

Testing the Physics of Nuclear Isomers

FOR much of the past century, physicists have searched for methods to control the release of energy stored in an atom's nucleus. Nuclear fission reactors have been one successful approach, but finding other methods to capitalize on this potential energy source have been elusive.

One possible source being explored is nuclear isomers. An isomer is a long-lived excited state of an atom's nucleus—a state in which decay back to the nuclear ground state is inhibited. The nucleus of an isomer thus holds an enormous amount of energy. If scientists could develop a method to release that energy instantaneously in a gamma-ray burst, rather than slowly over time, they could use it in a nuclear battery.

Research in the late 1990s indicated that scientists were closer to developing such a method—using x rays to trigger the release of energy from the nuclear isomer hafnium-178m (^{178m}Hf). To further investigate these claims, the Department of Energy (DOE) funded a collaborative project involving Lawrence Livermore, Los Alamos, and Argonne national laboratories that was designed to reproduce those earlier results.

A Concern for National Defense

DOE was interested in the hafnium claims because, if verified, they presented new national security issues as well as potential scientific and energy applications. Nuclear isomers with a long lifetime and a high energy release offer the potential to be a stand-alone energy source. However, if scientists could accelerate an isomer's decay so that gamma rays are emitted in an instantaneous burst, they could also use these isomers to develop propellants and explosives.

"Many applications might be possible if we could duplicate the gamma-ray burst reported in the original research," says Livermore physicist John Becker, who led the tri-laboratory effort. "For example, we might consider developing a gamma-ray laser or a nuclear battery that could power a spacecraft. But we did a textbook nuclear physics experiment, and our results did not match the original claim."

A Nucleus with Energy to Burn?

A nuclear isomer is an atom whose nucleus is in a higher energy state than its ground state. This excited state is very long-lived compared with the usual lifetimes of excited nuclear states.

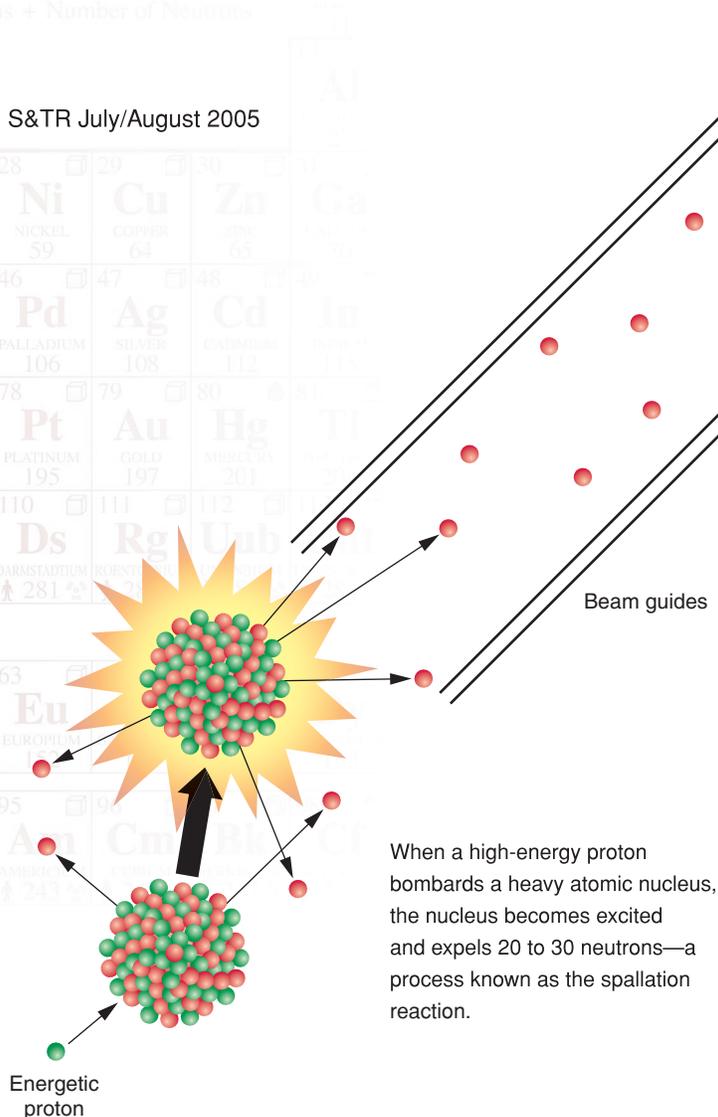
The long lifetime results because transition to the ground state would require a large change either in the spatial structure of the atom's nucleus (for a shape isomer) or in the angular momentum (a measure of the spin of the nucleus) between the isomer and the nuclear ground state (for a spin isomer). Both types of isomers release energy, usually as electromagnetic radiation, when the nuclei transition from a high energy state to a lower one.

Nuclear isomers have a wide range of lifetimes, radiating away the extra energy anywhere from about a picosecond (one-trillionth of a second) to years. A common nuclear isomer is tantalum-180m (^{180m}Ta), whose half-life is about 10^{15} years (a quadrillion years). In its ground state, tantalum-180 (^{180}Ta) is very unstable and decays to other nuclei in about 8 hours. Tantalum-180 is never found in natural samples, which are billions of years old, but its isomeric state, ^{180m}Ta , is found in natural samples. This metastable excited state has an excitation energy 75 kiloelectronvolts (keV) higher than ^{180}Ta , and its decay is inhibited because the angular momentum of the isomer's nucleus is so different from that of the ground state's nucleus.

Hafnium-178m, the isomer studied by Becker's team, has a long half-life of 31 years and a high excitation energy of 2.4 megaelectronvolts (MeV). As a result, 1 kilogram of pure ^{178m}Hf contains approximately 1 million megajoules (10^{12} joules) of energy. Some estimates suggest that, with accelerated decay, 1 gram of 100-percent isomeric ^{178m}Hf could release more energy than the detonation of 200 kilograms of TNT.

Reality Check

To verify the results of the earlier experiments, the tri-laboratory collaboration used Argonne's Advanced Photon Source (APS) as the x-ray trigger for the energy release. This light source is 100,000 times



The Advanced Photon Source at Argonne National Laboratory.

more intense than the x-ray machine used in the 1990s. Thus, if results from those experiments were valid, Becker's team would easily see gamma-ray emissions characteristic of the accelerated decay of $^{178\text{m}}\text{Hf}$.

Scientists at the Los Alamos Neutron Science Center fabricated the isomer samples for the Argonne experiments. Using the center's proton linear accelerator, they bombarded the atomic nucleus of tantalum with 800-MeV photons to induce spallation—a nuclear reaction that causes neutrons to be knocked out of the atom's nucleus, or spalled. The team then separated this material to produce hafnium samples containing about 4 parts $^{178\text{m}}\text{Hf}$ to 10,000 parts ^{178}Hf .

With Argonne's APS, the tri-laboratory team generated a broadband x-ray beam with a wide range of wavelengths, called a white beam, to stimulate the isomer samples. "The precise x-ray energy required to induce the hafnium decay had not been cited in the earlier results," says Becker. "We chose to bombard the sample with a white beam of x rays so that our experiments would include all the energies at which enhanced decay had been reported."

If the previous results were valid, the tri-laboratory experiments would result in the prompt decay of the isomer samples—that is, decay time would decrease from 31 years to less than seconds. Instead, the collaboration's results were consistent with expected prediction of nuclear physics. In fact, the team's cross-section limits, which represent the probability of an interaction event between the x rays and $^{178\text{m}}\text{Hf}$, were more than 100,000 times lower in the relevant energy regions than those previously reported. Says Becker, "We conducted a classic experiment, but we saw no evidence of triggered decay."

These findings can allay DOE's concern about potential applications of the purported isomer energy source. X-ray induced decay of the hafnium isomer does not present a new concern for national security. It also is not a viable alternative as a stand-alone energy source. Nuclear physicists at Livermore and throughout the world continue to investigate such unusual nuclear processes.

—Maurina S. Sherman

Key Words: Advanced Photon Source (APS), gamma rays, gamma-ray lasers, hafnium, Los Alamos Neutron Science Center, nuclear battery, nuclear isomers, radioactive decay, stimulated emission.

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