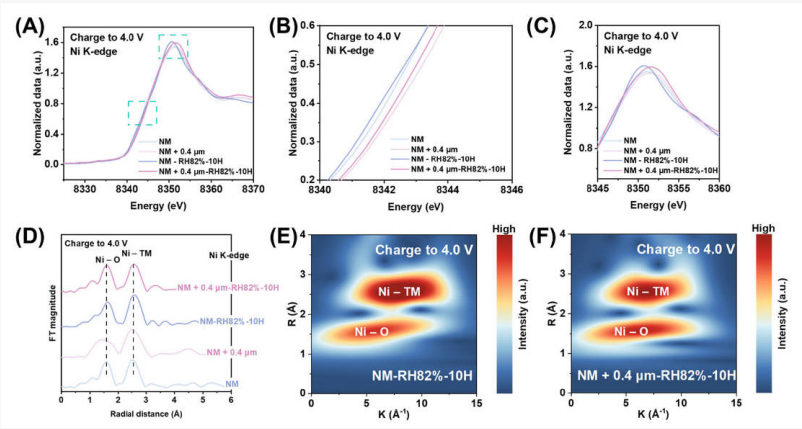
Gradient cathode boosts sodium battery stability

GA, UNITED STATES, March 18, 2026 /EINPresswire.com/ -- A research team has developed a new cathode material that significantly improves the environmental stability and cycling performance of sodium-ion batteries. By designing a radial gradient distribution of phase structure, sodium concentration, and transition-metal valence states, the researchers created a layered cathode that resists degradation caused by moisture and carbon dioxide. The innovative architecture reduces sodium-ion diffusion barriers, suppresses harmful phase transitions, and enhances structural integrity during battery operation. As a result, the material maintains high capacity and long-term stability even after exposure to humid air or water. This strategy provides a promising pathway for building safer, more durable sodium-ion batteries that could support large-scale energy storage systems and sustainable energy technologies.



After 200 cycles and charging to 4.0 V at 2.0–4.0 V and 0.1 C current density.

Lithium-ion batteries currently dominate portable electronics and electric vehicles, but the uneven distribution and high cost of lithium resources have raised concerns about long-term supply. Sodium-ion batteries have emerged as a promising alternative because sodium is abundant, inexpensive, and widely distributed. Among the many cathode materials studied, layered transition-metal oxides have attracted particular attention due to their high capacity and relatively simple synthesis. However, these materials suffer from several major limitations, including structural instability, complex phase transitions during cycling, and poor air stability. When exposed to moisture or carbon dioxide, the active sodium can react to form inactive compounds, blocking ion transport and reducing battery performance. Based on these challenges, further research is needed to develop more stable cathode structures for sodium-ion batteries.

Researchers from Central South University and collaborating institutions reported (DOI: 10.1002/cey2.70115) a new cathode design strategy in the journal Carbon Energy that enhances

the stability of sodium-ion batteries. The study introduces a layered cathode material with a radial gradient distribution of sodium content, phase structure, and transition-metal valence states. This structural design simultaneously improves ion transport kinetics and resistance to environmental degradation. By preventing harmful reactions with water and carbon dioxide, the cathode maintains its electrochemical performance even under humid conditions, addressing one of the key challenges limiting the commercialization of sodium-ion batteries.

To construct the gradient structure, the team first synthesized nickel–manganese hydroxide precursors with a core–shell configuration using a controlled coprecipitation method. The inner core consisted mainly of Ni□.□Mn□.□(OH)□, while the outer layer had a different composition, forming a radial concentration gradient. During subsequent solid-state sintering, elemental diffusion gradually blurred the interface between layers, generating a continuous transition from an outer P2/O3 mixed phase to an inner O3 phase structure.

Advanced microscopy and spectroscopy techniques confirmed the presence of radial gradients in sodium concentration, phase distribution, and transition-metal valence states. This architecture provides multiple functional advantages. The surface P2/O3 mixed phase increases the oxidation state of transition metals, suppressing Na□/H□ exchange reactions and improving resistance to water and CO□. Meanwhile, the O3 phase in the interior maintains high sodium storage capacity.

Electrochemical tests showed that the optimized material delivered significantly improved cycling stability compared with the conventional cathode. After 200 cycles, the modified sample retained about 80% of its capacity, whereas the unmodified material retained only about 21%. The gradient structure also enhanced sodium-ion diffusion kinetics and reduced polarization during charge and discharge.
Importantly, the cathode demonstrated remarkable environmental stability. Even after 10 hours of exposure to humid air containing CO□, the material maintained a first-cycle capacity of 103.8 mAh g□¹, and the capacity loss decreased dramatically from 50.12% to 12.35%.

According to the researchers, the success of the design lies in integrating multiple stability mechanisms into a single architecture. The radial gradient structure simultaneously regulates composition, phase distribution, and electronic states across the material. This approach not only stabilizes the crystal lattice during repeated sodium insertion and extraction but also protects the surface from environmental reactions. The team notes that such structural engineering could serve as a general strategy for designing next-generation cathode materials with improved durability and safety, especially for large-scale energy storage technologies where cost and long-term stability are critical.

The findings provide an important step toward the commercialization of sodium-ion batteries. Because sodium is abundant and inexpensive, these batteries are considered strong candidates for grid-scale energy storage, renewable energy integration, and backup power systems. However, poor air stability of cathode materials has been a major obstacle to practical

deployment. The gradient-structured cathode introduced in this study addresses this issue by preventing moisture- and CO□-induced degradation while maintaining high electrochemical performance. In the future, similar gradient design strategies could be applied to other battery materials, accelerating the development of cost-effective and environmentally resilient energy storage technologies for the global transition toward clean energy.

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