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Electrocatalytic synthesis of methylamine from nitrate and carbon dioxide on a heterometallic polyphthalocyanine

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Electrocatalytic coreduction of nitrate and CO₂ provides an opportunity for the synthesis of organonitrogen chemicals. The major challenge is to realize the simultaneous reduction of nitrate and CO₂ into active intermediates for C–N bond formation. In this work, methylamine is synthesized from nitrate and CO₂ on a polyphthalocyanine electrocatalyst with heterometal centers (Co₂Cu₁PPc). Notably, it is found that the Co and Cu centers coordinated with the conjugated macrocyclic network of polyphthalocyanine can catalyze CO₂ reduction to formaldehyde and nitrate reduction to hydroxylamine, respectively. The nucleophilic attack of hydroxylamine on formaldehyde generates a formaldoxime intermediate, which is then further reduced to methylamine. The overreduction reactions of hydroxylamine and formaldehyde intermediates are suppressed by Co₂Cu₁PPc. This bifunctional catalyst with heteronuclear active centers simultaneously catalyzes nitrate and CO₂ reduction to key intermediates for C–N bond formation.

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Introduction

The electrocatalytic coreduction reaction of nitrate (NO₃[−]) and CO₂ {denoted as (NO₃[−] + CO₂)RR} offers an opportunity for the sustainable synthesis of valuable organonitrogen chemicals, such as urea and amines, under mild conditions, and is of significance from the perspective of alleviating energy and environmental issues.^{1–6} Wang *et al.*⁷ have demonstrated the feasibility of the (NO₃[−] + CO₂)RR for forming methylamine, which is the simplest amine widely used in the pharmaceutical and agrochemical industries.^{8,9} Yet, the electrocatalytic (NO₃[−] + CO₂)RR usually generates multiple products, and the efficiency of the aimed organonitrogen product remains to be improved.^{10–14} The formation of key intermediates is difficult and they tend to be reduced to inactive species, resulting in a low efficiency of C–N coupling. Therefore, the challenge is to generate active intermediates towards C–N bond formation in competition with other parallel processes during the NO₃[−] reduction reaction (NO₃[−]RR) and the CO₂ reduction reaction (CO₂RR).

Single atom electrocatalysts such as Cu and Co based metal phthalocyanines (MPcs) and metal doped carbon materials

have been reported to be active for nitrate or CO₂ reduction reactions.^{15–20} Metal polyphthalocyanines (MPPcs) with atomically dispersed metal–N₄ sites have well-defined and adjustable structures, featuring a large conjugated structure and fully in-plane π -delocalization.^{21–23} These characteristics enable more stable multi-phase interfaces compared with MPcs.^{24–26} In addition, the electronic structure of MPPcs can be modulated *via* constructing a multinuclear structure and may be favorable for electrocatalysis.^{27–29} These points motivated us to design MPPc catalysts with heterometal centers for the electrocatalytic (NO₃[−] + CO₂)RR to selectively form C–N bonds and methylamine.

Herein, a series of MPPcs {CoPPc, Co_xCu₁PPc ($x = 1, 2, 3$) and CuPPc} supported on carbon nanotubes (CNTs) were investigated for the synthesis of methylamine from NO₃[−] and CO₂. The heterometallic Co₂Cu₁PPc catalyst gives a Faradaic efficiency (FE) of 11.3% for methylamine, much higher than those of its monometallic and non-polymeric counterparts (below 3.2%). Experiments and theoretical calculations show that the Co and Cu centers in the conjugated macrocyclic network of Co₂Cu₁PPc can catalyze the CO₂RR to formaldehyde (HCHO) and the NO₃[−]RR to hydroxylamine (NH₂OH), respectively. The C–N coupling between NH₂OH and HCHO forms a formaldoxime (CH₂=NOH) intermediate, which is further reduced to the desired methylamine on Co centers. In addition, the introduction of Cu centers can suppress the overreduction of hydroxylamine and formaldehyde and thus boost the C–N coupling process. Co₂Cu₁PPc works as a heteronuclear bifunctional catalyst for the (NO₃[−] + CO₂)RR to active intermediates for C–N coupling and further production of methylamine.

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Results and discussion

Materials and characterization

MPPCs were synthesized by a modified solid-phase polymerization method (Fig. S1 and S2, SI) according to the literature.^{21,30} Commercial CoPc and CuPc monomers were studied for comparison (Fig. S3). The elemental mapping images show the uniform distribution of different elements in Co₂Cu₁PPc (Fig. 1a). These MPPCs are amorphous as revealed by X-ray diffraction (XRD) patterns and the high-resolution TEM image (Fig. S4).³¹ Further, these MPPCs were supported on CNTs (Fig. 1b) to prevent the stacking or aggregation of polymer molecules during electrocatalysis. The high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image displays atomically dispersed metal atoms (circled in yellow, Fig. 1c).

The phthalocyanine framework of these MPPCs can be proved by the Fourier transform infrared spectra (Fig. S5)^{21,27} and the Raman spectra (Fig. S6).²⁹ As shown in Fig. 1d, there is a shift in the B_{1g} Raman signal related to the stretching of C–N–C bonds

between CoPPc and CuPPc due to the different electron delocalization in the phthalocyanine macrocycle.^{29,31} Notably, Co₂Cu₁PPc shows two B_{1g} peaks of CoPPc and CuPPc, resulting from the two kinds of local metal–N₄ coordination centers. The UV-visible absorption spectra of MPPCs show two typical absorbance bands of phthalocyanine, which reflects the $\pi \rightarrow \pi^*$ transition of the macrocyclic ligand (Fig. 1e).^{21,25} Compared with CoPPc, the Q band of Co₂Cu₁PPc shifts to a longer wavelength, suggesting that the π -conjugation structure is modified due to the incorporation of Cu.

In addition, the X-ray photoelectron spectroscopy (XPS) results of Co₂Cu₁PPc show typical signals of the polymer skeleton (Fig. S7). And the metal centers exist as Co^{2+/3+} and Cu^{1+/2+} species, as shown in Fig. 1f and g. The Co 2p_{3/2} peaks of Co₂Cu₁PPc shift to lower binding energy compared with those of CoPPc, while the Cu 2p_{3/2} peaks shift oppositely compared with CuPPc. This suggests that the electronic properties of metal centers are modified *via* hybridizing CoPPc and CuPPc together. Moreover, compared with the mixture of CoPc and CuPc monomers (named CoPc–CuPc), the bonding and electron delocalization in the polyphthalocyanine macrocycles of

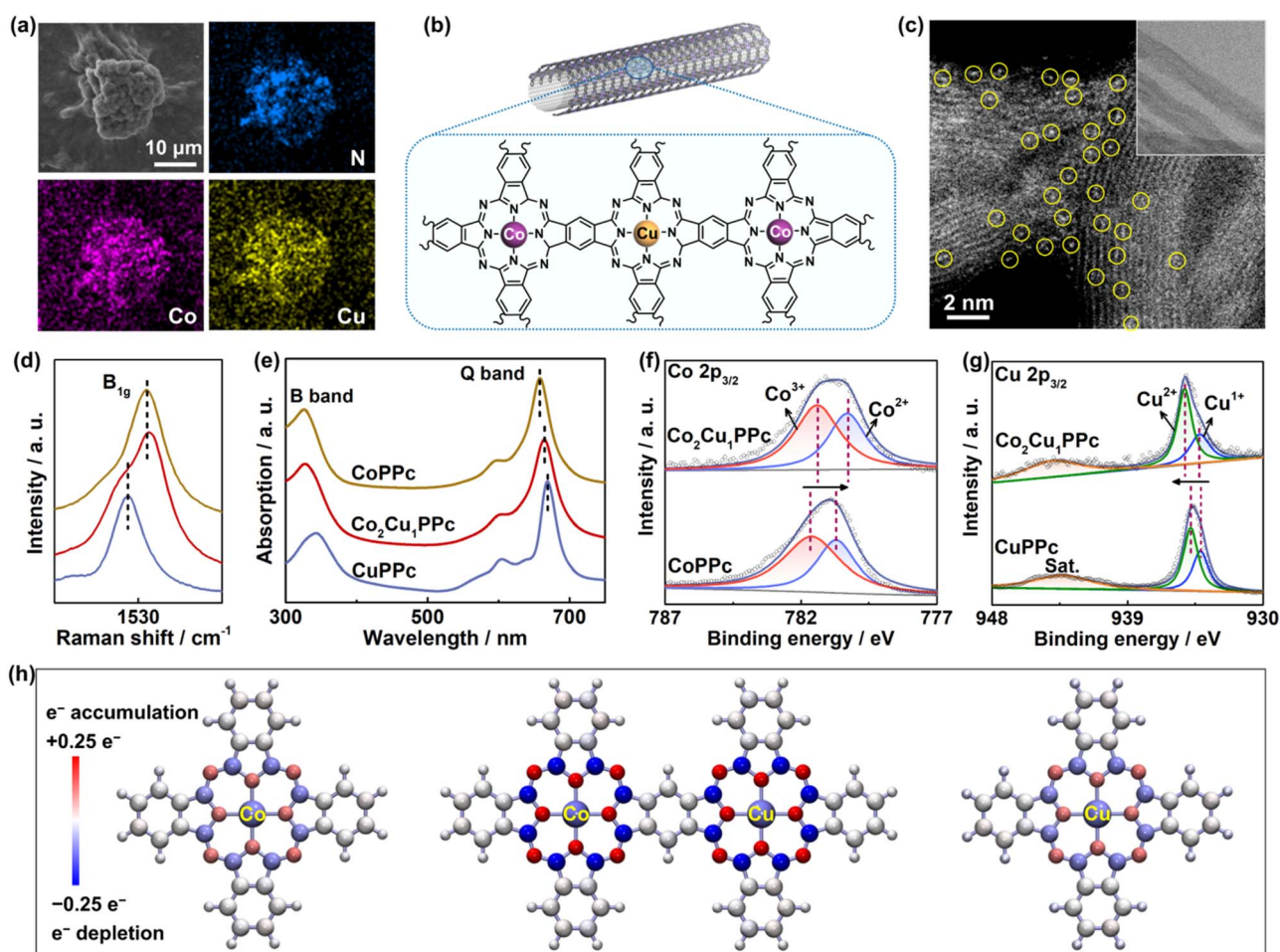


Fig. 1 Material characterization. (a) SEM and EDS mapping of unsupported Co₂Cu₁PPc. (b) Schematic diagram of Co₂Cu₁PPc supported on CNTs. (c) Atomic-resolution HAADF-STEM images of Co₂Cu₁PPc supported on CNTs (circled bright spots represent the metal atoms; inset: HRTEM). (d) Raman and (e) UV-Vis spectra of unsupported CoPPc, Co₂Cu₁PPc and CuPPc. High-resolution XPS spectra of (f) Co 2p_{3/2} and (g) Cu 2p_{3/2} of CoPPc, Co₂Cu₁PPc and CuPPc. (h) Bader charge analysis of CoPc, CuPc and simplified heteronuclear Co₂Cu₁PPc (the red and blue colors represent accepting and losing electrons, respectively).

Co₂Cu₁PPc are enhanced, judging from the shift in N 1s spectra and higher π - π^* satellite in C 1s spectra (Fig. S7a–c).²¹ And the average valence states of both Co and Cu in Co₂Cu₁PPc are higher than those in CoPc–CuPc (Fig. S7d and e). Further, we did Bader charge calculations on CoPc, CuPc and the simplified model of heteronuclear Co₂Cu₁PPc. Fig. 1h shows that there is more electron transfer from the metal center to the polyphthalocyanine ligand in heterometallic Co₂Cu₁PPc, and the polyphthalocyanine macrocycle may serve as an electron reservoir during electrocatalysis. Briefly, the characterizations above verify that the electronic structures of metal centers and the macrocycle network are both modified *via* constructing the heterometallic polyphthalocyanine.

Electrocatalytic performance for methylamine synthesis and mechanism analysis

We then evaluated the performance of various catalysts for methylamine synthesis *via* the (NO₃[−] + CO₂)RR in an H-type cell

with 0.1 M KHCO₃ and 0.8 M KNO₃ saturated with CO₂. For all electrochemical measurements, the MPc and MPPc catalysts were supported on CNTs, and all potentials were reported after 80% *i*R-correction unless otherwise noted. Reaction products were determined by nuclear magnetic resonance (¹H NMR), UV-visible spectrophotometry and gas chromatography (Fig. S8 and S9).

Fig. 2a shows the FE(CH₃NH₂) of Co_xCu₁PPc (*x* = 1, 2, 3) as a function of potential, in comparison with CoPPc, CoPc, and the CoPc–CuPc mixture for methylamine production. All catalysts exhibit similar potential-dependent performance, and the optimized FEs are summarized in Fig. S10. CoPPc displays a FE(CH₃NH₂) of 3.2% at −0.84 V vs. RHE (denoted as *V*_{RHE}), higher than that of CoPc (2.1%). CuPPc and CuPc show no activity for methylamine production (Fig. S11). In contrast, Co₂Cu₁PPc exhibits the highest FE(CH₃NH₂) of 11.3% at −0.76 *V*_{RHE} among these catalysts. The FE(CH₃NH₂) values of both Co₃Cu₁PPc and Co₁Cu₁PPc are lower than that of Co₂Cu₁PPc, but are obviously higher than those of CoPPc and CuPPc.

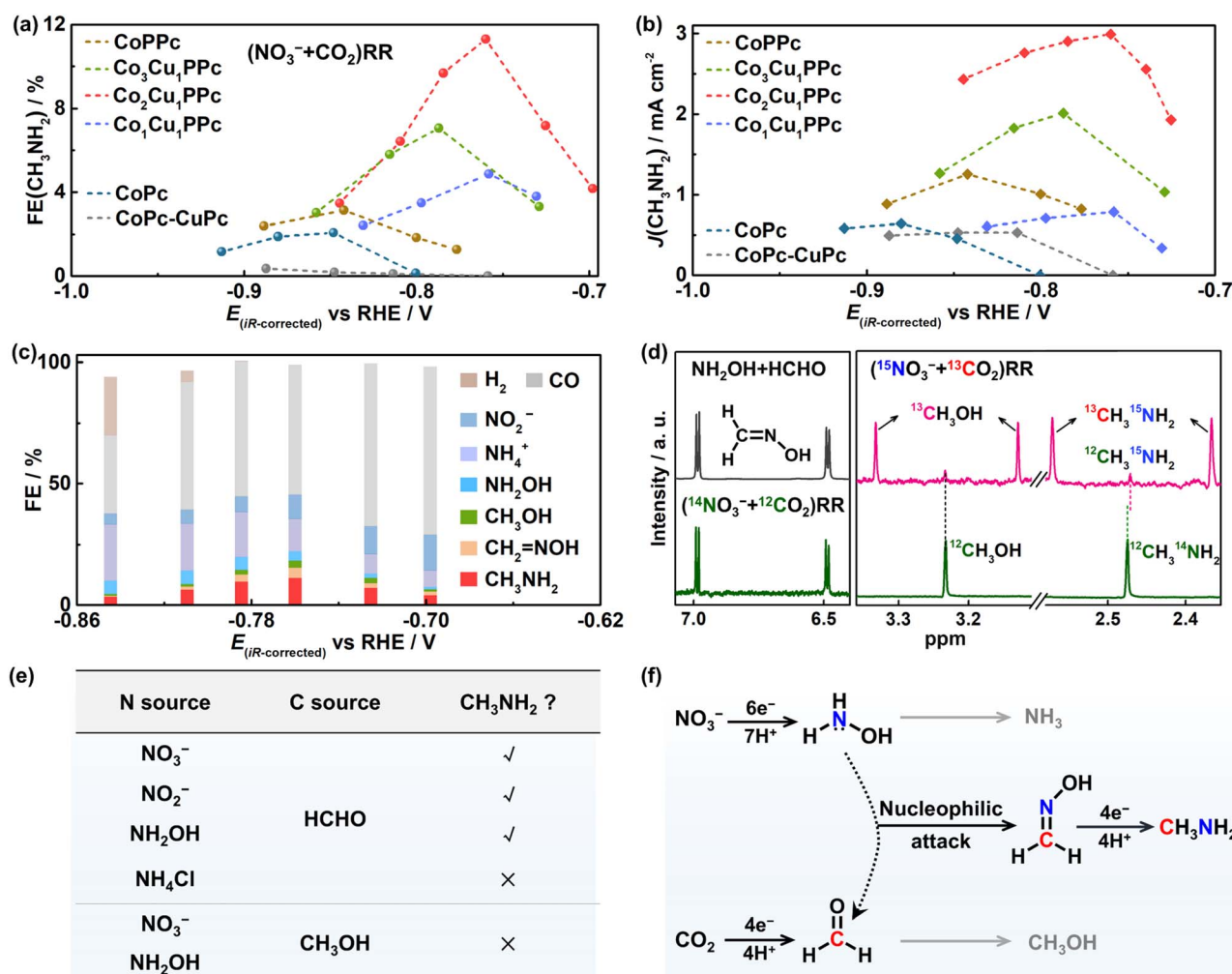


Fig. 2 Electrocatalytic performance of the (NO₃[−] + CO₂)RR and reaction mechanism. (a) FE(CH₃NH₂) and (b) *J*(CH₃NH₂) for the (NO₃[−] + CO₂)RR with CoPPc, Co_xCu₁PPc (*x* = 1, 2, 3), CoPc and CoPc–CuPc (mixture of CoPc and CuPc) as a function of potential. (c) FEs of all products of the (NO₃[−] + CO₂)RR with Co₂Cu₁PPc at different potentials. (d) ¹H NMR spectra of the formaldoxime formed from the mixture of NH₂OH and HCHO (black trace), and the solution after the (NO₃[−] + CO₂)RR (green trace) and the isotopic-labelling (¹⁵NO₃[−] + ¹³CO₂)RR (pink trace). (e) Control experiments of different nitrogen and carbon sources. (f) Proposed reaction pathway for methylamine synthesis from NO₃[−] and CO₂.

Accordingly, Fig. 2b shows that $\text{Co}_2\text{Cu}_1\text{PPc}$ gives the highest partial current density of methylamine production (3 mA cm^{-2}), and the overpotential corresponding to the optimized activity shifts positively with the increase of Cu content. In addition, the CoPc-CuPc mixture delivers a $\text{FE}(\text{CH}_3\text{NH}_2)$ of only 1.6% (Fig. S12), lower than that of $\text{Co}_2\text{Cu}_1\text{PPc}$ by one order of magnitude. In $\text{Co}_2\text{Cu}_1\text{PPc}$, the two kinds of metal centers are uniformly dispersed and hybridized together in the same conjugated macrocyclic network, and their electronic structures are modified, different from the physically mixed CoPc and CuPc monomers. Briefly, heterometallic polyphthalocyanines show higher performance for methylamine synthesis than the monometallic and non-polymeric counterparts. Moreover, the reaction current is steady as a function of reaction time and there is negligible change in XPS spectra before and after the reaction (Fig. S13), suggesting $\text{Co}_2\text{Cu}_1\text{PPc}$ remains stable during the electrolysis.

To understand the reaction mechanism of methylamine formation, we first evaluated the pH effect on the $(\text{NO}_3^- + \text{CO}_2)$ RR. An optimal $\text{FE}(\text{CH}_3\text{NH}_2)$ is achieved at a neutral pH (~ 6.8), which balances the competing pathways during the $(\text{NO}_3^- + \text{CO}_2)$ RR (Fig. S14). At this pH condition, NH_2OH ($\text{p}K_a = 5.96$) exists predominantly in its neutral form. Fig. 2c illustrates the FEs of all products which are close to 100%. CO is the main side product, and there is a small quantity of CH_3OH . NH_4^+ is the main inorganic side-product with higher FE at more negative potentials, and some NO_2^- and NH_2OH are also detected. The hydrogen evolution reaction (HER) is only observed at potentials more negative than $-0.80 \text{ V}_{\text{RHE}}$. Formaldoxime and methylamine display similar volcanic curves as a function of the applied potential. Importantly, the detection of formaldoxime indicates the formation of NH_2OH and HCHO during the $(\text{NO}_3^- + \text{CO}_2)$ RR (Fig. 2d). In the isotope-labelling experiment of $(^{15}\text{NO}_3^- + ^{13}\text{CO}_2)$ RR, typical signals of $^{13}\text{CH}_3\text{OH}$ and $^{13}\text{CH}_3^{15}\text{NH}_2$ are observed in the ^1H NMR spectra, and a minor signal of $^{12}\text{CH}_3^{15}\text{NH}_2$ is also detected at 2.47 ppm. These results confirm that the produced methylamine indeed originates from NO_3^- and CO_2 .

Then, other N-sources and C-sources were examined to confirm the active species for methylamine formation. Fig. 2e shows that NO_3^- , NO_2^- and NH_2OH can all serve as N-sources to form methylamine over $\text{Co}_2\text{Cu}_1\text{PPc}$. However, no methylamine is detected with $\text{NH}_3 \cdot \text{H}_2\text{O}$ as the N-source, which excludes the direct involvement of $\text{NH}_3 \cdot \text{H}_2\text{O}$ in C–N bond formation and indicates that NH_2OH is the active N-species for C–N coupling. As for the C-sources, we found that HCHO is active in generating methylamine in the presence of NO_3^- , NO_2^- or NH_2OH , but CH_3OH cannot. This suggests that HCHO from CO_2 RR is the key intermediate for C–N bond formation.

Taken together, we propose the reaction pathway of methylamine synthesis from NO_3^- and CO_2 (Fig. 2f). First, NH_2OH and HCHO intermediates are formed from the independent NO_3^- RR and CO_2 RR through multi-proton and multi-electron transfer processes. Then, the NH_2OH intermediate attacks the α -carbon of HCHO to form formaldoxime. This C–N coupling process is a spontaneous condensation reaction, as evidenced by the rapid and high-yield formation of oximes *via*

the reaction between NH_2OH and aldehydes such as HCHO or CH_3CHO (Fig. S15). The further reduction of formaldoxime through the transfer of four protons and four electrons generates the desired methylamine. This nucleophilic coupling route may also be applied for the formation of other amines from NO_x and CO/CO_2 .

Active sites for the conversion of C-species and N-species

We further tried to unveil the roles of different metal centers in heterometallic polyphthalocyanines during the $(\text{NO}_3^- + \text{CO}_2)$ RR by studying the NO_3^- RR and CO_2 RR separately. Fig. 3a shows that the current densities for NO_3^- RR follow the trend $\text{CuPPc} > \text{Co}_2\text{Cu}_1\text{PPc} > \text{CoPPc} \approx \text{metal-free polyphthalocyanine (PPc)}$, and the onset potential of CuPPc for NO_3^- RR is most positive. The current density of $\text{Co}_x\text{Cu}_1\text{PPc}$ for the NO_3^- RR increases with the content of Cu (Fig. S16a).

Moreover, by density functional theory (DFT) calculations, we found that the Cu center in $\text{Co}_2\text{Cu}_1\text{PPc}$ shows strong affinity for NO_3^- , and thus $^*\text{NO}_3^-$ (* represents surface adsorbed species) tends to be adsorbed on the Cu site rather than the Co site (Fig. 3b, S17). Accordingly, CuPPc exhibits the highest performance for the NO_3^- RR to NO_2^- (Fig. 3c), which may be the rate-determining step for the NO_3^- RR on $\text{Co}_2\text{Cu}_1\text{PPc}$ as the current density of NO_2^- reduction is much higher than that of the NO_3^- RR (Fig. S16b).^{32,33} In addition, Fig. 3d shows that the Cu site in $\text{Co}_2\text{Cu}_1\text{PPc}$ adsorbs $^*\text{NO}_2$ much more strongly than the Co site. Therefore, we deduce that the NO_3^- RR mainly occurs on the Cu centers of $\text{Co}_2\text{Cu}_1\text{PPc}$.

Interestingly, Fig. 3e shows that $\text{Co}_2\text{Cu}_1\text{PPc}$ displays a superior performance for the NO_3^- RR to NH_2OH , with an optimized $\text{FE}(\text{NH}_2\text{OH})$ of 25.2% (detailed data in Fig. S18), about 2.5 times those of CoPPc, CoPc and the CoPc-CuPc mixture. The $\text{FE}(\text{NH}_2\text{OH})$ values of CuPPc and CuPc are the lowest. That's to say, although CuPPc is very active for the NO_3^- RR, its performance for NH_2OH formation is low. Metal-free PPc does not show activity for NH_2OH production (Fig. S19a). So, the Cu centers play a crucial role in catalyzing the NO_3^- RR, and the process of NH_2OH formation is obviously enhanced *via* the construction of heterometallic polyphthalocyanines.

Once NH_2OH is generated, it may participate in the C–N coupling process, or be further reduced to inactive NH_3 . Fig. 3f shows that the overreduction of NH_2OH with the CoPPc catalyst is serious, which mainly occurs on Co centers as the PPc shows low activity for this reaction. Interestingly, CuPPc shows very low activity for the NH_2OH reduction reaction. The $^*\text{NH}_2\text{OH}$ adsorption energy on the Co site in $\text{Co}_2\text{Cu}_1\text{PPc}$ changes little compared with that on CoPPc (Fig. S19b). The absolute number of Co sites available for $^*\text{NH}_2\text{OH}$ reduction is obviously decreased in $\text{Co}_2\text{Cu}_1\text{PPc}$. Therefore, the overreduction of NH_2OH is obviously reduced on $\text{Co}_2\text{Cu}_1\text{PPc}$. In other words, the Cu centers in $\text{Co}_x\text{Cu}_1\text{PPc}$ not only serve as active sites for NO_3^- reduction to NH_2OH , but also keep the active NH_2OH intermediate from overreduction, thus enhancing the efficiency for C–N bond formation.

Then, what is the active site for CO_2 reduction? From the LSV curves, CoPPc and $\text{Co}_2\text{Cu}_1\text{PPc}$ display large current densities for



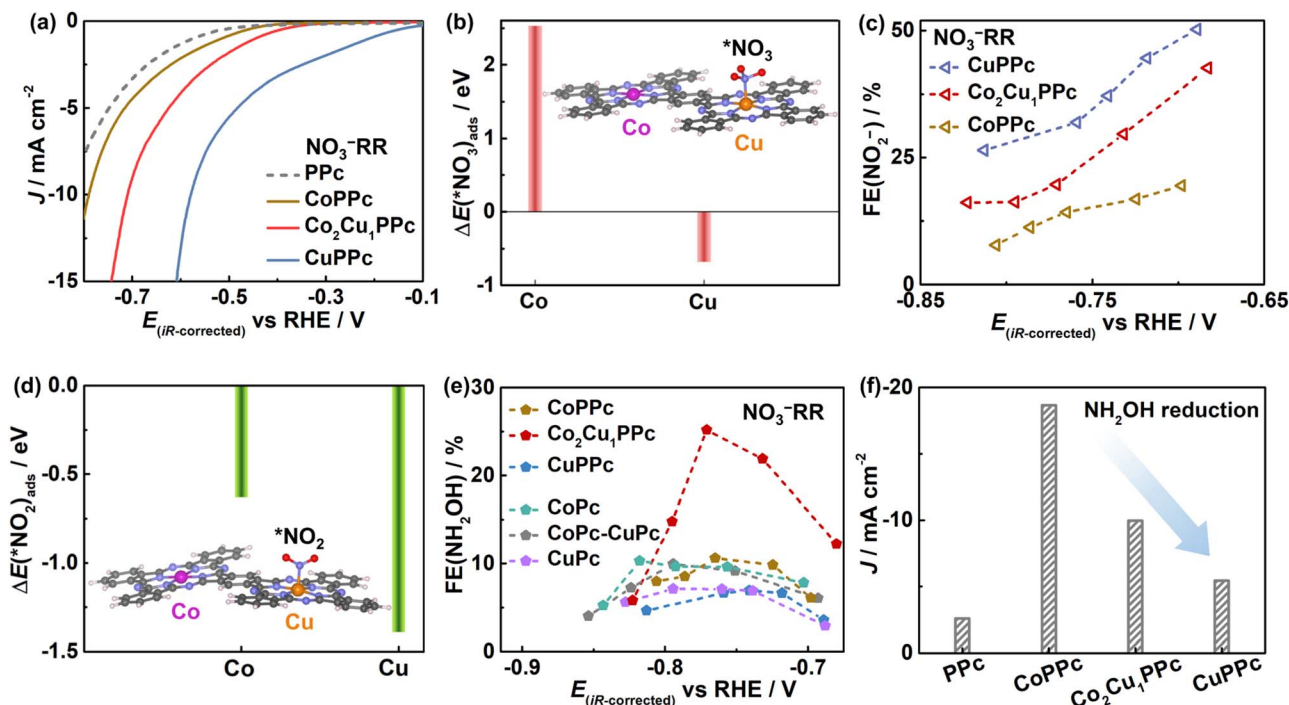


Fig. 3 Electrocatalytic performance for the NO₃⁻RR. (a) LSV curves of PPc, CoPPc, Co₂Cu₁PPc and CuPPc in Ar-saturated 0.1 M KHCO₃ containing 0.8 M KNO₃. (b) Adsorption energy of ^{*}NO₃ on the Co or Cu sites of Co₂Cu₁PPc (inset: the most stable adsorption configurations of ^{*}NO₃). (c) FEs of NO₂⁻ formation after the NO₃⁻RR with CoPPc, CuPPc, and Co₂Cu₁PPc. (d) Adsorption energy of ^{*}NO₂ on the Co or Cu sites of Co₂Cu₁PPc (inset: the most stable adsorption configurations of ^{*}NO₂). (e) FE(NH₂OH) for the NO₃⁻RR with CoPPc, CuPPc, Co₂Cu₁PPc, CoPc, CuPc, and CoPc-CuPc as a function of potential. (f) Current densities for the side-reaction of NH₂OH reduction at -0.76 V_{RHE} in 0.1 M KHCO₃ containing 30 mM NH₂OH.

the CO₂RR, whereas CuPPc and metal-free PPc exhibit negligible activity (Fig. 4a). The activity of the CO₂RR is enhanced when increasing the Co content in Co_xCu₁PPc (Fig. S20). Based on the above results, HCHO is the active intermediate for C–N coupling, yet HCHO is not detected in the electrolyte after the CO₂RR or (NO₃⁻ + CO₂)RR (Fig. S21), possibly as adsorbed ^{*}HCHO can be easily reduced to CH₃OH or consumed by C–N coupling with NH₂OH before its desorption into the solution. So, we used the amount of CH₃OH derived from HCHO reduction to assess the performance of forming active C-species from the CO₂RR. Notably, Fig. 4b shows that Co₂Cu₁PPc gives the highest FE(CH₃OH) of 20.7%, about 5 times that of CoPc-CuPc and 3 times that of CoPPc (details in Fig. S22). And CH₃OH is not detected with CuPPc and CuPc. These results reveal that the Co atoms in Co_xCu₁PPc are the active sites for the CO₂RR to form the ^{*}HCHO intermediate, and the introduction of the Cu component boosts HCHO formation possibly through modifying the electronic structure of Co atoms. Furthermore, Fig. 4c shows that CoPPc is very active for HCHO reduction, which is unfavorable for methylamine synthesis. In contrast, it is suppressed with Co₂Cu₁PPc, and is negligible with CuPPc. Theoretical calculation shows that the adsorption of HCHO on the Co site in Co₂Cu₁PPc is weakened (Fig. S23), and thus its subsequent reduction to CH₃OH is inhibited.

The above results show that CuPPc presents high performance for the NO₃⁻RR, but can hardly catalyze the CO₂RR. CoPPc is rather active for the CO₂RR but shows low activity for

the NO₃⁻RR. However, the heterometallic polyphthalocyanines are active for both the NO₃⁻RR to NH₂OH and CO₂RR to HCHO, and the overreduction of NH₂OH and HCHO intermediates is suppressed. These points promote the formation of key intermediates and are crucial for the high performance of methylamine production.

Further, theoretical calculations for the CO₂RR on the heterometallic catalyst were conducted to verify the proposed mechanism (Fig. 4d). It is found that ^{*}CO₂ on the Co center is reduced to ^{*}CO, which is subsequently reduced to ^{*}CHO rather than ^{*}COH. The next proton-electron transfer process yields ^{*}HCHO with an energy barrier of 0.52 eV, lower than that of ^{*}CHOH formation. Further, CH₃OH is formed by exothermic processes. Additionally, the desorption of ^{*}HCHO shows a high energy barrier of 2.2 eV, so it tends to exist as a surface-bound intermediate for further formation of CH₃OH or C–N coupling with NH₂OH. Consistently, free HCHO is not detected in the electrolyte (Fig. S21). These theoretical and experimental results strongly support the participation of ^{*}HCHO in the (NO₃⁻ + CO₂)RR.

As for the formaldoxime reduction process, theoretical calculations reveal that the ^{*}formaldoxime molecule tends to be adsorbed on the Co site of Co₂Cu₁PPc (Fig. 4e). CoPPc and Co₂Cu₁PPc show similar current densities for the reduction of formaldoxime, and both are more active than CuPPc (Fig. 4f). Therefore, the Co centers in Co₂Cu₁PPc are also the active sites for the reduction of formaldoxime to methylamine. In addition,

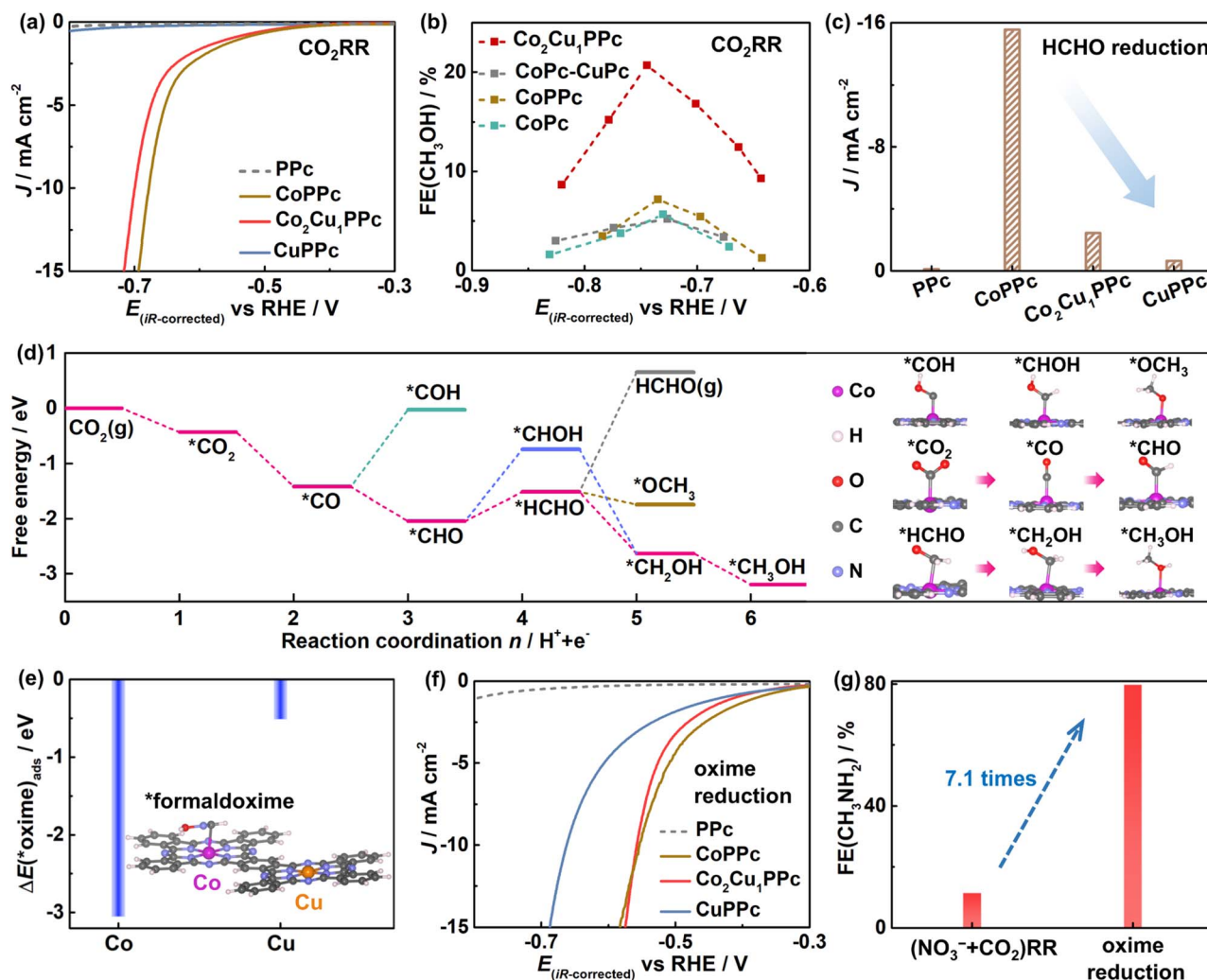


Fig. 4 Electrocatalytic performance for the CO₂RR and oxime reduction reaction. (a) LSV curves of PPc, CoPPc, Co₂Cu₁PPc and CuPPc for the CO₂RR. (b) FE(CH₃OH) for the CO₂RR with CoPPc, Co₂Cu₁PPc, CoPPc, and CoPPc-CuPPc as a function of potential. (c) Current densities for the side-reaction of HCHO reduction at $-0.55 V_{RHE}$ in Ar-saturated 0.1 M KHCO₃ containing 30 mM HCHO. (d) Free-energy diagram and adsorption configurations for the CO₂RR to CH₃OH on Co₂Cu₁PPc. (e) Adsorption energy of *formaldoxime on the Co and Cu sites of Co₂Cu₁PPc (inset: the most stable adsorption configurations of *formaldoxime). (f) LSV curves of PPc, CoPPc, Co₂Cu₁PPc and CuPPc for formaldoxime reduction. (g) Maximum FE(CH₃NH₂) with Co₂Cu₁PPc for the (NO₃⁻ + CO₂)RR and oxime reduction. Conditions: CO₂RR in CO₂-saturated 0.1 M KHCO₃; oxime reduction in Ar-saturated 0.1 M KHCO₃ containing 30 mM NH₂OH and 30 mM HCHO.

as shown in Fig. 4g, the formaldoxime reduction with Co₂Cu₁-PPc shows an optimized FE(CH₃NH₂) as high as 80% (details in Fig. S24a), which is about 7.1 times that of the (NO₃⁻ + CO₂)RR. And the current density of formaldoxime reduction is higher than that of the CO₂RR and NO₃⁻RR (Fig. S24b). All of this indicates the formaldoxime reduction process is relatively easier than the NO₃⁻RR and CO₂RR.

Subsequently, the formation rates of NH₂OH and HCHO intermediates are investigated. Fig. 5a and b show that the production rates of NH₂OH and HCHO during the (NO₃⁻ + CO₂)RR with CoPPc are mismatched in a wide potential range. In contrast, with Co₂Cu₁PPc, the formation rates of NH₂OH and HCHO are enhanced at low overpotentials (Fig. 5b), becoming comparable at $-0.76 V_{RHE}$, which corresponds to the peak performance for methylamine production. Interestingly, the

formation rate of NH₂OH during the (NO₃⁻ + CO₂)RR with Co₂Cu₁PPc is enhanced compared with that during individual NO₃⁻RR (Fig. 5c). This suggests a possible synergetic effect between CO₂ and NO₃⁻ conversion, which promotes C-N coupling during the (NO₃⁻ + CO₂)RR.

Taking all results together, we propose an electrocatalytic-chemical-electrocatalytic mechanism of the (NO₃⁻ + CO₂)RR to methylamine with the Co₂Cu₁PPc catalyst (Fig. 5d). The electrocatalytic reduction of CO₂ to *HCHO mainly occurs on the Co centers of Co₂Cu₁PPc, while the process of NO₃⁻ reduction to NH₂OH is mainly catalyzed by the Cu centers. Then, the nucleophilic attack of NH₂OH on the adsorbed *HCHO forms a formaldoxime intermediate with a C-N bond *via* a chemical process. The formaldoxime intermediate is further electro-reduced on Co centers to produce methylamine.

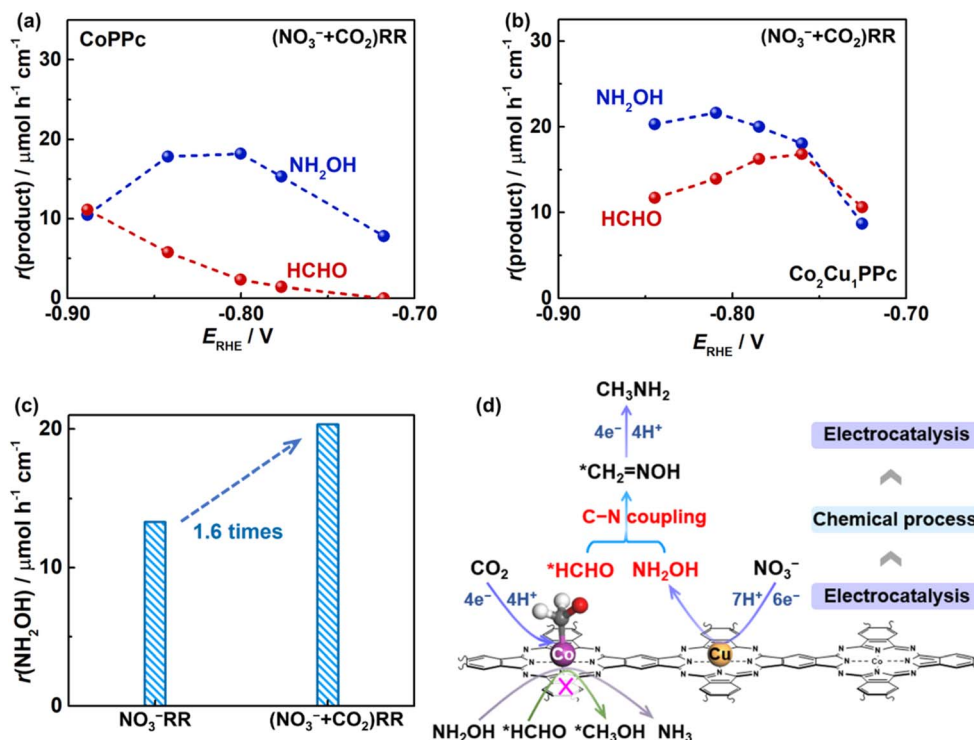


Fig. 5 Calculated NH₂OH and HCHO species produced during the (NO₃⁻ + CO₂)RR on (a) CoPPc and (b) Co₂Cu₁PPc. (c) Optimized activity of NH₂OH formation from the NO₃⁻-RR and (NO₃⁻ + CO₂)RR on Co₂Cu₁PPc. (d) Illustration of methylamine synthesis from the (NO₃⁻ + CO₂)RR catalyzed by the bifunctional metal polyphthalocyanine.

In the heterometallic polyphthalocyanines, the heteronuclear metal centers are atomically dispersed and hybridized together in the same conjugated macrocyclic network. Cu sites modulate the electronic structure of Co, thereby suppressing the over-reduction of NH₂OH and HCHO. Such a unique structure enables the heterometallic polyphthalocyanines to work as bifunctional catalysts for efficient reduction of nitrate and CO₂ parallelly to key intermediates for C-N coupling to the formaldoxime intermediate and its further reduction to methylamine. In addition, no urea product is observed, possibly as the spatially separated metal centers enforced by the macrocyclic ligand make the proximity of surface-adsorbed species such as *NO_x/*NH_x and *CO₂/*CO on adjacent active sites more difficult. Briefly, the special structure of Co₂Cu₁PPc steers the reaction toward methylamine in the (NO₃⁻ + CO₂)RR.

Conclusions

We developed a polyphthalocyanine electrocatalyst with heterometal centers (Co₂Cu₁PPc) for the synthesis of methylamine from NO₃⁻ and CO₂. It shows a much higher Faradaic efficiency for methylamine production than the monometallic and nonpolymeric counterparts. We found that the Co centers in Co₂Cu₁PPc are the active sites for CO₂ reduction to formaldehyde, and Cu sites are active for the NO₃⁻ reduction to hydroxylamine. The nucleophilic attack of NH₂OH on HCHO forms a formaldoxime intermediate, which is further reduced to methylamine. The overreduction of NH₂OH and HCHO

intermediates is suppressed with heterometallic Co₂Cu₁PPc. Overall, the heterometallic centers coordinated with the conjugated macrocyclic network of polyphthalocyanine enable the efficient reduction of NO₃⁻ and CO₂ parallelly on different active sites to the key intermediates for C-N coupling. This work provides a new class of bifunctional electrocatalysts for the synthesis of organonitrogen chemicals from CO₂ and NO_x.

Author contributions

Y. Z. conducted the characterization and electrocatalytic measurements, performed data analysis, and drafted the manuscript. R. D. conducted DFT calculations. L. L. assisted in GC-based gas-phase product analysis. C. D. and C. L. conceived the idea, devised the project, revised the manuscript, and developed the conceptual ideas. All authors were involved in the discussion and analysis of this manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the SI. See DOI: <https://doi.org/10.1039/d5sc04641f>.



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