

Cite this: *J. Mater. Chem. A*, 2023, 11, 6814Received 2nd February 2023  
Accepted 3rd March 2023

DOI: 10.1039/d3ta00606a

rsc.li/materials-a

## Main-group indium single-atom catalysts for electrocatalytic NO reduction to NH<sub>3</sub>†

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Main-group metal elements show great potential for exploring high-performance catalysts for electrochemical reduction of NO to NH<sub>3</sub> (NORR) but remain largely unexplored. Herein, as a proof-of-concept, main-group In single atoms confined in an amorphous MoO<sub>3</sub> substrate (In<sub>1</sub>/a-MoO<sub>3</sub>) are explored as an efficient NORR catalyst, showing a maximum NH<sub>3</sub> yield of 242.6 μmol h<sup>-1</sup> cm<sup>-2</sup> and NH<sub>3</sub>-faradaic efficiency of 92.8%. Further experiments and theoretical results identify single-site In atoms as the dominating active centers to simultaneously inhibit the hydrogen evolution and optimize the hydrogenation energetics of the NO-to-NH<sub>3</sub> pathway.

Ammonia is a critical industrial chemical which is widely used in modern economic development.<sup>1–3</sup> Electrochemical N<sub>2</sub> fixation through N<sub>2</sub> electroreduction (NRR) enables sustainable NH<sub>3</sub> synthesis under ambient conditions with near-zero CO<sub>2</sub> emissions.<sup>4–8</sup> Unfortunately, the NRR is still far from being practicable on account of the competitive hydrogen evolution reaction (HER) and ultrastrong N≡N bond.<sup>9–15</sup>

Compared with the NRR, electrochemical NO-to-NH<sub>3</sub> conversion (NORR) is a more energy-efficient and practically feasible approach for sustainable NH<sub>3</sub> synthesis.<sup>16–21</sup> Meanwhile, NO is one of the common atmospheric pollutants, arising from vehicle exhaust emissions and insufficient combustion of fossil fuels.<sup>18</sup> Therefore, the NORR represents a fascinating method for realizing both detrimental NO treatment and effective NH<sub>3</sub> electrosynthesis.<sup>18</sup> Nevertheless, the NORR is a multi-step process involving a complex five-electron process and hindered by the competing HER.<sup>22–25</sup> Therefore, exploring high-performance catalysts to achieve both NORR promotion and HER inhibition is urgently demanded.

Diverse transition metal-based materials have been reported as active NORR catalysts,<sup>26–29</sup> by virtue of their partially occupied

d-orbitals to enhance NO adsorption and dissociation. Nonetheless, d-orbitals also contribute to \*H binding on the catalyst surface, which is beneficial for the competitive HER and unfavorable for FE<sub>NH<sub>3</sub></sub>.<sup>30</sup> Alternatively, main-group metals, such as In, Sn, Sb and Bi, with partially occupied p-orbitals but an intrinsic characteristic of poor \*H binding, have attracted growing attention for selective NH<sub>3</sub> electrosynthesis.<sup>31–36</sup> On the other hand, single atom catalysts (SACs) with isolated metal sites have been extensively demonstrated to exhibit superior properties for various electrocatalytic reactions owing to their maximized atomic utilization and unique coordination configuration.<sup>37–42</sup> Inspired by the above, main-group SACs may hold great promise toward the active and selective NORR.

In this study, as a proof-of-concept, we first explore main-group In single atoms confined in amorphous MoO<sub>3</sub> (In<sub>1</sub>/a-MoO<sub>3</sub>) as an effective NORR catalyst, which exhibits a maximum FE<sub>NH<sub>3</sub></sub> of 92.8% and NH<sub>3</sub> yield rate of 242.6 μmol h<sup>-1</sup> cm<sup>-2</sup>. Detailed experiments and computational studies are performed to elucidate the origin for the exceptional NORR properties of In<sub>1</sub>/a-MoO<sub>3</sub>.

In<sub>1</sub>/a-MoO<sub>3</sub> was prepared by a facile supercritical CO<sub>2</sub> approach.<sup>43–45</sup> The characteristic transmission electron microscopy (TEM, Fig. 1a) image of In<sub>1</sub>/a-MoO<sub>3</sub> presents a nanosheet morphology, while the high-resolution TEM (HRTEM, Fig. 1b) image shows no obvious lattice fringes, similar to bare a-MoO<sub>3</sub> (Fig. S1†). The corresponding fast Fourier transform (FFT, Fig. 1c) pattern unravels a sun-like feature, consistent with the lunar halo displayed in the selected area electron diffraction (SAED, Fig. S2†) pattern. Additionally, no noticeable diffraction peaks can be seen in the X-ray diffraction (XRD, Fig. 1d) pattern. All these HRTEM/FFT/SAED/XRD results confirm the amorphous structure of In<sub>1</sub>/a-MoO<sub>3</sub>. In the aberration-corrected high angle annular dark-field scanning transmission electron microscopy (AC-HAADF-STEM) image (Fig. 1e), there are numerous bright points (marked by red circles) that are highly dispersed on the amorphous substrate, and this can be further unveiled by the 3D intensity profile (Fig. 1f), proving that In species are atomically dispersed on a-MoO<sub>3</sub>. Elemental

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† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d3ta00606a>

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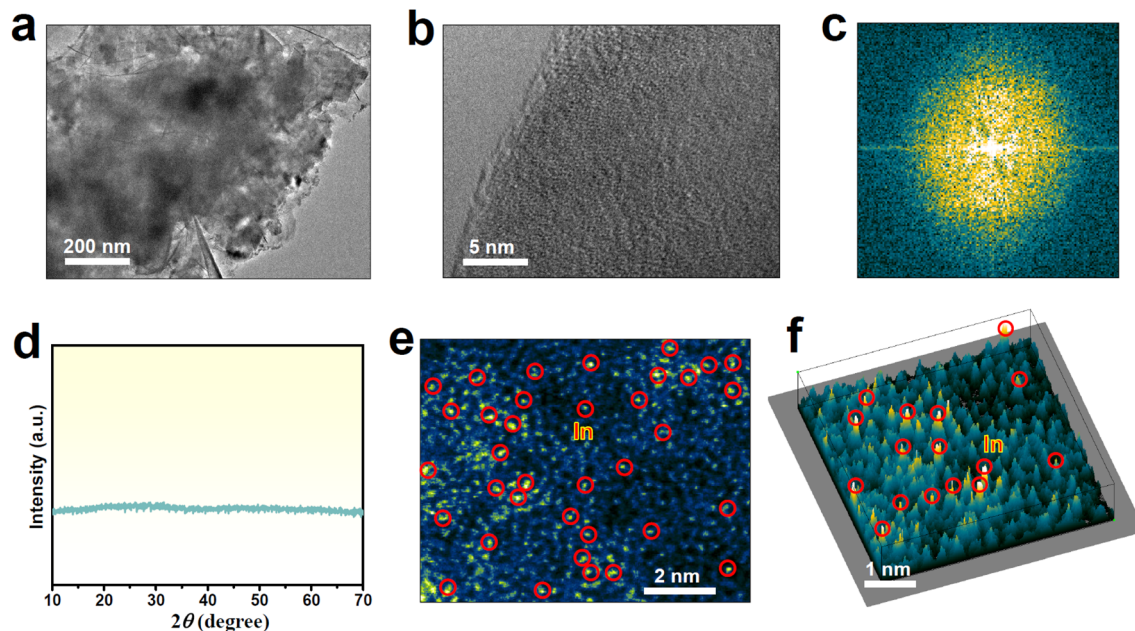


Fig. 1 Characterization of  $\text{In}_1/\text{a-MoO}_3$ : (a) TEM image, (b) HRTEM image and corresponding FFT pattern (c), (d) XRD pattern, (e) AC-HAADF-STEM image and corresponding (f) 3D intensity profile.

mapping images (Fig. S3†) display an even distribution of In single atoms over the a-MoO<sub>3</sub> support. The In content in  $\text{In}_1/\text{a-MoO}_3$  is measured to be as high as 8.2 wt%, much higher than that of reported In single atoms on carbon substrates.<sup>40,46,47</sup>

The valence states and local atomic coordination structure of  $\text{In}_1/\text{a-MoO}_3$  are studied by X-ray absorption fine structure (XAFS) analyses. The In K-edge X-ray absorption near-edge structure (XANES) spectra show that the absorption edge of  $\text{In}_1/\text{a-MoO}_3$  (Fig. 2a) lies between In foil and  $\text{In}_2\text{O}_3$  references, indicating

that In single atoms are in a positive valence state.<sup>48</sup> In the In K-edge extended X-ray adsorption fine structure (EXAFS) spectra (Fig. 2b),  $\text{In}_1/\text{a-MoO}_3$  shows a distinct peak located at 1.61 Å, which is ascribed to the In–O coordination bond. The absence of the In–In coordination bond (2.97 Å) indicates that In presents as an isolated atomic state,<sup>49–52</sup> consistent with the AC-HAADF-STEM observation (Fig. 1e). Meanwhile, unlike the  $\text{In}_2\text{O}_3$  reference, no second-shell In–O–In bond (3.09 Å) shows up in  $\text{In}_1/\text{a-MoO}_3$ , excluding the existence of  $\text{In}_2\text{O}_3$  species on

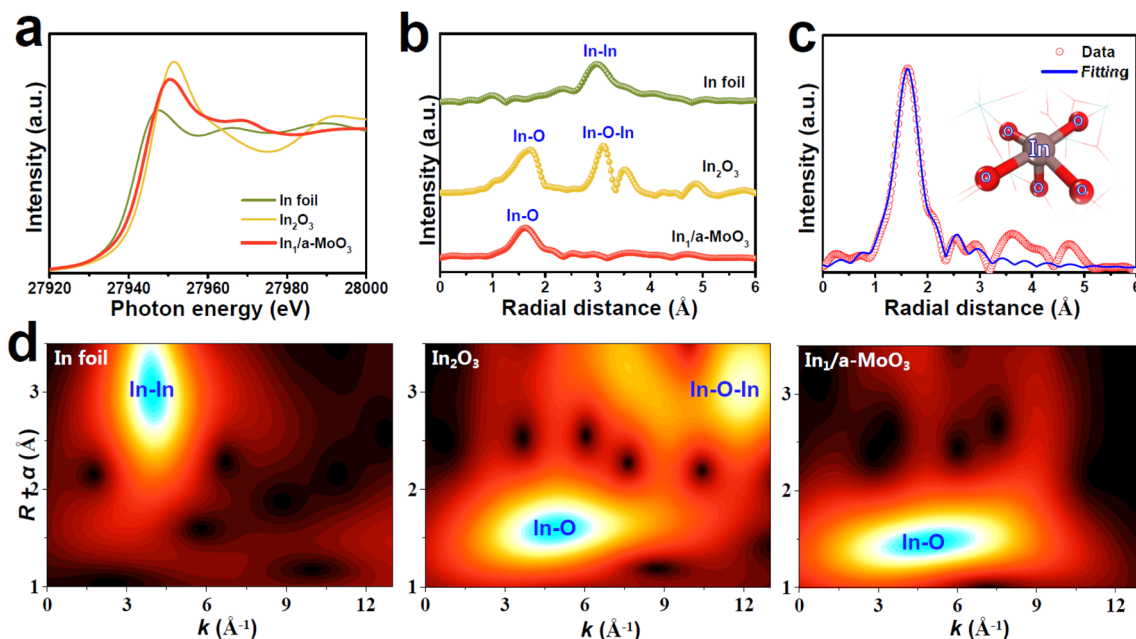


Fig. 2 (a) In K-edge XANES, (b) EXAFS spectra and (d) WT pattern of  $\text{In}_1/\text{a-MoO}_3$  and reference samples. (c) EXAFS fitting curve of  $\text{In}_1/\text{a-MoO}_3$  (inset: fitting model).

In<sub>1</sub>/a-MoO<sub>3</sub>. These EXAFS findings can be further corroborated by wavelet transform (WT) analysis (Fig. 2d), revealing that In<sub>1</sub>/a-MoO<sub>3</sub> exhibits the solo In–O maximum intensity with no presence of In–In/In–O–In WT signals. Quantitative EXAFS fitting of In<sub>1</sub>/a-MoO<sub>3</sub> (Fig. 2c and S4†) uncovers that single-site In is coordinated with five O atoms to form an In<sub>1</sub>–O<sub>5</sub> motif. Moreover, *ab initio* molecular dynamic (AIMD, Fig. S5†) simulations reveal that the In<sub>1</sub>–O<sub>5</sub> motif can well maintain the equilibrium temperature/energy states at temperature as high as 500 K, confirming the high thermodynamic stability of the In<sub>1</sub>–O<sub>5</sub> motif, which is attributed to the strong In<sub>1</sub>–O<sub>5</sub> electronic coupling to well stabilize In single atoms on the a-MoO<sub>3</sub> substrate (Fig. S6†).

The electrocatalytic NORR properties of In<sub>1</sub>/a-MoO<sub>3</sub> are assessed in a gas-tight H-type cell with 0.5 M Na<sub>2</sub>SO<sub>4</sub>.<sup>29</sup> Colorimetric methods are used to detect the liquid reduction products (Fig. S7 and S8†), while gas products are detected by gas chromatography. To initially assess the NORR activity of In<sub>1</sub>/a-MoO<sub>3</sub>, we perform linear sweep voltammetry (LSV) measurements (Fig. 3a). A remarkable current density (*j*) enhancement can be observed in NO-solution relative to Ar-solution, verifying a good electrocatalytic NORR ability of In<sub>1</sub>/a-MoO<sub>3</sub>. We then quantify the NORR performance of In<sub>1</sub>/a-MoO<sub>3</sub> at various potentials through combined chronoamperometry (Fig. 3b) and colorimetric methods. As shown in Fig. 3c, with increasing the potentials, In<sub>1</sub>/a-MoO<sub>3</sub> shows a volcano-type variation in both the NH<sub>3</sub> yield rate and FE<sub>NH<sub>3</sub></sub>, attaining their highest values of 242.6 μmol h<sup>-1</sup> cm<sup>-2</sup> and 92.8% at -0.6 V, respectively, which are higher than those of nearly all previously reported catalysts (Fig. 3d, Table S2†). Strikingly, In<sub>1</sub>/a-MoO<sub>3</sub> drastically outperforms bare a-MoO<sub>3</sub> in both the NH<sub>3</sub> yield rate and FE<sub>NH<sub>3</sub></sub> (Fig. S9 and S10†), suggesting that single-atomic In introduction plays a pivotal role in greatly boosting the NORR performance. The significant reduction of the NH<sub>3</sub> yield rate and FE<sub>NH<sub>3</sub></sub> at -0.7 V is

due to the enhancement in the competing HER process (Fig. 3e). Meanwhile, Fig. 3e shows that the FE<sub>NH<sub>3</sub></sub> of In<sub>1</sub>/a-MoO<sub>3</sub> is much higher than the FEs of other nitrogen-containing N<sub>2</sub> and N<sub>2</sub>H<sub>4</sub> by-products, in accordance with the partial current density data (Fig. S11†), indicating that In<sub>1</sub>/a-MoO<sub>3</sub> has an exceptional NORR selectivity for NO-to-NH<sub>3</sub> conversion. The NORR stability of In<sub>1</sub>/a-MoO<sub>3</sub> is assessed by 15 h of continuous electrolysis (Fig. S12†), which shows that the current density is rather steady and the corresponding FE<sub>NH<sub>3</sub></sub> does not show remarkable changes, suggesting that In<sub>1</sub>/a-MoO<sub>3</sub> has good long-term stability. Besides, during seven electrolysis cycles (Fig. 3f), the resulting NH<sub>3</sub> yield rates and FE<sub>NH<sub>3</sub></sub> only slightly fluctuate, proving the excellent cycling stability of In<sub>1</sub>/a-MoO<sub>3</sub>.<sup>53</sup> After the stability test, In<sub>1</sub>/a-MoO<sub>3</sub> well retains its nanosheet morphology, amorphous structure and atomic Ir dispersion state (Fig. S13†), demonstrating that the surface reconstruction of In<sub>1</sub>/a-MoO<sub>3</sub> barely occurs and thus In<sub>1</sub>/a-MoO<sub>3</sub> possesses high structural stability. Furthermore, the control colorimetric test (Fig. S14†), Ar–NO alternating cycle test (Fig. S15†), and <sup>1</sup>H nuclear magnetic resonance test (NMR, Fig. S16†) prove that the generated NH<sub>3</sub> comes from the NORR process.

Theoretical computations are carried out to shed light on the NORR mechanism of In<sub>1</sub>/a-MoO<sub>3</sub>. Based on the EXAFS fitting result (Fig. 2c), an isolated In<sub>1</sub>–O<sub>5</sub> motif constructed on a-MoO<sub>3</sub> is employed to simulate In<sub>1</sub>/a-MoO<sub>3</sub>. Upon the adsorption of NO on the In site, the charge density difference map (Fig. 4a) depicts a considerable \*NO/In electronic interaction. Notably, \*NO shows pronounced positive charge accumulation, implying that the In site can effectively activate the NO molecule through a “σ-donation” mechanism. Prior to assessing the hydrogenation energetics of the NORR pathway, we conduct online differential electrochemical mass spectrometry (DEMS) to monitor the key intermediates and determine the optimal reaction path on In<sub>1</sub>/a-MoO<sub>3</sub>. Fig. 4b displays the absence of the

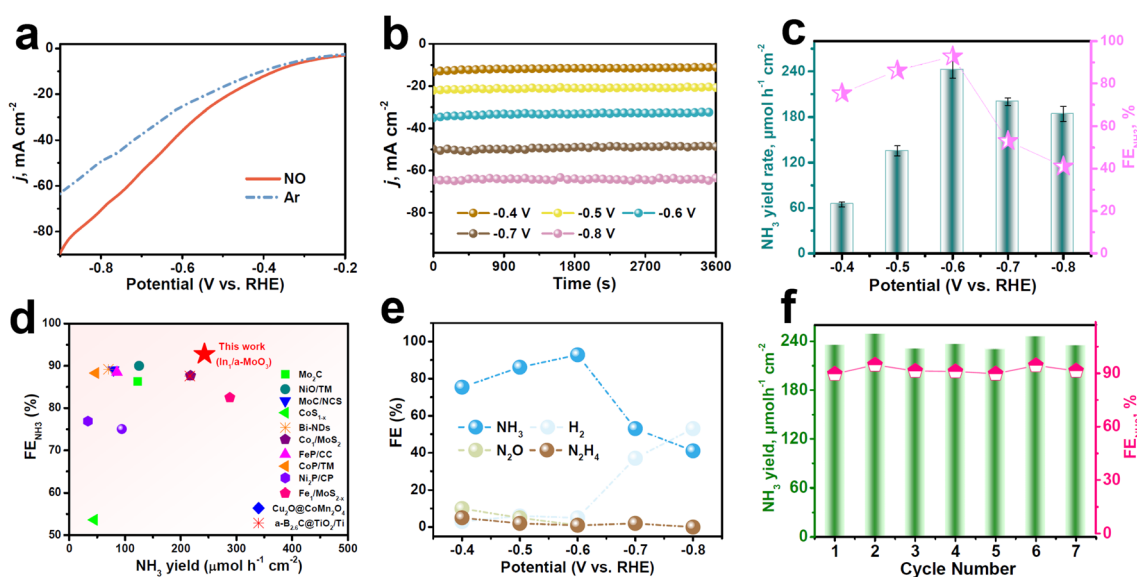


Fig. 3 (a) LSV curves of In<sub>1</sub>/a-MoO<sub>3</sub> in Ar/NO-saturated 0.5 M Na<sub>2</sub>SO<sub>4</sub> at a rate of 10 mV s<sup>-1</sup>. (b) Chronoamperometry test of In<sub>1</sub>/a-MoO<sub>3</sub> at various potentials, and resulting (c) NH<sub>3</sub> yield rates and FE<sub>NH<sub>3</sub></sub>. (d) Comparison of NH<sub>3</sub> yields and FE<sub>NH<sub>3</sub></sub> between In<sub>1</sub>/a-MoO<sub>3</sub> and reported NORR catalysts. (e) FEs of different products on In<sub>1</sub>/a-MoO<sub>3</sub> after NORR electrolysis at various potentials. (f) Cycling test of In<sub>1</sub>/a-MoO<sub>3</sub> at -0.6 V.

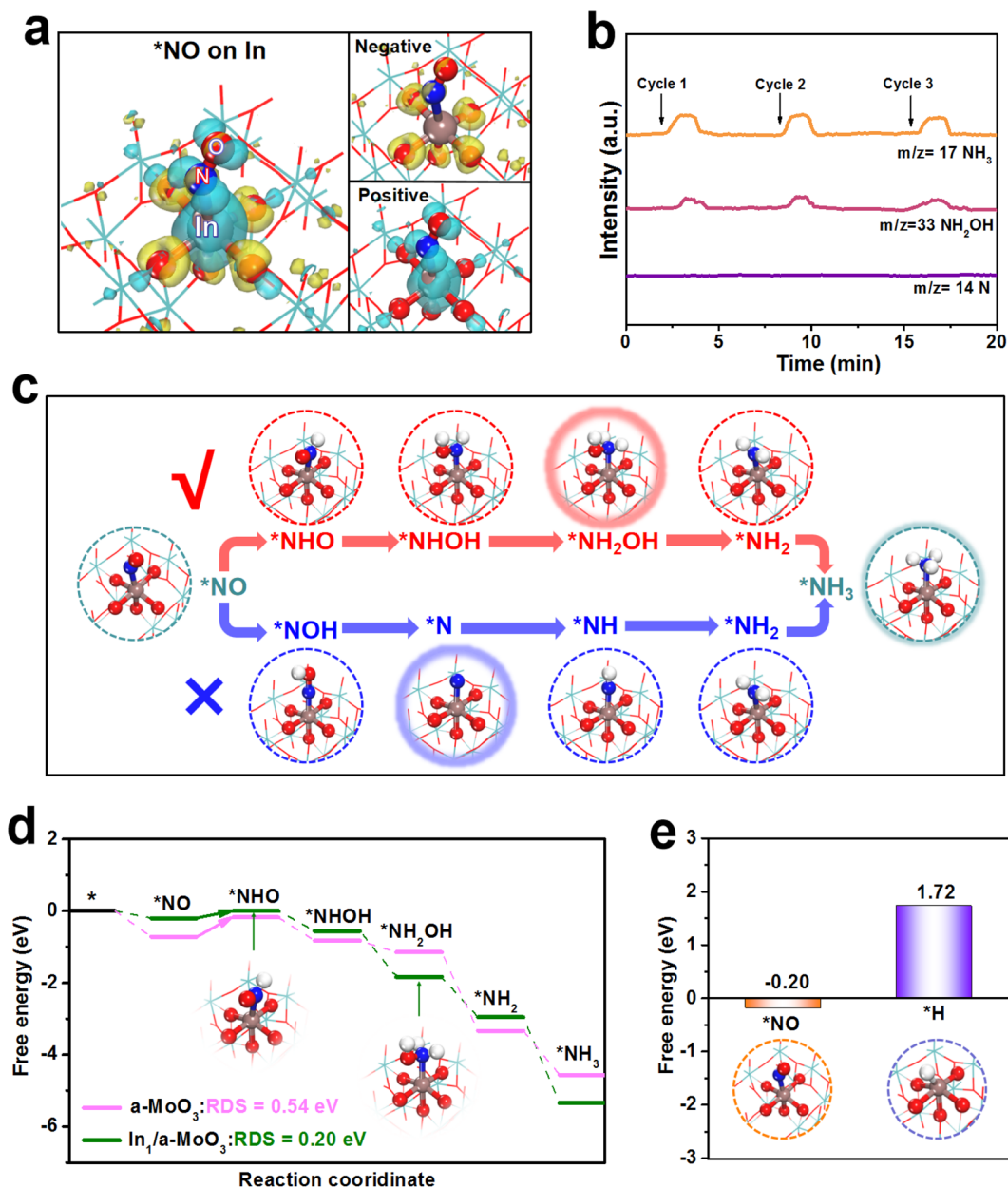


Fig. 4 (a) Charge density difference of adsorbed NO ( $^*\text{NO}$ ) on  $\text{In}_1/\text{a-MoO}_3$ . Yellow and cyan regions represent electron depletion and accumulation, respectively. (b) Online DEMS spectra of  $\text{In}_1/\text{a-MoO}_3$  during the electrolysis at  $-0.6 \text{ V}$ . (c) Schematic of typical NOH and NHO pathways on  $\text{In}_1/\text{a-MoO}_3$ . (d) Free energy profiles of the NORR process (NHO pathway) on the Mo site ( $\text{a-MoO}_3$ ) and In site ( $\text{In}_1/\text{a-MoO}_3$ ). (e) Binding free energies of  $^*\text{NO}$  and  $^*\text{H}$  on the In site of  $\text{In}_1/\text{a-MoO}_3$ .

N intermediate but the presence of the  $\text{NH}_2\text{OH}$  intermediate, implying that  $\text{In}_1/\text{a-MoO}_3$  prefers to adopt a NHO pathway ( $^*\text{NO} \rightarrow ^*\text{NHO} \rightarrow ^*\text{NHOH} \rightarrow ^*\text{NH}_2\text{OH} \rightarrow ^*\text{NH}_2 \rightarrow ^*\text{NH}_3$ ) rather than a NOH pathway ( $^*\text{NO} \rightarrow ^*\text{NOH} \rightarrow ^*\text{N} \rightarrow ^*\text{NH} \rightarrow ^*\text{NH}_2 \rightarrow ^*\text{NH}_3$ ) to drive the NORR process (Fig. S17<sup>†</sup>),<sup>54,55</sup> as illustrated in Fig. 4c. As shown in the free energy diagrams along the NHO pathway (Fig. 4d), the In site presents the initial  $^*\text{NO}$  protonation ( $^*\text{NO} \rightarrow ^*\text{NHO}$ ) as the rate-determining step (RDS) with a low energy barrier of 0.20 eV. As a sharp comparison, the Mo site of bare  $\text{a-MoO}_3$  shows the same  $^*\text{NO} \rightarrow ^*\text{NHO}$  as the RDS, but exhibits a largely increased RDS barrier of 0.54 eV due to too strong  $^*\text{NO}$  binding on the Mo site. Thus, single-site In can

effectively optimize the binding energy of  $^*\text{NO}$  to reduce the RDS barrier, thereby significantly promoting the hydrogenation energetics of the NO-to- $\text{NH}_3$  pathway.

As the HER is regarded as the major competitive reaction against the NORR,<sup>56–62</sup> we further evaluate the HER activity of  $\text{In}_1/\text{a-MoO}_3$ . Fig. 4e shows that the binding free energy of  $^*\text{H}$  (1.72 eV) on the In site is much more positive than that of  $^*\text{NO}$  ( $-0.20 \text{ eV}$ ), proving that the In site can favorably absorb NO while restricting H binding. In the molecular dynamics (MD) simulations (Fig. S18<sup>†</sup>),  $^*\text{NO}/\text{In}$  interaction is found to be much stronger than  $^*\text{NO}/\text{In}$  interaction after simulations, as evidenced by the radial distribution function (RDF, Fig. S19<sup>†</sup>)

curves and integrated RDF curves (Fig. S20†), verifying the priority of In<sub>1</sub>/a-MoO<sub>3</sub> for the absorption and coverage of NO over H.<sup>63–66</sup> Therefore, in addition to promoting the NO hydrogenation energetics, single-site In can facilitate HER suppression to enable the achievement of a high NORR selectivity.

In summary, In<sub>1</sub>/a-MoO<sub>3</sub> is validated as an effective NORR catalyst. As unraveled by the experimental measurements and theoretical calculations, the prominent NORR properties of In<sub>1</sub>/a-MoO<sub>3</sub> are attributed to the ability of single-site In to inhibit the HER and boost the hydrogenation energetics of the NO-to-NH<sub>3</sub> pathway. This work would open a new avenue for the development of efficient main-group SACs for high-performance NORR electrocatalysis.

## Conflicts of interest

There are no conflicts of interest to declare.

## Acknowledgements

This work is supported by the Central Government Guides Local Science and Technology Development Project (206Z1003G) and Fundamental Researches Top Talent Program of Lanzhou Jiaotong University (2022JC03).

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