Introducing Highly Redox-Active Atomic Centers into Insertion-Type Electrodes for Lithium-Ion Batteries

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The development of alternative anode materials with higher volumetric and gravimetric capacity allowing for fast delithiation and, even more important, lithiation is crucial for next-generation lithium-ion batteries. Herein, the development of a completely new active material is reported, which follows an insertion-type lithiation mechanism, metal-doped CeO₂. Remarkably, the introduction of carefully selected dopants, herein exemplified for iron, results in an increase of the achievable capacity by more than 200%, originating from the reduction of the dopant to the metallic state and additional space for the lithium ion insertion due to a significant off-centering of the dopant atoms in the crystal structure, away from the original Ce site. In addition to the outstanding performance of such materials in high-power lithium-ion full-cells, the selective reduction of the iron dopant under preservation of the crystal structure of the host material is expected to open up a new field of research.

1. Introduction

The steadily increasing demand for lithium-ion batteries (LIBs) with high energy and power density is triggering the development of new active materials.[1,2] With respect to a potential rapid charging (<10–15 min), this concerns particularly the replacement of the graphite anode, for which the lithium intercalation storage capacity and potential similar to (or better than) graphite and, additionally, fast kinetics. Insertion-type materials, thanks to the conserved structural integrity of the crystalline host material when the mobile guest species is entering the available structural sites, are the best candidates.[10,11] Nonetheless, apart from graphite, only few candidates have been reported so far. Li₄Ti₅O₁₂ and TiO₂ have attracted some interest, but suffer...
from substantially lower capacities (about half that of graphite) and higher operative voltages (1.5−1.7 V).[12–15] This results in a decrease in energy density by a factor of 3−4 on the full-cell level. Another insertion-type material that, however, has attracted only little attention so far is CeO2 due to the following reasons: First, CeO2 is more expensive than titanates (even though cerium is as abundant as copper[16]) and, second, the insertion-type capacity is rather limited, i.e., ≈155 mAh g⁻¹ when considering a maximum lithium uptake of one Li⁺ per CeO2. Furthermore, the precise reaction mechanism is still under debate.[17–19] For our proof-of-concept study, however, it provides a distinct advantage, as it does not undergo any phase transition upon de-/lithiation. This allows us to rule out any potential impact of such structural rearrangement, therefore facilitating the overall investigation and interpretation of the results.

In this study, we show that the introduction of selected metal dopants, exemplarily illustrated for iron, occupying an off-centered position in the CeO2 crystal structure, allows for a dramatic increase in capacity by more than 200%. The key to such an improvement lies in the reduction of the dopant atoms to the metallic state without affecting the crystalline host structure. Such a mechanism—to the best of our knowledge—is reported herein for the first time. Fe-doped CeO2 negative electrodes coupled with high-voltage LiNi0.5Mn1.5O4 positive electrodes provide high-power LIBs with excellent cycling stability and gravimetric energy and power densities up to 200 Wh kg⁻¹ and 8500 W kg⁻¹, respectively.

2. Results and Discussion
2.1. Synthesis and Physicochemical Characterization

Figure 1a presents the X-ray diffraction (XRD) patterns of CeO2 and Ce0.9Fe0.1O2. All reflections are typical for the cubic CeO2

Figure 1. a) X-ray diffraction (XRD) patterns of CeO2 (in black) and Fe-doped CeO2 (Ce0.9Fe0.1O2, in cyan); the JCPDS card No. 81−0792 of the fluorite cubic structure is given as reference in the bottom; b−c) Rietveld refined diffractograms of (b) CeO2 and (c) Ce0.9Fe0.1O2; d−f) X-ray photoelectron spectroscopy (XPS) analysis of pure CeO2 and Ce0.9Fe0.1O2. d) Comparison of the Ce 3d spectra for both samples. e) Fe 3p spectra for Ce0.9Fe0.1O2, and comparison of the O 1s spectra for both samples (f). g−h) Normalized X-ray absorption spectroscopy (XAS) spectra collected at the (g) Ce LIII edge for both samples and (h) Fe K-edge for Ce0.9Fe0.1O2 (inset: background-subtracted Fe pre-edge peak). i) Ultraviolet-visible (UV−vis) absorption spectra for pure CeO2 and Ce0.9Fe0.1O2; as inset the corresponding plots for the determination of the band gap.
structure (Fm$\overline{3}$m space group, JCPDS reference 81-0792), indicating the formation of crystalline CeO$_2$. The absence of any Ce and/or Fe-bearing impurities suggests that Fe was successfully incorporated into the CeO$_2$ lattice. The Rietveld refinement (Figure 1b,c and Table S1, Supporting Information) provides an accurate determination of the unit cell parameters and atomic positions. The introduction of the iron dopant results in an increasing full width at half maximum (FWHM) of the recorded reflections, indicating a slight decrease in crystallite size (20 versus 18 nm), accompanied by a significant decrease of the unit cell volume. X-ray photoelectron spectroscopy (XPS; see Figure S1a,b, Supporting Information, for the survey spectra) confirmed the presence of cerium and oxygen in both samples and iron in Ce$_{0.9}$Fe$_{0.1}$O$_2$. A detailed comparison of these two samples is provided in Figure 1d–f, revealing that Ce is purely tetravalent$^{[20,21]}$ in both cases, while Fe is trivalent$^{[21,22]}$ in Ce$_{0.9}$Fe$_{0.1}$O$_2$ (see Supporting Information for a detailed discussion of the spectra). For a further analysis of the oxidation states and local structure, we performed X-ray absorption spectroscopy (XAS) measurements, collecting data at both the Ce L$_{III}$-edge and Fe K-edge. The XANES spectra at the Ce L$_{III}$-edge of CeO$_2$ and Ce$_{0.9}$Fe$_{0.1}$O$_2$ (Figure 1g) confirm that Ce has the same local environment in both phases.$^{[23]}$ The position and the shape of the main absorption edge indicate that Ce is in its tetravalent state (Figure S2a, Supporting Information). Furthermore, results from the EXAFS region, which can be fitted according to the model obtained from the XRD data, and the unit cell parameters as estimated on the basis of the Ce–O distance, are in good agreement with the results obtained by XRD (Figure S2b,c, Table S2, and Table S3, Supporting Information). The pre-edge feature of the Fe-doped compound in the Fe K-edge XANES spectrum (Figure 1h) infers the presence of Fe$^{3+}$, compatible with a noncentrosymmetric bonding environment. This aliovalent Fe doping results in a slightly reduced band gap of 3.23 eV compared to 3.38 eV for pure CeO$_2$, in good agreement with previous findings$^{[24,25]}$ and thus an increased electronic conductivity (Figure 1i)—presumably also due to the presence of oxygen vacancies to balance the incorporation of the aliovalent dopant. In fact, a comparison of the Raman spectra recorded for Fe-doped CeO$_2$, self-synthesized CeO$_2$, and commercial CeO$_2$ (serving as additional reference) reveals a clear indication for an increased presence of oxygen vacancies as a consequence of the Fe doping (Figure S3, Supporting Information). Nonetheless, as we cannot quantify the amount of oxygen vacancies, we will continue referring to Ce$_{0.9}$Fe$_{0.1}$O$_2$ rather than the theoretically expected composition of Ce$_{0.9}$Fe$_{0.1}$O$_{1.95}$ in the following text.

The two materials were characterized also by (high-resolution) transmission electron microscopy (HR)TEM (Figure 2). The TEM micrographs for pure CeO$_2$ reveal a cubic

![Figure 2. TEM–HRTEM (where TEM is transmission electron microscopy and HRTEM is high-resolution transmission electron microscopy) micrographs of (a–c) CeO$_2$ and (d–f) Ce$_{0.9}$Fe$_{0.1}$O$_2$. g,h) High-angle annular dark-field scanning transmission electron microscopy (HAADF–STEM) micrographs of an exemplary Ce$_{0.9}$Fe$_{0.1}$O$_2$ particle in [110] orientation. The rectangle in (g) shows the area for the subsequent local energy-dispersive X-ray spectroscopy (EDX) mapping for Ce and Fe presented in (i) and (j), respectively. The reflections in the FFT pattern, shown as inset in the HAADF-reference map in panel (h), verifies near-atomic EDX mapping. The extracted elemental maps in (i) and (j) show the distribution of Ce and Fe, respectively, within the exemplary Ce$_{0.9}$Fe$_{0.1}$O$_2$ particle.](https://www.advancedsciencenews.com/doi/abs/10.1002/aden.2000783)
particle shape with an average diameter of around 16 nm, whereas the introduction of Fe into the CeO$_2$ lattice results in a decreased particle size of around 12 nm (Figure 2a,d), which is in good agreement with the XRD results. The corresponding (HR)TEM micrographs (Figure 2b,e) nicely confirm the synthesis of well-crystallized nanoparticles with the characteristic lattice fringes of 0.31, 0.27, and 0.19 nm for the fluorite-related (111), (200), and (220) planes, respectively. Moreover, the fluorite-structured Ce$_{0.9}$Fe$_{0.1}$O$_2$ material does not show any apparent secondary phases, further confirming the successful incorporation of the iron dopant into the CeO$_2$ structure (Figure 2c,f). The well-crystallized structure of the Ce$_{0.9}$Fe$_{0.1}$O$_2$ nanoparticles was also confirmed by conducting high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) together with parallel energy-dispersive X-ray spectroscopy (EDX) for spatially resolved element analysis. Figure 2g shows a uniformly resolved HAADF image of an exemplary Ce$_{0.9}$Fe$_{0.1}$O$_2$ particle in [110] orientation. The rectangle in Figure 2g marks the area of a local EDX mapping to determine the elemental composition of this particle. The near-atomically resolved element mapping (verified by the crystal reflection of the FFT taken from the HAADF reference (inset in Figure 2h)) shows a uniform and atomic-level distribution of Ce and, more importantly, Fe within the nanocrystal (Figure 2i,j, respectively). The quantification of the elemental ratio between Ce and Fe resulted in a value of 9.5:1 which is in very good agreement with the intended ratio of 9:1 and the ratio obtained by inductively coupled plasma optical emission spectroscopy (ICP-OES), revealing a ratio of (9.3:1 for Ce:Fe).

2.2. Electrochemical Characterization with Li Counter Electrodes

For the electrochemical characterization, CeO$_2$ and Ce$_{0.9}$Fe$_{0.1}$O$_2$ based electrodes were subjected to galvanostatic cycling (Figure 3). The first cycle potential profiles are provided in Figure S4a, Supporting Information. The CeO$_2$ electrodes show a reversible capacity of about 168 mAh g$^{-1}$ when applying a specific current of 0.02 A g$^{-1}$. In the subsequent cycles, however, the specific capacity is gradually fading and finally stabilizes at 82 mAh g$^{-1}$ for a specific current of 0.05 A g$^{-1}$ (Figure 3a). This decrease is mainly due to the loss of reversible capacity at higher voltages (i.e., above 1.0 V), as apparent from the dis-/charge profiles (Figure 3b) and, additionally, the cyclic voltammetry (CV) measurements (Figure S4b, Supporting Information).

Doping CeO$_2$ with Fe results in a substantially enhanced specific capacity of 305 mAh g$^{-1}$ in the first cycle (Figure S4a, Supporting Information), which subsequently stabilizes at around 260 mAh g$^{-1}$ (Figure 3a), reflecting an increase of more than 200% compared to pure CeO$_2$. Remarkably, in contrast to pure CeO$_2$, there is no significant capacity fading in the initial cycles, as illustrated by the almost perfect overlap of the dis-/charge profiles (Figure 3b) and the CV sweeps (Figure S4c, Supporting Information). Such a superior capacity performance also translates into much better rate capability as shown in Figure 3c, with the corresponding dis-/charge profiles depicted in Figure 3d. Electrodes based on Ce$_{0.9}$Fe$_{0.1}$O$_2$ reveal higher specific capacities for all applied specific currents, ranging from 0.05 A g$^{-1}$ to 5.0 A g$^{-1}$. For example, at a very high current of 5 A g$^{-1}$, Ce$_{0.9}$Fe$_{0.1}$O$_2$ still provides a capacity of about 70 mAh g$^{-1}$ compared to only 30 mAh g$^{-1}$ for CeO$_2$. Moreover, when
lowering the current to 0.1 A g\(^{-1}\), the doped material provides a capacity of 224 mAh g\(^{-1}\), which is still about thrice as high as for CeO\(_2\) (78 mAh g\(^{-1}\)), underlining again the excellent reversibility of the de-/lithiation reaction in Ce\(_{0.95}\)Fe\(_{0.05}\)O\(_2\). Noteworthy, this increase in capacity is directly correlated to the concentration of the Fe dopant. Lowering the Fe ratio from 0.1 to 0.05 (i.e., Ce\(_{0.95}\)Fe\(_{0.05}\)O\(_2\)) leads to a significant decrease in capacity, i.e., a reversible capacity of 209 mAh g\(^{-1}\) in the first cycle, which subsequently stabilizes at around 180 mAh g\(^{-1}\) (Figure S5, Supporting Information). This increase in reversible capacity is about half the increase when introducing 0.1 Fe, further corroborating the important contribution of the Fe dopant to the superior capacity.

2.3. Elucidating the Reaction Mechanism and Impact of the Fe Dopant

To investigate the impact of the Fe dopant on the de-/lithiation mechanism and, thus, to understand the reason for the enhanced performance, we used a highly complementary set of different techniques, starting with the in situ XRD analysis of CeO\(_2\) and Ce\(_{0.9}\)Fe\(_{0.1}\)O\(_2\) based electrodes (Figure 4a,b). For both measurements, we present the corresponding waterfall diagrams and the contour plots of the recorded XRD patterns in combination with the simultaneously recorded two dis-/charge cycles. For CeO\(_2\) (Figure 4a), the evolution of the XRD patterns reveals a continuous shift of the fluorite-related (111), (200), (220), and (311) reflections to lower \(2\theta\) values due to the increasing unit cell volume upon lithiation, accompanied by a slight broadening of the reflections and decrease in intensity. During the subsequent charge the reflections shift back to the initial \(2\theta\) values and increase in intensity, though remaining slightly lower as compared to the initial pattern. For the second dis-/charge cycle, we observe exactly the same behavior, indicating a highly reversible de-/lithiation. In fact, no new phase is observed, demonstrating that the lithiation occurs solely by solid-solution de-/insertion (in agreement with previous in situ XRD results\([17]\)), while the slight decrease in crystallinity is assigned to extended lattice expansion during the first lithiation. For Fe-doped CeO\(_2\) (Figure 4b), the evolution of the XRD patterns shows essentially the same trend. However, the shift to lower angles is dramatically increased, indicating a substantial increase in unit cell volume resulting from more lithium cations being reversibly inserted, which is in excellent agreement with the extensive capacity increase. For a detailed analysis, we also conducted an ex situ analysis of pristine, discharged (0.01 V), and charged (3.0 V) CeO\(_2\) and Ce\(_{0.9}\)Fe\(_{0.1}\)O\(_2\) electrodes (Figure S6 and Table S2, Supporting Information). Comparing the cubic lattice parameter \(a_0\) for pure and Fe-doped CeO\(_2\) in the pristine and lithiated state reveals an increase from 5.418(1) Å to 5.545(1) Å and from 5.396(1) Å to 5.683(1) Å, respectively, which is in line with the remarkable shift of the (111) and the (200) diffraction peaks shown in Figure S6b (Supporting Information; CeO\(_2\)) and Figure S6d (Supporting Information; Ce\(_{0.95}\)Fe\(_{0.05}\)O\(_2\)). Remarkably, delithiated CeO\(_2\) reveals a minor fraction of Ce\(_2\)O\(_3\) (similar to a previous study\([18]\)), which is not observed for Ce\(_{0.9}\)Fe\(_{0.1}\)O\(_2\). These findings further support our conclusion that the Fe doping leads to a substantially larger amount of Li\(^+\) being reversibly inserted into the crystalline lattice. As a matter of fact, the crystal structure is very well preserved after a complete dis-/charge cycle as confirmed by the ex situ HRTEM micrographs depicted in Figure 4c,d. Cycled Ce\(_{0.9}\)Fe\(_{0.1}\)O\(_2\) reveals the same lattice fringes as the pristine sample, i.e., 0.31, 0.27, and 0.19 for the (111), (200), and (220) planes, respectively (Figure 4c), as well as an essentially perfect atomic ordering even at the very edge of the particle (Figure 4d).

To complement this study, ex situ XAS analysis was performed. XANES spectra were recorded at the Ce LIII-edge of CeO\(_2\) and Ce\(_{0.9}\)Fe\(_{0.1}\)O\(_2\) before and after lithiation and are presented in Figure 4e,f and Figure S2a (Supporting Information). For both cases, the XANES data clearly show a complete reduction of Ce\(^{4+}\) to Ce\(^{3+}\) (Figure S2a, Supporting Information). Moreover, the EXAFS fits (Table S3 and Figure S2b,c, Supporting Information) performed on the first coordination shell of the lithiated samples confirm the reduction of Ce, showing a marked increase of the Ce–O distance (Table S3, Supporting Information) in good agreement with XRD data (Table S2, Supporting Information). The reduction occurs also for the Fe dopant, as highlighted by the comparison of the XANES regions measured on pristine and lithiated Ce\(_{0.9}\)Fe\(_{0.1}\)O\(_2\) at the Fe K-edge, indicating the reduction of Fe to the metallic state (Figure 4g). The quantitative EXAFS analysis has also been performed at the Fe K-edge (Figure 4h, i and Table S3, Supporting Information). The results for the pristine sample are in agreement with the analyses of the pre-edge and XANES regions. Specifically, Fe shows a first coordination shell containing ≈5 oxygen atoms with an average Fe–O bond distance of 1.97(1) Å. A weak second shell signal, corresponding to a small bump at ≈3.3 Å is resolved in Figure 4i. This feature is satisfactorily modeled by a mixed Ce/Fe shell with Fe and Ce atoms at 2.96(1) Å and 3.45(1) Å, respectively. The rather short Fe–O distance and the low coordination number suggest that Fe does not substitute Ce at the center of the CeO\(_2\) cube, but occupies a significantly off-centered position, close to one face of the CeO\(_2\) cube. To the best of our knowledge such a coordination geometry has never been reported for Fe\(^{3+}\) in inorganic compounds. The metallic character of Fe in the lithiated sample is evident when comparing the length of the EXAFS oscillation in Figure 4h and the relative Fourier Transform (FT) profile (Figure 4i) with that of the pristine sample. Fit results indicate a first shell mainly composed of Fe atoms with a Fe–Fe bond distance of 2.42(1) Å. The shoulder at the low-R side of the main FT peak, though, can be modeled in the EXAFS multiparameter fit as a Fe–O bond, suggesting that the first shell comprises Fe and O, which prevents us from an accurate estimation of the coordination number. Interestingly, the Fe–Fe interatomic distance is significantly shorter than the one observed in BCC Fe (2.48 Å), indicating that Fe in the lithiated sample forms extremely small subnanometric clusters\([26,27]\). Such shortening can be explained in terms of surface stress due to the higher surface to volume ratio in the clusters\([26]\). Montano et al.\([26,29]\) studied Fe clusters isolated in solid argon via EXAFS, observing a gradual reduction of the Fe–Fe distance as the cluster size decreased. The Fe–Fe distance was close to 2.40 Å in oligo-clusters with a mean diameter of 9 Å. They also noticed that the 9 Å particle size marks a threshold between clusters showing a BCC structure and a less ordered structure compatible with an FCC or HCP lattice. In
our case, no Fe second shell signal can be observed, indicating
the lack of an ordered structure, which fits well with the ear-
lier mentioned presence of a mixed O/Fe first shell and the
small value for the Fe−Fe distance; all being in agreement with
the hypothesis of very small subnanometric Fe clusters.\cite{30,31}

According to Fritsche and Benfield,\cite{30} a coordination number

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Figure 4. a) In situ X-ray diffraction (XRD) analysis of pure CeO$_2$: Waterfall diagrams (left) and contour plots (middle; the different coloring in red and blue represents the lowest and highest relative intensity of the XRD peaks, respectively) of consecutively recorded XRD patterns as well as the corresponding galvanostatic dis-/charge profiles for the first two de-/lithiation cycles (right; specific current: 10 mA g$^{-1}$; cut-off voltages: 0.01 and 3.0 V versus Li/Li$^+$. b) In situ XRD analysis of Ce$_{0.8}$Fe$_{0.2}$O$_2$: Waterfall diagrams (left) and contour plots (middle; see panel (a) for the color coding) of consecutively recorded XRD patterns as well as the corresponding galvanostatic dis-/charge profiles for the first two de-/lithiation cycles (right; specific current: 20 mA g$^{-1}$; cut-off voltages: 0.01 and 3.0 V versus Li/Li$^+$. c, d) Ex situ transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) micrograph, respectively, of Ce$_{0.8}$Fe$_{0.2}$O$_2$ subjected to one complete dis-/charge cycle. e–g) Ex situ XANES data obtained for CeO$_2$ and Ce$_{0.8}$Fe$_{0.2}$O$_2$: Comparison of the normalized XANES spectra collected at the Ce L$_{III}$-edge for the pristine material and after discharge to 0.01 V for (e) CeO$_2$ and (f) Ce$_{0.8}$Fe$_{0.2}$O$_2$. g) Comparison of the normalized XANES spectra collected for Ce$_{0.8}$Fe$_{0.2}$O$_2$ at the Fe K-edge for the pristine material and after discharge to 0.01 V (inset: background subtracted Fe pre-edge peak). h–i) Ex situ EXAFS spectra and corresponding multiparameter fit for pristine and discharged Ce$_{0.8}$Fe$_{0.2}$O$_2$ (cyan and black lines, respectively). h) The Fe K-edge k$^3$-weighted EXAFS region of Ce$_{0.8}$Fe$_{0.2}$O$_2$. i) The Fourier transforms (uncorrected for phase shifts) of the EXAFS for Ce$_{0.8}$Fe$_{0.2}$O$_2$. 

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close to 3 would indeed be compatible with a Fe tetramer with tetrahedral geometry. Our EXAFS results therefore suggest that Fe in the lithiated sample is mainly present as an extremely small cluster, presumably a dimer or tetramer (including a minor interaction with the surrounding oxygen). Considering that the crystalline structure of cerium oxide is well preserved upon reduction of Fe to the metallic state (Figure 4c,d), the mixed Fe/O first shell in the lithiated state, and the mixed Ce/Fe shell in the pristine state, we propose the following model: Beside the very homogeneous Fe distribution observed at the sale of Figure 2j, there are presumably always two Fe$^{3+}$ cations in direct vicinity, which is, in fact, reasonable regarding the need to balance the aliovalent doping induced point defects (similar to Fe-doped ZnO$^{32,33}$). In the reduced state, these iron atoms experience an increased attractive interaction, thus getting closer, without, however, destroying the crystalline host structure. In such a way, the available sites for lithium cations are increased.

To further deepen our understanding of the reaction mechanism, density functional theory (DFT) based calculations on pure and Fe-doped CeO$_2$ were conducted. In agreement with the experimental data, Ce in CeO$_2$ is eightfold coordinated by oxygen, resulting in a cubic environment (Figure 5a). However, as the atomic radius of Fe is about 25% smaller than the one of Ce, the Fe–O distances in the eightfold-coordinated position are too large to allow for strong Fe–O interaction. Rather, a shift of Fe toward the face center of the surrounding oxygen cube is observed, resulting in fourfold coordinated Fe with shorter Fe–O distances. This scenario is depicted in Figure 5a for supercells of pure and Fe-doped CeO$_2$, where in case of the Fe-doping one Ce atom per supercell is replaced by Fe (corresponding to ≈3 at% Fe doping). The configuration with fourfold-coordinated Fe is energetically more stable by ≈2 eV. It should be noted that the Fe–O bond distance of 1.83 Å is somewhat smaller than the experimental value, which may be a consequence of the different doping levels (i.e., 3 at% versus 10 at%). Apart from being energetically more favorable, the shift of the dopant away from the cube center provides additional space in the structure that may enable the insertion of further Li. For more insight, we investigated pure and Fe-doped CeO$_2$ structures with different degrees of lithiation. First, we compared half-lithiated ordered-like structures with 0.5 Li per formula unit (Figure 5b). The non-doped compound is unstable with respect to a decomposition into Li-metal and CeO$_2$ (in agreement with the structural instability non-doped CeO$_2$ upon lithiation, resulting in the formation of Ce$_2$O$_3$ as discussed.

![Figure 5](https://www.advenergymat.de)

**Figure 5.** a) Crystal structure of pure CeO$_2$ and Fe-doped CeO$_2$ and the local environments corresponding to both cases. b) Prototype structure for a half-lithiated (i.e., 0.5 Li per unit formula), ordered, Fe-free CeO$_2$, and Fe-doped structure. c) Prototype structures for incorporating additional Li within the structure of Fe-doped CeO$_2$. 

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earlier), whereas the doped compound is stable with respect to the elemental constituents. When introducing 1 Li into the Fe-doped CeO$_2$ lattice (Figure 5c), the inserted Li is preferably located in the vicinity of the Fe dopant.

Moreover, Bader charge analysis as well as the magnetic moment of iron clearly indicate the reduction of iron (see Table S4, Supporting Information). The addition of further Li per supercell results in the accumulation of additional charge on the Fe atom. Only once Fe approaches the Fe$^{0}$ oxidation state, significant changes of the Bader charges on the Ce sites are observed. Together with the evolution of the magnetic moment of Fe, this strongly indicates a reduction of Fe$^{3+}$ to Fe$^{0}$ (see Supporting Information for the detailed discussion). Our findings clearly support the experimentally observed improved Li uptake of the Fe-doped compound as compared to pure CeO$_2$ and corroborate the surprising reduction of Fe to its metallic state.

Considering that the complete reduction of Fe and the reduction of Ce$^{4+}$ to Ce$^{3+}$ correspond to a theoretical total lithium uptake of 1.2 Li per formula unit Ce$_{0.9}$Fe$_{0.1}$O$_2$, a theoretical capacity of 196 mAh g$^{-1}$ would be expected. This value, however, is lower than the experimentally determined specific capacity. To understand this aspect, we conducted a comparative kinetic analysis of the lithium storage process for CeO$_2$ and Ce$_{0.9}$Fe$_{0.1}$O$_2$ using CV to determine the ratio of the diffusion- and pseudocapacitive contribution to the overall capacity. Figure 6a,b displays the CV data for CeO$_2$ and Ce$_{0.9}$Fe$_{0.1}$O$_2$. The general shape is well preserved upon increasing the sweep rate from 0.05 to 2.0 mV s$^{-1}$. Utilizing the equation $i(V) = k_1 v + k_2 v^{1/2}$ (see Supporting Information for a detailed discussion), we find that at a scan rate of 1.0 mV s$^{-1}$ ~79% of the charge storage for CeO$_2$ arises from pseudocapacitive processes (Figure 6c), while it is “only” 57% in case of Ce$_{0.9}$Fe$_{0.1}$O$_2$ (Figure 6d). In fact, the pseudocapacitive contribution is substantially higher for pure CeO$_2$ across all applied sweep rates (Figure 6e), reaching 85% for CeO$_2$ and 73% for Ce$_{0.9}$Fe$_{0.1}$O$_2$ at 2.0 mV s$^{-1}$, indicating that the slightly smaller particle size and, thus, larger surface area of the Fe-doped material does not lead to a greatly extended pseudocapacitive charge storage (especially relatively speaking, while it may slightly increase, indeed, when considering absolute values—see also the following comparison at the end of this paragraph). Generally, though, the small particle size presumably contributes to the excellent rate performance.$^{34,35}$ Even more important for the understanding of the lithiation mechanism, the rather high pseudocapacitive contribution even at low sweep rates (e.g., 44% and 30% for CeO$_2$ and Ce$_{0.9}$Fe$_{0.1}$O$_2$ at 0.05 mV s$^{-1}$, respectively) provides an explanation for the significantly higher specific capacity values compared to the theoretical maxima, i.e., about 160 and 305 mAh g$^{-1}$ compared to <78 (Li$_{1.5}$CeO$_2$) and 196 mAh g$^{-1}$ for CeO$_2$ and Fe-doped CeO$_2$, respectively. As a matter of fact, in case of Ce$_{0.9}$Fe$_{0.1}$O$_2$, the complete reduction of Ce$^{4+}$ to Ce$^{3+}$ and Fe$^{3+}$ to Fe$^{0}$ corresponds to a capacity contribution of 196 mAh g$^{-1}$, while the pseudocapacitive contribution at such low rates is about 30%, i.e., the remaining ~100 mAh g$^{-1}$.

2.4. Enhancing the Performance by Applying a Carbon Coating

Focusing on the electrochemical performance, we added a carbon coating to Ce$_{0.9}$Fe$_{0.1}$O$_2$ (denoted as Ce$_{0.9}$Fe$_{0.1}$O$_2$-C) using a rather simple, but effective method based on glucose as carbon precursor.$^{36,37}$ The final carbon content was determined via TGA to be ~16 wt% (Figure S7, Supporting Information). Comparison of the XRD pattern with those of pure CeO$_2$ and noncoated Ce$_{0.9}$Fe$_{0.1}$O$_2$ (Figure 7a) shows that the additional processing did not affect the crystal structure.

Figure 6. Kinetic analysis of the lithium storage contributions for CeO$_2$ and Ce$_{0.9}$Fe$_{0.1}$O$_2$. a,b) Cyclic voltammograms for electrodes based on (a) CeO$_2$ and (b) Ce$_{0.9}$Fe$_{0.1}$O$_2$ at different sweep rates. c,d) Illustration of the capacitive contribution for (c) CeO$_2$ (black area) and (d) Ce$_{0.9}$Fe$_{0.1}$O$_2$ (cyan area) in comparison to the diffusion-controlled contribution (light gray area in both cases) to the overall charge storage at 1.0 mV s$^{-1}$. e) Comparison of the percentage of the capacitive contribution to the overall recorded capacity at different scan rates for CeO$_2$ (in black) and Ce$_{0.9}$Fe$_{0.1}$O$_2$ (in cyan).
In line with this, the HRTEM micrograph presented in Figure 7b reveals the same lattice fringes as the as-synthesized \( \text{Ce}_{0.9}\text{Fe}_{0.1}\text{O}_2 \). In addition, the HRTEM analysis reveals the presence of a thin (≈5 nm) carbon layer on the outer surface of the secondary particles, as highlighted by the dashed black line, which simultaneously interconnects the primary nanocrystals. In situ XRD analysis of the electrodes based on \( \text{Ce}_{0.9}\text{Fe}_{0.1}\text{O}_2\text{-C} \) (Figure 7c) reveals generally the same trend as for the non-coated material, with one slight difference: The shift to lower 2\( \theta \) values upon lithiation is more pronounced in this case, suggesting an even greater lithium storage capacity—presumably due to the increased electronic conductivity induced by the carbon coating. In fact, subjecting \( \text{Ce}_{0.9}\text{Fe}_{0.1}\text{O}_2\text{-C} \) based electrodes to constant (Figure 7d) and elevated current (Figure 7e) cycling reveals a clear improvement in terms of reversibly achievable capacity across all specific currents applied. \( \text{Ce}_{0.9}\text{Fe}_{0.1}\text{O}_2\text{-C} \) shows a stable specific capacity of 350 mAh g\(^{-1}\) over 50 cycles at 50 mA g\(^{-1}\), which is 1.3 and 4.5 times higher than that of \( \text{Ce}_{0.9}\text{Fe}_{0.1}\text{O}_2 \) and \( \text{CeO}_2 \), respectively. Even at 5 A g\(^{-1}\) \( \text{Ce}_{0.9}\text{Fe}_{0.1}\text{O}_2\text{-C} \) provides the remarkable capacity of about 160 mAh g\(^{-1}\) compared to 70 and 30 mAh g\(^{-1}\) for \( \text{Ce}_{0.9}\text{Fe}_{0.1}\text{O}_2 \) and \( \text{CeO}_2 \), respectively. The comparison of the corresponding dis-/charge profiles (Figure S8, Supporting Information) shows that this is partially related to the reduced polarization.
and IR drop. But also the de-/insertion dynamics appear to be improved, especially when comparing the profiles recorded for Ce₀.₉Fe₀.₁O₂ (Figure S8b, Supporting Information) and Ce₀.₉Fe₀.₁O₂·C (Figure S8c, Supporting Information).

2.5. High-Performance Ce₀.₉Fe₀.₁O₂·C/LNi₀.₅Mn₁.₅O₄ Full-Cells

Finally, we coupled (pre-cycled) Ce₀.₉Fe₀.₁O₂·C anodes with high-voltage LiNi₀.₅Mn₁.₅O₄ (LNMO) cathodes to realize LIBs with a suitable full-cell voltage and high power density to benefit from the excellent rate capability of Ce₀.₉Fe₀.₁O₂·C (Figure 8a). Such Ce₀.₉Fe₀.₁O₂·C/LNMO full-cells show an initial specific discharge capacity of ≈85 mAh g⁻¹ (based on the mass of LNMO; 10ᵗʰ cycle) at 1C in a voltage range of 1.0–4.4 V (Figure 8b). Even at 10C—meaning that the cell is dis-/charged in less than 6 min—with a slightly extended voltage range of 0.5–4.5 V, the cell still provides an excellent performance with a high specific capacity of 71 mAh g⁻¹ after 200 cycles and a coulombic efficiency of about 99.8%. The corresponding dis-/charge profiles recorded for the 11ᵗʰ, 100ᵗʰ, and 200ᵗʰ cycle (Figure 8c; all efficiency of about 99.8%). The corresponding dis-/charge profiles recorded for the 11ᵗʰ, 100ᵗʰ, and 200ᵗʰ cycle (Figure 8c; all efficiency of about 99.8%).

The introduction of redox-active dopants into insertion-type active materials is a very promising strategy to maintain the advantages of the insertion mechanism, while simultaneously increasing the lithium storage capability—in our case by more than 200%. We have shown that this beneficial effect results from both the reduction of the off-centered Fe dopant to the metallic state, which occurs without affecting the crystalline host structure, and the additional available space for Li⁺. Coupling this new active material with high-voltage LiNi₀.₅Mn₁.₅O₄ as cathode provides high-power LIBs with excellent cycling stability and gravimetric energy and power densities of >200–110 Wh kg⁻¹ and 105–8500 W kg⁻¹, respectively. While

Figure 8. Electrochemical performance of Ce₀.₉Fe₀.₁O₂·C/LNMO Li-ion full-cells with an anode/cathode capacity ratio of around 1.2–1.3 (at 1C), subjected to galvanostatic cycling (all capacity values given herein refer to the cathode active material). a) Schematic presentation of the full-cell configuration. b,c) Constant current cycling for 200 cycles at 10C after 10 formation cycles at 1C (voltage range: 1.0–4.4 V for the first 10 cycles and 0.5–4.5 V for the following cycles) with (b) the plot of the specific dis-/charge capacity and coulombic efficiency versus the cycle number and (c) the corresponding full-cell dis-/charge profiles for the 11ᵗʰ, 100ᵗʰ, and 200ᵗʰ cycle at 10C. d) Multirate galvanostatic cycling, plotting the dis-/charge capacity versus the cycle number at C/3, C/2, 1C, 2C, 3C, 5C, 10C, 20C, and 30C before getting back to C/3 (voltage range: 1.0–4.4 V). e) Ragone-type plot, providing a comparison of the specific energy and power of the Ce₀.₉Fe₀.₁O₂·C/LNMO lithium-ion full-cell presented herein (based on the mass of the anode and cathode active material) and earlier reported lithium-ion batteries (LIBs; marked with colored triangles) as well as lithium-ion capacitors (LIC; marked with colored asterisks). The corresponding data are also listed in Table S6, Supporting Information.

3. Conclusions

To compare these results with literature, focusing especially on high-power devices such as fast-charge LIBs [38–41] and lithium-ion capacitors (LICs), [42–45] we plotted the given specific energy and power at different C rates in a Ragone-type plot (Figure 8e). Obviously, the Ce₀.₉Fe₀.₁O₂·C/LNMO full-cell outperforms the LIB and LIC references. Even at an extremely high specific power of 8.5 kW kg⁻¹, such a LIB cell still delivers a specific energy of 111 Wh kg⁻¹. Notably, the maximum power values provided by Ce₀.₉Fe₀.₁O₂·C/LNMO full-cells are similar or even exceeding those of very recently reported LICs [42–45], while providing significantly higher specific energies (see also the detailed comparison provided in Table S6, Supporting Information), rendering it very suitable for high-power applications.
this result by itself is already remarkable, we may anticipate that particularly the highly reversible, selective reduction of the dopant on the atomic scale within the maintained crystalline CeO$_2$ lattice will allow for reconsidering the introduction of (transition) metal dopants in insertion-type battery materials and, ideally, also for the investigation of metallic atoms and their general properties as such when being confined in physically stable host structures.

4. Experimental Section

Materials Synthesis: Fe-doped CeO$_2$ (Ce$_{0.9}$Fe$_{0.1}$O$_2$) was synthesized by dissolving 1 mmol Fe(NO$_3$)$_3$·9H$_2$O (Alfa Aesar) and 9 mmol of Ce(NO$_3$)$_3$·6H$_2$O (Sigma-Aldrich) in 80 mL deionized water. After stirring the solution for 1 h at room temperature, an aqueous solution (Cu-K$_\alpha$ = 1.540598 Å) or an automated Philips Bragg-Brentano diffractometer equipped with a graphite monochromator. For the latter, the long-focus Cu tube was operated at 40 kV and 40 mA with a 0.02° step size for the pre-edge (for measurements at the Fe K-edge) and in fluorescence mode by means of the ARTEMIS software in the Fourier Transform (FT) space. UV–vis DRS spectra were recorded with a UV–vis spectrophotometer (Shimadzu UV-2600). The band gap was calculated using the following equation:

$$E_g = \frac{\hbar^2}{2m^*} \left( \frac{1}{\alpha} \right)^2$$ (1)

where $E_g$ is the optical energy band gap, $h$ is the photon energy, $\alpha$ is the absorption coefficient, and $A$ is a proportionality constant; $n$ is equal to 1 for a direct gap and equal to 4 for an indirect gap. The values of $E_g$ for direct and indirect transitions can be obtained by linear interpolation and extrapolation. The particle morphology was studied by TEM (Jeol JEM-3000) and HRTEM (Image C$_2$-corrected FEI Titan 80–300 kV at 300 kV). HAADF–STEM was conducted using a Thermo Fisher Titan Themis Z equipped with a probe-corrector (S-COR) and operated at 60 kV. To lower the effect of chromatic aberrations, the energy width of the Schottky electron source was lowered from 0.8 to 0.3 eV by slight excitation of the monochromator. Drift-corrected elemental mappings were acquired using an EDX detector (Thermo Fisher SuperX). Typical mapping times for the EDS analysis were about 10 min using multiple drift-corrected single scans (512 × 512 pixels). ICP–OES was performed on a Spectro Auros-SOP system. For the ICP–OES analysis, 10 mg of each sample was dissolved in hot hydrochloric acid and subsequently diluted with deionized water before performing the measurement. Thermogravimetric analysis (TGA; TA Instruments Q5000) was performed at a heating rate of 5 °C min$^{-1}$ under O$_2$ atmosphere. Raman spectroscopy was carried out with a confocal Raman microscope (InVia Renishaw) in the spectral range of 100–1000 cm$^{-1}$ using a 633 nm laser excitation source and a power of 25 mW. Each spectrum was taken as the average of 30 accumulations with 60 s of acquisition.

Electrode Preparation: The Ce$_{0.9}$Fe$_{0.1}$O$_2$-C and CeO$_2$ based electrodes were composed of the active material (75 wt%), conductive carbon (Super C65, TIMCAL, 20 wt%), and sodium carboxymethyl cellulose (CMC, Dow Wolff Cellulosics, 5 wt%). For the slurry preparation, CMC was dissolved in ultrapure water (1.25 wt% solution) and subsequently Super C65 and the active material were added. The resulting mixture was dispersed by planetary ball milling for 2 h. The resulting electrode paste was cast on dendritic copper foil (Schlenk, 99.9%) using a laboratory doctor blade (wet film thickness: 120 μm). After drying overnight at room temperature, disk-shaped electrodes (12 mm in diameter) were cut and dried under vacuum at 120 °C for 24 h. The active material mass loading of each disk electrode ranged between 1.3 and 1.6 mg cm$^{-2}$. The Li$_2$Mn$_{2}$Ni$_{0.4}$O$_{4}$ (LNMO) cathode material used for the full-cell assembly has been described in our previous work. The LNMO-based electrodes were prepared by mixing the corresponding active material (80 wt%), conductive carbon (Super C65, TIMCAL, 15 wt%), and polyvinylidene fluoride (PVDF 6020, Solvay, 5 wt%) in N-methyl-2-pyrrolidone (NMP, Alrich). The resulting slurry was cast on aluminum foil using a laboratory doctor blade (wet film thickness: 120 μm).
thickness: 60 μm. The wet electrodes were immediately dried at 60 °C to remove the NMP, then punched to obtain disk electrodes (r = 12 mm), which were further vacuum-dried at 150 °C for 12 h. The active material mass loading (LNMO) was about 2.2 mg cm⁻².

Electrochemical Measurements: The electrochemical performance was evaluated either in CR2032 coin cells or in Swagelok-type three-electrode cells using lithium foil (Honjo, battery grade) as counter and reference electrodes. All cells were assembled in an argon-filled glove box (MBraun UNIlab), H₂O and O₂ content < 0.1 ppm). The electrolyte consisted of a 1 M solution of LiPF₆ in ethylene carbonate/diethyl carbonate (EC/DEC; 3:7 by volume). Prior to the electrochemical characterization, the cells were allowed to rest for 6 h. CV was carried out using a VMP3 potentiostat (BioLogic), applying 0.01 and 3.0 V as reversing potentials. Galvanostatic cycling tests were performed by means of a battery tester (Maccor 4300), setting the cut-off voltages to 0.01 and 3.0 V versus Li/Li⁺ for the half-cell experiments. It is important to note that the mass of the carbon coating for Ce₀.⁹Fe₀.¹O₂-C was included for the calculation of the specific capacity. For the full-cells, the Ce₀.⁹Fe₀.¹O₂-C anodes were first preactivated in half-cells (Swagelok-type), which were galvanostatically charged for 20 cycles and finally charged to 1.75 V in the 20th cycle. Subsequently, the cells including the preactivated Ce₀.⁹Fe₀.¹O₂-C were disassembled in a glove box (MBraun UNIlab) and the electrodes were washed with fresh electrolyte before assembling the Ce₀.⁹Fe₀.¹O₂-C/LNMO full-cells. The cut-off voltages for the full-cell tests were set to 1.0–4.4 or 0.5–4.5 V, as indicated in the text. All electrochemical measurements were performed in thermostatic climatic chambers at a temperature of 20 ± 1 °C.

In Situ XRD Analysis: The in situ XRD experiments were carried out employing a self-designed in situ cell.[36] The composition of the electrodes was the same as for those used for the electrochemical characterization described above. In this case, however, the electrode paste was cast directly on the beryllium (Be) disk (wet film thickness: 250 μm), acting simultaneously as current collector and “window” for the X-ray beam. The coated Be electrode was dried at 50 °C under vacuum for 12 h. Lithium foil served as counter and reference electrode, while glass fiber sheets (GF/D, Whatman) soaked with 300 μL of the electrolyte were used as separator. The in situ cell was allowed to rest for 12 h before starting the measurement. Galvanostatic cycling was performed using a potentiostat/galvanostat (SP-150, BioLogic) and applying a specific current of 10, 20, and 25 mA g⁻¹ for CeO₂, Ce₀.⁹Fe₀.¹O₂, and Ce₀.⁹Fe₀.¹O₂-C, respectively (cut-off potentials: 0.01 and 3.0 V). XRD analysis was carried out in a 2θ range of 20–80° with a time per scan of around 30 min.

Ex Situ TEM Analysis: For the ex situ TEM characterization of Ce₀.⁹Fe₀.¹O₂, half-cells were subjected to one full dis-/charge cycle at 20 mA g⁻¹ and subsequently opened in an argon-filled glove box. The electrodes were rinsed with DMC to remove any residual electrolyte and dried in the glove box. Small amounts of the electrode coating were scratched off and dispersed in DMC. The solution was drop-casted onto holey carbon films mechanically supported by a copper-mesh (standard 3 mm TEM grid). The DMC solvent was removed under argon atmosphere prior to the transfer of the specimen to the vacuum of the TEM.

Ex Situ XANES and EXAFS Analysis: For the ex situ XANES and EXAFS analysis of Ce₀.⁹Fe₀.¹O₂ and CeO₂, half-cells were discharged at 20 mA g⁻¹ to 0.01 V and then opened in an argon-filled glove box. The electrodes were rinsed with DMC to remove any residual electrolyte, then dried and sealed within polyethylene (PE) foil to avoid any potential air contamination during the transport to the synchrotron and during the measurement.

DFT Calculations: DFT calculations have been conducted with the Vienna ab initio simulation package (VASP).[37] VASP is a periodic plane wave code, in which the electron–ion interaction is described by pseudopotentials for effective computation. Spin-polarized calculations were conducted using the projector augmented wave method,[38] while the exchange and correlation were accounted for by the generalized gradient approximation in the formulation of Perdew, Burke, and Ernzerhof.[39] All structures investigated are based on a 2 × 2 × 2 supercell of the CeO₂ archetype structure and were optimized with respect to atomic positions and lattice parameters using a plane wave energy cut-off of 500 eV and a 4 × 4 × 4 k-point mesh. For the determination of the oxidation states, Bader charges and magnetic moments were analyzed.[60–63]

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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