Particle storage ring enables a role reversal in proton capture

A novel technique for measuring nuclear reaction cross sections may yield long-sought parameters for short-lived isotopes.

The key nuclear reactions that allow the synthesis of heavy nuclei in stars and stellar explosions are well established. Elements heavier than iron form through a sequence of neutron captures and radioactive beta decays. In so-called asymptotic giant branch stars, neutron-capture events can be separated by decades, so there's plenty of time for beta decay to take place. In cataclysmic environments such as supernovae, on the other hand, a nucleus may capture several neutrons within seconds. Together, those two versions of the mechanism, called the s- and r-processes for slow and rapid neutron capture, do a good job of explaining the observed abundances of most isotopes.[1]

But a few dozen naturally occurring nuclides, all proton rich and neutron poor, still defy explanation.[2] Any putative s- or r-process path to their formation is blocked by stable nuclei that don't undergo beta decay. Figure 1 shows a few examples of those so-called p nuclei. To help understand their synthesis, nuclear astrophysicists turn to the proton-capture reaction.

The conventional technique for measuring proton-capture cross sections, necessary for modeling nucleosynthesis, involves accelerating a beam of protons onto a stationary heavy-atom target. Because that method requires a target material that doesn't decay away over the course of the experiment, many important proton-capture reactions of radioactive nuclides have been inaccessible.

Now René Reifarth and colleagues, working at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, are flipping the script: They circulate a heavy nuclide of interest in GSI's Experimental Storage Ring and allow it to interact with a stationary hydrogen target.[3] For their proof-of-principle experiment, they looked at proton capture by ruthenium-96, which is stable, but they anticipate that their method can work for nuclei with half-lives as short as a few minutes. (For more on GSI, see the news story on page 22.)

Mysterious origins

Proton capture alone probably can't explain the formation of the p nuclei. Unlike neutron capture, proton capture is a reaction of two like-charged particles that need to overcome their mutual repulsion if they are to merge. At the kinetic energies present in stars and even supernovae, the reaction is highly suppressed by the Coulomb barrier.

A more likely explanation is that the p nuclei are not the product of any single nuclear process, but of a complex network of thousands of reactions working in concert. That network includes the proton-capture reactions, written as (p,γ) in nuclear-physics notation because they consume a proton and emit a gamma ray, and also various gamma-initiated photodisintegration processes such as (γ,n), (γ,α), and (γ,p). Accurately modeling the entire process requires measuring or calculating the parameters of each of the component reactions. And because (p,γ) is the inverse of (γ,p), studying the former also gives information about the latter.

The Darmstadt researchers' starting material, ^{96}Ru, is itself a p nucleus; their reaction product, rhodium-97, an unstable isotope with a half-life of tens of minutes, is not. Nevertheless, as the University of Hertfordshire's Thomas Rauscher, who was part of a collaboration to study the same reaction using conventional techniques,[4] explains, "Proton capture by ^{96}Ru appears in a proposed astrophysical process to explain the origin of a number of the p nuclei. The combination of the previous and newly obtained data not only shows the validity of the new experiment but also reduces the uncertainty in the astrophysical reaction rate."

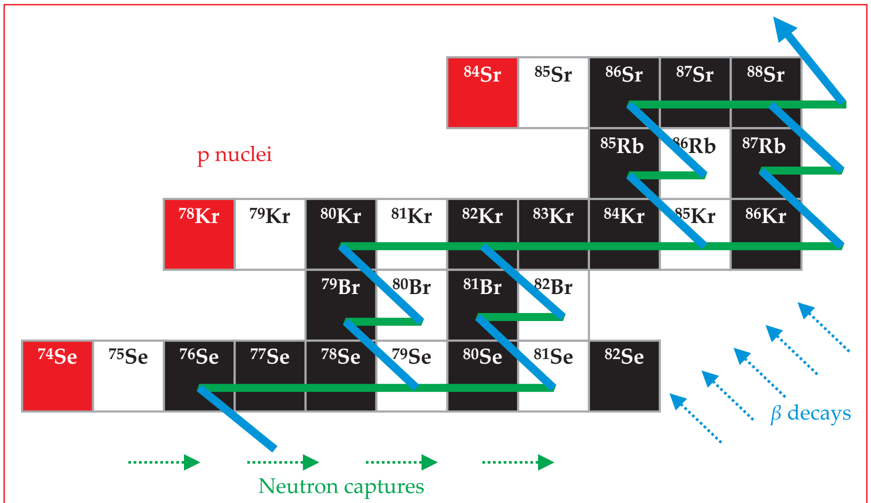

Figure 1. Neutron captures and beta decays together explain the origins of most observed isotopes of elements heavier than iron, as shown here for selenium, bromine, krypton, rubidium, and strontium. (Isotopes shown in black are either stable or nearly stable; those shown in white are not.) But a few dozen stable isotopes called p nuclei, such as the ones shown in red, can't be formed by that mechanism; other nuclear processes must be invoked to explain their origin. (Adapted from ref. 2.)

Around and around

Figure 2 shows a simplified schematic of the part of the storage ring where the reaction takes place. The ^{96}Ru ions, each one stripped of all 44 of its electrons, circulate in the ring, making some 400 000 round-trips per second. They interact with a hydrogen target in the form of a stream of liquid H_2 microdroplets sprayed across their path. A dipole magnet then separates the ions by their charge-to-mass ratio; the ^{97}Rh^{45+} proton-capture products are intercepted by a detector, while the unre-

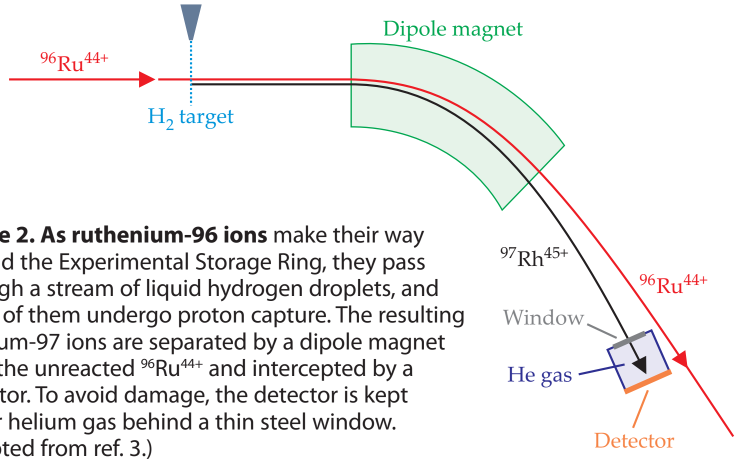

Figure 2. As ruthenium-96 ions make their way around the Experimental Storage Ring, they pass through a stream of liquid hydrogen droplets, and some of them undergo proton capture. The resulting rhodium-97 ions are separated by a dipole magnet from the unreacted $^{96}Ru^{44+}$ and intercepted by a detector. To avoid damage, the detector is kept under helium gas behind a thin steel window. (Adapted from ref. 3.)

acted $^{96}Ru^{44+}$ ions continue their journey around the ring.

Because reactant ions can be continuously produced and injected into the ring, the technique lends itself to the study of proton capture by unstable nuclei. Furthermore, the storage ring offers an additional advantage over an alternative setup involving a linear beam of ions interacting just once with a H_2 target. In the linear configuration, says Reifarth, "If you want to use the expensively and freshly produced ions most effectively, you should make your proton target very thick. However, if you do that, the ions lose energy as they travel through the target," which hampers the measurement. The storage ring, in which unreacted ions are accelerated back to their initial energy after every pass through the H_2 stream, captures all the advantages of a thick target with none of the drawbacks.

The Coulomb barrier to proton capture means that the reaction cross section depends strongly on the collision energy. The Darmstadt researchers conducted their experiment at 9 MeV, 10 MeV, and 11 MeV per nucleon. Though low by particle-accelerator standards—and well outside the relativistic regime—that range is still several times higher than the energies most relevant for astrophysics.

Repeating the experiment at lower energies is not a simple task. The lower the momentum of an ion in the storage ring, the greater the likelihood that a collision with a stray gas molecule will knock it out of the beam. "At 400 MeV per nucleon, the beam can be stored for days," says Reifarth. "At astrophysically interesting energies, it vanishes in 10 to 30 seconds."

To achieve the ultrahigh vacuum required for the beam to last even a few seconds, the researchers must bake the ring at 400 °C for several hours. Because the detector they used for their proof-of-principle experiment would be damaged by that temperature, they placed it behind a window—actually a thin sheet of stainless steel—to isolate it from the rest of the ring. But the window's presence limits the experiment to high reaction energies: Below 9 MeV per nucleon, the product ions would no longer be energetic enough to penetrate the window and reach the detector.

Recently the researchers have installed a new detector that doesn't require a window. That should enable them to work at energies as low as 5 MeV per nucleon. Further planned improvements to the apparatus could allow lower energies still. Reifarth also hopes to try replacing the H_2 target with a helium one to study alpha-induced reactions, also thought to have a role in nucleosynthesis.

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References

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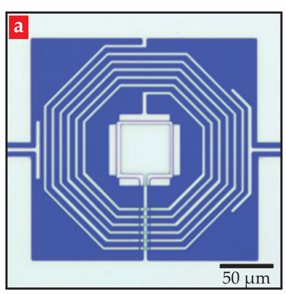
A quantum squeezed state of a mechanical resonator has been realized

Manipulating zero-point fluctuations may pave the way for ultraprecise measurements of forces and positions.

The uncertainties imposed by quantum mechanics, though unavoidable, take the form of a trade-off: It's always possible, at least in theory, to reduce the uncertainty in a parameter of interest (a particle's position, say) at the expense of increasing the uncertainty of something else (its momentum).

In optics, the trade-off gives rise to so-called squeezed states of light, which can be constructed, for example, with lower uncertainty in their amplitude and higher uncertainty in their phase, or vice versa. More generally, if the waveform is written as $X\cos(\omega t) + Y\sin(\omega t)$, where t is time and ω is the wave's frequency, then X and Y, called the quadratures, are the requisite pair of noncommuting quantities whose uncertainties can be manipulated. The ability to produce squeezed light using nonlinear optics enables greater sensitivity in optical measurements such as those made by large interferometers (see PHYSICS TODAY, November 2011, page 11, and the Quick Study by Sheila Dwyer in PHYSICS TODAY, November 2014, page 72).



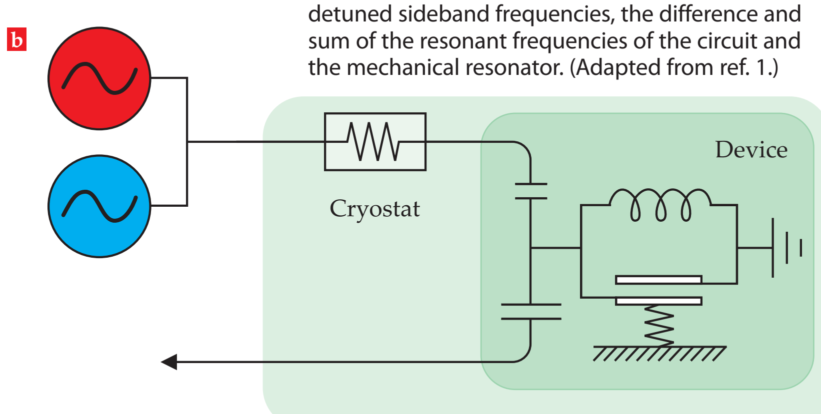


Figure 1. Coupling between a mechanical resonator and an *LC* circuit allows engineering of the resonator's quantum state. **(a)** In this optical micrograph, the center square is a parallel-plate capacitor, and the spiral wire is an inductor. The capacitor's top plate, which has a vibrational degree of freedom, is also the mechanical resonator. Capacitors at left and right provide input and output coupling. **(b)** Here, the same system is shown schematically. The device is cooled by a cryostat to 10 mK, and the circuit is then driven at its red-detuned and blue-detuned sideband frequencies, the difference and sum of the resonant frequencies of the circuit and the mechanical resonator. (Adapted from ref. 1.)