with energy consumption of approximately 25 kWh per cubic metre of treated water[4].

Joule heating of membrane surfaces via the application of electric current should be compared with other approaches, such as photothermal surface heating. One such approach involves the incorporation of plasmonic nanoparticles in the membrane structure, which are excited by electromagnetic irradiation to generate local heating[11]. This approach has recently been applied to enhance desalination performance of MD by incorporating silver nanoparticles in a thermal desalination membrane and irradiation by UV light to provide local surface heating of the membrane[12]. Employing photothermal desalination membranes with nanostructures that can generate effective local heating by illumination with solar light can further improve the cost and energy efficiency of desalination by MD[13]. However, one of the major limitations of the photothermal approach for self-heating membranes compared with Joule heating via the application of electric current is the difficulty to irradiate a very large membrane surface area by UV or solar energy, which may limit this approach to small-scale MD systems. ☐

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LITHIUM–OXYGEN BATTERIES

The reaction mechanism revealed

Using *in situ* environmental transmission electron microscopy, the structural and phase changes of the reaction products of an air cathode during discharging and charging can be visualized in real time.

Yang-Kook Sun and Chong S. Yoon

With increasing deployment of electric vehicles and large-format energy storage systems, Li battery technology is on the verge of transforming the way we use and distribute energy worldwide. However, conventional lithium-ion batteries[1] cannot satisfy the energy density requirements of mid- and large-scale systems. Due to their theoretical specific energy density, which is about 10 times higher than that of lithium-ion cells, lithium–oxygen (Li–O$_2$) batteries are in the spotlight as a potentially viable way forward[2,3]. Despite these promises, however, the reaction mechanism during charging and discharging of Li–O$_2$ batteries is still unclear. Writing in *Nature Nanotechnology*, Luo et al. now report an *in situ* transmission electron microscopy (TEM) analysis that provides important insights on the physico-chemical reaction pathway between O$_2$ and the Li-metal anode during oxygen reduction and oxygen evolution reactions[4].

Various analytical methods have been applied to capture the formation and decomposition of reaction products in Li–O$_2$ batteries. The formation of Li$_2$O$_2$ toroidal structures nucleating on a carbon fibre surface during discharge[5], as well
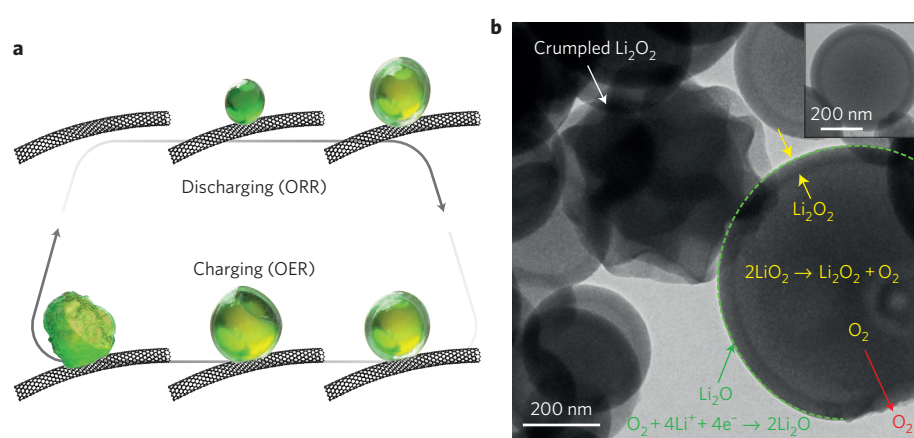

Figure 1 | Reaction products of a Li–O$_2$ cell. **a**, Schematic illustration of formation and collapse of the reaction products in the Li–O$_2$ battery during discharging (oxygen reduction reaction, ORR) and charging (oxygen evolution reaction, OER) observed by *in situ* environmental TEM. **b**, *Ex situ* TEM image of the reaction product in the Li–O$_2$ battery illustrating the chemistry of the discharge product. The red arrow indicates the escape of O$_2$ from the hollow particle. The main reaction product is labelled in yellow and the surface passivation layer is indicated by the green dashed line. The inset shows the hollowness of the spherical particles. Panel **b** adapted from ref. 7, American Chemical Society.

as hollow Li$_2$O$_2$ structures, have been observed[6,7]. To understand the decomposition of Li$_2$O$_2$ during charging, *in situ* TEM experiments were carried out in vacuum, but in this way only the decomposition of preformed Li$_2$O$_2$ structures could be observed[8]. The main experimental advance of Luo et al. is to have carried out their

investigation under O_2 atmosphere using an environmental TEM. The O_2 gas is kept at a constant pressure, simulating the same oxygen-rich environment of a real Li–O_2 battery during operation. This setup enabled the researchers to directly observe a full electrochemical cycle, clarifying the chemistry as well as the growth and decomposition kinetics of the reaction products.

Luo *et al.* use Li_2O formed on the surface of Li metal as a solid electrolyte, and carbon nanotubes dressed with a RuO_2 nanoparticle catalyst as a cathode (the catalyst enables the reversible formation and decomposition of reaction products). Upon discharging, the researchers observe the formation of hollow spheres at the contacting sites between the nanotubes, Li^+, and O_2. These spheres grew up to ~50–200 nm in size during the oxygen reduction reaction; and shrank and collapsed to crumpled shells within a few minutes during the oxygen evolution reaction (Fig. 1a). Luo *et al.* also observe other unique morphologies after partial charge — these are the result of a local inward contraction of the shell[4]. As a general validation of this mechanism, *ex situ* TEM images show hollow, crumpled, and ruptured spherical structures that are remarkably similar to the ones observed *in situ.*

The formation mechanism of such structures has remained unexplained due to an inability to investigate the intermediate chemical species, and this work provides clear insights on this aspect. In an oxygen-rich environment and in the presence of a solid electrolyte, LiO_2 structures covered by Li_2O are the initial discharging products. LiO_2 is subsequently converted to Li_2O_2 and O_2 through a disproportionation reaction inside the particle (Fig. 1b). The released O_2 gets trapped inside the nanostructures, inflating them and finally forming hollow structures. Meanwhile, a Li_2O passivation film forms on their surface by $O_2 + 4Li^+ + 4e^- \rightarrow Li_2O$ so that at the end of the discharge the final products are Li_2O and Li_2O_2. The Li_2O outer layer protects the particle from cracking and this is why these structures remain stable even in *ex situ* experiments.

The direct observation of the metastable nature of LiO_2 during oxygen reduction and oxygen evolution reactions confirms the conclusions of a previous work in which crystalline LiO_2 was detected indirectly by stabilizing the intermediate phase using iridium nanoparticles[9].

In their *in situ* TEM experiments, Luo *et al.* employ a solid electrolyte out of necessity — the reaction mechanism of which can differ from that of an organic liquid electrolyte used in practical Li–O_2 cells. However, Luo and colleagues' interpretation of the formation and decomposition of discharge products agrees well with other *ex situ* TEM results obtained using a liquid electrolyte[6,7].

There remains much work to be done to make Li–O_2 batteries practical, especially on the materials and the cell-design side. But the observation and nanoscale physico-chemical elucidation of the cell operation mechanism is a solid foundation for future Li–O_2 battery designs and optimization. ❑

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NANOMACHINES

A light-powered clockwork

An organogel is made of molecular motors and modulators that act cooperatively to perform a full mechanical cycle of contraction and expansion at the macroscale.

Chenfeng Ke

The field of molecular machines, first envisioned by Richard Feynman in 1961[1], was recognized with the 2016 chemistry Nobel prize[2]. The synthetic machines of Jean-Pierre Sauvage, Sir J. Fraser Stoddart and Bernard L. Feringa can be operated upon by external stimuli such as light[3], pH change[4] or oxidation/reduction[5], thereby undergoing translational motions or rotations. A challenging next step consists of amplifying these molecular-level mechanical movements to obtain a sizeable effect at the macroscale[6]. The random orientation of these molecular machines in solution, however, results in no useful work being performed at the macroscale. To overcome this obstacle, nanomachines should be assembled in a controlled manner to achieve synchronized molecular motion. Writing in *Nature Nanotechnology*, Foy *et al.* now report an organogel that can reversibly contract and expand as a result of the photo-actuation of two molecular machinery parts (a unidirectional motor and a switchable modulator) embedded in it[7]. The operation is similar to a mechanical watch in which the winding of the mainspring transfers energy to turn gears and run the hands on a dial (Fig. 1).

The first component of the system by Foy *et al.* is a Feringa-type light-driven unidirectional molecular motor[3]. This consists of a bis-helicene backbone connected by an alkene double bond with axial chirality and two stereocentres. The rotary cycle is made of four steps (Fig. 2a). First, a photoisomerization rotates the rotor clockwise to approach the stator, resulting in a high-energy-state conformation. Subsequently, this high-energy rotor moves across the stator to reach a thermodynamically favourable conformation that prohibits the rotor from going back. A second photo-isomerization followed by a helix-inversion completes the cycle. Continuous photo-irradiation makes these motors rotate up to megahertz frequencies[8].

In solution, an Avogadro's number of these motors would rotate unidirectionally