

Autonomous Exploitation of Reaction Pathways for Electrochemical C–N Coupling on Single-Atom Catalysts

Junjie Pan,[#] Haowen Ding,[#] Xinzhe Yang,[#] Xianhui Liang, Shanglin Wu, Mingzheng Zhang, Shunning Li,^{*} Shisheng Zheng,^{*} and Feng Pan^{*}



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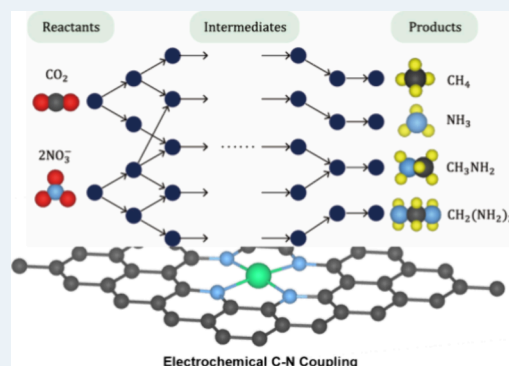
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ABSTRACT: Electrochemical C–N coupling between CO₂ and N-containing small molecules is a promising strategy to close both the carbon and nitrogen loops to support the establishment of a net-zero carbon economy. However, the intricate reaction network and the contentious C–N coupling mechanism hinder the development of efficient electrocatalysts for industrial applications. Herein, we develop a graph-based approach to enable autonomous analysis of the C–N coupling mechanism for coreduction of CO₂ and NO₃[−] on single-atom catalysts (SACs). 1400 potential intermediates and 2490 C–N coupling modes are investigated based on the Cu–N₄–C prototypical catalyst. We demonstrate that N-containing species with a higher reduction degree are more likely to undergo C–N coupling and the initial coupling of the C–N bond tends to occur on CO₂. It is revealed that the hydrogenation energies of *NH₂ and CO₂, as well as their coupling energies, can serve as key indicators for catalyst recommendation. Using this approach, SACs with Mo, W, or Sb metal centers are identified as promising electrocatalysts for C–N coupling. This work presents a paradigm for automatically exploring the mechanisms of complex electrocatalytic reactions and offers a strategy for predicting highly active and selective SACs.

KEYWORDS: electrochemical C–N coupling, single-atom catalyst, graph theory, density functional theory, reaction network



INTRODUCTION

The decarbonization of the chemical industry poses a significant challenge as we seek to reduce our dependence on fossil resources.^{1,2} Electrochemical CO₂ reduction reactions (CO₂RR) driven by renewable energy have emerged as a promising strategy for converting CO₂ into value-added products to achieve carbon neutrality or carbon negativity.^{3–5} Despite the impressive progresses of electrocatalysts in generating a range of single-carbon (C₁) and multicarbon (C₂₊) products containing C–H, C–C, and/or C–O bonds, their potential to produce higher value and diversified products is currently limited by the use of CO₂ and proton sources as the sole reactants.⁶ Compared to the pure CO₂RR, the combination of CO₂RR with the electrochemical reduction of N-integrated small molecules (N₂, NO, NO₂, NO₃[−], NH₃, etc.) to generate C–N bond-containing compounds, e.g., urea and amine, presents a promising strategy for economical production of valuable organonitrogen products.^{7–19} These compounds have widespread applications in chemical production, drug development, farming, and aerospace manufacturing, making this approach highly appealing.⁸

The diverse chemical bond properties of N-containing small molecules give rise to numerous potential reaction modes for C–N coupling, particularly when employing NO_x, e.g., NO₃[−], as the nitrogen sources. Residues of pesticides and fertilizers, as

well as industrial wastewater, carry significant amounts of NO₃[−] that can seep into groundwater and pose health risks to humans.^{20,21} The reduction of NO₃[−] can effectively recycle it to prevent harm to the environment. Additionally, the dissociation energy of NO₃[−] (204 kJ mol^{−1}) is relatively low in N-containing small molecules, especially when compared with the inert N₂ molecules (941 kJ mol^{−1}).⁸ NO₃[−] is reduced to ammonia (NH₃) via an intricate eight-electron process,²² with most of the intermediates presenting the possibility of coupling with the CO₂-reduced intermediate to form a C–N bond. This complexity has left current research on the mechanism of C–N coupling in its early stages. Experimental techniques such as in situ Raman and infrared spectroscopy can be conducted to determine the types of chemical bonds present, but specifically identifying the intermediates involved in C–N coupling can often prove challenging.^{10,11}

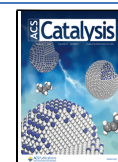
Density functional theory (DFT) simulations offer an efficient way to explore the underlying reaction mechanisms

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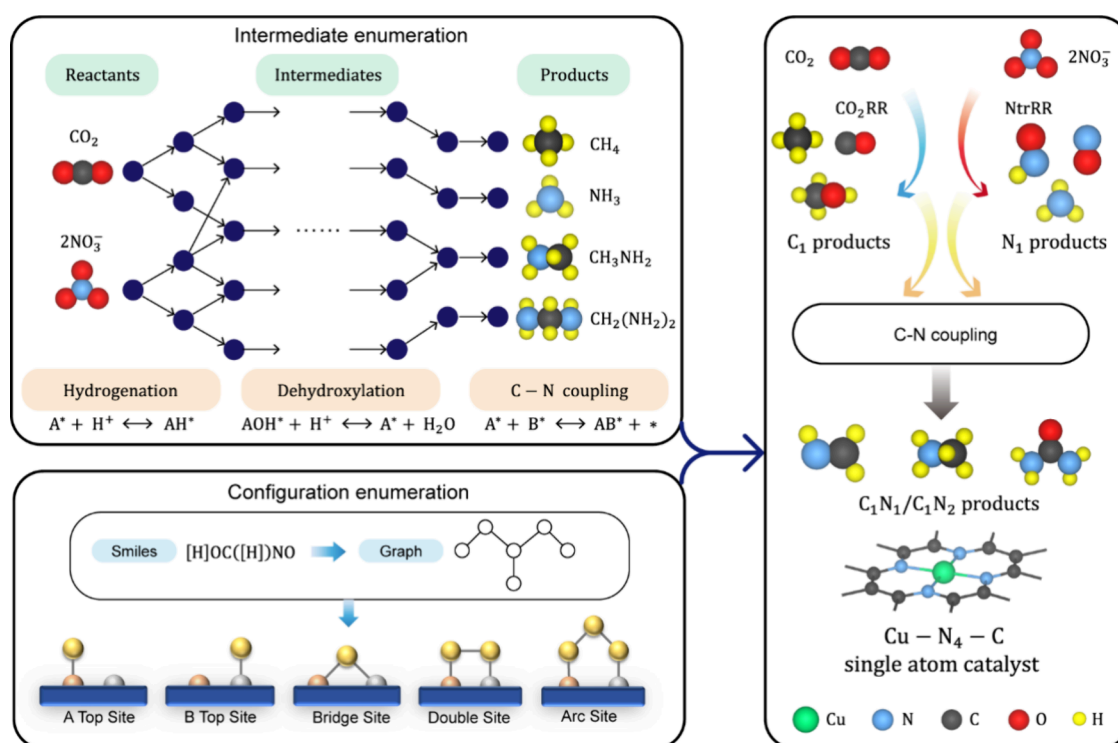


Figure 1. Flowchart of reaction network construction. The intermediates' enumeration and corresponding adsorption configuration enumeration are sequentially carried out.

for catalytic reactions.^{23–28} This research paradigm typically involves a manual enumeration of the possible intermediates involved between the reactants and products to form an overall reaction network.^{29–31} Subsequently, the possible adsorption configurations of these intermediates on the catalyst surface are enumerated and evaluated through DFT calculations to determine the preferred reaction pathways in terms of their thermodynamic and kinetic properties. This strategy has already been widely used to investigate the reaction mechanism for chemical processes that only involve a limited number of intermediates, such as oxygen evolution reaction (OER), CO₂ reduction reaction (CRR), nitrogen reduction reaction (NRR), and so on.^{32–36} Although DFT calculations have been a success for these relatively simple reactions, they are impractical for more complex catalytic processes, such as the coreduction of CO₂ and NO₃[−] to form C–N bond-containing compounds, since the reaction network may include hundreds and thousands of intermediates. Notably, the challenge is not merely the complexity in the reaction network; extra complexity will arise due to the relatively large molecule size of the intermediates. Consequently, a variety of adsorption configurations can emerge for each intermediate on the catalyst surface.^{37,38} The identification of the most stable adsorption configuration is critical in determining the preferred reaction pathway. The combinatorial size of these two hierarchical levels of complexity has forced researchers to make assumptions and eliminate some of the intermediates so that the computational burden could be reduced when investigating the reaction pathways. However, this approach will possibly overlook important reaction intermediates and elementary steps, resulting in misidentification of the preferred reaction pathways.^{30,39} A detailed understanding of the reaction mechanism of C–N coupling is, therefore, difficult to achieve, which hinders the rational design of the related electrocatalysts.

Under this circumstance, developing a method that can generate and analyze the complex catalytic reaction network in an automated way is urgently needed for further advancing the field of electrochemical C–N coupling.

In this work, we develop a graph-based automatic approach for systematic analysis of the reaction pathways for the coreduction of CO₂ and N-containing small molecules to C–N bond-containing products. This approach enables the automation of reaction network generation and the enumeration of the adsorption configurations of intermediates. We employed the coreduction of NO₃[−] and CO₂ on a Cu–N₄–C single-atom catalyst (SAC) as a demonstration platform for our algorithm.¹⁵ SACs are at the forefront of catalytic research due to their high atom utilization efficiency, high catalytic activity, and low cost^{40–43} and have recently been shown to be capable of achieving electrochemical C–N coupling.^{11,14,15,18} It was found that the reaction network can contain up to more than 1400 possible intermediate species and 2490 possible C–N coupling modes. The energy required for C–N coupling is directly related to the degree of reduction for N-containing species, which can be attributed to the increased nucleophilicity of N species with a higher reduction degree. The initial coupling of the C–N bond tends to utilize gaseous CO₂ as the carbon source. Based on this critical finding, we propose that the hydrogenation energies of *NH₂ and CO₂, as well as their coupling energies, can serve as the key indicators for the rapid screening of potential electrocatalysts. Collectively, we have developed an algorithm for automatically analyzing the reaction networks, which enables high-throughput exploration of atomic-level mechanisms for complex electrocatalytic reactions and facilitates the rational design of related electrocatalysts.

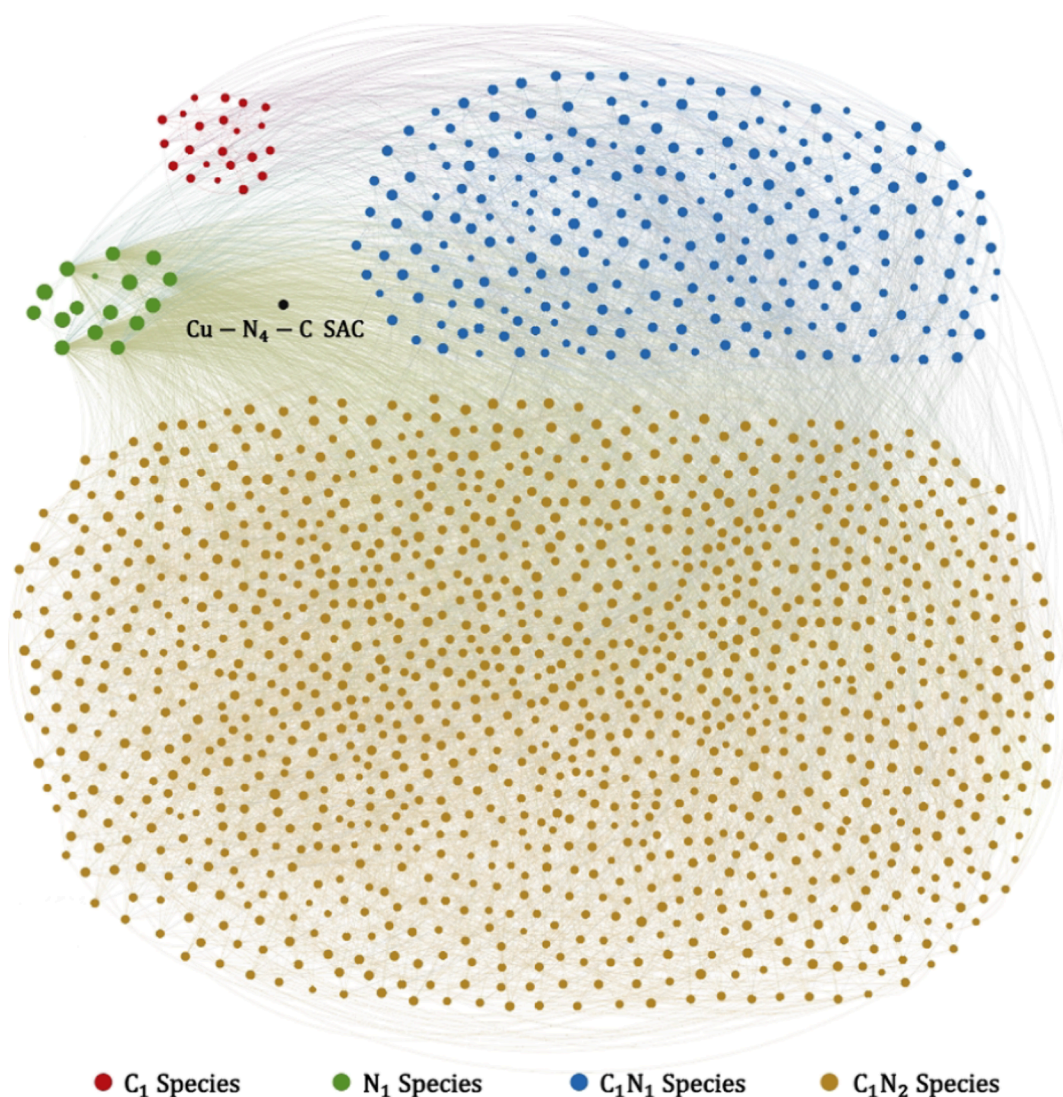


Figure 2. Reaction network for intermediates on the Cu–N₄–C SAC. Red dots represent C₁ intermediates, green dots represent N₁ intermediates, blue dots represent C₁N₁ intermediates, and orange dots represent C₁N₂ intermediates. The size of nodes is positively correlated with the size of degrees.

RESULTS AND DISCUSSION

The electrochemical coreduction of CO₂ and NO₃[−] to synthesize compounds containing one carbon and two nitrogen atoms, such as urea, has gained considerable attention recently. Here, we showcase the capability of our algorithm by analyzing a reaction network involving one CO₂ and two NO₃[−] molecules as reactants and CH₂(NH₂)₂ as the ending product (Figure 1). The CH₂(NH₂)₂ is chosen as the end point of the reaction network because it represents the fully hydrogenated state of both C and N, making it the most reduced product from the coreduction of CO₂ and two NO₃[−].

The initial stage is to enumerate all the possible intermediates connecting the reactants and the products to build the pool of potential intermediates, which is achieved by a molecule graph-based enumeration algorithm with RDKit.⁴⁴ In a molecule graph, atoms are represented as nodes and chemical bonds are abstracted as edges connecting these nodes.^{45,46} The graph-based representation of molecules is convenient for computer recognition and manipulation because the graph can be further transformed into a matrix or SMILES representation. Considering that the reactants of

CO₂ and NO₃[−] are converted to be as molecule graphs, the generation of intermediates can be iteratively implemented by editing the graph with preset elementary step types, such as hydrogenation and C–N coupling. In this process, the boundary conditions are applied to check whether the generated intermediate violates the bonding principles. Specifically, the number of chemical bonds that N atoms, C atoms, and O atoms can form is limited to 4, 4, and 2, respectively. Those valid intermediates will be added into the pool with their corresponding elementary steps, and the algorithm continues to generate new intermediates until CH₂(NH₂)₂ is included (more details are shown in Figure S1). Once all possible intermediate species are obtained, the next step is to construct the adsorption structures of each intermediate on the surface. This requires the definition of the possible active sites on the catalytic surface. Previous works have demonstrated that in M–N–C single-atom catalysts, not only the metal center but also the surrounding coordination atoms may exhibit catalytic activity.^{47,48} Thus, we considered Cu and N as the possible active sites and defined five possible adsorption modes, namely, the Cu top site, N top site, Cu–N

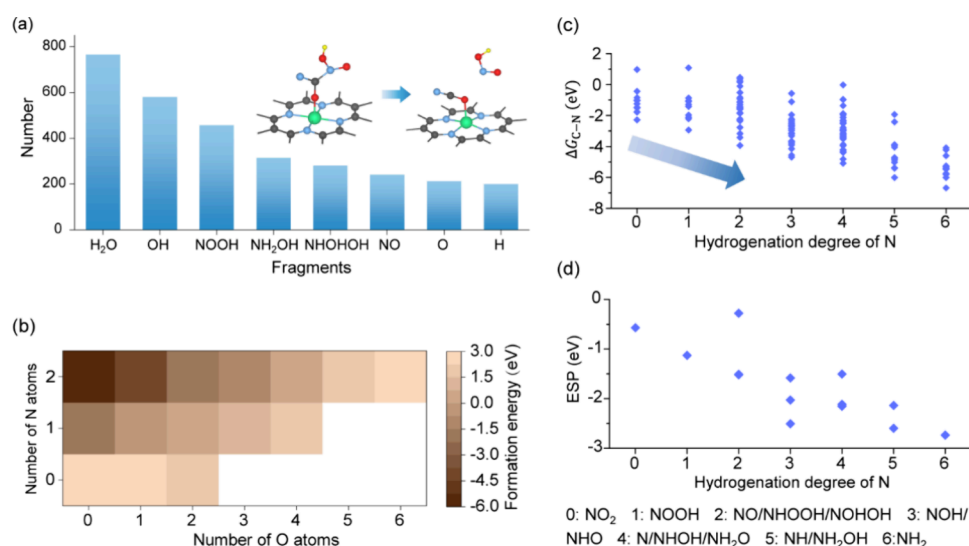


Figure 3. (a) Number of decomposition fragments from the decomposed configurations. The inset shows the initial configuration and optimized configuration of a typical structure (CONNOOH) with the NOOH group detaching. (b) Relationship between the formation energy and the number of N and O atoms. A blank grid indicates that the corresponding configuration does not exist. (c) Relationship between the free energy of the coupling reaction between C_1 and N_1 and the degree of hydrogenation of N_1 intermediates. (d) Relationship between the electrostatic potential and the degree of hydrogenation of N_1 species. Note that the NOH and NHOH overlap in the figure.

bridge site, Cu–N double, and Cu–N Arc (lower panel of Figure 1). Subsequently, we enumerated possible surface-binding atom or atoms of each intermediate considering these five adsorption modes. The geometric rules and the connectivity of molecular graph are then applied to generate different adsorption configurations for DFT calculation (more details are provided in the Methods Section).

The overall resultant reaction network includes a total of 1478 intermediates and more than 8168 elementary steps (Figure 2). The intermediates are clustered into four categories according to the number of carbon and nitrogen atoms. The amounts of C_1 intermediates, N_1 intermediates, C_1N_1 intermediates, and C_1N_2 intermediates are 22, 16, 240, and 1200, respectively. For the elementary steps, there are a total of 3914 hydrogenation reactions, 1764 dehydroxylation reactions, and 2490 C–N coupling reactions. The reaction network can also be treated as a graph, in which the node is the intermediate and the edge is the elementary step.^{49,50} By employing the simple path algorithm⁵¹ in the graph theory, we can obtain the number of reaction pathway for each possible product starting from the reactants (Table S1). For example, there exist 14 distinct pathways from CO₂ to CH₄. Urea (CO(NH₂)₂), a typical product for electrochemical C–N coupling, has 130,332 different reaction pathways from the reactants with at least one intermediate different. It turns out that this task is beyond our capability upon manual exploration. In graph theory, the degree of a node represents the number of edges connected to this node, which indicates the number of potential reactions that a specific intermediate involves. The N_1 intermediates exhibit the highest average degree among all of the intermediates (Table S2), as they are capable of participating in both hydrogenation reactions and C–N coupling reactions with C_1 or C_1N_1 intermediates. The number of degrees in C_1N_1 and C_1N_2 intermediates positively correlates with their average number of adsorption configurations on the surface because the species with higher degrees generally contain more unsaturated atoms and thus more adsorption modes (Figure S2).

After obtaining the intermediates and their corresponding adsorption configurations, we conducted a high-throughput DFT calculation procedure. To reduce the computational cost, we assessed the stability of each adsorption structure during the optimization process (details provided in the Methods Section). If a structure is found to undergo decomposition or reconstruction, the optimization calculation will be stopped since a stable structure is a prerequisite for a specific reaction to occur. The configuration of the DFT-calculated structures is converted to a graph by determining the connectivity between atoms. The graph isomorphism algorithm is then employed to compare whether there are any connectivity changes in the molecule graph. The stable structures are continually optimized until the force convergence.

According to the calculation results (Table S3), 3586 adsorption configurations will suffer structure decomposition or reconstruction, resulting in 665 intermediates that cannot form any stable configurations at the catalyst surface. The unstable intermediates may stem from the intrinsic properties of the intermediates and the interaction between the intermediates and the catalytic surface. The molecule fragments generated by the decomposed and reconstructed configurations are sorted by frequency of occurrence (Figure 3a). The incidence of H₂O fragments is the most frequent. The larger the number of atoms the configuration accommodates, the higher the likelihood of its decomposition to generate H₂O (Figure S3). This is because intermediates with more atoms tend to contain more O–H bonds, while H₂O is a relatively stable molecule, making intramolecular dehydration more likely to occur. When the H₂O molecule is not formed, the hydroxyl groups and oxygen also have a tendency to detach (Figure 3a). Consequently, the products that contain a significant amount of oxygen or hydroxyl groups may not easily form in electrochemical C–N coupling. Following the fact that the H₂O and hydroxyl fragments are the N-containing fragments, including NOOH, NH₂OH, NHOH, and NO, due to the presence of lone pair electrons or the formation of large π bonds, these N-containing intermediates can exist

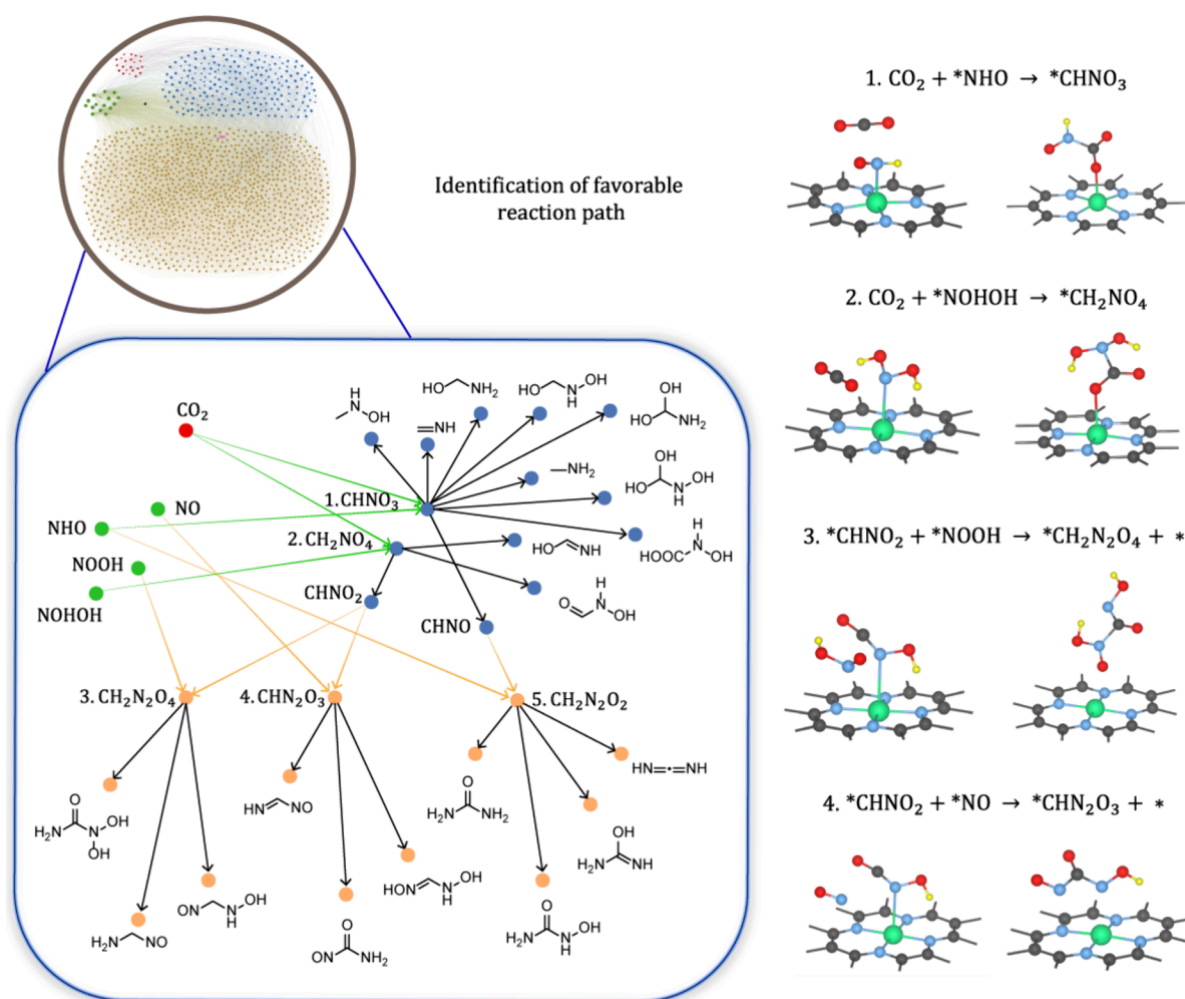


Figure 4. C–N coupling steps correspond to different possible products. Green lines represent the coupling between C_1 and N_1 intermediates, and orange lines represent the coupling between C_1N_1 and N_1 intermediates. The right panel shows the initial and final configurations of the most frequent C–N coupling modes in the formation pathways of these products.

independently and remain stable (Figure S4). However, this also makes it difficult for them to form a C–N bond with C-containing intermediates.

For the 813 stable intermediates, we analyzed their lowest energy configurations. Among them, 290 intermediates tend to be physically adsorbed near the interface (Figure S4), indicating a greater likelihood of desorption to become products or migration at the interface for C–N coupling with other species. In the case of 523 species chemisorbed on the interface, we conducted an analysis of the atoms involved in their interactions. While most of them tend to adsorb on the Cu metal center, a significant proportion of structures exhibit a preference for adsorption on the surrounding N/C atoms (Figures S5 and S6). This indicates that N/C atoms can also act as active centers, which creates favorable conditions for the occurrence of C–N coupling since the C–N coupling requires a local enrichment of intermediates. Simultaneously, this suggests that by modifying the types of nonmetal atoms coordinated to the metal center, researchers may fine-tune the performance of electrochemical C–N coupling. This strategy has already been demonstrated to be effective in reactions such as ORR.⁴⁸

Then, we calculated the formation energies of these lowest energy configurations (Figure 3b). Intermediates containing

more O atoms tend to have higher average formation energies, whereas those containing more N atoms tend to have lower average formation energy. The C_1N_2 intermediates have the lowest formation energy, indicating that the coreduction of CO_2 and NO_3^- becomes easier as more hydrogenation steps are carried out. The rate-determining step of the reaction is more likely to occur during the hydrogenation of C_1/N_1 species or the C–N coupling of C_1 and N_1 intermediates. We calculated the reaction energies of all possible $\text{C}_1\text{–N}_1$ coupling steps. Theoretically, there could be 300 $\text{C}_1\text{–N}_1$ coupling modes since there are 20 intermediates solely from CO_2 reduction and 15 intermediates solely from NO_3^- reduction. However, there are indeed only 110 $\text{C}_1\text{–N}_1$ coupling steps due to the electronic structure of some intermediates being saturated, and some intermediates after C–N coupling become unstable at the interface. The results (Figure 3c) show that the higher the degree of hydrogenation the N-containing species undergo, the smaller the energy consumption will be in $\text{C}_1\text{–N}_1$ coupling. This trend is correlated to the change in electrostatic potential of N_1 intermediates (Figure 3d), which is negatively correlated with the degree of hydrogenation. The lower the electrostatic potential of the intermediates, the stronger the nucleophilicity and the more easily they can attack the carbon atom, which explains why the N_1 intermediates with a high degree of

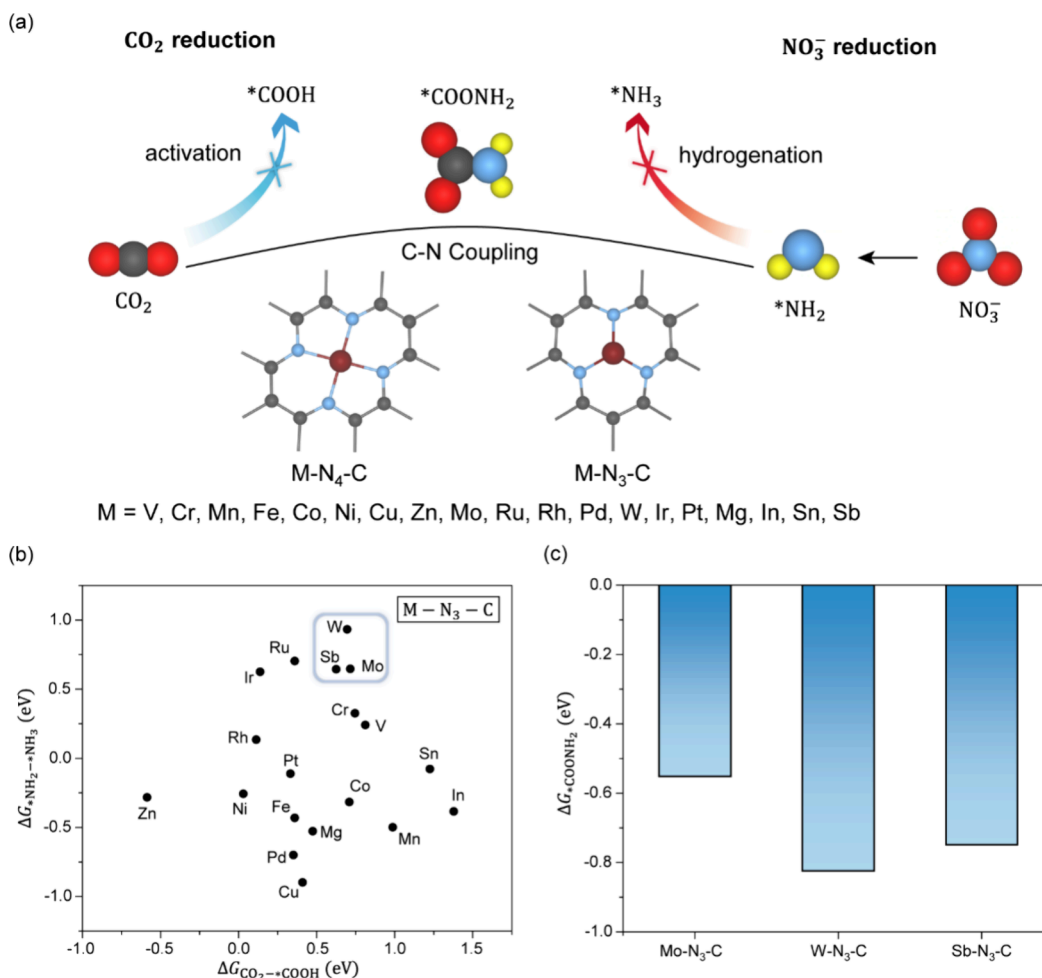


Figure 5. (a) Schematic diagram of CO₂ and *NH₂ coupling on M-N₄-C and M-N₃-C to generate *COONH₂. (b) Free energy of the CO₂ activation and *NH₂ hydrogenation steps on M-N₃-C. (c) Free energy of CO₂ and *NH₂ coupling on Mo-N₃-C, W-N₃-C, and Sb-N₃-C.

hydrogenation are more likely to participate in the C–N coupling reaction. It is worth noting that the trend in electrostatic potential change is independent of the catalytic surface. Hence, we speculate that this pattern may hold true for other catalysts as well, as supported by recent studies demonstrating that the coupling between carbon-containing species and *NH₂ is generally energetically exothermic.^{15,16,52–54}

We select 35 possible products from the coreduction of CO₂ and NO₃⁻ (Table S1) to analyze the C–N coupling mode when generating a particular product. The results show that the initial C–N coupling step for all products generally involves the combination of CO₂ and nitrogen-containing species, e.g., NOHOH and NHO (Figure 4 and Table S4). This is because the activation of CO₂ to form *COOH requires a relatively high energy input on Cu–N₄-C (1.60 eV, Figure S7). According to the Arrhenius equation and approximating this process as a first-order reaction, it can be inferred that CO₂ can exist at the interface for a long time, which also helps reduce the formation of byproduct CO. On the other hand, the energy needed for the coupling of CO₂ and nitrogen-containing species is comparatively low (Table S5). The formation of the second C–N bond in the C₁N₂ products also shows a preference toward nitrogen-containing species that have undergone a certain degree of hydrogenation (NOHOH/NHO) (Figure 4, details provided in Table S4), which further

supports the pattern observed in Figure 3c. Notably, we found that when participating in the C–N coupling process, CO₂ tends to remain in a physisorbed state near the active sites, while nitrogen-containing species approach and bond with Cu single atoms at the interface. Therefore, we did not consider the *CO₂⁻ chemisorbed state of CO₂.

Although various products can be generated, CO(NH₂)₂ is found to be the major C–N bond-containing product in the experiments.^{8,55} In general, intermediates with fewer oxygen atoms and more nitrogen atoms tend to have lower formation energies. CO(NH₂)₂, which contains only one oxygen atom and two deeply reduced *NH₂ groups, is thus thermodynamically favored (Figures S8 and S9). It is worth noting that the energy required for further hydrogenation of CON₂H₄ to COHN₂H₄ increases sharply (ΔG = 1.54 eV, Figure S10), which limits the possibility of its further reduction and makes it more likely to desorb as the final product (ΔG_{desorb} = 0.34 eV). However, on Cu–N₄-C, the pathway for the reduction of NO₃⁻ to NH₃ is also energetically favorable (Figure S11). The free energy of the rate-determining step is only 0.42 eV, which results in the formation of a significant amount of byproduct NH₃.¹⁵

From the above analysis, it can be concluded that an effective electrocatalyst for CO₂ and NO₃⁻ coreduction could have appropriate resistance for CO₂ hydrogenation, which can facilitate the direct coupling of CO₂ and nitrogen-containing

species while reducing the generation of carbon-containing byproducts such as CO (Figure 5a). Concurrently, for the reduction of NO_3^- , it is ideal to have an intermediate species with a highly hydrogenated state that can remain stable at the interface for an extended period. This will enable the coupling of CO_2 and the intermediate species to form C–N bonds. $^*\text{NH}_2$ represents an optimal candidate for this role, as the reaction energy for the coupling between $^*\text{NH}_2$ and CO_2 is the lowest. From the perspective of the electronic structure, $^*\text{NH}_2$ is also likely to be stabilized on the active center. There still be an sp^3 hybrid orbital of the N atom in $^*\text{NH}_2$ half-filled. On the contrary, all four sp^3 hybrid orbitals are fully filled in NH_3 , resulting in a less stable adsorption of NH_3 on the metal center compared to $^*\text{NH}_2$. Consequently, the free energy change for $^*\text{NH}_2 + \text{H}^+ + \text{e}^- = ^*\text{NH}_3$ has a tendency to be uphill in essence.^{56,57}

Based on the above knowledge, we calculated the free energy changes of the CO_2 activation and $^*\text{NH}_2$ hydrogenation steps on 38 single-atom catalysts with M– N_4 –C and M– N_3 –C structures (M = V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Ru, Rh, Pd, W, Ir, Pt, Mg, In, Sn, and Sb, Figure 5a), all of which can be experimentally synthesized.^{58–61} The results show that for the M– N_4 –C structure, $\Delta G(\text{CO}_2 \rightarrow ^*\text{COOH})$ and $\Delta G(^*\text{NH}_2 \rightarrow ^*\text{NH}_3)$ are negatively correlated, indicating that the M– N_4 –C SAC may not be efficient for C–N bond formation with high selectivity (Figure S12). The Faradaic efficiency of the recently reported Cu– N_4 –C and Co– N_4 –C with the reactants of NO_3^- and CO_2 to generate products containing C–N bonds is indeed not higher than 30%.^{11,15} The Mo– N_3 –C, W– N_3 –C, and Sb– N_3 –C can satisfy both requirements with the corresponding free energy change exceeding 0.5 eV (Figure 5b). The reaction energies for the CO_2 and $^*\text{NH}_2$ coupling are also low on these catalysts (Figure 5c). Moreover, we calculated the complete pathway of NO_3^- reduction to $^*\text{NH}_2$ on these three catalysts, and the results show that the formation of $^*\text{NH}_2$ is favorable (Figures S13–S15). These suggest that the Mo– N_3 –C, W– N_3 –C, and Sb– N_3 –C are capable of efficient C–N coupling and thus are likely to be excellent CO_2 and NO_3^- coreduction catalysts.

As final remarks, we discuss the improvement directions in the future. The main goal of the proposed graph-based scheme is to enable pathway prediction, overpotential estimation, and the assessment of general trends across the reaction network, which can provide experimentally relevant insights into electrocatalysis. We acknowledge that this approach does not yet allow for selectivity predictions for specific products as this would require activation energy calculations and a microkinetic model. Performing kinetic calculations for systems with thousands of intermediates by DFT remains challenging. Machine learning potentials and pretrained models may offer a possible solution.^{62–64} The solvent effects may influence the optimal reaction pathways toward the targeted products by the stabilizing effect of hydrogen bonding and the electrostatic interactions from cations, which are still difficult to consider in a high-throughput framework due to their complexity and variability.^{26,65–67} A feasible solution is to perform empirical numerical corrections for intermediates with electron-withdrawing tendency.⁶⁸ Future models will also attempt to make performance predictions under constant potential conditions.⁶⁹

CONCLUSIONS

In summary, we have developed a graph-based high-throughput reaction network analysis algorithm, which can achieve automated enumeration of intermediates and corre-

sponding adsorption configurations. We have applied this framework to analyze the reaction mechanism of the coreduction of NO_3^- and CO_2 on the Cu– N_4 –C SAC. It is revealed that CO_2 can directly couple with N-containing species without the hydrogenation and that the higher the hydrogenation degree of N-containing species, the lower the reaction energy for C–N coupling. Based on the above knowledge, the Mo– N_3 –C, W– N_3 –C, and Sb– N_3 –C SACs are predicted to be efficient catalysts for C–N coupling. Our work provides a paradigm for the mechanism exploration of complex electrocatalytic reactions and the strategy to predict the related electrocatalysts.

METHODS

DFT calculations: The spin-polarized DFT calculations were performed using the Vienna ab initio simulation package (VASP),^{70–72} with the Perdew–Burke–Ernzerhof (PBE) exchange–correlation functional.⁷³ The projector augmented wave method (PAW)^{74,75} with a plane-wave kinetic energy cutoff of 400 eV was used, and a k-mesh of $2 \times 2 \times 1$ was adopted to sample the Brillouin zone. In structural relaxation, the total energy and the force on each relaxed atom were converged to 10^{-5} eV and $0.05 \text{ eV } \text{\AA}^{-1}$, respectively. We first performed a 90-step ionic relaxation for each configuration. If the configuration was neither decomposed nor reconstructed and was determined to be stable based on the graph connectivity algorithm, it was further optimized until force convergence. The structure of Cu– N_4 –C was based on a one-layer two-dimensional graphene structure with a 4×4 super cell lateral size. A vacuum layer of 20 Å in the z-direction was set to avoid unwanted interactions between periodic images. A VASPsol implicit solvation model was used for solvation corrections in our energy calculations.⁷⁶ A Debye screening length of 3 Å was chosen, as this corresponds to a bulk ion concentration of 1 M. The nonelectrostatic parameter TAU was set to zero to avoid numerical instabilities. For the C–N coupling steps involved in the 35 selected products, we performed barrier calculations using the CI-NEB method. Three images were inserted along the CI-NEB pathway, with a force tolerance set to $0.05 \text{ eV } \text{\AA}^{-1}$.

The calculated relative Gibbs free energy (ΔG) was evaluated as follows:

$$\Delta G = \Delta E + \Delta \text{ZPE} - T\Delta S + k_{\text{B}}T \ln(10) \times \text{pH} + eU \quad (1)$$

where ΔE is the DFT-calculated relative energy, ΔZPE is the change in zero-point energy (ZPE), and ΔS is the change in entropy. The ZPE and entropic contributions were calculated from the vibrational frequencies, which were obtained using the finite displacement method with only the degrees of freedom of adsorbates and the transition-metal single atom included. The last term corresponds to the free energy correction of pH. In this work, the free energy profiles were calculated at 0 V vs RHE and pH = 6.8.

The formation energies of each intermediate is calculated by

$$G_{\text{f}} = G_{\text{slab+ads}} - G_{\text{slab}} - \sum_{i \in \{\text{C,H,O,N}\}} n_i \mu_i \quad (2)$$

where $G_{\text{slab+ads}}$ is the Gibbs free energy of the surface and adsorbate, G_{slab} is the Gibbs free energy of the surface slab, n_i is the number of atoms of species i in the adsorbate, and μ_i are

the reference energies. In this case the reference energies are computed by³⁰

$$\begin{aligned}\mu_{\text{H}} &= G_{\text{H}_2}/2 \\ \mu_{\text{O}} &= G_{\text{H}_2\text{O}} - G_{\text{H}_2} \\ \mu_{\text{C}} &= G_{\text{CO}_2} - 2\mu_{\text{O}} \\ \mu_{\text{N}} &= G_{\text{NO}_2} - 2\mu_{\text{O}}\end{aligned}\quad (3)$$

where G_j is the Gibbs free energy of species j .

$\Delta G_{\text{C-N}}$ represented in Figure 3c is calculated by

$$\Delta G_{\text{C-N}} = G_{\text{product}} - G_{\text{reactant}} - G_{\text{N}} \quad (4)$$

where G_{product} is the Gibbs free energy of products of the C–N coupling reaction, G_{reactant} is the Gibbs free energy of reactants of the C–N coupling reaction, including C_1 , C_1N_1 species, and G_{N} is the formation energy of N_1 species. For example, $\Delta G_{\text{C-N}}(*\text{COONH}_2) = G_{*\text{COONH}_2} - G_{*\text{CO}_2} - G_{\text{NHO}}$, and $G_{\text{NHO}} = \mu_{\text{N}} + \mu_{\text{H}} + \mu_{\text{O}}$.

The generation of species and adsorption configurations by graph theory: Because of the saturated electron configuration and steric hindrance of NO_3^- , it can hardly be an intermediate for C–N coupling. Thus, we used $*\text{NO}_2$, which is the direct reduction intermediate of NO_3^- , and CO_2 as the reactants to generate the possible intermediates.

The RDKit,⁷⁷ which is an open-source tool for cheminformatics, is used to generate the possible species. The overall scheme is presented in Figure S1. To enumerate all species, we defined three types of elementary steps as follows:

1. Hydrogenation reaction, denoted as $\text{A}^* + \text{H}^+ \leftrightarrow \text{AH}^*$.
2. Dehydroxylation reaction, denoted as $\text{AOH}^* + \text{H}^+ \leftrightarrow \text{A}^* + \text{H}_2\text{O}$.
3. C–N coupling reaction, denoted as $\text{A}^* + \text{B}^* \leftrightarrow \text{AB}^* + *$.

The elementary step is realized by editing the molecular graphs with RDKit. Take the hydrogenation reaction as an example, the molecular graph of A will add a H node and an A–H edge and then become a new molecular graph of AH.

Meanwhile, the new species will be verified under several boundary conditions:

1. No more than four, four, and two bonds can be found on carbon, nitrogen, and oxygen atoms, respectively.
2. No more than two nitrogen atoms in each species.
3. No N–N bonds, N–O–N bonds, and N–O–C bonds. Notably, we also did not consider C–C coupling products as they were not experimentally observed on Cu–N–C.¹⁵

Subsequently, we considered the bond principles to ensure a bond reasonable of adatoms: the C atom and N atom can connect with up to three atoms, and the O atom can connect with up to one atom.

The geometric rules and the connectivity of the molecular graph are then applied to generate different adsorption configurations for DFT calculation. We defined five possible adsorption modes, namely, the Cu top site, N top site, Cu–N bridge site, Cu–N double, and Cu–N Arc site. The geometric rules are listed as follows:

1. For the Cu/N top site, the adatom was placed on the top site of one Cu/N active site, and the distance is set to the sum of the radii of the adatoms and Cu/N atoms.

2. For the Cu–N bridge site, the adatom was placed on the plane that passes through the bridge site of Cu and N active sites. The distances between the adatom and the two atoms are equivalent to corresponding radii summation d .
3. For the Cu–N double site, two adatoms were initially placed vertically above on the Cu and N active sites. Then, they move on the plane that passes through these four atoms until the distance between them is equal to the sum of their radii. Note that the order of the two adatoms can be reversed.
4. For the Cu–N Arc site, two adatoms were initially placed vertically above on the Cu and N active sites according to their sum of atomic radii. Then, they moved away each other to ensure that the angle between the two adatoms and the interval atom would not be too small. The interval atom was placed via the same approach for the bridge site adsorption.

■ ASSOCIATED CONTENT

Data Availability Statement

All data are available in the main manuscript or the Supporting Information. The related codes are positioned in <https://github.com/Jackistudy/graph-theory-code>.

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acscatal.4c05751>.

Schematic diagram of possible products; reaction pathways of possible products; energy statistics for C–N coupling steps; atomic structure of intermediates; free energy diagram of reaction pathways (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

Shunning Li – School of Advanced Materials, Peking University, Shenzhen Graduate School, Shenzhen 518000, China; orcid.org/0000-0002-5381-6025; Email: lisin@pku.edu.cn

Shisheng Zheng – College of Energy, Xiamen University, Xiamen 361000, China; orcid.org/0009-0000-4529-7440; Email: zhengss@xmu.edu.cn

Feng Pan – School of Advanced Materials, Peking University, Shenzhen Graduate School, Shenzhen 518000, China; orcid.org/0000-0002-8216-1339; Email: panfeng@pkusz.edu.cn

Authors

Junjie Pan – School of Advanced Materials, Peking University, Shenzhen Graduate School, Shenzhen 518000, China

Haowen Ding – School of Advanced Materials, Peking University, Shenzhen Graduate School, Shenzhen 518000, China

Xinzhe Yang – School of Advanced Materials, Peking University, Shenzhen Graduate School, Shenzhen 518000, China; orcid.org/0009-0008-1921-0629

Xianhui Liang – College of Energy, Xiamen University, Xiamen 361000, China

Shanglin Wu – School of Advanced Materials, Peking University, Shenzhen Graduate School, Shenzhen 518000, China

Mingzheng Zhang — School of Advanced Materials, Peking University, Shenzhen Graduate School, Shenzhen 518000, China

Complete contact information is available at:
<https://pubs.acs.org/10.1021/acscatal.4c05751>

Author Contributions

[#]J.P., H.D., and X.Y. contributed equally.

Notes

The authors declare no competing financial interest.

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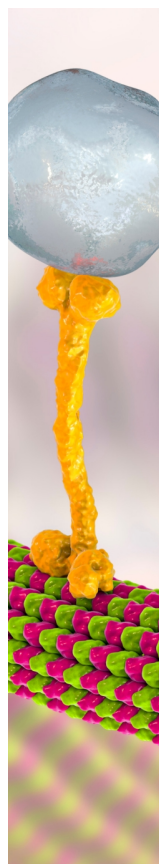
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