

Electron scattering provides a long-awaited view of unstable nuclei

Nuclear reactions produce a plethora of short-lived artificial isotopes. Figuring out what they look like has been a challenge.

The cartoon picture of an atomic nucleus looks kind of like the inside of a gumball machine that dispenses only two flavors: protons and neutrons, evenly mixed in a compact, spherical cluster.

That's not generally what real nuclei look like. Neutron-rich lead-208, for example, has a thick skin of neutrons encasing its proton-endowed core (see *PHYSICS TODAY*, July 2021, page 12). Some nuclei are flattened, and some are elongated. Some are even pear shaped.

The more unstable a nucleus, the

stranger the structures it can adopt. Short-lived nuclei might form bubble structures with depleted central density, or they might have a valence nucleon or two that form a halo around a compact central core. (See the article by Filomena Nunes, *PHYSICS TODAY*, May 2021, page 34.) Frustratingly, though, those exotic structures are hard to experimentally confirm, because the gold standard for probing nuclear structure—electron scattering—has been off limits to short-lived nuclei.

That could change soon. Kyo Tsukada

and colleagues, working at RIKEN's Radioactive Isotope Beam Factory (RIBF) in Wako, Japan, have performed the first electron-scattering experiment on unstable nuclei produced on the fly in a nuclear reaction.¹ Their isotope of choice, cesium-137, has a half-life of 30 years. It's not so exotic that the researchers expected—or found—anything unusual about its structure. But the technique they used is applicable to shorter-lived nuclei, so more experiments are on the way.

Backscatter

Probing nuclei through particle scattering dates back to the discovery of the nucleus itself, in 1911, when Ernest



FIGURE 1. RADIOACTIVE IONS too short-lived to be made into a solid target can nevertheless be trapped in an electron beam. The beam itself traps the ions in two dimensions; the cage of thin wire electrodes creates an electric potential that traps them in the third. (Courtesy of Tetsuya Ohnishi.)

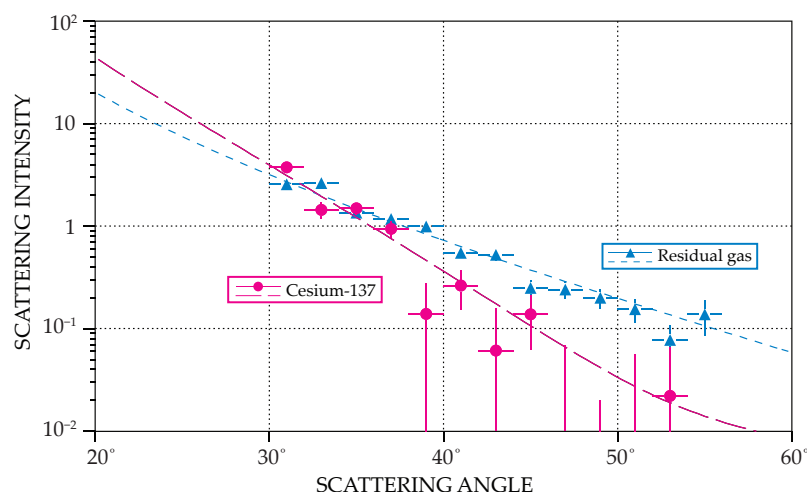


FIGURE 2. CESIUM-137 is the first unstable artificial nuclide to be studied by electron scattering. To obtain the ^{137}Cs data, shown in pink, researchers first had to measure and subtract out the background from residual gas, shown in blue. Theoretical calculations (dashed lines) agree reasonably well with the data for both the ^{137}Cs signal and the residual-gas background, although the ^{137}Cs error bars at high scattering angles are large. (Adapted from ref. 1.)

Rutherford and colleagues fired alpha particles at a thin gold foil. Most of the alpha particles passed straight through. But unexpectedly, a few were scattered to high angles, with some even bouncing straight back the way they came. The only way such a thing could happen, Rutherford reasoned, is if most of the atomic mass is concentrated in a seemingly impossibly tiny volume.

Alpha particles are nuclei themselves, so they're rather crude probes of nuclear structure. When an alpha particle strikes a larger nucleus, it jostles the arrangement of protons and neutrons. And because we now know that protons and neutrons are made up of quarks, the nucleon-nucleus scattering interaction is rather complicated to model.

Electrons, on the other hand, are light, structureless, fundamental particles. With enough energy, an electron can bore straight through a nucleus almost without disturbing it. As Robert Hofstadter discovered in the 1950s, electrons are a near-perfect probe of nuclear structure: From the distribution of electron-scattering angles, one can derive the distribution of charge in the nucleus. For his work, Hofstadter was awarded a share of the 1961 Nobel Prize in Physics (see *PHYSICS TODAY*, December 1961, page 68).

Hofstadter, like Rutherford, used solid foils and other stationary bulk samples as targets for his scattering experi-

ments. And it's hard to imagine doing electron scattering any other way. For alpha-particle or proton scattering, there's the option of so-called inverse kinematics: shooting a beam of heavier nuclei into a stationary target of helium or hydrogen, rather than the other way around. But that approach isn't feasible for electron scattering.

At the RIBF and a growing number of other facilities around the world (see *PHYSICS TODAY*, June 2023, page 21), researchers are producing purified beams of rare and radioactive isotopes, and they're already using inverse kinematics to do proton-scattering experiments on short-lived unstable nuclei. Electron scattering, on the other hand, has been limited to stable isotopes and a few long-lived, naturally abundant radioisotopes, such as carbon-14.

From bug to feature

The RIKEN researchers' new achievement was decades in the making. Electron scattering from unstable nuclei was a primary goal for the RIBF ever since the facility was conceived in 1996. "At the time, nobody knew how to make it possible," says Masanori Wakasugi, an author on the new paper who's been involved in the project from the beginning.

At first, the only idea on the table was to create countercirculating beams of electrons and radioactive ions and smash

them together. But the RIBF was to be a cyclotron facility, whereas electrons would need to be held in a synchrotron storage ring. Getting the incompatible beams to meet and collide was a technical challenge that ultimately proved too difficult and expensive to tackle.

In search of a better idea, Wakasugi and colleagues found inspiration in what had been a thorn in the side of electron-storage-ring operators: The negative charge of a circulating electron beam creates an electric potential that attracts and traps positively charged ions. "Usually the ions are due to residual gas in the ring, and they're disliked for ring operation," says Wakasugi. "But we noticed that if we can replace the residual gas ions with unstable nuclear ions, then electron scattering is possible."

Thus was born the idea of SCRIT—the self-confining radioactive-isotope ion target—which Wakasugi and colleagues laid out in a 2004 paper.² The electron beam itself traps ions in two dimensions, so all that's left is to add a set of electrodes (as shown in figure 1) to trap them in the third dimension and to funnel atoms from a low-energy beam into the SCRIT trap. The trap can be emptied and filled with fresh ions every few seconds, so it could eventually be possible to use SCRIT to study isotopes with half-lives as short as 10 seconds.

The past two decades have been spent building, refining, and testing the necessary instrumentation. The first tests of the SCRIT system used the stable isotopes cesium-133 and xenon-132: Researchers formed the ions into a beam, caught them in the SCRIT trap, and measured their electron-scattering distributions.³ Satisfied that those parts of the experiment were working, they were ready to move on to artificial radioisotopes.

Electrons and beyond

The subject of the new experiment, ^{137}Cs , isn't found in natural cesium samples. But it's abundantly produced in the fission of uranium-235 and other fissionable isotopes. With its half-life of 30 years, it sticks around for a moderately long time, and it's one of the main radioactive contaminants in the vicinities of both the Chernobyl and Fukushima Daiichi nuclear power plants. If researchers really wanted to, they could

make a bulk ^{137}Cs target for a conventional electron-scattering experiment. But because it's easy to extract with high purity from a beam of uranium fission products, it's the perfect isotope for a proof-of-concept SCRIT experiment.

To achieve controlled uranium fission, Tsukada and colleagues shoot their electron beam at a small disk of uranium carbide. When electrons strike the solid target, they rapidly decelerate and create a shower of bremsstrahlung gamma rays that break the uranium nuclei apart. The photofission produces a multitude of isotopes, including ^{137}Cs . Just a few seconds after forming, the ionized ^{137}Cs atoms are separated out and loaded into the SCRIT trap, where their electron scattering can be measured.

But it's not just ^{137}Cs ions in the SCRIT trap. Ions of residual gas—the inspiration for the SCRIT technique—are still present, and they outnumber the target ^{137}Cs atoms. To single out the ^{137}Cs signal, Tsukada and colleagues measured the electron-scattering signal with and without ^{137}Cs ions loaded into the trap. If the residual gas presence is

the same in both cases, all they have to do is subtract.

The results are shown in figure 2. As expected, the residual-gas ions—mostly small, compact nuclei such as nitrogen and oxygen—scattered more electrons to high angles than the large, spread-out ^{137}Cs nuclei did. As a consequence, although the ^{137}Cs signal agrees with expectations, the error bars on the high-angle data points are large. To improve their measurement precision, the researchers are simultaneously working on better understanding the residual-gas background and upgrading their isotope separator to load more target atoms into the SCRIT trap.

As they continue to improve their apparatus, Tsukada and colleagues have their sights set on some specific unstable isotopes. In particular, they'd like to study tin-132, one of the 11 known doubly magic nuclei whose closed shells of both protons and neutrons grant it extra stability against decay. With 82 neutrons and just 50 protons, ^{132}Sn is so neutron rich that it's still unstable, with a half-life of 40 seconds, so not much has been di-

rectly measured about its shape and charge distribution. "That's the goal of the first stage of the SCRIT project," says Tsukada.

"The current facility is dedicated to elastic electron scattering," he continues, "but the SCRIT method can be used for other applications." SCRIT creates a fixed, stationary target of unstable nuclei—something that has never been possible before—which can be used not just for all kinds of scattering experiments but also for photoabsorption measurements, reactive nuclear collisions, and more. Especially intriguing to the RIKEN researchers is the prospect of studying collisions between two unstable isotopes: one in a beam and one in the SCRIT trap.

Johanna Miller

References

1. K. Tsukada et al., *Phys. Rev. Lett.* **131**, 092502 (2023).
2. M. Wakasugi, T. Suda, Y. Yano, *Nucl. Instrum. Methods Phys. Res. A* **532**, 216 (2004).
3. T. Suda et al., *Phys. Rev. Lett.* **102**, 102501 (2009); K. Tsukada et al., *Phys. Rev. Lett.* **118**, 262501 (2017). 

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