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Filomena M. Nunes

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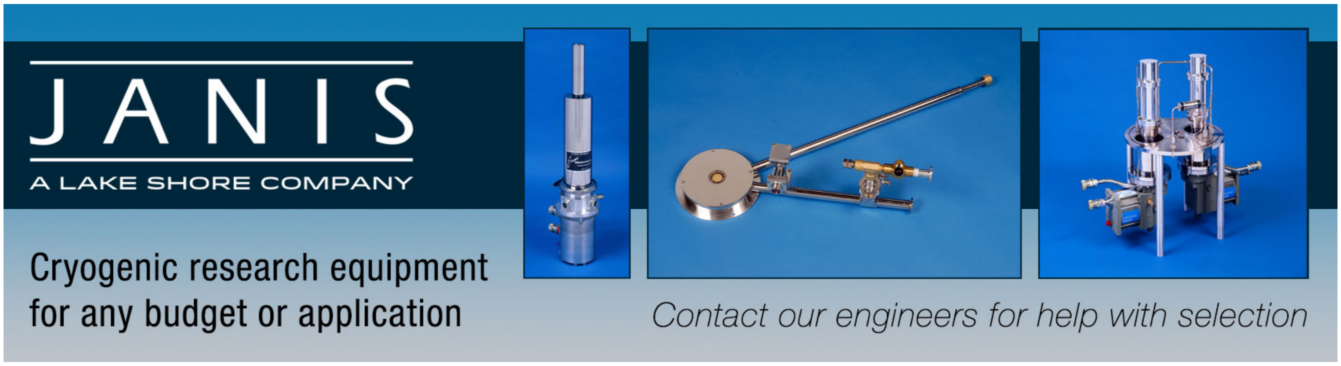
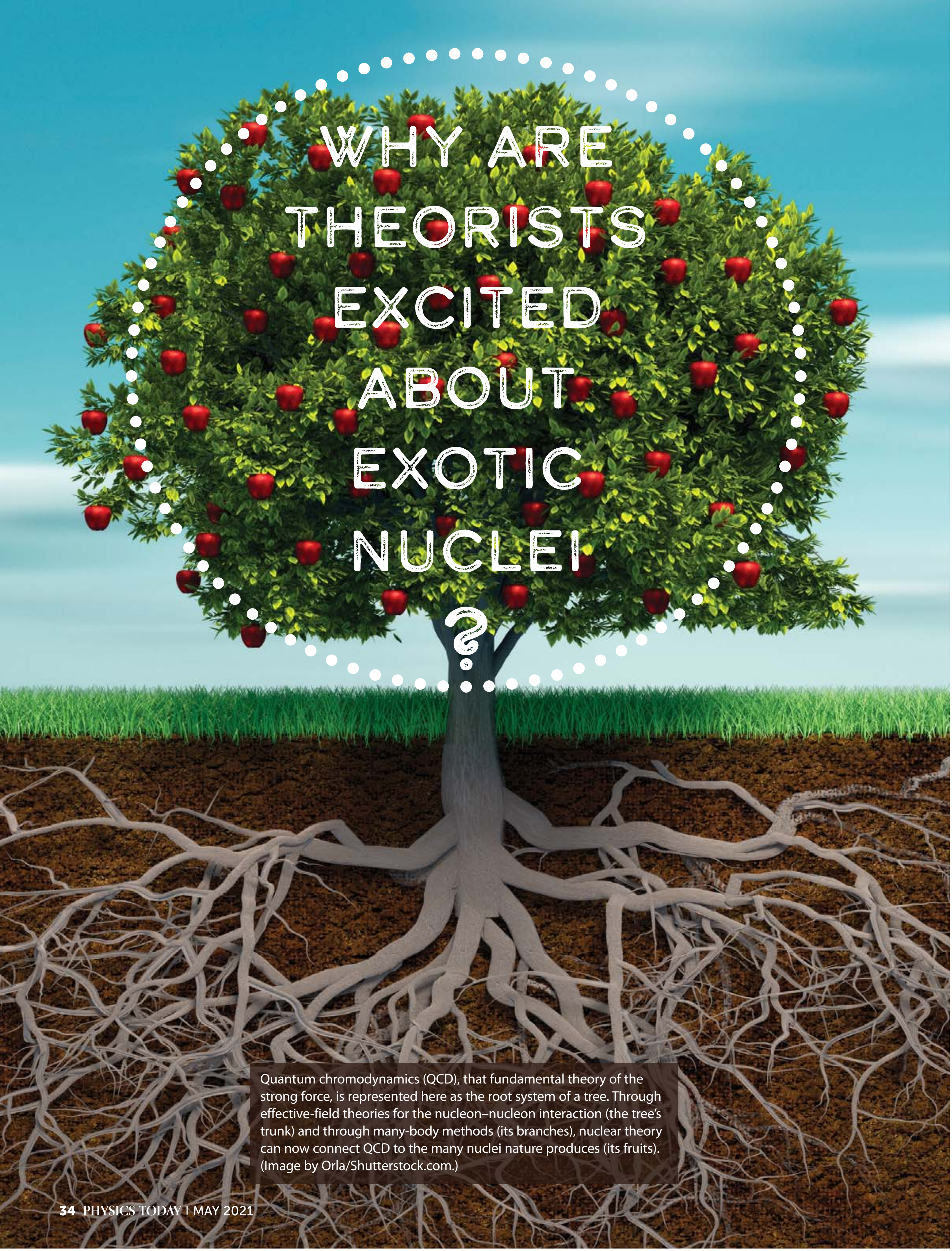


WHY ARE THEORISTS EXCITED ABOUT EXOTIC NUCLEI?



Quantum chromodynamics (QCD), that fundamental theory of the strong force, is represented here as the root system of a tree. Through effective-field theories for the nucleon–nucleon interaction (the tree's trunk) and through many-body methods (its branches), nuclear theory can now connect QCD to the many nuclei nature produces (its fruits). (Image by Orla/Shutterstock.com.)

Filomena Nunes (nunes@frib.msu.edu) is the managing director of the FRIB Theory Alliance and a professor of physics and astronomy, both at Michigan State University in East Lansing.

Filomena M. Nunes

The limits of nuclear stability provide deep insights into the fundamental force responsible for the presence of matter.

Nuclei are at the heart of all palpable matter.[1] Although we understand the properties of things we touch every day—from the carbon in our bodies to the lanthanum in our cell phones—so much more may be revealed by investigating elements at the limits of their stability. Those limits become apparent when too many neutrons or protons are added to a nucleus. Matter falls apart in different ways, by emitting particles and radiation, say, or by fissioning into much lighter elements. Indeed, the world's elements seem to be finely tuned as a subtle interplay of components of the nuclear force. Those components can either hold a nucleus together or doom it to nonexistence.

Collectively known as nucleons, neutrons and protons form the building blocks of nuclei. A nuclear isotope is characterized by a mass number A and charge Z; each isotope contains Z protons and $N = A–Z$ neutrons. A few hundred isotopes exist naturally on Earth. Many thousands of others are short-lived and are constantly being created in numerous corners of the universe.

Nuclear physics has always been an essential component of astrophysical phenomena. Roughly half of the heavy elements found in our solar system originate from chain reactions triggered by neutron star mergers or the violent collapse of massive stars. Exotic nuclei are created, if only for an instant. A major ambition of our generation is to understand where and how heavy matter forms.[2] Exotic neutron-rich nuclei are an essential piece of that puzzle.

Discerning the properties of nuclei and their reactions constitutes the research field known as low-energy nuclear physics. At state-of-the-art facilities, rare-isotope beams are produced by purifying the shower of products of violent nuclear collisions between stable nuclei. Those isotopes are then either stopped in traps for high-precision measurements of their basic properties, such as mass and radius, or sent to beamlines, where they interact with target nuclei to produce various reactions that provide crucial information about the underlying force.

Despite the massive undertaking—from planning and executing the experiments to interpreting their results—those experiments are most often designed to study one single isotope. Over the past five decades, researchers have measured hundreds of isotopes to fill in the so-called nuclear chart. Critics often complain that what's done in low-energy nuclear physics amounts to mere stamp collecting. But the process is an important step to understanding how the world works: Simple patterns emerge from the chart, outlined in figure 1; and from those patterns, we gather deep insights into the nuclear force and predict new phenomena.

The theorists' dream is to understand all the manifestations of nuclear matter as it originates from fundamental forces—strong, weak, electromagnetic, and gravitational. Nuclei are primarily a consequence of the strong and electromagnetic forces. But as its name implies, the strong force is so strong that in many instances it cannot be treated as a perturbation. Quantum chromodynamics (QCD) explains how quarks come together in triples to form neutrons and protons. Because a perturbative approach to QCD is not applicable to neutrons, protons, or nuclei, large-scale numerical computations are required, in which quarks are placed on a lattice acted upon by the QCD Lagrangian. (See the article by Carleton DeTar and Steven Gottlieb, PHYSICS TODAY, February 2004, page 45.)

Why don't theorists calculate the properties of carbon-12 as a 36-quark problem or those of uranium-238 as a 714-quark problem? That would be a more direct approach. But the computations required to solve a problem with even half a dozen quarks would take years using the largest supercomputer in the US. Evidently, simulating the vast majority of nuclei directly from QCD will remain a dream for the future.

Fortunately an alternative to QCD exists. The energy scale of quarks is orders of magnitude higher than the energies required to determine the properties of nuclei, and there are well-controlled ways to connect the force between quarks with the force between neutrons and protons. And through that connection, the theorists' dream may become reality.

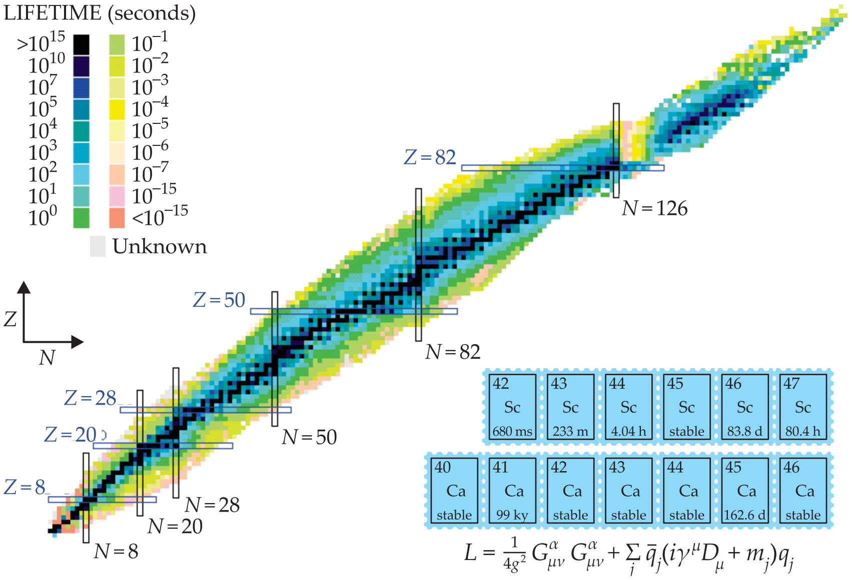
Connecting to the root

Nuclear theorists have long known that they do not need to explicitly include quarks in models to describe nuclear properties. Simply taking neutrons and protons as the building blocks is enough to reproduce many features of known isotopes.

The effective force between neutrons and protons was traditionally determined through fits to a large body of nucleon–nucleon (NN) data. Thanks to close collaborations between theorists and experimentalists over the decades, those fits had improved enough by the end of the 1990s that the resulting NN interactions perfectly described all relevant few-nucleon properties.[3] Even so, no connection had been established between the fundamental theory of QCD and the NN interaction from which nuclei emerge. What was needed was a path to bridge the effective NN interaction to fundamental interactions between quarks and gluons. Only through that transformation could nuclear theory have a chance of evolving from a descriptive to a predictive science.

The path toward bridging nuclei with QCD was first introduced by Ubirajara (Bira) van Kolck and collaborators using effective-field theory.[4] Imagine you have an image with enormous resolution, but all you really need to know is whether a giant gorilla sits at the center of the image. To that end, a low-resolution picture would suffice. Effective-field theory is the tool a nuclear physicist would use to controllably blur the picture, reduce its complexity, and make the problem computationally tractable.

Effective-field theory averages out QCD interactions' short-range components not relevant to the physics of nuclei, and it provides a form of the NN force using parameters that can be determined directly from QCD. The resulting NN force can then be used to solve the nuclear many-body problem and calculate all relevant nuclear properties.



$$L = \frac{1}{4g^2} G^{\alpha}_{\mu\nu} G^{\alpha}_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^{\mu} D_{\mu} + m_j) q_j$$

FIGURE 1. NUCLEAR CHART of isotopes, plotted by atomic number Z and neutron number N and color coded according to the isotopes' lifetimes. The inset shows a detail of the calcium and scandium isotopic chains. The nuclear force is a consequence of the quantum chromodynamic Lagrangian L. Identifying the patterns that emerge from the isotopic chains yields a deeper understanding of the nuclear force. (Image by Donna Padian.)

Limits of stability

Not all is settled in nuclear-force land. In the limits of stability, theory encounters the most stringent tests. Such encounters are why theorists should be excited about studies with exotic nuclei. Those nuclei have the answers; they detect when the theory is wrong.

Were there no Coulomb force, nuclei would come together in pairs of neutrons and protons, because the interaction between those nucleons is slightly more attractive than either the neutron–neutron interaction or the proton–proton interaction. Because of the Coulomb repulsion between protons, as the system gets heavier, it needs more neutrons to provide the glue that keeps the matter together. For example, the most stable carbon isotope is ^{12}C, with six neutrons and six protons, whereas the most stable lead isotope is ^{208}Pb, with 126 neutrons and 82 protons.

Nature produces isotopes with an asymmetry of neutrons and protons much larger than ^{208}Pb's. But when the imbalance becomes too large, the nucleus becomes unstable and decays, either through nucleon emission or beta decay. In both cases nature tries to restore the system's stability with that decay. The limits of stability, often referred to as the drip line, are determined by the last isotope, for which there is a bound state in a given isotopic chain.

Strange things can happen at those limits: Nuclei, often thought of as compact objects, can develop halos and extended neutron skins (see, for example, reference 5). Lithium-11 is one famous example. It is composed of a tightly bound core (lithium-9) and two valence neutrons, which spend most of their time away from the core and resemble a halo. An example of an extended neutron skin is found in neutron-rich tin isotopes. Their valence neutron probability distribution extends farther from the nuclear center than the proton distribution, such that at the surface of the nucleus only neutrons exist.

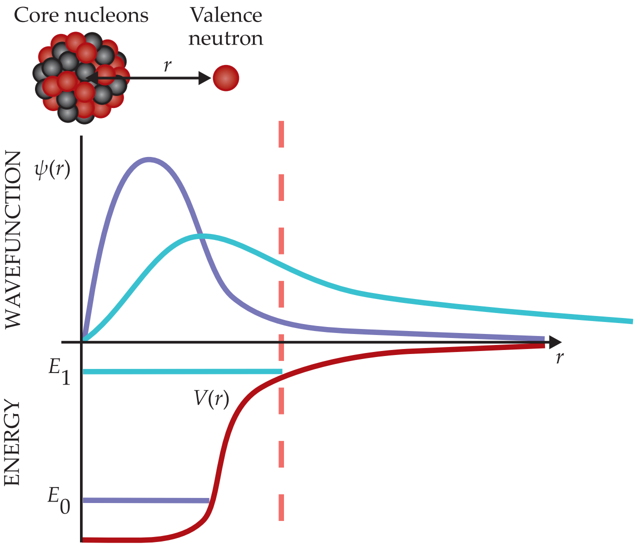


FIGURE 2. EXOTIC NUCLEI are quantum states at the limit of stability. The potential $V(r)$ between a nucleus's core and a valence neutron a distance r from the center is sketched in red. Classically, the neutron would not be able to move outside the classically allowed region (vertical dashed line). In stable nuclei, the valence neutron is well bound: Its energy E_0 is typically about −7 MeV and its wavefunction (purple curve) dies quickly outside that region. The valence nucleon for a nucleus at the limits of stability is loosely bound: Its energy E_1 is typically about −0.1 MeV and its wavefunction (blue curve) extends well beyond the classically allowed region. (Image by Donna Padian.)

Nuclei are quantum systems, and to a large extent one can describe them by solving the nonrelativistic Schrödinger equation. In the so-called valley of stability, the likelihood of finding a valence neutron far from the center of mass of the nucleus is close to zero. But that is not the case for nuclei at the limits of stability. Figure 2 contrasts a wavefunction of a valence neutron in a stable nucleus with one in an unstable, loosely bound nucleus.

In unstable isotopes, the valence neutron lives most of its life in the classically forbidden region, far from the nuclear center of mass. And it exhibits a characteristically long tail in its wavefunction. Those long tails strongly imprint themselves on the nucleons' binding energies, radii, deformations, and electromagnetic responses.

In the early days of rare-isotope facilities, studies at the limit of stability posed several challenges for theory. First, theorists needed far greater precision in their calculations. The average energy per nucleon in ^{12}C and ^{208}Pb is about 7 MeV. However, if we look at the last bound isotope in an isotopic chain, the typical energy that binds each valence nucleon is about 0.1 MeV. For studying stable nuclei, a theory with the precision of 1 MeV is good enough. But when studying nuclei at the limits of stability, theorists need that precision to improve by an order of magnitude.

Second, the traditional methods in many-body nuclear physics simply could not capture long tails in the wavefunction and fell short in their predictions. In the past decade, efforts to develop many-body methods that can deal with loosely bound systems have exploded. It used to be common for theorists to expand the nuclear wavefunction into harmonic-oscillator basis states—functions that fall off much faster than the known exponential dependence with radius—to exploit their analytic advantages. But a revolution has recently taken place, with theorists introducing different bases to capture the long tails.

What's more, with the enormous increase in computational power, many-body methods have improved the scaling of computation time with mass number. At the turn of the millennium, the largest *ab initio* many-body calculation could only calculate the properties of nuclei up to ^{12}C. But today, *ab initio* methods can compute ^{132}Sn, an extraordinary feat.[6] And the precision of the most competitive many-body *ab initio* approaches is now nearing the 0.1 MeV standard.

The impressive progress in many-body methods has uncovered shortcomings in our understanding of the NN force. Although the precision has increased, the mismatch to experiment at the limits of stability reveals a lack of accuracy in the interaction. It appears the blurry picture mentioned earlier is too blurry to pick out the details one needs for barely bound systems. As it turns out, exactly at the limits of stability is where small components of the NN force—those that are not significant for stable systems—become key.

Because the interaction is now rooted in QCD through effective field theory, ways now exist to improve the accuracy with which the interaction is calculated. But the improvement comes at the cost of some technical complications embodied in higher-order forces. Nevertheless, a courageous bunch of theorists are tackling that work.

Probing nuclei with reactions

Ever since Ernest Rutherford's gold-foil experiment, scientists have used reactions to study nuclear properties. Now, more than ever, that tool is essential. The rare isotopes we are interested in are unstable and will decay away if made into targets. Fortunately, isotope factories are able to generate them in a beam. Those isotopes then interact with a target that serves as a probe.

Nuclear reactions are versatile tools because they offer various knobs to turn.[7] On one hand, the energy at which the reaction takes place and the scattering angles that are measured serve to adjust the penetrability of the beam. The energy and angle variability allow experimentalists to scan a nucleus in a way akin to tomography. As in positron emission tomography (PET) scans, researchers may be able to create a three-dimensional image of the nucleus.

On the other hand, depending on the choice of the particle measured in the detector, one gets different information. When, for example, the halo nucleus beryllium-11 collides with a ^{12}C target, many things may happen at the same time. Most of the time the ^{11}Be nucleus—composed of a well-bound ^{10}Be core and a valence neutron in a radially extended orbital—passes through the target unscathed. But when ^{11}Be does react, it may remain in its ground state and yet suffer an elastically scattered deflection. Or it may undergo an inelastic excitation, break up into fragments, gain mass by picking up nucleons from the target, or even fuse with the target.

The type of detector that's used determines the reaction channel to be studied and the properties that can be extracted. For example, to measure inelastic scattering, researchers examine the radiation from the de-excitation; from it they can extract the probability that the transition between states in the halo nucleus will occur.

Like nuclei themselves, nuclear reactions are ruled by quantum mechanics. As depicted in figure 3, the simple picture for nuclear scattering consists of an incoming wave that impinges on a target nucleus. The field generated by that target nucleus distorts the incoming wave, and from that distortion one can determine properties of the nucleus. The part of the wave deflected in the near side of the collision interferes with the part deflected on the far side in a way that, to first order, is analogous to the diffraction of light. The resulting pattern gives a measure of the range of the relevant interaction.

Because the original wave can give rise to many other reaction channels, the intensity of the incoming wave will be reduced.[7] We can think about the reaction process as being driven by another sort of effective interaction—that between the two reacting nuclei. That interaction is referred to as the optical potential, as it contains an imaginary component that removes flux from the incoming wave. The process is analogous to what happens when light is absorbed as it travels through a medium.

The fundamental theory for nuclear reactions is QCD. However, studying the reaction of ^{11}Be and ^{12}C isotopes from the perspective of QCD is a daunting pursuit. The same effective-field theories discussed earlier can help address the many-body scattering problem at hand. Such *ab initio* efforts to simulate nuclear reactions are ongoing, but they're limited to light systems.[8] For heavier systems, another level of simplification is required: casting the problem as a few-body problem and introducing the above-mentioned optical potential.

Although the theory that connects quark degrees of freedom to nucleon degrees of freedom is clean and straightforward, albeit technologically challenging, the theory that goes from the nucleon–nucleon interaction to the nucleus–nucleus interaction is less controlled and still largely phenomenological. One of the greatest challenges in low-energy nuclear physics is to make a formal connection to QCD, so that reaction theory can become less dependent on data. In that respect, much work remains to be done.[9]

Theory crosses borders

The physics of nuclei sits at the crossroads of many different research fields—from astrophysics to fundamental particle physics and from chemistry to condensed-matter physics. Theory plays a key role in establishing connections between those fields.

An important example of that interdisciplinarity is the research in fundamental symmetries at the interface between nuclear physics and high-energy physics. The quest for neutrinoless double beta decay, which tells us whether a neutrino is its own antiparticle, will involve a giant detector (see PHYSICS TODAY, January 2010, page 20). Accurate theoretical predictions for the nuclear-structure properties of the relevant detecting

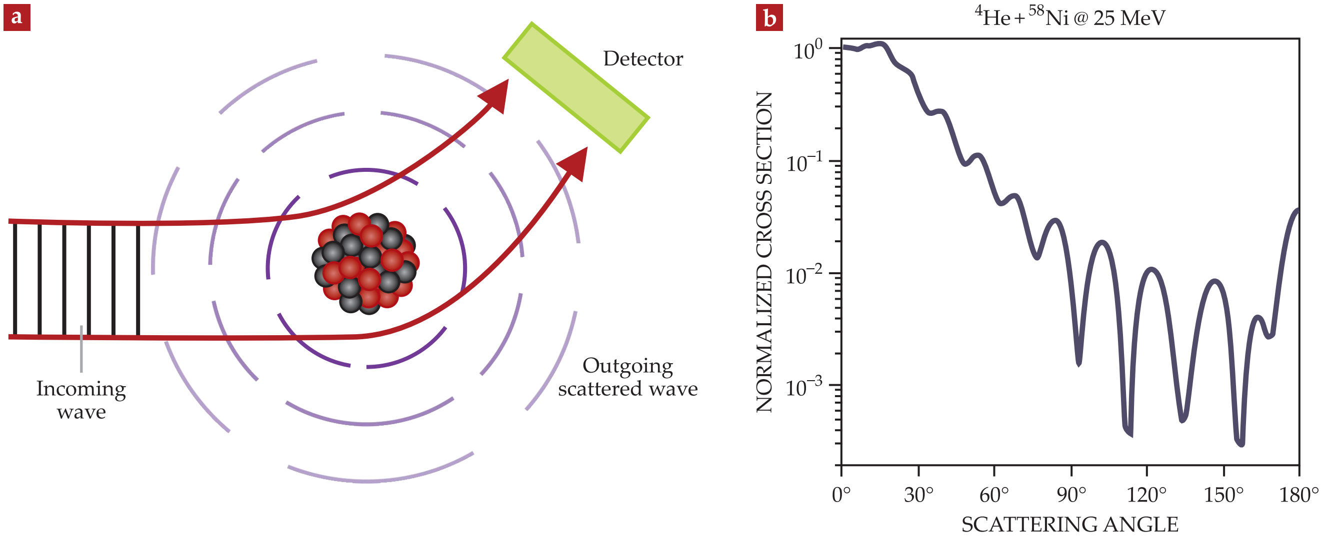


FIGURE 3. ELASTIC SCATTERING of a nucleus off a target is best described using waves: **(a)** Part of the incoming beam is deflected on the near side of the target, whereas other parts are deflected on the far side. Because their paths differ, they have accumulated different phases by the time they reach the detector. **(b)** The result at the detector is an interference pattern that's directly related to the size of the target nucleus. (Image by Donna Padian.)

isotopes will be an essential ingredient for the experiment's success.

In many respects, nuclei can serve as test beds of new physics beyond the standard model. One example involving rare isotopes has to do with baryon asymmetry in the universe. The asymmetry can be explored by searching for permanent electric dipole moments[10] in such pear-shaped nuclei as radium-225 and protactinium-229. (See the article by Norval Fortson, Patrick Sandars, and Steve Barr, Physics Today, June 2003, page 33.)

THE PHYSICS OF NUCLEI SITS AT THE CROSSROADS OF MANY DIFFERENT RESEARCH FIELDS—FROM ASTROPHYSICS TO FUNDAMENTAL PARTICLE PHYSICS AND FROM CHEMISTRY TO CONDENSED-MATTER PHYSICS.

The nuclear connection that has received the most public attention is astrophysics. Since the first 10 seconds in the history of the cosmos, nuclei have shaped our universe. Nuclear reactions are the fuel for large astronomical objects, and through those reactions the universe has synthesized the matter that pervades our lives. Nucleosynthesis, the chain reactions by which nuclei are produced, occurs in stars and explosive environments such as supernovae and neutron star mergers. In such extreme environments, nucleosynthesis steps through many neutron-rich and proton-rich nuclei, and thus their properties are important inputs to large-scale astrophysical simulations.

An illustration of the deep intersection between nuclear physics and astrophysics is the first detection of gravitational waves and their electromagnetic counterpart from the neutron-star merger GW170817. The electromagnetic signal offered an independent constraint on the equation of state of neutron stars.[11] The merger caused shivers in both the gravitational and nuclear communities. Often, reactions of astrophysical interest cannot be measured directly, and indirect reactions must be used to probe the same information.[12,13]

The technical challenges in the theory of nuclei also cut across fields. Nuclei are complex systems from which simple phenomena emerge, just as in molecular physics.[14] So it should be no surprise that similar phenomena—halos, Efimov states, deformation, phase transitions, and others—occur in the two fields. Likewise, many-body methods are widely applied both in chemistry and in nuclear physics; few-body methods that describe reactions with molecules can also be used to study reactions of nuclei at the limits of stability. With efforts to make nuclear theory more predictive, the field has been learning from statistics to quantify uncertainties and to help with experimental design.[15]

Beyond stability

The mass frontier and the asymmetry frontier are both important in the theory of nuclei. As Z goes beyond around 100, at some point the Coulomb repulsion becomes so strong that no matter how many neutrons are used to glue a particular nucleus together, it becomes energetically more advantageous for the isotope to either emit alpha particles or break apart and decay into lighter nuclei. As theorists move toward ever larger neutron–proton asymmetry, they also eventually reach a limit in which valence nucleons are no longer able to stay attached to the core nucleus. In both cases, theory needs to deal with the effects of the continuum—the range of unbound states that exist above a particle threshold.

Many large-mass isotopes are of interest to our society. The mercury found in thermometers and barometers; the lead found in weights and batteries; and ^{238}U, the main fuel in reactors, all spring to mind. Oganesson, the heaviest element in the periodic table, has $Z = 118$ and a lifetime of less than a millisecond. Because of exponential growth in the computational cost in *ab initio* many-body methods, theories for describing it and other heavy systems rely on density functionals (see the article by Andrew Zangwill, Physics Today, July 2015, page 34).

Although informed by theory, the functionals are typically fitted to experimental masses and other data. The models predict an island of stability of superheavy nuclei. (See the article by Yuri T. Oganessian and Krzysztof P. Rykaczewski, Physics Today, August 2015, page 32.) Although the location of those superheavy elements on the nuclear chart is uncertain, they should reside above copernicium-112 on the neutron-rich side, around $N \approx 184$. The problem with phenomenological density functional theories is that, despite their validity in regions where data exist, they become unreliable in extrapolating to regions where no data exist. Although the path is complex, here, too, theorists are trying to connect the density functionals to more fundamental theories.

The second frontier concerns the neutron–proton asymmetry. For light nuclei, the most stable isotopes have a neutron-to-proton ratio (N/Z) around one. With their increasing Coulomb repulsion, heavier isotopes, such as ^{208}Pb, reach $N/Z = 1.5$. But near the limits of stability are exotic nuclei such as helium-8 ($N/Z = 3$) and ^{9}C ($N/Z = 0.5$); long isotopic chains, such as Sn, which has 32 isotopes; and neutron stars, the most perplexing form of nuclear matter that exists, with N/Z of about 20. Precisely predicting the maximum number of neutrons that can be added to a stable nucleus while keeping the system bound is one of the greatest challenges for *ab initio* many-body theories, especially for systems whose Z exceeds 20.

For nuclei with Z less than 20, the limits of stability have produced halos, in which valence nucleons hang around a central core nucleus in the classically forbidden region, as discussed earlier. Because the halo nucleons are decorrelated from the rest of the nucleus, few-body theories—in which nuclei are composed of a core nucleus with few valence nucleons—are often adequate to describe their properties.

When the attraction obtained by adding another neutron to an isotopic chain is not enough to keep it bound, the nucleus steps into the positive energy domain. States beyond the limits of stability are sometimes elusive for theory, particularly if they have short lifetimes. Examples of those states include the tetra-

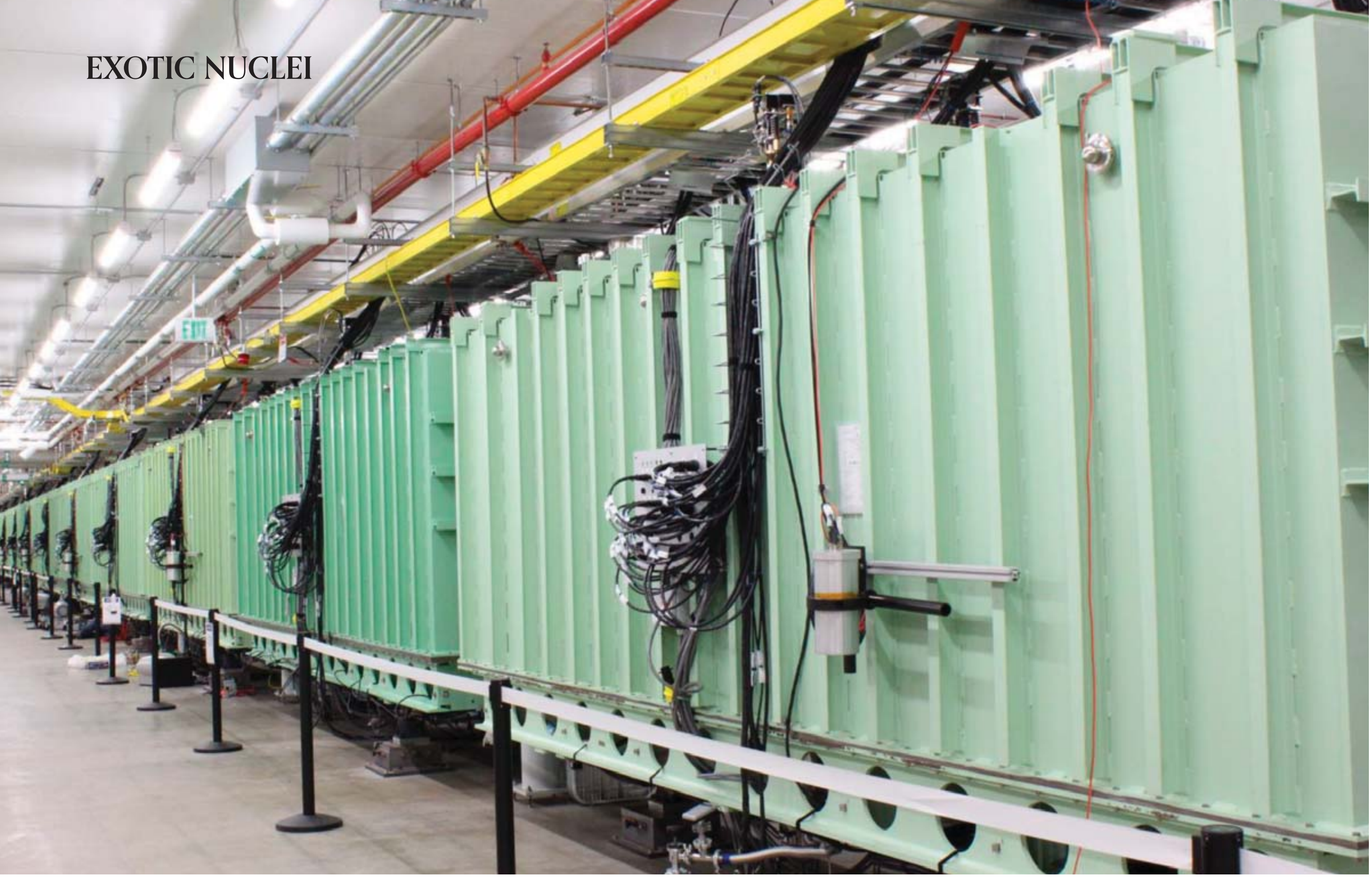


FIGURE 4. THE FACILITY for Rare Isotope Beams is taking shape as the highest-energy superconducting heavy-ion linear accelerator in the world. When it begins operating in 2022, the facility will be able to accelerate all ions from hydrogen to uranium to at least 200 MeV/nucleon and produce thousands of rare isotopes by in-beam fragmentation. (Courtesy of the Facility for Rare Isotope Beams.)

neutron,[16] a hypothetical stable cluster of four neutrons; the ^{10}He resonance ($N/Z = 5$); and two-neutron radioactivity[17] in ^{16}Be.

New facilities

Around the world, technology to study rare isotopes has been advancing rapidly. Many isotopes have been discovered since the Rare Isotope Beam Factory began its operation a decade ago at the RIKEN National Science Institute in Japan. But nuclear physicists are most excited for the start of operations at the Facility for Rare Isotope Beams (FRIB) next year at Michigan State University.[18] That facility, partly shown in figure 4, is expected to produce nearly 80% of all the isotopes predicted by density functional theory, including many on the neutron dripline.

A linear accelerator bent into three segments, FRIB accelerates a heavy-ion primary beam up to half the speed of light. Many different isotopes can be formed in the violent collisions between nuclei in the beam and nuclei in the production target. The rare isotopes of interest will be separated and either guided directly into the relevant high-energy experimental halls, or stopped and reaccelerated to the low-energy beamlines.

Nuclear facilities have been producing rare isotopes for decades. Unique about FRIB is the 400 kW power of the accelerator. The increase in power expands the accelerator's reach into exotic areas: The machine will be able to explore the properties of long isotopic chains, such as the Sn isotopes, and thus allow theorists to test their understanding of the NN interaction and its dependence on neutron–proton asymmetry. With the beam's intensity, FRIB will be able to measure several reaction channels simultaneously and more accurately than could be done before. Along the way, FRIB will likely unveil some unexpected phenomena to keep theorists scratching their heads.

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