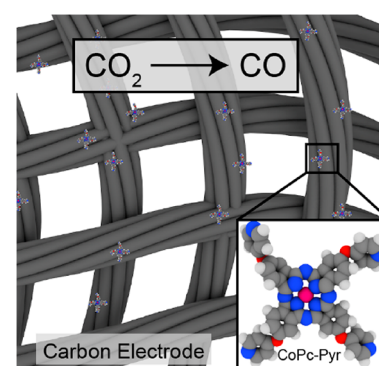


Heterogenized Pyridine-Substituted Cobalt(II) Phthalocyanine Yields Reduction of CO₂ by Tuning the Electron Affinity of the Co Center

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ABSTRACT: Conversion of CO₂ to reduced products is a promising route to alleviate irreversible climate change. Here we report the synthesis of a Co-based phthalocyanine with pyridine moieties (CoPc-Pyr), which is supported on a carbon electrode and shows Faradaic efficiency ~90% for CO at 490 mV of overpotential (−0.6 V vs reversible hydrogen electrode (RHE)). In addition, its catalytic activity at −0.7 V versus RHE surpasses other Co-based molecular and metal–organic framework catalysts for CO₂ reduction at this bias. Density functional theory calculations show that pyridine moieties enhance CO₂ adsorption and electron affinity of the Co center by an inductive effect, thus lowering the overpotential necessary for CO₂ conversion. Our study shows that CoPc-Pyr reduces CO₂ at lower overpotential and with higher activity than noble metal electrodes, such as silver.



1. INTRODUCTION

The need for renewable sources of sustainable energy has been a major scientific interest over the last several decades.^{1,2} In this context, the conversion of carbon dioxide (CO₂) into chemical fuels is an attractive way to reach a sustainable energy future.^{3,4} CO₂ removal from polluting sources could mitigate the effects of global warming,⁵ while its conversion could provide a sustainable way to produce carbon-based fuels.^{6–8} However, challenges such as the high stability of CO₂, its low reactivity to chemical transformation, and the lack of selectivity of many existing catalysts toward narrow product distributions hamper progress in this field. Researchers have tried to address this problem by electrochemical CO₂ reduction (CO₂R) using various metallic electrodes as electrocatalysts.^{9,10} The advantage of electrochemistry mainly lies in its compatibility with renewable energy sources such as solar photovoltaics, while allowing the possibility to alter the reaction pathway by tuning the applied potential. However, there are also several drawbacks. When electrochemical CO₂R is performed in an aqueous environment, it is always in competition with the undesired hydrogen evolution reaction (HER).¹¹ As such, an ideal CO₂R catalyst should selectively guide CO₂ to the desired product while minimizing parasitic current to H₂ production. Successful CO₂R has been demonstrated using transition-metal catalysts,¹² semiconductors,^{13,14} and metal ion complexes.¹⁵ However, while these catalysts exhibit activity for

CO₂R, problems with stability and poor selectivity limit their commercial applicability.

Among all of the CO₂R products, carbon monoxide (CO) requires the lowest overpotential to obtain, and its industrial importance as a feedstock for Fischer–Tropsch chemistry makes it an attractive target. While CO can be produced electrochemically on silver or gold, there is a need for a more abundant electrode material to facilitate this conversion. In this view, molecular catalysts based on cyclam, porphyrin, and phthalocyanines offer the possibility to have high selectivity and high yield for CO₂R by using non-noble metals.¹⁵ In particular, phthalocyanines are a class of aromatic molecules with good chemical and thermal stability that are known to be efficient catalysts for a wide range of reactions that make them a promising choice for CO₂R electrocatalysis, including generating product mixtures of CO and H₂ under CO₂R conditions.^{16–20} Co(II)- and Fe(II)-based examples were found to be effective in (photo)electrocatalytic CO₂ reduction producing CO and formate.^{21,22} Nonetheless, while the catalytic properties of Co(II) phthalocyanine (CoPc) have

been known for several decades, there are limited examples of highly selective CO₂R at lower overpotentials.^{23,24} Continued research in catalyst modification could bring about the desired properties in phthalocyanine catalysts.

Apart from tuning the electronic properties of the molecular catalysts with coordinating molecules in the axial position,²⁵ building composite electrodes is equally important to integrating molecular catalysts into electrodes.^{15,26} For example, Kramer et al. showed that grafting CoPc onto a pyridine-substituted polymer increases the selectivity of CO likely due to axial coordination with the metal center.^{27,28} In its application with phthalocyanine, pyridine has been used as a ligand for the metal center, limiting its use as coordinating agent.²⁹ Pyridine's other possible role as a peripheral substituent could yield changes to the catalytic properties by either changing the electronic density on the macrocycle or giving another catalytic path versus the one that involves coordination of CO₂ to the Co(II) center.^{24,30}

Herein, we report the synthesis of a pyridine-substituted cobalt phthalocyanine (CoPc-Pyr) and compare its activity with a non-substituted one (CoPc). We fabricate a composite electrode by supporting these derivatives onto a carbon paper. The heterogenized compound shows the beneficial effect of the pyridine moieties on the selectivity for CO and on the onset potential for CO₂ reduction measuring a Faradaic efficiency (FE%) ~90% for CO at only 490 mV of overpotential (-0.6 V vs reversible hydrogen electrode (RHE)). To the best of our knowledge, this may be the highest FE for CO at this overpotential and is higher than the one obtained for CO with CoPc in the same identical conditions. This finding is supported by our density functional theory (DFT) calculations, which show that the pyridine substituents provide an inductive effect to enhance CO₂ adsorption and the electron affinities of the metal center, resulting in lower overpotentials and greater selectivity for CO₂R versus HER.

2. EXPERIMENTAL SECTION

2.1. Methods and Instruments. FT-IR spectra were recorded on a JASCO FT-IR 660 Plus spectrometer. NMR spectra were recorded on a Bruker Avance 400 (400 MHz) using CDCl₃ as solvent. Product detection data were acquired by Agilent Mass Hunter system software (version 6.0). The mass spectrometer was operated in full-scan mode in the *m/z* range of 100–1000.

The surface chemical composition was obtained by X-ray photoelectron spectroscopy (XPS) on a Kratos Axis Ultra DLD system at a takeoff angle of 0° relative to the surface normal at room temperature. An aliquot of 100 μL of 1 × 10⁻⁴ M CoPc-Pyr in trifluoroethanol (TFE) was dropcasted onto silicon wafer. It was air-dried for 18 h. A monochromatic Al Kα source (*hν* = 1486.6 eV) was used to excite the core-level electrons of the material. C 1s, N 1s, O 1s, and Co 2p core levels were collected, with pass energy of 20 eV, step size of 0.05 eV, and eight sweeps each to obtain a good signal-to-noise ratio. The sample was loaded to the chamber a day prior to the measurement to achieve a good vacuum condition (7.5 × 10⁻⁹ Torr). Spectral fitting was conducted using CasaXPS analysis software. Spectral positions were corrected using adventitious carbon by shifting the C 1s core level position to 284.8 eV.

UV-Vis spectra in solution were obtained on a Shimadzu SolidSpec-3700 UV/vis/NIR spectrometer (NIR = near-infrared). A diluted solution of Co-Pc-Pyr (4) was prepared in TFE, dimethylformamide (DMF), or ethyl acetate. In addition, two CoPc-Pyr (4) modified electrodes were placed into a centrifuge tube after electrochemical testing. An aliquot (5 mL) of TFE was added to dissolve ~4.6 × 10⁻⁹ mmol of CoPc-Pyr, which underwent

electrochemical CO₂ reduction. It was vortexed for 30 s to ensure that almost all of the CoPc-Pyr on the electrodes dissolved in TFE. This solution was used for UV-vis analysis.

Inductively coupled plasma mass spectrometry (ICP-MS) measurements were performed with an Agilent 7900 using a standard configuration consisting of Micromist nebulizer and quartz sample introduction system of Scott type with a spray chamber and a one-piece torch with a 2.5 mm inner diameter injector; Ni cones were used throughout. Internal standards were added online via the sample delivery peristaltic pump. The instrument was optimized using default autotune conditions directly from the MassHunter Workstation for U-HMI. Samples were measured in helium collision mode for all analytes.

Electrochemical measurements were performed in an electrochemical cell made from poly(ether ether ketone) (PEEK) in-house using a commercial benchtop milling machine from Othermill. Each half-cell is 5.1 cm wide, 5.1 cm tall, and 1.27 cm thick. Each half has a circular hole on one face with a radius of 0.64 cm, which slopes to an opening on the other face that is two semicircles separated by 0.64 cm to form an oblong circle. The electrochemical cell was cleaned in 20% nitric acid in Millipore water overnight. Then, the cell was rinsed with Millipore water three times and sonicated in Millipore water for 30 min. It was dried with nitrogen gas before it was assembled for electrochemically testing the fabricated working electrodes. On the cathode side three ports were added, one on the bottom for the CO₂ inlet (through a glass frit of Adam & Chittenden), one on the side for Ag/AgCl reference electrode (LF-1, 1.0 mm outer diameter, Innovative Instruments, Inc.), and a third one on the top for gas chromatography (GC) connection. On the anode side, only one port for O₂ evolution was added. The two electrodes (working and counter) were placed and sealed against the external part of the compartment through two squeezing plates of polyethylene. Seals between layers were created with Viton o-rings inserted into milled channels in the PEEK half cells, and a Selemion membrane was placed between the two compartments. The gas flow was maintained by Alicat mass flow controllers with mass flow meters downstream to leak check. Product detection analysis was conducted in such homemade electrochemical cell by using Pt as counter electrode and 0.05 M K₂CO₃ (99.995%) as electrolyte.³¹ The two compartments of the cell were divided by a Selemion membrane, and CO₂ was continuously purged in the cell during all of the experiment at a flow rate of 5 sccm. The gaseous products were detected by in-line Shimadzu 490GC, while the liquid products were analyzed using UltiMate 3000 HPLC at the end of the electrochemical experiment.

The procedure for taking into account the impedance compensation in the calculation of the applied voltage was similar to the one reported by Kuhl et al.¹² Briefly, impedance spectroscopy was performed to calculate the resistance of the solution that normally is not compensated by the potentiostat, and that causes a voltage drop between the reference and the working electrode. A measurement of the real and imaginary contribution to the impedance at open-circuit voltage at various frequencies was performed. Considering that, at high frequency, the contributions to the impedance other than the resistance of the solution are negligible, a scan from 100 Hz to 0.5 MHz was performed. 5 kHz was found to be the appropriate frequency to determine only the real contribution to the resistance solution, and this value was used for all of the measurements. The potentiostat was allowed to compensate for the resistance at 5 kHz for the 85% (after this value the current becomes unstable) of its total value; the remaining 15% was manually compensated after the measurement using Ohm's law $V = IR$.

Cyclic voltammograms (CVs) were collected after 20 min of CO₂ purging at 5 sccm to register the performance of the electrode. The chronoamperometry measurement (CA) started while continuously flowing the gas. A constant potential was applied for 40 min, and after 10 min samples were taken every 10 min. Each CA was repeated three times with three different electrodes, and the results reported are the average of the three measurements. Another CV was registered at the end of each experiment to look for any eventual modification of the electrode after the CA. Both H₂ and CO were detected on two

different molecular sieve columns (MOL 5A-Agilent): for H₂ detection, helium was used as balance gas, and the temperature of the column was maintained constant at 170 °C as well as the pressure (207 kPa); for CO detection, N₂ was used as balance gas.

Turnover frequency (TOF) calculations are based on Faradaic efficiency (FE) and current using

$$\text{TOF} = \frac{Q \times \text{FE}}{t \times N \times F \times n_{\text{catalyst}}} = \frac{i \times \text{FE}}{N \times F \times n_{\text{catalyst}}}$$

where Q is the total charge passed in time t , i is the current, FE is the Faradaic efficiency for the desired product, N is the number of electrons in the half reaction ($N = 2$ for CO₂ to CO conversion), F is the Faraday constant ($F = 96485$ C/mol electrons), and n_{catalyst} is the mole of catalyst CoPc-Pyr deposited onto the active area of carbon paper. n_{catalyst} was quantified by coulometric methods by integrating the current of the cyclic voltammograms at ~0.25 V versus RHE and ~0.1 V versus RHE peaks for CoPc-Pyr and CoPc, which corresponds to the Co(II) → Co(I) reduction. The loading for CoPc-Pyr was estimated to be 10⁻⁸ moles, whereas the loading for the CoPc was estimated to be 2.3 × 10⁻⁹ moles. The total amount of CoPc-Pyr and CoPc loaded onto the electrode was measured by ICP-MS and estimated to be on the order of 10⁻⁸ moles in both cases. TOF calculations were based on the number of active catalysts measured electrochemically.

Spin-unrestricted DFT calculations were performed using the Gaussian suite of programs. Geometries were optimized at the ωB97X-D/6-31G(d,p) level, and the reported energies were computed with the same method but adding diffuse functions to heavy atoms (i.e., 6-31+G(d,p) basis), to better describe negatively charged ions (test calculations indicate that the addition of diffuse functions can affect energies and Mulliken charges significantly but not the geometries, which are rather constrained due to conjugation). All calculations used the polarizable continuum model (PCM) to model solvent effects (water). The IQmol software was used for orbital visualization and analysis of results. Energies for reactions involving simultaneous proton and electron transfer were computed using the computational hydrogen electrode model. Zero-point energy (ZPE) and vibrational thermal corrections were calculated according to the rigid-rotor/harmonic-oscillator interpolation method of Grimme.³²

2.2. Materials. DMF, potassium carbonate, dichloromethane, methanol, hydrochloric acid, 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), 1-hexanol, dimethyl sulfoxide (DMSO), 4-nitrophthalonitrile, and 4-hydroxy-pyridine were purchased from Sigma-Aldrich. And, they were used as received. Selemion AMV anion-exchange membrane was purchased from AGC Engineering Co., Ltd. Carbon paper (Sigracet 29BC) was purchased from Fuel Cell Store. Carbon dioxide (99.995%) and nitrogen (99.999%) were obtained from Praxair.

2.2.1. Synthesis of 4-(4-Oxypyridinyl)phthalonitrile (3). 4-(4-Oxypyridinyl)phthalonitrile (3) was synthesized with the following procedure (Scheme S1, Supporting Information): in a 50 mL round-bottom flask, 4-nitrophthalonitrile (2) (5.78 mmol, 1.0 g) was mixed with 4-hydroxypyridine (1) (6.31 mmol, 600 mg). Thirty milliliters of DMSO were added. The solution was heated at 60 °C, and K₂CO₃ (14.5 mmol, 2.0 g) was slowly added. The suspension was then heated at reflux for 16 h under N₂ atmosphere. The crude of reaction was filtered to remove all the unreacted K₂CO₃, and 100 mL of water were added to the filtrate. A solution of CH₂Cl₂/methanol (MeOH) 5% was used to extract the product of synthesis from the water/DMF solution. The complete extraction was followed by thin-layer chromatography (TLC) (R_f of PyO_Pn ≈ 0.46 in CH₂Cl₂/MeOH 10% solution). The organic solvent was removed under low pressure. The pale yellow solid was dried in an oven at 60 °C. A second step of purification was needed to remove the unreacted 1 from the obtained powder. The powder was washed several times with a small volume of 10% NaOH solution. Various isomers of 3 (700 mg, 55% yield) were obtained. The final product was characterized with ¹H NMR (Figure S1, Supporting Information), ¹³C NMR (Figure S2, Supporting

Information), and Fourier transform infrared (FTIR) spectroscopy (Figure S3, Supporting Information).

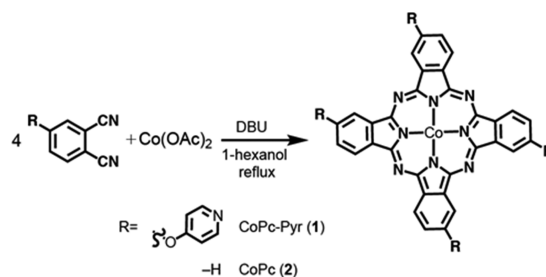
2.2.2. Synthesis of CoPc-Pyr (4). CoPc-Pyr (4) was synthesized in the following way (Scheme S2, Supporting Information): the isomers mixture of 3 (2.71 mmol, 600 mg) was added into a 50 mL three-necked round-bottom flask. Excess of cobalt acetate (Co(OAc)₂) (0.50 mmol, 125 mg) was added into the flask. They were dissolved in 5 mL of 1-hexanol. The reaction was heated under inert atmosphere (N₂). Once the reflux temperature (160 °C) was reached, DBU (0.20 mmol, 30 μL) was added to the reaction. The color of solution turned from pale yellow to light blue, the intensity of which intensified during the time. The reaction refluxed for 12 h. The solvent was removed under low pressure. The blue precipitate was washed several times with HCl solution (pH = 3) and with MeOH to eliminate the unreacted precursor. 4 is soluble in DMF, DMSO, and partially in trifluoroethanol and 1 M HCl solution. The final product was characterized with FTIR (Figure S4, Supporting Information), XPS (Figures S5–S8, Supporting Information), and UV–vis (Figure S9, Supporting Information).

2.3. Electrode Preparation. The carbon paper electrode (Sigracet 29BC) was cut in a circle with a diameter of 1.25 cm and immersed for 15 min in 65% HNO₃ to remove iron impurities possibly present in the fibers. Application of the catalyst to the electrode was achieved by dip coating. The carbon paper was dip-coated for 1 min in a solution of 10⁻⁴ M CoPc-Pyr in trifluoroethanol and 10⁻⁴ M CoPc-Pyr in DMF solution and allowed to dry overnight under vacuum at 80 °C to remove the possible trace of solvent. The same procedure was followed also for the CoPc catalyst. In particular, 23.2 mg of CoPc was dissolved in 4 mL of DMF resulting in a 0.6 × 10⁻³ M solution of phthalocyanine in DMF. This solution was further diluted to obtain the dip-coating solution. The final loading of catalyst on the carbon electrode was estimated to be ~2.3 × 10⁻⁹ mmol by integration of the cyclic voltammetry peak at ~0.14 V versus RHE.

3. RESULTS AND DISCUSSION

The CoPc-Pyr was synthesized by cyclotetramerization of its precursor in the presence of Co(II) salt. Briefly, a nucleophilic substitution of a nitro group on 4-nitrophthalonitrile by 4-hydroxypyridine gave the phthalocyanine precursor, which was cyclotetramerized in the presence of cobalt acetate (see Experimental Section, Scheme 1, and Figures S1–S9 in the

Scheme 1. Synthesis of Phthalocyanine-Based CO₂ Reduction Catalyst



Supporting Information for full details). To assess the catalytic performance of CoPc-Pyr, cyclic voltammetry of both CoPc and CoPc-Pyr heterogenized on a carbon paper electrode was performed under CO₂ and N₂ atmosphere to determine catalytic activity (Figure 1).

The electrochemical reduction of CoPc in the absence of CO₂ shows a reversible peak around 0.15 V versus RHE and a quasi-reversible one at -0.4 V versus Ag/AgCl. The first redox couple arises from the reduction of Co(II) to Co(I) (generating [Co(I)Pc-Pyr]¹⁻), while the second reduction produces [Co(I)Pc-Pyr]²⁻, where the charge can be

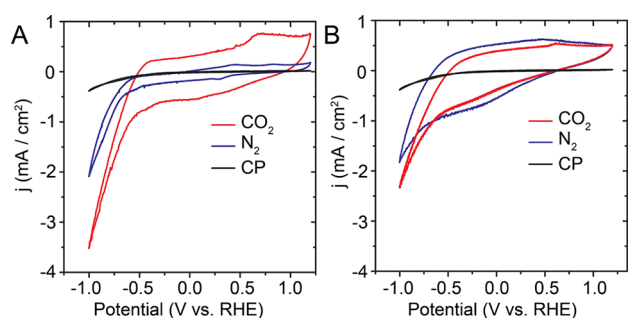


Figure 1. Cyclic voltammetry of CoPc-Pyr (A) and CoPc (B) deposited on carbon paper under CO₂ (red) and N₂ (blue) atmospheres in 0.05 M K₂CO₃ at 100 mV/s with 5 sccm for the flow rate of CO₂ (pH = 6.8). CV of carbon paper (Cp) in CO₂ atmosphere (black) is reported for comparison.

delocalized onto the macrocycle. These peaks are still present, even if slightly shifted, when the solution is saturated with CO₂. Moreover, the second peak is closely associated with the potential for CO₂ reduction (−0.4 V vs RHE), suggesting that [Co(I)Pc-Pyr]^{2−} is the catalytically active species.

To assess the CO₂R abilities of CoPc-Pyr and the resulting product distribution, we loaded the CoPc-Pyr on a carbon paper electrode and used it as a cathode in a custom reaction cell consisting of a Pt counter-electrode and Selemion membrane (Figure 2a,b; see Experimental Section for additional details).

For CoPc-Pyr, a high FE% for CO (95%) can be measured at low potential (−0.7 V vs RHE at pH 6.8). Interestingly, good selectivity (2:1 CO/H₂) for the CO₂R is still present at very low current and more positive potential (−0.45 V vs RHE). Considering that the thermodynamic potential for CO formation is −0.11 V versus RHE and that this potential is increased by the reaction kinetics, the CoPc-Pyr shows a

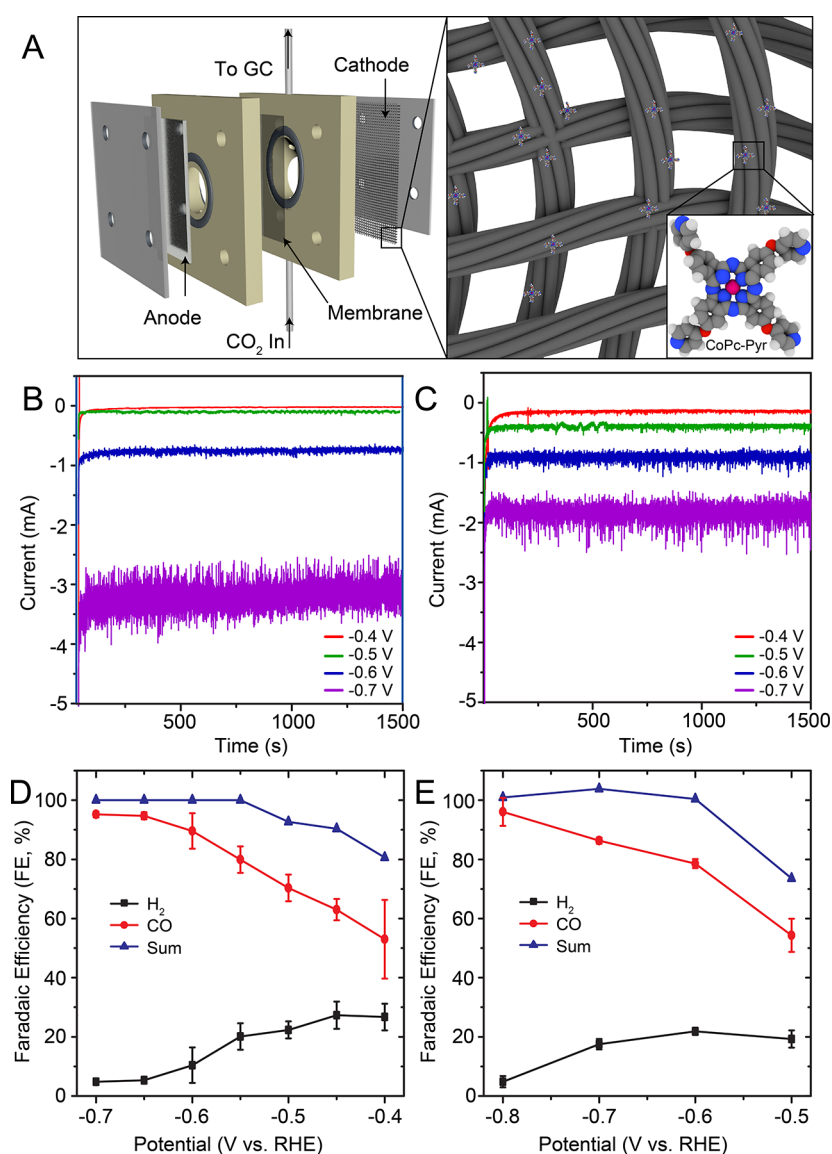


Figure 2. (A) Schematic of a two-chamber electrochemical cell used for CO₂R experiments (left). Carbon paper cathode with physisorbed CoPc-Pyr used as working electrode (right). Chronoamperometry measurements for (B) CoPc-Pyr and (C) CoPc at various potentials under CO₂R conditions vs RHE. Faradaic efficiency plots for (D) CoPc-Pyr and (E) CoPc. For the sake of completeness, a full list of the chronoamperograms at all different potentials tested for CoPc-Pyr are reported in the Supporting Information (Figure S10).

Table 1. Activity Comparison of Highly Efficient Co-Based Electrocatalysts^a

catalyst	applied potential (V vs RHE)	electrolyte	FE CO	current density (mA/cm ²)	TOF (s ⁻¹)	ref
CoPc-Pyr	-0.7	0.05M K ₂ CO ₃	95%	2.5 ^b	6.9	this study
CoPc	-0.7	0.05M K ₂ CO ₃	86%	1.3 ^b	3.5	this study
perfluorinated CoPc	-0.8	0.5 M NaHCO ₃	93%	4.4	1.6	19
CoPc-P4VP	-0.7	0.1 M NaH ₂ PO ₄	92%	2.9	6.3	28
COF-367-Co	-0.7	0.5 M KHCO ₃	91%	3.3	0.04	34
COF-367-Co (10%)	-0.7	0.5 M KHCO ₃	70%	1.4	0.1	34
COF-367-Co (1%)	-0.7	0.5 M KHCO ₃	40%	0.45	0.2	34

^aThese testing conditions were chosen for each catalyst to lead to best performance, and more details are reported in the original citations.

^bCurrent density was obtained by dividing the measured current by the area of the electrode (1.25 cm², see [Experimental Section](#)).

reduced overpotential of 290 mV for conversion of CO₂ to CO. CoPc-Pyr is also able to catalyze the conversion of CO₂ to CO with a FE% ~90% at -0.6 V versus RHE (490 mV of overpotential). In contrast, CoPc has an overpotential of 390 mV for conversion of CO₂ to CO and catalyzes the conversion of CO₂ to CO with ~80% FE at -0.6 V versus RHE. Compared to polycrystalline Ag, which is one of the most selective catalysts for CO₂ to CO formation and which shows an onset potential for CO₂ reduction ca. -0.7 V versus RHE and 98% FE for CO at -1.0 V versus RHE,³³ CoPc-Pyr has an onset for the CO₂R more positive than noble-metal electrode.

In addition to its high selectivity toward CO production, CoPc-Pyr demonstrates high catalytic performance for CO₂ reduction to CO. Considering the electrochemically active CoPc-Pyr (10⁻⁸ moles), at applied potential of -0.7 V versus RHE, the catalyst has turnover frequency of 6.9 s⁻¹ while maintaining its selectivity at 95% FE to CO ([Table 1](#), [Table S1](#)). The Pyr moiety increases the FE for CO and doubles the TOF with respect to the unsubstituted derivative at -0.7 V versus RHE. The CoPc-Pyr catalyst has similar selectivity but higher TOF when compared to perfluorinated CoPc, when the latter operates at a slightly higher overpotential (-0.8 V vs RHE). Compared to CoPc-P4VP, the electrode where CoPc immobilized in a poly(4-vinylpyridine) (P4VP), CoPc-Pyr has slightly higher TOF and more pronounced CO selectivity.²⁸ Compared to other heterogeneous cobalt catalysts with 4-N ligand like COF-367-Co, CoPc-Pyr shows significantly higher catalytic activity and selectivity.³⁴ It is noted that, as reported by Liang, Wang and co-workers, immobilization of the catalyst on carbon nanotubes may help to further decrease the measured overpotential.³⁵ In addition, Manthiram and co-workers suggest that, due to aggregation of catalysts with extended π - π networks, optimization of the catalyst loading on the electrode could have a positive effect on increasing the apparent TOF of the catalyst.²³ In this view, CoPc-Pyr has a more extended π - π network than CoPc that can aid aggregation, whereas its structure causes increased steric hindrance and, hence, inhibits aggregation. This observation is also supported by DFT calculations (vide infra), where it is shown that the core of the Pc and the pyridine rings are not coplanar.

Chronoamperometric measurements show a stable current during operation for both catalysts, thus supporting no degradation of the molecules or decrease in activity ([Figure 2B,C](#)). In addition, UV-vis spectroscopy of the CoPc-Pyr catalyst recovered from the carbon paper electrode after performing CO₂R measurements supports no degradation of the molecular catalyst during CO₂R ([Figure S11](#)). A few studies have shown the stability of similar complexes, and they have concluded that CO does not originate from catalyst

degradation.^{23,24} At -0.7 V versus RHE, CoPc-Pyr has a higher current than CoPc, while maintaining higher selectivity as already mentioned. Moreover after 5 h of electrolysis at various potentials, CoPc-Pyr is still able to catalyze the CO₂ to CO conversion without significant difference in the measured current. Both of the molecules are not soluble in water at pH 6.8, so homogeneous catalysis can be excluded as well. We analyzed the FE for H₂ and CO, when CoPc-Pyr or CoPc are used as catalysts in a CO₂ atmosphere as a function of potential ([Figure 2D,E](#)). CoPc-Pyr has a higher selectivity for CO with respect to CoPc at same potential ([Table 1](#), [Table S2](#)). The only product other than CO detected is H₂, and the sum of the FE accounts for all of the current.

Interestingly, while CoPc and tetraphenylporphyrin modified with electron-withdrawing ligands show improved CO₂R activity, a complete mechanistic interpretation is still missing.²⁰ To understand how the presence of the pyridine moiety tunes the selectivity for CO generation, we calculated the binding energy of the different intermediates that yield CO or H₂. Specifically, the formation of CO proceeds through a *COOH intermediate that further extracts a proton from water and yields CO through liberation of a water molecule.³⁶ Thus, as an indicator of the selectivity between the CO₂R and formation of H₂, we considered the relative energy for binding an intermediate that leads to the CO, E^*_{COOH} , compared to the binding energy for an intermediate that leads to H₂ (the catalyst bound to a proton), E^*_{H} . In agreement with experiment, the DFT calculations predict higher selectivity of both molecules for CO₂R with respect to H₂ production, with $E^*_{\text{COOH}} < E^*_{\text{H}}$. In addition, the computed binding energies for CoPc and CoPc-Pyr are very similar, although the values of E^*_{COOH} and E^*_{H} are consistently lower for CoPc-Pyr. This finding is a consequence of the higher electron affinity of CoPc-Pyr as compared to CoPc (see [Table 2](#) and discussion below), as the binding of H and COOH both involve reduction steps.

Our DFT calculations also support the experimental finding that CoPc-Pyr is the superior catalyst. [Table 2](#) summarizes the computed energies of various reactions (for both CoPc and CoPc-Pyr) that are related to properties such as CO₂ and electron affinities (EAs). According to these results, the binding of CO₂ to the monoanion is very weak (0.05 eV). This binding energy is insufficient to overcome the entropy of CO₂ in solution (0.18 eV)³⁷ at room temperature; thus, the driving force for CO₂ to bind to the monoanion species is minimal ($\Delta G_{\text{bind}} = +0.13$ eV; enthalpic contributions are negligible). In contrast, CO₂ attaches to the dianion with a binding energy of 0.33 eV. This energy is large enough to overcome the loss in entropy due to binding and favor

Table 2. Calculated Energies^a

reaction	CoPc	CoPc-Pyr
CoPc + e ⁻ → [CoPc] ⁻	-4.36	-4.50
[CoPc] ⁻ + e ⁻ → [CoPc] ⁻²	-4.38	-4.62
[CoPc] ⁻ + CO ₂ → [CO ₂ -CoPc] ⁻	-2.97	-3.10
[CoPc] ⁻² + CO ₂ → [CO ₂ -CoPc] ⁻²	-3.08	-3.18
[CoPc] ⁻ + H ⁺ + e ⁻ → [H-CoPc] ⁻	-0.11	-0.05
[CoPc] ⁻² + CO ₂ + H ⁺ + e ⁻ → [HOOC-CoPc] ⁻	-0.06	0.02
	-0.37	-0.33
	-0.21	-0.22
	0.39	0.36
	0.55	0.53
	0.03	-0.01
	0.45	0.42

^aCalculated energies (in eV) of reduction and CO₂ adsorption to CoPc and CoPc-Pyr. The second energy value in each reaction includes the zero-point energy and vibrational thermal corrections according to the rigid-rotor/harmonic-oscillator interpolation method of Grimme.³²

formation of the [CO₂-Co(I)Pc-Pyr]⁻² adduct ($\Delta G_{\text{bind}} = -0.14$ eV).

The lower onset potential for CO₂ reduction of CoPc-Pyr as compared to CoPc can be rationalized by two observations that have been already pointed out: (1) that the catalytically active species is the dianion ([Co(I)Pc]⁻² or [Co(I)Pc-Pyr]⁻²) and (2) that CoPc-Pyr has a higher electron affinity than CoPc (and thus is easier to reduce). Indeed, the computed electron affinities (Table 2) of [Co(I)Pc-Pyr]⁻¹ and [CO₂-Co(I)Pc-Pyr]⁻¹ are, respectively, 0.24 and 0.14 eV higher than for their unsubstituted counterparts, which correlates well with the 0.15 eV difference between the CO₂R onset potential of the two catalysts. The DFT-optimized structure of CoPc-Pyr shown in Figure 3 suggests that steric interactions break the conjugation

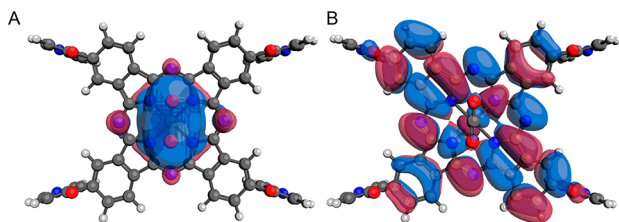


Figure 3. HOMO-2 (A) and HOMO (B) for the DFT-optimized structure of [CO₂-CoPc-Pyr]⁻². The spin state is a doublet, and the geometry of CO₂ is bent. The HOMO-2 is the main orbital responsible for the catalyst-CO₂ interaction, involving the d_{z²} orbitals of the metal and the π* orbitals of CO₂.

between the pyridine groups and the core of the catalyst, because the phthalocyanine and pyridine rings are not coplanar. In turn, this characteristic indicates that the greater electron affinity of the CoPc-Pyr is due to electron-withdrawing inductive effects of the oxygen atoms linking the pyridine rings to the phthalocyanine. Combining these observations with the experimental results reported here implies that one may enhance the selectivity and lower the onset potential for the CO₂R of a CoPc catalyst by subtle changes on the electron affinity of the catalyst via substituents that act, effectively, as electron-withdrawing groups. A more drastic increase in electron affinity may not be as effective due to the possibility of reducing the affinity for electrophilic CO₂ too much, hindering the necessary first step of CO₂ binding.

In addition to the optimized structure of [CO₂-CoPc-Pyr]⁻², Figure 3 shows the isosurfaces for two molecular orbitals that reveal properties of the catalytic species. The first orbital shown, the HOMO-2 (HOMO = highest occupied molecular orbital), is the main orbital responsible for the CO₂-catalyst interaction. The metal's d_{z²} orbitals donate electron density to the π* orbitals of CO₂ in a bonding interaction. Thus, the cobalt center is acting as a Co(I) in a tetrahedral crystal field, which makes the filled d_{z²} orbital the highest occupied energy level localized on the metal. Although it seems unintuitive to have the HOMO-2 as being responsible for the bonding between CO₂ and the catalyst, other researchers have made analogous observations for cobalt porphyrins.³⁸ The second orbital shown is the HOMO, which is singly occupied for the doublet spin state that was calculated. The shape of this orbital suggests delocalization over the phthalocyanine ring of this single electron, in agreement with what has been deduced from experiments. It is also worth mentioning that the structure of CO₂ is bent when attached to the complex and that the sum of its Mulliken charges is -0.64, corroborating the formation of a negatively charged CO₂ when it binds to the catalyst.

CONCLUSION

In conclusion, we have shown the synthesis of a Co-based phthalocyanine bearing pyridine groups, which has been heterogenized on a carbon paper support and tested for CO₂R. We have demonstrated that the pyridine groups are responsible for reducing the overpotential for conversion of CO₂ to CO with respect to unfunctionalized phthalocyanine. DFT calculations support the idea that the overpotential reduction is due to an enhanced energy of CO₂ adsorption and greater electron affinity of the Co center induced by the pyridine moieties. On the one hand, through a combination of experimental evidence and DFT calculations, we show that the presence of electron-withdrawing groups may beneficially tune the electron affinity of the catalyst, thereby increasing the activity of a CoPc derivative for CO₂R. On the other hand, a drastic increase in electron affinity can also inhibit CO₂ binding thus hindering CO₂R. Striking a fine balance between these two effects can aid the design of novel, efficient molecular catalysts for CO₂R. In addition, this study shows that heterogenized molecular catalysts exhibit improved overpotential and selectivity to CO₂R versus HER than noble-metal catalysts, thus providing a tunable route to CO production with good energy efficiency using more earth-abundant elements.

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsami.9b18924>.

Reaction schemes, FTIR, NMR, XPS, and UV-vis data of the synthesized compounds. Additional chronoamperometry data for CoPc-Pyr (4) and Vis spectrum of the material recovered from the electrode after the electrochemical CO₂ reduction compared to the starting CoPc-Pyr (4). Table used for calculation of turnover frequency values (PDF)

All the source data that support the findings of Figures 1a,b and 2b-e (XLSX)

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Notes

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