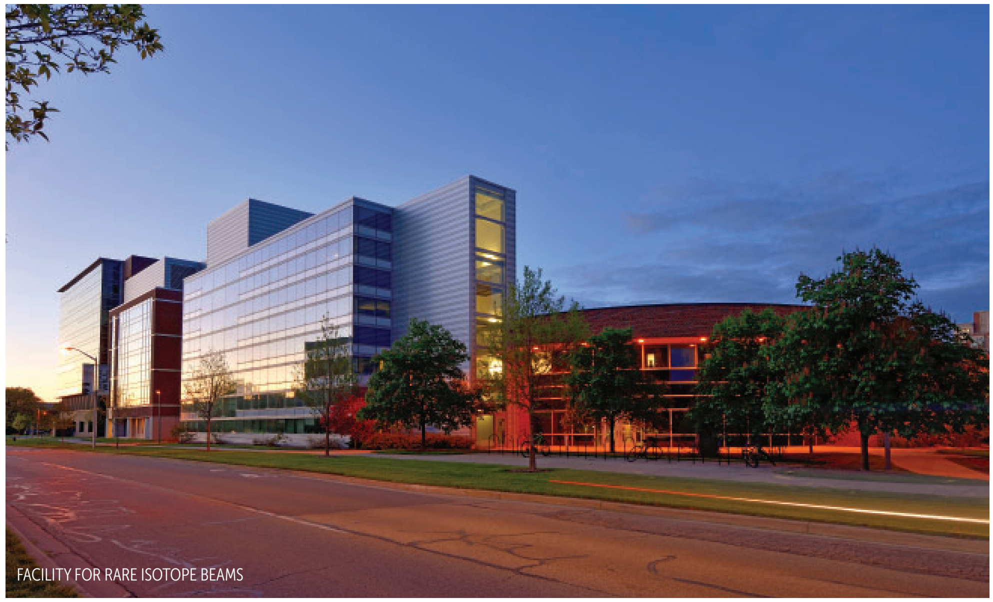
World-leading rare isotope facility is on line in Michigan

Ion beams from oxygen to uranium contribute to research for applications and fundamental nuclear science at a new DOE user facility.



THE FACILITY FOR RARE ISOTOPE BEAMS at Michigan State University is used for basic science and development of applications. The Department of Energy's 28th user facility, it opened in May 2022 and is ramping up to full power over the next few years.

How many neutrons can you squeeze into a nucleus before it falls apart? What can compressed atomic nuclei in the lab reveal about gravitational-wave sources? What is responsible for the relative abundances of elements in the universe? Can physics beyond the standard model be observed by studying pear-shaped nuclei? Those are some of the questions that researchers hope to explore with radioactive isotopes of unprecedented variety, intensity, and manipulability at the new Facility for Rare Isotope Beams (FRIB). (See the article by Filomena Nunes, Physics Today, May 2021, page 34.)

Located at and operated by Michigan State University, the $730 million Department of Energy user facility broke ground about a decade ago and celebrated its on-budget, early completion with a ribbon-cutting ceremony in May 2022.

Bob Laxdal, who is head of the superconducting-RF department and deputy director for accelerators at TRIUMF, Canada's particle accelerator center in Vancouver, British Columbia, chairs the FRIB Technical Systems Advisory Committee. Once FRIB has ramped up to full power, he says, it "will eclipse other rare-isotope facilities. It will allow you to reach low-probability exotic isotopes. And it will produce rare isotopes in larger amounts than has yet been possible."

Research at FRIB is divided into four categories: properties of rare isotopes, nuclear astrophysics, fundamental interactions, and applications for society.

Fast, stopped, reaccelerated

FRIB produces radioactive isotopes through fragmentation. Beams of stable and very long-lived ions are accelerated in a paperclip-shaped 457-meter linear accelerator. As the ions progress through a total of 324 superconducting resonators, they traverse a liquid lithium curtain, which strips the ions of more electrons. The more charged the ions, the easier they are to accelerate. In using a flowing lithium film, says FRIB scientific director Brad Sherrill, "the stripper regenerates constantly, so there's no damaging it." A conventional solid carbon foil couldn't withstand FRIB's high-power beams, he says.

The initial beam can consist of ions ranging from oxygen to uranium. Flying at 10–60% the speed of light, the ions pass through a target, and collisions in the target material produce a cocktail of isotopes in the emerging beam. "You can't determine what isotopes you make, but you can select which ones you want to use," says Sherrill.

Rare-isotope facilities in China, Japan, and Germany also use the fragmentation technique. So did FRIB's predecessor at Michigan State, NSF's National Superconducting Cyclotron Laboratory (NSCL), which was a workhorse for 40 years starting in 1982. FRIB ups the game in terms of beam power, energy, and available isotopes. "For lighter ions the beam power will be 1000 times higher than at NSCL, and for heavier ones it could be up to a million times better," Sherrill says. FRIB will produce about 4500 distinct isotopes, compared with the NSCL's roughly 1000. One of the NSCL cyclotrons is being converted into a chip-testing center; some of the lab's detectors and other equipment are being used at FRIB.

Other facilities, including TRIUMF and CERN's ISOLDE, use isotope separation on line (ISOL). In that approach, protons smash into a thick target, and resulting rare isotopes are thermalized, ionized, and extracted as a low-energy beam. With ISOL, says Laxdal, "it's easier to control the beam quality" through acceleration after the isotopes have been extracted. With fragmentation facilities, he says, "because they create beams at high energy, they can measure things that have a shorter half-life. They can access isotopes that are more exotic. The two methods are very complementary." TRIUMF and other older facilities remain relevant, he adds. "There are more than enough experiments to go around."

A unique feature of FRIB is that it can provide isotopes in fast, stopped, and reaccelerated modes. The fast, high-energy beams exiting the target are a source for in-line experiments with short-lived isotopes and for studies in which protons or neutrons are knocked out of nucleons or that otherwise simulate astrophysical reactions. Trapping nuclei allows for precision measurements of fundamental and symmetry-violating nuclear properties and nuclear decay. And reaccelerating

SUNFLOWERS absorb arsenic and so could be used to detoxify soil. That's one of many horticultural and other potential applications for harvested isotopes at the Facility for Rare Isotope Beams.

slowed isotopes produces high-quality beams that can be used, for example, to simulate lower-energy reactions that occur in stars.

For now, FRIB is running with beam intensities of 5–10 kilowatts. Increasing to the design intensity of 400 kilowatts will be done in steps over time, says FRIB director Thomas Glasmacher. "We need to balance supporting the user community in making discoveries and ramping up power deliberately and carefully," he says. "You have to worry about many things, make sure everything works, and be mindful of radiological hazards." If it were clear from the outset what parts of the setup might have to change to avoid damage at higher power, he says, "we would have built that way. The development of a higher-power accelerator is a science project in itself."

"Waste to wealth"

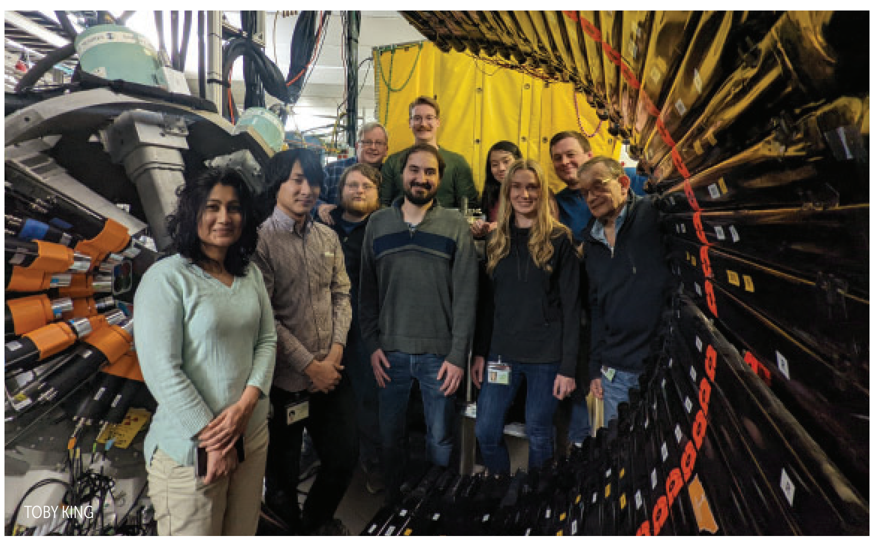
Gregory Severin, a radiochemist at Michigan State, spearheads an isotope-harvesting initiative at FRIB. At most 20% of the initial beam reacts in the target; the remainder is dumped. That's because the target has to be thin, on the order of 1–20 millimeters, in order to create short-lived exotic isotopes that retain forward momentum, he explains. Severin has his eye on the huge dumped portion of isotopes; he wants to "convert waste to wealth."

The dumped isotopes will land in a 7000-liter tank of water. From there, they'll be extracted with an ion exchanger and be put in hot cells for separation and delivery to researchers. Severin hopes the process will be efficient enough to use isotopes that have half-lives down to two hours.

DOE is investing $13 million over four years to build up the harvesting capability, with the aim of facilitating development of applications that benefit society. Planned applications so far include medical therapies and diagnostics, stewardship of the nuclear weapons arsenal, astrophysics, and horticulture. Severin leads the effort to identify potential users and, often, to help them get started. "Part of my job is to make people aware of what they might be able to do with radiotracing," he says.

MIT physicist Ronald Garcia Ruiz and colleagues are working out details on how they might use harvested isotopes. Garcia Ruiz also hopes to do in-line fast-isotope experiments at FRIB, he says, but the team "won't get more than a week or two a year." With harvesting, "we can collect isotopes in a parasitic way from the beam dump and have them almost all the time. Unprecedented access to rare isotopes, especially actinides with pear-shaped nuclei, is going to revolutionize our field." Pear-shaped and other deformed, nonspherical nuclei have unusual shell structures.

One beauty of FRIB, says Garcia Ruiz, is that it can create rare nuclei that enhance symmetry-breaking properties. Using harvested isotopes, he and a large international team of colleagues want to insert pear-shaped nuclei into trapped molecules and perform high-precision measurements. "Because these are molecules that have never before been created," Garcia Ruiz says, the team has a lot to figure out, including what lasers, molecules, and experimental techniques to use. Molecules with an unstable, heavy,



THE FIRST EXPERIMENT at the Facility for Rare Isotope Beams measured decay times for exotic nuclei. The research team assembled the detector, known as the FRIB Decay Station initiator, using subsystems from many of the dozen collaborating institutions. The arc on the right is a neutron time-of-flight detector, at left is an array of high-purity germanium and lanthanum bromide gamma-ray detectors, and the yellow device in back is a total-absorption spectrometer. The experiment was led by scientists at Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Florida State University, Mississippi State University, and the University of Tennessee, Knoxville.

asymmetric nucleus would be "extremely sensitive" to time-reversal violation, he explains. "If we find something that the standard model doesn't predict, it would be a sign of new physics."

More generally, notes Severin, isotopes could be harvested and then fed back into FRIB's secondary accelerators for experiments that require isotopes at a precise beam energy.

High demand

FRIB has 11 experimental stations. Some are outfitted with general-purpose instruments, and some allow for scientists to install custom detectors. So far, the facility is oversubscribed about threefold.

Heather Crawford of Lawrence Berkeley National Laboratory was a principal investigator on the first FRIB experiment, a multi-institution collaboration conducted in May last year. "We looked at beta-decay properties of neutron-rich nuclei from sodium through phosphorus," she says. The researchers obtained half-lives of exotic nuclei and reconstructed energy excitation levels within the nuclei. The data are important for testing models of nuclei far from stability, she says, and for understanding the shape of the nucleus and how neutrons and protons exist in asymmetric nuclei. "The strong and weak forces that govern the nuclear system are not well known. The ultimate goal is a truly predictive model of nuclei to eventually understand nuclear decay and synthesis."

Michigan State nuclear astrophysicist Chris Wrede is keen to gain insights into x-ray bursts from FRIB experiments. He led the development of a detector to look at decay pathways of certain isotopes. For example, by studying beta decay of gallium-60 to excited states of zinc-60, which can emit protons or alpha particles, the researchers can learn about reaction rates and competition between copper-59 reactions in x-ray bursts: proton capture to form zinc-60 and proton capture followed by alpha emission, resulting in nickel-56. Wrede and his colleagues ran an experiment last November and are gearing up for more. The nuclear-reaction rates they obtain provide input to refine comparisons between computer models and x-ray observations from space telescopes.

Nuclear-reaction rates are important for modeling many astrophysical events, says Filomena Nunes, a theoretical physicist at Michigan State. For example, in 1998 she and others used NSCL data on the breaking of boron-8 into a proton plus beryllium-7 to validate a model and extract a critical reaction rate for the solar neutrino puzzle. (See, for example, the article by John Bahcall and coauthors, Physics Today, July 1996, page 30.) She says she hopes to learn about many nuclei with FRIB. "I'm particularly interested in heavy tin isotopes and neutron capture," she says. "I'd like to go all the way to tin-132. This is a region where models have a lot of uncertainty." Understanding the reaction rates and the competition with other processes are steps to understanding the abundances of elements, she says. "How much you get of each element depends on how you get there."

FRIB will discover new isotopes. And any predictive model of the nucleus should be able to say how many neutrons you can add before the nucleus falls apart, says Nunes. FRIB will help with all of those things, partly through improved statistics. "It will replace the little dribble of exotic isotopes by a fire hose."

Toni Feder PT