The test model of the battery produced 3.65 V at a temperature of 110°C (230°F), meaning that the battery offered about 40% more voltage at a much lower temperature than many commercial molten-sodium batteries.

A lower operating temperature will decrease the manufacturing cost of the battery, which could make it easier to deploy at large scales. "Now we can start using plastic seals and cheaper wiring, even in our lab-scale testing," Small says. In addition, the higher voltage means that fewer battery cells are needed per unit of energy stored, which could provide cost savings for power grid operators.

In performance tests, the battery model maintained its quality through eight months of use and 400 charging cycles with essentially no loss of voltage or energy efficiency (*i.e.,* the amount of power stored relative to the power used to charge the battery). "It was surprisingly stable — it was rather impressive that it lasted for that period of time," Small says.

The researchers made an unexpected discovery when they had to temporarily shut down operations in their lab, including disconnecting the battery from power and allowing it to freeze. After returning, the researchers found they still could successfully charge the battery, indicating that its chemistry remains stable even after freezing. The result suggests that the battery can be shipped without special insulation. "If you can ship a battery and you don't have to worry about it reacting during transport, that's very useful," Small says.

One of the quickest ways for battery manufacturers to implement the new findings would be to modify current molten-sodium batteries to include aspects of the new design described in the study, Small says. For example, manufacturers could adopt the $NaI\text{-}GaCl_3$ catholyte or the ceramic separator from this study for use in existing batteries.

The scientists' ongoing research aims to reduce the amount of gallium needed for the battery, as gallium is much more expensive than sodium. One potential solution involves using aluminum or other inexpensive metals along with a smaller amount of gallium in the battery's catholyte.

Gross, M., *et al.*, "A High-Voltage, Low-Temperature Molten Sodium Battery Enabled by Metal Halide Catholyte Chemistry," *Cell Reports Physical Science*, doi: 10.1016/j.xcrp.2021.100489 (July 21, 2021).

Crafting Carbon Membranes to Separate Paraxylene

A new membrane with the scalability of a polymer and the precision of zeolite molecular sieves may help make the production of a key fundamental chemical less expensive and more energy-efficient.

Paraxylene is a key component of hundreds of other chemicals, including polyethylene terephthalate (PET) and polyester. But it takes heavy lifting to separate it from its isomers, orthoxylene and metaxylene. This trio must either be separated by crystallization, taking advantage of the slightly different freezing points of the three molecules, or by adsorption. But crystallization is extremely energy-hungry, says Ryan Lively, a chemical engineer at the Georgia Institute of Technology. And adsorption requires incredibly complex and expensive machinery, plus an additional distillation step that also requires energy. Each year, Lively says, the separation of paraxylenes and similar molecules consumes enough energy to power 40 million homes.

In new research funded by ExxonMobil, Lively and his colleagues have tested a low-energy alternative: membrane separation.

"Membranes are the sweet spot here, because membranes can separate these things based on very subtle differences in size and shape, it can do this very consistently and at room temperature," Lively says.

Some researchers have studied the possibility of using

Researchers created carbon-based molecular sieves, made by heating thin layers of polymer precursors in such a way as to drive off all the atoms other than carbon, resulting in a charcoal-like substance that has molecule-sized holes.

The membranes for paraxylene separation will be fabricated in the form of hollow fibers. The thread-like fibers used to make these membranes will need to be produced by the hundred million for industrial use.

zeolite membranes in the lab, which have the advantage of being highly selective for paraxylene. But zeolite membranes are hard to manufacture on a large scale. Lively and his collaborator, Georgia Tech chemist M.G. Finn, are focused on carbon-based molecular sieve membranes, which are polymer membranes that are cooked in inert gas to decompose them into thin sheets of carbon pitted with microscopic holes. In 2016, Lively and his team reported in the journal *Science* that these membranes are capable of selectively separating paraxylene from other xylene molecules. Now, in a new study, Lively, Finn, and their colleagues have fine-tuned these carbon sieves, demonstrating that tiny changes in their molecular structure can have major impacts on the yield of paraxylene they filter.

The researchers fabricate these membranes as hollow fibers, which stand up well against transmembrane pressure. They start with a polymer precursor, in this case the polymer of intrinsic microporosity PIM-1 and the spirobifluorene-based polymer of intrinsic microporosity PIM-SBF. PIM-1 had been previously tested, but PIM-SBF was an intriguing new material to test, as it is more thermally stable than PIM-1. PIM-SBF was also promising because its spirobifluorene structure is highly aromatic, meaning that during decomposition, it forms carbon chains that don't pack well together. This, in turn, makes it less likely that the pores in the membrane will collapse.

The researchers found they could further tune the pores of their carbon membrane sieves during the decomposition process. Varying the level of hydrogen in the gas in which they decomposed the polymer precursors altered the ratio of three-dimensional, diamond-like carbon centers and two-dimensional graphite-like carbon centers in the membrane. Small changes in this 3D:2D ratio made a big difference in how well the membranes separated paraxylene: A change in the ratio from 0.25 to 0.35 increased the membrane productivity by almost a factor of 100, Lively says. A change from 0.2 to 0.7 increased the productivity by a factor of 1,000.

"It turns out that one of our key levers is the concentration of hydrogen in the gas," Lively says. "That allows us to manipulate that carbon ratio pretty precisely."

The challenge now is to manufacture the membrane at large scales and develop an industrial process to handle large amounts of paraxylene. The good news, Lively says, is that unlike zeolite membranes that have also been studied in the lab for xylene separations, polymer membrane precursors are easy to manufacture in large quantities, whereas zeolites tend to accrue defects easily at industrial scales.

The thread-like fibers used to make these membranes will need to be produced by the hundred million for industrial use, Lively says, and there will need to be a method to decompose them continuously, rather than in batches, as is done at the lab scale. Carbon fibers used in airplanes and high-end bicycles are produced by continuous decomposition, Lively says, but such a process has never been tried for membranes.

"At our core we're engineers," Lively says. "We are interested in figuring out how to make more of this, and make it faster."

Ma, Y., *et al.*, "Zeolite-Like Performance for Xylene Isomer Purification Using Polymer-Derived Carbon Membranes," *Proceedings of the National Academy of Sciences*, doi: 10.1073/pnas.2022202118 (Sept. 14, 2021).