The presence and role of the intermediary CO reservoir in heterogeneous electroreduction of CO₂

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Despite the importance of the microenvironment in heterogeneous electrocatalysis, its role remains unclear due to a lack of suitable characterization techniques. Multistep reactions like the electroconversion of CO₂ to multicarbons (C₃₊) are especially relevant considering the potential creation of a unique microenvironment as part of the reaction pathway. To elucidate the significance of the microenvironment during CO₂ reduction, we develop on-stream substitution of reactant isotope (OSRI), a method that relies on the subsequent introduction of CO₂ isotopes. Combining electrolytic experiments with a numerical model, this method reveals the presence of a reservoir of CO molecules concentrated near the catalyst surface that influences C₂⁺ formation. Application of OSRI on a Cu nanoparticle (NP) ensemble and an electropolished Cu foil demonstrates that a CO monolayer covering the surface does not provide the amount of CO intermediates necessary to facilitate C-C coupling. Specifically, the C₂⁺ turnover increases only after reaching a density of ~100 CO molecules per surface Cu atom. The Cu NP ensemble satisfies this criterion at an overpotential 100 mV lower than the foil, making it a better candidate for efficient C₂⁺ formation. Furthermore, given the same reservoir size, the ensemble’s intrinsically higher C-C coupling ability is highlighted by the four-fold higher C₂⁺ turnover it achieves at a more positive potential. The OSRI method provides an improved understanding of how the presence of CO intermediates in the microenvironment impacts C₂⁺ formation during the electroreduction of CO₂ on Cu surfaces.

**Significance**

The electroconversion of CO₂ to value-added products is a promising path to sustainable fuels and chemicals. However, the microenvironment that is created during CO₂ electroreduction near the surface of heterogeneous Cu electrocatalysts remains unknown. Its understanding can lead to the development of ways to improve activity and selectivity toward multicarbon products. This work introduces a method called on-stream substitution of reactant isotope that provides quantitative information of the CO intermediate species present on Cu surfaces during electrolysis. An intermediary CO reservoir that contains more CO molecules than typically expected in a surface adsorbed configuration was identified. Its size was shown to be a factor closely associated with the formation of multicarbon products.

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Powering the conversion of small molecules into value-added products using renewable electricity is a promising approach to achieve the sustainable production of fuels and chemicals (1–3). The field of electrocatalysis has been moving toward this goal but remains hampered by activity and selectivity challenges. A molecular-level understanding of reactions is required to overcome these difficulties. More importantly, it should involve a thorough consideration of all factors that influence electrochemical conversion at heterogeneous surfaces. Previous studies have suggested that environmental aspects beyond the surface active site may be as critical for facilitating electrocatalytic reactions (4, 5).

Studies in heterogeneous electrocatalysis have largely focused on controlling the active sites and understanding how it influences reaction pathways through techniques such as surface spectroscopy (e.g., in situ Raman and infrared spectroscopy) combined with theory (6–8). However, locally confined environments also play a critical role in mediating reactions as demonstrated in other fields of catalysis. For example, in biocatalysis and homogeneous catalysis, the role of the microenvironment and the secondary coordination sphere have been widely investigated, respectively (9–14). The high selectivity achieved by bio- and molecular catalysts has often been associated with the characteristics of such regimes. Likewise, understanding the influence of a microenvironment in the context of heterogeneous electrocatalysis is necessary to gain a better control of reactions. It is expected that the microenvironment created near a catalytically active surface will exhibit specific physicochemical properties that differ from the bulk.

Microenvironment effects may be especially important for the CO₂ reduction reaction (CO₂RR), particularly on Cu catalysts where a variety of value-added, higher-order products (e.g., ethylene, ethanol) are generated (15). Up to now, probing key surface intermediates using surface spectroscopy coupled with theoretical calculations has led to the consensus that *CO is necessary for the formation of multicarbons (C₃₊) (16–18). Further investigation has revealed the importance of its binding mode (i.e., *COₚₘᵦ or *COₜᵢₜ) in determining CO₂RR selectivity (19–21). Other studies have reported high *CO coverage leading to C-C coupling necessary for C₂⁺ formation (22, 23). However, beyond the surface-bound *CO, recent findings suggest the presence of near-surface CO species during CO₂ electroreduction relevant to C₂⁺ formation.
Furthermore, structural modifications presumed to affect the environment surrounding catalysts have been shown to improve C$_2$+ selectivity (20, 28–30). Considering its critical influence, an in-depth characterization of the microenvironment under CO$_2$ electroreduction conditions is needed.

However, the characteristics of the microenvironment remain elusive due to the lack of suitable techniques. Despite the insights acquired into surface species present during the reaction, the use of surface spectroscopy has been limited to analyze present within a few nanometers from the surface (31, 32). Vibrational spectroscopy methods, such as Raman or Fourier-transform infrared spectroscopy, are also constrained to rely on surface enhancing effects to overcome the signal loss associated with the electrolyte (33, 34). Additionally, the enhancement decays rapidly away from the surface (inversely proportional to the cube of the distance), exclusively favoring surface-bound species (35–37). At high catalytic rates, optical interference from product bubble formation limits the use of such techniques under catalytically relevant operando conditions (26, 38). Overall, the limitations of surface vibrational spectroscopy prevent us from understanding the microenvironment during electrochemical reactions on heterogeneous surfaces.

In this work, we introduce on-stream substitution of reactant isotope (OSRI) as a method that can provide insights into the microenvironment near Cu surfaces during CO$_2$RR. The OSRI method employs isotopic labeling of the reagent CO$_2$ in a specific sequence and monitors its transformation to various products. Through the analysis of product isotopic compositions, it reveals the presence of a reservoir of intermediary CO (CO$_{int}$) molecules necessary for C$_2$ formation. Applied to two different systems (i.e., Cu nanoparticle [NP] ensemble and polycrystalline Cu foil), a density reaching $\sim100$ CO$_{int}$ molecules per surface Cu atom is identified as a common characteristic of the reservoir linked to CO$_2$ conversion to mult carbons. Furthermore, the intrinsic C-C coupling ability of a catalyst can be gauged independently from the availability of CO$_{int}$. Ultimately, we find that the higher C$_2$+ turnover of the Cu NPs compared against the Cu foil originates from both its ability to form a large CO$_{int}$ reservoir at low overpotentials and its intrinsically higher C-C coupling rate. Through the OSRI method, we identify the importance of a CO$_{int}$ reservoir in the formation of C$_2$+ over Cu surfaces, which has remained inaccessible thus far from conventional spectroscopic techniques.

Results and Discussion

The OSRI method starts with the application of a cathodic bias under $^{12}$CO$_2$(g) at a constant flow in aqueous conditions for 1 h, followed by a consecutive hour in which $^{12}$CO$_2$(g) feed is substituted with $^{13}$CO$_2$(g) under continued bias (Fig. 1A). The propagation of $^{13}$C can then be tracked across all products generated during electrolysis, using multiple modes of product analysis in both the gas and liquid phase that quantify the isotopic compositions of different products (Fig. 1B). Throughout

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Fig. 1. Study of Cu for CO$_2$ electroreduction by OSRI. (A) Schematic describing OSRI and the catalytic results of Cu. Cathodic bias is applied and maintained for 2 h, while the 0.1 M KH$_2$CO$_3$ electrolyte is purged with $^{12}$CO$_2$(g) (green) for the first hour followed by $^{13}$CO$_2$(g) (purple) during the second hour. (B) The experimental setup of OSRI where WE, CE, and RE, respectively refer to the working, counter, and reference electrodes. Products that contain $^{12}$C (green) and $^{13}$C (purple) accumulate in the gas (gas bag #1) and liquid phase (electrolyte) for isotopic analysis by GC-MS and NMR, respectively. All effluent gases are collected in gas bag #1 for the second hour only. Regular quantification of gas products is conducted by sampling the outlet stream at 20-min intervals by GC. NMR spectroscopy is used to quantify and determine the isotopic composition of the liquid products accumulated after 2 h in both the catholyte and the anionic membrane. Formate is the only product that accumulates in the membrane during OSRI. (C) After 2 h of electrolysis, the application of bias is terminated (left at open circuit voltage [OCV]), and the electrolyte is purged with Ar into a second gas bag (gas bag #2) for another hour to collect all the gases remaining in the chamber. The contents of gas bag #2 are analyzed using GC (quantification) and GC-MS (isotopic composition).
the 2 h, the outlet gas stream is sampled at regular intervals by gas chromatography (GC) for product quantification in real time. Furthermore, since the products contain a mix of $^{12}$C and $^{13}$C after switching to $^{13}$CO$_2(g)$, the gas products during the second hour are collected in a gas bag (gas bag #1) to study their isotopic composition by GC-mass spectrometry (GC-MS) (SI Appendix, Fig. S1 and Supplementary Text 1). Finally, the liquid products accumulated in the catholyte, as well as the membrane during OSRI, are analyzed using $^1$H and $^{13}$C NMR (SI Appendix, Supplementary Texts 2 and 3). Consequently, both the production rate and the isotopic composition of all formed products can be determined (Materials and Methods). Throughout OSRI, the current density and product Faradaic efficiencies (FEs) remained stable (SI Appendix, Fig. S9). All potentials are reported on the reversible hydrogen electrode (RHE) scale.

The first catalytic system studied by OSRI was an ensemble of 7-nm Cu NPs as reported in previous studies at $-0.60$ V with CO and HCOO$^-$ as CO$_2$RR products (39). Because the complete exchange of $^{13}$C for the $^{12}$CO$_2$(aq) is delayed by its equilibration with H$^{12}$CO$_3^-$ (aq), the average overall of $^{12}$CO$_2$(aq) available should be >50% (Fig. 1A). As expected, while the $^{12}$C/$^{13}$C ratio of CO$_2$(aq) supplied was 1:1, all products were found with a consistently higher $^{12}$C content (Fig. 2A). The delay of CO$_2$(aq) to complete the exchange was theoretically verified through a multiphysics simulation (Materials and Methods).

Regardless of any CO$_2$(aq) consumption taking place at the electrode due to applied potentials, there remains a substantial amount of $^{12}$CO$_2$(aq) available in solution after an hour of purging $^{13}$CO$_2$(g) into a $^{12}$CO$_2$(g) saturated 0.1 M KH$^{12}$CO$_3$ electrolyte (SI Appendix, Fig. S10). The multiple equilibria following CO$_2$(g) dissolution including HCO$_3^-$ (aq) and CO$_2^-$ (aq) are responsible for the slow exchange of all $^{12}$C in solution (SI Appendix, Supplementary Text 4 and Fig. S11). It should be noted that the colored segments for CO$_2$(aq) and the products in Fig. 1A are simply divided to qualitatively depict their average composition during OSRI; however, the true isotopic shift from $^{12}$C to $^{13}$C takes place gradually throughout the 2 h as shown in SI Appendix, Figs. S10 and S11. Varying the flow rate of CO$_2$(g) or the rate of CO$_2$(aq) consumption results in changes in the isotopic composition of electrolytically available CO$_2$(aq) that are consistent with this analysis (SI Appendix, Supplementary Text 5 and Fig. S12).

Although both CO and HCOO$^-$ are enriched in $^{13}$C due to the electrolyte equilibration, CO is more enriched in $^{12}$C than HCOO$^-$ (Fig. 2A). The difference in isotopic composition likely originates from the CO$_2$-$\text{to-HCOO}^-$ mechanism that, unlike the CO$_2$-$\text{to-CO}$ conversion, is known for not involving CO as an intermediate (e.g., *CO) (40–42). Without an accumulation of intermediates involved in HCOO$^-$ formation, its isotopic composition should closely track that of CO$_2$(aq) available during OSRI. On the other hand, a buildup of CO population on a Cu surface is expected for CO formation (40, 43, 44). In previous works, this buildup of CO has been suggested to result in a locally concentrated near-surface CO acting as an intermediate state for CO and, eventually, other higher-order product formation (e.g., C$_2$H$_4$) (24, 25, 27). This hypothesis has inspired improved CO$_2$ reduction strategies by combining CO-generating catalysts (e.g., Ag, Au) with Cu-based electrodes (45–48). Furthermore, these studies infer that chemically adsorbed CO (i.e., *CO) may not be the only configuration of

![Fig. 2](https://doi.org/10.1073/pnas.2201922119) Identification of the CO$_{int}$ reservoir on the Cu NP ensemble. (A) Isotopic composition of CO$_2$(aq) supplied and the products of CO$_2$RR measured during OSRI at −0.6 V vs. RHE. (B) Model-derived isotopic composition of HCOO$^-$ and CO produced over time during OSRI considering the presence of a CO$_{int}$ reservoir of constant size at steady state. The green areas under the H$^{12}$COO$^-$ (dark green) and $^{13}$CO (light green) curves divided by the total period (2 h) indicate the average isotopic fraction of $^{12}$HCOO$^-$ and $^{13}$CO, respectively, for the entire run. The $^{12}$CO$_{int}$ at the end of OSRI correspond to $^{12}$CO$_{int}$($t=120$ min). The $\delta$ steady-state density of CO$_{int}$ per Cu$_{int}$ measured experimentally and reproduced by the model are illustrated and compared to the monolayer of adsorbed *CO. The number of Cu$_{int}$ was estimated by measuring the postelectrolysis ECSA by Pb underpotential deposition. (C) Comparison of model-derived and experimental values for the average isotopic fraction of $^{12}$HCOO$^-$ and $^{13}$CO during OSRI, $\delta$ the steady state CO$_{int}$ density, and $\delta$ the isotopic fraction $^{12}$CO$_{int}$($t=120$ min). Error bars are one SD of three independent measurements for the experimental data.
CO as an intermediate. Therefore, we refer to all CO species during CO2 electroreduction, whether chemically bound or otherwise physically confined near the catalyst surface, as COint. The build-up and formation of a large reservoir of COint will lead to a lag between the available CO2(gas) (reagent) and CO (product) released at steady state. Specifically, in an experiment that switches from one isotope of CO2(gas) (12C) to another (13C), CO produced is expected to be more enriched in 13C than the average isotopic composition of available CO2(gas) (Fig. 1A).

To understand this isotopic lag phenomenon quantitatively, we construct a mathematical model that describes a COint reservoir attached to a Cu surface during OSRI (Fig. 2B). The applicability of the model to the experimental observations was evaluated and confirmed based on its close reproduction of four key experimental results: (1) the average isotopic fraction of H12COO−, (2) the average isotopic fraction of 12CO, (3) the density of the COint reservoir per surface Cu atom (Cusurf), and (4) the isotopic fraction of 13CO at the COint reservoir by the end of OSRI (details available in SI Appendix, Supplementary Text 6, and Figs. S13 and S14). Owing to the presence of the COint reservoir, the model reproduced the delayed exchange to 13C in the CO produced, leading to the trends shown in Fig. 2B for the isotopic fraction of H12COO− and 12CO over time. Values 1 and 2 are essentially the areas of each curve for H12COO− and 12CO divided by the entire period (i.e., 120 min), respectively. Furthermore, the steady-state size of the COint reservoir predicted by the model can be compared to the experimental value measured after stopping the bias at the end of the second hour of OSRI. All CO present in the cell then is purged with Ar for 1 h and collected in gas bag #2 (Fig. 1C). The amount of COint present at steady state near the Cu surface is determined after quantifying all the collected CO and subtracting the headspace and bulk electrolyte-dissolved CO contributions (Materials and Methods and SI Appendix, Fig. S15). The number of Cusurf necessary to determine the COint density per Cusurf atom can be derived from Pb underpotential deposition (SI Appendix, Supplementary Text 7 and Fig. S16). Because of any possible structural changes that may take place as bias is applied, the electrochemically active surface area (ECSA) of the catalyst was determined postelectrolysis (39, 49). The model also predicts the trend of the isotopic fraction of 12COint throughout OSRI leading to value 3 at 120 min (SI Appendix, Fig. S13D). The model-derived isotopic fraction of 12COint at this final time point can be compared to the experimental isotopic fraction, measured as 54% 12CO, for all CO remaining postelectrolysis and collected in gas bag #2 (Fig. 1C). Overall, the model closely reproduced the experimental values as summarized in Fig. 2C.

As stated earlier, the difference in isotopic composition between values 1 and 2 is a result of the COint reservoir being present during CO2 electrolysis. Changing experimental conditions to accelerate the rate of CO2(gas) exchange from 12C to 13C (e.g., by the use of a liquid flow cell simultaneously switching to a KH13CO3 electrolyte) does not alter this difference (SI Appendix, Fig. S17). The duration of operation upon substituting to 13CO2(gas) is another parameter that could be considered, and a longer electrolysis period is not desirable as the larger amount of total products formed obscures the relative difference between H12COO− and 13CO (SI Appendix, Fig. S18). Altogether, the chosen experimental conditions that define OSRI are adequate to assess the presence of the COint reservoir.

The results obtained from OSRI and reproduced by the model confirm the hypothesis of a COint reservoir present during CO2RR. Furthermore, the size of the COint reservoir verified offers valuable insights into the local environment of catalytically active Cu surfaces during CO2 electrolysis. We find that the COint density is around 78 COint per Cusurf, which is much higher than the monolayer coverage expected for *CO alone (i.e., 1 COint per Cusurf) (Fig. 2B). Assuming that this density of COint molecules is confined in a volume extending as far as ~100 μm from the electrode (i.e., up to the Nernst diffusion layer), then its concentration is ~1.8 mM (where typical CO solubility in water is 1 mM). Such a high concentration (20 to 100 times the solubility) has previously been verified near the surface of gas-evolving electrodes and is associated with gas bubble nucleation and growth (50–54). Although not reported for CO specifically, its physical properties akin to H2 or N2 suggest it would behave similarly during electrolysis (SI Appendix, Supplementary Text 8 and Table S7).

Therefore, we expect the physical state of COint to approach a condensed gas phase on and near the electrode surface. Such a large accumulation of CO molecules is likely enabled by the physical properties of the electrode-gas-electrolyte interface formed during CO2 electrolysis. In the presence of a large production of CO molecules, the Cu electrode can facilitate heterogeneous bubble nucleation on its surface by lowering the energy barrier of this process (50–54). We hypothesize that these favorable conditions for bubble formation enable the retention of a high COint density close to the catalyst surface.

To understand the role of the COint reservoir in the formation of C2+ products, we investigated more negative potentials where a CO2-to-C2+ conversion takes place. Experimentally, not only were the C2+ products also higher in 12C content relative to HCOO− but also they shared a similar average isotopic composition with CO, highly suggesting that the COint reservoir acts both as a source of product CO and as an intermediate pool for the C2+ (SI Appendix, Fig. S19). The model was therefore expanded to reproduce the isotopic composition of C2+ products, as well as HCOO− and CO, at more negative potentials. The conversion rate of the COint reservoir was adjusted to include the amount of COint consumed to C2+ products (SI Appendix, Supplementary Text 9). Once more, the model was found to closely reproduce the experimental data obtained during OSRI supporting the COint reservoir as an intermediate to C2+ formation. For instance, the isotopic composition of gas products measured in real time by GC-MS for the CO-derived products, such as CO and C2H4, matched closely with the trend expected by the model (Fig. 3A and SI Appendix, Fig. S21). Similarly, the isotopic composition of HCOO− measured at different time intervals (e.g., 80 and 100 min) by 1H NMR matched closely with the corresponding H12COO− expected by the model (SI Appendix, Fig. S22). Furthermore, the model closely replicated all the experimental values to 4 (SI Appendix, Fig. S20). Overall, instead of the traditional reaction pathway of CO2 first reduces to COint that accumulates to a concentrated reservoir near the catalyst surface before subsequent conversion to higher-order products (Fig. 3B), the Cu electrode supports the COint reservoir in the formation of CO, C2H4, EtOH, and n-PrOH (Fig. 3C). The relative portion of the COint reservoir utilized per unit time (% s−1) does not increase significantly and reaches only up to 1.05% per second as the potential is biased more negative. Instead, the distribution of products formed from the COint reservoir changes in favor of C2+ (Fig. 3D). Simultaneously, this shift in selectivity coincides with an increase of the COint density, roughly doubling from 78 to 147 molecules per Cusurf (Fig. 3D). These observations suggest that
C_{24}-formation correlates with a sizeable amount of CO_{int} per Cusurf (∼100 CO_{int}/Cusurf). Interestingly, we note that a CO_{int} reservoir conversion of 1.05% per second is equivalent to a conversion rate of ∼1 CO_{int} monolayer per second. This indicates that, unlike a monolayer of CO_{int}, a large CO_{int} reservoir can sustain the necessary conditions to attain a conversion rate at the scale of a monolayer of intermediates per second.

Previous works have commented on the importance of obtaining high CO surface coverage to facilitate C-C coupling (22, 25, 55). The OSRI results suggest that this configuration extends to a CO_{int} reservoir present near the catalyst surface that may act as the source for C_{24} formation downstream. Hence, the former notion of the traditional "CO monolayer" is replaced with a locally concentrated large population of CO molecules as intermediates. Furthermore, OSRI experimentally verifies the often-speculated idea of CO-rich environments on the surface of Cu catalysts during CO_{2} electrolys (24–27).

To verify that the CO_{int} reservoir is not unique to the Cu NP ensemble catalyst, the OSRI method was applied to an electropolished Cu foil, a well-known benchmark Cu catalyst for CO_{2}RR. The potential range selected to study the Cu foil was negatively shifted in comparison to the Cu NP ensemble to generate a similar product distribution (SI Appendix, Fig. S23 and Table S8). Cu foil exhibits a similar gap in the 12^{13}C isotopic fraction between HCOO− and all CO_{int}-derived products (SI Appendix, Fig. S24). Unlike the Cu NP ensemble, Cu foil displays a high FE toward CH_{4} that allows for its isotopic distribution to be more thoroughly analyzed. The 12^{13}C fraction of CH_{4} is consistent with all other CO_{int}-derived products that corroborates the importance of CO as an intermediate for CH_{4} production during CO_{2} electroreduction (15, 56). However, a collection of gases (i.e., CO, CH_{4}, and C_{2}H_{4}) was detected when trying to identify the contents of the reservoir experimentally as described in Fig. 1C (SI Appendix, Supplementary Text 10 and Fig. S25). The presence of products such as CH_{4} together with CO concentrated near the surface is expected to result from the morphological features of the Cu surface promoting the retention of gases (57). Therefore, the model was used to fit the Cu foil data while taking into consideration the presence of gases beyond CO as part of a larger reservoir regulating product formation and release (SI Appendix, Supplementary Text 11 and Fig. S26). Ultimately, the model closely replicates the experimental data, thus confirming the existence of a CO_{int} reservoir on Cu foil during CO_{2}RR (SI Appendix, Fig. S27).

Interestingly, both catalysts appear to enable C-C coupling after reaching a sufficiently high density of CO_{int} per Cusurf. Similar to the Cu NP ensemble, an analysis of the Cu foil indicates a transition from C_{1} to C_{2} formation at a CO_{int} density of ∼100 CO_{int} per Cusurf (Fig. 4A). The Cu foil further resembles the Cu NP ensemble with a CO_{int} to C_{2} conversion rate of ∼1 CO_{int} monolayer per second that is achieved after reaching ∼100 CO_{int} per Cusurf (SI Appendix, Fig. S28). These results suggest that a high surface coverage restricted to a monolayer does not provide the amount of CO_{int} necessary for C_{24} formation. This principle is also in line with a recent finding showing that even a Ag catalyst can improve its otherwise negligible selectivity toward C_{24} products given a high enough CO pressure (58). Taking these data, a key consideration in the development of catalysts moving forward should be increasing the CO_{int} density at lower overpotentials. Accordingly, the Cu NP ensemble reaches an adequate CO_{int} density at an overpotential 100 mV lower than the foil (Fig. 4B).

In addition to producing a sufficiently concentrated CO_{int} reservoir, a catalyst's activity should also be determined by its innate
ability to convert the CO\textsubscript{int} reservoir to C\textsubscript{2+}. So far, Cu-based electrocatalysts have been evaluated based on their C\textsubscript{2+} FE and turnover at a fixed potential. However, such an analysis does not account for the availability of CO\textsubscript{int}, which is critical; without the sufficient formation of CO\textsubscript{int}, a catalyst is unlikely to form C\textsubscript{2+} efficiently. Therefore, considering both the applied potential and availability of CO\textsubscript{int} is necessary to accurately assess the intrinsic ability of a catalyst to form C\textsubscript{2+} through the C-C coupling of C\textsubscript{1} intermediates. This is readily apparent in the comparison of C\textsubscript{2+} turnover between the Cu NP ensemble and the foil around −0.85 V where the former displays a CO\textsubscript{int} reservoir three times as large as the latter (Fig. 4B). This difference in the size of the CO\textsubscript{int} reservoir brings into question whether the Cu foil may yield a C\textsubscript{2+} turnover comparable to the NP ensemble provided there is enough CO\textsubscript{int} allowed at a lower overpotential. However, we find this unlikely given the trend in the C\textsubscript{2+} turnover frequency (TOF) of the Cu foil (Fig. 4B). Despite reaching a CO\textsubscript{int} density of ∼100 CO\textsubscript{int} per Cu\textsubscript{surf}, its TOF does not rise steeply to reach comparable levels as the NP ensemble; a TOF of 0.1 C\textsubscript{2+} per Cu\textsubscript{surf} s\textsuperscript{-1} at −0.92 V is fourfold lower than the NP ensemble whose TOF is 0.4 C\textsubscript{2+} per Cu\textsubscript{surf} s\textsuperscript{-1} at only −0.86 V. Furthermore, under CO reduction (CORR) conditions with identical CO availability, we find that the NP ensemble exhibits higher TOF\textsubscript{C+2} than the Cu foil as well (SI Appendix, Fig. S29). Hence, the formation of a concentrated CO\textsubscript{int} reservoir is necessary but not sufficient for high C\textsubscript{2+} turnover.

In addition, both catalysts react noticeably higher levels of TOF\textsubscript{C2+} during CO\textsubscript{2}RR in comparison to CORR (SI Appendix, Fig. S29). This likely results from the formation of the reservoir during the electroreduction of CO\textsubscript{2}, which sustains ∼100 CO molecules per Cu\textsubscript{surf}. In contrast, within the 100-μm layer away from the catalyst surface, only 5 CO molecules per Cu\textsubscript{surf} would be available under CORR. The concentrated CO microenvironment formed during CO\textsubscript{2}RR overcomes the constraint of low CO solubility (1 mM in water at 1 atm, room temperature) that limits CORR activity in aqueous conditions. Therefore, instead of the concentration of CO\textsubscript{2}, the size of the CO\textsubscript{int} reservoir is a more accurate representation of the reactants necessary to the formation of multicarbons. We suggest that such considerations are also important for CO\textsubscript{2} reduction in gas-diffusion electrode systems; recent works have reported the importance of optimizing both the CO\textsubscript{2} and CO availability to maximize C-C coupling (55, 59, 60).

The results from the OSRI method suggest that both the contribution of CO\textsubscript{int} availability and intrinsic C-C coupling ability are necessary to a catalyst’s CO\textsubscript{2}-to-C\textsubscript{2+} activity. Concretely, a good catalyst must possess the ability to form a large CO\textsubscript{int} reservoir at low overpotentials as well as exhibit high intrinsic activity for the coupling of CO\textsubscript{int}. The Cu foil’s moderate C\textsubscript{2+} intrinsic activity is ascribed not only to its low intrinsic C-C coupling capacity but also to the high overpotential required to form a large enough CO\textsubscript{int} reservoir. Therefore, maximizing CO\textsubscript{int} availability at low overpotentials emerges as an additional parameter in future catalyst design, in addition to the necessary structural traits that favor C-C coupling (39, 61, 62). Namely, CO\textsubscript{int} availability can be enhanced through improved retention of CO upon its formation. A few approaches along this line have been considered, such as modifying surface morphologies of electrodes to impact product release or functionalizing the catalyst with surface additives that promote gas affinity through increased hydrophobicity (28, 63–65). Beyond catalyst design implications, these results indicate that further investigations to determine the intrinsic C-C coupling of Cu-based catalysts under controlled (micro)environments are needed.

In summary, we present OSRI, a unique method that probes the microenvironment surrounding Cu surfaces during CO\textsubscript{2}RR. It has led to the discovery of a concentrated reservoir of CO molecules near catalyst surfaces that is necessary for efficient C-C coupling. Instead of CO\textsubscript{2}, this reservoir is identified as a more accurate representation of the reactants determining the rate of multicarbon formation during CO\textsubscript{2}RR. Through these findings, the importance of the microenvironment formed during the reaction is better distinguished from the intrinsic activity of the catalyst surface. Furthermore, OSRI is a promising method to investigate the effects of the microenvironment in other catalytic reactions similar to CO\textsubscript{2}RR. Specifically, the significance of intermediates residing near the surface during multistep electrocatalytic reactions can be gauged, thus guiding future improvements in catalyst selectivity and activity.

Materials and Methods

NP Synthesis and Electrode Fabrication. The 7-nm Cu NPs were synthesized as previously reported (39). NP concentrations by mass of Cu were measured by inductively coupled plasma optical emission spectroscopy (Perkin-Elmer Optima 7000 DV), after which 68.9 μg of Cu was deposited on a 1-cm\textsuperscript{2} area of carbon paper (Sigracet 29AA, Fuel Cell Store) to make working electrodes.

![Fig. 4. Comparison between the Cu foil and the Cu NP ensemble. (A) CO\textsubscript{int} conversion yield (CO\textsubscript{int} consumed for each product/all CO\textsubscript{2} consumed) partitioned across different CO\textsubscript{int}-derived products and CO\textsubscript{int} density measured as a function of applied potential on the Cu foil. The number of CO\textsubscript{int} converted to each product is labeled as n× CO\textsubscript{int}, where n corresponds to the number of CO\textsubscript{int} required for its formation (e.g., 2× CO\textsubscript{int} for C\textsubscript{2}H\textsubscript{4}). (B) C\textsubscript{2+} turnover (dashed line) of the Cu foil and Cu NP ensemble with their CO\textsubscript{int} density (by the size of the bubble) as a function of applied potential. Bubbles are plotted to scale with respect to their diameter. Error bars are one SD of three independent measurements.](https://doi.org/10.1073/pnas.2201922119)
Cu foil (0.1 mm thick, Puratronic, 99.999%) was electropolished before utilization in 85% phosphoric acid at 3 V against a counter electrode for 1 min. Once treated, the Cu foil was thoroughly rinsed with deionized water and dried with N₂ gas. The electrode of a 4-cm² geometric surface area was placed inside an electrochemical cell for further testing.

**OSRI.** All electrochemical measurements were carried in a custom-made H-cell consisting of two main compartments separated by a Selenan AMV anion exchange membrane (AEM). Ag/AgCl (WPI, 3 M KCl) was used as a reference electrode, and a platinum wire was used as a counter electrode. A total of 0.1 M KHCO₃ electrolyte was prepared by purging a 0.05 M K₂CO₃ (99.997% trace metal basis) solution with CO₂(g) overnight. Both the working and counter chamber were filled with 15 mL of the electrolyte, and vigorous stirring was maintained in the working chamber. The input stream of CO₂(g) was humidified by being bubbled through distilled water before being introduced into the cell. Before each measurement, the 15-mL catholyte was purged with 20 sccm ¹²CO₂(g) for 15 to 20 min until saturated. Then, ¹³CO₂(g) was purged while applying a cathodic bias for 60 min and subsequently switched to ¹²CO₂(g) (¹³C diox- ide, 99 atom % ¹³C, 99.93 atom % ¹⁰O) while maintaining the same potential for another 60 min. Depending on the operating conditions, the flow rate was adjusted to 20, 10, or 5 sccm. For instance, low flow rates were used for conditions that exhibit low current densities (e.g., at more positive potentials). This ensured higher concentrations of gas products to be measured in real time using the gas chromatograph. All electrode potentials measured against the 3 M KCl Ag/AgCl reference were corrected to the RHE scale using E (vs. RHE) = E (vs. Ag/ AgCl) + 0.21V + 0.0591 × pH. For all electrochemical experiments, 84% of ohmic loss was compensated by the potentiostat (Biologic) in real time and the remaining 16% was manually postcorrected.

The concentration of gases produced throughout OSRI were measured regardless of their isotopic identity using a gas chromatograph (SRI GC) connected at the outlet of the cell. The gas chromatograph is equipped with a molecular sieve 3 Å (1/8” × 6’’ × 6’) and a Hayesep D (1/8” × 6’) column with Ar flow- ing as a carrier gas. A sample for GC was collected at 20-min intervals, and the separated gas products were analyzed by a thermal conductivity detector (TCD) for H₂ and a flame ionization detector (FID) for CO and hydrocarbons. Quantification of the products was performed with conversion factors derived from the standard calibration gases, and the concentration of gas measured was further converted to partial current density.

Upon substitution of the reactant isotope from ¹²CO₂(g) to ¹³CO₂(g), all produced gases were collected to determine their isotopic composition. A 2-L Supel- linert multilayer foil gas bag (gas bag #1) was connected to the exhaust of the SRI GC sampling loop at the same time as the onstream substitution at 60 min. After another 60 min of electrolysis while purging ¹³CO₂(g), the application of bias was terminated, and the gas stream was substituted with Ar. Gas bag #1 was simultaneously sealed and substituted for a second gas bag (gas bag #2) to collect any leftover gases still present inside the cell to determine the size and composition of the CO_{int} reservoir (see Materials and Methods section Determining the Size and Isotopic Composition of the CO_{int} Reservoir).

The isotopic composition of gas products in gas bag #1 was determined by GC/MS using an AutoSpec Premier mass spectrometer (Waters), equipped with an Agilent 7890A gas chromatograph, and an electron impact ion source. The collected gases were sampled and manually injected using a gas-tight 1-mL syringe (Agilent PN 5190-1531). They were passed through a Supelco, Carboxen: 1010 PLOT column with He as a carrier gas to separate CO, CH₄, and C₂H₄ from N₂, O₂, and CO₂ (SI Appendix, Fig. S1). The mass spectrometry was analyzed to extract the isotopic composition of all CO₂RR gas products as described in SI Appendix, Supplementary Text 1.

Meanwhile, the liquid products accumulated during OSRI were analyzed by quantitative NMR (Bruker AV-600) using dimethyl sulfoxide as an internal standard. The standard presaturation technique was implemented to suppress the water peak. The collection of all liquid products was ensured by analyzing the catholyte and the AEM. The latter was soaked in 15-mL blank electrolyte overnight to ensure all trapped products would diffuse back into the liquid (SI Appendix, Supplementary Text 2). A further isotopic analysis was carried on the liquid products combining ¹H with ¹³C NMR on the same instrument. ¹³CNMR was determined by decoupling the signals from their multiple isotopologues as described in SI Appendix, Supplementary Text 3.

FEs were calculated from the amount of charge passed to produce each product divided by the total charge passed at a specific time (gas) or during the overall run (liquid).

**Determining the Size and Isotopic Composition of the CO_{int} Reservoir.**

After the second hour of electrolysis while purging ¹³CO₂(g), the bias was terminated and all CO present in the cell was purged out with Ar for 60 min and collected in gas bag #2. Ar purge of 60 min ensured that there were no remaining gases in the working electrode chamber. Depending on the flow rate employed for each experiment, ranging from 5 to 20 sccm, gas bag #2 was filled with a total gas volume of 300 to 1,200 mL, respectively. The low CO concentration collected in gas bag #2 was measured after injecting the bag content into another gas chromatograph (Agilent 7890B GC) setup for manual injection. This gas chromatograph is equipped with a molecular sieve SA (60/80° × 6’’), hayesep Q (80/100° × 6’’), and hayesep Q (80/100° × 1.5’) column with Ar flowing as a carrier gas. The same detectors (i.e., FID and TCD) listed for the SRI GC are used. Using the measured CO concentration, the total amount of CO molecules was calculated considering the total volume of gas collected. Gas bag #2 contained CO collected from the headspace, dissolved in the bulk electrolyte, and locally concentrated near the catalyst surface (i.e., CO_{int} reservoir), which were all present upon stopping bias. CO present in the cell headspace was determined from the concentration of CO measured at steady state during electrolysis (SRI GC) and the headspace volume of 30 mL. Furthermore, Henry’s law was applied to obtain the number of dissolved CO in equilibrium with that headspace. The size of the CO_{int} reservoir was estimated by subtracting both values from the total amount of CO collected in gas bag #2. The isotopic composition of the CO_{int} res- ervoir was determined following the GC-MS procedure (described for gas bag #1) applied to gas bag #2. The composition of the CO_{int} reservoir is assumed to be identical to the headspace and dissolved CO. The same method of quantifica- tion was employed at more negative potentials.

**ECSA and Cu Surface Atom Determination.** Lead underpotential deposition (Pb UPD) was conducted immediately postelectrolysis in a solution of 0.1 M NaClO₄, 10 mM HClO₄, and 3 mM Pb(II)(ClO₄)₂. Cyclic voltammetry in the Pb underpotential region was conducted at 10 mV/s six times, for which the cycles were confirmed consistent, and the fifth scan was reported. The potentials are referenced against a 1.0 M KCl Ag/AgCl electrode.

The number of Cu surface atoms was then determined using the assumption that each of the low index facets (100), (110), and (111) are equally likely to be present on the surface. We used the relationship between the number of Cu atoms and surface area for each facet as established in the work of Giri and Sakar to determine the number of surface Cu atoms from the measured Cu surface area by Pb UPD (66).

\[ \text{Planar density of Cu}(100) \text{ plane} = 15.3065 \times 10^{14} \text{ atoms cm}^{-2} \]
\[ \text{Planar density of Cu}(110) \text{ plane} = 10.8371 \times 10^{14} \text{ atoms cm}^{-2} \]
\[ \text{Planar density of Cu}(111) \text{ plane} = 17.7556 \times 10^{14} \text{ atoms cm}^{-2} \]

**COMSOL Multiphysics Simulation.** The change in isotopic composition taking place during the purging of CO₂ gas into a ¹²CO₂ equilibrated electrolyte was simulated using COMSOL Multiphysics. The transport of species present was calculated for the bulk volume of the well-mixed electrolyte. The Bubbly Flow, Laminar Flow module was used to solve for the velocity and mass transfer of CO₂ bubbles into the liquid electrolyte. Assuming only a small volume fraction is occupied by the bubbles, the Navier-Stokes equations were used only to solve for the flow of the liquid phase while the velocity of the bubbles was determined by a slip model. The gas mass flux was set to replicate the experimental flow rate employed during OSRI (e.g., 5 sccm) with a bubble size of 0.4 cm. The number of bubbles per unit volume is tracked over time in the electrolyte to calculate the total interfacial area (m²). Mass transport \( m_{gy} \) (kg · s⁻¹) taking place at this interface was calculated using two-film theory:

\[ m_{gy} = k(c^* - c)Ma, \quad c^* = \frac{P + P_{atm}}{H} \]
where $k$ (m.s$^{-1}$) corresponds to the mass transfer coefficient, $c$ (mol.m$^{-3}$) corresponds to the concentration of the gas dissolved in solution, $M$ (kg.mol$^{-1}$) corresponds to the gas molecular weight, $p$ (Pa) corresponds to the gas pressure, and $H$ is Henry's constant (Pa.m$^3$.mol$^{-1}$). Upon dissolution, the further equilibration of CO$_2$ at $pH < 7$ is described by the following equations:

$$ CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+ \quad pK_{a1} = 6.37 $$

$$ HCO_3^- \rightleftharpoons CO_3^{2-} + H^+ \quad pK_{a2} = 10.25 $$

Water self-ionization equilibrium is also included:

$$ H_2O \rightleftharpoons OH^- + H^+ \quad pK_w = 14 $$

Using their respective equilibrium constants, the concentrations of all species present in the electrolyte were solved for, using the Transport of Dilute Species module. Dissolved CO$_{2\text{eq}}$, bicarbonate anions (HCO$_3^-$), carbonate anions (CO$_3^{2-}$), hydroxide anions (OH$^-$), protons (H$^+$), and potassium cations (K$^+$) were all accounted for during the time-dependent study. All 13C and 12C equivalents were considered for all carbon-containing species. The initial concentration of all species was established assuming the 0.1 M KH$_2$13CO$_3$ electrolyte is equilibrated under a 12CO$_2$-saturated atmosphere and respects the condition of electroneutrality:

$$ \sum_i z_i c_i = 0 $$

Following the introduction of 13CO$_{2\text{eq}}$, the transport of all solvated species was set to respect mass conservation such as:

$$ \frac{\partial c_i}{\partial t} + \nabla \cdot (\mathbf{J}_i) + \nabla \cdot \mathbf{c} = - R_i $$

where $c_i$ corresponds to the concentration of the species, $\mathbf{J}_i$ corresponds to their diffusion coefficient, $R_i$ corresponds to their reaction rate expression, $\nabla \cdot \mathbf{c}$ corresponds to the mass average velocity vector, $J_i$ corresponds to the mass flux diffusive flux vector, $z_i$ corresponds to the charge number of the ionic species, $\nabla \cdot \mathbf{J}_i$ corresponds to their ionic mobility, $F$ is Faraday's constant, and $\nabla$ corresponds to the electric potential. The velocity $\mathbf{v}$ describes the convective transport that results from the magnetic stirring in the cell as well as the bubbly flow solved in the previous module. All constants utilized for the simulation are summarized in Table S6.

OSR Kinetic Model. Molecular mass flow taking place during OSRI was modeled to reproduce the composition of isotopes observed in the products. The model was built based on the kinetic relationship between supplied CO$_{2\text{gas}}$, available CO$_{2\text{eq}}$, a CO$_{2\text{int}}$ reservoir, and all CO$_{2\text{RR}}$ products. Once determined mathematically as described in the SI Appendix, Supplementary Text 6, the model was run using MATLAB.

CORR Measurements. CORR experiments were conducted in a similar three-electrode electrochemical H-cell constructed from polytetrafluoroethylene, using 0.1 M KOH (Sigma, 99.99%) as electrolyte. CO (99.99%, Praxair) was purged through the electrolyte for at least 30 min before electrolysis and maintained at 15 scm throughout electrolysis. Hg/Hgo 1 M NaOH (0.13 V vs. standard hydrogen electrode (SHE)) reference electrode and Neopenta AHA membrane were used for their tolerance to the alkaline electrolyte. Electrolysis was conducted for 30 min to 1 h before gas and liquid samples were collected. All gas and liquid products were analyzed using the same procedure described above for GC and NMR measurements, respectively.

Data Availability. All study data are included in the article and/or SI Appendix.

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