Lead-208 nuclei have thick skins

A precise measurement of the nucleons' radial extent constrains models of dense nuclear matter.

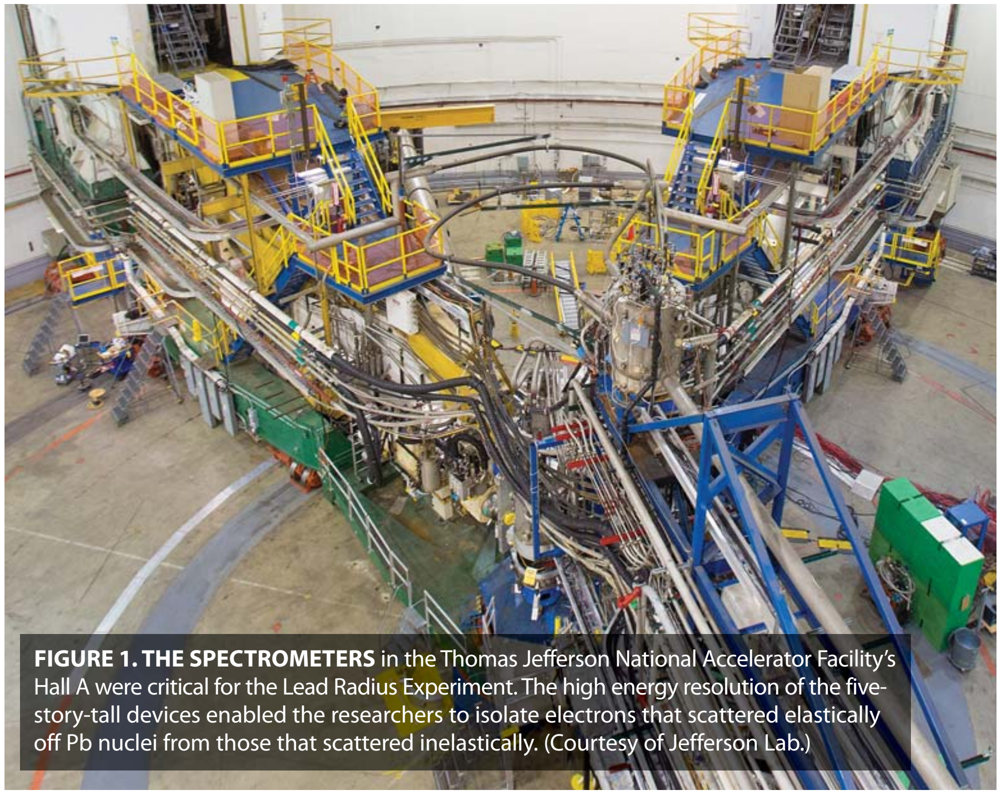

FIGURE 1. THE SPECTROMETERS in the Thomas Jefferson National Accelerator Facility's Hall A were critical for the Lead Radius Experiment. The high energy resolution of the five-story-tall devices enabled the researchers to isolate electrons that scattered elastically off Pb nuclei from those that scattered inelastically. (Courtesy of Jefferson Lab.)

In studies of nuclear structure, lead-208 is special. It has a whopping 44 more neutrons than protons, but unlike most other neutron-rich isotopes, it's stable and doubly magic—both its proton and neutron numbers, 82 and 126 respectively, correspond to full nuclear energy shells. Each nucleon type thus forms a sphere of nearly constant density.

The radius R_p of the proton distribution in an atomic nucleus is straightforward to measure using electron scattering. But because neutrons lack electric charge, an atom's neutron-distribution radius R_n is much trickier to probe. Models indicate that the extra neutrons in ^{208}Pb extend beyond R_p, and the difference between the two radii—the neutron-skin thickness—depends on just how hard the extra neutrons push back against being crammed in tightly among the protons.

The Lead Radius Experiment (PREX) at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, was designed to directly measure the neutron-skin thickness of ^{208}Pb. The collaboration's first analysis,[1] published in 2012, found $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm. That result was twice the 0.15–0.18 fm range that was generally expected. But the measurement's large error bars left room for doubt.

Now the researchers have reduced the measurement uncertainty by more than half. The new result, $R_n - R_p = 0.283 \pm 0.071$ fm, corroborates the researchers' initial finding of a thick neutron skin and challenges existing models of neutron-rich matter.[2]

Skewed scattering

Studying the distribution of neutrons in a nucleus requires a probe that is sensitive to the neutral particles. Earlier experiments used hadrons, such as pions and protons, that interact with neutrons through the same strong force that holds nuclei together. But those scattering events typically involved multiple interactions between the probe and the target, and the resulting neutron-skin values were therefore highly model dependent.

PREX's measurements rely on the weak force's contribution to electron–nucleus scattering. The upside of using electrons is that their interactions with nuclei are easier to interpret because they don't interact through the strong nuclear force. And weak scattering off nuclei is dominated by neutron contributions because, compared with the proton, the neutron couples to the weak force an order of magnitude more strongly.

The challenge, however, is that electrons scatter off nuclei primarily through their electromagnetic interaction with protons. At the energies relevant for probing nuclear structure, electromagnetic-scattering cross sections are about 10^{12} times as large as weak-scattering ones.

To disentangle neutron-dominated weak scattering from the proton-dominated electromagnetic contribution, PREX took advantage of an asymmetry in weak scattering that doesn't affect electromagnetic scattering. When an electron scatters elastically off a neutron by exchanging a weak-force-mediating Z^0 boson, the exchange depends on chirality. All other things being equal, right-handed electrons—those whose spins are aligned with their direction of motion—scatter off Pb nuclei more often than left-handed ones whose spins are antialigned. Data collection therefore entailed flipping the polarization of an incident electron beam and measuring the slight difference in the number of scattered electrons over millions of cycles.

PREX conducted both of its runs in Jefferson Lab's Hall A, shown in figure 1. The facility's high-resolution spectrometer was critical for isolating the elastically scattered 1 GeV electrons, which leave the nucleus in its ground state, from inelastically scattered ones that excite it. In the PREX setup, the energy difference can be as small as 3 MeV. A magnetic field in the spectrometer sorts the electrons by energy, and that tiny energy difference manifests as a spatial separation of about 5 cm at the top of the five-story-tall device.

The first PREX run in 2010 was successful enough to yield a measurement, but it also uncovered some unexpected experimental challenges. The researchers discovered, for example, that over the course of a few days, the incident electron beam degraded the Pb target. Although the soft metal was cooled to 20 K, it still melted and deformed under the beam's bombardment. Small nonuniformities in the target thickness vary the scattering rate, and over the course of the experiment they eventually generated enough noise to swamp the tiny weak-scattering signal.

The PREX researchers found that they could significantly reduce the sensitivity to target-thickness variations by synchronizing the scattering-rate measurements with the back-and-forth motion of the beam as it sampled different areas on the target. That technique was used for their second run in 2019, and they made extra targets so each one could be switched out as soon as it showed signs of degradation. Those improvements proved crucial for gathering enough data, plotted in figure 2, to precisely measure R_n.

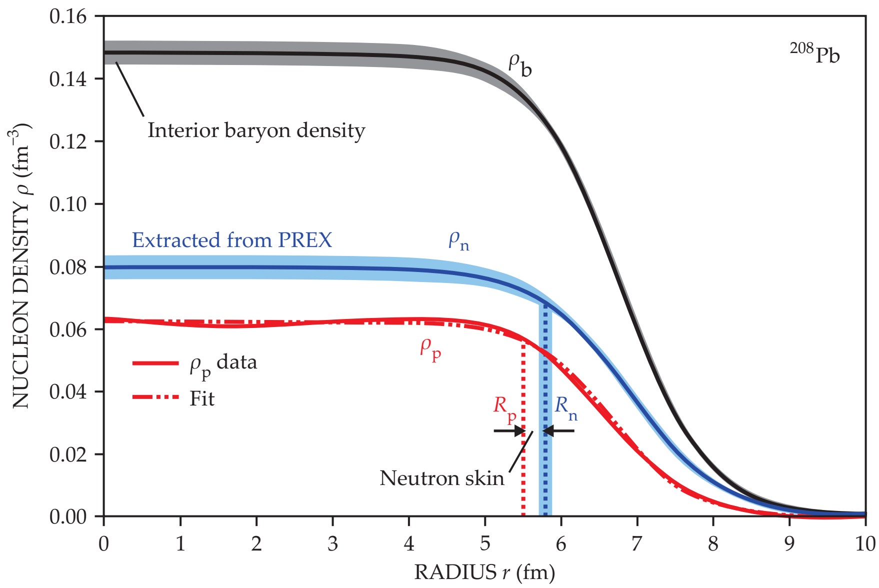

FIGURE 2. A LEAD-208 NUCLEUS has nearly constant interior densities of protons (ρ_p) and neutrons (ρ_n). The nuclide has 44 more neutrons than protons, and because the additional neutrons push back against being squeezed in with the protons, the neutron distribution extends beyond that of the proton one. The difference between the two radial extents is the neutron-skin thickness. Its measured value of $R_n - R_p = 0.283 \pm 0.071$ fm is larger than the 0.15–0.18 fm that most researchers expected. (Adapted from ref. 2.)

Ad astra

The size of the neutron sphere in ^{208}Pb is set by a balance between surface tension, which favors a compact configuration, and symmetry pressure, an outward push caused by having more neutrons than protons. The competition between those forces is captured in the nuclear equation of state, which relates the density of nuclear matter to the outward pressure it generates.

Physicists studying atomic nuclei aren't the only ones interested in pinning down the equation of state for neutron-rich matter. "That's the holy grail of nuclear astrophysics," says Krishna Kumar, a professor at the University of Massachusetts Amherst and a member of the PREX collaboration. The equation is also important for describing neutron stars because the same symmetry pressure that determines R_n in a nucleus also supports the stars against collapse. (For more about the connection, see the article by Jorge Piekarewicz and Farrukh Fattoyev, Physics Today, July 2019, page 30.)

Atomic nuclei have core nucleon densities around 0.15 fm^{-3}, whereas neutron stars can reach several times that density; they constitute the densest stable matter in the universe. Theoretical descriptions of neutron-rich matter connect the disparately sized systems by predicting how symmetry pressure changes with density. Although the descriptions are consistent with all well-understood observables, they accommodate a range of neutron-skin thicknesses and neutron star properties.

The new PREX result further constrains theoretical models, and "there are relatively few models that would be comfortable describing a 0.28-femtometer neutron skin with all the other data they have," says Kent Paschke, a professor at the University of Virginia and a member of the PREX collaboration. Such a thick neutron skin would indicate a strong symmetry pressure, so a neutron star of a given mass would be larger and less dense than many predictions.[3] It also suggests that neutron stars might contain a higher fraction of protons than previously thought, which could trigger an enhanced cooling process at smaller-than-expected stellar masses.

NASA's Neutron Star Interior Composition Explorer (NICER), an x-ray spectrometer mounted on the International Space Station, is measuring the masses and radii of the dense structures.[4] So far, the NICER data are consistent with a ^{208}Pb neutron-skin thickness of up to about 0.31 fm, although they would also have been consistent with a thinner skin in the predicted range. Together, the NICER and PREX data sets rule out a handful of models.

Gravitational-wave data throw a wrench in the machinery. Observations by the LIGO (Laser Interferometer Gravitational-Wave Observatory) and Virgo collaborations of a merging binary neutron star system yielded a measurement of the stars' tidal deformability, a parameter that describes how much each one could be stretched by the other's gravitational pull.[5] That measurement points to a decidedly smaller neutron-skin thickness that would lie more than one standard deviation below the PREX measurement.

The disagreement, though, doesn't cast doubt on PREX's measurement of the neutron-skin thickness. "The power of our technique is the cleanliness of the interpretation and the fact that we are statistics limited," says Kumar. Detection of a few more neutron star mergers would help clarify whether the discrepancy is real. If it is, "then you start to question all kinds of assumptions about how you go from neutron-skin to neutron star observables," says Paschke.

Existing theories suggest that the properties of dense nuclear matter can be extrapolated from the average density of about 0.1 fm^{-3} found in ^{208}Pb to the 0.3–0.6 fm^{-3} of neutron stars, but the situation might not be so straightforward. For example, the material could undergo a phase transition. Superfluid and superconducting phases are thought to exist inside neutron stars, but the phases' dynamics are poorly understood. Some researchers have speculated that the environment could support a fluid of deconfined quarks or even host hyperons, which are baryons that contain the usually unstable strange quark.

Tighter constraint

A more precise measurement of the neutron-skin thickness would help clarify the connection between atomic nuclei and neutron stars, but PREX has reached its limit. There's no way PREX could get an entire year of run time at Jefferson Lab, which is what it would need to appreciably improve its measurement precision. A new dedicated facility in Germany, the Mainz Radius Experiment (MREX), is its planned successor. In addition to enjoying longer run times, MREX will be able to capture and isolate elastically scattered electrons at a higher rate using a purpose-built spectrometer.

With its targeted design, MREX is expected to shrink the uncertainty of the ^{208}Pb neutron-skin-thickness measurement by a factor of two. But, according to Paschke, the experiment's start is likely at least five years away. In the meantime, the NICER and LIGO–Virgo collaborations will continue generating data to inform evolving models, and theorists have their work cut out for them.

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References

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A microscope for measuring surface acidity

An atomic tug-of-war offers a rare insight into the chemistry of complex environments.

Atoms and molecules, the invisible building blocks of everything around us, quickly become complicated as their size and numbers increase. A molecule of just two atoms can occupy any of a multitude of rotational, vibrational, and electronic quantum states, each with potentially different behavior in a chemical reaction. With lasers and molecular beams, physical chemists can prepare and probe many of those states individually and thus dissect the dynamics of a gas-phase molecular reaction in exquisite detail.

But when a reaction takes place on a solid surface—a common scenario in industrial catalysis, materials science, and geology—it's much more of a black box. Because every atom on a rough, irregular surface is situated a little bit differently, they can have dramatically different reactivities, even to the point of steering the reaction toward different sets of products (see PHYSICS TODAY, September 2018, page 17).

Those chemical distinctions among surface sites are extremely difficult to assess directly. Experiments usually measure only the average reaction output for the whole surface; they can't readily track individual reactant molecules to see where on the surface they reacted. Re-

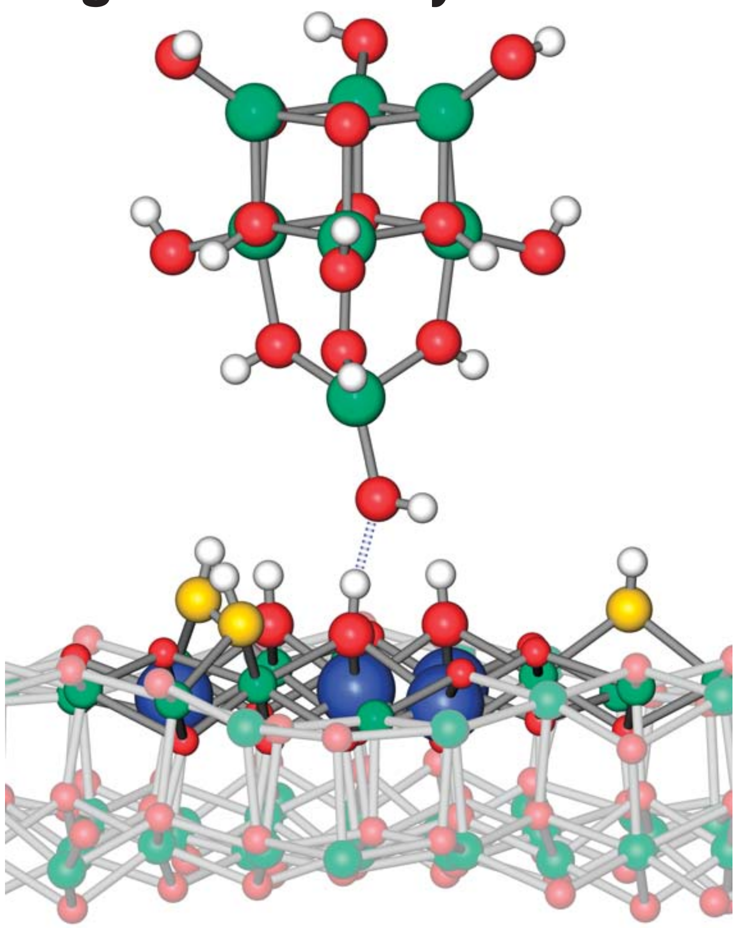

FIGURE 1. ACIDITY MICROSCOPE. When an atomic force microscope tip made of hydroxylated indium oxide descends toward a surface of the same material, the oxygen atom at the end of the tip feels an attractive force (dotted line) to a hydrogen atom on the surface below it. The force is related to the surface site's acidity: how readily it releases its H atom in a chemical reaction. Indium atoms are shown in green and blue, O atoms from adsorbed water in yellow, other O atoms in red, and H atoms in white. (Adapted from ref. 1.)