

Insights into the mechanism of photosynthetic H₂ evolution catalyzed by a heptacoordinate cobalt complex†

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H₂ evolution catalyzed by a heptacoordinate complex under both electro- (1) and photo-chemical (2) conditions is analyzed in detail in order to gain insights into the mechanism of the processes. The complex shows high catalytic activity for hydrogen production in acetonitrile, in the presence of trifluoroacetic acid and triethylammonium tetrafluoroborate as proton sources. Foot-of-the-wave analysis (FOWA) and Tafel plot analysis have been applied to elucidate the kinetics of the hydrogen evolution mechanism and to benchmark the catalytic performances, respectively, with remarkably high rates being obtained at the expense of high overpotentials. Transient absorption spectroscopy measurements have been performed to characterize the kinetics and relevant intermediates formed under photocatalytic conditions. A computational investigation, based on density functional theory (DFT) and time-dependent DFT (TD-DFT), has also been carried out to characterize the intermediate species and support the experimental results. A combination of both experimental and theoretical data suggests the formation of catalytic intermediates displaying dangling pyridine groups in both the one- and two-electron reduced species, possibly acting as proton-transfer relays to enable efficient H–H bond formation.

1. Introduction

Defining the mechanism behind a reaction is crucial in the quest for the improvement and development of processes such as hydrogen production. Hydrogen plays a primary role in the thrilling and arduous challenge of replacing fossil fuels with renewable and clean sources of energy. In fact, the light-driven reduction of water to H₂ by sunlight is a promising way to store solar energy in the form of chemical bonds since hydrogen can be used as a green fuel and its combustion releases a large amount of energy (120 MJ kg^{−1}).^{1,2} This process draws inspiration from natural photosynthesis where microalgae and

cyanobacteria carry out the production of hydrogen using hydrogenase enzymes based on nickel and/or iron clusters.^{3,4} In artificial photosynthesis, light is used to extract electrons from water, resulting in O₂ evolution, and the photogenerated electrons are used to reduce CO₂, to produce organic fuels or to reduce protons to H₂ (*i.e.* light-driven water splitting).⁵ In light-driven water splitting, the half-reaction involving the reduction of protons is widely studied and has been a subject of great interest in the last decade.⁶ The photochemical production of H₂ requires a multicomponent system based on at least three components: a photosensitizer which is responsible for light-harvesting and the consequent primary photoinduced electron transfer processes, an electron donor which provides the reducing equivalents to foster the photochemical reaction, and a hydrogen evolving catalyst (HEC) capable of stepwise storage of electrons and binding of protons to promote hydrogen formation at low activation energy.⁷ Numerous synthetic noble metal-free catalysts based on Co,^{8–10} Ni,^{11–13} Fe¹⁴ and Mo¹⁵ have been developed so far for photochemical H₂ production. Among these catalysts, polypyridyl cobalt complexes are considered the most promising ones because of the robustness of the coordination sphere, the possibility of operating under fully aqueous conditions and their high efficiency.¹⁶ In 2011, Chang, Long and co-workers reported the first series of Co complexes coordinated with pentapyridyl ligands, based on pyridine units, that were investigated in water in the presence of ascorbic acid as the sacrificial electron donor and Ru(bpy)₃²⁺ (where bpy = 2,2'-

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bipyridine) as the photosensitizer.¹⁷ Chang, Long, Castellano and co-workers¹⁸ also synthesized another type of pentadentate ligand containing redox-active 2,2'-bipyridine moieties that were expected to stabilize the reduced form of the metal center. They observed improved activity and stability of the catalysts, attributing the end of the catalysis to the decomposition of the photosensitizer during the photocatalytic process. Another modification was made by Zhao and co-workers,¹⁹ who introduced an alkylamine into the ligand containing pyridine and bipyridine groups. This polypyridyl cobalt complex showed high activity with a turnover number (TON) higher than 4400 mol H₂ (mol cat)⁻¹ in the presence of Ru(bpy)₃²⁺ and ascorbic acid in water, under optimal conditions. In contrast, Alberto, Probst and co-workers²⁰ demonstrated that the slight change induced upon replacing a single carbon atom with a nitrogen on the bridge connecting two bipyridyl ligands causes a reduction in the catalytic rate and the stability of the catalyst. Another important aspect is the role of the ligand, which can be protonated and therefore can actively participate in the catalytic process as observed for a cobalt pentadentate ligand synthesized by Chang and co-workers²¹ and by a recent transient X-ray absorption study.²² The investigation of the mechanistic profile of each catalyst is imperative for a comprehensive understanding of all the factors that influence the catalytic activity. Cobalt hydrides such as Co(III)-H and Co(II)-H generated from the protonation of Co(I) have been generally acknowledged as the key intermediates for the production of hydrogen, which can occur through either a heterolytic (a proton reacting with a cobalt hydride to evolve H₂) or a homolytic (two cobalt hydrides giving reductive elimination to produce H₂) mechanism. However, it has been proved that the catalytic mechanism could vary depending on the experimental conditions, even for the same system.^{16,23-29}

In our recent work, we reported a new heptacoordinate cobalt complex (Fig. 1) and we studied its activity in H₂ photosynthesis using Ru(bpy)₃²⁺ as a photosensitizer and ascorbic acid as a sacrificial electron donor in aqueous solution.³⁰ Herein, we go deeper into the investigation of the mechanism, to highlight the pathways of the hydrogen evolution catalysed by this heptacoordinate cobalt complex in electrocatalytic and light-driven systems. The present investigation has been carried out combining pieces of evidence obtained by using electrochemistry, transient absorption spectroscopy and quantum chemistry calculations. Concerning the electrochemical studies, they have been accomplished in acetonitrile as the solvent to gain information on the electrocatalytic behaviour of complex **1** (Fig. 1) employing two different proton donors with known pK_a (i.e., trifluoroacetic acid (TFA) and triethylammonium tetrafluoroborate (Et₃NHBF₄)) in order to have suitable control over the proton transfer steps.¹⁶ Importantly, foot-of-the-wave analysis (FOWA), bulk electrolysis and catalytic Tafel plot analysis have been used to shine light on the operating catalytic mechanism, to extract kinetic rate constants, and to benchmark catalytic performances with respect to previously reported systems.³¹ Transient absorption spectroscopy has been exploited to characterize some of the intermediates involved during photocatalytic hydrogen evolution catalysed by complex

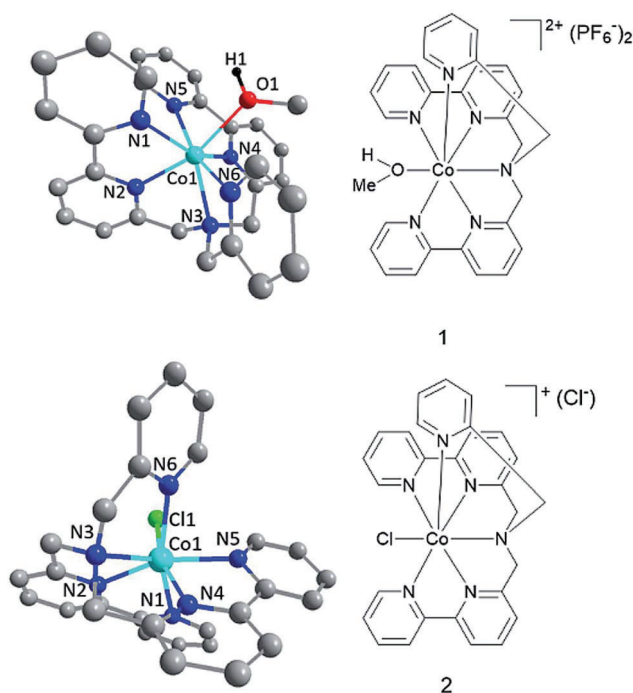


Fig. 1 X-ray structures of complexes **1** and **2** together with the atom labeling scheme. Further details of the structures are provided in ref. 30.

2 (Fig. 1) in the presence of Ru(bpy)₃²⁺ and ascorbic acid as a sensitizer and donor, respectively, and to gain information on the kinetics of the relevant electron transfer processes. Density functional theory (DFT) and time-dependent DFT (TD-DFT) calculations have been used to corroborate mechanistic considerations and to characterize the electronic structure and optical response of the possible intermediates involved in the catalysis.

2. Experimental

2.1 General

All products and solvents were purchased from standard sources and directly used without further purification. Cyclic voltammetry experiments were performed using an Autolab PGSTAT-30 potentiostat and controlled potential electrolysis experiments were performed on a BioLogic SP300 potentiostat. The H₂ produced during bulk electrolysis experiments was analysed with a PerkinElmer Clarus 500 gas chromatograph (GC).

The results were validated with at least two sets of measurements.

2.2 Electrochemical investigations

Cyclic voltammograms were recorded in acetonitrile (ACN) in the presence of 0.1 M tetrabutylammonium hexafluorophosphate (nBu₄NPF₆) as the supporting electrolyte in an inert atmosphere (N₂). The setup consisted of three electrodes: glassy carbon as the working electrode, platinum wire as the

counter electrode and a Ag/AgCl (KCl 3 M) electrode as the reference electrode. Ferrocene was used as the internal standard.

Controlled potential coulometry experiments were carried out in a two-compartment cell, with the mercury pool working electrode separated by a porous frit from the coiled platinum wire counter electrode. In the working compartment, 8 mL solutions of ACN containing 0.1 M $n\text{Bu}_4\text{NPF}_6$, 1 mM catalyst and 100 mM acid (*i.e.* trifluoroacetic acid (TFA) and triethylammonium tetrafluoroborate (Et_3NHBF_4)) were used for the measurements. Before the measurements, the solutions were degassed with N_2 within 30 minutes and during the experiments the cell was continuously purged with N_2 (5 mL min^{-1}). The headspace was analyzed every two minutes by GC over 4 hours.

2.3 Optical spectroscopy

Emission spectra were recorded on an Edinburgh Instruments spectrofluorometer equipped with a 900 W Xe arc lamp as the excitation source, a photomultiplier tube, and an InGaAs detector for visible and NIR detection, respectively. Nanosecond transient absorption measurements were performed with a custom laser spectrometer consisting of a Continuum Surelite II Nd:YAG laser (FWHM = 8 ns) with a frequency doubling (532 nm, 330 mJ) option, an Applied Photophysics Xe light source including a model 720 150 W lamp housing, a model 620 power-controlled lamp supply and a model 03-102 arc lamp pulser. Laser excitation was provided at 90° with respect to the white light probe beam. The light transmitted by the sample was focused onto the entrance slit of a 300 mm focal length Acton SpectraPro 2300i triple grating, flat field, double exit monochromator equipped with a photomultiplier detector (Hamamatsu R3896). Signals from the photomultiplier (kinetic traces) were processed by means of a Teledyne LeCroy 604Zi (400 MHz, 20 GS/s) digital oscilloscope. Before all the measurements the solutions were purged with nitrogen for 10 minutes.

2.4 Computational studies

All the electronic structure calculations were carried out using the Gaussian09 package,³² and, following the computational protocol employed in our previous work,³⁰ the B3LYP functional³³ in combination with a 6-311G** basis set was adopted. Further details are given in the ESI.[†]

3. Results and discussion

3.1 Electrochemical characterization

Cyclic voltammetry (CV) of complex **1**, performed at various scan rates in ACN with a glassy carbon electrode and in the presence of tetrabutylammonium hexafluorophosphate ($n\text{Bu}_4\text{NPF}_6$) as the supporting electrolyte, showed two reversible signals at $-1.50\text{ V vs. Fc}^{+/0}$ and at $-2.06\text{ V vs. Fc}^{+/0}$ (Fig. 2 and S4 (ESI[†])). The B3LYP calculated potentials in ACN corresponding to the two reductions are 3.35 and 2.70 eV (-1.40 and $-2.04\text{ V vs. Fc}^{+/0}$, respectively), in perfect agreement with the

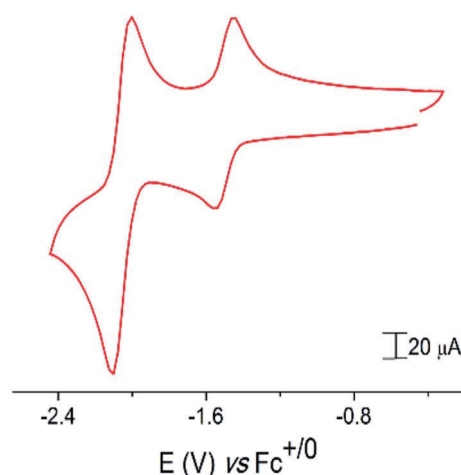
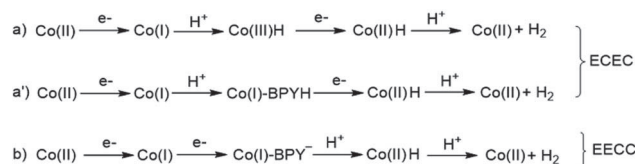


Fig. 2 Cyclic voltammogram of complex **1** recorded at 1 V s^{-1} with glassy carbon as the working electrode in ACN with 0.1 M $n\text{Bu}_4\text{NPF}_6$ as the supporting electrolyte.

experimental values. Analysis of the β unoccupied orbitals of complex **1** in its high spin electronic configuration (Fig. S1,[†] left panel) suggests that the first electron likely occupies a mixed Co-bipyridine orbital (BPY1, as indicated in the right panel of Fig. S1[†]), while the second electron seems to be completely delocalized on the other bipyridine ligand (BPY2, right panel in Fig. S1[†]). Even if it has been observed that standard DFT functionals tend to give too delocalized spin densities in the case of metal-ligand bonds,³⁴⁻³⁶ one can look at the charge (Mulliken) localized on the cobalt center to gain further insights into the nature of the two reductive processes (Table S2[†]).[‡] Complex **1**, with a total charge of +2 and in its high spin quartet electronic configuration, presents a calculated Mulliken charge of +1.44 a.u. and a spin density of 2.73 e^- on the metal center. Upon addition of the first electron (total charge of +1 and spin multiplicity of 3), the charge and spin density on the cobalt center decrease only slightly to +1.39 a.u. and 2.64 e^- , respectively. The second electron (neutral complex and spin multiplicity of 2) essentially delocalizes over BPY2 as shown in Fig. S1[†] and by the data in Table S2,[†] leading even to slightly increased charge (+1.41 a.u.) and spin density (2.67 e^-) on the cobalt atom. As also shown by the calculated bond distances, the reduction processes involving the two BPY ligands are also accompanied by strengthening of the N-Co bonds of the reduced ligand. Thus, according to the DFT picture the two reductive processes mainly involve the BPY ligands leading to a “formal Co(I) ” and a “formal Co(0) ” species; for the sake of simplicity and clarity in the discussion of the catalytic mechanisms (Scheme 1) we will, however, denote these intermediates as “ Co(I) ” and “ Co(0) ” hereafter.

[‡] It should be considered that these values can only provide qualitative information due to the limitations of Mulliken's population scheme. Nevertheless, other methods to analyse the charge (as the Hirshfeld one)⁶¹ can result in even less accurate results for non-neutral molecules,⁶² as is seen in our case.



Scheme 1 Possible pathways for the catalytic hydrogen formation using TFA as the proton source with initial protonation (a) on the metal or (a') on the ligand and (b) using Et_3NH^+ as the proton donor (BPY = BPY1 or BPY2).

Addition of increasing amounts of TFA ($\text{pK}_a = 12.7$ in ACN)³⁷ triggers the appearance of a catalytic wave in the CV with a peak current (i_{cat}) that increases with the amount of acid added (Fig. 3 and S5†).

The potential at the mid-wave E_{cat} of -1.46 V vs. $\text{Fc}^{+/0}$, independent of the amount of acid and scan rate (Fig. S16†), is 40 mV more positive than the reduction potential of $\text{Co}^{\text{II/I}}$.

These observations are consistent with catalysis proceeding *via* an ECEC process (with E being the electron transfer and C the chemical reaction, *i.e.* the protonation) with the second electron transfer being easier than the first one (Scheme 1a) and the second protonation step being rate-determining.³⁸

Foot-of-the-wave analysis (FOWA), developed by Costentin and Savéant, enables the use of cyclic voltammetry to gain information on the catalytic mechanism and to quantify the rates of the first step during hydrogen evolution.³¹

The plot of i_{cat}/i_p (where i_p is the peak current of a reversible non-catalytic wave) *versus* $1/(1 + \exp(F/RT(E - E_{\text{cat}})))$ can be linearly fitted near the foot of the catalytic wave. From the slope of such a linear fit it is possible to calculate the rate constant (k_1) of the first protonation process (details of FOWA are provided in the ESI†).³⁸ A value of $k_1 = 1.5(\pm 0.2) \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ was obtained as an average of independent CVs measured at increasing concentrations of TFA (10, 15, and 20 mM) and at five different scan rates (5–50 V s^{-1}).

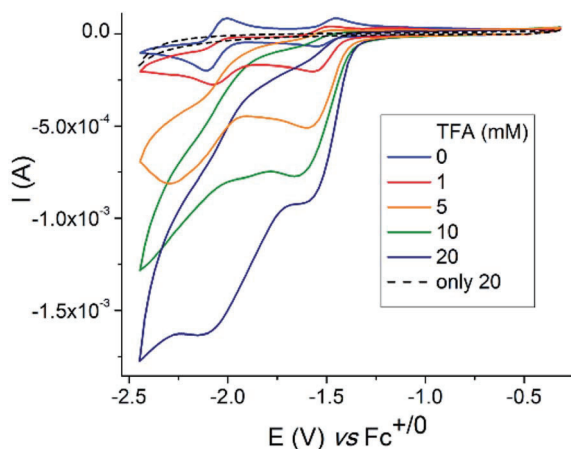


Fig. 3 Cyclic voltammograms of complex 1 (1 mM) with increasing amounts of TFA (1–20 mM) in ACN (0.1 M $n\text{Bu}_4\text{NPF}_6$, glassy carbon working electrode) at 30 V s^{-1} . The dotted line is obtained for 20 mM TFA in the absence of complex 1.

The rate constant of the rate-determining step in catalysis (k_2) can then be derived from the shift in potential between the catalytic process (mid-wave potential) and the triggering redox couple (here the $\text{Co}^{\text{II/I}}$ couple) using eqn (S2) (see the ESI†).^{38,39} An average value of $k_2 = 8.5(\pm 0.7) \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$ was obtained. A similar value ($k_2 = 10.25(\pm 0.05) \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$) was independently obtained from the scan-rate independent plateau current observed for 20 mM TFA at 35–40 V s^{-1} .

Catalytic Tafel plots constitute a useful methodology to benchmark the performances of molecular catalysts. Such plots can be outlined from the knowledge of three values characterizing the catalyst: the catalytic potential E_{cat} , the maximum turnover frequency ($\text{TOF}_{\text{max}} = 8.5 \times 10^5 \text{ s}^{-1}$ extrapolated to 1 M acid by convention) and the apparent equilibrium potential of the H^+/H_2 couple (-0.61 V vs. $\text{Fc}^{+/0}$) under such extrapolated conditions.^{37,39–41} To the best of our knowledge, catalytic Tafel plots have never been determined for polypyridyl cobalt catalysts. In Fig. 4, the catalytic Tafel plot obtained for complex 1 (blue line) is compared with those of two known hydrogen evolution catalysts.^{41,42} Catalyst 1 shows high catalytic activity, albeit at the expense of high overpotential values. These properties are common for polypyridyl cobalt catalysts, which are usually known to have higher overpotentials with respect to other cobalt catalysts such as cobaloximes (green plot in Fig. 4), even though they are more stable and faster in photocatalysis.²⁰ Similarly, high TOFs correlated with high overpotentials have been observed by Bullock, DuBois and co-workers¹³ for $[\text{Ni}(\text{P}_2^{\text{Ph}}\text{N}^{\text{Ph}})_2]^{2+}$ where the well placed proton relays allowed very fast proton transfer for H_2 formation.¹³ At overpotentials higher than 500 mV where $\log(\text{TOF})/\text{s}^{-1} > 1$, the activity of catalyst 1 is also comparable to that of other electrocatalysts such as FeTPP (orange plot in Fig. 4).^{39,42}

Bulk electrolysis experiments were performed at -1.53 V vs. $\text{Fc}^{+/0}$ at a mercury pool electrode in the presence of TFA (100 mM) and the catalyst (1 mM) in a solution of ACN for 4 h (Fig. S14†). Production of hydrogen at the catalytic wave was

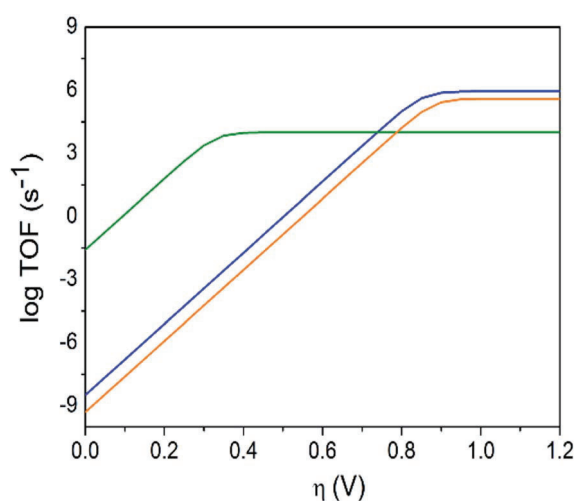


Fig. 4 Catalytic Tafel plots. Blue: complex 1 and 1 M TFA in ACN. Catalysts reported in the literature: green: $[\text{Co}^{\text{II}}(\text{dmgH})_2\text{py}]$,^{39,41} DMF, Et_3NH^+ (1 M); orange: $\text{Fe}^{\text{II}}\text{TPP}$,^{39,42} DMF, Et_3NH^+ (1 M).

confirmed, with **1** achieving a turnover number (TON) of 21 with a faradaic yield of 75%. We also investigated the electrochemical behaviour of complex **1** in the presence of the weaker acid Et_3NHBF_4 ($\text{p}K_a = 18.7$ in ACN)³⁷ (Fig. 5). In contrast to the results obtained with TFA, the catalytic wave was observed at more negative potentials with $E_{\text{cat}} = -2.06$ V vs. $\text{Fc}^{+/0}$, corresponding to the second redox process in the CV recorded in the absence of acid. This observation can be explained considering that Et_3NH^+ may not be able to protonate the Co(I) produced after the first reduction. FOWA of the cyclic voltammograms shown in Fig. 5 gives an average value for the first protonation step of $k_1 = 2(\pm 0.1) \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$. At a high scan rate (45 V s^{-1}) and at 25 mM Et_3NH^+ , the k_2 value can be estimated with eqn (S5)[†] assuming that a scan-rate independent plateauing behaviour is approached under these conditions (Fig. S12[†]), giving a value of $5 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$. The fact that k_2 is larger than k_1 is consistent with a catalytic EECC process with a mid-wave catalytic potential identical to the redox potential of the second redox process observed for complex **1** (Scheme 1b). Bulk electrolysis experiments confirmed the evolution of hydrogen at -2.1 V vs. $\text{Fc}^{+/0}$ with a faradaic yield of 76% and TON of 26 (Fig. S15[†]). Of note, a similar reactivity has been observed for NiFe complexes with a Ni-bound bipyridine ligand, with H_2 evolution from Et_3NHBF_4 triggered by a bpy-centered redox process.^{43–45} In that case, however, the catalysis took place *via* a different mechanism, namely with protonation occurring after the two reductive processes [E[CEC] process with the third electron transfer easier than the second one].

3.2 Photochemical characterization

As already reported in our previous work, the heptacoordinate complex **2** was found to be efficient in producing hydrogen upon photoirradiation in the presence of $\text{Ru}(\text{bpy})_3^{2+}$ as the light-harvesting photosensitizer and ascorbic acid as the sacrificial electron donor. Quantum yields between 3% and 11% were measured in the concentration range of $[\text{2}] = 0.1\text{--}10 \text{ }\mu\text{M}$ with $[\text{Ru}(\text{bpy})_3^{2+}] = 0.5 \text{ mM}$, achieving turnover numbers (TONs) up

to $16\,300 (\pm 1600)$.³⁰ The remarkable activity observed under strongly diluted conditions clearly suggests that catalyst **2** is effective in undergoing consecutive electron transfer processes from the photogenerated reducing agent. A combination of steady-state and time-resolved techniques has thus been exploited in order to shine light on the mechanism and kinetics of the three-component photochemical system responsible for such an efficient hydrogen evolution activity.

In a three-component photochemical system based on a catalyst, a photosensitizer, and a sacrificial electron donor, activation of the catalyst towards hydrogen evolution may be attained through two different mechanisms:⁴⁶ (i) an oxidative route, where excitation of the sensitizer is followed by photoinduced electron transfer to the catalyst and the oxidized chromophore is recovered by electron transfer from the donor; (ii) a reductive route, in which the sensitizer, upon excitation, undergoes reductive quenching by the donor first and then the photogenerated reduced dye transfers the electron to the catalyst. In order to establish the operating mechanism in photoinduced hydrogen evolution catalysed by **2**, emission measurements were performed. In 1 M acetate buffer (pH 4), inefficient quenching of the $^3\text{*Ru}(\text{bpy})_3^{2+}$ luminescence (<5% yield) was observed upon addition of complex **2** up to $10 \text{ }\mu\text{M}$ concentration (Fig. S18[†]). On the other hand, ascorbic acid is known to quench the triplet excited state of the $\text{Ru}(\text{bpy})_3^{2+}$ photosensitizer. However, since the ascorbate anion is the competent quencher, the efficiency of the reductive photoinduced electron transfer is expected to be pH dependent.^{47,48} In 1 M acetate buffer (pH 4), a rate constant of $k = 1.0 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ has been estimated for such a bimolecular electron transfer reaction.⁴⁹ This corresponds to a pseudo-first order rate of $1.0 \times 10^6 \text{ s}^{-1}$ and a *ca.* 70% quenching efficiency under the conditions adopted in the light-driven hydrogen evolution experiments (0.1 M ascorbic acid). Overall, these data suggest that photoinduced hydrogen evolution in the three-component system based on **2**, $\text{Ru}(\text{bpy})_3^{2+}$, and ascorbic acid in 1 M acetate buffer (pH 4) follows a reductive mechanism. It is worth mentioning that these results are consistent with the typical behaviour observed in other photochemical hydrogen production systems involving the same sensitizer/donor couple and polypyridine cobalt complexes as catalysts.¹⁶

According to the mechanism outlined above, it is important to monitor the fate of the photogenerated reduced sensitizer $\text{Ru}(\text{bpy})_3^+$ in order to give an estimate of the kinetic of the electron transfer to catalyst **2** and obtain qualitative information on the catalytic intermediate produced. This data can be conveniently obtained by transient absorption spectroscopy in the ns– μs time range on the three-component system. Upon 532 nm excitation of a solution containing $50 \text{ }\mu\text{M}$ $\text{Ru}(\text{bpy})_3\text{Cl}_2 \cdot 6\text{H}_2\text{O}$, 0.1 M ascorbic acid, and 0.1 mM **2** in 1 M acetate buffer (pH 4), the transient spectrum obtained at a 2 μs time-delay (Fig. 6) corresponds to the differential spectrum of the reduced sensitizer $\text{Ru}(\text{bpy})_3^+$, prepared by reductive quenching of $^3\text{*Ru}(\text{bpy})_3^{2+}$ by ascorbic acid, as confirmed by its featuring maximum at *ca.* 500 nm.⁵⁰ During the first 10 μs this spectrum decays to give a broad transient signal with maxima at *ca.* 480–500 nm and *ca.* 700 nm (a clear isosbestic point can be seen at *ca.* 575 nm). Interestingly, the kinetics of the $\text{Ru}(\text{bpy})_3^+$ decay at

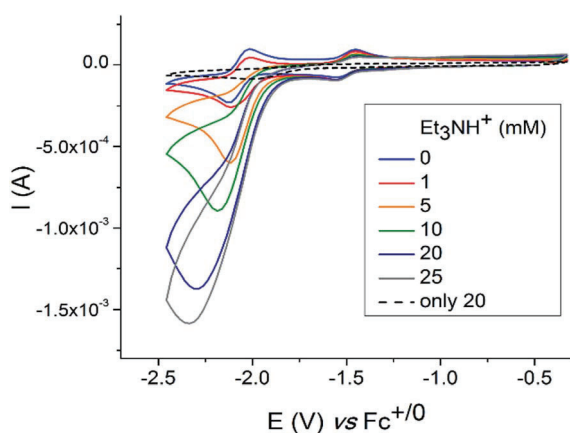


Fig. 5 Cyclic voltammograms of complex **1** (1 mM) with increasing amounts of Et_3NH^+ (1–20 mM) in ACN (0.1 M $n\text{Bu}_4\text{NPF}_6$ glassy carbon working electrode) at 30 V s^{-1} . The dotted line is obtained at 20 mM Et_3NH^+ in the absence of complex **1**.

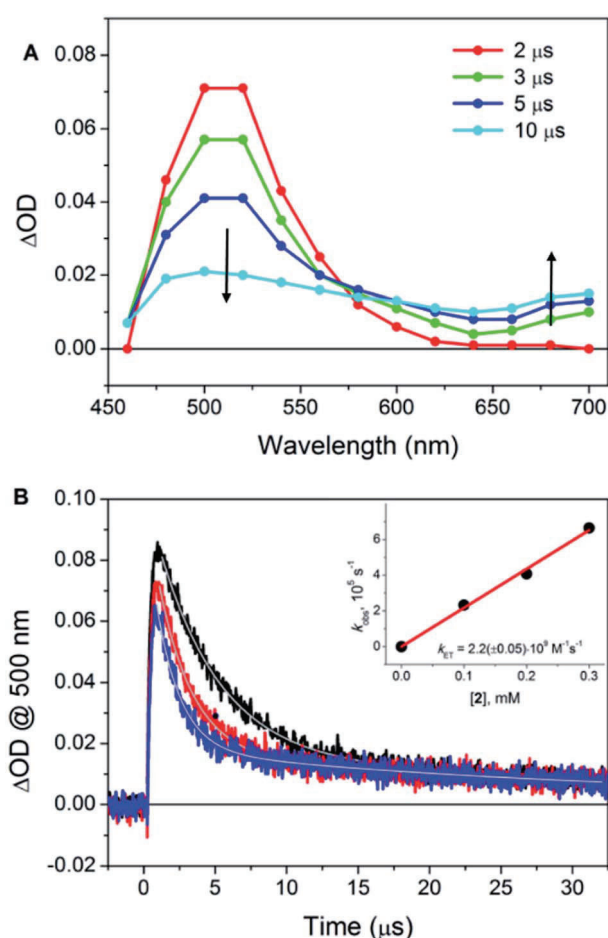


Fig. 6 Laser flash photolysis experiments (excitation at 532 nm) of N_2 -purged solutions containing 50 μ M $Ru(bpy)_3Cl_2 \cdot 6H_2O$, 0.1 M ascorbic acid, and 2 in 1 M acetate buffer (pH 4): (A) spectral evolution between 2 and 10 μ s with 0.1 mM 2; (B) kinetic traces at 500 nm with related fitting in the presence of 0.1 mM (black trace), 0.2 mM (red trace), and 0.3 mM (blue trace) 2; (inset) plot of the observed rate vs. [2] for the estimation of the bimolecular rate constant.

500 nm is dependent on the concentration of catalyst 2 (Fig. 6), thus consistent with a bimolecular process involving electron transfer from the photogenerated reduced sensitizer to complex 2.

Under pseudo-first order kinetics conditions (namely $[2] \gg [Ru(bpy)_3^+]$), a bimolecular rate constant of $k = 2.2(\pm 0.05) \times 10^6 M^{-1} s^{-1}$ can be estimated for such an electron transfer process. This rate is considerably high, close to the diffusion-controlled regime and is comparable to the values obtained for the electron transfer from $Ru(bpy)_3^+$ to other cobalt(II) polypyridine complexes.^{23,49,51–53} It is worth pointing out that fast electron transfer from the photogenerated reduced dye to the catalyst is pivotal in hydrogen evolution photocatalysis in order to minimize parallel, competitive deactivation routes of the chromophore. Accordingly, this peculiar *figure-of-merit* of catalyst 2 may actually explain the achievement of remarkable hydrogen evolution yields as well as the impressive turnover number (TON) experimentally observed during continuous photocatalysis.³⁰ More importantly, the transient spectrum obtained

after the decay of the $Ru(bpy)_3^+$ transient absorption may also provide information on the nature of the cobalt species formed upon electron transfer from the photogenerated reduced chromophore. The present transient signal is comparable with the transient spectra experimentally measured for Co(I) species of related cobalt polypyridine complexes,^{51,53} while being apparently different from that measured for a related Co(III)–H species (with protonation occurring at the metal center).²³ Also, molar extinction coefficients of $\Delta\epsilon \sim 2300$, 1500, and 1600 $M^{-1} cm^{-1}$ at 500, 600, and 700 nm, respectively, in line with those previously reported for Co(I) intermediates,⁵³ can be estimated from the transient absorption experiments using the $Ru(bpy)_3^+$ absorption as a reference ($\Delta\epsilon = 9000 M^{-1} cm^{-1}$ at 500 nm, quantitative formation of 2^- by photogenerated $Ru(bpy)_3^+$ is assumed).^{48,49,54} Accordingly, these pieces of evidence seem to favor a simple electron transfer pathway over a proton-coupled electron-transfer. Nevertheless, it is worth pointing out that, as suggested by theoretical calculations (see below), the experimental results can also support the hypothesis that, in the present system, one-electron reduction of the cobalt(II) center by photogenerated $Ru(bpy)_3^+$ might be coupled with protonation of the ligand.

The transient spectrum formed from the decay of the reduced $Ru(bpy)_3^+$, ascribable to the reduced catalyst 2^- (either in the protonated or non-protonated form), undergoes decay to the baseline in the 10–100 μ s timescale. The kinetics of this decay, followed at 600 nm, is independent of the catalyst concentration and displays well-behaved second-order profiles (Fig. 7).

As already shown in similar systems,⁵³ this process can be reasonably attributed to the bimolecular re-oxidation of the reduced catalyst 2^- by the photogenerated ascorbate radical.

Kinetic treatment of the associated decay allows for the determination of a bimolecular rate constant of $k = 3.9 \times 10^9 M^{-1} s^{-1}$ for this process.

The mechanistic information on the three-component photochemical system obtained from steady-state and time-resolved studies is summarized in Scheme 2. It should be pointed out that all these processes are bimolecular in nature and thus dependent on the concentration of the species involved.

Accordingly, while the charge recombination processes are efficient in the transient absorption experiments, this cannot be directly extracted to the continuous photolysis conditions.

Firstly, the concentration of these transient species is typically orders of magnitude lower due to the different irradiation power. Secondly, during continuous irradiation, subsequent electron and proton transfer to the cobalt complex are expected to take place, thus altering the concentration of the corresponding intermediates. Also, competition of the charge recombination reaction with the disproportionation of the ascorbate radical ($k \approx 8 \times 10^7 M^{-1} s^{-1}$),^{55,56} on the basis of the “sacrificial” nature of the ascorbic acid electron donor, should be considered.

3.3 Theoretical calculations

Calculation of UV-Vis absorption spectra of the intermediates was used here to corroborate the transient absorption results discussed above, which suggest the formation of a Co(I)

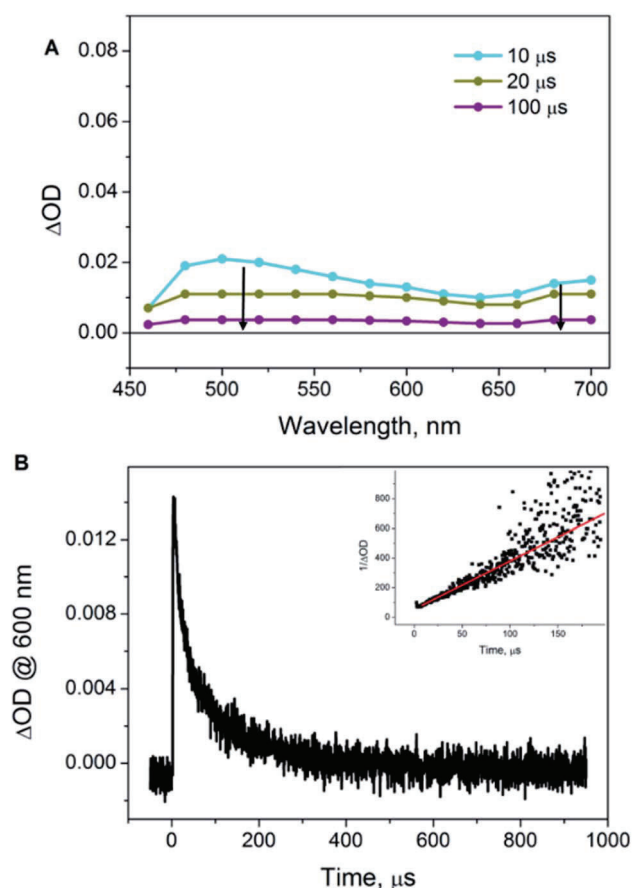
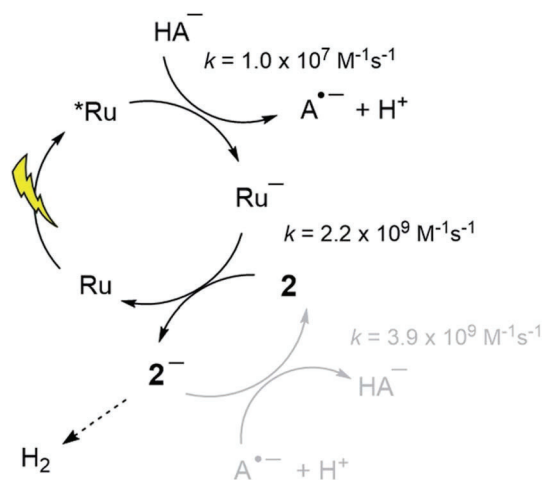


Fig. 7 Laser flash photolysis experiments (excitation at 532 nm) of N_2 -purged solutions containing 50 μM $\text{Ru}(\text{bpy})_3\text{Cl}_2 \cdot 6\text{H}_2\text{O}$, 0.1 M ascorbic acid, and 0.1 mM **2** in 1 M acetate buffer (pH 4): (A) spectral evolution between 10 and 100 μs ; (B) kinetic trace at 600 nm; (inset) second-order kinetics treatment for the estimation of the bimolecular rate constant, $\Delta\epsilon$ (600 nm) = 1500 $\text{M}^{-1}\text{cm}^{-1}$ and a path length of 0.74 have been used⁵⁴ to estimate the concentration of the 2^- species.

intermediate rather than a Co(III)-H species. The absorption spectra of complex **2** (hereafter Co(II)), the reduced species Co(I) and the three possible protonated reduced species, Co(III)-H (protonation on the metal center), Co(I)-BPY1H and Co(I)-BPY2H (the nomenclature is shown in Fig. S1†), were calculated using unrestricted TD-DFT (B3LYP) and are displayed in the right panel of Fig. 8, while some representative (more intense) excitations are listed in Table S3† and analyzed in terms of the associated density difference between the excited and the ground state. In the left panel of Fig. 8, the structures of the optimized intermediates are also shown. A first comment concerns the perfect agreement between the experimental absorption spectrum of complex **2** recorded in water (Fig. S17†) and the calculated one (black line in Fig. 8), which shows an intense peak centered at 300 nm and a weak shoulder at around 350 nm.

As listed in Table S3,† the intense absorption of complex **2** at 300 nm is dominated by three transitions involving mixed metal-ligand to ligand (MLL') and metal to ligand (ML) excitations, as displayed by the corresponding isodensity plots of the density difference between the excited and the ground state, also



Scheme 2 Primary photoinduced processes with related kinetics for light-driven hydrogen generation by the three-component system based on $\text{Ru}(\text{bpy})_3^{2+}$ (Ru) as the photosensitizer, ascorbic acid as the sacrificial electron donor (HA^- and $\text{A}^{\bullet-}$ are the ascorbate anion and radical, respectively), and **2** as the catalyst. Forward, favourable processes are shown in black; backward, short-circuiting processes are shown in grey.

displayed in Table S3.† The weaker band appearing at ~ 350 nm is instead ascribable to a pure metal to bipyridine excitation. Compared to complex **2**, the reduced species Co(I) is characterized by a completely different spectral profile (red line in Fig. 8), with a less intense but broadened absorption in the UV-Vis region extending up to the NIR and a clear absorption band between 600 and 700 nm. This is in agreement with the measured absorption spectra of a related Co(I) species²³ and nicely supports the assignment of the transient absorption to a Co(I) intermediate. The low energy absorption (600–700 nm) mainly involves excitations from the reduced mixed Co-BPY1 orbital (see the 129 β orbital in Fig. S1†) toward empty metal-ligand or pure ligand orbitals, as displayed in the density difference isosurface plots associated with the 13th and 14th excited states (Table S3†). In the 300–500 nm region, a three-band profile appears, characterized by mixed MLL', ligand-to-ligand (LL') and inter-ligand (IL) excitations, involving excitations out of the highest occupied α and β orbitals. As shown in Table S3,† the charge depletion (red lobes) always involves the reduced BPY1 ligand, with the electron being promoted (blue lobes) to the second BPY2 ligand. A sizeable destabilization (0.6–1.0 eV) of the occupied α and β Kohn–Sham orbitals accompanied by only a minor upshift of the unoccupied ones (0.3–0.4 eV) explains the overall red shift of the absorption spectrum and the absorption in the NIR portion of the spectrum. The protonation of the reduced species at the metal center, *i.e.* Co(III)-H , completely alters the optical properties of the reduced complex. The absorption spectrum of the Co(III)-H complex (yellow line in Fig. 8) closely resembles that of Co(II) , with an intense band appearing around 300 nm. A closer look at the results reveals that this is the direct consequence of the strong energetic stabilization of the occupied and virtual Kohn–Sham orbitals, whose eigenvalues are close to the ones obtained for the Co(II) species, which follows the protonation process. For the optimized Co(III)-H intermediate in water, the predicted Co-H

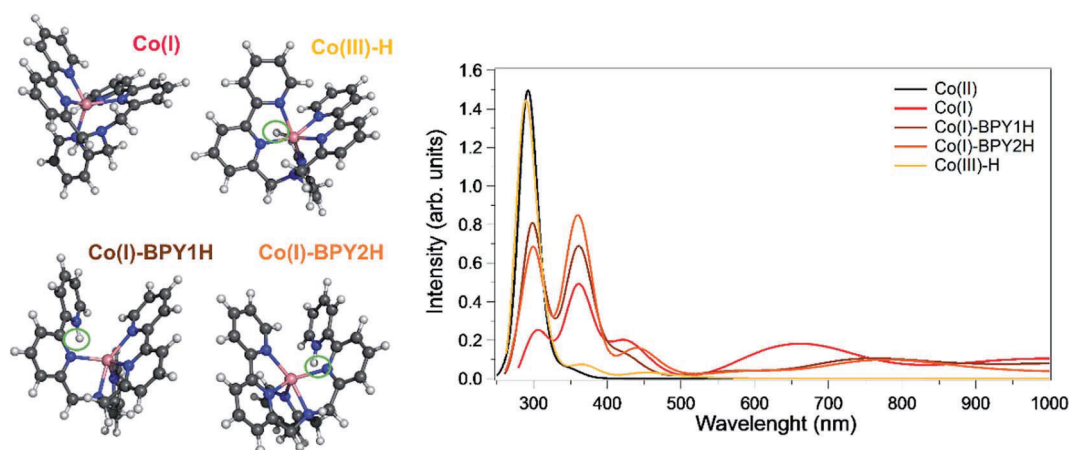


Fig. 8 Right: calculated absorption spectra of various intermediate species (Co(I) red line, Co(III)-H yellow line, Co(I)-BPY1H brown line and Co(I)-BPY2H orange line) and of the original catalyst (Co(II) black line); left: optimized ground state structures and labelling of the different intermediates considered.

bond polarization yields positive charges of 0.25 and 1.38 a.u. on the H and Co atoms, respectively, with a bond distance of 1.467 Å. The two lowest energy peaks at ~ 450 and ~ 370 nm (Table S3[†]) are ascribable to excited states having similar nature and characterized by charge transfer from mixed ML orbitals to the H and N atoms (on the bipyridines; see the density difference plots for states 8 and 11 in Table S3[†]). The higher-energy intense band is instead a complex mixing of different MLL', LL', IL and ML excitations. This result is fully supported by the experimental evidence found for another Co system,²³ since the absorption spectra of Co(II) and Co(III)-H present a coincident band at about 300 nm and that of Co(III)-H also shows a weak and broadened band at about 480 nm; the absorption spectrum of Co(I) is, on the other hand, completely different, as discussed above.

Besides the protonation of the Co(I) complex on the metal, we investigated if protonation could occur on bipyridine ligands associated with partial decoordination. The protonation of the reduced species on the bipyridines (Co(I)-BPY1H and Co(I)-BPY2H), as expected, yields intermediates showing an absorption profile closely resembling that of Co(I), with the exception of the absorption band at about 560 nm, which is less intense and shifted at slightly lower energies (*ca.* 700–800 nm) in the case of the protonated reduced complexes. The Mulliken charge on the metal center is 1.43 and 1.45 a.u. in Co(I)-BPY1H and Co(I)-BPY2H, respectively, while in both cases a charge of $-0.65/+0.38$ is calculated for N/H. On the basis of the TD-DFT results, we can thus suggest the formation of a Co(I) intermediate, ruling out the appearance of the Co(III)-H hydride intermediate. Finally, the formation of the protonated Co(I)-BPY1H and Co(I)-BPY2H cannot be completely discarded, considering the similar absorption properties in the 600–800 nm region (see the red, orange and brown lines in Fig. 8).

3.4 Mechanistic considerations

As to the potential intermediates formed after the first reduction, energetic considerations based on the relative free energy changes associated with the formation of various intermediates

during the reaction (Table S4[†] and Fig. 9) seem to rule out the formation of Co(III)-H. In fact, the direct protonation of the metal center in Co(I) implies a ΔG of $+13.5$ kcal mol⁻¹, whilst the protonation of one of the bipyridine moieties is almost thermodynamically costless (see Fig. 9). As shown in Fig. S5,[†] moreover, the only other intermediate leading to a de-coordinated pyridine is Co(I)-PYH, requiring a ΔG of about 8 kcal mol⁻¹ after the first reduction step being therefore less favourable when compared to both Co(I)-BPY1H and Co(I)-BPY2H. In accordance with this reasoning, we have found that de-coordination of the BPY ligands from Co(I) – prior to protonation – is an accessible path requiring *ca.* 5 kcal mol⁻¹, while de-coordination of the PY ligand from Co(I) is energetically unfeasible (see Fig. S4 and Table S1[†]). On the other hand, protonation of the other pyridine moiety of both BPYs (producing Co(I)-BPY1'H and Co(I)-BPY2'H, Fig. S5[†]) does not allow this de-coordination because of the geometrical

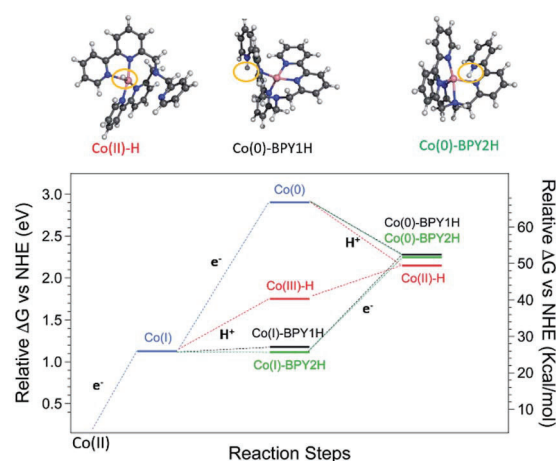


Fig. 9 Top: optimized molecular structure of the three possible intermediates after the two reductions and the protonation steps. Bottom: calculated free energy differences (in eV and kcal mol⁻¹) in acetonitrile (as an implicit solvent) for the possible reaction steps involved in the proposed mechanism.

constraints imposed by the methylamine and by the second coordinated pyridine. The second reduction/protonation, leads to three structurally different intermediates of comparable energies (Fig. 9): $\text{Co(II)}\text{-H}$, having the proton on the cobalt, and the two possible $\text{Co(0)}\text{-BPYH}$ intermediates, having one of the two bipyridines in a protonated form. As to the $\text{Co(II)}\text{-H}$ intermediate, the calculated Mulliken charge in solution on the Co atom is 1.16 a.u. with a spin density of 1.10; the H atom bonded to the metal (Co-H 1.53 Å) has a calculated charge of -0.42 a.u., clearly indicating that the Co-H bond is accepting almost the totality of the second electron (about 0.2 and 0.5 e^- on the metal and H, respectively). As is apparent in Fig. 9, important structural changes involve the metal coordination sphere, with dissociation of the $\text{Co-N}_{\text{pyridine}}$ bond (3.80 Å) and a strong elongation of the $\text{Co-N}_{\text{amine}}$ bond (2.75 Å). Within this intermediate, considering the pK_a of pyridine in water ($pK_a = 5.3$), protonation of the pendent pyridine is expected to occur at acidic pH resulting in a favourable proton relay for facilitating H-H bond formation,^{13,47} as recently proposed by Smolentsev and co-workers for a similar Co-based polypyridyl catalyst.²² The other two possible intermediates originating from the reduction of the two $\text{Co(I)}\text{-BPYH}$ species have a positive charge of 1.38 a.u. on the cobalt center, indicating that only a very small fraction of the second electron reduces the metal, while, as expected, it largely delocalizes on the bi-coordinated BPY ligand that is not protonated. The charges on the nitrogen atoms (N4 and N5 for $\text{Co(0)}\text{-BPY1H}$ and N1 and N2 for $\text{Co(0)}\text{-BPY2H}$, labelling in Fig. S1†) are indeed between -0.65 and -0.72 a.u. and Co-N bond distances are between 1.98 and 2.07 Å. Even in this option, the presence of a protonated BPY ligand produces pendent N bases, which possibly play the role of proton relays for the H_2 evolution step.§

In summary, DFT calculations suggest that hydrogen evolution catalyzed by the heptadentate Co(II) complex involves a first reduction/protonation step generating $\text{Co(I)}\text{-BPY1H}$ or $\text{Co(I)}\text{-BPY2H}$ intermediates featuring a cobalt(I) metal center and a protonated ligand. These intermediates are indeed expected to be more stable than the one attainable by direct protonation of the metal center (namely $\text{Co(III)}\text{-H}$). The population of $\text{Co(III)}\text{-H}$ in equilibrium with $\text{Co(I)}\text{-BPY1H}$ or $\text{Co(I)}\text{-BPY2H}$ can also be ruled out, since relatively high energy barriers (20–25 kcal mol^{-1}) are calculated for their interconversion (see Fig. S3†). These pieces of evidence are consistent with the experimental results obtained by transient absorption spectroscopy, which showed that the reduction of catalyst 2 by the photogenerated Ru(bpy)_3^+ reducing agent leads to the formation of a catalytic intermediate, 2^- . Such an intermediate can in fact be unambiguously assigned to a Co(I) species and can thus be compatible with both $\text{Co(I)}\text{-BPY1H}$ and $\text{Co(I)}\text{-BPY2H}$. Indeed, considering the pK_a of pyridine in water (5.3), protonation of the pyridine moiety detached from the bidentate bipyridine ligand is expected to occur at pH 4, at which hydrogen evolution experiments have been performed.³⁰

§ We should note that the calculation of full reaction paths including transition states connecting the intermediates is not presently achievable with state-of-the-art techniques, since it would require explicit modeling of electron and proton donors apart from the cobalt complex, most probably including dynamics effects, hence resulting in an overwhelming simulation.^{63,64}

Moreover, these considerations might also support the observation that in the electrochemical experiments the first EC process (namely reduction/protonation) from the cobalt(II) species occurs only when trifluoroacetic acid is used as the proton source. As a matter of fact, protonation of the pendent pyridine in $\text{Co(I)}\text{-BPY}$ ($pK_a = 12.5$ for pyridine in acetonitrile)⁵⁷ might be thermodynamically feasible using TFA ($pK_a = 12.7$ in acetonitrile),⁵⁷ while being substantially uphill when employing Et_3NH^+ ($pK_a = 18.8$ in acetonitrile).⁵⁷ An additional reduction step is indeed required in this latter instance to allow protonation (EEC process).

As to the second reduction step, a $\text{Co(II)}\text{-H}$ derivative, featuring a dangling pyridine moiety, can be envisaged based on purely thermodynamic considerations.

Calculations were then performed to establish the limiting step to possibly convert $\text{Co(0)}\text{-H-BPY1/2H}$ into $\text{Co(II)}\text{-H}$, corresponding to the proton transfer from bipyridine to the metal center (Fig. S2†). The energy barrier (27–28 kcal mol^{-1}) is similar to that observed with previously reported molecular catalysts^{62–64} and comparable to that observed for the interconversion between $\text{Co(I)}\text{BPY1/2H}$ and $\text{Co(III)}\text{-H}$ (see above). Taken together, these data suggest that the reduction of the $\text{Co(I)}\text{BPY1/2H}$ intermediate is coupled with intramolecular proton transfer from the

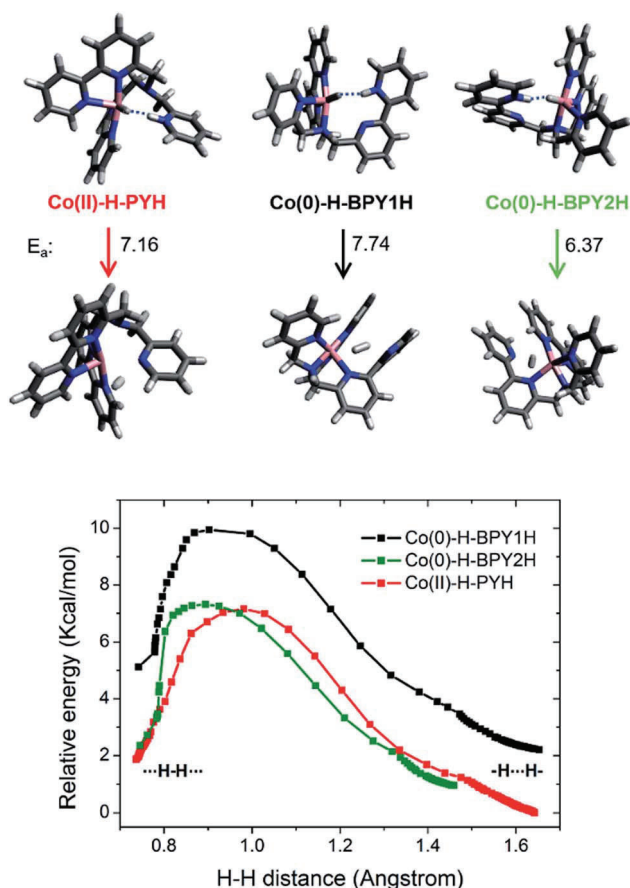


Fig. 10 Bottom: minimum energy path of the doubly protonated species from their respective minima ($-\text{H}\cdots\text{H}-$) to H_2 formation ($\cdots\text{H}-\text{H}\cdots$) as a function of the hydrogen interatomic distance. Top: initial (top) and final (bottom) structures of the minimum energy paths, including the required activation energy barrier (E_a) in kcal mol^{-1} .

bipyridine to the metal centre, with electron and proton transfers occurring in a concerted manner.^{58–60}

Within this hypothesis the presence of a pendent N base in the doubly reduced and protonated form could easily assist the eventual H–H bond formation. In this respect, the intrinsic ability of the catalyst to provide suitable proton relays in the singly and doubly reduced states represents a peculiar property of this class of catalysts and may potentially explain the high turnover frequencies measured under electrochemical conditions as well as the high quantum efficiencies observed in light-driven hydrogen evolution.³⁰

Finally, the possible generation of H₂, after protonation of the pyridine (Co(II)–H–PYH) or the Co center (Co(0)–H–BPY1H or Co(0)–H–BPY2H), was studied in detail by calculating their respective minimum energy path (Fig. 10). In all three cases, a highly feasible energy barrier (6–8 kcal mol^{−1}) was found, with the newly formed H₂ molecule almost released from the complex.

4. Conclusions

In this work, we have reported a detailed mechanistic study on a recently synthesized cobalt catalyst based on a hexadentate polypyridyl ligand that displays high activity for photoinduced hydrogen production in water. The electrochemical investigation in CH₃CN elucidated the kinetics of the catalytic process in the presence of TFA or Et₃NH⁺ as the proton source. Remarkably high rates have been observed, although at the expense of high overpotentials. Transient absorption studies and theoretical calculations showed that hydrogen evolution occurs *via* a series of electron and proton transfer processes involving formation of two relevant intermediates. The first one (Co(I)–BPY1H or Co(I)–BPY2H) is obtained upon electron transfer at the metal center followed by protonation at the ligand, and the second one (most plausibly Co(II)–H with a dangling pyridine) is obtained upon further electron transfer and protonation of the metal center. Within this picture, the presence of extended coordination sites based on multidentate polypyridyl ligands, besides providing a stable coordination environment to the cobalt center, plays a beneficial role in the catalytic mechanism by supplying suitable relays for promoting intramolecular proton transfer processes. In conclusion, such a multidisciplinary approach could suggest an affinity between the highly efficient reduction/protonation mechanism evidenced under photochemical conditions and the fast EC mechanism observed under electrochemical conditions in the presence of TFA. However, care should be taken when comparing mechanistic evidence derived from such different techniques: important factors like experimental conditions and the nature of the limiting steps might affect the significance of such a comparison. Further studies including those on modification of the ligands with different groups in the peripheral position to promote intramolecular proton transfer are currently in progress.

Conflicts of interest

There are no conflicts to declare.

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