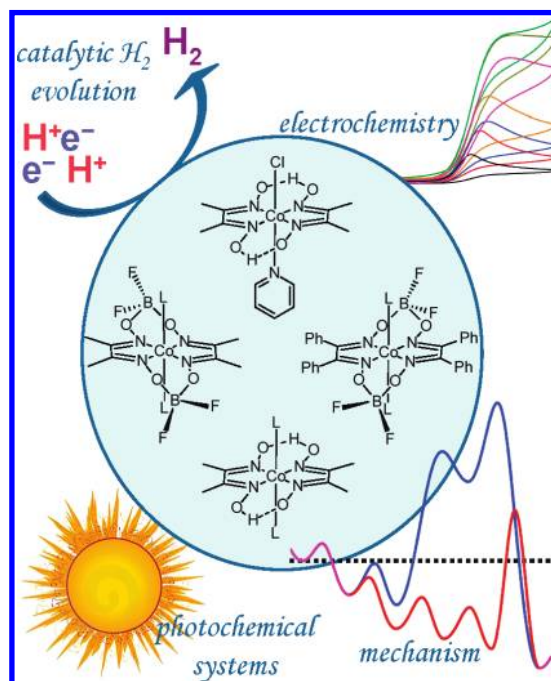
CON SPECTUS

Natural photosynthesis uses sunlight to drive the conversion of energy-poor molecules (H_2O , CO_2) to energy-rich ones (O_2 , $(\text{CH}_2\text{O})_n$). Scientists are working hard to develop efficient artificial photosynthetic systems toward the “Holy Grail” of solar-driven water splitting. High on the list of challenges is the discovery of molecules that efficiently catalyze the reduction of protons to H_2 . In this Account, we report on one promising class of molecules: cobalt complexes with diglyoxime ligands (cobaloximes).

Chemical, electrochemical, and photochemical methods all have been utilized to explore proton reduction catalysis by cobaloxime complexes. Reduction of a Co^{II} -diglyoxime generates a Co^{I} species that reacts with a proton source to produce a Co^{III} -hydride. Then, in a homolytic pathway, two Co^{III} -hydrides react in a bimolecular step to eliminate H_2 . Alternatively, in a heterolytic pathway, protonation of the Co^{III} -hydride produces H_2 and Co^{III} .

A thermodynamic analysis of H_2 evolution pathways sheds new light on the barriers and driving forces of the elementary reaction steps involved in proton reduction by Co^{I} -diglyoximes. In combination with experimental results, this analysis shows that the barriers to H_2 evolution along the heterolytic pathway are, in most cases, substantially greater than those of the homolytic route. In particular, a formidable barrier is associated with Co^{III} -diglyoxime formation along the heterolytic pathway.

Our investigations of cobaloxime-catalyzed H_2 evolution, coupled with the thermodynamic preference for a homolytic route, suggest that the rate-limiting step is associated with formation of the hydride. An efficient water splitting device may require the tethering of catalysts to an electrode surface in a fashion that does not inhibit association of Co^{III} -hydrides.



Introduction

In response to the current global energy crisis, scientists are going to great lengths to develop renewable resources capable of meeting projected energy demands.^{1,2} Solar energy conversion is an area of enormous promise; using sunlight to make “solar fuels” such as H_2 (from H_2O splitting, Figure 1) and CH_3OH (by reducing CO_2) is one of the Holy Grails of 21st century chemistry.^{3,4} Splitting water is highly

desirable, because 4.92 eV is stored when two H_2O molecules are split into two H_2 and O_2 , but running the reaction is challenging; it involves two separate multielectron redox processes, a four-electron oxidation and a two-electron reduction.⁵ Because sequential electron or hole transfers directly to H_2O produce extremely high-energy intermediates, an energy-efficient process requires catalysts that avoid formation of these species.^{6,7} Coordination to metals in some cases can stabilize these energetic inter-

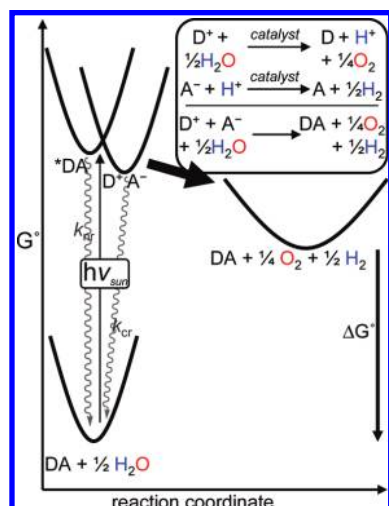


FIGURE 1. Solar energy conversion is initiated by photoexcitation ($h\nu_{\text{sun}}$) of DA to *DA , which undergoes excited-state electron transfer to yield a charge-separated state (D^+A^-). D^+ and A^- drive water oxidation and proton reduction via catalysts.

mediates, thereby lowering the barriers for hydrogen evolution.⁸ One of the best catalysts is platinum, which operates at the thermodynamic potential for H^+/H_2 conversion (0 V vs SHE, pH 0).⁹ Notable among other highly active catalysts are [FeFe], [NiFe], and [Fe] hydrogenases,^{10–21} which have inspired a great deal of work on synthetic metallobiomolecules aimed at mimicking proton reduction and H_2 oxidation functionalities.^{22–31}

Although the ultimate objective is to use water as a feedstock,^{32–38} many potential H_2 evolving catalysts are tested for catalytic activity in organic solvents, because they often are not soluble or stable in aqueous environments. The electrocatalytic behavior of proton sources in organic solvents is markedly different from that in aqueous environments. In nonaqueous solvents, the standard potential for hydrogen evolution, $E_{\text{HA}/\text{H}_2}^\circ$, is directly related to acid strength, and can be described by

$$E_{\text{HA}/\text{H}_2}^\circ = E_{\text{HA}/\text{H}_2}^\circ - (2.303RT/F)pK_{\text{a,HA}}$$

where $E_{\text{H}^+/\text{H}_2}^\circ$ is the solvated proton/dihydrogen couple standard potential in the given solvent and $K_{\text{a,HA}}$ is the acid dissociation constant for the proton source.³⁹ The standard potentials for hydrogen evolution from a variety of commonly used acids is given in Table 1. The overpotential for proton reduction, is the difference between the potential of catalytic activity and $E_{\text{HA}/\text{H}_2}^\circ$; we do not expect to achieve catalysis at potentials more positive than $E_{\text{HA}/\text{H}_2}^\circ$.

Metal complexes that catalyze the reduction of protons to H_2 in organic solvents^{40–43} include $(\text{CpMo}\mu\text{-S})_2\text{S}_2\text{CH}_2$,⁴⁴ which operates at -0.26 V vs SCE in CH_3CN with (*p*-cyanoanilinium)-

TABLE 1. pK_{a} Values and Standard Potentials for Reduction of Acids in Acetonitrile

acid	pK_{a}^a	$E_{\text{HA}/\text{H}_2}^\circ$ (V vs SCE) ^c
$\text{HBF}_4 \cdot \text{Et}_2\text{O}$	0.1 ^b	0.23
trifluoromethanesulfonic acid	2.6	0.09
<i>p</i> -cyanoanilinium	7.6	-0.21
$\text{TsOH} \cdot \text{H}_2\text{O}$	8.0 ^b	-0.23
$\text{HCl} \cdot \text{Et}_2\text{O}$	8.9 ^b	-0.29
CF_3COOH	12.7 ^b	-0.51
$[\text{Et}_3\text{NH}]^+$	18.7	-0.86
$[\text{Et}_3\text{NH}]^+$	9.2 (DMF)	-0.84
acetic acid	13.2 (DMF)	-1.08

^a Reference 39 unless noted otherwise. ^b Reference 81. ^c $E_{\text{HA}/\text{H}_2}^\circ = E_{\text{H}^+/\text{H}_2}^\circ - 0.059pK_{\text{a}}(\text{HA})$. A potential of 0.24 V vs SCE was chosen as the thermodynamic potential for $E_{\text{H}^+/\text{H}_2}^\circ$ in acetonitrile (ref 50).

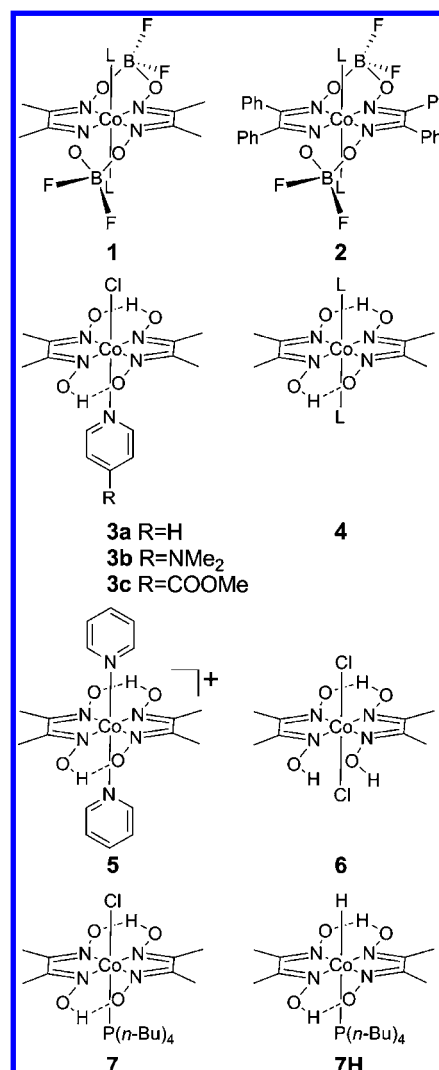


FIGURE 2. Cobaloxime complexes. L is typically H_2O or CH_3CN .

BF_4 as a proton source, and $[\text{Ni}(\text{P}^{\text{Ph}}_2\text{N}^{\text{Ph}}_2)_2(\text{CH}_3\text{CN})]^{2+}$, which is active at -0.46 V vs SCE with trifluoromethanesulfonic acid.⁴⁵ Cobalt complexes with diglyoxime ligands (Figure 2) also have been shown to catalyze hydrogen evolution at low overpotentials; the proton reduction chemistry of these catalysts will be highlighted in this Account.

TABLE 2. Electrochemical Potentials (V vs SCE in Acetonitrile)

complex	$E^{\circ}(\text{Co}^{\text{III/II}})$	$E^{\circ}(\text{Co}^{\text{II/I}})$	ref
1	$\sim -0.2^a$	-0.55	48
2	$\sim -0.3^a$	-0.28	48
3a	-0.68	-1.13	59 ^b
3b	-0.84	-1.13	59 ^b
3c	-0.78	-1.09	59 ^b
5	-0.39	-1.1	59 ^b
6	-0.49	-0.8	59 ^b
7	-0.92	-0.99	59 ^b

^a Irreversible couple. ^b NHE vs SCE = -0.25 V in acetonitrile (ref 82).

Electrochemical Systems

Connolly and Espenson first reported that $\text{Co}(\text{dmgBF}_2)_2(\text{L})_2$ (**1**, dmgBF_2 = difluoroboryl-dimethylglyoxime) catalyzes the reduction of HCl_{aq} using $\text{Cr}^{2+}_{\text{aq}}$ as a stoichiometric electron donor.⁴⁶ Dissociation of an intermediate chloro-bridged complex, $[(\text{H}_2\text{O})_5\text{Cr}-\text{Cl}-\text{Co}(\text{dmgBF}_2)_2]^+$, which was formed during inner-sphere electron transfer from Cr^{II} to Co^{II} , produces $[\text{Co}(\text{dmgBF}_2)_2\text{L}]^-$ (**1**⁻). In the presence of acid, it is likely that the Co^{I} anion is rapidly protonated to form a hydride, $[\text{HCo}(\text{dmgBF}_2)_2\text{L}]$, which evolves H_2 .

Complex **1** and a related species, $\text{Co}(\text{dpgBF}_2)_2(\text{L})_2$ (**2**, dpg = difluoroboryl-diphenylglyoxime),⁴⁷ were later shown electrochemically to catalyze H_2 evolution in CH_3CN .^{48,49} The reversible, one-electron reduction of **1** occurs at -0.55 V vs SCE in CH_3CN (Table 2). Upon addition of a sufficiently strong acid, catalytic currents were observed near the $\text{Co}^{\text{III/II}}$ couple. Increasing acid concentration produced an increase in peak current, a slight positive shift in peak position, and loss of the return oxidation wave, with the current eventually approaching a plateau. Since Co^{II} is regenerated during H_2 production, there is no return oxidation wave. Bulk electrolysis experiments confirmed near quantitative Faradaic yields of H_2 . A range of proton sources was examined: catalysis was observed with CF_3COOH , $\text{HCl}\cdot\text{Et}_2\text{O}$, *p*-toluenesulfonic acid monohydrate ($\text{TsOH}\cdot\text{H}_2\text{O}$),⁵⁰ (*p*-cyanoanilinium) BF_4 , and $\text{HBF}_4\cdot\text{Et}_2\text{O}$. Although $\text{HBF}_4\cdot\text{Et}_2\text{O}$ was shown to effect H_2 evolution with substantially increased rates, competitive degradation pathways of the catalyst greatly limited reaction efficiencies.

Substitution of methyl groups by electron-withdrawing phenyl substituents to form **2** shifts the $\text{Co}^{\text{III/II}}$ reduction potential 270 mV positive to -0.28 V vs SCE. Electrocatalysis was observed with $\text{HCl}\cdot\text{Et}_2\text{O}$, (*p*-cyanoanilinium) BF_4 , $\text{TsOH}\cdot\text{H}_2\text{O}$, and $\text{HBF}_4\cdot\text{Et}_2\text{O}$, but *not* CF_3COOH , with currents reaching a plateau at high acid concentrations.

Studies of cobalt difluoroboryl-diglyoximes as well as related compounds with [14]-tetraene- N_4 ligands led to a correlation between catalyst activity (H_2 evolution) and $\text{Co}^{\text{III/II}}$ potentials.⁵⁰ Complexes with more negative reduction poten-

TABLE 3. Electrochemical Potentials (V vs SCE in DMF)^a

complex	$E^{\circ}(\text{Co}^{\text{III/II}})$	$E^{\circ}(\text{Co}^{\text{II/I}})$	ref
3a	-0.67	-1.06	52
3b	-0.74	-1.09	52
4		-1.06	52
5	-0.32	-1.06	52
7	-0.70	-0.89	52

^a Converted to SCE from $\text{Ag}/\text{AgCl}/3 \text{ mol L}^{-1} \text{ NaCl}$, Fc^+/Fc vs $\text{Ag}/\text{AgCl} = 0.55 \text{ V}$ in DMF (ref 52), Fc^+/Fc vs SCE = 0.47 V in DMF (ref 83).

tials were able to catalyze proton reduction with weaker acids at higher rates than those with more positive reduction potentials. Metal hydride pK_a values increase as the Co^{III} reduction potentials become more negative; thus the $\text{Co}^{\text{II/I}}$ potentials are related to Co^{I} basicities.⁵¹

The overpotentials for proton reduction catalyzed by cobaloxime complexes can be estimated from the difference between $E^{\circ}_{\text{H}^+/\text{H}_2}$ and the potential where catalytic behavior is observed, which occurs just negative of $E^{\circ}(\text{Co}^{\text{III/II}})$. Catalysts that reduce protons near the thermodynamic potential also should oxidize H_2 in the presence of a conjugate base. Indeed, slow oxidation of H_2 by **1** in the presence of $[\text{NBU}_4]\text{CF}_3\text{CO}_2$ has been observed. The H_2 evolution overpotential was calculated to be 90 mV based on the reaction equilibrium constant.⁵⁰

The electrocatalytic behavior of similar cobalt diglyoximes also has been examined. $\text{Co}(\text{dmgH})_2\text{pyCl}$ (**3a**, py = pyridine) catalyzes H_2 evolution at a $\text{Co}^{\text{III/II}}$ potential of -1.06 V vs SCE in DMF with $[\text{Et}_3\text{NH}^+]\text{Cl}$ (Table 3).⁵² Upon reduction to the Co^{II} species, the halide ligand is labilized, while the axial pyridine stays coordinated. Substitution of the axial pyridine for 4-(dimethylamino)pyridine (**3b**) does not substantially modify the $\text{Co}^{\text{III/II}}$ potential, but the catalyst appears to be more electroactive.

$\text{Co}(\text{dmgH})_2\text{L}_2$ (**4**) has the same $\text{Co}^{\text{III/II}}$ reduction potential as **3** in DMF.⁵² The glyoxime bridging BF_2 groups, produced via reaction of the complex with $\text{BF}_3\cdot\text{Et}_2\text{O}$,⁵³ shift $\text{Co}^{\text{III/II}}$ potentials to values $\sim 0.5 \text{ V}$ more positive than their corresponding hydrogen-bridged counterparts but require stronger acids for electrocatalytic hydrogen evolution. The bridging BF_2 groups also increase the stability of the catalysts in acidic solutions.

Photochemical Systems

Catalytic hydrogen production can be driven directly with light when a sacrificial electron donor is present to scavenge the oxidized photosensitizer.^{54,55} Photosensitizers can act as both light harvesters and photoreductants; quenching their electronic excited states by electron transfer, directly to a catalyst or via an electron mediator, generates the reduced catalyst. Zeissel and co-workers demonstrated a multicomponent photochemical system for homogeneous H_2 generation with a cobaloxime catalyst in organic solvents, utilizing

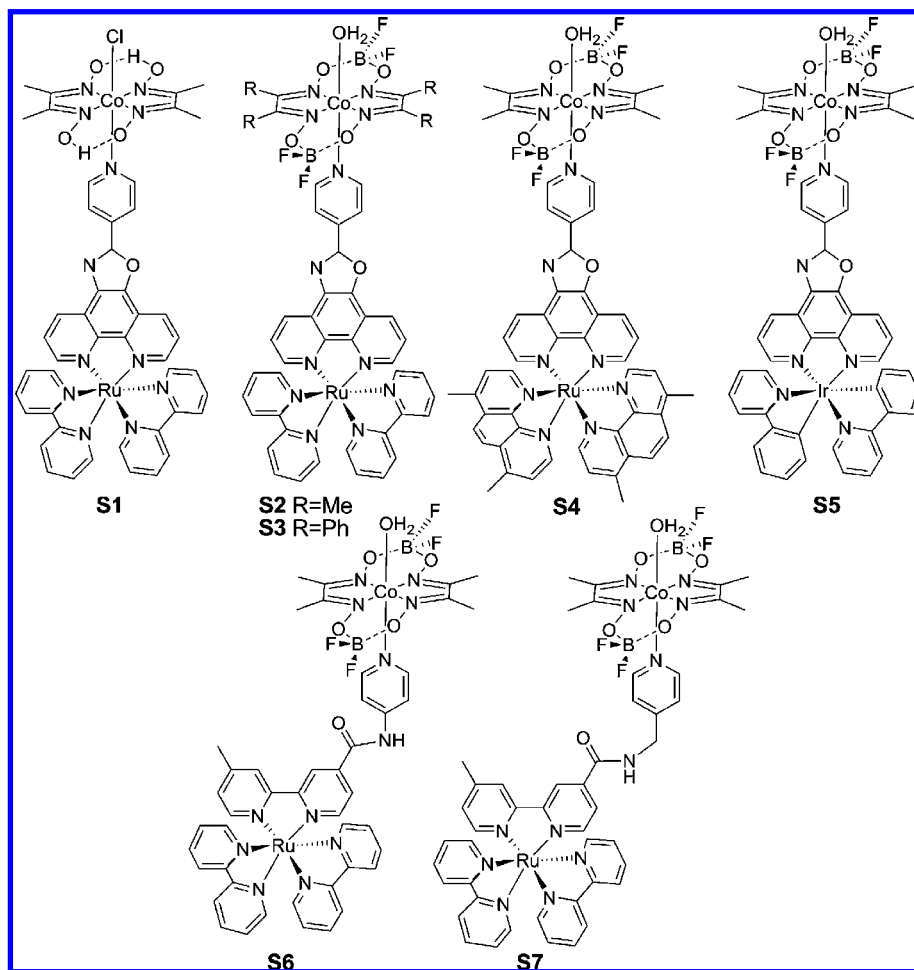


FIGURE 3. Sensitizer–cobaloxime conjugates for photocatalytic hydrogen evolution.

$[\text{Ru}(\text{bpy})_3]^{2+}$ (bpy = 2,2'-bipyridine) as photosensitizer, triethanolamine (TEOA) as sacrificial electron donor, and **4** as catalyst.⁵⁶ In DMF solution at pH 8.8, the turnover number for 1 h of irradiation (based on photosensitizer concentration) was 38.

Among other work of note,⁵⁷ Eisenberg and co-workers have shown that **3a** catalyzes H_2 evolution with a platinum(II) terpyridyl phenylacetylide complex, $[\text{Pt}(\text{ttpy})(\text{C}\equiv\text{CPh})]^+$ (ttpy = 4'-p-tolylterpyridine), as photosensitizer and TEOA as a donor in 3:2 (v/v) $\text{CH}_3\text{CN}/\text{H}_2\text{O}$ solutions between pH 7 and pH 12.⁵⁸ At pH 8.5 with 0.27 M TEOA, 1000 turnovers were achieved after 10 h irradiation ($\lambda > 410$ nm).

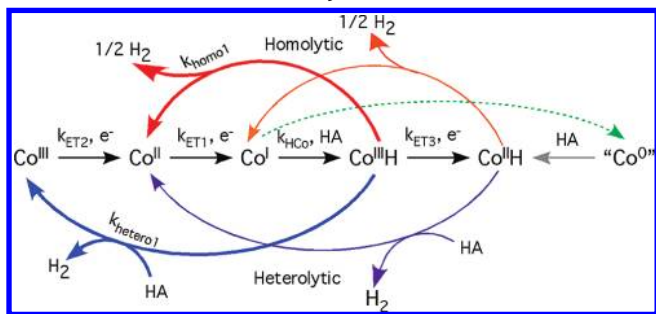
Other cobaloxime catalysts with varying axial bases (**3a–c**, **5–7**) and Pt(II) acetylide photosensitizers have been investigated.⁵⁹ With **3a** as catalyst, 2150 turnovers of H_2 were achieved after 10 h irradiation ($\lambda > 410$ nm) in a 24:1 (v/v) $\text{CH}_3\text{CN}/\text{H}_2\text{O}$ mixture at pH 8.5. Systems also have been reported in which organic chromophores replaced noble metal photosensitizers.⁶⁰ In 12 h of irradiation ($\lambda > 450$ nm), 900 turnovers were achieved using the eosin Y photosensitizer with **3a**, TEOA, and 3 mM free dimethylglyoxime in 1:1

$\text{CH}_3\text{CN}/\text{H}_2\text{O}$ at pH 7. Degradation of the photosensitizer/catalyst system was minimized with added dimethylglyoxime.

Fontecave and co-workers have focused on multicomponent photosystems for H_2 evolution with **1** and both $[\text{Ir}(\text{ppy})_2(\text{phen})]^+$ (ppy = 2-phenylpyridine, phen = phenanthroline) and $[\text{ReBr}(\text{CO})_3(\text{phen})]$ as photosensitizers in acetone. Solutions were buffered using $\text{Et}_3\text{N}/\text{Et}_3\text{NH}^+$, which provided both a sacrificial donor (Et_3N) and a proton source (Et_3NH^+).⁶¹ A quantum yield of $16\% \pm 1\%$ and 273 turnovers were achieved with $[\text{ReBr}(\text{CO})_3(\text{phen})]$ in a 15 h experiment ($\lambda > 380$ nm) with 600 equivalents each of Et_3N and Et_3NH^+ .

Alberto and co-workers studied a similar photosystem with **4**, employing $[\text{ReBr}(\text{CO})_3(\text{bpy})]$ as a photosensitizer, 1 M TEOA as sacrificial electron donor, and 0.1 M acetic acid as a proton source in DMF.⁶² They observed 150 turnovers in 9 h irradiation ($\lambda > 400$ nm) for the system, which had a $26\% \pm 2\%$ quantum yield. Dimethylglyoxime (7.5 mM) was added to enhance catalytic activity.

Bifunctional systems (Figure 3) have been reported recently with photosensitizers coordinated directly via axial pyridine

SCHEME 1. H₂ Evolution Pathways

ligands to [Co(dmgBF₂)₂(H₂O)] and [Co(dmgH)₂Cl] (**S1–S5**).^{61,63} Irradiation of these sensitizer–catalyst conjugates in Et₃N/Et₃NH⁺ buffered acetone solution triggers intramolecular electron transfer from photoexcited ruthenium or iridium sensitizers to the cobalt center, leading to H₂ evolution. Notably, these conjugates exhibited efficiencies up to 8.5 times greater than analogous multicomponent systems under the same conditions: [(ppy)₂Ir((L-pyr)Co(dmgBF₂)₂(H₂O))]⁺ (**S5**, L-pyr = (4-pyridine)oxazolo[4,5-f]phenanthroline) managed 210 turnovers after 15 h irradiation with 600 equivalents of Et₃N and Et₃NH⁺ in acetone. Li et al. studied related heterobinuclear Ru–Co systems with (**S6**) and without (**S7**) linker conjugation.⁶⁴ While both complexes were more active than the corresponding multicomponent systems, the one with a non-conjugated bridge exhibited more turnovers.

Reaction Pathways

Pathways for proton reduction by cobalt complexes are shown in Scheme 1. Reduction to a Co^I species that can be protonated to form Co^{III}H must occur first. The hydride can react in a bimolecular step with another hydride to eliminate H₂ (homolytic or bimetallic route, red pathway), or it can be protonated,⁶⁵ release H₂, and generate Co^{III} that is subsequently reduced (heterolytic or monometallic route, blue pathway). Alternatively, the Co^{III}H can be reduced further to yield Co^{II}H,⁴³ which can react via an analogous homolytic (orange) or heterolytic (purple) pathway. If the Co^I species is not protonated, it can be reduced further to a “Co⁰” species (which could be Co^I with a ligand radical), which, upon protonation to form Co^{II}H (green pathway), can react as above.

Chao and Espenson studied the reactivity of kinetically stabilized [HCo(dmgH)₂P(*n*-C₄H₉)₃] (**7H**) in order to ascertain the pathway of H₂ formation.⁶⁶ Interpretation of hydride reaction kinetics in the presence of acid (aqueous) required a rate expression that was both first- and second-order in **7H** concentration, suggesting parallel homolytic and heterolytic hydridocobaloxime pathways. Detailed mechanistic work indicated that the homolytic pathway predominates with a rate con-

stant of $1.7 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$. Since the hydridocobaloxime protonation rate constant was found to be $0.42 \text{ M}^{-1} \text{ s}^{-1}$, the heterolytic pathway is competitive only at low catalyst or high acid concentrations.

Fontecave and co-workers investigated catalysis by **1** in both DMF and CH₃CN;⁴⁹ (*p*-cyanoanilinium)BF₄ was shown to give rise to irreversible cathodic waves near the Co^{III} potential, indicative of electrocatalytic proton reduction. Lower current densities were seen near the same potential when CF₃COOH was employed as a proton source and an additional catalytic wave appeared near -1.0 V vs SCE, which was attributed to the reduction of Co^{III}H to Co^{II}H and subsequent reaction. With a weak acid, [Et₃NH]Cl, catalytic waves were observed near the Co^{I/0} potential (-1.47 V vs SCE). Since Co^I is not sufficiently basic to be protonated by this acid and the thermodynamic potential for hydrogen evolution from [Et₃NH]Cl lies negative of the Co^{II} potential, catalysis was not seen until the second reduction. It is noted that the peak currents at these negative potentials were convoluted with direct [Et₃NH]Cl reduction at the glassy carbon electrode. Modeling of the cyclic voltammetry data⁶⁷ suggested that reactions with (*p*-cyanoanilinium)BF₄ and CF₃COOH proceed by a heterolytic proton reduction (monometallic pathway) via both Co^{III}H and Co^{II}H. It was concluded that with acids strong enough to protonate both Co^I and Co^{III}H (e.g., (*p*-cyanoanilinium)BF₄), hydrogen evolution occurred via a heterolytic pathway. In cases where the acid is strong enough to protonate Co^I but not the Co^{III}H intermediate, the hydride is further reduced to Co^{II}H before reacting either heterolytically or homolytically. Weak acids like [Et₃NH]Cl that are unable to protonate the Co^I intermediate can protonate “Co⁰”, and H₂ evolution can be catalyzed through the intermediacy of a Co^{II}H species.

Cyclic voltammograms of **1** and **2** also showed catalytic waves upon addition of TsOH · H₂O, as discussed above.⁵⁰ The shape of the catalytic wave of **1** indicated a rapid reaction limited by proton diffusion to the electrode surface. At higher concentrations of TsOH · H₂O, the wave approached but did not reach a plateau. A quasi-reversible peak at about -1.0 V vs SCE observed for **1** at low acid concentration was attributed to the Co^{III}H/Co^{II}H couple; the reduction potential was similar to that seen for cobalt(III) alkyl species.⁶⁸ Because catalysis at the Co^{II} potential was relatively rapid, the concentration of Co^{III}H remained low in the reaction layer near the electrode, and only small amounts of Co^{II}H were generated under these conditions (the hydride reacts slowly with itself or with acid at low concentrations).

Catalytic waves for **2** reached a plateau at high concentrations of TsOH · H₂O, indicating that catalyst reduction at the

electrode is equal to the rate of reoxidation. At lower acid concentrations, a second wave observed at -0.85 V vs SCE indicated electrocatalytic hydrogen evolution by a $\text{Co}^{\text{II}}\text{H}$ species formed by reduction of $\text{Co}^{\text{III}}\text{H}$. Because the catalytic reaction of **2** is slow compared with that of **1**, concentrations of $\text{Co}^{\text{III}}\text{H}$ and acid are high enough to yield catalytic behavior upon reduction to $\text{Co}^{\text{II}}\text{H}$.

On the basis of digital simulations of catalytic waves of **1** in the presence of $\text{TsOH} \cdot \text{H}_2\text{O}$, it was concluded that bimolecular reactivity of $\text{Co}^{\text{III}}\text{H}$ was responsible for hydrogen evolution, consistent with the findings of Chao and Espenson.⁶⁶ Catalytic waves of **2**, however, could be simulated equally well assuming either a heterolytic or homolytic mechanism thus neither reaction pathway has been identified as predominant. Because electrocatalysis occurred near the Co^{III} reduction potentials, it was concluded that pathways through $\text{Co}^{\text{II}}\text{H}$ were unlikely, although those routes could open up at more negative potentials.

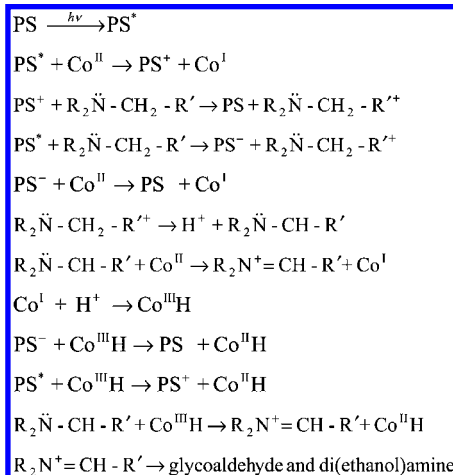
In an attempt to shed more light on H_2 evolution pathways, Peters and co-workers evaluated catalysis by **1** with (*p*-cyanoanilinium) BF_4 , employing higher acid/catalyst ratios (>10) than in earlier work.⁵⁰ With ratios less than 10, these simulations were successful for both homolytic and heterolytic pathways. Over a wider range (1:1 to 40:1), however, the data could only be simulated successfully assuming a homolytic route for H_2 evolution.

The overall rate constant for H_2 evolution was estimated directly from the plateau currents. For complexes **1** and **2**, the rate constants are 7×10^3 and $\sim 2 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$, respectively. In both cases, the reactions are first-order in acid concentration. On the basis of these data, it is clear that hydride formation is a key step in the catalysis of H_2 evolution.

Attempts to isolate a $\text{Co}^{\text{III}}\text{H}$ complex with glyoxime ligands have been unsuccessful, except for the kinetically stabilized phosphine-supported hydride **7H**.⁶⁶ Protonation of isolable Co^{I} species with a variety of proton sources, as well as reaction of Co^{III} halide species with borohydrides, consistently yielded Co^{II} complexes and H_2 , suggesting that $\text{Co}^{\text{III}}\text{H}$ is extremely reactive.⁵⁰

Photocatalytic hydrogen generation systems are considerably more complex than the corresponding electrocatalytic ones. Reactions in photosystems with tertiary amine sacrificial donors (TEOA or Et_3N) are set out in Scheme 2. The excited photosensitizer (PS^*) can be quenched by cobaloxime, producing PS^+ , which reacts with $\text{R}_2\text{N}-\text{CH}_2-\text{R}'$ to generate $\text{R}_2\text{N}-\text{CH}_2-\text{R}'^+$; PS^* also can be reductively quenched by $\text{R}_2\text{N}-\text{CH}_2-\text{R}'$, producing PS^- . Decomposition of $\text{R}_2\text{N}-\text{CH}_2-\text{R}'^+$ yields a proton and a second reducing equivalent,

SCHEME 2. H_2 Evolution Pathways in Photochemical Systems^a



^a The $\text{Co}^{\text{III}}\text{H}$ and $\text{Co}^{\text{II}}\text{H}$ intermediates may react via homolytic and heterolytic reaction pathways (Scheme 1) to evolve H_2 . Similar pathways exist with Et_3N as a sacrificial electron donor.

$\text{R}_2\text{N}-\text{CH}-\text{R}'$. Co^{I} can be reduced by PS^* , PS^- , or $\text{R}_2\text{N}-\text{CH}-\text{R}'$ and is then protonated to give $\text{Co}^{\text{II}}\text{H}$, which can be reduced to $\text{Co}^{\text{I}}\text{H}$ by any of the powerful reductants. The weakly basic conditions under which these photocatalytic systems operate disfavor protonation of $\text{Co}^{\text{II}}\text{H}$.

Eisenberg's work on photochemical systems using Pt^{II} acetylide chromophores^{58,59} and organic photosensitizers⁶⁰ with **3** (as well as other cobaloximes) showed that hydrogen evolution was first-order in catalyst concentration. The authors favor a monometallic route via $\text{Co}^{\text{II}}\text{H}$ to produce hydrogen. The $[\text{Re}(\text{CO})_3\text{Br}(\text{phen})]/1/\text{Et}_3\text{N}/\text{Et}_3\text{NH}^+$ system examined by Fontecave and co-workers also exhibited a first-order dependence on catalyst concentration, although above a certain concentration, the yield decreases, likely owing to competition for light absorption between the colored catalyst and photosensitizer.⁶¹ In the $[\text{Re}(\text{CO})_3\text{Br}(\text{bpy})]/4/\text{TEOA}/\text{AcOH}/\text{DMF}$ system studied by Alberto and co-workers, the observation of a second-order dependence on **4** in the rate of H_2 evolution ($3.7 \text{ M}^{-1} \text{ s}^{-1}$) led to the conclusion that the reaction occurred primarily via a homolytic route, although other mechanisms were not ruled out.⁶² The authors noted that a heterolytic process likely would require the generation of $\text{Co}^{\text{II}}\text{H}$ as a reactive intermediate.

Thermodynamic Analysis of Reaction Pathways

Electrochemical hydrogen evolution catalyzed by **1**, **2**, and **3a** occurs near Co^{III} potentials, where $\text{Co}^{\text{III}}\text{H}$ cannot be reduced further. Analysis of the barriers and driving forces associated with homolytic and heterolytic reaction pathways of $\text{Co}^{\text{III}}\text{H}$ suggests that the homolytic route is favored.⁶⁹

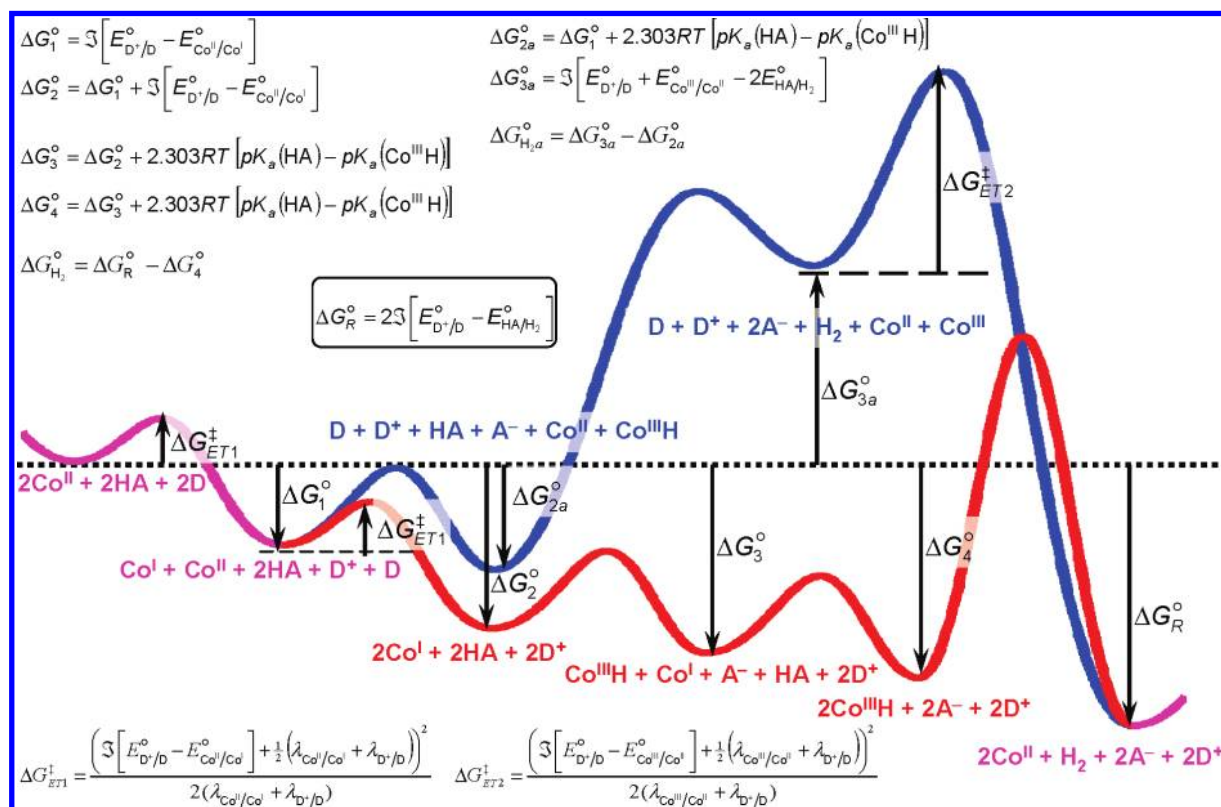


FIGURE 4. Thermodynamic analysis of cobaloxime-catalyzed H_2 evolution pathways.

As illustrated in Figure 4, the initial step in catalysis involves electron transfer from a donor (D) to Co^{II} ; the barrier to this transformation (ΔG_{ET1}^\ddagger) depends on the driving force and reorganization parameter (λ). A nuclear reorganization energy of 1.4 eV has been estimated for Co^{II} – Co^I electron exchange in **2**, consistent with facile electron transfer.⁶⁹

Protonation of the reduced catalyst is described by a driving force ($\Delta G_3^\circ - \Delta G_2^\circ$) proportional to the pK_a difference of the proton donor (HA) and $Co^{III}H$. As noted above, the $Co^{III}H$ pK_a increases as $E^\circ[Co^{III/II}]$ decreases,⁵¹ and substantially stronger acids are required to protonate the more easily reduced complexes. More strongly reducing Co^I intermediates produce substantially stabilized $Co^{III}H$ species upon protonation by strong acids. The extent of stabilization of the hydride will directly affect its tendency to produce H_2 . Weaker Co – H bonds are correlated with low-barrier homolytic cleavage to eliminate H_2 .⁸ The hydricity of the hydride, however, will facilitate reaction with a proton source in heterolytic H_2 production. The free energy of hydride transfer depends on the hydride pK_a and the $Co^{III/II}$ and $Co^{II/I}$ reduction potentials: a lower pK_a corresponds to a better hydride donor.⁷⁰

The driving force for the overall hydrogen evolution reaction (ΔG_R°) depends on the reduction potentials of the electron donor relative to the standard potential for hydrogen evolution from HA (E_{HA/H_2}°). In a homolytic reaction pathway

(red curve, Figure 4), all elementary steps on the way to proton reduction are exergonic when sufficiently powerful reductants and proton sources are used. The largest barrier to catalysis likely is associated with the elementary step that forms H_2 . Little is known about the rates or barriers to bimolecular reductive elimination from metal hydrides, but it is probable that the rate of H_2 formation through this elementary step will be proportional to $k_{\text{homo1}}[Co^{III}H]^2$.

In the heterolytic route (blue curve, Figure 4), H_2 is released upon protonation of $Co^{III}H$, generating Co^{III} that must be converted to Co^{II} by the pool of reducing equivalents. The driving force for this elementary H_2 forming step, ΔG_{3a}° , depends on the average of $E^\circ[Co^{III/II}]$ and $E^\circ[Co^{II/I}]$ (relative to the proton reduction potential), which, in most cases, renders the heterolytic reaction pathway extremely unfavorable. While exact details are not known, the reaction barrier for this step will be greater than 11 kcal mol⁻¹ for Co -diglyoxime complexes and the rate of H_2 formation will likely be proportional to $k_{\text{hetero1}}[HA][Co^{III}H]$. The exergonic conversion of Co^{III} to Co^{II} by reducing equivalents involves substantial nuclear reorganization: λ for Co^{III} – Co^{II} electron exchange in **2** is estimated to be ~ 3.9 eV,⁶⁹ almost three times greater than that for Co^{II} – Co^I exchange.

The heterolytic pathway to H_2 evolution catalyzed by cobaloximes involves relatively high energy barriers and unfav-

avorable driving forces. Nevertheless, it is important to remember that the dominant route to H₂ formation will depend not just on the barrier heights for elementary steps but also on the relative concentrations of HA and Co^{III}H. At very high acid concentrations, the heterolytic pathway becomes more favorable and can be faster even with a higher barrier height.

Summary and Prospects

Electrochemical and photochemical investigations have shed light on potential pathways of cobalt-catalyzed hydrogen evolution from solutions. Our thermodynamic analysis of these pathways has emphasized the critical role played by the barriers and driving forces of the elementary steps involved in catalytic H₂ evolution; it highlights the lower barrier of a homolytic reaction pathway. To date, however, no studies have provided detailed chemical kinetics of H₂ production nor have any key intermediates been detected.

Photochemical methods coupled with time-resolved spectroscopy offer unique opportunities to identify and monitor intermediates in the reaction cycle leading to H₂ evolution. For example, laser flash-quench methods^{71–73} can be used to trigger the reduction of Co^{II} to Co^I, permitting optical⁷⁴ or infrared^{75,76} detection of intermediates on time scales appreciably shorter than those accessible by conventional stopped-flow spectroscopy. Transient spectroscopic and kinetics measurements can offer critical insights into rate-limiting processes and the mechanism as a whole. A major challenge in this area is the development of photosensitizers and electron relays that are not inhibited by acids.⁷⁷

The low-barrier homolytic pathway relies on the diffusion of two hydride species together in solution. A rate law with a first-order dependence on both cobalt and acid is fully consistent with electrochemical data and a first-order dependence on cobalt concentration also has been found for photochemical systems. These findings, coupled with the thermodynamic preference for a homolytic route, suggest that the limiting rate may be associated with formation of the hydride. While a bimolecular reaction of cobalt hydrides may not be rate limiting, a homolytic pathway would preclude the immobilization of catalyst on an electrode surface by preventing bimolecular diffusion pathways. Although there has been very little work on immobilizing these cobaloxime species on surfaces,⁷⁸ an efficient water splitting device³ may require catalysts to be tethered to a photoelectrode surface.

Eliminating bimolecular diffusion by covalent linking of cobalt centers in a dinuclear catalyst could potentially enhance the rate of H₂ production. Any increase in rates of H₂ production relative to that of a mononuclear analogue could be probed via electrochemical methods. Work on Ru and Os diporphyrins indicates that cofacial orientation of metallocenters enhances H₂ evolution under certain conditions.^{40,42} There have been very few reports of dinuclear cobalt species with glyoxime⁷⁹ or glyoxime-like ligands,⁸⁰ and none has demonstrated proton reduction activity. Current work in our laboratory is focused on proton reduction by covalently linked dicobalt catalysts.

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BIOGRAPHICAL INFORMATION

Jillian L. Dempsey is a graduate student at the California Institute of Technology where she is investigating the mechanism of proton reduction by cobaloximes with Harry B. Gray and Jay R. Winkler. She received her S.B. in chemistry from the Massachusetts Institute of Technology in 2005.

Bruce S. Brunshwig studied physical chemistry at the Polytechnic Institute of NYU (Ph.D. 1972) before joining the faculty of Hofstra University in 1972. He moved to Caltech in 2004 from Brookhaven National Laboratory. He is Director of the Molecular Materials Resource Center, Member of the Beckman Institute, and a Powering the Planet NSF CCI Principal Investigator.

Jay R. Winkler studied inorganic chemistry at Caltech (Ph.D. 1984). He moved to Caltech in 1990 from Brookhaven National Laboratory. He is Director of the Beckman Institute Laser Resource Center, Member of the Beckman Institute, and a Powering the Planet NSF CCI Principal Investigator.

Harry B. Gray studied inorganic chemistry at Northwestern University (Ph.D. 1960) and the University of Copenhagen (1960–1961) before joining the chemistry faculty of Columbia University. In 1966, he moved to Caltech, where he is the Arnold O. Beckman Professor of Chemistry, Founding Director of the Beckman Institute, and Powering the Planet NSF CCI Principal Investigator.

FOOTNOTES

*To whom correspondence should be addressed. E-mail addresses: bsb@caltech.edu; winklerj@caltech.edu; hbgray@caltech.edu.

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