FORUM Nuclear physics

Exotic pear-shaped nuclei

The elusive pear shapes of certain nuclei, which are challenging to predict theoretically, have at last been measured precisely. Two experts offer their views on what the results mean for nuclear physics and particle physics. SEE ARTICLE P.199

THE PAPER IN BRIEF

- Atomic nuclei are not only spherical, but can be found in a variety of shapes — for example, squashed or stretched spheres.
- The existence of pear-shaped nuclei has long been predicted, but although some qualitative signatures of this nuclear shape have been found, only sparse quantitative information has been obtained.
- Using accelerated beams of heavy, radioactive ions, Gaffney *et al.*[1] have studied short-lived isotopes of radon and radium that are expected to be pear-shaped, and found a clear pear shape in the radium nucleus.
- The results have ramifications both for the understanding of nuclear structure and for testing the standard model of particle physics.

Novel nuclear antennas

C. J. (KIM) LISTER

At the centre of every atom lies a dense, highly charged nucleus containing 99.999% of the atom's mass. Although this has been known for 100 years — since Ernest Rutherford's discovery of the nucleus — there is still much that we do not understand about nuclei and nuclear matter. Gaffney *et al.* have improved our knowledge of nuclear structure by quantifying one specific and unusual nuclear shape.

In an atom, the static external electric field generated by the tiny central nuclear charge is spherical, so the cloud of electrons that defines its chemical and mechanical properties is always spherical. The nucleus, however, is very different. It generates its own binding field, driven by the strong force that exists between all of its constituent nucleons (neutrons and protons). As such, nuclei have a much less well-defined 'centre'. Nuclei are easily polarized away from spherical shapes (Fig. 1) — in fact, more than one-third of all nuclei are bound most tightly if they settle away from sphericity and into elongated, axially symmetrical 'rugby ball' shapes.

Quantum correlations between the nucleons are expected occasionally to favour more exotic shapes, such as pears, bananas or pyramids, although few of these shapes have been proven to exist in nature. These special nuclei represent specific tests of such correlations, so experimental verification of exotic shapes allows a direct comparison of theoretical models to data. Gaffney and colleagues' study was specifically aimed at testing the octupole correlations that are predicted to lead to asymmetrical pear-shaped nuclei. These particular correlations arise only when a certain combination of quantum states straddles the Fermi surface, the boundary between states that are occupied by particles and those that are empty. Excitation of coherent correlated pairs of nucleons between these states drives the whole nucleus into a pear shape. Of all known nuclei, the isotopes of radon, radium, thorium and uranium are predicted to have the strongest octupole correlations of this type, leading to static pear shapes as the most bound configuration.

Although the existence of pear-shaped nuclei has been predicted for a long time[2], many of those anticipated to be the best candidates do not occur as stable nuclei in nature, so they have to be synthesized in a nuclear reaction before study. Practically, the nuclear charge distribution is a small rotating aerial, or antenna, so it radiates a special pattern of electromagnetic radiation. A pear-shaped antenna should emit enhanced electric-dipole and electric-octupole radiation patterns. In their study, Gaffney *et al.* report a direct measurement of these radiation patterns and their enhancement.

Their experiment is special: instead of using nuclei from the world around us, the authors tailor-made specific isotopes of radon and radium in a preparatory nuclear reaction. These special short-lived isotopes were harvested, prepared for acceleration by tearing off many of their electrons and then accelerated to about 10% of the speed of light as a beam of particles. The beams of heavy radioactive nuclei can then be scattered off thin metal foils to excite the antennas and make them radiate. This is the technique of Coulomb excitation — a purely electromagnetic technique for probing nuclear shapes

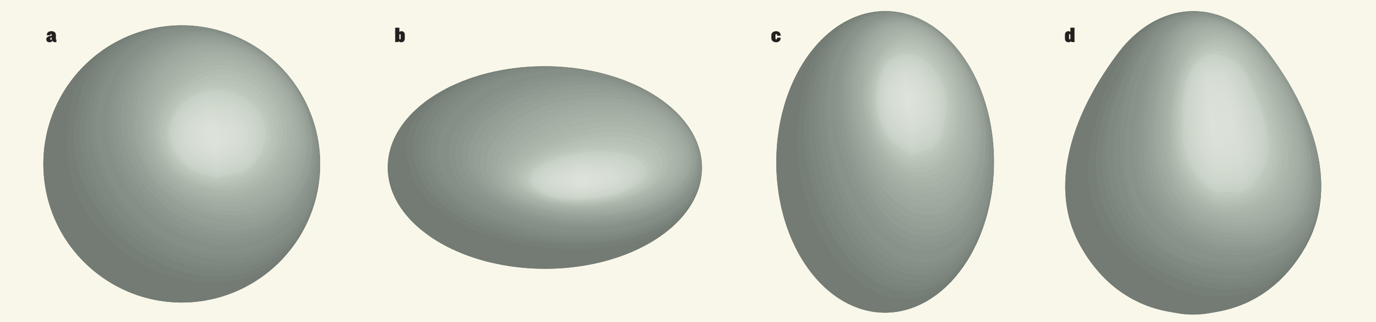

Figure 1 | Nuclear shapes. Nuclei can take several shapes, including a sphere (**a**), an oblate spheroid (**b**) and a prolate spheroid (**c**). Gaffney *et al.*[1] have observed the more exotic pear shape (**d**).

that is well understood. The authors found a lower boundary beyond which nuclei exhibit enhanced electric-octupole patterns: radon, which has a proton number (Z) of 86, showed only modest enhancement of these patterns, whereas radium ($Z = 88$) showed strong enhancement. The next heavier nuclei, thorium ($Z = 90$) and uranium ($Z = 92$), are expected to exhibit even stronger patterns, but we must await the next generation of accelerators to produce these nuclei in sufficient quantity to measure.

With new accelerators being built around the world with the aim of producing beams of exotic isotopes, and ever more sensitive detectors for measuring electromagnetic radiation patterns, we can expect more of this 'isotope tailoring' followed by Coulomb excitation. By picking out special and interesting features for study, these methods will allow us to gain a more profound understanding of how all nuclei really work. Beyond testing models of nuclear structure, pear-shaped 'drops' of nuclear matter do not have the same centre of mass and centre of charge. This effect is predicted to favour searches for static nuclear electric dipole moments and other new physical phenomena.

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Particle-physics laboratory

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Gaffney and colleagues' results on exotic pear-shaped nuclei are of significance to the search for a putative permanent electric-dipole moment (EDM) in particles. Nuclei, like the protons and neutrons that comprise them, are complex objects made up of quarks, bound together by the exchange of gluons — the force carriers of the strong interaction. Because the interaction is strong, the equations that describe it cannot be solved using conventional approaches based on perturbation theory. Numerical techniques, principally lattice approximations in which space-time is broken up into discrete chunks on a lattice, have made much progress, but most of these particles' properties still cannot be calculated from first principles. For nuclei, it is even more complex than for protons and neutrons, and many different approximations are applied to try to understand nuclear structure.

Given all of this, it may come as a surprise that such objects can be excellent laboratories for studying the standard model — the theory that elegantly encapsulates everything we know about elementary particles and fundamental forces. Perhaps most famously, the smashing together of protons at CERN's Large Hadron Collider near Geneva, Switzerland, led to the discovery of a Higgs boson, and has extended the possible validity of the standard model to a new range of high energies. But on much smaller energy scales, precision experiments use nuclei too. For example, searching for rare nuclear decays is the only way to discover whether the neutrino is its own antiparticle. And searching for an EDM of any particle, including a nucleus, is an indirect probe of physics beyond the standard model[3], through one of its key underlying approximate symmetries — time reversal (T). The current limits on the EDM of mercury nuclei[4] are among the most stringent.

The standard model is approximately invariant under T symmetry. This means that most individual, fundamental interactions between particles work equally well backwards and forwards. There is also a theorem, called CPT invariance, that states that all fundamental interactions are invariant if you swap particles for antiparticles (charge, C), swap left for right (parity, P) and swap forwards in time for backwards (T). Thus, breaking T symmetry, as an EDM would do, implies breaking CP symmetry too, so that CPT symmetry can still hold overall.

The CPT theorem connects the hunt for an EDM to the hunt for matter–antimatter asymmetry. Although there is a small amount of CP-symmetry violation in the standard model, it is not enough to explain why we live in a matter-dominated Universe, with so little antimatter around. Many theories of physics beyond the standard model introduce new sources of CP violation, in part to deal with this. As a result, they also violate T symmetry, and often give particles a relatively large EDM.

To see why an EDM violates T symmetry, one has to consider the fact that a particle generally has a magnetic dipole moment (MDM), which can be thought of as being due to a tiny current flowing in a circle, or to the particle spinning. And there is a contribution to the particle's energy that depends on the relative alignment of the EDM and the MDM. If T is reversed, the current flows in the opposite direction, so the MDM changes direction. But the EDM remains unchanged. So the alignment between the two has changed, the energy has changed and the symmetry is broken.

The structure of the nucleus cannot itself generate an EDM, at least not in the standard model. However, if a small EDM exists, it can be amplified by distortions in the shape of the nucleus, such as the pear shapes reported by Gaffney and colleagues. This means that, in evaluating how sensitive an EDM search really is to physics beyond the standard model, or indeed to understanding the implications should an EDM be measured, a good understanding of these kinds of exotic nuclear shapes is essential. The authors' results look like a big step forward. ■

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GALAXY FORMATION

The cosmic web in focus

Detection of the trace neutral fraction of hydrogen gas that stretches between the nearby Andromeda and Triangulum galaxies has allowed resolved spectral imaging of this elusive intergalactic medium. SEE LETTER P.224

ROBERT BRAUN

The historical concept that galaxies are 'island universes' that formed in the distant past and have since evolved in isolation from their surroundings has long been recognized as inadequate. That model was replaced by the hierarchical growth scenario[1,2], which highlights the role of galaxy interactions, collisions and mergers in shaping the mature galaxies that we see today. But as Wolfe *et al.*[3] report on page 224 of this issue, it could be argued that another model is now taking precedence, in which a diffuse 'cosmic web' between the discrete galaxies is the dominant reservoir for continued galaxy growth and evolution.

The impetus for looking further than the hierarchical growth scenario to better explain galaxy evolution has come from simple observational evidence. Over the past decade, it has become clear that the rate at which stars are forming in the Universe has varied markedly with time, first increasing to a peak some 10 billion years ago and then declining more