Operando Investigation of Ag-Decorated Cu\textsubscript{2}O Nanocube Catalysts with Enhanced CO\textsubscript{2} Electroreduction toward Liquid Products

Antonia Herzog, Arno Bergmann, Hyo Sang Jeon, Janis Timoshenko, Stefanie Kühl, Clara Rettenmaier, Mauricio Lopez Luna, Felix T. Haase, and Beatriz Roldan Cuenya*

Abstract: Direct conversion of carbon dioxide into multi-carbon liquid fuels by the CO\textsubscript{2} electrochemical reduction reaction (CO\textsubscript{2}RR) can contribute to the decarbonization of the global economy. Here, well-defined Cu\textsubscript{2}O nanocubes (NCs, 35 nm) uniformly covered with Ag nanoparticles (5 nm) were synthesized. When compared to bare Cu\textsubscript{2}O NCs, the catalyst with 5 at\% Ag on Cu\textsubscript{2}O NCs displayed a two-fold increase in the Faradaic efficiency for C\textsubscript{2}, liquid products (30\% at –1.0 V\textsubscript{RHE}), including ethanol, 1-propanol, and acetaldehyde, while formate and hydrogen were suppressed. Operando X-ray absorption spectroscopy revealed the partial reduction of Cu\textsubscript{2}O during CO\textsubscript{2}RR, accompanied by a reaction-driven redispersion of Ag on the Cu\textsubscript{2}O, NCs. Data from operando surface-enhanced Raman spectroscopy further uncovered significant variations in the CO binding to Cu, which were assigned to Ag–Cu sites formed during CO\textsubscript{2}RR that appear crucial for the C–C coupling and the enhanced yield of liquid products.

Introduction

In the quest for developing a sustainable energy economy, the electrochemical reduction of carbon dioxide (CO\textsubscript{2}RR) into value-added chemicals and fuels offers the potential to close the anthropogenic carbon cycle and store renewable (wind, solar, hydro) energy into chemical bonds.\cite{[1]} It has been therefore of particular interest to develop efficient and selective electrocatalysts, which reduce the reaction over-potential and steer the reaction toward hydrocarbons and multicarbon oxygenates (C\textsubscript{x}O\textsubscript{y}). The selective generation of liquid products such as ethanol, 1-propanol, and acetaldehyde is highly desirable due to their high energy densities and advantages for storage/transport as compared to gaseous products.\cite{[2,3]}

A variety of metal electrodes can be used to catalyze CO\textsubscript{2}RR as demonstrated in the pioneering work by Hori.\cite{[4]}

While some metals primarily reduce CO\textsubscript{2} to CO (Ag, Au, Zn) or formate (Sn, In, Bi), copper is the only metal yielding products such as methane, ethylene, and ethanol in considerable amounts.\cite{[5]}

However, the selective conversion to C\textsubscript{2} products in the form of liquids (alcohols and carbonyls) still requires high overpotentials, suffers from low current densities that can be achieved, and the generation of parasitic hydrogen through the competing hydrogen evolution reaction (HER). Various strategies have been developed to enhance the performance of Cu-based catalysts, including nanostructuring Cu (control of exposed facets, defects and low-coordinated sites),\cite{[6]}

engineering the Cu-electrolyte interface (change of local pH),\cite{[7]}

and adjusting the Cu oxidation state (compositional change).\cite{[8]}

For example, Cu\textsubscript{2}O nanocubes (NCs) with well-ordered (100) facets have been shown to lead to an increase in the selectivity toward ethylene, while suppressing methane production.\cite{[9,10]}

A promising way to further improve the catalyst’s performance and selectivity is the introduction of a secondary metal.\cite{[11]}

Recent studies of Cu–Ag bimetallic systems showed enhanced selectivity for C\textsubscript{2}, products. In particular, a phase-blended Ag-Cu\textsubscript{2}O catalyst had a three times higher Faradic efficiency (FE) toward ethanol than Ag-free Cu\textsubscript{2}O but suffered from low activity (|\textit{j}\textsubscript{CO}\textsubscript{2}RR| < 1 mA).\cite{[10]}

Additionally, Ag-covered Cu\textsubscript{2}O nanowires prepared via a galvanic replacement reaction enabled a 1.4 times higher current density toward ethylene production as compared to pure Cu\textsubscript{2}O nanowires.\cite{[11]}

Furthermore, CuAg surface alloys have been found to be more selective for the formation of multi-carbon products than pure copper.\cite{[12]}

The facilitated yield of C\textsubscript{2}, products in the bimetallic system is usually linked to the suppression of HER due to the enhanced coverage of CO adsorbates as compared to *H,\cite{[12a]}

and the diffusion of CO from Ag sites to Cu sites that enables C–C coupling (CO spillover).\cite{[10,11]}

Note here that a short diffusion path of CO and therefore a homogeneous distribution of Cu and Ag at the surface of the catalyst are essential for an effective CO spillover.\cite{[10,12a]}

Nonetheless, although the spatial arrangement of Cu and Ag in these studies seems to play a key role for the different CO\textsubscript{2}RR selectivity trends obtained, the key parameters for achieving an optimal synergy in Cu–Ag bimetallic systems are still unknown. In particular, open questions still remain on the composition and structure of the most active and C\textsubscript{2}-selective systems under operando CO\textsubscript{2}RR conditions, including the stability of Cu\textsubscript{2}O, which might be modified by introducing Ag.\cite{[13]}

* A. Herzog, Dr. A. Bergmann, Dr. H. S. Jeon, Dr. J. Timoshenko, Dr. S. Kühle, C. Rettenmaier, M. Lopez Luna, F. T. Haase, and B. Roldan Cuenya

References:

\[1\] A. Herzog, Dr. A. Bergmann, Prof. Dr. B. Roldan Cuenya

Department of Interface Science

Fritz-Haber Institute of the Max-Planck Society

Faradayweg 4–6, 14195 Berlin (Germany)

E-mail: roldan@fhi-berlin.mpg.de

Supporting information and the ORCID identification number(s) for the author(s) of this article can be found under: https://doi.org/10.1002/anie.202017070.

© 2021 The Authors. Angewandte Chemie International Edition published by Wiley-VCH GmbH

Angew. Chem. Int. Ed. 2021, 60, 7426 – 7435
Herein, we prepared well-defined Cu$_2$O NCs (35 nm) uniformly covered with Ag nanoparticles (NPs, 5 nm) by a facile wet-chemical ligand-free synthesis. Employing ex situ, in situ and operando characterization techniques, we gained insight into the morphology, chemical state, composition, and adsorbates of the Cu–Ag catalyst under CO$_2$RR conditions. In particular, we discuss reaction-induced Ag redispersion, Cu–Ag surface alloy formation, the influence of Ag on the reduction of Cu$_2$O, the adsorption of CO on Cu and Ag, and the effect of the former parameters in the CO$_2$RR activity and selectivity.

**Results and Discussion**

Figure 1 shows STEM-HAADF and STEM-EDX maps of pure and Ag NP-decorated Cu$_2$O NCs. The as-prepared Cu$_2$O NCs have an edge length of 35 ± 7 nm (Figure 1a). The STEM-EDX data (Figure 1b, S1, Table S1) reveal an average Cu/O at% ratio of 66:34, which corresponds to the composition of Cu$_2$O. In the following, the Cu$_2$O NCs decorated with 3 and 5 at% of Ag will be denoted 3-Ag/Cu$_2$O and 5-Ag/Cu$_2$O. The Ag NPs with a diameter of 4.6 ± 1.1 nm (3-Ag/Cu$_2$O, Figure 1c, S2) and of 6.0 ± 2.1 nm (5-Ag/Cu$_2$O, Figure 1e, S3) appear to be uniformly distributed on the surface of the Cu$_2$O NCs. The STEM-EDX maps of the as-prepared 3- and 5-Ag/Cu$_2$O catalysts (Figure 1f,j) indicate a clear phase separation between the Ag NPs and the Cu$_2$O NCs.

After 2 h of CO$_2$RR at $-1.0$ V$_{\text{RHE}}$ in 0.1 M KHCO$_3$, the cubic morphology appeared less pronounced and hollow structures formed in all cases (Figure 1c,g,k). Simultaneously, the edge length of the NCs decreased in average by 3 nm (Table S2) and the size distribution broadened, as reported in the literature for pure Cu$_2$O NCs after CO$_2$RR.$^{[3]}$ STEM-EDX maps after reaction (Figure 1d,h,l) reveal that Cu$_2$O is partially reduced to metallic Cu (Table S3) and that the clear phase separation between Ag and Cu is lost. Instead, small Ag clusters are dispersed on the Cu surface. In addition, some Ag-rich areas with sizes of 6.3 ± 1.6 nm (3-Ag/Cu$_2$O) and 9.5 ± 2.5 nm (5-Ag/Cu$_2$O) were also found (Table S2).

X-ray diffraction (XRD) was applied to confirm the phase purity of the catalysts and to track the evolution of the crystal structure after CO$_2$RR. Figure S4 shows the XRD pattern of the as-prepared Cu$_2$O NCs and Ag/Cu$_2$O with the main Cu$_2$O reflections assigned to (111) at 36.4° and (200) at 42.3°. The presence of metallic Ag can be seen by the Ag(111) at 38.2° and Ag(200) at 44.5° for the Ag/Cu$_2$O. The low intensity of the fcc Ag reflections can be attributed to the low Ag loading and XRD peak broadening due to small particle sizes.

**Figure 1.** STEM-HAADF images with corresponding EDX maps of Cu$_2$O NCs, 3-Ag/Cu$_2$O, and 5-Ag/Cu$_2$O in the upper, middle, and lower panels, respectively. As-prepared samples are shown on the left (a,e,i) with EDX maps in (b,f,j) and samples after 2 h of CO$_2$RR at $-1.0$ V$_{\text{RHE}}$ on the right (c,g,k) with EDX maps in (d,h,l). The scale bars correspond to 50 nm.
Table 1: Atomic fraction and structural coherence length of Cu$_2$O and metallic Cu and Ag phases.$^\text{[a]}$

| Sample          | Atomic fraction [at%] | Structural coherence length [nm] |
|-----------------|-----------------------|---------------------------------|
|                 | Cu$_2$O | fcc Cu | fcc Ag | Cu$_2$O | fcc Cu | fcc Ag |
| As-prepared     |          |         |        |          |         |        |
| Cu$_2$O NC      | 100      | –       | –      | 32.6(3)  | –       | –      |
| 3-Ag/Cu$_2$O    | 97.55(9) | 2.45(6) | 32.3(7) | –        | 5.9(7)  | –      |
| 5-Ag/Cu$_2$O    | 95.1(7)  | 4.9(5)  | 23.1(3) | –        | 6(2)    | –      |
| After CO$_2$RR  |          |         |        |          |         |        |
| 5-Ag/Cu$_2$O    | 56(16)   | 24(9)   | 20(7)  | 6.8(3)   | 9(2)    | 4.4(5) |

$^\text{[a]}$ Derived from Rietveld refinement of ex situ XRD patterns of as-prepared Cu$_2$O NCs, 3-Ag/Cu$_2$O, and 5-Ag/Cu$_2$O, and of 5-Ag/Cu$_2$O deposited on carbon paper after 2 h of CO$_2$RR at $-1.0$ V$_{RHE}$.

Table 1 shows the as-prepared composition and coherence length derived from Rietveld refinement of the XRD patterns. The coherence length of Cu$_2$O agrees well with the size distribution obtained by STEM analysis, although it is slightly smaller than the mean NC edge length. The atomic fractions of metallic Ag in the as-prepared Ag/Cu$_2$O agree well with the Cu/Ag composition obtained by ICP-MS (Table S5). This confirms that the majority of the added Ag from the AgNO$_3$ solution was incorporated in the Ag NPs, and that the initial ratios of the metal salts utilized were maintained.

The structural evolution of the 5-Ag/Cu$_2$O catalyst was investigated before and after 2 h of CO$_2$RR using ex situ grazing incidence (GI) XRD (Figure 2, Table 1) and shows the reduction of Cu$_2$O to metallic Cu as prominently seen in the Cu(111) reflection at 43.2°. The background arises from the carbon paper support (Figure S5). Rietveld refinement of 5-Ag/Cu$_2$O after CO$_2$RR suggests a mixture of Cu$_2$O and metallic Cu and a significantly increased Ag fraction, while ICP-MS did not show changes in the catalyst composition (Table S6). Thus, we are seeing a considerable fraction of Cu/Cu$_2$O after reaction according to XRD. This suggests that Cu might be present in non-crystalline domains, resulting in an increased Ag/Cu ratio. Additionally, there is a slight contraction of the Ag lattice (4.092 ± 0.003 to 4.088 ± 0.003 Å), which could be explained by the incorporation of Cu into the Ag lattice (Table S4). Notably, the coherence length of Cu$_2$O decreased strongly from 23.1 nm (as-prepared) to 6.8 nm (after CO$_2$RR), reaching a similar value to the coherence length of the metallic Cu phase (9 nm). We conclude that the hollow structures after CO$_2$RR (Figure 1) might consist of a mixture of Cu$_2$O and Cu crystallites as seen in XRD. The coherence length of the metallic Ag phase is on average slightly decreased after CO$_2$RR, which agrees with the partial re-dispersion of Ag on the Cu surface and the Ag-rich domains likely being formed from multiple Ag NPs.

Quasi-in situ X-ray photoelectron spectroscopy (XPS) measurements were performed to gain deeper insight into the surface composition and chemical state of the Ag NP-decorated and pure Cu$_2$O NCs before and after 2 h of CO$_2$RR. Figure 3 presents the Ag 3d and Cu Auger LMM spectra, while Figure S6 shows the Cu 2p spectra. The Ag 3d core level regions of 3- and 5-Ag/Cu$_2$O (Figure 3a,b) reveal that Ag is in the metallic state before and after CO$_2$RR, which is also consistent with the XRD results. The Ag/Cu surface composition ratios were determined by integrating the peak areas of Ag3d$_{5/2}$ and Cu2p$_{3/2}$. As expected for Ag NPs decorating the surface of Cu$_2$O NCs, the Ag/Cu ratio extracted from the more surface-sensitive XPS technique was higher than the bulk composition obtained from the XRD and ICP-MS analysis. After CO$_2$RR, the Ag/Cu XPS ratios further increased from 4.96 to 7.93 at% in 3-Ag/Cu$_2$O and from 9.91 to 11.89 in 5-Ag/Cu$_2$O. Thus, we conclude that a more homogeneous distribution of Ag (redispersion) on the Cu$_2$O surface takes place during CO$_2$RR. Furthermore, we can exclude significant preferential dissolution of Cu during CO$_2$RR due to the constant bulk Ag/Cu ratio before and after CO$_2$RR as demonstrated by ICP-MS (Table S6). The higher Ag signal observed after CO$_2$RR agrees with the formation of smaller Ag NPs and clusters and an enhanced Ag dispersion, as also revealed by the STEM and XRD data.

Additionally, deconvolution of the Cu LMM spectra (Figure 3c,d, Table S7) was carried out to distinguish Cu$^0$, Cu$^+$, and Cu$^{2+}$ near-surface species. In the as-prepared state, the samples consisted mainly of Cu$_2$O with a contribution of CuO. After 2 h of CO$_2$RR, the near-surface regions of the Cu$_2$O NCs and Ag/Cu$_2$O samples were fully reduced to metallic Cu within the error margin. In contrast to prior studies, our samples were not exposed to air after CO$_2$RR, since our electrochemical cell is directly connected to the XPS chamber. Thus, even though no potential is applied during the XPS measurement, re-oxygenation in air can be excluded.

The electrocatalytic performance of Ag NP-decorated and pure Cu$_2$O NCs deposited on carbon paper was evaluated by chronoamperometric measurements for 2 h at potentials...
As-prepared  

(a) Ag 3d  

Intensity / arb. units  

5-Ag/CuO  

3-Ag/CuO  

5-Ag/CuO  

(b) Ag 3d  

Intensity / arb. units  

5-Ag/CuO  

3-Ag/CuO  

5-Ag/CuO  

(c) Cu LMM  

Intensity / arb. units  

CuO NCs  

CuO NCs  

CuO NCs  

(d) Cu LMM  

Intensity / arb. units  

CuO NCs  

CuO NCs  

CuO NCs  

Figure 3. Quasi-in situ Ag 3d XPS and Cu LMM XAES spectra of CuO NCs, 3-Ag/CuO, and 5-Ag/CuO (a,c) in the as-prepared state and (b,d) after 2 h of CO_RR at −1.0 V_RHE (without air exposure) with the corresponding fits (red line) and reference spectra.

Research Articles

between −0.7 and −1.1 V_RHE in a CO₂-saturated 0.1 m KHCO₃ electrolyte (Figures 4, S7–S11, Table S8). Figure 4 displays the Faradaic efficiencies (FEs) of the main C₂ and C₃ products, namely, ethanol, 1-propanol, and ethylene, as well as the combined FEs of all C₂, products of the C₂, liquid products, and of the C₂, carbonyl products; see also Figures S8 (C₁ products), S9 (minor C₂, products), S10 (sum of all liquid products), and S11 (geometric and mass current densities).

The production of ethanol at −1.0 V_RHE increases significantly with the amount of Ag. CuO NCs, 3-, and 5-Ag/CuO reach 10%, 13%, and 17% FE for ethanol at −1.0 V_RHE, respectively (Figures 4a, S7a). Thus, FE_ethanol increased 1.5 times by the addition of 5 at% of Ag to CuO NCs. Additionally, the production of 1-propanol is doubled in the Ag/CuO samples with FE of 5–6% at −0.9 V_RHE compared to 3% for the CuO NCs (Figure 4b). This increase in alcohol yield has been previously linked to CO spillover from Ag to Cu, since the weaker binding between Ag and the *CO intermediate is considered to facilitate CO production as compared to the moderate binding energy between Cu and the *CO intermediate leading to the formation of hydrocarbons.[14,15] Also in our case, the Ag/CuO samples show higher FEs for CO at low overpotentials, with almost 40% FE to 0.49 for 5-Ag/CuO. The C₂, selectivity is the highest for the two Ag/CuO samples with a FE of 65% at −0.98 V_RHE, which is an increase of 10% compared to pure CuO NCs (Figure 4d, S7d).

Furthermore, the parasitic HER (Figure S8a) and the production of formate (the only C₁ liquid. Figure S8d) were (slightly) suppressed. The latter has also been recently observed for AgCu foam catalysts as compared to pure Cu foams.[14] In contrast, the formation of acetaldehyde (Figure S9a) and propionaldehyde (Figure S9b) is significantly increased for 5-Ag/CuO, which results in an enhancement of the carbonyl C₂, products by a factor of three (Figure 4f, S7f). Overall, introducing Ag increases the FE of the desired C₂, liquid products (Figure 4e, S7e) for 5-Ag/CuO by 15% in comparison to CuO NCs at −1.0 V_RHE. This is assigned to the enhanced production of ethanol, 1-propanol, allyl alcohol, and carbonyl C₂, products (Figure 4a,b,f, S9c). We additionally performed long-term CO₂RR measurements for 12 h at −1.0 V_RHE to track the stability of the catalytic performance (Figure S12) and found a good stability for all catalysts. For the Ag/CuO samples, the amount of C₂, liquid products remains stable over time with a decrease of the aldehydes and at −0.7 V_RHE in comparison to 20% FE for the pure CuO NCs (Figure S8b). At higher overpotentials, the FE_CO decreases for all catalysts, and starting from −1.0 V_RHE the selectivity for CO of the Ag/CuO is even similar to that of the bare CuO NCs (FE_CO = 3–5%). We note that 3-Ag/CuO shows a better ability to transform CO into C₂, products at lower overpotentials than 5-Ag/CuO, which is also related to a lower FE of CO starting from −0.83 V_RHE (Figure S8b). These differences might originate from the different sizes of the Ag NPs in the two samples as extracted by STEM analysis (Table S2), which can affect the electrocatalytic reduction of CO₂ to CO as well as the CO spillover to the Ag/Cu interface.

The production of ethylene on the CuO NCs peaks at −0.95 V_RHE with 40% FE (Figures 4c, S7c), while for the 3-Ag/CuO the FE is slightly larger (45%). In contrast, 5-Ag/CuO shows a lower FE_O, (34%), paralleled by an enhancement in the ethanol production. Consequently, the FE_ethanol/FE_ethylene ratio at −1.0 V_RHE increases with Ag loading from 0.28 for CuO NCs, 0.33 for 3-Ag/CuO,

Angew. Chem. Int. Ed. 2021, 60, 7424–7435 © 2021 The Authors. Angewandte Chemie International Edition published by Wiley-VCH GmbH www.angewandte.org 7429
increase of 1-propanol as well as acetate for the 5-Ag/Cu catalyst.

In order to further examine the Cu–Ag interaction and its role in the CO$_2$RR selectivity, we also investigated the catalytic performance of the pure Cu$_2$O NCs deposited on a polished Ag foil (Cu$_2$O/Ag). In this configuration (Figure S13), the production of C$_2$$_+$ liquids is also enhanced on the Cu$_2$O/Ag sample at $-1.0$ V$_{RHE}$, indicating again the importance of the CO generated at the Ag sites for the further hydrogenation of the C$_2$$_+$ products generated on the Cu sites. However, the Cu$_2$O/Ag sample shows a drastic increase of HER as compared to the 5-Ag/Cu$_2$O, namely from 20 to 40% FE, and a suppression of the ethylene FE from 30% to 20%. This might be correlated to the decrease of the total area of the Ag/Cu interface, which decreases the atomic interaction and synergy between Ag and Cu. Consequently, the well-distributed Ag NPs, which redispersed on the surface of our Cu$_2$O NCs, appear to play a significant role in the observed synergistic effect and the C–C coupling mechanism.

Further insight into the Ag-Cu interaction can be extracted from operando X-ray absorption spectroscopy (XAS) data. Figure 5 depicts the normalized Cu K-edge and Ag K-edge X-ray absorption near edge structure (XANES) spectra of the Ag NP-decorated and pure Cu$_2$O NCs in their as-prepared state (Figure 5a,c) and during CO$_2$RR in a steady-state after 5 h of the reaction (Figure 5b,d). The position of the absorption edge in the Cu K-edge XANES spectra of the as-prepared Cu$_2$O NCs compared to the reference spectra shows that the NCs mainly exhibit a Cu$^1$ oxidation state with the characteristic pre-edge feature at 8981 eV. Linear combination analysis (LCA) of Cu K-edge XANES data revealed the presence of Cu$^1$ and Cu$^2$ species (Figure S14), as already seen in the more surface-sensitive XPS analysis. The decoration with the Ag NPs does not change the Cu XANES spectra (Figure 5c). Ag K-edge XANES spectra, in turn, confirm the metallic state of Ag with all XANES features resembling those of the Ag foil. These findings are consistent with the STEM, XRD, and XPS results, emphasizing the lack of significant interaction between the Cu$_2$O and Ag species in the as-prepared state.

The reduction of the Cu$_2$O NCs was investigated during CO$_2$RR at $-1.0$ V$_{RHE}$ for 5 h (Figure S14). In the final state, the Cu K-edge XANES spectrum resembles that of the metallic Cu foil reference (Figure 5b). We tracked the evolution of the Cu$^1$/Cu$^0$ ratios by LCA (Figure S14b,c) and our analysis revealed that a significant fraction of Cu$^1$ was preserved under CO$_2$RR reaction conditions with 15–25% of Cu$^1$ present in all samples. Figure 5d shows the Ag K-edge XANES spectra under CO$_2$RR conditions at $-1.0$ V$_{RHE}$ after reaching stationary conditions. Ag remained metallic, but an attenuation of the post-edge oscillations is visible during CO$_2$RR, explainable by a decrease in the size of the Ag NPs due to their redispersion on the Cu$_2$O NC surface. [15]

To achieve a deeper understanding of the local atomic structure, Fourier transformed extended X-ray absorption fine structure (FT-EXAFS) spectra of the Ag NP-decorated and pure Cu$_2$O NCs are shown in Figure 6 with the corresponding Fourier-filtered EXAFS spectra in Figure S15. The peaks at 1.5 Å and 2.8 Å (phase uncorrected) in Cu K-edge FT-EXAFS and at 2.8 Å in Ag K-edge FT-EXAFS for the as-
prepared samples indicate the presence of Cu–O and Cu–Cu bonds (typical for CuO) and Ag–M bonds (here, M is Ag or Cu), respectively, in agreement with the XANES analysis.

Under CO₂RR conditions at $-1.0 \, \text{V}_{\text{RHE}}$, a strong peak at 2.2 Å (phase-uncorrected) appeared in the Cu K-edge FT-EXAFS, which can be attributed to the Cu–Cu contribution in metallic Cu. The Ag–M peak position at 2.8 Å in Ag K-edge FT-EXAFS did not change significantly, and no additional peaks appeared. Nonetheless, the comparison of the FT-EXAFS before and during CO₂RR shows a decrease in the Ag–M peak intensities. Moreover, the intensity of both, the Cu–Cu and Ag–M peaks decreases with an increase in Ag loading (Figure 6). These differences suggest structural changes in the Ag and Cu atomic environment under CO₂RR conditions, which we further investigated using quantitative fitting of the EXAFS spectra to obtain the structural parameters presented in Tables S10–S11. For the as-prepared state, we obtained a Cu–O coordination number ($N_{\text{Cu-O}}$) of circa 2 and a Cu–O distance ($R_{\text{Cu-O}}$) of circa 1.87 Å, which agree with the values of these parameters in bulk CuO. Furthermore, in the as-prepared samples, the $N_{\text{Ag-Ag}}$ decreased from 12 in the Ag foil over 11.4 ± 0.4 in 3-Ag/Cu₂O to 10.5 ± 0.3 in 5-Ag/Cu₂O, indicating an enhanced disorder within the Ag NPs. However, the $R_{\text{Ag-Ag}}$ distances in all samples are comparable to that of the Ag foil, 2.833 ± 0.003 Å, which means that there is no significant lattice contraction due to alloying in the as-prepared state.

Under stationary CO₂RR conditions, the Cu–Cu coordination number of approx. 9 is lower than that of the Cu foil reference. We also observe Cu–O bonds with $N_{\text{Cu-O}} \approx 0.3$. The Cu–Cu distance ($R_{\text{Cu-Cu}}$) during CO₂RR, 2.524 ± 0.003 Å, is comparable to that in the bulk Cu foil reference (2.527 ± 0.002 Å). The Cu/Ag ratio under CO₂RR, as obtained from the EXAFS analysis, agrees well with the XANES data (Table S9), showing the partial reduction of the Cu₂O to metallic Cu under CO₂RR conditions. Our primary finding from the Cu K-edge is the increasing disorder of the Cu–Cu bonds with higher Ag loading and thus reveals the decoration of the Cu₂O NPs with Ag NPs during CO₂RR, but one cannot exclude that this could also be a result of incomplete CuO reduction.

One of the main goals of this study is to explore the interaction between Cu and Ag at the atomic scale under CO₂RR conditions. Due to the low concentration of Ag as compared to Cu, information on the interplay between Ag and Cu atoms can be best extracted from the analysis of Ag EXAFS data (Figure 6c,d, S16). During CO₂RR, we identified an additional contribution of Ag–Cu bonds with $R_{\text{Ag-Cu}}$ of 2.623 ± 0.005 Å (3-Ag/Cu₂O) and 2.596 ± 0.008 Å (5-Ag/Cu₂O), while the bond lengths in the more prominent Ag–Ag component did not contract significantly for 3-Ag/Cu₂O (2.840 ± 0.005 Å), but did so for 5-Ag/Cu₂O (2.787 ± 0.007 Å). The Ag–Ag coordination number decreased from 12 (bulk) to 9, and an Ag–Ag coordination number ($N_{\text{Ag-Ag}}$) of up to 1 was observed under CO₂RR conditions, being larger for the 3-Ag/Cu₂O sample than for 5-Ag/Cu₂O. The obtained Ag–Cu bond length is in between the values for the Cu–Cu distance in bulk Cu (2.527 ± 0.002 Å) and the Ag–Ag distance in bulk Ag (2.833 ± 0.003 Å). The Ag–Cu bond lengths as...
In the as-prepared state, the characteristic peaks of Cu$_2$O are observed at 415 cm$^{-1}$, 527 cm$^{-1}$, and 623 cm$^{-1}$.[16] The Cu$_2$O peaks vanished for all samples after applying a reductive potential of $-0.4 \text{ V}_{\text{RHE}}$, which indicates a prompt reduction of the surface Cu$_2$O species independently from the Ag loading. The latter is in agreement with the quasi-in situ XPS analysis.

At more negative potentials, the operando SERS data of the Ag NP-decorated Cu$_2$O NCs exhibit significant differences compared to the bare Cu$_2$O NCs during CO$_2$RR: 1) At higher Raman shifts, a broad band of the C–O vibrations appeared at 2088 cm$^{-1}$ for Cu$_2$O NCs during CO$_2$RR, while for Ag/Cu$_2$O a shoulder at 2031 cm$^{-1}$ is more pronounced. This might be assigned to the multisite binding mechanism on the Ag–Cu surface, where each binding configuration has a different electron donating ability.[17] 2) For the Ag NP-decorated Cu$_2$O NC samples, two additional peaks at 490 and 530 cm$^{-1}$ appeared, which might be assigned to Ag–CO vibrations.[11,18] 3) Two peaks evolve differently at 280 cm$^{-1}$ and 366 cm$^{-1}$, caused by the Cu–CO frustrated rotation and stretching vibration, respectively.[16b,18] Thus, we can track the CO adsorbed on Cu and Ag separately by using operando SERS and identified significant differences in the CO adsorption characteristics on Cu in the presence of dispersed Ag atoms during CO$_2$RR as, interestingly, the peak intensity ratio of the two Cu–CO Raman peaks shifts towards the Cu–CO stretching vibration with decreasing electrode potential. A similar trend can also be seen with increasing Ag content at $-1.0 \text{ V}_{\text{RHE}}$. These drastic changes might originate from the way that CO predominantly binds to Cu. While on pure Cu$_2$O NCs the CO binding configuration is similarly prone to Cu–CO rotation and stretching, the presence of Ag sites gives rise to a CO binding configuration that facilitates the Cu–CO stretching with thus stronger lateral confinement. We anticipate that the latter plays a critical catalytic role in enhancing the C–C coupling of neighboring CO adsorbates and thus increases the C$_2$H$_4$ liquid product formation.

Figure 6. Moduli of Fourier-transformed Cu and Ag K-edge EXAFS spectra of Cu$_2$O NCs (black), 3-Ag/Cu$_2$O (blue), and 5-Ag/Cu$_2$O (green) in the as-prepared state (a,c) and in the final state under operando CO$_2$RR conditions at $-1.0 \text{ V}_{\text{RHE}}$ (b,d) with corresponding fits (red). Partial contribution of Ag–Cu bonds, as obtained from EXAFS data fitting, is also shown in (d) with dotted lines. Reference spectra of Cu foil, Cu and Ag foils are shown for comparison.
From the ex situ and operando studies performed under CO₂RR we gained a detailed insight into the structural evolution of the Ag NP-decorated Cu₂O NC catalysts. In their as-prepared state, the Cu₂O NCs as well as the Ag NP-decorated samples mainly consist of Cu₂O, with some contribution from CuO. During CO₂RR, Cu₂O is partially reduced to metallic Cu, while the contribution of CuO vanishes. Indeed, the operando XANES data evidenced the incomplete reduction of Cu₂O in all samples after five hours of CO₂RR (up to 30% of Cu₂O remained in the 3-Ag/Cu₂O sample). However, we did not find a correlation between the content of Cu₂O (in the bulk, XAS data) and the increased selectivity for C₂⁺ liquid products, which might be due to the complete reduction (XPS, SERS) of the surface Cu₂O species to metallic Cu during CO₂RR.

Since the fraction of Ag in the near-surface is low (<11 at%), intermixing is plausible although a precise determination of the Ag/Cu ratio in the Ag/Cu₉₉ regions is not possible. Therefore, our system consists of three classes of potentially active sites during CO₂RR: Ag/AgCu/Cu.

To further understand how the structural/chemical rearrangements influence the reaction mechanism, it is useful to correlate such changes with the formation and stability of different intermediates during CO₂RR. The production of CO increased at lower overpotentials with increasing Ag content in the samples. It has been suggested that *CO, which is a key intermediate for the C–C coupling mechanism, might couple with *CH₂ to form the *CH₂CHO intermediate, which plays a central role in the formation of C₂⁺ liquid products. The *CH₂CHO intermediate can be hydrogenated to *CH₃CHO and form acetaldehyde [Eq. (1)] or be further hydrogenated to yield ethanol [Eq. (2)].

\[
\begin{align*}
*\text{CH}_2\text{CHO} + \text{H}^+ + e^- & \rightarrow *\text{CH}_3\text{CHO} \rightarrow \text{CH}_3\text{CHO} \\
*\text{CH}_3\text{CHO} + 2\text{H}^+ + 2e^- & \rightarrow \text{C}_2\text{H}_5\text{OH}
\end{align*}
\]

If *CH₃CHO couples with another *CO, propionaldehyde [Eq. (3)] and 1-propanol [Eq. (4)] can be formed.

\[
\begin{align*}
*\text{CH}_3\text{CHO} + \text{CO} + 2\text{H}^+ + 2e^- & \rightarrow \text{C}_2\text{H}_5\text{OH} \\
*\text{CH}_2\text{CH}_2\text{CHO} + \text{H}_2\text{O} & \rightarrow \text{CH}_3\text{CH}_2\text{CHO} \\
*\text{CH}_3\text{CH}_2\text{CHO} + 2\text{H}^+ + 2e^- & \rightarrow 1\text{-C}_3\text{H}_7\text{OH}
\end{align*}
\]

On Cu surfaces, acetaldehyde and propionaldehyde are usually hydrogenated to ethanol, and 1-propanol is only detected with FE ≈ 1%, as seen for the Cu₂O NCs. Therefore, we can relate the enhancement of the two aldehyde selectivities to the dispersion of the Ag atoms/small clusters on the Cu surface during CO₂RR, which induces locally strained Cu sites with expanded Cu–Ag distances compared to Cu–Cu and, most importantly, differences in the predominant CO binding motifs. DFT calculations of our previous study showed that an expanded Cu lattice increases the binding energies for the intermediates of CO₂RR (e.g., *CO on Cu). Additionally, Ag incorporation in Cu weakens the binding energies of the reduced aldehyde intermediates and inhibits their further reduction to ethanol and 1-propanol as demonstrated in a recent DFT study. However, the structural analysis of the catalysts showed that the surface partially consists of CuAg areas, which also leads to the formation of ethanol and 1-propanol at the Cu sites, since they are expected to have higher binding energies for the oxygenated intermediates as compared to the Ag–Cu mixed...
regions. Therefore, having Ag/AgCu/Cu interfaces as active surface sites appears to enhance the yield of C₂ liquid products.

**Conclusion**

In summary, Ag NP-decorated Cu₂O nanocubes displayed enhanced selectivity toward C₂ liquid products, while the production of formate and hydrogen was suppressed. By means of ex situ, quasi-in situ, and operando spectroscopy studies under CO₂RR conditions, we could gain insight into the structural and chemical transformations of these catalysts that were shown to influence the selectivity trends. In particular, we observed the redispersion of the Ag NPs on Cu and a certain Cu–Ag miscibility, leading to expanded Cu–Ag distances compared to metallic Cu–Cu distances. Such structural rearrangements were found to result in an enhanced formation of alcohols and aldehydes.

By comparing the selectivity of pure Cu₂O and Ag NP-decorated Cu₂O NCs we concluded that even though Cu₂O species were partially preserved under reaction conditions, they are not the sole species responsible for the enhancement in the C₂ liquid products, which is favored when large Ag/Cu interfaces are formed. Importantly, we correlate the enhancement to variations in the predominant CO adsorption motif on Cu in the presence of dispersed Ag atoms.

Our work contributes to the fundamental understanding of the CO₂RR by highlighting the intricate interplay of different parameters affecting the selectivity. These include the content of residual Cu₂O species, the presence of a secondary metal near Cu where efficient CO spillover can take place, and the alloying of Cu with another metal that is able to locally increase the interatomic distance, leading to a change in the binding energies of adsorbates and intermediates, thus favoring the formation of C₂ liquid products.

**Acknowledgements**

This work was funded by the Deutsche Forschungsgemeinschaft (DFG), project no. 406944504–SPP 2080 and Germany’s Excellence Strategy—EXC 2008–390540038–UniSysCat, and the European Research Council under grant ERC-OPERANDOCAT (ERC-725915). A.H., C.R., and F.T.H. acknowledge support by the IMPRS Functional Interfaces in Physics and Chemistry. We acknowledge SOLEIL for provision of synchrotron radiation facilities, and thank the “SAMBA” beamline staff for their great assistance. Experiments were also performed at CLAESS beamline at ALBA synchrotron with the collaboration of ALBA staff. We thank See Wee Chee and Osman Karlsiglo (FHI) for STEM support and Chao Zhan (FHI) for feedback concerning the SERS data. Open access funding enabled and organized by Springer.

**Conflict of interest**

The authors declare no conflict of interest.

**Keywords:** CO₂ electroreduction · Cu₂O · CuAg alloy · operando surface-enhanced Raman spectroscopy · operando X-ray absorption spectroscopy

[1] a) S. Chu, Y. Cui, N. Liu, Nat. Mater. 2017, 16, 16–22; b) P. De Luna, C. Hahn, D. Higgins, S. A. Jaffer, T. F. Jaramillo, E. H. Sargent, Science 2019, 364, eaav3506.

[2] a) M. Jouny, W. Luc, F. Jiao, Ind. Eng. Chem. Res. 2018, 57, 2160–2171; b) S. I. Mussatova, G. Dragone, P. M. R. Guimarães, J. P. A. Silva, L. M. Carneiro, I. C. Roberto, A. Vicente, L. Dominguez, J. A. Teixeira, Biotechnol. Adv. 2010, 28, 817–830.

[3] Y. Hori, K. Kikuchi, A. Murata, S. Suzuki, Chem. Lett. 1986, 15, 897–898.

[4] Y. Hori, in Modern Aspects of Electrochemistry (Eds.: C. G. Vayenas, R. E. White, M. E. Gamboa-Aldeco), Springer, New York, 2008, pp. 89–189.

[5] a) H. Mistry, A. S. Varela, S. Küh, P. Strasser, B. Roldan Cuenya, Nat. Rev. Mater. 2016, 1, 1609; b) R. Reske, H. Mistry, F. Behafarid, B. Roldan Cuenya, P. Strasser, J. Am. Chem. Soc. 2014, 136, 6978–6986; c) H. Mistry, R. Reske, Z. Zeng, Z.-J. Zhao, J. Greczy, P. Strasser, B. Roldan Cuenya, J. Am. Chem. Soc. 2014, 136, 16473–16476; d) H. S. Joon, I. Sinev, F. Scholten, N. J. Divins, I. Zegkinoglou, L. Pielsticker, B. Roldan Cuenya, J. Am. Chem. Soc. 2018, 140, 9383–9386; e) A. Loiduc, P. Lobaccaro, E. A. Kamali, T. Thao, B. H. Huang, J. W. Agcr, R. Buonsanti, Angew. Chem. Int. Ed. 2015, 55, 5789–5792; Angew. Chem. 2016, 128, 5883–5886; f) Z. Wang, G. Yang, Z. Zhang, M. Jin, Y. Yin, ACS Nano 2016, 10, 4559–4564.

[6] a) A. S. Varela, M. Kroschel, T. Reier, P. Strasser, Catal. Today 2018, 266, 8–13; b) D. Ren, J. Fong, B. S. Yeo, Nat. Commun. 2018, 9, 925; c) Y. Lum, B. Yue, P. Lobaccaro, A. T. Bell, J. W. Agcr, J. Phys. Chem. C 2017, 121, 14191–14203; d) D. Gao, F. Scholten, B. Roldan Cuenya, ACS Catal. 2017, 7, 5112–5120; e) J. Resasco, L. D. Chen, E. Clark, C. Tsai, C. Hahn, T. F. Jaramillo, K. Chan, A. T. Bell, J. Am. Chem. Soc. 2017, 139, 11277–11287.

[7] a) J.-J. Velasco-Vélez, T. Jones, D. Gao, E. Carbonio, R. Arrigo, C.-J. Hsu, Y.-C. Huang, C.-L. Dong, J.-M. Chen, J.-F. Lee, P. Strasser, B. Roldan Cuenya, R. Schlögl, A. Knap-Göricke, C.-H. Chuang, ACS Sustainable Chem. Eng. 2019, 7, 1485–1492; b) H. Mistry, A. S. Varela, C. S. Bonifacio, I. Zegkinoglou, I. Sinev, Y.-W. Choi, K. Kisslinger, E. A. Stach, J. C. Yang, P. Strasser, B. Roldan Cuenya, Nat. Commun. 2016, 7, 12123; c) C. Liu, M. P. Lourenço, S. Hedström, F. Cavalcá, O. Díaz-Morales, H. A. Duarte, A. Nilsson, L. G. M. Pettersson, J. Phys. Chem. C 2017, 121, 25010–25017; d) R. M. Arán-Ais, F. Scholten, S. Kunze, R. Rizo, B. Roldan Cuenya, Nat. Energy 2020, 5, 317–325.

[8] a) D. F. Gao, I. Zegkinoglou, N. J. Divins, F. Scholten, I. Sinev, P. Grosse, B. Roldan Cuenya, ACS Nano 2017, 11, 4825–4831; b) D. F. Gao, D. F. Gao, F. Scholten, I. Sinev, H. Mistry, B. Roldan Cuenya, Angew. Chem. Int. Ed. 2018, 57, 6192–6197; Angew. Chem. 2018, 130, 6300–6305.

[9] a) S. Ma, M. Sadakiyo, M. Heima, R. Luo, R. T. Haasch, J. I. Gold, M. Yamauchi, P. J. A. Kenis, J. Am. Chem. Soc. 2017, 139, 47–50; b) D. Kim, J. Resasco, Y. Yu, A. M. Asiri, P. Yang, Nat. Commun. 2014, 5, 4948; c) M. Bernal, A. Baggar, F. Scholten, I. Sinev, A. Bergmann, M. Ahmadni, J. Rossmeisl, B. Roldan Cuenya, Nano Energy 2018, 53, 27–36; d) H. S. Joon, J. Timoshenko, F. Scholten, I. Sinev, A. Herzog, F. T. Haase, B. Roldan Cuenya, J. Am. Chem. Soc. 2019, 141, 19879–19887.

[10] S. Lee, G. Park, J. Lee, ACS Catal. 2017, 7, 8594–8604.
[11] J. Gao, H. Zhang, X. Guo, J. Luo, S. M. Zakeeruddin, D. Ren, M. Grätzel, J. Am. Chem. Soc. 2019, 141, 18704 – 18714.

[12] a) D. Higgins, A. T. Landers, Y. Ji, S. Nitopi, C. G. Morales-Guio, L. Wang, K. Chan, C. Hahn, T. F. Jaramillo, ACS Energy Lett. 2018, 3, 2947–2955; b) E. L. Clark, C. Hahn, T. F. Jaramillo, A. T. Bell, J. Am. Chem. Soc. 2017, 139, 15848–15857.

[13] T. T. H. Hoang, S. Verma, S. Ma, T. T. Fister, J. Timoshenko, A. I. Frenkel, P. J. A. Kenis, A. A. Gewirth, J. Am. Chem. Soc. 2018, 140, 5791–5797.

[14] a) A. Dutta, I. Z. Montiel, R. Erni, K. Kiran, M. Rahaman, J. Drnec, P. Broekmann, Nano Energy 2020, 68, 104331–104342; b) T. Kottakkat, K. Klingan, S. Jiang, Z. P. Jovanov, V. H. Davies, G. A. M. El-Nagar, H. Dau, C. Roth, ACS Appl. Mater. Interfaces 2019, 11, 14734–14744.

[15] J. Timoshenko, S. Roese, H. Hövel, A. I. Frenkel, Radiat. Phys. Chem. 2020, 175, 108349–10852.

[16] a) Y. Deng, A. D. Handoko, Y. Du, S. Xi, B. S. Yeo, ACS Catal. 2016, 6, 2473–2481; b) S. Jiang, K. Klingan, C. Pasquini, H. Dau, J. Chem. Phys. 2019, 150, 041718–1–041718–12; c) G. Niaura, Electrochim. Acta 2000, 45, 3507–3519; d) A. Singhal, M. R. Pai, R. Rao, K. T. Pillai, I. Lieberwirth, A. K. Tyagi, Eur. J. Inorg. Chem. 2013, 2640–2651.

[17] Y. C. Li, Z. Wang, T. Yuan, D.-H. Nam, M. Luo, J. Wicks, B. Chen, J. Li, F. Li, F. P. G. de Arquer, Y. Wang, C.-T. Dinh, O. Voznyy, D. Sinton, E. H. Sargent, J. Am. Chem. Soc. 2019, 141, 8584–8591.

[18] I. Oda, H. Ogawara, M. Ito, Langmuir 1996, 12, 1094–1097.

[19] a) J. H. Montoya, C. Shi, K. Chan, J. K. Norskov, J. Phys. Chem. Lett. 2015, 6, 2032–2037; b) D. F. Gao, I. T. McCrum, S. Deo, Y. W. Choi, F. Scholten, W. M. Wan, J. G. G. Chen, M. J. Janik, B. Roldan Cuenya, ACS Catal. 2018, 8, 10012.

[20] L. R. L. Ting, O. Piqué, S. Y. Lim, M. Tanhaei, F. Calle-Vallejo, B. S. Yeo, ACS Catal. 2020, 10, 4059–4069.

[21] a) R. Kortlever, J. Shen, K. J. P. Schouten, F. Calle-Vallejo, M. T. M. Koper, J. Phys. Chem. Lett. 2015, 6, 4073–4082; b) E. L. Clark, A. T. Bell, J. Am. Chem. Soc. 2018, 140, 7012–7020.

[22] L. Wang, D. C. Higgins, Y. Ji, C. G. Morales-Guio, K. Chan, C. Hahn, T. F. Jaramillo, Proc. Natl. Acad. Sci. USA 2020, 117, 12572–12575.

Manuscript received: December 23, 2020
Accepted manuscript online: January 26, 2021
Version of record online: February 22, 2021