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Unveiling capacity limitations of MnO₂ in rechargeable Zn chemistry

Cheng Liu,^a Vlad Martin-Diaconescu,^b Ashley Phillip Black,^a
Siavash Khabazian,^a Bernat Mundet,^c Krzysztof Matlak,^d Lorenzo Stievano,^{e,f}
Andrea Sorrentino,^b Laura Simonelli^{b,*} and Dino Tonti^{b,*a}

Aqueous Zn–MnO₂ batteries with mildly acidic electrolytes deliver attractive experimental capacities, however the underlying mechanisms remain elusive, particularly regarding the interactions of Zn²⁺ and H⁺ with MnO₂, as well as the formation of Mn²⁺ and Zn₄SO₄(OH)₆·xH₂O (ZSH). Although these products are compatible with a two-electron dissolution mechanism, the observed first-discharge capacity is limited to approximately 300 mA h g^{−1} MnO₂, close to that of a one-electron reaction. To address this contradiction, commonly used α-MnO₂ nanowires were chosen as cathode material and investigated by a systematic multimodal and multiscale approach under *operando* or *ex situ* conditions to analyze the processes that occur during the first discharge. MnO₂ dissolution into Mn²⁺ and ZSH precipitation were confirmed, and the formation of a disordered phase at the nanowire surface with the accumulation of Mn(III) was detected. An in-depth analysis indicates that such Mn(III) species correspond to protonated corner-sharing MnO₂ octahedra, which, unlike the edge-sharing ones, are hindered from undergoing disproportionation, limiting the MnO₂ dissolution and explaining the reduced capacity. This comprehensive mechanistic understanding opens new pathways for the selection of the most appropriate MnO₂ phases and the optimization of electrodes to improve the performance of aqueous Zn–MnO₂ battery systems.

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Broader context

A safe and sustainable energy storage system is essential for achieving Net Zero Emissions by 2050. Thanks to the inherent safety, energy density comparable to lithium-ion chemistry, and low cost, rechargeable mildly acidic aqueous zinc–manganese dioxide (Zn–MnO₂) chemistry is drawing increasing interest. However, while encouraging performance has been repeatedly reported, several contradictory mechanisms have been proposed. Notably, a contradiction persists between the specific capacity and the most accepted mechanism. In fact, while a 2-electron MnO₂ dissolution into soluble Mn²⁺ has been shown by several authors, the experimental 1st discharge capacities are usually close to the equivalent 1 electron. Using multiple spectroscopy and microscopy techniques, we verify that while the 2-electron mechanism is correct, a peculiar passivation effect builds up during discharge, involving the accumulation of Mn–Mn configurations that hinder the second step, the disproportionation of Mn(III) requiring a fast charge transfer between Mn centers. Understanding this essential problem unlocks the perspectives for a more comprehensive control of the electrode chemistry and the design of more efficient Zn–MnO₂ batteries.

^a Institut de Ciència de Materials de Barcelona, Consejo Superior de Investigaciones Científicas (ICMAB-CSIC), Carrer dels Til·lers sn, 08193 Bellaterra, Spain.
E-mail: chengliu@icmab.es, ablack@icmab.es, skhabazian@icmab.es, dino.t@csic.es

^b ALBA Synchrotron Light Source, 08290 Cerdanyola del Vallès, Barcelona, Spain.
E-mail: vmartind@cells.es, asorrentino@cells.es, lsimonelli@cells.es

^c Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus de la Universitat Autònoma de Barcelona (UAB), Barcelona, Bellaterra, 08193, Spain. E-mail: bernat.mundet@icn2.cat

^d SOLARIS National Synchrotron Radiation Centre, Czerwone Maki 98, 30-392 Kraków, Poland. E-mail: krzysztof.matlak@uj.edu.pl

^e Institut Charles Gerhardt Montpellier (ICGM), Univ. Montpellier, CNRS, ENSCM, 34293 Montpellier, France

^f Réseau sur le Stockage Electrochimique de l'Energie (RS2E), CNRS, 80039 Amiens, France. E-mail: lorenzo.stievano@umontpellier.fr

Introduction

A carbon-neutral society requires safe and sustainable energy storage technologies that overcome the limitations of current Li-ion batteries.^{1,2} One of the most promising options is rechargeable aqueous zinc manganese dioxide (Zn–MnO₂) chemistry. Indeed, the Zn abundance, quick response, non-flammable nature of the electrolyte, and high theoretical specific capacity provided by both electrodes (respectively 616 mA h g^{−1} MnO₂, based on a 2e[−] reaction, and 820 mA h g^{−1} Zn)^{3–6} make them attractive for energy storage purposes. Although research on neutral Zn–MnO₂ batteries began over 30 years ago,⁷ stable performance at large areal capacities and wide



current ranges has not been demonstrated consistently, and significant aspects of the mechanism remain unclear.^{8,9} Understanding the evolution and degradation of MnO₂ cathodes in a typical mildly acidic aqueous electrolyte still remains challenging,^{8,10} because of the intrinsic system complexity, arising from multiple equilibria and the formation of poorly crystalline phases with several coexisting Mn redox states.^{11,12}

Assuming a straightforward transition from Mn^{IV}O₂ to Mn(III)-based species in the cathode, a Zn intercalation/deintercalation mechanism has been initially proposed.^{13–16} This process in aqueous Zn and Mn electrolytes would produce Zn–Mn compounds during cycling, which have been occasionally observed *ex situ* by weak X-ray diffraction (XRD) signals.^{13–18} Instead, the more frequent observations of zinc hydroxysulfates, (Zn₄SO₄(OH)₆·xH₂O, ZSH) formation, suggested conversion or insertion reactions involving protons (H⁺), along with the formation of MnOOH, “HMnO₂” or dissolved Mn species.^{19–22} Within this pathway, the formation of ZSH acts as a buffer to hinder pH increase and stabilize local pH fluctuations.^{23–25} Consistently with this picture, Mn²⁺ dissolution in aqueous Zn²⁺ electrolytes has been frequently reported.^{13,24,26,27} The most common explanation is that high-spin Mn(III)-based species are inherently unstable and affected by Jahn–Teller distortions, inducing disproportionation into Mn^{IV}O₂ and aqueous Mn²⁺.¹³ However, Mn(III), expected as intercalation product or as intermediate for a two-step reduction has proven quite elusive. Although previous studies have reported various Mn(III) species using *ex situ* characterization under ambient conditions,^{15,26,28,29} bulk-sensitive *operando* data cannot detect them.

Several *operando* techniques, such as X-ray absorption spectroscopy (XAS),^{30,31} electron spin resonance (ESR),³² X-ray fluorescence spectroscopy (XRF),³³ and Raman,³⁴ indicate a dissolution/redeposition of MnO₂ involving a two-electron reaction, with Mn^{IV}O₂ conversion to Mn²⁺, which then diffuses into the electrolyte. Despite this evidence, the vast majority of studies on chemically prepared MnO₂ report scattered values of experimentally delivered capacities despite the limited number of reaction paths, with a maximum delivered capacity typically confined below 350 mA h g^{−1}_{MnO₂}^{29,35–43} (closer to 1e[−] reaction) during the first discharge. Instead, the usual addition of Mn²⁺ to the initial electrolyte to moderate dissolution can artificially enhance the electrode capacity during cycling. The underlying cause of this contradiction between experimental capacity and the generally accepted 2-electron mechanism remains unclear.

Herein, this inconsistency was investigated using a combination of *operando* and *ex situ* techniques and data analysis methods. *Operando* bulk sensitive XRD and XAS confirmed the main mechanism of α-MnO₂ dissolution into soluble Mn²⁺ with ZSH formation. However, *ex situ* soft X-ray transmission microscopy (TXM), scanning transmission electron microscopy-electron energy loss spectroscopy (STEM-EELS), and Mn X-ray emission spectroscopy (XES) revealed an increased presence of a Mn(III) minority phase on the remaining MnO₂ nanowire surfaces after discharge. Interestingly, the extended X-ray absorption fine structure (EXAFS) analysis allowed us to identify a

decreased ratio of Mn–Mn_{edge} vs. Mn–Mn_{corner} contribution in the discharge with respect to the pristine state, indicating that Mn–Mn_{edge} sites are the ones which dissolve along discharge into the electrolyte, where their unavailability at the surface seems to be the cause that terminates the 2e[−] process before all α-MnO₂ is removed.

Results and discussion

Capacity limitations

Several electrodes based on the synthesized α-MnO₂ active material were tested in standard ZnSO₄ electrolytes with MnSO₄ additive. The concentrations of ZnSO₄ and MnSO₄ additive in the electrolyte and the loading of the α-MnO₂ in the cathode at the pristine state were chosen as a compromise between common electrochemical conditions reported in the literature (e.g. for optimal Zn cycling⁴⁴ and MnO₂ stability^{19,45,46}) and the absorption ranges required for optimal spectroscopic signal quality of *operando* XAS. As depicted in Fig. S5, the effect of Zn and Mn salt concentrations in the electrolyte is modest. To understand the extent to which electron conductivity or ion diffusion influences the experimental capacity, the electrode mass loadings and carbon content were varied. As shown in Fig. 1(a), while the experimental capacity shows different trends depending on the electrode formulation, it remains limited to ca. 350 mA h g^{−1}_{MnO₂}. A lower current did not lead to a substantial increase in capacity (Fig. 1(b)). Possible modifications in the electrolyte composition during cycling were ruled out, because the capacity was not extended by refreshing the electrolyte after discharge or using a significantly larger volume, suggesting that the discharge capacity is intrinsically related to the active material itself.

The relatively low capacity could be attributed to some limiting mechanisms, or to a simple one-electron reduction from Mn^{IV}O₂ to Mn(III) species. However, Mn(III) as the main oxidation state at the end of discharge should be ruled out based on abundant previous literature,^{30,47–52} and on the results reported below. Nevertheless, discharge in an organic aprotic electrolyte delivered only a small capacity (Fig. S4), confirming the involvement of protons in the mechanism.

From another perspective, *operando* XRD data indicated that incomplete MnO₂ dissolution was observed at the end of the first discharge (Fig. S16). Admitting a 2-electron mechanism leading to Mn²⁺, a passivation of MnO₂ could prevent its complete dissolution. In the past, ZSH formation was suggested to block Mn dissolution.⁴⁶ We carefully analyzed the details of the α-MnO₂ surface by TEM. The STEM-HAADF images in Fig. 1(c), (d) and Fig. S6 show evident lattice planes at the surface of pristine α-MnO₂. In contrast, the surface of the discharged material was amorphous and irregular. The Mn, K, and Zn distributions in the discharged state obtained by TEM-EDX are shown in Fig. 5(e) and (f). The images show similar Mn and K distributions. Instead, Mn and Zn do not coexist (Fig. S7 and S8), confirming the absence of any Zn intercalation in the α-MnO₂ structure. Remarkably, Zn is





Fig. 1 First discharge capacities obtained from several cells using cathodes of different conductivities and mass loadings, with and without the MnSO_4 additive (a). Additional attempts to enhance the capacity of $\alpha\text{-MnO}_2$ with low C rate (C/50), excess electrolyte (bulk cell), and refreshing electrolyte (C/10) (b). STEM-HAADF images of pristine (c), and the discharged (d) electrodes. TEM-EDX maps of K, Mn, Zn, S, and O elements in the discharged sample (e).

essentially segregated at the surface. However, as shown in Fig. S9 and Table S5 within the Zn layer, we found a S:Zn atomic ratio of 0.076 ± 0.009 , far from the value expected for ZSH (*ca.* 0.25), whereas the Zn:O ratio was close to 1:1, which is compatible with ZnO. The formation of ZnO could be favored by a local increase in pH, which is associated with MnO_2 protonation. To prove the specific role of pH and the presence of Zn species in the electrolyte, the same electrode was discharged in Zn-free, large-volume cells (Fig. S10). As reported in previous studies,⁴⁹ the pH modulates the discharge potential, but we observe that capacities are only slightly affected by the presence of Zn. Since localized pH close to the surface of $\alpha\text{-MnO}_2$ cathode is challenging to measure, we stabilized pH by using a bulk electrolytic cell with electrolyte buffered at pH 5.0 and 2.0 and under stirring, to minimize composition gradients (Fig. S11). Particularly at pH 2.0, ZSH or ZnO formation should be suppressed.^{53–55} Nevertheless, we observed again similar capacities as in the thin-electrolyte cells. This rules out pH or cell geometry as responsible for the capacity limitation. A possible passivating role of ZnO, leading to incomplete MnO_2 dissolution and limitation of the discharge capacity, seems unlikely.

Mn oxidation state in pristine $\alpha\text{-MnO}_2$

Since Zn in the environment did not demonstrate a key role in the discharge mechanism, we focused on the analysis of the Mn active material itself. A more accurate estimation of the expected capacity should be based on the pristine oxidation state of Mn. The K:Mn atomic ratio determined by Inductively coupled plasma-optical emission spectrometry (ICP-OES) was 0.107 ± 0.003 , which corresponds to a Mn oxidation state in pristine $\alpha\text{-MnO}_2$ of 3.893 ± 0.003 , assuming the formation of stoichiometric $\text{Mn}:\text{O} = 1:2$ and no oxygen vacancies (Table S6).

The energy position of the first-derivative maximum of the bulk-sensitive Mn K-edge X-ray absorption near edge structure (XANES) corresponds to an average Mn oxidation state of 3.89 ± 0.05 (Fig. S12),¹⁶ which is in excellent agreement with this value. Compatible results were obtained by fitting the XANES pre-edge features with the corresponding $\text{Mn}^{\text{IV}}\text{O}_2$, $\text{Mn}^{\text{III}}_2\text{O}_3$, and Mn^{II} (aq.) references (Fig. 3(c) and Table S2). Moreover, TEM-EDX showed a K:Mn atomic ratio of 0.082 ± 0.006 , corresponding to a Mn oxidation state of 3.92 ± 0.01 (Fig. S13 and Table S7), where the minor quantitative discrepancy probably depends on the limited region probed. Both TXM cluster analysis and onset energy analysis of the STEM-



EELS data showed an evident Mn energy shift towards low energies on the α -MnO₂ nanowire surface, implying an accumulation of Mn(III) species there (Fig. S14), in agreement with the XPS data showing a high Mn(III)/Mn(IV) surface ratio, close to 1 (Fig. S15).⁵⁶ Considering an experimental initial Mn oxidation state of +3.89 allows a more accurate estimation of the theoretical capacity, resulting in 263 and 557 mA h g⁻¹_{MnO₂} from the exchange of 1 or 2 electrons, respectively. From the same initial value, after a discharge of 350 mA h g⁻¹_{MnO₂}, an average Mn oxidation state of +2.7 would be expected, which is much smaller than that reported in the following, supporting again the substantial Mn dissolution mechanism rather than simply Zn or H intercalation in α -MnO₂, which should instead lead to Mn(III) in the discharged electrode.

Direct observation of α -MnO₂ dissolution

Operando XRD and XAS measurements were carried out to follow the evolution of the main species involved along the first discharge. The evolution of the XRD patterns is shown in Fig. S16. During discharge, the intensity of the α -MnO₂ reflections rapidly decrease compared with that of the Ti foil reference. Meanwhile, ZSH continuously forms as the process progresses. However, a few new weak peaks, possibly matching defective MnO₂ with formula K_{0.66}Mn₄O₈ appear (Fig. S17), while incomplete α -MnO₂ dissolution is observed. *Operando* Mn and Zn K-edge XAS data were acquired quasi-simultaneously in transmission mode on coin cells with Kapton windows, with the cells assembled such that both the cathode and electrolyte regions could be probed (Fig. 2(c)). The electrolyte composition utilized was 0.5 M ZnSO₄ and 0.2 M MnSO₄,

and the electrode loading *ca.* 2.12 mg cm⁻² to optimize the XAS signal. The possible effect of the X-ray beam on the studied system was characterized and suppressed prior to the *operando* measurements by unfocusing and attenuating the incoming beam. The spectra at the exposed point at the end of the discharge overlapped with those collected at a freshly irradiated point in the same state of charge, whereas the delivered capacity along the first discharge was 275 mA h g⁻¹_{MnO₂}, comparable to typical laboratory experiments (Fig. S18), validating the representativeness of the reported results.

Mn and Zn K-edge XANES evolutions along the first discharge, carrying out information on the Mn and Zn oxidation state and local environment,^{57,58} are presented in Fig. 2(a) and (b), respectively. The intensity of the signal related to dissolved Mn²⁺ (aq.) continuously increased during discharge at the expense of α -MnO₂, evidencing a few isosbestic points, indicating direct conversion without intermediates. Similarly, the Zn²⁺ (aq.) signal decreased, whereas the ZSH signal increased during discharge, also showing few isosbestic points. In both cases, the electrolyte signals remained unaltered during the entire discharge process, indicating that no additional soluble Mn or Zn species were formed (Fig. S19).

The evolution of Mn and Zn species was quantified by LCF with respect to the electrolyte and α -MnO₂ or ZSH references, respectively, and confirmed by advanced statistical methods (PCA and MCR-ALS analyses). Indeed, the PCA of the *operando* Mn and Zn K-edge spectra collected during discharge identified two components, which were then reconstructed using MCR-ALS (Fig. S20). Both LCF and MCR-ALS reliably reproduced the experimental datasets, with consistent results between the two

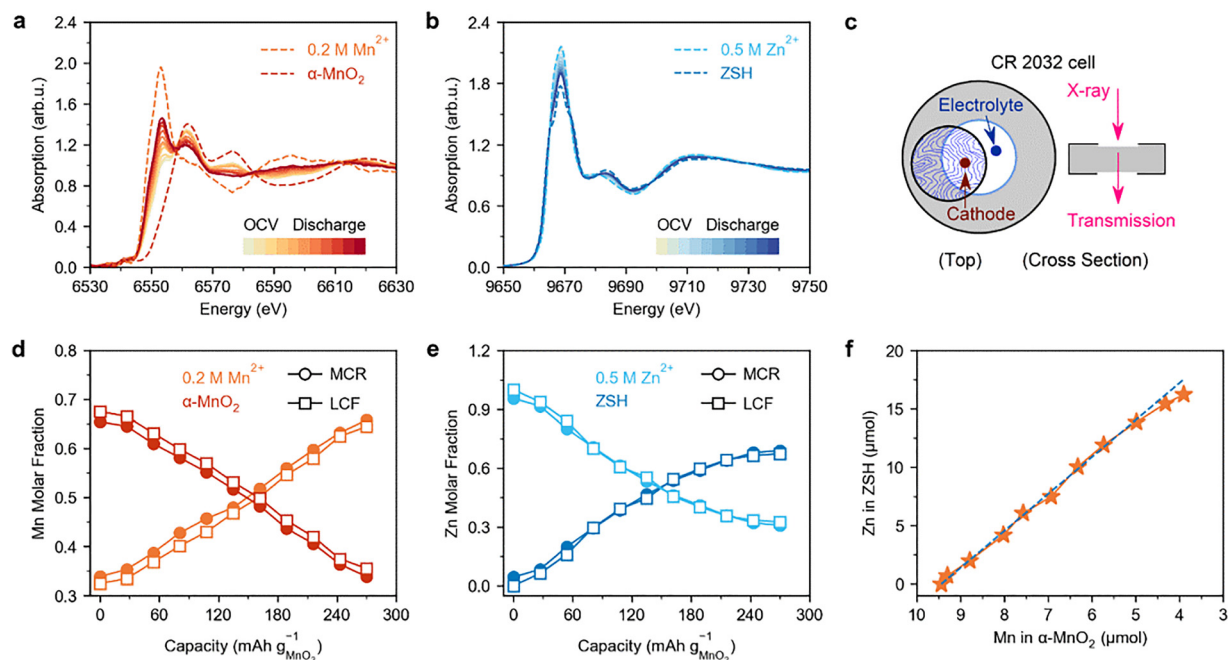


Fig. 2 *Operando* XANES at the Mn (a) and Zn (b) K-edge on α -MnO₂ cathode. The LCF fitting and statistical MCR-ALS results were compared for both the Mn (d) and Zn (e) K-edges. Sketch of the experimental geometry used to acquire *operando* XAS (c). Correlation of absolute Zn and Mn amounts in the cell based on the edge jump of *operando* XAS (f).



To explain these results, we propose that the Mn-Mn_{corner} configuration is essentially maintained when the surface layers of the crystal are protonated and Mn reduced. As a consequence, the charge transfer implied by disproportionation can occur under these Mn-Mn_{corner} and Mn-Mn_{edge} possible configurations, but with the shorter edge-shared configuration being much more efficient. As a result, the formed Mn(II) will



dissociate from its oxygen ligands so that the corresponding octahedron, mainly originally in the Mn–Mn_{edge} configuration, is lost. This would bring to an accumulation of inactive protonated and reduced Mn–Mn_{corner} octahedra, which would block further reactions.

Mn oxidation state in the discharged electrode

The Mn K-edge pre-peak and Mn K_{β1,3} XES features are sensitive to the details of the local Mn electronic properties. During discharge, the evolution of the Mn K-edge pre-peak shown in Fig. 3(c) suggests an increase in the Mn(III)/Mn(IV) ratio, whereas the *ex situ* Mn K_{β1,3} spectra are compatible with a minor overall increase in Mn(III) in the electrode (Fig. S25).

Complementary information was obtained at the Mn L-edge, which is usually more sensitive than the K-edge to oxidation states, and is less affected by the local coordination environment.⁵⁷ In particular, *ex situ* TXM, *in situ* Mn L₃-edge STXM and *ex situ* STEM-EELS experiments were carried out to assess the spatial distribution of the detected Mn and Zn species, where microscopy allowed the detection of inhomogeneously distributed minority species. TXM clearly shows that the nanowires in the discharged state (Fig. 4(b)) were eroded compared with the pristine ones (Fig. 4(a)), appearing broken and shrunk in both *ex situ* and *in situ* images (Fig. S26) because of the α-MnO₂ dissolution. *In situ* STXM confirmed the wire erosion and spectral changes observed by *ex situ* TXM (Fig. S26c and d). As detailed in eqn (S23), we define a shape index for the Mn L-edge spectrum as the arctangent of the absorption feature intensity ratio at energies of maximum sensitivity to Mn(III) and

Mn(IV) species.⁵⁹ Thus, the shape index is directly related to the degree of contribution of Mn(III) to Mn(IV). In Fig. 4, the higher shape index distribution reflects the higher Mn(III) content on the surface of the nanowires, with an average shift towards reduced Mn after discharge, as indicated by the peak shift in the histograms (Fig. 4(c)). This is consistent with the Mn(III)-rich surface determined by *ex situ* X-Ray photoelectron spectroscopy (XPS) analysis (Fig. S27). The fact that all the distributions generally shift towards higher values of the shape index without new obvious components in the histogram indicates that no localized new phases are formed within the TXM spatial resolution (*ca.* 40 nm, half pitch). In addition, the shift is modest compared to the position of the Mn^{III}OOH reference, as reduced Mn still involves a small fraction of the remaining Mn. This reduction was further confirmed by the lower onset energy of the Mn L₃ edge,⁶⁰ as shown in Fig. S28. To appreciate the variability of the spectra, image pixels were grouped within ranges of the shape index, and their L₃ edge spectra were averaged (Fig. 4(d)). The averaged Mn L₃ edge spectra clearly show the coexistence of the majority Mn(IV) with a characteristic sharp peak at 641.7 eV and a minority reduced phase. The discharged sample shows that more reduced Mn is found towards the surface of the nanowires (Fig. 4(c)). Cluster analysis of STEM-EELS showed a similar difference between the bulk and surface spectra (Fig. S28a–c). Given the minor contribution of Mn(III) in every image pixel, the spectra reported in Fig. 4(d) do not show major variations. However, the three pure components were clearly differentiated by PCA and MCR-ALS (Fig. 4(e) and Fig. S29).

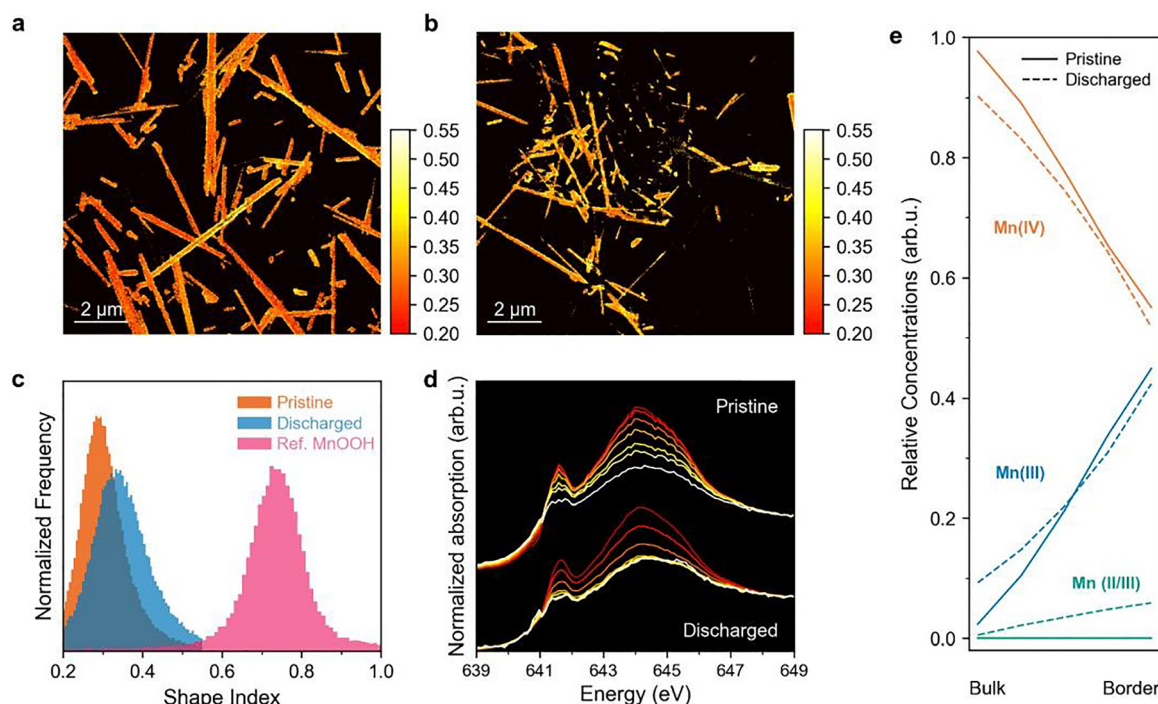


Fig. 4 Maps of shape index of the Mn L-edge, sensitive to the Mn reduction for pristine (a) and discharged (b) electrodes. Corresponding histogram (c) and average spectra for different ranges of shape index that are considered sufficiently representative of the collected pixels and used for PCA and MCR-ALS analysis (d). Relative concentrations of the calculated Mn L-edge components determined by PCA and MCR-ALS analysis (e).



diffraction pattern.^{68,69} Also in our case, we observed discharges with a coulombic efficiency above 90% (Fig. S30). The FTs-EXAFS spectrum (Fig. 5(d)) exhibits a strong peak at 2.42 Å and a very weak peak at 3.00 Å, with less than 15% corner-sharing Mn–Mn octahedra, demonstrating that the edge-sharing configuration is essential for the quantitative dissolution of MnO₂.

Conclusions

The capacity limitation and mechanism of rechargeable aqueous Zn–MnO₂ batteries were revealed using a multimodal and multi-scale characterization approach. Both *operando* XAS and XRD confirm α -MnO₂ dissolution and ZSH formation during discharge. The erosion of α -MnO₂ during discharge produces disorder and accumulation of reduced Mn species at the surface of the nanowires. The substantial decline in the Mn–Mn_{edge} distances vs. Mn–Mn_{corner} suggests that the second reaction step, that is, Mn(III) disproportionation, requires edge-connected Mn octahedral pairs. The accumulation of corner-sharing protonated octahedra at the surface of the nanowires blocks electron and ionic exchange before α -MnO₂ complete dissolution. Given that capacity limitation is observed to different extents with most MnO₂ polymorphs,⁶¹ corner-sharing Mn in the pristine structure could be not the only factor limiting the capacity. The here reported results suggest that efficient electron and ion conduction paths in the active cathode material should persist during discharge. Short diffusion paths, as typically present in nanostructured particles,^{42,70} or doping,^{71–74} should effectively contribute to an optimal discharge. However, nanostructuring,^{75–77} or doping^{38,78,79} alone do not seem generally sufficient for quantitative MnO₂ dissolution. Instead, generally high reversibility is observed with MnO₂ phases electrodeposited during charge. These typically offer faster ion/electron transfer that originates from porous nanostructured and defective layered phases,⁸⁰ for which the isolation of corner–corner configurations should be less likely, and short ion diffusion paths are expected.

Experimental

Materials synthesis

α -MnO₂ nanowire was prepared *via* a standard hydrothermal method.²⁶ Briefly, 3.5 mmol potassium chlorate (KClO₃, 99 + % ACS Reagent, Thermos Scientific), 2 mmol manganese(II) sulfate monohydrate (MnSO₄·H₂O, 99%, Labkem), and 3.5 mmol potassium acetate (CH₃COOK, 99%, Thermos Scientific) were dissolved in 30 mL Milli-Q water. After adding 1.6 mL of glacial acetic acid (EssentQ, Scharlab) was added and stirred for half an hour, and the homogeneous solution was transferred into a Teflon-lined autoclave (50 mL, Canrd) and maintained at 160 °C for 12 h. Finally, the as-synthesized sample was filtered under vacuum using Milli-Q water/ethanol and then dried at 60 °C overnight. The α -MnO₂ nanowire powder had a single-phase tetragonal structure (*I4/m*, PDF#00-044-0141, K_{1.33}Mn₈O₁₆), which consisted of a typical 1 × 2 [MnO₆] tunneled framework with K⁺ ions partially occupying the tunnel center (Fig. S2).⁸¹

Transmission electron microscopy energy-dispersive X-ray spectroscopy (TEM-EDX) and HRTEM confirmed that potassium had a uniform distribution in the structure (Fig. S3).

Electrochemical measurements

Binder-free MnO₂ electrodes were prepared using α -MnO₂ nanowires and multiwall carbon nanotubes (MWCNT) with a mass ratio of 7 : 3. The normal cathode was obtained using α -MnO₂ nanowire, carbon black (Super P, Timcal), polyvinylidene fluoride (PVdF, Sigma-Aldrich), and multiwall carbon nanotubes (MWCNT) with a weight ratio of 80 : 9 : 9 : 2. The mass loading of the α -MnO₂ electrodes was *ca.* 0.8–2.5 mg cm^{−2}. Electrochemical Swagelok cells were assembled with cathodes, glass fiber separators (thickness, 270 mm, PRAT-DUMAS), zinc foils (thickness, 0.125 mm, Advent Research-Materials), and different aqueous electrolytes: 1 M ZnSO₄ with 0.2 M MnSO₄, and 1 M ZnSO₄. To minimize the effects of the limited electrolyte volume, 40 mL homemade bulk cells were also used with α -MnO₂ cathodes and Zn foils or carbon paper as anodes, both with an area of 3 cm² in various aqueous liquid electrolytes: 1 M ZnSO₄ + 0.2 M MnSO₄, 1 M Na₂SO₄ + 0.2 M MnSO₄, or 1 M ZnSO₄ + 0.2 M MnSO₄ supplemented with various buffered agents, including 0.1 M potassium acetate with acetic acid (pH at 5.0), H₂SO₄ (pH at 2.0), and 1 M acetic acid adjusted with ammonia (pH at 4.2). The configurations of the *in situ* coin cells for *operando* XRD and XAS were similar to those of the Swagelok cells, but 0.5 M ZnSO₄ and 0.2 M MnSO₄ was utilized in XAS to obtain a better signal-to-noise ratio. A 6 mm hole (coin cell Kapton window size) was made in the Zn anode to allow the transmission of X-rays. Galvanostatic cycling tests were conducted using a LANHE M340A cyler at different C-rates with the potential limitations of 0.9–1.8 V vs. Zn/Zn²⁺, 1C = 308 mA g^{−1}. *Operando* XAS tests were conducted using a BioLogic VSP potentiostat, and *in situ* STXM using a BioLogic SP-200 potentiostat.

Material characterization

XRD patterns were collected by a Siemens D-5000 diffractometer of Cu K α radiation. *Operando* XRD data were acquired by a Bruker D8 Advance A25 diffractometer in a Debye–Scherrer geometry equipped with a Johansson monochromator of the Mo K α radiation and its standard transmission diffraction collection mode. Scanning electron microscopy (SEM) was performed using a FEI Quanta 200 FEG-ESEM equipment (10–15 kV). XPS data were recorded by a SPECS EA10P hemispherical analyzer with a monochromatic Al K α radiation. ICP-OES was taken on samples digested by duplicate in a microwave oven with a mixture of concentrated HNO₃ and HCl solutions. Scanning Transmission electron microscopy (STEM), TEM-EDX and STEM-EELS were acquired with a super-X EDX spectrometer and a Gatan Continuum K3 EELS spectrometer, respectively. Spectra were collected at a beam energy of 200 keV with an energy step of 0.9 eV. Mn K-edge XAS and Mn K _{β 1,3} XES experiments were carried out at the CL β SS beamline of ALBA CELLS synchrotron, Spain.^{82,83} *Ex situ* energy-resolved full-field soft TXM was performed at the MISTRAL beamline of ALBA



CELLS synchrotron, Spain.⁸⁴ *In situ* scanning X-ray transmission microscopy (STXM) was carried out at the DEMETER beamline of SOLARIS Synchrotron, Poland.⁸⁵ The STXM images were obtained at the energy of *ca.* 1010 eV to optimize the compromise between contrast and radiation damage. More details are provided in SI Part I.

XPS fitting was carried out with CasaXPS for Mn 2p_{3/2}, K 2p, and O 1s lines following the procedure described in our previous report.⁵⁶ For XAS techniques, the Zn and Mn mole evolutions in the electrode and electrolyte of the *operando* cell were calculated from the XANES edge jumps with a in-house model detailed in the SI. The EXAFS portion of the *operando* XAS data was analyzed using ATHENA and ARTEMIS.^{86,87} For the fitting of the pre-edge, the baseline was modeled with the Larch package.⁸⁸ The MnO₂ and Mn₂O₃ reference spectra were taken as models of Mn(IV) and Mn(III) components, respectively, using the Hyperspy package.^{89–92} For XES measurements, a linear background was subtracted in SpectroChemPy,⁹³ considering 0.5–2 eV of the low- and high-energy tails. Subsequently, each spectrum was normalized to its area. The integrated absolute difference (IAD) with respect to a low-spin reference method was utilized to extract the local magnetic moment quantitatively.^{94–96} The *ex situ* TXM data were processed following previous work.^{59,97,98} *In situ* STXM images and Mn spectra were obtained in aXis2000.⁹⁹ (S)TEM-related dataset (HRTEM, STEM-HAADF images, TEM-EDX, and STEM-EELS) were treated with eXSpy.¹⁰⁰ More details are provided in SI Part I.

For big datasets such as *operando* XAS and *ex situ* TXM, linear combination fitting (LCF) was exploited to extract the relative ratios of coexisting components whenever the correct reference set was available. Advanced statistical methods were applied to all large datasets. In particular, principal component analysis (PCA) was performed to determine the maximum number of independent components necessary to reconstruct the information contained in the entire dataset using both MATLAB and the SpectroChemPy package. Finally, multivariate curve resolution-alternating least squares (MCR-ALS) was applied using the MATLAB-based MCR-ALS 2.0 toolbox,¹⁰¹ to determine physically meaningful spectra and corresponding concentrations.^{102,103} For image stack datasets, such as *ex situ* TXM and STEM-EELS, cluster analysis (CA) was applied to determine spatially correlated spectra,^{59,104} which was implemented in eXSpy and Hyperspy.^{92,100} The pixel analysis in *ex situ* TXM was grouping spectra by shape index between Mn(III) and Mn(IV) features. Additional details are provided in SI Part I.

Author contributions

C. L.: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – original draft, writing – review & editing. V. M. D.: data curation, formal analysis, investigation, methodology, validation, writing – review & editing. A. P. B.: formal analysis, methodology, writing – review & editing. S. K.: data curation, formal analysis,

writing – review & editing. B. M. B.: data curation, formal analysis, validation, writing – review & editing. K. M.: data curation, writing – review & editing. L. S.: formal analysis, funding acquisition, methodology, software, validation, writing – review & editing. A. S.: data curation, formal analysis, funding acquisition, methodology, software, validation, visualization, writing – review & editing. L. S.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, software, validation, writing – review & editing. D. T.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

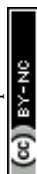
Data availability

The data supporting this paper have been included as part of the supplementary information (SI). Supplementary information: experimental details and results. See DOI: <https://doi.org/10.1039/d5ee03588k>.

Raw data and analysis results are available at Zenodo at: <https://doi.org/10.5281/zenodo.17092706>.

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