



The Magnesium Charge

The Mg-Freightliners: Designing electrolytes for rechargeable magnesium-ion batteries

Introduction

Lithium-ion batteries are at the forefront of today's battery technology, powering applications ranging from portable electronics to electric vehicles. However, concerns about the long-term availability, supply security, and sustainability of key materials used in conventional lithium-ion batteries, including lithium, graphite, cobalt, and nickel, have driven research into alternative battery chemistries. These alternatives, often referred to as post-lithium-ion batteries, include, among other technologies, multivalent-ion batteries.

Magnesium is a promising candidate for next-generation battery technology. As a multivalent element, magnesium forms Mg^{2+} ions, which can transfer two electrons per ion. This offers the potential for high volumetric energy density, making magnesium-based batteries an attractive research direction for applications where efficient use of space is important, especially for transportation and energy storage devices.

"Magnesium batteries must overcome strong Mg^{2+} interactions with their surroundings. Weakly coordinating anions offer a promising solution but must balance ion transport, electrochemical stability, and electrode compatibility."



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Johannes Thiemann is a PhD student at the University of Freiburg focusing on the development of novel electrolytes for practical use in batteries. His focus is the electrolyte development of rechargeable magnesium-ion batteries.



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The HighMag project aims to advance the development of rechargeable magnesium batteries (RMBs) through a more sustainable approach to energy storage. By exploring abundant materials such as magnesium and sulphur, the project seeks to reduce reliance on critical raw materials and establish the scientific foundations for more sustainable battery technologies.

Transporting magnesium

One of the key challenges in developing magnesium-ion batteries lies in the electrolyte, which enables magnesium ions to move between the electrodes during charging and discharging. Electrolytes typically consist of a solvent, a conducting salt, and, in some formulations, additives. The interactions between these components and the electrode surfaces strongly influence ion transport, electrochemical stability, and the overall performance and lifetime of the battery.

Unlike conventional lithium-ion batteries, which commonly use carbonate-based solvents, magnesium-ion batteries face specific challenges when selecting suitable electrolyte components. Carbonate solvents can react with magnesium metal and form surface layers that hinder plating and stripping of magnesium – the key electrochemical processes required for charging and discharging in battery operation. For this reason, 1,2-dimethoxyethane (DME) is widely investigated as a solvent of choice for magnesium-based electrolytes, since it is compatible with magnesium and within a wide electrochemical window.

Additionally common conducting salts used in lithium salts are not suitable for magnesium-ion batteries. The strong electrostatic interactions between Mg^{2+} ions and negatively charged anions can not only hinder magnesium-ion transport but prevent transport altogether. One approach to addressing this challenge is the use of novel weakly coordinating anions (WCAs), which interact less strongly with the magnesium ions and may facilitate their movement through the electrolyte. Designing suitable conducting salts therefore requires carefully balancing ion transport with the chemical stability of the electrolyte and its compatibility with the electrodes.

Within HighMag, the University of Freiburg is investigating two complementary approaches to conducting salt development implementing these WCAs: established fluorinated alkoxy aluminate salts as a baseline and a carbaborate-based salt as a potential alternative.



By studying these different systems, the aim is to better understand how electrolyte composition affects magnesium-ion solvation, transport, electrode compatibility, and the overall performance of magnesium-ion batteries.

Establishing a baseline: Highly fluorinated conducting salts

The first research direction focuses on conducting salts based on fluorinated compounds, including aluminium- and boron-centred variants. These materials build on an established field of electrolyte research and provide a starting point for investigating the interactions between the conducting salt, solvent, and electrode materials. The University of Freiburg focuses on the aluminate-based electrolytes, a counterion the Krossing group introduced to the literature already in 2001. This highlights how fundamental research set light to the two most prominently used electrolyte anions used for RMBs, the hexafluoroisopropoxy-borate and -aluminate. Both were developed in our group in 2001 and 2011 for very different purposes, but now found their way to application and, the borate, even to commercialisation.

Hence, these compounds have already been part of ongoing investigations and can be produced in relatively large quantities at laboratory and even technical scale. This provides a practical foundation for systematic electrolyte development and allows their properties to be evaluated under different conditions. Establishing a reliable baseline is essential for understanding which characteristics contribute to effective magnesium-ion transport and stable battery operation.

Exploring an alternative: Carbaborate-based electrolytes

Alongside established conducting salts, the University of Freiburg is investigating the carba-closo-dodecaborate, commonly referred to as carbaborate, as an alternative conducting salt anion for magnesium-ion battery electrolytes. Again, the origin suggesting these compounds to be well-suited for RMBs is fundamental chemistry. Here, this class of compounds has shown promising reaction and electrochemical behaviour, making it an interesting candidate for further development.

The properties of carbaborate-based salts can be adjusted through modifications to their molecular structure. This offers opportunities to tailor their chemical and electrochemical behaviour to the requirements of magnesium-ion batteries. In addition, the investigated synthesis route uses readily available starting materials, providing a basis for exploring future scale-up.



Conclusion

Although the two approaches differ in their chemical composition and level of maturity, they share the same objective: developing electrolytes that enable efficient magnesium-ion transport while maintaining stability and compatibility with battery electrodes. Comparing established conducting salts with emerging alternatives will help deepen our understanding of the relationship between electrolyte composition and battery performance. Within HighMag, the University of Freiburg is experienced in both, fundamental as well as battery research and works alongside project partners to investigate these complex interactions and advance the understanding of magnesium-battery systems. This collaborative research contributes to the project's broader goal of establishing the scientific foundations for more sustainable magnesium-based energy storage and lift it from fundamentals to application.



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