TOPICAL REVIEW — Fundamental physics research in lithium batteries DOI: 10.1088/1674-1056/25/1/018214

Editorial

The editor of *Chinese Physics B* decided to organize a special topic on lithium batteries. We are sure the decision is very correct because one of the important tasks of physics is to serve the needs of society. Energy and environment are two related major problems facing mankind today. Physics has been dedicating itself to semiconductors for several decades. Now is the right time for physicists to study the problems related to new energy sources and related tools. Currently, it is most urgent to develop electric vehicles (EVs) and to develop renewable energies. The rechargeable battery is essential for both. Scientists and engineers have been racing to design smaller, cheaper and more efficient rechargeable batteries to meet society's power storage needs. At the moment, the lithium-ion battery has proven to be the most suitable rechargeable battery. That lithium-ion battery you can find in your smart phone is a familiar, small-scale example. The key components include an anode, the negative pole from which electrons flow out into a power-hungry device, and a cathode, where the electrons re-enter the battery once they have traveled through the circuit. Separating them is a liquid electrolyte, loaded with positively charged lithium ions that travel between the anode and cathode. At the present the popular anode and cathode materials are, respectively, graphite and transition metal oxide containing lithium ions. The typical electrolyte is a combustible organic solvent containing lithium salt. During charging, lithium ions desorb from the cathode lattice, pass through the electrolyte and are absorbed into the negatively charged anode. During discharge the process is reversed. This means the cathode is the Li-ion source and the anode is the Li-ion bank. Energy density is limited by the capacity and voltage of the electrode materials. Today's most useful materials for anodes are graphite and/or Si. A few cathode materials are commonly used; examples are $LiMn_2O_4$, $LiCoO_2$, $LiFePO_4$, and $Li(NiCoMn)_{1/3}O_2$. The minimum energy density required for EV applications is about 100–130 Wh/kg at the pack level. The running range of a standard-size EV powered by such a Li-ion battery pack is about 150 km. Going forward, the lithium-ion battery faces four requirements that are difficult to meet simultaneously: energy density higher than 300 Wh/kg, complete charging within 10 minutes, no risk of fire under abuse, and a service life exceeding eight years.

We have to start immediately to study next-generation lithium batteries. What would they be like? Most importantly, they must be solid-state. The two differences between solid state lithium batteries and Li-ion batteries are: 1) the electrolyte is a solid lithium ion conductor, which inherently improves safety; 2) the anode is lithium metal, which provides more Li ions to increase energy density. However, in order to realize the transition to solid state, many problems must be solved. For instance, a solid state electrolyte that has Li-ion conductivity comparable to that of liquid electrolytes at room temperature must be created. And problems at the electrolyte-lithium metal interface must be studied and solved, as must those at the cathode interface.

This special issue is related to the physics of lithium batteries. Viewed through the science of physics, a battery is a complicated system. The electrode material is a mixed conductor in which both electrons and ions are mobile and interact with each other, as well as with the lattice. The physical properties of the electrode materials, such as band structure, lattice structure, symmetry, and the thermal, magnetic, optical and mechanical properties, change gradually during lithiation and delithiation. Such changes lead to a series of unique and interesting phenomena, such as staging structure, varied electronic structure, electrochromism and giant electrostriction. As for the electrolyte, as mentioned above, it could be either liquid or solid. In a liquid electrolyte, both cations and anions are mobile. In a solid, lithium cations could be the only charge carrier in the electrolyte. The electrolyte phase should have negligible mobile electrons. A space charge layer exists on both sides of the electrolyte–electrode interface, which varies dynamically with regard to mobile ions and electrons during charging and discharging. Both the electrolyte and the electrode can be regarded as many-body systems. In some cases, adiabatic approximation is not suitable. So far, the kinetics of the transport, storage and reaction of ions and electrons in the electrode and electrolyte are not understood clearly at the atomic level. Advanced theory and experimental techniques are sorely needed to enhance our understanding of many fundamental issues in batteries, and consequently overcoming the technological challenges in making better batteries. Moreover, in the long term, new knowledge about batteries will definitely enrich the broader studies of solid state physics, solid state ionics, and the electrochemistry of solids and liquids.

The authors in this special topic are seasoned experts in the field. Some of them are physicists. They have turned their attention to physical problems in lithium-ion batteries for a long time. Although perfect answers cannot be provided and many important topics have not been touched, we hope this special topic will inspire more physicists to investigate the complicated physical problems in batteries. We chose to dedicate this special issue to solid state lithium batteries, which will become the breakthrough technology for charging up the future.

Guest Editors: Hong Li and Liquan Chen
Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
September 14, 2015