


 Cite this: *Chem. Commun.*, 2020, 56, 12142

 Received 21st June 2020,
Accepted 17th September 2020

DOI: 10.1039/d0cc04310a

rsc.li/chemcomm

Hydrogenation and electrocatalytic reduction of carbon dioxide to formate with a single Co catalyst†

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A cobalt(i) complex is shown to be capable of both electrocatalytic reduction and hydrogenation of CO₂ to formate. Several proposed intermediates are characterized and thus form the basis for a proposed mechanism that allows for the dual reactivity: reduction of CO₂ via H₂ addition, and H⁺/e⁻ equivalents. The work makes use of a novel tris(phosphino) ligand. When a pendent amine is attached to the ligand, no change in catalytic reactivity is observed.

Reduction of CO₂ to fuels and/or fuel precursors is integral to minimize global warming and advance future energy schemes.¹ One approach is to use H₂ to hydrogenate CO₂ to formic acid (FA) or MeOH, though challenges include transportation of the gas, the necessity of high pressures of H₂ and/or elevated temperatures required for many catalysts, and improving catalyst performance. Lifecycle analysis for CO₂ hydrogenation to FA (using a homogeneous catalyst) suggests that this approach can decrease the net greenhouse gas emissions when compared to FA production from CO.² Despite showing an improvement, this analysis also indicates that H₂ production accounts for a significant amount of the emissions.³

An alternative method is the solar-derived electrochemical reduction of CO₂.⁴ While the 2e⁻/2H⁺ reduction of CO₂ to CO is well-established, reduction to FA has proven more challenging at homogenous systems due to competing H₂ production.⁵ This latter reaction can be thought of as an electrochemical hydrogenation. It necessitates a proton source capable of generating a metal hydride, and that the subsequent insertion of CO₂ be favoured over loss of H₂; both reactions have similar thermodynamic driving forces.⁴ Berben's group showed that selectivity for FA over H₂ can be achieved by exclusion of a pendent proton shuttle, which alters the kinetics of proton transfer to the

active-site.⁶ Recently, the groups of Kubiak⁷ and Yang⁵ have shown how H₂ production can be circumvented on thermodynamic arguments if the product is formate and not FA.

Given the widespread utility of hydrogenations, advancement of electrochemical alternatives may have significant impact. Waymouth showed that a Ru transfer hydrogenation catalyst can serve as an electrocatalyst for the oxidation of alcohols to ketones;⁸ in this system a cationic solvent species is proposed as an intermediate. With regards to CO₂ conversion to formate, Meyer and Brookhart reported that the 2e⁻/1H⁺ reduction of a PCP-ligated IrH(MeCN)₂⁺⁹ gives a species capable of inserting CO₂, with subsequent formate release. This system also necessitates a labile solvent molecule to avoid an 18-electron species that cannot be reduced. The limited literature examples of electrocatalytic hydrogenations re-enforce the need for better understanding how the two mechanistic pathways intersect, as well as establishing catalyst design criteria that allows for the desired reactivity.

Herein we describe a new family of Co complexes that perform both hydrogenation and electrocatalytic reduction of CO₂ to formate with excellent product selectivity. To our knowledge, this is the first system capable of this dual reactivity: reaction of CO₂ with H₂ to give FA, and reaction of CO₂ with H⁺ and e⁻ equivalents to selectively give FA (over competing H₂ production). Mechanistic studies indicate how the mechanisms are related. The ligand features a pendent amine that does not impact either reaction type.

To explore the dual reactivity of electrocatalytic reduction^{10,11} and hydrogenation¹²⁻¹⁵ of CO₂, phosphine-ligated Co complexes were targeted. Electrocatalytic generation of Co-H is known to occur for proton reduction catalysts;¹⁶ one example¹⁷ employs a tris(phosphino) ligand that has also been shown to catalytically hydrogenate CO₂ to MeOH using Co.¹⁸ To explore the role that pendent proton-relays may have on both catalytic pathways, a tris(phosphino) scaffold was developed that features a single pendent amine and is flexible in *mer/face* coordination to the metal.

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† Electronic supplementary information (ESI) available. CCDC 2010200–2010206, 2022544 and 2022545. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d0cc04310a



Chart 1 Ligands and abbreviations used in this study.

Tris(phosphino) ligands with a central phosphine that can be functionalized were prepared (Chart 1). The ligands that feature a pendent amine are readily prepared by addition of a suitable amine and paraformaldehyde to the precursor secondary phosphine (see ESI†).¹⁹ For this study, two tertiary amines (Bz_2NP_3 , Ph_2NP_3) were chosen for the pendent amine. A ligand with no amine, MeP_3 was also synthesized.²⁰

Metalation of the ligands is achieved by stirring equimolar ligand with CoCl_2 or $\text{Co}(\text{PPh}_3)_3\text{Cl}$ to give $(\text{P}_3)\text{CoCl}_2$ or $(\text{P}_3)\text{CoCl}$ respectively. Solid-state structures of $(\text{Bz}_2\text{NP}_3)\text{CoCl}_2$, $(\text{Ph}_2\text{NP}_3)\text{CoCl}_2$, $(\text{Bz}_2\text{NP}_3)\text{CoCl}$, $(\text{Ph}_2\text{NP}_3)\text{CoCl}$ and $(\text{MeP}_3)\text{CoCl}$ were obtained and exemplary structures shown in Fig. 1. All of the $\text{Co}(\text{II})$ species feature two inner-sphere chloride ions, and have distorted square pyramidal geometry ($\tau \sim 0.15$).²¹ The $\text{Co}(\text{I})$ species are 4-coordinate and are best described as distorted tetrahedral ($\tau \sim 0.75$).²² In no instances does the amine nitrogen coordinate the metal centre.

Hydrogenation of CO_2 under basic conditions was then explored with the $\text{Co}(\text{I})$ complexes (Table 1). No MeOH was observed by GC analysis, and the only product detected was formate.

Entries 1–3 of Table 1 indicate that the base strength impacts catalysis; increasing the base strength from K_3PO_4 to KO^tBu gives higher turnover number (TON), suggesting that a deprotonation event may limit the catalysis. Two of the $\text{Co}(\text{I})\text{Cl}$ species gave \sim quantitative TON with respect to base (entries 5, 8) when 100 eq. KO^tBU is employed. Increasing the amount of base diminishes catalysis (entries 5–7); a color change is noted when large amounts of base are added to the catalyst solution, suggestive of catalyst degradation. Recycling studies indicate that a viable catalyst is present at the end of catalysis, though the paramagnetic nature of the complexes makes it difficult to ascertain the identity (see ESI†).

Table 1 Catalytic hydrogenation of CO_2 to formate with $\text{Co}(\text{I})$

Entry	Catalyst	base + CO_2 + H_2		5 mmol catalyst (1 mol%) 120 °C, 16 h	HCOO^-
		30 bar	30 bar		
		Base	Equiv. of base	Formate	TON ^c
1 ^a	$(\text{Ph}_2\text{NP}_3)\text{CoCl}$	K_3PO_4	100	12	
2 ^a	$(\text{Ph}_2\text{NP}_3)\text{CoCl}$	KO^tBu	100	65 (± 6)	
3 ^a	$(\text{Ph}_2\text{NP}_3)\text{CoCl}$	DBU	100	51	
4 ^b	$[(\text{Ph}_2\text{NP}_3)\text{Co}(\text{MeCN})][\text{BARF}]$	KO^tBu	100	111 (± 4)	
5 ^b	$(\text{Bz}_2\text{NP}_3)\text{CoCl}$	KO^tBu	100	124 (± 9)	
6 ^b	$(\text{Bz}_2\text{NP}_3)\text{CoCl}$	KO^tBu	200	37 (± 8)	
7 ^b	$(\text{Bz}_2\text{NP}_3)\text{CoCl}$	KO^tBu	2000	242	
8 ^b	$(\text{MeP}_3)\text{CoCl}$	KO^tBu	100	122 (± 6)	
9 ^b	$(\text{Bz}_2\text{NP}_3)\text{CoCl}$	—	—	9	
10 ^{b,d}	—	KO^tBu	100	20	

^a Reactions run in 3 mL THF, at 150 °C for 20 h. ^b Reactions run in 10 mL THF with the conditions provided in the scheme. ^c Average of two runs with standard deviation in parenthesis. If no standard deviation, single run. ^d Run for 20 h.

To determine if the chloride is pertinent to catalysis, $\text{Ph}_2\text{NP}_3\text{CoCl}$ was treated with NaBARF to give cationic $[(\text{Ph}_2\text{NP}_3\text{Co}(\text{MeCN}))][\text{BARF}]$ (BARF = tetrakis[3,5-bis(trifluoromethyl)phenyl]borate), the structure of which is shown in Fig. 1. Using the cation as a catalyst for the hydrogenation of CO_2 improves the TON compared to that of the chloride (entries 2 and 4) and indicates that \sim quantitative conversion is possible using complexes of all ligands examined.

A mechanism that includes CO_2 insertion into a Co-H (to give Co-OCHO) seems plausible and hence this reactivity was explored. Addition of 2 eq. of NaBHET_3 to a stirring THF solution of $\text{Ph}_2\text{NP}_3\text{CoCl}_2$ at -70 °C results in formation of a new species. The ^{31}P NMR spectrum shows two singlets at 101.6 and 98.9 ppm, suggesting that a single diamagnetic $\text{Co}(\text{I})$ species has formed. The corresponding ^1H NMR spectrum shows a doublet of triplet at -11.35 ppm, consistent with a Co-H and IR analysis shows a stretch at 2082 cm^{-1} . Vapor diffusion of benzene into heptane gave crystals suitable for diffraction, and the solid-state structure indicates the formation of a dimeric species, $\{(\text{Ph}_2\text{NP}_3\text{CoH})_2(\mu\text{-N}_2)\}$ (Fig. 1). Each Co is 5-coordinate with the hydride in the plane of the three phosphines and the N_2 coordinating in the apical position.

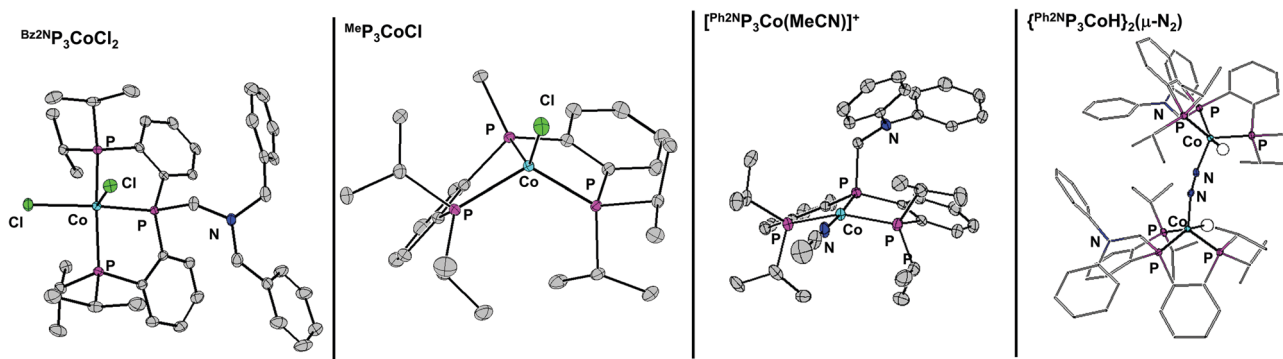


Fig. 1 50% thermal ellipsoid plot of several complexes. All hydrogen atoms not located in the difference map are removed for clarity. Only the cation of $[(\text{Ph}_2\text{NP}_3\text{Co}(\text{MeCN}))][\text{BARF}]$ is shown.

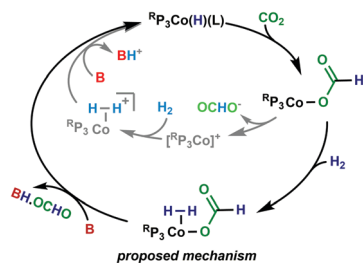
To determine if the hydride is sufficiently hydridic to insert CO₂, 0.85 atm of CO₂ was added to a solution of {^{Ph²N}P₃CoH}₂(μ-N₂). NMR analysis shows complete conversion of the diamagnetic hydride to a new paramagnetic species. Now, the IR spectrum shows disappearance of the hydride resonance and a new peak at 1628 cm⁻¹, consistent with formation of a species such as ^{Ph²N}P₃Co-OCHO. The related species, (PPh₃)₃Co(H)(N₂), inserts CO₂ to give (PPh₃)₃Co(OCHO),²³ and the corresponding formate stretch is at 1620 cm⁻¹.

A proposed mechanism is shown in Scheme 1. Entry into the catalytic cycle occurs from the reaction of ^RP₃CoCl with H₂ and base, which would give a 5-coordinate species such as ^RP₃Co(H)(L) (L = N₂ or solvent). Subsequent insertion of CO₂ gives ^RP₃Co-OCHO. The resulting 16-electron species ^RP₃Co-OCHO may then coordinate H₂ to give the proposed 18-electron ^RP₃Co(H₂)-OCHO. Base-mediated deprotonation of the bound H₂ coupled with formate loss regenerates ^RP₃Co(H)(L). Another mechanism would be deprotonation of the bound H₂ by the inner-sphere formate to generate ^RP₃Co(H)(L) and formic acid (B = formate in Scheme 1). Indeed, this may explain the >100 TON (entries 4, 5, 8) when only 100 equivalents of base is added, as well as the low TON obtained in the absence of base (entry 9). This is proposed to be a minor pathway that is viable in the absence of base, that proceeds with slower kinetics.

An alternative mechanism that has been proposed for related complexes is that the formate dissociates from the Co to give [^{Ph²N}P₃Co(MeCN)]⁺ and free formate (Scheme 1, inner pathway). The cation then coordinates H₂ and base-mediated deprotonation of the bound H₂¹² or oxidative addition product (not shown) then ensues.^{13,14} Given that both [^{Ph²N}P₃Co(MeCN)]⁺ and ^RP₃Co-OCHO are stable, this seems unlikely. Moreover, in related work on Ru we have shown that binding of formate to a cationic Ru centre is favorable.²⁴

Though it was envisioned that the pendent amine may facilitate deprotonation of H₂ *via* hydrogen-bonding,²⁵ the similar catalytic performances amongst all the catalysts indicates that such an effect, if present, is irrelevant in the catalytic hydrogenations investigated.

With the feasibility to hydrogenate CO₂ to formate established, we sought to determine if electrocatalytic hydrogenation of CO₂ is also accessible. The cyclic voltammograms (CVs) of several complexes are shown in Fig. 2. Cationic [^{Ph²N}P₃Co(MeCN)]⁺ shows a reversible reduction at -0.863 V (vs. Fc⁺⁰) that corresponds to the Co(II/I) couple. A second reduction event occurs at ~-1.9 V,



Scheme 1 Proposed mechanism for hydrogenation of CO₂ to formate, with alternate mechanism shown in grey.

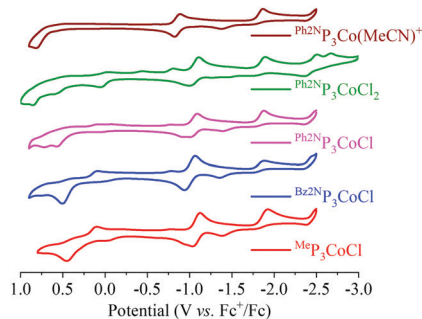


Fig. 2 Cyclic voltammograms of the various Co complexes. Conditions: GC working electrode, 0.1 M TBAPF₆ electrolyte in MeCN. Initial scan is in the positive direction.

with a return oxidation at ~-1.3 V. This tentatively is assigned to the Co(I/0) couple. Consistent with this, the reaction of ^{Ph²N}P₃CoCl with Na/Hg gives ^{Ph²N}P₃Co(N₂) (see ESI†); the irreversible nature of the couple is attributed to N₂ coordination upon reduction. The irreversibility may also be attributed to different numbers and types of L-type ligands upon reduction (L = MeCN or N₂). The CVs of ^{Ph²N}P₃CoCl₂ and ^{Ph²N}P₃CoCl are similar, and show a quasi-reversible reduction at -1.050 V. Both CVs show peaks that correspond to [^{Ph²N}P₃Co(MeCN)]⁺, consistent with chloride loss upon reduction to Co(0). Notably, the peaks that correspond to the second reduction are super-imposable with those in the CV of [^{Ph²N}P₃Co(MeCN)]⁺. Modest changes in the reduction potentials is anticipated as the R group on the central phosphine is varied.¹⁰ Indeed, the Co(II/I) potential of ^{Bz²N}P₃CoCl occurring at -1.013 V, and that of ^{Me}P₃CoCl at -1.089 V.

In the presence of 50 eq. water, no noticeable changes to the CVs are observed for all ^RP₃CoCl (Fig. 3 and ESI†). However, upon addition of CO₂, a catalytic current is observed, suggesting formation of CO or formate. The current increases further with 1617 eq. H₂O (3% by volume, see ESI†) at potentials close to the Co^{I/0} couple; other Co electrocatalysts reduce CO₂ at potentials well shifted from the redox couples of the catalyst.¹⁰ Indeed, rapid current enhancement at ~-2.5 V suggests that there may be two pathways for catalytic reduction.

Controlled potential electrolysis with 3% water and 0.85 atm of CO₂ at -2.1 V vs. Fc/Fc⁺ was conducted using ^{Me}P₃CoCl and

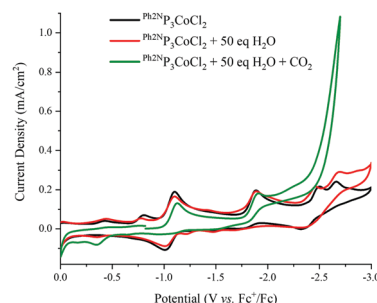
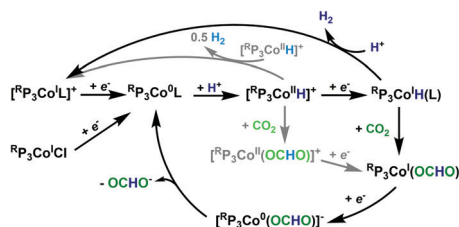


Fig. 3 Cyclic voltammograms of 1 mM ^{Ph²N}P₃CoCl₂ under various conditions. (Black): under N₂; (red): in the presence of 50 eq. H₂O; (green): in the presence of 50 eq. H₂O and CO₂. Conditions: GC working electrode, 0.1 M TBAPF₆ electrolyte in MeCN solvent, scan rate of 0.06 V s⁻¹, initial scan is positive.

Table 2 Product distribution of the controlled potential electrolysis (CPE) experiments^a

Complex	FE ^b H ₂	FE ^b CO	FE ^b HCOO ⁻
^M P ₃ CoCl	2.5 (±2.8)	nd ^c	58 (±15)
^{Bz2N} P ₃ CoCl	3.2 (±0.4)	nd ^c	36 (±18)

^a See ESI. ^b Faradaic efficiency; average of four runs, standard deviation given in parentheses. ^c None detected.



Scheme 2 Proposed (black) & alternative (gray) mechanisms for CO₂ and H⁺ reduction.

^{Bz2N}P₃CoCl as the catalyst (Table 2). This potential is chosen to see if catalysis does occur near the reduction potential of the complexes. In both instances, no CO was detected in the headspace, and H₂ is only produced in small quantities with both catalysts. No other gaseous products are produced, and the solution phase shows the presence of formate and MeOH.

The catalysts are stable, as ascertained by CVs after electrolysis and the steady current (see ESI[†]).

A proposed mechanism is shown in Scheme 2. Upon reduction to ^RP₃Co⁰L (L = N₂ or solvent), protonation ensues to give [^RP₃Co^HH]⁺. This is reduced at the electrode to give ^RP₃Co^IH, which then inserts CO₂ to give ^RP₃Co^I(OCHO); this sequence being identical to that in the hydrogenation reaction. Reduction to ^RP₃Co⁰(OCHO) and subsequent formate release then regenerates ^RP₃Co⁰L. The lack of lability of the formate in ^RP₃Co^I(OCHO) and the cathodic potential of catalysis is consistent with this EC mechanism. While we cannot rule out initial CO₂ insertion to [^RP₃Co^HH]⁺ followed by reduction, this reactivity is not known for this system. Finally, the pH of the solution increases during the course of catalysis, indicating that formate and not formic acid is lost.

Regarding proton reduction, the following can be gleaned. As ^RP₃Co^IH is stable, we rule out a bimetallic mechanism that would generate ^RP₃Co⁰L. A bimetallic mechanism from [^RP₃Co^HH]⁺ also seems unlikely, as it would not explain why H₂ is only produced in the presence of pendent amines; these species are also more sterically encumbering and hence should minimize this pathway on steric grounds. Protonation of ^RP₃Co^IH seems most plausible, and literature precedence is consistent with proton relays enhancing H₂ production over formate.⁶

The work presented here provides the first example of a well-defined catalyst that can hydrogenate CO₂ to formate and electrocatalytically reduce CO₂ to formate. Notably, the latter reaction occurs with good selectivity for formate. The stability

of several intermediates, including a cationic solvent species that seems essential for the dual reactivity, allows for further mechanistic insight. Optimization studies and detailed mechanistic work is ongoing.

The authors gratefully acknowledge the NSF CAREER (1945646), NSF REU (1659579) and start-up funds. NIH provided funds for the NMR facilities (1S10OD25241-01, 1C06RR017539-01A1, 3R01GM063540-17W1). We acknowledge Dr. Stacey J. Smith and BYU for the use of their single crystal X-ray instrumentation.

Conflicts of interest

There are no conflicts to declare.

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