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1 Evidence for product specific active sites on 2 oxide-derived Cu catalysts for electrochemical 3 CO₂ reduction

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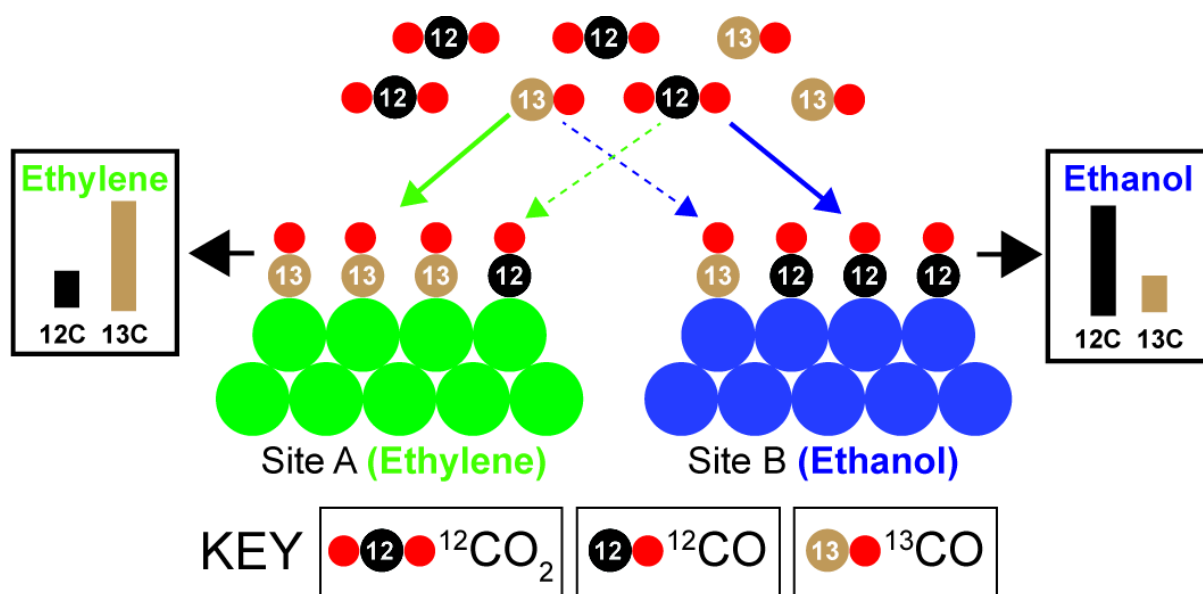
12 CO₂ electroreduction in aqueous media using Cu catalysts can generate many
13 different C₂/C₃ products, leading to the question whether all products are
14 generated from the same types of active sites or if product specific active sites
15 are responsible for making certain products. Here, by reducing mixtures of ¹³CO
16 and ¹²CO₂, we show that oxide derived (OD) Cu catalysts have 3 different types
17 of active sites for C-C coupled products, one for producing ethanol/acetate,
18 another for ethylene and yet another for 1-propanol. In contrast, we do not find
19 evidence of product specific sites on polycrystalline Cu and oriented (100) and
20 (111). Analysis of the isotopic composition of the products leads to the prediction
21 that the adsorption energy of *COOH (product of the first step of CO₂ reduction)
22 may be a descriptor for the product selectivity of a given active site. These new
23 insights should enable highly selective catalysts to be developed.

24 The last few decades alone have seen large increases in atmospheric
25 CO₂ concentrations, mainly due to mankind's consumption of fossil fuels
26 for energy.¹ It has been projected that global energy consumption will
27 continue to rise, leading to tripling of CO₂ emissions by 2040.¹ There is
28 therefore an urgent need to develop technologies capable of efficiently
29 harvesting and storing renewable energy to reduce our dependence on
30 fossil fuels.²

31 Electrochemical CO₂ reduction (CO₂R) in aqueous media presents an
32 attractive and viable strategy to reduce carbon emissions by directly
33 converting CO₂ into valuable hydrocarbons and oxygenates such as
34 ethylene and ethanol.^{3,4} To date, Cu remains the most promising catalyst
35 capable of driving this conversion process at reasonable current
36 densities.^{5,6} While methane, ethylene, and ethanol are the major products,
37 up to 18 different possible products can be produced.⁷⁻⁹ It is commonly
38 accepted that except for formate, CO₂R on Cu is initiated by reducing CO₂
39 to adsorbed CO (*CO).¹⁰⁻¹³ Further protonation of *CO results in methane/
40 methanol formation (C₁ pathway) or *CO can couple with another *CO (C-C
41 coupling), leading to C₂/C₃ products such as ethylene and 1-propanol.¹⁴⁻¹⁶
42 However, although there have been intriguing reports of selective
43 ethylene production under a certain range of conditions and at high
44 current densities^{17,18}, it has been experimentally difficult to control
45 selectivity to a given C₂ or C₃ product. To further improve catalyst
46 performance and selectivity, it is crucial to first identify and understand
47 the nature of the active sites that are present on Cu electrocatalysts. A
48 related and important question is whether all products are produced from
49 the same active sites or if specific active sites are responsible for
50 generating a given product. In other words, are there product specific
51 active sites that mostly generate only one product?

52 We reasoned that it would be possible to answer these critical questions
53 by performing electroreduction of a mixture of ¹³CO and ¹²CO₂. To explain
54 our rationale, consider a hypothetical catalyst that possesses only 2 types
55 of active sites for C₂ production (see Fig. 1). We assume that one site (A)
56 is selective for ethylene while the other (B) is selective for ethanol.

57 Because their catalytic properties are different, we would expect that the
 58 adsorption energies of intermediates, often used as a descriptor for
 59 catalytic activity,¹⁹⁻²¹ should also be different on the two sites. Due to the
 60 difference in intermediate adsorption energies, we would naturally expect
 61 that the turn over frequencies for generating these intermediates will be
 62 different. As a specific example, the rate of the initial step of CO₂R,
 63 converting CO₂ to *CO, will be different on the two sites. As a result, if we
 64 were to reduce a mixture of ¹³CO and ¹²CO₂, the turn over frequency for
 65 ¹²CO₂ reduction to *¹²CO should be active site dependent, resulting in sites
 66 A and B having different probabilities of being occupied by *¹²CO vs *¹³CO.
 67 In this case, we assume that the turn over frequency of ¹²CO₂ reduction to
 68 *¹²CO is higher for site B, leading to a higher (lower) probability of *¹²CO
 69 (*¹³CO) on this site.



70
 71 **Fig. 1 | Hypothetical scenario in which reduction of a mixture of ¹³CO and ¹²CO₂**
 72 **is carried out on a catalyst with 2 types of active sites, A and B.** Site A favours
 73 ethylene formation (green) while site B favours ethanol formation (blue). Also, it is
 74 assumed that the turn over frequency of ¹²CO₂ reduction to *¹²CO is higher for ethanol
 75 selective sites, leading to a higher probability of *¹²CO on site B. This results in ethylene
 76 having more ¹³C compared to ethanol.

77 In the next electrocatalytic step, C-C coupling between the *CO on the
 78 sites, followed by a series of proton-coupled electron transfers and
 79 dehydration steps^{16,22-24}, results in formation of ethylene (for site A) and
 80 ethanol (for site B). Crucially, the isotopic composition of the products will
 81 be different: in this hypothetical case, ethylene will have more ¹³C than

82 ethanol. More generally, this analysis shows that if a mixture of ^{13}CO and
83 $^{12}\text{CO}_2$ is reduced, the isotopic composition of the C-C coupled products will
84 serve as a fingerprint of the active sites which produced them. That is, if
85 two C-C coupled products have different isotopic compositions, then they
86 have been produced by different types of active sites. On the other hand,
87 if the catalyst does not have product specific active sites, then all
88 products should have similar isotopic compositions.

89 In this work, we apply this isotope labelling concept to analyse the
90 active sites on oxide-derived (OD) Cu catalysts. Such catalysts are
91 typically prepared by oxidation of a Cu foil/film, followed by reduction to
92 its metallic state.²⁵⁻²⁹ This class of catalysts, originally reported by Kanan
93 and co-workers, is of significant interest because they have shown
94 dramatically reduced overpotentials for the reduction of CO to oxygenate
95 products (e.g. ethanol) with high faradaic efficiencies.^{27,30} Furthermore,
96 work from many research groups have shown that these catalysts exhibit
97 enhanced selectivity for reducing CO_2 to C_2/C_3 products, whilst
98 suppressing the formation of C_1 products.^{25,26,28,31-33}

99 There have been a number of studies aimed at identifying the active
100 sites responsible for the unique catalytic properties of OD Cu.
101 Chorkendorff and co-workers used temperature programmed desorption
102 to detect strong CO binding sites that are not present on polycrystalline
103 Cu.³⁴ They posited that these strong binding sites could be the grain
104 boundaries observed in their OD Cu catalysts. In related work, Kanan and
105 co-workers demonstrated that grain boundaries are the active sites for
106 reduction of CO to C_2/C_3 products.^{34,35} However, it is not known whether all
107 the grain boundaries are active or if only the ones with specific structures
108 are responsible for generating most of the products.

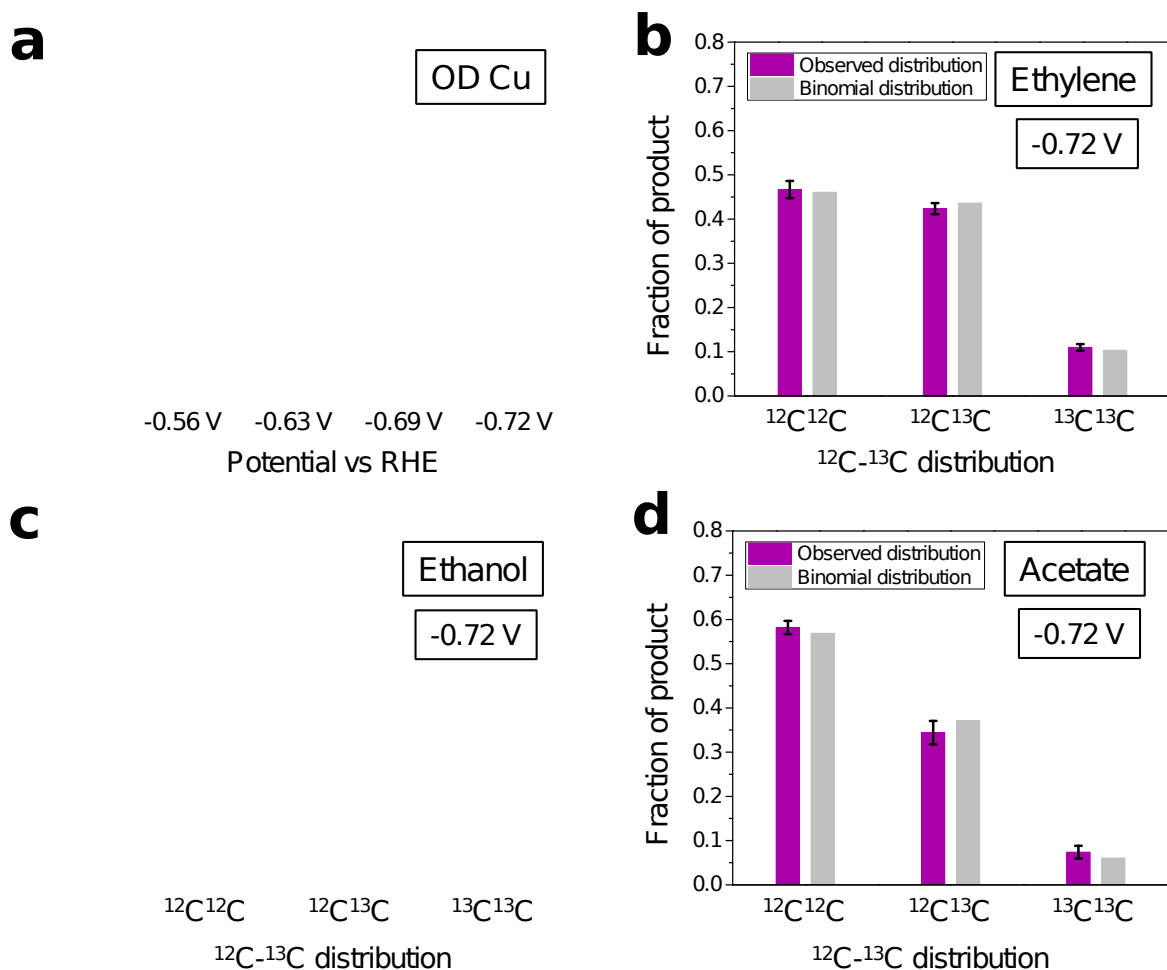
109 The objective of this work is to determine if product specific active sites
110 are responsible for the superior C_2/C_3 selectivity of OD Cu. Evidence of
111 product specific sites will motivate future studies to understand how each
112 of these different active sites work and to develop methods for building
113 specific types of product specific sites into a single structure, both of
114 which could lead to CO_2R catalysts with greatly improved product

115 selectivity. Indeed, we have discovered that OD Cu has at least three
116 types of active sites which selectively produce ethylene, ethanol/acetate
117 and 1-propanol, respectively. In contrast, polycrystalline Cu and as well as
118 Cu (100) and Cu (111) oriented surfaces do not appear to have product
119 specific active sites.

120 **Results**

121 **Reduction of ^{13}CO and $^{12}\text{CO}_2$ mixtures.** Due to the large differences in
122 the aqueous solubility between ^{13}CO (1 mM) and $^{12}\text{CO}_2$ (33.4 mM),
123 selecting their ratio to achieve a given $^{12}\text{CO}:^{13}\text{CO}$ surface coverage merits
124 some discussion. Based on calculations and experiments (Supplementary
125 Figs. 1-2), we estimated that a 70:30 ratio of ^{13}CO to $^{12}\text{CO}_2$ would allow for
126 similar rates of $^*^{13}\text{CO}$ and $^*^{12}\text{CO}$ formation to occur. OD Cu catalysts were
127 prepared according to procedures described by Kanan and co-workers²⁷
128 (Supplementary Figs. 3-5). Polycrystalline Cu (PC Cu) was prepared by
129 electropolishing of Cu foil and oriented surfaces of Cu (100) and Cu (111)
130 were fabricated using procedures developed by Jaramillo and co-
131 workers.³⁶ Natural abundance CO_2 reduction in 0.1 M KHCO_3 with these
132 catalysts qualitatively reproduced previously reported results
133 (Supplementary Fig. 6 and Supplementary Figs. 8-10). Natural abundance
134 CO reduction in 0.1 M KOH (Supplementary Fig. 7) confirmed that our OD
135 Cu catalysts performed similarly to those reported by Kanan and co-
136 workers.²⁷ Gas chromatography-mass spectrometry (GCMS) and ^{13}C NMR
137 were employed to determine the isotopic composition of the gas and
138 liquid products (see Methods and Supplementary Figs. 11-23 and
139 Supplementary Tables 1-8 for details). For experimental validation we
140 reduced $^{13}\text{CO}/^{12}\text{CO}$ in ratios of 1:3, 1:1 and 3:1 on the OD Cu catalyst and
141 observed the expected statistical isotope compositions and distributions
142 (see Supplementary Tables 9-14 for details). Throughout this work, we
143 will refer to the isotopic composition as the fraction of ^{13}C in the product.
144 Additionally, the ^{12}C - ^{13}C distribution, for example of ethylene, refers to the
145 fractions of the 3 possible product variants: $^{12}\text{CH}_2^{12}\text{CH}_2$, $^{12}\text{CH}_2^{13}\text{CH}_2$ and
146 $^{13}\text{CH}_2^{13}\text{CH}_2$.

147 Confident of our experimental and analytical methods, we proceeded to
148 carry out the reduction of the 70:30 $^{13}\text{C}/^{12}\text{C}$ gas mixture with the oxide-
149 derived Cu catalyst. Fig. 2a shows the isotopic compositions of ethylene,
150 ethanol, acetate and 1-propanol produced by OD Cu at 4 different applied
151 potentials in 0.1 M KHCO_3 electrolyte. There are a number of striking
152 findings. Firstly, regardless of the applied potential, the isotopic
153 composition (^{13}C fraction) of ethanol and acetate are identical, which
154 strongly suggests that these products are generated from the same active
155 sites. Secondly, it also appears that ethylene is produced from a different
156 set of active sites, as evidenced by its consistently higher ^{13}C fraction as
157 compared to ethanol/acetate. It is also observed that the ^{13}C fraction of
158 ethylene changes more strongly with potential compared to the other
159 products. Finally, 1-propanol also has a ^{13}C fraction that appears distinct
160 from either that of ethylene or ethanol/acetate, which means that this
161 product is generated by yet another set of active sites.



162

163 **Fig. 2 | Isotopic compositions and ^{12}C - ^{13}C distributions of products generated by**
 164 **OD Cu.** (a) Isotopic composition (in terms of the ^{13}C fraction) of ethylene, ethanol,
 165 acetate and 1-propanol produced by reduction of the $^{13}\text{CO}/^{12}\text{CO}_2$ gas mixture with OD Cu
 166 at 4 different potentials. (b), (c) and (d) are ^{12}C - ^{13}C distributions of ethylene, ethanol and
 167 acetate, respectively, at -0.72 V vs RHE. For the ^{12}C - ^{13}C distributions at other potentials,
 168 see Supplementary Fig. 27. All distributions appear to be binomial, based on comparisons
 169 with the predicted binomial distribution based on the isotopic composition (calculation
 170 details in Supplementary Tables 3-5). Faradaic efficiency and current density data are
 171 shown in Supplementary Fig. 24. Catalyst stability data are shown in Supplementary Figs.
 172 25-26. Error bars correspond to the standard deviation of 3 independent measurements.

173 A more detailed analysis of the isotopic compositions provides
 174 information on the properties of the different active sites. For these 4
 175 products, it appears that the ^{13}C fraction decreases with more negative
 176 applied overpotential. This is likely due to the fact that at more negative
 177 applied overpotentials, the turn over frequency for converting $^{12}\text{CO}_2$ to
 178 $^*^{12}\text{CO}$ on all active sites should increase, thereby increasing the
 179 probability of having a $^*^{12}\text{CO}$ vs $^*^{13}\text{CO}$ on all active sites. Since the ^{13}C
 180 fraction of ethanol/acetate is consistently lower than that of the other

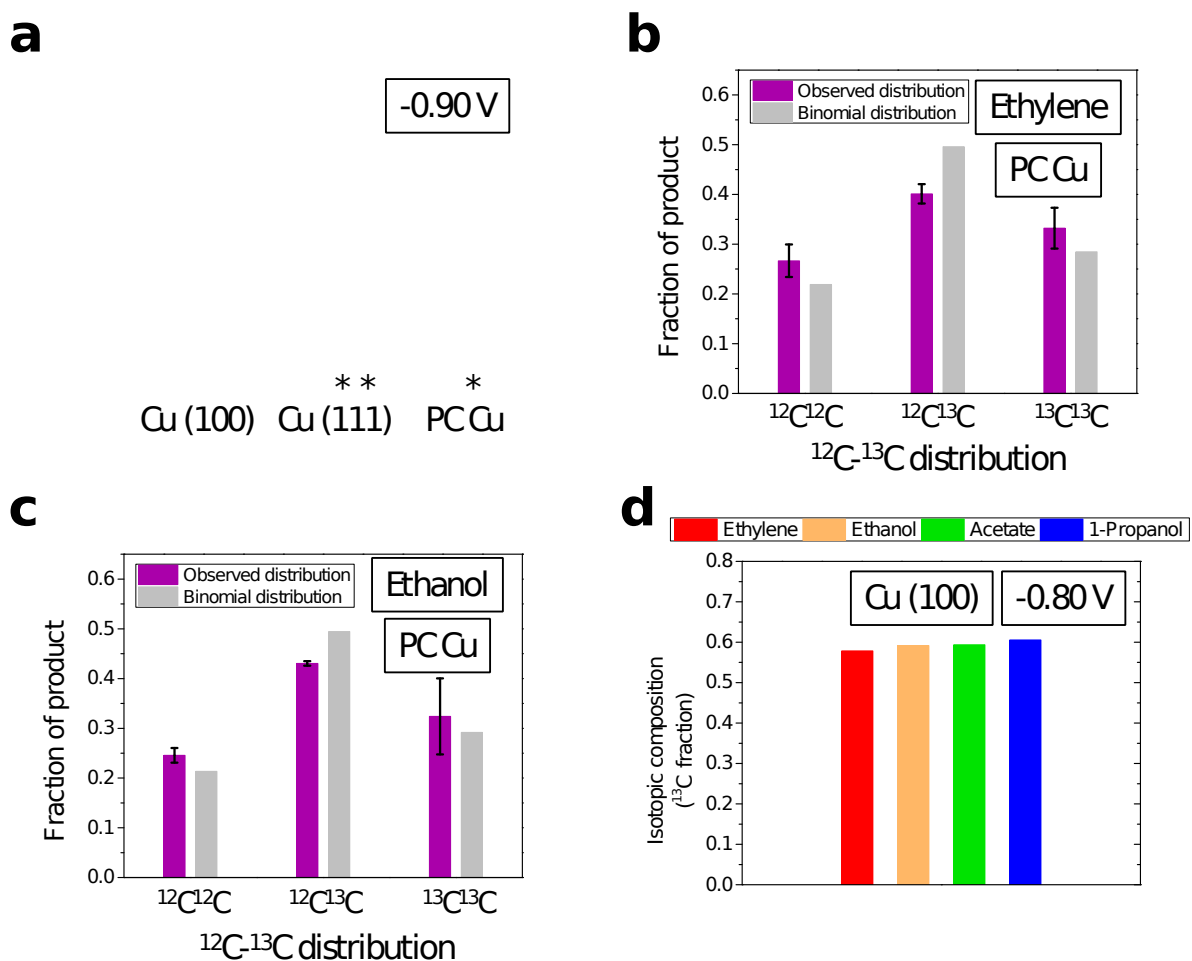
181 products, it must mean that the active sites that generate these products
182 have a higher probability of having a $^{*12}\text{CO}$. Therefore, the active sites
183 that generate ethanol/acetate should have catalytic properties such that
184 they are also able to drive $^{12}\text{CO}_2$ to $^{*12}\text{CO}$ with a turnover frequency larger
185 than that of the ethylene active sites or 1-propanol active sites. Finally,
186 the stronger potential dependence of the ^{13}C fraction of ethylene implies
187 that the turn over frequency of $^{12}\text{CO}_2$ to $^{*12}\text{CO}$ should also have the largest
188 potential dependence compared to the other active sites.

189 The notion that ethylene and ethanol/acetate are formed on product
190 specific active sites on OD Cu is further supported by the binomial nature
191 of their ^{12}C - ^{13}C distributions. The ^{12}C - ^{13}C distributions for these products at
192 -0.72 V are shown in Figs. 2b-2d (see Supplementary Fig. 27 for the ^{12}C - ^{13}C
193 distributions at other potentials). As a comparison, the predicted binomial
194 distributions for each product are shown as well in each of the figures
195 (calculated based on the isotopic composition, see Supplementary Tables
196 3-5 for more details). If products were generated from multiple active
197 sites which are not product specific, we would observe that the ^{12}C - ^{13}C
198 distribution would be a superposition of multiple binomial distributions,
199 which would result in deviations from a true binomial distribution. Another
200 observation is that the observed ^{12}C - ^{13}C distributions of ethanol and
201 acetate (Figs. 2c and 2d) appear to be identical, which is further evidence
202 that these products are generated from the same active sites.

203 We have developed a multisite kinetic model which predicts product
204 isotopic distributions as a function of the selectivity of the active sites, the
205 $^{*13}\text{CO}:^{*12}\text{CO}$ ratio at a given site, and the number of active sites of a given
206 type and their turnover frequency (see Supplementary Figs. 28-30 and
207 Supplementary Table 15-17 for model details). The model allows
208 consideration of effects which would cause the $^{*13}\text{CO}:^{*12}\text{CO}$ ratio to be
209 similar for all sites such as surface diffusion of $^{*}\text{CO}$ and/or desorption and
210 readsorption events. Clearly, the fact that we see differences in isotopic
211 composition between the products means that reduction of CO to
212 products necessarily outcompetes these isotopic scrambling effects. The
213 model also shows that the sites must be substantially selective to observe

214 both differences in ^{13}C composition and a ^{12}C - ^{13}C distribution which does
215 not differ significantly from a binomial distribution.

216 Next, to determine if the existence of product specific active sites is a
217 feature of Cu electrocatalysts in general, we performed reduction of the
218 $^{13}\text{CO}/^{12}\text{CO}_2$ gas mixture with polycrystalline (PC) Cu, Cu (111) and Cu (100)
219 oriented surfaces. Fig. 3a shows the isotopic composition of the products
220 at -0.9 V vs RHE. In some cases, the isotopic compositions of acetate and
221 1-propanol could not be determined accurately as their formation rates
222 were too low. In contrast to the case for OD Cu, we observe that the
223 isotopic composition for the products generated are very similar, which
224 means that these catalysts do not have product specific active sites. In
225 Figs. 3b and 3c, the ^{12}C - ^{13}C distributions of ethylene and ethanol
226 generated by PC Cu appear to deviate slightly from the predicted binomial
227 distribution. This might suggest that PC Cu may have multiple active sites
228 which are not product specific. In this scenario, each type of active site
229 might have a different probability of $^*^{12}\text{CO}$ vs $^*^{13}\text{CO}$, which results in the
230 ^{12}C - ^{13}C distributions of the products being a superposition of a few
231 binomial distributions. To ensure that the similar isotopic compositions of
232 the products was not just a coincidence, happening only at -0.9 V vs RHE,
233 we tested Cu (100) at -0.8 V vs RHE. As expected, all products possess
234 similar isotopic compositions, albeit with higher ^{13}C fractions due to the
235 lower overpotential that was applied (Fig. 3d).

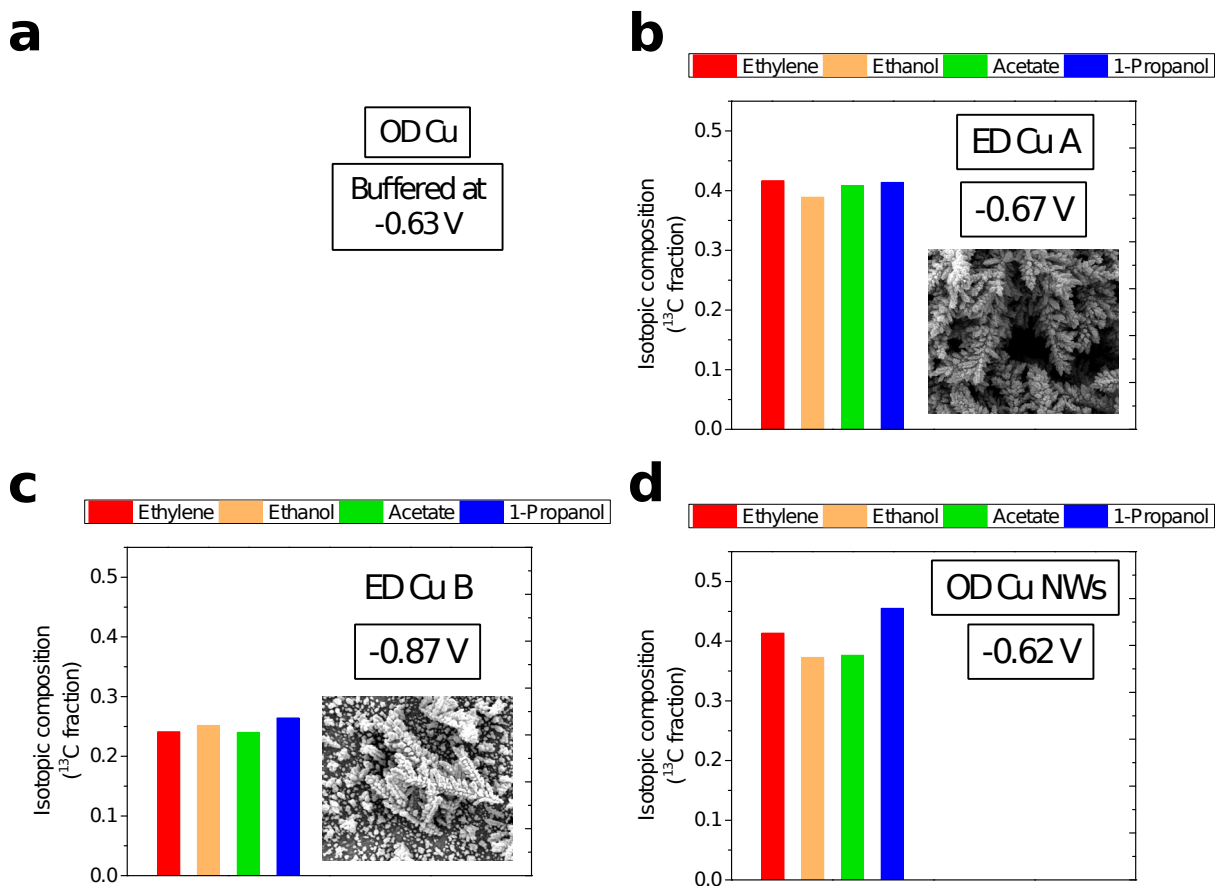


236

237 **Fig. 3 | Isotopic compositions and ^{12}C - ^{13}C distributions of products generated by**
 238 **Cu (111), Cu (100) and PC Cu.** (a) Isotopic compositions (^{13}C fraction) of products
 239 generated by Cu (100), Cu (111) and PC Cu at -0.9 V vs RHE. The * in the figure appears
 240 whenever the isotopic composition could not be determined accurately. (b) and (c)
 241 Observed and predicted binomial ^{12}C - ^{13}C distributions of ethylene and ethanol
 242 respectively for PC Cu. (d) Isotopic compositions (^{13}C fraction) of products generated by
 243 Cu (100) at -0.8 V vs RHE. ^{12}C - ^{13}C distributions for Cu (100) and Cu (111) are shown in
 244 Supplementary Fig. 31. Catalysis data is shown in Supplementary Fig. 32. Error bars
 245 correspond to the standard deviation of 3 independent measurements.

246 **Control experiments.** We performed a series of control experiments to
 247 rule out local pH, surface area/roughness and catalyst morphology effects
 248 as possible explanations for our striking findings on OD Cu. Firstly, during
 249 CO_2R the local pH of the surface rises above the bulk pH because protons
 250 from water are consumed to drive reduction of CO_2 and hydrogen
 251 evolution.^{3,37} This rise in local pH of the catalyst surface during CO_2R has
 252 been observed to suppress C_1 formation and enhance C-C coupling,
 253 thereby increasing selectivity towards C_2 products.^{17,25,29,38} For high surface
 254 area catalysts such as OD Cu, the rise in local pH is larger as compared to

255 planar Cu electrodes due to the larger geometric current densities.²⁶
 256 Therefore, to minimize local pH changes, we reduced the ¹³CO/¹²CO₂ gas
 257 mixture with OD Cu in a 0.1 M phosphate buffer (pH 7.2) at a potential of
 258 -0.63 V. Such a buffer has been previously shown to be effective in
 259 significantly mitigating rises in local pH.^{3,28,39} Fig. 4a shows that the
 260 isotopic compositions of ethylene, ethanol/acetate and 1-propanol remain
 261 distinct from each other in phosphate buffer, which allows us to rule out
 262 local pH effects as a possible explanation for our results.



263

264 **Fig. 4 | Isotopic compositions of products generated in control experiments.**
 265 Isotopic compositions (¹³C fraction) of products generated by (a) OD Cu in 0.1 M
 266 phosphate buffer at a potential of -0.63 V vs RHE, SEM image shown as inset with scale
 267 bar 1 μm. (b) ED Cu A at -0.67 V in 0.1 M KHCO₃, SEM image shown as inset with scale
 268 bar 4 μm. (c) ED Cu B at -0.87 V in 0.1 M KHCO₃, SEM image shown as inset with scale
 269 bar 4 μm. (d) OD Cu NWs at -0.62 V in 0.1 M KHCO₃, SEM image shown as inset with scale
 270 bar 5 μm. Catalysis data is shown in Supplementary Fig. 37. More SEM images are
 271 available in Supplementary Figs. 34-36.

272 To rule out surface area/roughness effects, we tested Cu catalysts
 273 prepared by electrodeposition (ED Cu). This process generates high
 274 surface area catalysts but does not involve an oxidized Cu intermediate

275 (see Methods section for details). Two catalysts were prepared; ED Cu A,
276 which has a comparable roughness factor to OD Cu (Supplementary Table
277 18), and ED Cu B which has a smaller roughness factor (SEM images as
278 insets in Figs. 4b and 4c). Fig. 4b shows that products of $^{13}\text{CO}/^{12}\text{CO}_2$
279 reduction -0.67 V vs RHE on ED Cu A have similar isotopic compositions.
280 Similar results were also obtained on ED Cu B, which was tested at -0.87 V
281 vs RHE (Fig. 4c). Since we did not observe differences in isotopic
282 composition between the products as was the case with OD Cu, we rule
283 out surface area/roughness as a possible explanation of our results.
284 Additionally, it is apparent that such catalyst preparation methods do not
285 result in creation of product specific sites.

286 Finally, catalyst morphology has been shown to be important in
287 determining the selectivity of Cu catalysts.⁴⁰ To explore this effect, we
288 synthesized an oxide-derived Cu catalyst with a distinctly different
289 morphology from OD Cu. Oxide-derived Cu nanowire (OD Cu NWs)
290 catalysts were synthesized according to the procedure described by Smith
291 and co-workers²⁵ with some modifications (see Methods section for details
292 and SEM images as inset in Fig. 4d). Fig. 4d shows that the isotopic
293 compositions of ethylene, ethanol/acetate and 1-propanol obtained by
294 reduction of $^{13}\text{CO}/^{12}\text{CO}_2$ at -0.62 V vs RHE are also different from each
295 other. This means that like OD Cu, OD Cu NWs also possesses product
296 specific active sites. Similarly, we can rule out the possibility that the
297 observed differences in isotopic composition are a result of morphology
298 effects.

299

300 **Mechanistic insights.** Besides the finding that the active sites on OD Cu
301 are product specific, several other mechanistic insights can be gained
302 from this work. To explain oxygenate generation on Cu-based catalysts
303 from CO_2R , several research groups have proposed that mobile
304 nonadsorbed CO can undergo an insertion reaction with surface bound
305 $^*\text{CH}_2$ species to form a $^*\text{COCH}_2$ intermediate.⁴¹⁻⁴³ Further reduction of
306 $^*\text{COCH}_2$ would lead to formation of ethanol and possibly 1-propanol as
307 well.¹³ Also, Meyer and co-workers further proposed that this $^*\text{COCH}_2$

308 intermediate could lead to the formation of acetate.⁴² This type of CO
309 insertion mechanism was first proposed by Hori and co-workers, using an
310 analogy to Fischer-Tropsch catalysis and we will refer to it as the CO
311 insertion mechanism.¹³

312 Using our approach, evidence of a CO insertion mechanism could be
313 observed in two ways. Firstly, according to the mechanism proposed by
314 Hori, $^{12}\text{CO}_2$ would be reduced to surface bound $*^{12}\text{CO}$ and subsequently to
315 $*^{12}\text{CH}_2$. Labelled CO insertion would yield a $*^{13}\text{CO}^{12}\text{CH}_2$ intermediate, which
316 then reduces to form ethanol, 1-propanol or acetate. Importantly, this
317 mechanism predicts that the ^{13}C should be in the α carbon position (-
318 CH_2OH) rather than the β carbon position ($-\text{CH}_3$). Similarly, for 1-propanol,
319 ^{13}C would be in the α position ($-\text{CH}_2\text{OH}$) rather than the β ($-\text{CH}_2-$) or γ (-
320 CH_3) positions. As for acetate, ^{13}C should be in the carboxyl group ($-\text{COO}^-$)
321 rather than the α position ($-\text{CH}_3$). However, ^{13}C NMR reveals no such
322 preference for ^{13}C to be in any of the positions relative to another (see
323 Supplementary Figs. 39-44 for more details). Secondly, CO insertion would
324 not produce a binomial distribution of ^{12}C and ^{13}C in the C_2 products but
325 rather a distribution with enhanced $^{12}\text{C}^{13}\text{C}$ formation, as compared to the
326 $^{12}\text{C}^{12}\text{C}$ or $^{13}\text{C}^{13}\text{C}$. The ^{12}C - ^{13}C distributions of ethanol or acetate do not
327 appear to display a strong bias for formation of the $^{12}\text{C}^{13}\text{C}$ product (Figs. 2
328 and 3, Supplementary Figs. 27 and 31). Thus, we conclude that the CO
329 insertion mechanism does not occur in the catalyst systems in this study.

330 Another interesting experimental observation is that ethanol and
331 acetate are generated from the same active sites on OD Cu. This means
332 that these products are likely to be linked mechanistically and thus share
333 the same selectivity determining intermediates/steps. Indeed, ethanol and
334 acetate have been linked closely together in previous reports. Kanan and
335 co-workers observed substantial acetate formation at high pH during CO
336 reduction on OD Cu, which they ascribed to attack of carbonyl-containing
337 intermediates by OH^- .²⁷ As the increased acetate formation at high pH was
338 accompanied by a decrease in ethanol, it can be inferred that the
339 products share a common intermediate. As another example, Koper and
340 co-workers proposed that Cannizzaro disproportionation of acetaldehyde

341 generates both acetate and ethanol simultaneously.⁴⁴ On the other hand,
342 our observation that ethylene and 1-propanol are generated from different
343 sites suggest that these products do not share common selectivity
344 determining intermediates/steps and branch early on after C-C coupling
345 from the ethanol/acetate pathway. Additionally, our results do not support
346 the mechanism proposed by Head-Gordon and co-workers, which places
347 acetate on the ethylene pathway rather than on the ethanol pathway.¹²

348 Additionally, our experimental observations on OD Cu may also be
349 rationalized from the point of view of scaling relations. In CO₂R,
350 intermediates bind to the surface through the C and/or the O atom.^{10,12,24,45}
351 Because of scaling relations, intermediates that bind through the C atom
352 are expected to have adsorption energies that are linearly related to each
353 other, with the same rationale applying to intermediates that bind through
354 the O atom. For ethylene selective sites, the adsorption energies of
355 intermediates must all be shifted in a way such that after C-C coupling,
356 formation of the ethylene intermediate is by far the most kinetically
357 favourable compared to the ethanol/acetate or 1-propanol intermediates.
358 On the other hand, shifting the adsorption energies of intermediates in a
359 different way could result in favouring the formation of the
360 ethanol/acetate intermediate or the 1-propanol intermediate. Recalling
361 the identification of a range of strong CO adsorption sites on OD Cu not
362 present on polycrystalline Cu by Chorkendorff and co-workers,³⁴ we find it
363 possible that these strong CO adsorption sites are associated with the
364 product specific sites that we have discovered. We further posit that these
365 sites have specific combinations of C and O adsorption energies that
366 enable them to become product specific. Kanan and co-workers have
367 shown that grain boundaries are the active sites on OD Cu for the
368 reduction of CO to C₂/C₃ products.^{34,35} We therefore think it possible that
369 the structure of each product specific active site may be a specific type of
370 grain boundary termination.

371 Another consequence of scaling relations is its effect on the formation
372 of *¹²CO from ¹²CO₂. Theoretical studies have predicted that the rate
373 limiting step of this reaction is the formation of *COOH from *CO₂.^{11,15,46}

374 Since we have consistently observed that ethanol/acetate have the
375 highest ^{12}C fractions (Fig. 2a), their active sites should have the highest
376 $^{12}\text{CO}_2$ to $^*^{12}\text{CO}$ turn over frequencies. We thus posit that due to scaling
377 relations, enhancing the formation of the $^*^{12}\text{COOH}$ intermediate by tuning
378 catalyst adsorption energies also enhances formation of the
379 ethanol/acetate intermediate. Additionally, ethylene and 1-propanol
380 selective sites should have different $^*\text{COOH}$ adsorption energies from
381 ethanol/acetate selective sites since their ^{13}C fractions depend differently
382 on the applied potential (Fig. 2a). This likely means that $^*\text{COOH}$ adsorption
383 energies may be a descriptor for the product selectivity of an active site.
384 Because of this, turn over frequencies for $^{12}\text{CO}_2$ and $^*^{12}\text{CO}$ are active site
385 dependent, giving each site a different probability of $^*^{12}\text{CO}$ vs $^*^{13}\text{CO}$. This
386 gives rise to the different product isotopic compositions as we have
387 observed.

388 Finally, a theory paper published by Goddard and co-workers could
389 possibly offer some insight on our results and serve as a starting point
390 towards identifying the different active sites we have observed.⁴⁷ Using
391 molecular dynamics, they randomly generated sites on Cu nanoparticles
392 with different atomic configurations. Approximately 9% of these
393 generated sites had a larger CO binding energy than Cu (211). This would
394 seem to be consistent with the temperature programmed desorption
395 study of Chorkendorff and co-workers in which they found stronger CO
396 binding sites on OD Cu which are not present on polycrystalline Cu.³⁴
397 Among the strong CO binding sites, the theoretical study identified 2
398 atomic configurations which were proposed to be active for C-C coupling.
399 Relating these findings to our experimental work, it is conceivable that
400 some of the sites studied by Goddard and co-workers could also be
401 present on the OD Cu surface. It is possible that the differences in CO
402 binding energy for different surface configuration could be used to identify
403 C_2 and C_3 product selective sites, although more precise knowledge of the
404 selectivity determining steps would be required.

405 **Conclusions**

406 In summary, we have shown via isotope labelling that OD Cu has product
407 specific active sites for the CO₂R reaction, with one set of active sites
408 generating ethylene, another ethanol/acetate and yet another 1-propanol.
409 We reason that due to scaling relations, the rate of *COOH formation
410 (intermediate to *CO) should be different on each type of active site. This
411 means that each active site has a different probability of *¹²CO vs *¹³CO
412 and as a result, products generated from different sites possess different
413 isotopic compositions. In contrast, by performing similar experiments on
414 polycrystalline Cu, Cu (100) and Cu (111) we show that these have sites
415 that produces a mixture of C-C coupled products. Finally, our finding that
416 active sites on OD Cu are product specific should motivate future work to
417 understand these sites as well as ways to engineer specific types of sites
418 into a single structure, thereby creating catalysts with very high product
419 selectivity.

420 **Methods**

421 **Materials.** Potassium carbonate (99.995% metals basis), potassium hydroxide (99.99%
422 metals basis), ¹³C carbon monoxide (<5 atom % ¹⁸O, 99 atom % ¹³C), nitric acid (70%),
423 hydrochloric acid (37%), potassium phosphate monobasic (99.99% metals basis) and
424 potassium phosphate dibasic (99.95% metals basis) were purchased from Sigma-Aldrich.
425 Copper foil (0.1 mm thick, 99.9999%) and glassy carbon plates were purchased from Alfa
426 Aesar. Selemion AMV anionic exchange membranes were purchased from Asahi Glass
427 Co., Ltd. Si wafers of various orientations were purchased from UniversityWafer, Inc. The
428 copper sputtering target (99.999%) was purchased from Kurt J. Lesker Company. All
429 chemicals were used without further purification. Carbon dioxide (99.995%), nitrogen
430 (99.999%), argon (99.999%) and hydrogen (99.999%) were purchased from Praxair.
431 Natural abundance carbon monoxide (99.999% research purity) was purchased from
432 Matheson Tri-gas Inc. Hydrogen, argon, nitrogen and carbon dioxide gas purifiers
433 purchased from Valco Instruments Co. Inc were used on the gas feeds to the
434 electrochemical cell and gas chromatograph. 18.2 MΩ deionized (DI) water was produced
435 by a Millipore system and used for electrolyte preparation.

436 **Preparation of polycrystalline Cu (PC Cu).** Cu foil was cut into 2 cm by 2 cm square
437 pieces and then electropolished at a potential of 2V vs the counter electrode for a period
438 of 5 minutes. The counter electrode used was another Cu foil of larger dimensions (5 cm
439 by 5 cm).

440 **Preparation of oxide-derived Cu (OD Cu).** Oxide-derived Cu was prepared according
441 to the procedure developed by Kanan and co-workers.²⁷ Cu foil was first cut into 2 cm by
442 2 cm square pieces and then electropolished at a potential of 2 V vs the counter
443 electrode for a period of 5 minutes. The counter electrode used was another Cu foil of
444 larger dimensions (5 cm by 5 cm). To oxidize the surface, the Cu foil was thermally

445 annealed in air using a muffle furnace at a temperature of 500 °C for 1 hour. The muffle
446 furnace was then allowed to cool to room temperature before removing the oxidized Cu
447 foils.

448 **Preparation of oriented Cu surfaces.** Cu (100) and (111) oriented surfaces were
449 prepared according to similar procedures as described by Jaramillo and co-workers.³⁶ Si
450 wafers with different orientations were used as growth substrates to facilitate epitaxial
451 growth of Cu. Cu films grown on Si (100) and (110) wafers yield Cu orientations of (100)
452 and (111) respectively. The native oxide on the Si wafers was first removed via a HF etch
453 and subsequent growth of the films was carried out using sputtering with an AJA
454 International ATC Orion 5 sputtering system. In all cases, the thicknesses of the Cu films
455 were controlled to be 200 nm thick using a quartz crystal monitor. Samples were kept in
456 a N₂ filled glove box when not in use to minimize oxidation in ambient air. The
457 orientations was also confirmed according to similar procedures reported by Koper and
458 co-workers⁴⁸ as well as Yeo and co-workers.³² Briefly, this was accomplished with cyclic
459 voltammetry in Ar sparged 0.1 M KOH solution in the potential range of -1.3V to -0.45V vs
460 Ag/AgCl at a rate of 120 mVs⁻¹. OH⁻ adsorption and desorption peaks are unique and
461 depend on the Cu surface and thus may be used to identify and confirm its orientation.
462 Cyclic voltammetry was also carried out after CO reduction to confirm that loss of the
463 surface orientation did not occur. (See Supplementary Fig. 33).

464 **Preparation of oxide-derived Cu nanowires (OD Cu NWs).** Oxide-derived
465 nanowires were prepared according to the method described by Smith and co-workers,
466 with some modifications.²⁵ Firstly, Cu foil was first cut into 2 cm by 2 cm square pieces
467 and then electropolished at a potential of 2V vs the counter electrode for a period of 5
468 minutes. The counter electrode used was another Cu foil of larger dimensions (5 cm by 5
469 cm). The Cu foil was then immersed into an aqueous solution containing 0.133 M
470 (NH₄)₂S₂O₈ and 2.667 M NaOH for 10 minutes, resulting in growth of Cu(OH)₂ nanowires
471 on the surface. The foil was then thermally annealed in air using a muffle furnace at a
472 temperature of 500 °C for 30 mins to convert Cu(OH)₂ to CuO. The muffle furnace was
473 then allowed to cool to room temperature before removing the Cu foils.

474 **Preparation of electrodeposited Cu (ED Cu A and ED Cu B).** ED Cu A and ED Cu B
475 were prepared by electrodeposition of Cu onto an electropolished Cu foil using a solution
476 containing 0.1 M CuSO₄ adjusted to pH 1 using concentrated H₂SO₄. A constant cathodic
477 current density of -400 mA cm⁻² was applied for 8 minutes for ED Cu A and only 2
478 minutes for ED Cu B. Such a procedure results in a dendritic, porous structure with a high
479 surface area with the roughness factor increasing with increasing deposition time.

480 **Materials characterization and electroactive surface area measurements.**
481 Scanning electron microscopy images were taken on a FEI Quanta 200 FEG scanning
482 electron microscope using an accelerating voltage of 15 kV. X-ray diffraction patterns
483 were obtained using a Rigaku Smartlab x-ray diffractometer.

484 Electroactive surface area measurements were performed according to procedures
485 described by Nilsson and co-workers.³³ These measurements were performed in the
486 same electrochemical cell as that for electrolysis experiments. 0.1 M KHCO₃ was used as
487 the electrolyte and cyclic voltammetry was carried out in a region where faradaic
488 processes do not occur. This was carried out with various scan rates and the geometric
489 current density was plotted vs scan rate. The slope of this graph is equal to the double
490 layer capacitance.

491 **Electrochemical measurements.** For all electrochemical measurements described in
492 this work, a Biologic SP-300 potentiostat was used. CO reduction was carried out using a
493 custom-made electrochemical cell made of PEEK and fitted with Teflon o-rings for
494 chemical inertness and durability. In this cell, the working and counter electrodes are
495 both constrained to be 1 cm² and sit parallel to each other in order to ensure a uniform

496 potential distribution across the working electrode surface. In all electrochemical CO₂/CO
497 reduction experiments, glassy carbon was used as the counter electrode (anode) instead
498 of Pt due to concerns regarding Pt dissolution.⁴⁹ In order to ensure that the electrolyte
499 remains saturated with ¹²CO₂ and ¹³CO throughout electrolysis, these gases were
500 continuously introduced into the electrochemical cell at a rate of 1.5 and 3.5 sccm
501 respectively using mass-flow controllers. A custom-made glass frit fabricated by Adams &
502 Chittenden Scientific Glass was used to disperse the gas into the electrolyte as well as
503 provide adequate convection in the electrochemical cell.⁵⁰ Before carrying out bulk
504 electrolysis experiments, the gas mixture was allowed to flow through the electrolyte in
505 the cathode chamber for at least 15 minutes to ensure that the electrolyte is saturated.
506 To separate the electrolyte in the cathode and anode chambers, a Selemion AMV anion
507 exchange membrane was employed. Before use, the membrane was carefully rinsed
508 with DI water. The electrolyte volume used in both the cathode and anode were 1.8 ml
509 each. Before use in experiments, the electrochemical cell was sonicated in 20 wt.% nitric
510 acid for 1 hour. All bulk electrolysis experiments were conducted for 70 minutes. A leak-
511 free Ag/AgCl electrode from Innovative Instruments, Inc was employed as a reference
512 electrode. The accuracy of this reference electrode was ensured periodically by
513 comparison with a custom-made reversible hydrogen electrode. To convert potentials vs
514 Ag/AgCl to the RHE scale, the following equation as used:

$$515 \quad E(\text{vs. RHE}) = E(\text{vs. Ag/AgCl}) + 0.197 V + 0.0591 \text{ pH},$$

516 (1)

517 After saturation of the electrolyte with the gas mixture, the solution resistance was
518 determined using potentiostatic electrochemical impedance spectroscopy (PEIS),
519 scanning through a frequency range of 1 MHz to 10 Hz. 85% of the solution resistance
520 was then compensated using the software and the remaining 15% was post-corrected
521 after the experiment.

522 **Preparation of electrolyte and product analysis.** Preparation of electrolytes and
523 product analysis was performed according to similar procedures as reported previously.²⁶

524 **GCMS analysis of gas and liquid products.** Isotopic composition of both the gas and
525 liquid products were determined using gas chromatography-mass spectrometry (GCMS)
526 with an Agilent 7890A GC with 5975C inert XL MSD (triple axis detector). The column
527 used was an Agilent J&W PoraPLOT Q capillary column of length 25 m, internal diameter
528 0.25 mm and film thickness 8 μm (part number CP7549). Helium (99.999%) was used as
529 the carrier gas with a flow rate of 1.0 ml/min in the column. A glass wool liner was used
530 in the inlet, which was set to 250 °C.

531 For gas product analysis, 10 μl of gas was injected into the GCMS and the injection mode
532 was split with a 1:1 ratio. For the analysis method, the selected ion monitoring (SIM)
533 operating mode was used. Elution times of the target analytes (ethylene and ethane)
534 were determined by injecting known standards. During the run, the operating
535 temperature of the oven was set to 30 °C for 7.5 minutes. A bake out at 100 °C for 5
536 minutes was utilized at the end of each run.

537 For liquid product analysis, electrolyte samples were first acidified with concentrated
538 hydrochloric acid to pH 2 to convert acetate into the acetic acid form, which is amenable
539 to GCMS analysis. For each analysis, 0.5 μl of sample was injected and the injection
540 mode was split with a 25:1 ratio. The selected ion monitoring (SIM) operating mode was
541 used for liquid products. Similarly, the elution times of the target analytes (ethanol, 1-
542 propanol and acetic acid) were determined by injecting known standards dissolved in
543 water. During the run, the oven temperature was set to 145 °C for 10 minutes. A bake
544 out at 200 °C for 5 minutes was utilized at the end of every run.

545 To ensure that the mass spectra of different products obtained with our GCMS are
546 consistent with established databases,⁵¹ standards of natural isotopic abundances were

547 also injected and all mass fragments with m/z in the range 20 to 75 were scanned (see
548 Supplementary Figs. 11-13 for more details).

549 Determination of the isotopic composition based on the mass spectrometry data is
550 explained in the Supplementary Note 4.

551 **¹³C NMR spectroscopy of liquid products.** ¹³C NMR was utilized to analyze the
552 isotopic composition of the liquid products using a Bruker Avance III 500 MHz
553 spectrometer. 700 µl of the electrolyte with the liquid products was mixed with 35 µl of
554 D₂O containing 10 mM DMSO and 50 mM phenol. To prevent ¹H protons from splitting
555 the ¹³C nuclei, proton decoupling techniques were utilized. Samples were run for at least
556 12 hours to accumulate sufficient signal. Determination of the isotopic composition based
557 on the NMR results is explained in Supplementary Note 5.

558 **Data availability.** The data that support the findings of this study are available from
559 the corresponding author upon reasonable request.

560 References

- 561 1. Intergovernmental Panel on Climate Change, IPCC, Intergovernmental Panel on
562 Climate Change & Intergovernmental Panel on Climate Change (IPCC). *Climate*
563 *Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the*
564 *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*
565 (2014).
- 566 2. Chu, S., Cui, Y. & Liu, N. The path towards sustainable energy. *Nat Mater* **16**, 16-
567 22 (2017).
- 568 3. Hori, Y. Electrochemical CO₂ Reduction on Metal Electrodes. in *Modern Aspects of*
569 *Electrochemistry SE - 3* (eds. Vayenas, C., White, R. & Gamboa-Aldeco, M.) **42**,
570 89-189 (Springer New York, 2008).
- 571 4. Bushuyev, O. S. *et al.* What Should We Make with CO₂ and How Can We Make It?
572 *Joule* **2**, 825-832 (2018).
- 573 5. Raciti, D. & Wang, C. Recent Advances in CO₂ Reduction Electrocatalysis on
574 Copper. *ACS Energy Lett.* **3**, 1545-1556 (2018).
- 575 6. Hori, Y., Murata, A. & Takahashi, R. Formation of hydrocarbons in the
576 electrochemical reduction of carbon dioxide at a copper electrode in aqueous
577 solution. *J. Chem. Soc. Faraday Trans. 1 Phys. Chem. Condens. Phases* **85**, 2309
578 (1989).
- 579 7. Kuhl, K. P., Cave, E. R., Abram, D. N. & Jaramillo, T. F. New Insights into the
580 Electrochemical Reduction of Carbon Dioxide on Metallic Copper Surfaces. *Energy*
581 *Environ. Sci.* **5**, 7050-7059 (2012).
- 582 8. Kuhl, K. P. *et al.* Electrocatalytic Conversion of Carbon Dioxide to Methane and
583 Methanol on Transition Metal Surfaces. *J. Am. Chem. Soc.* **136**, 14107-14113
584 (2014).
- 585 9. Li, C. W. & Kanan, M. W. CO₂ Reduction at Low Overpotential on Cu Electrodes
586 Resulting from the Reduction of Thick Cu₂O Films. *J. Am. Chem. Soc.* **134**, 7231-
587 7234 (2012).
- 588 10. Peterson, A. A. *et al.* How copper catalyzes the electroreduction of carbon dioxide
589 into hydrocarbon fuels. *Energy Environ. Sci.* **3**, 1311-1315 (2010).

- 590 11. Cheng, T., Xiao, H. & Goddard, W. A. Reaction Mechanisms for the Electrochemical
591 Reduction of CO₂ to CO and Formate on the Cu(100) Surface at 298 K from
592 Quantum Mechanics Free Energy Calculations with Explicit Water. *J. Am. Chem.*
593 *Soc.* **138**, 13802–13805 (2016).
- 594 12. Garza, A. J., Bell, A. T. & Head-Gordon, M. Mechanism of CO₂ Reduction at Copper
595 Surfaces: Pathways to C₂ Products. *ACS Catal.* **8**, 1490–1499 (2018).
- 596 13. Hori, Y., Takahashi, R., Yoshinami, Y. & Murata, A. Electrochemical Reduction of CO
597 at a Copper Electrode. *J. Phys. Chem. B* **101**, 7075–7081 (1997).
- 598 14. Schouten, K. J. P., Qin, Z., Gallent, E. P. & Koper, M. T. M. Two Pathways for the
599 Formation of Ethylene in CO Reduction on Single-Crystal Copper Electrodes. *J. Am.*
600 *Chem. Soc.* **134**, 9864–9867 (2012).
- 601 15. Kortlever, R., Shen, J., Schouten, K. J. P., Calle-Vallejo, F. & Koper, M. T. M.
602 Catalysts and Reaction Pathways for the Electrochemical Reduction of Carbon
603 Dioxide. *J. Phys. Chem. Lett.* **6**, 4073–4082 (2015).
- 604 16. Calle-Vallejo, F. & Koper, M. T. M. Theoretical Considerations on the
605 Electroreduction of CO to C₂ Species on Cu(100) Electrodes. *Angew. Chemie* **125**,
606 7423–7426 (2013).
- 607 17. Dinh, C. T. *et al.* CO₂ electroreduction to ethylene via hydroxide-mediated copper
608 catalysis at an abrupt interface. *Science* **360**, 783–787 (2018).
- 609 18. Ma, S. *et al.* One-step electrosynthesis of ethylene and ethanol from CO₂ in an
610 alkaline electrolyzer. *J. Power Sources* **301**, 219–228 (2016).
- 611 19. Peterson, A. A. & Nørskov, J. K. Activity Descriptors for CO₂ Electroreduction to
612 Methane on Transition-Metal Catalysts. *J. Phys. Chem. Lett.* **3**, 251–258 (2012).
- 613 20. Hansen, H. A., Varley, J. B., Peterson, A. A. & Nørskov, J. K. Understanding Trends in
614 the Electrocatalytic Activity of Metals and Enzymes for CO₂ Reduction to CO. *J.*
615 *Phys. Chem. Lett.* **4**, 388–392 (2013).
- 616 21. Liu, X. *et al.* Understanding trends in electrochemical carbon dioxide reduction
617 rates. *Nat. Commun.* **8**, (2017).
- 618 22. Sandberg, R. B., Montoya, J. H., Chan, K. & Nørskov, J. K. CO-CO coupling on Cu
619 facets: Coverage, strain and field effects. *Surf. Sci.* **654**, 56–62 (2016).
- 620 23. Goodpaster, J. D., Bell, A. T. & Head-Gordon, M. Identification of Possible Pathways
621 for C–C Bond Formation during Electrochemical Reduction of CO₂: New Theoretical
622 Insights from an Improved Electrochemical Model. *J. Phys. Chem. Lett.* **7**, 1471–
623 1477 (2016).
- 624 24. Cheng, T., Xiao, H. & Goddard, W. A. Full atomistic reaction mechanism with
625 kinetics for CO reduction on Cu(100) from ab initio molecular dynamics free-energy
626 calculations at 298 K. *Proc. Natl. Acad. Sci.* **114**, 1795–1800 (2017).
- 627 25. Ma, M., Djanashvili, K. & Smith, W. A. Controllable Hydrocarbon Formation from the
628 Electrochemical Reduction of CO₂ over Cu Nanowire Arrays. *Angew. Chemie Int. Ed.*
629 **55**, 6680–6684 (2016).
- 630 26. Lum, Y., Yue, B., Lobaccaro, P., Bell, A. T. & Ager, J. W. Optimizing C-C Coupling on
631 Oxide-Derived Copper Catalysts for Electrochemical CO₂ Reduction. *J. Phys. Chem.*
632 *C* **121**, 14191–14203 (2017).

- 633 27. Li, C. W., Ciston, J. & Kanan, M. W. Electroreduction of carbon monoxide to liquid
634 fuel on oxide-derived nanocrystalline copper. *Nature* **508**, 504–507 (2014).
- 635 28. Ren, D. *et al.* Selective Electrochemical Reduction of Carbon Dioxide to Ethylene
636 and Ethanol on Copper(I) Oxide Catalysts. *ACS Catal.* **5**, 2814–2821 (2015).
- 637 29. Kas, R., Kortlever, R., Yilmaz, H., Koper, M. T. M. & Mul, G. Manipulating the
638 Hydrocarbon Selectivity of Copper Nanoparticles in CO₂ Electroreduction by
639 Process Conditions. *ChemElectroChem* **2**, 354–358 (2014).
- 640 30. Raciti, D. *et al.* Low-Overpotential Electroreduction of Carbon Monoxide Using
641 Copper Nanowires. *ACS Catal.* **7**, 4467–4472 (2017).
- 642 31. Mistry, H. *et al.* Highly selective plasma-activated copper catalysts for carbon
643 dioxide reduction to ethylene. *Nat. Commun.* **7**, 12123 (2016).
- 644 32. Huang, Y., Handoko, A. D., Hirunsit, P. & Yeo, B. S. Electrochemical Reduction of
645 CO₂ Using Copper Single-Crystal Surfaces: Effects of CO* Coverage on the
646 Selective Formation of Ethylene. *ACS Catal.* **7**, 1749–1756 (2017).
- 647 33. Roberts, F. S., Kuhl, K. P. & Nilsson, A. High Selectivity for Ethylene from Carbon
648 Dioxide Reduction over Copper Nanocube Electrocatalysts. *Angew. Chemie* **127**,
649 5268–5271 (2015).
- 650 34. Verdaguer-Casadevall, A. *et al.* Probing the Active Surface Sites for CO Reduction
651 on Oxide-Derived Copper Electrocatalysts. *J. Am. Chem. Soc.* **137**, 9808–9811
652 (2015).
- 653 35. Feng, X., Jiang, K., Fan, S. & Kanan, M. W. A Direct Grain-Boundary-Activity
654 Correlation for CO Electroreduction on Cu Nanoparticles. *ACS Cent. Sci.* **2**, 169–174
655 (2016).
- 656 36. Hahn, C. *et al.* Engineering Cu surfaces for the electrocatalytic conversion of CO₂:
657 Controlling selectivity toward oxygenates and hydrocarbons. *Proc. Natl. Acad. Sci.*
658 **114**, 5918–5923 (2017).
- 659 37. Singh, M. R., Clark, E. L. & Bell, A. T. Effects of electrolyte, catalyst, and membrane
660 composition and operating conditions on the performance of solar-driven
661 electrochemical reduction of carbon dioxide. *Phys. Chem. Chem. Phys.* **17**, 18924–
662 36 (2015).
- 663 38. Xiao, H., Cheng, T., Goddard, W. A. & Sundararaman, R. Mechanistic Explanation of
664 the pH Dependence and Onset Potentials for Hydrocarbon Products from
665 Electrochemical Reduction of CO on Cu (111). *J. Am. Chem. Soc.* **138**, 483–486
666 (2016).
- 667 39. Resasco, J., Lum, Y., Clark, E., Zeledon, J. Z. & Bell, A. T. Effects of Anion Identity
668 and Concentration on Electrochemical Reduction of CO₂. *ChemElectroChem* **5**,
669 1064–1072 (2018).
- 670 40. Dutta, A., Rahaman, M., Luedi, N. C., Mohos, M. & Broekmann, P. Morphology
671 Matters: Tuning the Product Distribution of CO₂ Electroreduction on Oxide-Derived
672 Cu Foam Catalysts. *ACS Catal.* **6**, 3804–3814 (2016).
- 673 41. Lee, S., Park, G. & Lee, J. Importance of Ag–Cu Biphase Boundaries for Selective
674 Electrochemical Reduction of CO₂ to Ethanol. *ACS Catal.* **7**, 8594–8604 (2017).
- 675 42. Wang, Y. *et al.* CO₂ reduction to acetate in mixtures of ultrasmall (Cu)_n(Ag)_m
676 bimetallic nanoparticles. *Proc. Natl. Acad. Sci.* **115**, 278–283 (2018).

- 677 43. Ren, D., Ang, B. S.-H. & Yeo, B. S. Tuning the Selectivity of Carbon Dioxide
678 Electroreduction toward Ethanol on Oxide-Derived Cu_xZn Catalysts. *ACS Catal.* **6**,
679 8239–8247 (2016).
- 680 44. Birdja, Y. Y. & Koper, M. T. M. The Importance of Cannizzaro-Type Reactions during
681 Electrocatalytic Reduction of Carbon Dioxide. *J. Am. Chem. Soc.* **139**, 2030–2034
682 (2017).
- 683 45. Calle-Vallejo, F. & Koper, M. T. M. Theoretical Considerations on the
684 Electroreduction of CO to C₂ Species on Cu(100) Electrodes. *Angew. Chemie Int.*
685 *Ed.* **52**, 7282–7285 (2013).
- 686 46. Singh, M. R., Goodpaster, J. D., Weber, A. Z., Head-Gordon, M. & Bell, A. T.
687 Mechanistic insights into electrochemical reduction of CO₂ over Ag using density
688 functional theory and transport models. *Proc. Natl. Acad. Sci. U. S. A.* **114**, E8812–
689 E8821 (2017).
- 690 47. Cheng, T., Xiao, H. & Goddard, W. A. Nature of the Active Sites for CO Reduction on
691 Copper Nanoparticles; Suggestions for Optimizing Performance. *J. Am. Chem. Soc.*
692 **139**, 11642–11645 (2017).
- 693 48. Pérez-Gallent, E., Marcandalli, G., Figueiredo, M. C., Calle-Vallejo, F. & Koper, M. T.
694 M. Structure- and Potential-Dependent Cation Effects on CO Reduction at Copper
695 Single-Crystal Electrodes. *J. Am. Chem. Soc.* **139**, 16412–16419 (2017).
- 696 49. Chen, J. G., Jones, C. W., Linic, S. & Stamenkovic, V. R. Best Practices in Pursuit of
697 Topics in Heterogeneous Electrocatalysis. *ACS Catal.* **7**, 6392–6393 (2017).
- 698 50. Lobaccaro, P. *et al.* Effects of temperature and gas-liquid mass transfer on the
699 operation of small electrochemical cells for the quantitative evaluation of CO₂
700 reduction electrocatalysts. *Phys. Chem. Chem. Phys.* **18**, 26777–26785 (2016).
- 701 51. NIST Mass Spec Data Center, S.E. Stein, director, 'Mass Spectra' in NIST Chemistry
702 WebBook, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and
703 W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD,
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713 **Author contributions**

714 Y.L and J.WA. conceived and designed the experiments. Y.L conducted all
715 the experimental work and analysed the data. All authors discussed the
716 results and wrote the manuscript.

717 **Competing interests**

718 The authors declare no competing interests.