volving a gang of young male elephants at Pilanesberg National Park in South Africa in the 1990s. The park had been stocked with young male and female elephants, but not large bull elephants, which were challenging to transport. Without the company of older males, the young males went into a state known as musth and were flooded with reproductive hormones years earlier than normal. They tried to mate with the park's rhinos and ended up killing 50 of them. In the end, hormonal and behavioral cues from six older males trucked in during the crisis modulated the young males' hormones and they became far less aggressive.

Some of the most mesmerizing videos showed social play among young male dolphins in Australia's Shark Bay. As juveniles, males spend many hours practicing synchronized leaps and turns, sometimes rolling each other and goosing other males' genitals. This seems to be preparation for behavior after puberty, when most males form alliances with one or two other males to herd females for mating, says behavioral biologist Kathryn Holmes of the Brookfield Zoo Chicago's Sarasota Dolphin Research Program, who presented the video, taken during her Ph.D. with Shark Bay Dolphin Research.

The cost of missing out on such teamwork can be high. Male dolphins that didn't join pods had fewer offspring, Holmes says.

For humans, too, finding older mentors and forming alliances with peers can be a key to social success. But in our species, the hormones that drive teens to find new friends and mates can also backfire in risk-taking behavior and hypersensitivity to peers' reactions and to social rejection. Overall morbidity and mortality increase dramatically worldwide during adolescence, and 75% of lifetime mental disorders begin by age 25, Dahl says.

By identifying skills and learning processes essential for adolescents across species, researchers in the working group hope to develop a general model of this tumultuous life stage. It would include testable hypotheses about key behaviors teens need to learn during pivotal points in development that might indicate the best times and targets for intervention in young humans struggling with the transition. For example, the onset of puberty represents a "window of opportunity for adaptive social learning," Dahl says, especially if teens can learn to overcome anxieties and develop key relational skills.

The study of other species might also suggest how and when it's most critical to provide mentorship, encourage creative risk taking, and foster social interactions with peers, Dahl says. The research holds an overarching lesson, he adds: "Adolescents have the capacity to learn how to change their identities in deep ways." ■

PHOTO: JIM WEST/REPORT DIGITAL-REA VIA REDUX

ENERGY TECHNOLOGY

Sodium batteries power up

Batteries based on sodium could aid a future green energy economy—if they can match lithium batteries' performance

By **Robert F. Service**

Lithium-ion batteries are ubiquitous, not just in earbuds, phones, and cars, but also in massive facilities that store renewable energy for when the Sun doesn't shine or the wind dies down. But lithium itself is relatively scarce and available from just a few countries. A world that runs on renewable energy would need 200 times more battery capacity than exists today—and that probably means a different kind of battery. "I don't know if we can get there with just lithium-ion," says Y. Shirley Meng, a battery chemist at the University of Chicago.

A decades-old technology may be rising to the challenge: batteries that use sodium rather than lithium ions to carry and store charge. Sodium is everywhere, in seawater and salt mines, so supply and cost aren't a problem. But the metal isn't as good at storing charge as lithium because its ions are three times bigger, hampering their ability to slip in and out of existing battery electrodes. Labs worldwide are developing new electrode materials to address that shortcoming, and in the past 6 months, several groups have announced sodium batteries that hold as much energy as low-end lithium cells. "The progress has been amazing," says Dan Steingart, a battery chemist at Columbia University. Meanwhile, commercial sodium-ion batteries are starting to roll off the assembly lines for electric vehicles, scooters, and grid power storage.

Researchers caution, though, that sodium batteries are not ready for widespread deployment. "We're not there yet," says Jean-Marie Tarascon, a solid-state chemist at the College of France. The batteries are still far from matching the performance of the best lithium-ion cells. And the economic incentive for a shift is lacking for now: Lithium shortages remain a theoretical concern, and the price of the metal actually dropped 70% in the past 3 years because of an oversupply.

Like lithium batteries, those based on sodium work by passing positively charged ions between a pair of electrodes separated by an ion-conducting electrolyte. During charging, electrons are fed to the negatively charged anode, attracting metal ions to flow through the electrolyte from the positively charged cathode. During discharge, electrons are drawn out of the battery, causing the ions to travel back from anode to cathode.

Because sodium ions are larger than lithium ions, fewer of them can squeeze into the anode to store charge. The need for larger cells to hold the same amount of power adds cost and bulk. Sodium batteries have struggled to reach even half the storage capacity of the best lithium batteries, which hold more than 300 watt-hours of energy per kilogram (Wh/kg). But Gui-Liang Xu, a battery chemist at Argonne National Laboratory, says, "There are multiple avenues to go down" to address the challenge.

There's no shortage of sodium, as salt piles at a facility in Oklahoma attest.

One is changing the composition of the anode. Most lithium-ion cells use graphite, a form of carbon whose tightly layered structure tends to exclude sodium ions. Many researchers have turned to an alternative form of carbon, called hard carbon, made up of a jumble of carbon particles that leaves pores into which sodium ions can wiggle.

Unfortunately, all those pores also reduce an anode's energy-storing volume. But researchers have found that adding tin to the anode can help. When stabilized on a carbon support, each tin atom can bind up to 3.75 sodium ions, boosting an anode's ability to hold sodium, and thus energy. For example, batteries developed at the San Diego–based startup UNIGRID hold 170 Wh/kg. Although this remains less than the 200 Wh/kg of a low-end lithium battery, "it looks very exciting," says Yan Yao, a sodium-ion battery expert at the University of Houston.

Another improvement comes from tweaking the composition of the positively charged cathode, typically made of metal oxides, for better sodium storage and flow. One of the most popular new materials is a mixture of sodium, vanadium, phosphorus, and oxygen (NaVPO), which tends to form a layered structure that allows sodium atoms to readily enter and exit.

For now, NaVPO's energy density is moderate compared with that of cathodes in lithium cells. But researchers led by Pieremanuele Canepa, a chemist at the University of Houston, recently used computer modeling and x-ray diffraction to identify a promising tweak to NaVPO's crystalline structure. In a report posted online on 23 October 2024 in *Nature Materials*, Canepa and his colleagues reported not only synthesizing the new material, but incorporating it into a sodium-ion battery cathode that could hold 15% more energy than previous NaVPO designs.

A more radical approach is to make cathodes out of organic compounds, which can also form layered structures able to hold and release sodium ions. Many organics decompose in the presence of a battery's electrolytes, but in the 5 February issue of the *Journal of the American Chemical Society*, researchers led by Mircea Dincă at the Massachusetts Institute of Technology reported creating a more durable layered organic cathode, called TAQ. The material not only proved stable for thousands of charge and discharge cycles, but TAQ's energy density was among the highest of any sodium-ion cathodes ever made. Canepa calls it "a beautiful piece of chemistry."

As a result of these and other advances, "Industry's interest is really high right now," says Laurence Croguennec, a chemist and managing director of the Institute of Condensed Matter Chemistry of Bordeaux. In November 2024, CATL, the world's largest batterymaker in China, unveiled its second-generation sodium-ion battery, which it claims holds 200 Wh/kg, up from 160 Wh/kg in its first-generation cells. Meanwhile, BYD, one of CATL's rivals, says it is building a factory to produce 30 gigawatt-hours' worth of sodium-ion batteries per year by 2027, in part for renewable-energy storage. At least a half-dozen other startups around the world are also jumping in with their own tweaks to battery chemistry.

Still, many battery experts remain both cautious about sodium's future and skeptical of some company announcements. "There's a lack of transparency" about the details of battery design and performance, says UNIGRID CEO Darren Tan.

The hurdles aren't just technical. For now, the low cost of lithium undercuts sodium's chief selling point, Steingart says. Sodium-ion battery manufacturers also remain too small to benefit from economies of scale. In November 2024, such challenges upended one of the field's pioneers when the Swedish sodium-ion battery firm Northvolt filed for bankruptcy.

> **"The progress [in sodium battery storage capacity] has been amazing."**
> **Dan Steingart**
> Columbia University

Politics is another wild card. When U.S. President Donald Trump swept into office last month, he immediately announced a halt to federal support for wind and solar power projects, a step that could shelve plans to deploy large-scale backup battery systems. (In a move that perhaps cuts the other way, in January China announced new export restrictions on graphite, a key component of lithium-ion batteries, in response to new 10% tariffs on Chinese goods announced by the Trump administration.)

But William Chueh, a materials scientist at Stanford University, says it's technological advances that will decide how cost effective sodium-ion batteries become. On 13 January, he and his colleagues published a paper online in *Nature Energy* evaluating more than 6000 road maps for producing them, and concluded that to be fully competitive with low-cost lithium-ion batteries, researchers will need several breakthroughs, including eliminating all of the expensive materials sodium batteries currently require, such as nickel and vanadium.

Steingart believes those advances are coming. When it comes to understanding the basic chemistry of sodium-ion batteries, he says, "we're still in the early days." ■

ASTROPHYSICS

A new origin story for the highest energy cosmic rays

Curious similarity among space particles points to neutron star mergers

By **Adrian Cho**

Earth is constantly pelleted with subatomic bullets. Every few seconds, a single, infinitesimal atomic nucleus traveling at near–light speed crashes into the atmosphere packing as much energy as a golf ball midflight. Physicists have struggled for decades to explain how and where the particles acquire such stupendous energy, invoking, for example, supermassive black holes at the cores of galaxies. But one theorist now argues that a subtle similarity among the highest energy rays points to a more modest source: the mergers of neutron stars. Proposed in a paper in press at *Physical Review Letters*, the idea has piqued the interest of astrophysicists, who now aim to test it.

"I totally agree that a neutron star merger is a promising candidate," says Toshihiro Fujii, a particle astrophysicist at Osaka Metropolitan University who works with the Telescope Array, a huge cosmic ray detector in Dugway, Utah. Markus Roth, a particle astrophysicist at the Karlsruhe Institute of Technology who works on the Pierre Auger Observatory, an even bigger detector in Argentina, says, "I do not see any argument that would contradict [the] proposal."

Scientists can't spot an ultra–high energy cosmic ray directly. Rather, they study the kilometers-wide avalanche of electrons and other charged particles like positrons and pions created when one strikes the atmosphere. For example, Auger consists of 1600 particle detectors spread over 3000 square kilometers of the Pampa Amarilla, an area more than four times the size of New York City. By counting charged particles and precisely timing when they hit its detectors, researchers can deduce the direction and energy of the original cosmic ray. From the periphery, telescopes in four