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Is alpha-V₂O₅ a cathode material for Mg insertion batteries?

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HIGHLIGHTS

• Demonstrated the critical role of trace water in electrolyte for reversible Mg deposition.

• First time report of proton participated intercalation for V₂O₅.

• Clarified misunderstandings from literature about the large capacity observed for V₂O₅.

A R T I C L E I N F O

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ABSTRACT

When designing a high energy density battery, one of the critical features is a high voltage, high capacity cathode material. In the development of Mg batteries, oxide cathodes that can reversibly intercalate Mg, while at the same time being compatible with an electrolyte that can deposit Mg reversibly are rare. Herein, we report the compatibility of Mg anodes with α -V₂O₅ by employing magnesium bis(trifluoromethane sulfonyl)imide in diglyme electrolytes at very low water levels. Electrolytes that contain a high water level do not reversibly deposit Mg, but interestingly these electrolytes appear to enable much higher capacities for an α -V₂O₅ cathode. Solid state NMR indicates that the major source of the higher capacity in high water content electrolytes originates from reversible proton insertion. In contrast, we found that lowering the water level of the magnesium bis(trifluoromethane sulfonyl)imide in diglyme electrolytes originates from reversible proton insertion. In contrast, we found that lowering the water level of the magnesium bis(trifluoromethane sulfonyl)imide in diglyme electrolytes is critical to achieve reversible Mg deposition and direct evidence for reversible Mg intercalation is shown. Findings we report here elucidate the role of proton intercalation in water-containing electrolytes and clarify numerous conflicting reports of Mg insertion into α -V₂O₅.

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1. Introduction

Development of a higher energy density, rechargeable battery is important for the future advancement of mobile energy storage systems. Although lithium-ion batteries (LIBs) are widely used for energy storage in many consumer electronic applications, issues associated with manufacturing a cost-competitive battery of sufficient energy density have slowed their development in large volume applications such as electric vehicles (EV) [1]. One solution to greater the energy density in LIBs would be to replace the current graphite anode with lithium metal. However, this solution has a long history of undesirable cycling behavior related to dendrite formation and the reactivity of Li metal with the electrolyte [2]. While techniques that incorporate Li metal anodes into LIBs are being investigated, magnesium (Mg) has started to draw sufficient attention as an inexpensive and earth-abundant metal that is potentially a safer anode alternative than lithium [3,4]. Mg shares many properties with lithium, but has more to offer: for instance, Mg is the eighth most abundant element in the earth's crust, making manufacturing cost efficient energy storage systems possible. In addition, Mg offers a reasonable alternative to Li with its fairly low reduction potential (-2.37 V vs SHE) and a high







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theoretical volumetric capacity (3833 mA h/cm^3) [5]. A major difference as compared to lithium is that Mg metal has been proposed to not form dendrites during deposition, which makes it potentially longer lasting and substantially safer than a Li metal anode [6,7].

While advantages of Mg have been recognized for a long time, research towards the development of Mg batteries is still at a very early stage, with many technological challenges ahead. Even though the Grignard or halogen-containing electrolyte systems works well with a Mg metal anode, at least in terms of cycling efficiency, and are compatible with a Chevrel phase cathode (1.1 V vs Mg) [3,8–11], however, two issues exist: 1) the use of ethereal solutions of Grignard/halogen based electrolytes are corrosive to cell components; and 2) they are not compatible with metal oxide cathodes [12,13]. Meanwhile, conventional electrolytes, based upon $Mg(ClO_4)_2$ or $Mg(NO_3)_2$ salts, show evidence of Mg intercalation with metal oxide cathodes, but have yet to be proven for reversible Mg deposition [14–17]. In a more recent work, Toyota demonstrated the utility of a halogen-free electrolyte based on a stable anionic boron cluster in a full cell [18]. However, the carborane anion involves a complex preparation procedure, which hinders its practical application. Herein, we utilize a more accessible system with a non-corrosive, halogen-free electrolyte, magnesium bis(trifluoromethane sulfonyl)imide in diglyme (Mg(TFSI)₂/G2), that can reversibly plate/strip Mg and at the same time is compatible with a high voltage orthorhombic V_2O_5 cathode (2.56 V vs Mg). In particular, our findings show that lowering the water level in the electrolyte is a critical step in achieving successful plating/stripping of Mg, and thus permits compatibility with both the Mg metal anode and the V₂O₅ cathode. Although near theoretical capacity can be achieved with a high water content electrolyte for the V₂O₅ cathode, such a system fails to incorporate Mg metal as anode. Results from solid state NMR spectroscopy have shown that the gain in capacity in a high water content system is mostly due to reversible proton intercalation. Furthermore, real and reversible Mg intercalation into V_2O_5 for Mg(TFSI)₂/G2 at a low water level was demonstrated and confirmed by X-ray absorption near-edge spectroscopy (XANES), energy-dispersive spectroscopy (EDX) and X-ray diffraction (XRD).

2. Experimental

2.1. Preparation of the orthorhombic V₂O₅ cathode

Vanadium oxide electrodes were prepared by casting an 8:1:1 weight-ratio slurry of vanadium oxide (Fluka, > 99%), Timcal Super C45 carbon black, and polyvinylidene fluoride (PVDF) dissolved in *N*-methyl-2-pyrrolidinone (NMP) onto a 304 stainless steel current collector. These laminates were then dried at 75 °C in an oven for at least one hour before being punched as 7/16" diameter electrodes. Average mass load of V₂O₅ is 2 mg/cm².

2.2. Electrolyte synthesis

Magnesium bis(trifluoromethane sulfonyl)imide (99.5%, Solvionic, France) was dried in a vacuum oven at 170 °C overnight before use. Diglyme (Aldrich, anhydrous, 99.5%) solvent was pretreated with molecular sieves (Aldrich, 3 Å beads, 4–8 mesh) overnight and then added into the dried Mg(TFSI)₂. The asprepared electrolyte was then stirred overnight before use. Water levels of the as-prepared electrolytes were determined from Karl-Fischer analysis.

2.3. Electrochemical characterizations

A three electrode setup with a Pt disk as the working electrode

(2 mm in diameter, CH instruments, Austin, TX) and polished Mg ribbon as the counter and reference electrode (99.9% purity, Sigma–Aldrich) is used to measure the cyclic and linear voltammograms of the electrolyte. Galvanostatic cycling of V_2O_5 vs Mg in coin cells was performed using a Maccor series 4000 cycler at 20 μ A/ cm². A three electrode Swagelok cell configuration is used for the cyclic voltammetry measurement, with V_2O_5 on a stainless steel current collector as the working electrode, and a polished magnesium disk (7/16″ diameter) as the counter and reference electrode. Electrochemical characterization was carried out using a multichannel potentiostat (Parstat MC, Princetion Applied Research, TN) under a pure argon atmosphere in a glove box where H₂O and O₂ level is kept under 1 ppm.

2.4. X-ray diffraction

High energy X-ray diffraction (XRD) was carried out at Beamline 11-ID-C of the Advanced Photon Source (APS) at Argonne National Laboratory (ANL). The X-ray energy was 114.76 keV (corresponding to 0.10804 Å, the fixed wavelength for this station), which has a large penetration capability that allowed for the detection of structural changes of the bulk material. The V₂O₅ powder was collected and sealed with kapton tape. An incident X-ray beam size of 0.5 mm \times 0.5 mm was used. A Perkin Elmer area X-ray detector was used to collect the 2-dimensional diffraction patterns in transmission mode. The measured 2D diffraction patterns were calibrated using a standard CeO₂ sample and converted to one-dimensional intensity *versus* scattering angle patterns using Fit2D software [19]. XRD patterns of cycled V₂O₅ at charged, discharged and recharged states are shown in Fig. S1.

2.5. X-ray absorption near-edge structure (XANES)

Ex-situ vanadium (V) K-edge X-ray absorption spectroscopy was performed to detect the change of the V valence states for charged and discharged cathodes at beamline 20-BM-B at APS of ANL. The measurements were carried out in transmission mode with a vanadium metal foil as a reference, which provides internal calibration for the X-ray energy. Coin cells with V₂O₅ as the cathode and Mg metal as the anode were cycled at a constant current mode, 20 μ A/cm², for 10 cycles before holding at certain charged/discharged potentials. V₂O₅ powder was then collected and mixed homogeneously with cellulose at a mass ratio of 1:5 and pressed into pellets for the measurement. The XANES spectra were normalized and analyzed using the ATHENA software package [20]. The full range XANES spectra shown in Fig. S2 indicate good normalization. The V metal K-edge position, located at the maximum of the first derivative, was defined as 5465 eV.

2.6. Scanning electron microscopy (SEM) and energy-dispersive Xray spectroscopy (EDX)

Scanning electron microscopy and energy-dispersive X-ray spectroscopy characterization were performed using a Hitachi S4700-II scanning electron microscope equipped with an EDX detector mounted at a 30° take-off angle. Elemental composition was determined using a standardless ZAF (atomic number, absorption and fluorescence) corrected analysis. Both EDX and SEM were performed at an electron energy of 30 keV. Cathode materials collected from cycled coin cells were soaked and rinsed with acetone to remove any electrolyte residue on the surface prior to the EDX analysis.

2.7. NMR characterization

¹H NMR experiments were performed using a Bruker Avance III spectrometer operating at a magnetic field strength of 11.7 T, corresponding to a ¹H Larmor frequency of 300 MHz with a Bruker HX double resonance 1.3 mm MAS probe. ¹H NMR spectra were referenced relative to acetone at 2.05 ppm. A hahnecho pulse sequence was used to acquire all ¹H NMR spectra. A recycled delay of 2 s was used in all experiments. Experiments were only performed after a stable probe temperature was reached (10 °C). Samples were carefully scraped off the stainless steel current collector and packed into a 1.3 mm rotor for signal acquisition, and the weight of the sample was recorded every time. The ¹H NMR spectra are normalized to the weight of the active materials in the sample holders.

3. Results and discussion

3.1. Investigation of effective Mg plating and stripping of Mg(TFSI)₂/ G2 at various water level

Besides effective magnesium plating and stripping, the primary characteristics required for a magnesium electrolyte are a wide electrochemical window and compatibility with current collectors, as pointed out by Ha. et al. recently [21]. In addition, we have found that the water content in the Mg(TFSI)₂/G2 electrolyte is critical to achieve reversible Mg deposition. For instance, Fig. 1(a, b) show typical cyclic voltammetry curves with 1 M Mg(TFSI)₂/G2 at water contents of 2600 and 300 ppm, where no clear electrochemical evidence of reversible Mg deposition can be observed. The same electrolyte at a lowered water level, 15 ppm, shows significant improvement of Mg plating/stripping as presented in Fig. 1c. Several issues need to be identified for practical consideration of utilizing Mg(TFSI)₂/G2 electrolyte in a Mg battery. Firstly, water level of electrolyte needs to be strictly regulated since cyclic voltammograms show that even trace water can passivate Mg metal and thus shut down the further activity of the Mg anode. Secondly, even though Mg(TFSI)₂/G2 electrolyte at a low water content gives reversible Mg deposition, the large overpotential and low coulombic efficiency are problems that still need to be solved. To understand the possible compatibility of the Mg(TFSI)₂/G2 electrolyte with a high voltage oxide cathode, its anodic stability was investigated by Linear sweep voltammetry (LSV), presented in Fig. 1d. Oxidation onset potential was determined to be 4.2 V (vs Mg/Mg²⁺), in agreement with reported literature [21]. As compared to the complex ether based organomagnesium electrolytes, where the largest window versus magnesium metal was limited to ~3.5 V [22–24]. An anodic stability larger than 4 V is of critical importance to allow the use of high voltage cathodes materials. It is worth noting that the mechanism of reversible deposition for Mg(TFSI)₂/ G2 electrolyte has not been fully described and further details will be presented in a future publication. We believe the diglyme solvent plays a critical factor by providing a well-solvated environment for Mg ions and therefore facilitates efficient Mg deposition and dissolution. Detailed solvation structure analysis for this system can be found from a pair distribution function study reported recently [25]; nevertheless, its halogen-free nature provides a simple approach to electrolyte design and exhibits promising potential for application in a cell containing a high voltage metal oxide cathode.

3.2. Performance of an α -V₂O₅ cathode for Mg intercalation in wet and dry electrolyte systems

Vanadium pentoxide (V₂O₅) is one of the classical intercalation

cathodes due to its potential insertion properties with divalent cations, with reports beginning in the late 1980s [26,27]. However, insertion of Mg^{2+} into a V_2O_5 cathode was claimed mainly using $Mg(ClO_4)_2$ based electrolytes, which contains a high water content and does not plate and strip Mg metal [26–28]. As a consequence, Mg metal was not used as the anode in these studies [26–32]. In addition, several publications report the necessity of water in the electrolyte to enable Mg intercalation [29,30,33]. For instance, Novak and Desilvestro reported reversible cycling of V_2O_5 with Ag/AgCl as a reference electrode and noted that the presence of water was critical to give reversible electrochemical response [33]. Large capacity was reported in these systems, however, no clear evidences of structural changes were given beyond electrochemical cycling data to indicate true Mg intercalation had occurred.

In this work we perform two sets of experiments of cycling α - V_2O_5 as cathode. One in Mg(TFSI)₂/G2 electrolyte with high water content (wet electrolyte) and another in low water content electrolyte (dry electrolyte). Firstly, V₂O₅ cell using 1 M Mg(TFSI)₂/G2 with 2600 ppm water as an electrolyte is constructed. Galvanostatic cycling of a coin cell composed of V₂O₅ and the high surface area carbon as capacitive anode is shown in Fig. 2a, where the cell's capacity can be achieved in close equivalent to theoretical value, ~260 mA h/g (ESI \dagger). It is worth mentioning that, the addition of water in the electrolyte necessitates replacing the Mg metal with a high surface carbon, as cells containing water are not compatible with Mg anodes. For comparison with the wet electrolyte system, galvanostatic cycling of V₂O₅ against a carbon electrode is performed in 1.0 M Mg(TFSI)₂/G2 electrolyte with 15 ppm H₂O. Results presented in Fig. 2b indicate a discharge capacity of ~60 mA h/g is achieved in the dry electrolyte system. To further understand the different performance of the dry electrolyte versus the wet electrolyte for an α -V₂O₅ cathode, galvanostatic cycling of V₂O₅ with a magnesium metal anode was performed in 1.0 M Mg(TFSI)₂/G2 electrolyte with 15 ppm H₂O, to investigate Mg intercalation in a prospective full cell design.(ESI⁺) A three electrode setup is used with V₂O₅ as cathode and Mg metal as reference and counter electrode and cycling results show reversible Mg insertion as presented in Fig. 2c. The discharge capacity for the 1st cycle is ~80 mA h/g and 94% of capacity was maintained starting from the 2^{nd} to the 10th cycle at ~50 mA h/g, as shown in Fig. 2d. The observed discharge capacity is significantly lower for the dry electrolyte as compared to the wet electrolyte system, but falls in good agreement with the capacity from the V₂O₅ cell with a carbon anode in the dry electrolyte system. At varied voltage escalation rates, oxidation peaks and reduction peak showed a slight voltage drift (less peak splitting at lowered rate), ascribed to the slow kinetics for Mg insertion. Capacity loss after the 1st cycle is due to the partially reversible insertion for magnesium intercalation and the likely film formation on the magnesium anode [24,34,35]. Potential correction for the Mg reference electrode is done by adding ferrocene, which is a redox couple that can be used as an internal standard. Cyclic voltammetry results indicate a 1.0 V potential shift to the lower value in Mg(TFSI)₂/G2 electrolyte with the Mg metal as reference (ESI[†]).

3.3. Characterization of cycled V_2O_5 in a wet versus dry electrolyte

The significant capacity difference observed for the dry electrolyte (1 M Mg(TFSI)₂/G2 with 15 ppm H₂O) *versus* wet electrolyte (1 M Mg(TFSI)₂/G2 with 2600 ppm H₂O) with the V₂O₅ cathode requires further understanding. Therefore, ¹H solid state NMR spectroscopy was carried out for electrochemically cycled V₂O₅ from a hybrid half-cell running against the carbon counter electrode with wet electrolyte, and a full V₂O₅ cell against Mg anode in a dry electrolyte. Fig. 3a shows the ¹H NMR spectra for pristine,



Fig. 1. Cyclic voltammograms (CV) of Mg(TFSI)₂/G2 at 1 M, (a) with 2600 ppm water; (b) with 300 ppm water; (c) with 15 ppm water. Arrows indicate the scan direction and sequence; (d) Linear sweep voltammetry (LSV) of Mg(TFSI)₂/G2 at 1 M with 15 ppm water (the inset shows the enlargement region between 3.3 V and 5.5 V). Dash line with arrow indicates the breakdown potential; CV and LSV were conducted with applying Pt disk as the working electrode and Mg ribbons as the reference and counter electrodes at scan rate of 25 mV/s.



Fig. 2. Cycling performance of a V_2O_5 cathode in Mg(TFSI)₂/G2 electrolyte. (a) Galvanostatic cycling of a V_2O_5 vs carbon coin cell in 1 M Mg(TFSI)₂/G2 with 2600 ppm H₂O at 20 μ A/cm²; (b) Galvanostatic cycling of a V_2O_5 vs carbon coin cell in 1 M Mg(TFSI)₂/G2 of 15 ppm H₂O at 20 μ A/cm²; (c) Cyclic voltammetry with V_2O_5 as the working electrode and Mg disks as the counter and reference electrodes at sweep rates of 2 mV/s (red) and 5 mV/s (black). 1 M Mg(TFSI)₂/G2 with 15 ppm H₂O is used as electrolyte; (d) Discharge capacity vs cycle number for the V_2O_5 vs Mg anode coin cell at 20 μ A/cm² in 1 M Mg(TFSI)₂/G2 with 15 ppm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

charged and discharged V_2O_5 cycled in the wet electrolyte. The growth and decay of the proton features upon charge and discharge, relative to the pristine state, indicates that protons participate in cell cycling. Three peaks can be resolved upon deconvolution, appearing at -1.3 ppm, 1.8 ppm and 4.4 ppm, respectively (ESI†). The peak at -1.3 ppm is ascribed to the participated proton co-intercalation in lattice. The features at 1.8 and 4.4 ppm are ascribed to the adsorbed surface water and the -OH bond in the V_2O_5 lattice. The disappearance of the -1.3 ppm

peak for the charged state confirms the proton de-intercalation, indicating the added water from the electrolyte participates in cycling. In contrast, the ¹H NMR spectra remained essentially unchanged for electrochemically cycled V_2O_5 in the dry electrolyte, as shown in Fig. 3b, the slight changes observed are assigned simply to the change of adsorbed water at the cathode surface. Based on the spectroscopic evidence and the electrochemical performance, it is hypothesized that the significant improvement in capacity from cells with high water content is due to proton intercalation into the



Fig. 3. ¹H NMR spectra of electrochemically cycled V₂O₅ electrodes at charged/discharged states: (a) V₂O₅ electrodes were harvested upon cycling against a carbon counter electrode in a wet Mg(TFSI)₂/G2 electrolyte (2600 ppm H₂O) at 1 M; (b) discharged and charged V₂O₅ electrodes were harvested upon cycling against a Mg metal anode in a dry Mg(TFSI)₂/G2 electrolyte (15 ppm H₂O) at 1 M. All cells were cycled at a current density of 20 μ A/cm². Spectra reported here are normalized to the mass of the sample.

V₂O₅ lattice.

It is crucial to verify that the source of measured current is contributed from real reversible Mg intercalation for the dry electrolyte system, rather than conversion [36] or side-reactions [12] due to the fact that much of the literature relating to Mg intercalation are ambiguous and errors have been reported in the past [36,37]. X-ray absorption near-edge spectroscopy (XANES) was applied to inspect changes of the vanadium (V) oxidation state in pristine, charged, and discharged V₂O₅ using dry electrolyte. The electrochemically charged/discharged V2O5 cathodes were collected from the cells cycled with the dry electrolyte followed with XANES measured in transmission mode (ESI[†]). Normalized vanadium K absorption edge spectra from Fig. 4a shows a ~0.8 eV edge shift (calculated by the first derivative of the normalized energy) of the main line towards lower energy for the discharged V_2O_5 electrode at 0 V (red), as compared with the pristine V_2O_5 (black). This change is accompanied by a 0.27 eV shift of the preedge peak toward lower energy. Lowered edge energy upon discharge indicates a partial reduction of the V oxidation state upon magnesium intercalation. In addition, the asymmetry of the preedge and reduction in fine structure in the near-edge region of the discharged electrode indicates a mixture of reduced and pristine vanadium states. A reduced pre-edge intensity for both charged and discharged states is observed, which is ascribed to the distortion of the square pyramidal coordination of V^{5+} with the nearby five oxygen atoms, since the pre-edge peak is considered to be a fingerprint that reflects the global symmetry around the V ions [38,39]. The pre-edge peak energy in the discharged state shifted



Fig. 4. (a) XANES spectra for pristine (black), charged (blue), and discharged (red) V_2O_5 at the vanadium K-edge; (b) the Fourier transform of the extended fine structure of pristine, charged, and discharged V_2O_5 at the vanadium K-edge. The spectra have not been phase-shifted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

back to higher energy for the electrode charged back to 2.8 V (blue), indicating an increase of the vanadium oxidation state and the reversibility of magnesium insertion into V₂O₅ [40]. However, the edge position and intensity at the charged state did not completely recover and overlap to the pristine state (0.06 eV difference), attributed to the incomplete extraction of Mg upon charging. The Fourier-transformed (FT) extended X-ray absorption fine structure (EXAFS) is shown in Fig. 4b. The decrease in intensity of the first and second FT peaks for the discharged state reflects the structural disorder intrinsic to heterogeneous Mg insertion. EXAFS suggests that the V₂O₅ lattice structure remains largely undisturbed after cycling. The nearly complete reversibility of the local atomic structure following charging is further evidence of reversible Mg intercalation in V_2O_5 through an intercalation pathway. The amount of Mg insertion is calculated to be about 0.2 mol per V₂O₅ based on the change of the vanadium valence state. This finding is consistent with the capacity value from the electrochemical cycling results and, as a consequence the capacity from the Mg anode based V_2O_5 cell is mainly contributed from Mg intercalation pathway.

EDX was applied to directly probe the presence of Mg in the discharged V_2O_5 electrode. Fig. 5a shows the signature spectra of elements C, O, Mg and V. An increase in the characteristic peak of Mg for the discharged V_2O_5 is clearly observed as compared to the charged and pristine electrodes, indicating the existence of a higher concentration of Mg in the discharged state. A minor amount of Mg remained in the charged electrode due to the incomplete removal of Mg, and this finding is in agreement with the XAS and the diffraction results (ESI†). EDX suggested that nearly pure Mg is being deposited on the Mg anode during the plating process, shown in Fig. 5. Surface morphology and elemental analysis for the Mg metal anode that went through 10 cycles *versus* V_2O_5 was

examined to study the morphology evolution on the Mg anode. The surface of the Mg anode appeared reasonably smooth without obvious dendrite formation formed, as shown in the inset image of Fig. 5b. Interestingly, upon a closer inspection, Fig. S7 (SI), pinholes that are hundreds of nanometers in diameter were observed. These pinholes are attributed to the stripping process of the Mg anode during cycling, and similar pinhole morphology was observed and reported for stripping Mg using Mg(TFSI)₂ in the mixture of glvme solvents as electrolyte [21]. Consistent with the XAS and EDX results, X-ray diffraction (XRD) shows the formation of a new phase for discharged V₂O₅ electrodes, as well as the presence of a MgV₂O₅ phase structure. Detailed discussions regarding this part can be found in the ESI[†].

4. Conclusions

In conclusion, it is demonstrated that water level in the (MgTFSI)₂/G2 electrolyte plays an important role for plating/stripping Mg. Using this electrolyte, we have demonstrated that Mg intercalation is occurring, but at capacities much lower than what has been reported previously. In contrast, Mg(TFSI)₂/G2 with a high water content gives higher capacity, with protons participating in intercalation, but such a system lacks the potential for leveraging the Mg metal anode. The presence of proton involvement in the capacity of the V₂O₅-Mg system is conclusively report and should be considered a caution for future investigations of possible Mg intercalation cathodes. Results presented in this work provide informative insights for designing beyond lithium energy storage systems and offer potential guidance for compatibility of metal oxide cathodes with Mg anode. We believe such full cell prototype



Fig. 5. (a) Normalized EDX spectrum for discharged (black), charged (red) and pristine (blue) V₂O₅, with insets of both magnified and offset data from the boxed area, and a SEM image of the discharged electrode; (b) SEM image and EDX spectrum of the cycled Mg anode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

provides a solid foundation for further understanding and development of Mg full cell with high voltage cathodes reasonable for commercial Mg batteries.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http:// dx.doi.org/10.1016/j.jpowsour.2016.05.028.

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