Introduction

Given the urgent need for next-generation energy storage systems for electric vehicles (EVs) to relieve climate change and secure energy sustainability, rechargeable nonaqueous Li–O₂ batteries have received significant attention because of their very high theoretical energy density (11 680 Wh kg⁻¹),[1–5] which is several times higher than that of state-of-the-art Li-ion batteries.[6–8] The high energy density arises from two factors: the use of the lightest metal Li as the anode and the use of abundant atmospheric O₂ as the cathode-active reactant.[9,10] The key electrochemical reactions during the discharge and charge processes in a nonaqueous Li–O₂ battery system are the oxygen reduction reaction (ORR) and the oxygen evolution reaction (OER), which can be depicted as 2Li²⁺+O₂+2e⁻→Li₂O₃, E = 2.96 V versus Li/Li⁺.[11,12] However, during discharge, the insoluble solid product lithium peroxide (Li₂O₃) can fill the porous cathode and block the electron, oxygen, and Li⁺ pathways to lead to an increased discharge capacity and, eventually, to the termination of the discharge process at quite a low specific capacity. Even worse, during charge, Li₂O₃ is hard to decompose into lithium ions and oxygen because of its insulating nature, which dictates the cell reversibility and leads to a poor cycling stability and high overpotential.[13–15]

Thus, many catalysts have been developed to improve the electrochemical performance of nonaqueous Li–O₂ batteries, such as transition-metal oxides (MnO₂, Co₃O₄, Fe₂O₃, CoFe₂O₄) and their composites,[11,16–24] noble-metal-based nanomaterials and their oxides (Au, Pt, Ag, Ru, MPt, MPd, and RuO₂),[12,25–35] and heteroatom-doped carbonaceous materials (N-doped graphene, carbon nanotubes (CNTs), and carbon spheres).[36–38] Among these catalysts, noble metals and their oxides have a high intrinsic catalytic activity for both the ORR and OER and thus have led to improvements in nonaqueous Li–O₂ battery performance.[39,40] However, the high cost and scarcity of noble metals impede the widespread application of these highly efficient catalysts.[41] Transition-metal oxides are much more abundant, less costly, more eco-friendly, and lower in weight and have been studied extensively for many electrochemical energy storage systems, such as Li-ion batteries, fuel cells, and supercapacitors.[42–45]

Recently, Fe₂O₃-based catalysts have been investigated and demonstrated in the nonaqueous Li–O₂ battery system and exhibit promising catalytic activities for the OER and ORR.[11,19,21,23,46–47] For example, a cathode made of Fe₂O₃-nanocluster-decorated graphene was reported by Zhang et al.,[48] with which a nonaqueous Li–O₂ battery displayed a high discharge capacity of 8290 mAhg⁻¹ and a round-trip efficiency of 65.9%. Lai et al.[49] synthesized Fe₂O₃ nanoflakes and explored the influence of this catalyst on the electrochemical performance of nonaqueous Li–O₂ batteries. With this catalyst, the discharge–recharge overpotential was reduced to approximately 0.83 V. The same group also prepared a γ-Fe₂O₃/carbon nanocomposite from metal–organic frameworks (MOFs) as a catalyst for nonaqueous Li–O₂ batteries that exhibited a low charge overpotential of approxi-
Sener et al. \[24\] prepared monodispersed CoFe$_2$O$_4$ nanoparticles supported on Vulcan XC-72 as a cathode for nonaqueous Li–O$_2$ batteries. With 16.4 wt% CoFe$_2$O$_4$, the battery exhibited a high discharge capacity of 13 380 mAh g$^{-1}$CoFe$_2$O$_4$. A high-capacity nonaqueous Li–O$_2$ battery with enhanced oxygen reduction and evolution utilizing a catalyst prepared by the in situ decoration of hematite nanoparticles on CNTs was presented by Jee et al.\[47\]. Their battery delivered a very high capacity of 26.5 Ah g$^{-1}$ in the first cycle and a relatively good cycling performance (48 cycles with a capacity limit of 1.5 Ah g$^{-1}$). Wu et al.\[23\] prepared monodispersed Fe$_3$O$_4$ nanoparticles supported on Vulcan XC-72 carbon as a catalyst for the OER and obtained a nonaqueous Li–O$_2$ battery with an excellent cycling stability (≈ 50 cycles with a capacity of 500 mAh g$^{-1}$).

In previous studies,\[20,21,23\] Fe$_3$O$_4$ was used mainly as nanoparticles that can connect to each other through a binder to form enough pores for oxygen diffusion and the deposition of the solid product. However, as a result of their similar scales to carbon materials, the pore sizes are similar to those formed by carbon nanoparticles, which leads to a limited discharge capacity.\[49\] Herein, the Fe$_3$O$_4$ nanotube structure is introduced into the oxygen electrode and is expected to form hierarchical pores on the micro-to the meso- and macroscale in the cathode structure to facilitate oxygen diffusion, electron delivery, and liquid-electrolyte distribution.\[49\] We fabricate paramecium-like Fe$_3$O$_4$ nanotubes (FNTs) by a modified template method.\[50,51\] Then, the obtained FNTs are mixed with Super P (SP) to construct a cathode for nonaqueous Li–O$_2$ batteries. Significantly, the nonaqueous Li–O$_2$ battery with this new catalyst exhibits an excellent electrochemical performance in terms of low discharge and charge overpotentials, high specific capacity, and long cycle life with enhanced cycling stability, which indicates that paramecium-like FNTs have much better catalytic activities for both the ORR and OER than Fe$_3$O$_4$ nanoparticles (FNPs) and SP.

**Results and Discussion**

**Characterization of FNTs and FNPs samples**

XRD patterns of as-synthesized FNTs and FNPs samples in the range of 2θ = 20–70° are presented in Figure 1a. There are eight diffraction peaks in the patterns of both samples, which match well to the characteristic peaks of a pure rhombohedral phase of hematite (α-Fe$_2$O$_3$, JCPDS # 33-0664) with a rhombohedrally centered hexagonal structure.\[52\] This indicates that the samples are not amorphous but well crystallized. Raman spectra of FNTs and FNPs samples in the range of ˜v = 100–1000 cm$^{-1}$ are presented in Figure 1b. The spectra of both samples are similar, and six peaks located at 226, 248, 291, 411, 499, and 613 cm$^{-1}$ are observed. The peaks at 226 and 499 cm$^{-1}$ are attributed to the $A_{1g}$ mode, and the other four peaks located at 248, 291, 411, and 613 cm$^{-1}$ correspond to the $E_g$ mode.\[53,54\] There are no other peaks observed for impurities, which further indicates that pure FNTs and FNPs were obtained.

The morphologies of the FNTs and FNPs samples were examined by using SEM and TEM (Figure 2). The SEM image shows the cubic shape of FNPs with different diameters in the range of 60–150 nm. However, the SEM image of FNTs demonstrates a tubular feature with an undulating surface and an open end. The TEM images shown in Figure 2b and c further verify the detailed nature of the FNTs with an outer diameter of approximately 300 nm, two walls of approximately 50 nm, and a hollow channel of approximately 200 nm. However, the surface of the FNTs is quite different from the smooth surface of conventional nanotube structures. From the TEM images, it can be seen that there are numerous nanowires coated over the surface of the FNTs that are of various lengths, the structure of which is similar to that of a cilia-covered paramecium.\[50\] The nanowires coated on the surface may not only increase the electrode–electrolyte area to enhance the lithium ion delivery but also fortify the electron transport.

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**Figure 1.** Characterization of FNTs and FNPs: (a) XRD patterns and the reference pattern of Fe$_3$O$_4$ according to the JCPDS database; (b) Raman spectra at 100–1000 cm$^{-1}$.

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in Figure 2d, the specific surface area of the FNTs and FNPs is calculated to be 158.05 and 75.74 m$^2$g$^{-1}$, respectively. Additionally, the pore size distributions shown in inset in Figure 2d reveal that the pore size of FNTs is mainly 20–60 nm and that the pore volume of FNTs is much larger than that of FNPs. The increased specific surface area of FNTs can be attributed to the nanowires on the surface of the nanotube that can intertwine with each other to form numerous mesopores. The high-resolution TEM image shown in Figure 2c presents the surface of FNTs, and the lattice fringes of Fe$_2$O$_3$ are observed distinctly, in which the regular interplanar spacing of 2.50 Å corresponds to the (110) plane of Fe$_2$O$_3$ (JCPDS #33–0664). All these results indicate that the as-prepared samples are well crystallized.

**Electrochemical performance of FNT/SP, FNP/SP, and SP cathodes**

Three cathodes with 10, 30, and 60% FNTs were prepared by the same procedure to examine the effect of catalyst loading on the battery performance. The results demonstrated that the optimal catalyst loading is approximately 30% (Supporting Information). Based on this result, subsequent cathodes were prepared with the optimal catalyst loading. The full initial discharge and charge curves of Li–O$_2$ batteries with SP, FNP/SP, and FNT/SP cathodes were compared and characterized at the same current density of 500 mA g$^{-1}$ (based on the total mass of catalyst) to evaluate the catalytic effects of FNTs and FNPs for the ORR and OER (Figure 3a). During discharge, the overpotential of the Li–O$_2$ battery with the FNT/SP cathode is as low as 0.19 V, which is approximately 60 and 220 mV lower than that of Li–O$_2$ batteries with FNP/SP and SP cathodes. In contrast, upon charging, the overpotential of the Li–O$_2$ battery with the FNT/SP cathode is only approximately 0.85 V, which is approximately 210 and 400 mV lower than that of Li–O$_2$ batteries with the other two cathodes. In addition, the Li–O$_2$ battery with the FNT/SP cathode delivers the largest specific capacity of approximately 6000 mAh g$^{-1}$, whereas the Li–O$_2$ batteries with FNP/SP and SP cathodes only exhibit specific capacities of approximately 5300 and 2200 mAh g$^{-1}$. The rate performance of the Li–O$_2$ battery with the FNT/SP cathode at discharge current densities of 200, 500, and 1000 mA g$^{-1}$ is presented in Figure 3b. At 200–1000 mA g$^{-1}$, the discharge overpotential increases from 0.18 to 0.22 V and the specific capacity decreases from 8050 to 3940 mAh g$^{-1}$; however, the charge
overpotential increases from 0.83 to 0.95 V, which indicates that the battery with the FNT/SP cathode exhibits a good rate capability. In addition, the charge overpotential is much lower than that of previous work (Table S1) and is even comparable to that of some noble-metal-based catalysts.\textsuperscript{[12,32]} The excellent catalytic activities for the OER and ORR of the Li–O\textsubscript{2} batteries with the FNT/SP cathode arise mainly from the following advantages of the paramecium-like FNTs catalyst: 1) the nanowires coated on the surface can extend the electrode–electrolyte area to enhance the Li ion delivery; 2) the open morphology of the FNTs can offer short diffusion channels for oxygen and electrolyte in the electrode to ensure the fast and uniform distribution of oxygen and electrolyte (Figure 4); 3) the electron transport can be facilitated by the tubular structure and the nanowires on the surface. All these advantages contribute to the striking enhancement in the electrochemical performance of the Li–O\textsubscript{2} battery with the FNT/SP cathode.

To verify the reversible formation and decomposition of Li\textsubscript{2}O\textsubscript{2} during discharge and charge, ex situ X-ray photoelectron spectroscopy (XPS) and XRD were conducted to test the compositions of the FNT/SP, FNP/SP, and SP cathodes after full discharge and charge (Figure 3c and d). The XRD patterns of the cathodes after discharge show three peaks attributed to the (100), (101), and (110) peaks of Li\textsubscript{2}O\textsubscript{2} (JCPDS #74-0115), which demonstrates that Li\textsubscript{2}O\textsubscript{2} is the main discharge product. Meanwhile, the peaks of Fe\textsubscript{2}O\textsubscript{3} (JCPDS #33-0664) disappear in patterns of the fully discharged cathodes, which suggests that the surfaces of FNTs and FNP are both covered with Li\textsubscript{2}O\textsubscript{2}. Conversely, after full charge, the three peaks related to Li\textsubscript{2}O\textsubscript{2} disappear and the (104) and (110) peaks of Fe\textsubscript{2}O\textsubscript{3} reappear, which indicates that Li\textsubscript{2}O\textsubscript{2} is totally or partially decomposed. The Li\textsubscript{1ls} XPS spectra of the cathodes after discharge and charge are presented in Figure 3d. After discharge, the Li\textsubscript{1ls} regions in the spectra of the FNT/SP, FNP/SP, and SP cathodes are located at similar positions and consist of two parts: the main discharge product, Li\textsubscript{2}O\textsubscript{2} (Li\textsubscript{1ls}: binding energy (BE) = 54.5 eV), and some side products, lithium carbonate species (Li\textsubscript{1ls} BE = 55.3 eV)\textsuperscript{[32,35]} formed by the corrosion of the carbon cathode or the decomposition of the electrolyte. In contrast, the Li\textsubscript{1ls} peaks that correspond to Li\textsubscript{2}O\textsubscript{2} in the three cathodes disappear at full charge, which indicates the decomposition of Li\textsubscript{2}O\textsubscript{2} for all cathodes. The morphologies of the FNT/SP cathode were analyzed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) after full charge and discharge.
SP, FNP/SP, and SP cathodes after discharge and charge were also investigated (Figure 5). In the FNP/SP and SP cathodes (Figure 5a–c), the active particles (SP or FNPs) connect to each other through polytetrafluoroethylene (PTFE) binder to form enough pores to accommodate solid Li$_2$O$_2$. In contrast, in the FNT/SP cathode, the FNTs samples are dispersed in a disorderly way and connect tightly with the SP nanoparticles to lead to the formation of hierarchical pores from the micro- to meso- and macroscale in the electrode structure, which provides sufficient space to accommodate the solid discharge product, and thus result in a much higher specific capacity. Besides, the nanowire-coated paramecium-like FNT itself could act as the oxygen and electrolyte transportation paths to reduce the distance of reactants to active sites and enhance the mass transport of intermediate species.

After full discharge at 500 mA g$^{-1}$, the surfaces of the three cathodes are covered by a disc-like solid product (Figure 5d–f), which is consistent with the Li$_2$O$_2$ morphology reported previously. In detail, the solid products are made up of split layers with rough boundaries, but the size of every particle is different for the three cathodes. For the SP cathode, the average size of the Li$_2$O$_2$ particles is the largest with a diameter of approximately 800–900 nm, whereas for the FNT/SP cathode, the diameter of the Li$_2$O$_2$ particles is approximately 400–500 nm. The smaller discharge product arises mainly from the uniform distribution of oxygen and electrolyte with the help of the FNTs in the cathode, and thus there are abundant active sites for the discharge product deposition at the same time. The morphologies of the three cathodes after charging are presented in Figure 5g–i. For the SP and FNP/SP cathodes, there are several disc-like Li$_2$O$_2$ particles left in the charged cathode; whereas all the disc-like Li$_2$O$_2$ particles disappear after charging in FNT/SP cathode, and the morphology of the FNTs appears again on the surface of this cathode, which indicates that FNT/SP cathode exhibits the best reversibility for the formation and decomposition of Li$_2$O$_2$ during discharge and charge and, consequently, shows the best discharge and charge performance.

The stability of the paramecium-like tubular structure of the FNT sample during the discharge and charge processes was proved by observing the SEM images of the FNT/SP cathode at different discharge and charge depths (Figure 6). On discharge, first a film was formed on the cathode; then, the disc-like discharge product with a small size appeared on the surface of whole cathode, but that on the surface of the FNT sample was smaller than that on the surface of the SP sample. With the increase of the specific capacity, the number of disc-like particles became increasingly larger, especially on the surface of the FNT sample (Figure 6c). The particles on the surface of the FNT sample remained smaller than that on the surface of the SP sample, which demonstrates that the FNT sample not only facilitates the access of oxygen and Li ions to active sites but also enhances the electron transport to the active sites. At the end of discharge, the disc-like particles on the surface of the FNT sample were of a similar size to those on the surface of the SP sample. Upon charging, the decomposition trend of the disc-like particles on the surface of the FNT sample appeared contrary to the formation trend during the discharge process. The discharge product decomposed faster than that on the surface of the SP sample because of the favorable mass transport of the in-

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**Figure 4.** SEM images of the O$_2$ electrodes (a) with and (b) without the FNT catalyst. Schematic illustration of the structures of (c) FNT/SP and (d) SP electrodes.
Intermediate species in FNT sample. Finally, the disc-like particles disappeared from the whole cathode, which reveals the reversible formation and decomposition of Li$_2$O$_2$ during the discharge and charge processes.

The cycling stability of the Li–O$_2$ batteries with SP, FNP/SP, and FNT/SP cathodes was tested at 500 mAg$^{-1}$ with a fixed capacity of 500 mAhg$^{-1}$ (Figure 7a–c). For the battery with the SP cathode, upon discharge, in the first cycle, the voltage plateau is approximately 2.65 V and with the increase of the cycle number, the plateau decreases continuously until the voltage is reduced to 2.0 V. In the 42nd cycle, the specific capacity decays to less than 500 mAhg$^{-1}$. During charge, the voltage increases rapidly to approximately 4.10 V and is maintained at approximately 4.20 V in the first cycle. With cycling, the charge voltage remains at a high level (>4.25 V), and after 40 cycles before the battery is fully charged, the voltage reaches the cutoff voltage of 4.5 V, which indicates that some discharge products (Li$_2$O$_2$) remain undecomposed. Additionally, under such a high charge voltage (>4.5 V), the decomposition of the organic electrolyte and the corrosion of the pure carbon cathode would occur to form byproducts (e.g., Li$_2$CO$_3$, RCOOLi, or LiF).\[32\] Not only irreversible products but undecomposed Li$_2$O$_2$ would accumulate and cover the surface of the cathode, which decreases the number of active sites and leads eventually to the discharge capacity decay in the 42nd cycle. For the FNP/SP cathode, although the voltage plateau remains at a similar level as that of the SP cathode during discharge, the voltage plateau is approximately 4.0 V in the first cycle on charge, which is approximately 200 mV lower than that of the SP cathode. Additionally, the voltage increases more slowly than that of the SP cathode with cycling, and finally, the cycle number reaches up to 67, which is 25 cycles more than the SP cathode. This reveals that Fe$_2$O$_3$ particles exhibit a good catalytic activity for the OER.\[21\] For the FNT/SP cathode, upon discharge, the voltage plateau is maintained at approximately 2.78 V in the first cycle, and the overpotential is only approximately 0.18 V, which is approximately 130 mV lower than that of the FNP/SP cathode. As the cycle number increases, the discharge voltage decreases slowly, but even in the 150th cycle, the voltage still remains higher than 2.50 V. During charge, in the first cycle, the voltage plateau is approximately

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**Figure 5.** SEM images of FNT/SP, FNP/SP, and SP cathodes: (a–c) before discharge, (d–f) after full discharge, and (g–i) after full charge.
3.75 V and the charge overpotential is only 0.79 V, which is approximately 450 and 250 mV lower than that of the FNP/SP and SP cathodes, respectively. If the cycle number increases to 150, the voltage plateau is still less than 4.30 V. Even at the end of the 150th cycle, the charge voltage is still lower than 4.5 V. With the addition of the FNTs sample, the cycling performance of the Li–O2 battery is further improved and enhanced, especially the cycling stability: at the discharge current density of 500 mAg⁻¹, the Li–O2 battery with the FNT/SP cathode can cycle stably up to 150 times, which is 83 cycles more than the Li–O2 battery with the FNP/SP cathode. Moreover, the Coulombic efficiency and discharge capacity of the battery with the FNT/SP cathode could be maintained for 150 cycles without any degradation (Figure 7d), which reveals the enhanced cycling stability of the Li–O2 battery with the FNT/SP cathode.

Conclusions

Nanowire-coated paramecium-like Fe2O3 nanotubes (FNTs) were synthesized by a hard-template method and applied as a cost-effective catalyst for nonaqueous Li–O2 batteries. The FNTs exhibit a high surface area of 158 m²g⁻¹, which is twice as high as that of Fe2O3 nanoparticles and can provide many active sites for the deposition of the solid product, Li2O2. With the FNT/SP cathode, the Li–O2 battery delivers a high capacity of 6000 mAhg⁻¹ at a discharge current density of 500 mAg⁻¹ with a low discharge and charge overpotential of approximately 0.19 and 0.85 V, respectively. Moreover, the battery can even be operated at a high discharge current density of up to 1000 mAg⁻¹ with a capacity of 3940 mAhg⁻¹, which indicates its excellent rate capability. In addition, the prepared catalyst enables the battery to be cycled stably in up to 150 cycles without any degradation at 500 mAg⁻¹ with a fixed capacity of 500 mAhg⁻¹, whereas the battery without the catalyst can be cycled for 40 cycles only. We also verified the effects of the FNTs loading on the electrochemical performance of nonaqueous Li–O2 batteries and found that the optimal loading of the FNTs sample is approximately 30%. These results demonstrate that the FNTs is a cost-effective catalyst that offers great promise for the enhancement of the electrochemical performance of nonaqueous Li–O2 batteries, and with an appropriate loading ratio of the FNTs catalyst, the battery may cycle stably for a longer life in the future.

Experimental Section

Fabrication of FNTs and FNPs

The paramecium-like FNTs were fabricated by using MoO3 nanorods as a hard template, removal of the template from the MoO3@FeOOH hybrids, and finally calcination of the FeOOH nanotubes. First, MoO3 nanorods were prepared according to previous reports by a hydrothermal method. In detail, MoO3 powders (2.88 g) from calcined solid (NH4)6Mo7O24·4H2O were dissolved into 30% aqueous H2O2 (22.0 mL) after stirring for 5 h at 35 °C and diluting with 2 M nitric acid solution to form a 50 mL peroxomolybdic acid solution, which was transferred into a
Teflon-lined stainless-steel autoclave and heated at 170°C for 24 h to synthesize the white MoO₃ nanorods hydrothermally. Second, a suspension of MoO₃ nanorods was used to fabricate the MoO₃@FeOOH hybrids, which was formed by dispersing MoO₃ nanorods (0.288 g) into a solution (200 mL) that contained 90% ethanol and 10% water and then adding NH₄Fe(SO₄)₂·12H₂O (80 mL, 1.928 g) aqueous solution under stirring at 70°C for 5 h. Afterwards, the MoO₃ templates were removed with NH₃·H₂O (28%) solution at 70°C for another 10 h to collect the red brown FeOOH nanotubes after rinsing with distilled water and ethanol. XRD patterns and TEM images of MoO₃ nanorods, MoO₃@FeOOH hybrids, and FeOOH nanotube are shown in Figure S1. Finally, the FNTs were obtained by calcination of the corresponding FeOOH nanotubes at a rate of 1°C min⁻¹ to 500°C for 5 h in air. For comparison, FNPWs were prepared by calcining the FeOOH nanotubes at a rate of 10°C min⁻¹ to 500°C for 5 h in air.

Cathode preparation
To fabricate cathode electrodes, the as-prepared FNTs and FNPWs were mixed with commercial SP and PTFE (as the binder) at a weight ratio of 3:6:1 in ethanol to form a slurry (for the pure carbon cathode, SP was mixed with PTFE at a weight ratio of 9:1). The slurry was stirred ultrasonically for 1 h and then cast uniformly onto carbon paper. Finally, the electrode was dried overnight under vacuum at 120°C, and the obtained cathodes were denoted as FNT/SP, FNP/SP, and SP. The total loading of the active materials (carbon, binder, and iron oxide) for all the cathodes was approximately 0.5 mg cm⁻².

Material characterization
The composition of FNTs and FNPWs was analyzed by using a Philips high-resolution X-ray diffraction system (model PW 1825) using a CuKα source operated at 40 keV and a Micro-Raman spectrophotometer (Renishaw RM 3000) at 514 nm excitation wavelength. N₂ adsorption–desorption was used to examine the BET specific surface area of the samples. The morphology of the active materials was observed by using (SEM, JEOL-6700F) at an acceleration voltage of 5.0 kV and a high-resolution JEOL 2010F TEM system with a LaB₆ filament at 200 kV. XPS was measured by using a Physical Electronics PHI 5600 multi-technique system using Al monochromatic X-rays at a power of

![Figure 7](image-url)
350 W to test the compositions of cathodes after discharge and charge. The peak position correction during the XPS operation was rectified by referencing the C1s peak position of carbon (BE = 284.8 eV. PHI Handbook of Photoelectron Spectroscopy), and accordingly, all other peaks were shifted in the spectrum. For all measurements, the cathode samples were transferred in homemade containers filled with Ar.

**Electrochemical measurements**

The testing of the homemade Li–O₂ battery was similar to that described previously.[12,23] The battery consisted of a Li metal foil as the anode, a glass-fiber (Whatman GF/C) as the separator, 100 μL electrolyte composed of 1.0 M lithium bis(trifluoromethanesulfonyl)imide (LiTFSI, Sigma–Aldrich, 99.95 %) in tetraethylamine glycol dimethylether (TEGDME, Sigma–Aldrich, 99 %) with a water concentration at less than 5 ppm, and an as-prepared cathode, which was assembled in an Ar-filled glovebox (Etelux, Lab 2000) at water and oxygen contents below 1 ppm. After assembly, the inlet of the battery was connected tightly to a constant O₂ flow with high purity (≥ 99.997 %, H₂O ≤ 1 ppm, CO₂ ≤ 1 ppm) to remove the remaining Ar. Subsequently, the outlet was sealed completely to ensure that the battery could run under a constant O₂ pressure of 1 atm. A battery cycling system (Neware, CT-3008W) was used to examine the galvanostatic charge–charge measurements of the batteries at three current densities within a voltage window of 2.0–4.5 V (vs. Li/Li²⁺).

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**Conflict of interest**

*The authors declare no conflict of interest.*

**Keywords:** batteries · cost-efficient · iron oxide · nanotubes · oxygen

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