SIMILAR TO BLUEBELLS, which bloom for just a few weeks in spring, some nuclei live for only short periods of time; their behaviors reveal interesting characteristics of the nuclear landscape. (Image by iStock.com/Olga Kaya.)

Witek Nazarewicz is a professor of physics at Michigan State University in East Lansing and the chief scientist at the US Department of Energy's Facility for Rare Isotope Beams, which is operated by the university. **Lee Sobotka** is a professor of chemistry and physics at Washington University in St. Louis.

The lessons learned from ephemeral nuclei

Witold Nazarewicz and Lee G. Sobotka

Recent experimental analyses of fleeting clusters of protons and neutrons put the very notion of the atomic nucleus in a new light.

Atomic nuclei can be divided into those that are stable and those that are not. The latter often are labeled radioactive. But this binary classification fails to capture the range of nuclear lifetimes, from those that last less time than it takes for light to cross atomic dimensions to those that dwarf the age of the universe.

The chart of the nuclides, shown in figure 1, displays the known assemblages of protons and neutrons, dubbed nucleons, that are glued together by the strong force and qualify as nuclei. They are grouped by the number of protons, or atomic number Z, and the number of neutrons N. Of the roughly 8000 isotopes with $Z < 120$ that are theorized to exist,[1] only about 300 can be found on Earth in more than trace quantities.[2,3] Those nuclei, indicated as black squares in figure 1, are usually characterized as either stable or practically stable because their half-lives are greater than Earth's age of 4.5 billion years, and they collectively define a valley of stability on the chart.

Most of the chart, however, comprises nuclei with short lifetimes. They are subject to various types of decay: Beta decay and electron capture are governed by the weak force; and alpha decay, spontaneous fission, and proton decay, by the strong and electromagnetic force. To achieve a broad understanding of atomic nuclei, the entire nuclear landscape must be studied.

The first lesson to learn about the nuclear landscape is that light, stable nuclei have about the same number of protons and neutrons, whereas heavier stable nuclei have more neutrons to compensate for the increasing electrostatic repulsion between protons. The valley of stability thus has a slightly concave curvature.

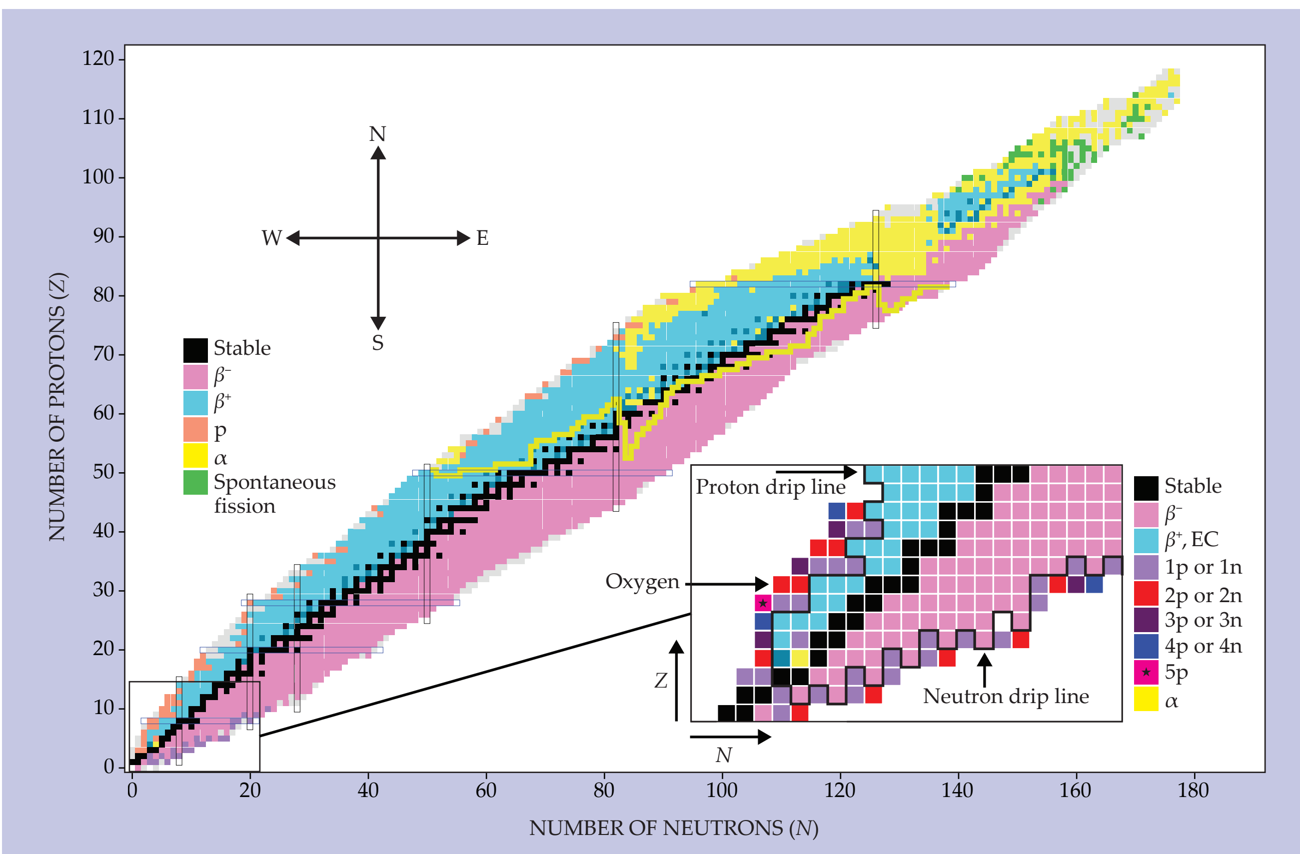

FIGURE 1. THE CHART OF THE NUCLIDES shows the main decay modes of the nuclear landscape. The yellow line corresponds to an alpha decay energy $Q_\alpha = 0$. Above the line, all nuclides are metastable to alpha-particle decay. The inset shows the region where all assemblages of nucleons that qualify as nuclei are known, with color-coded decays. The particle drip lines, indicated with a thick black line, mark the border between bound and unbound nuclei. All nuclides lying outside the drip lines can decay by emitting protons or neutrons. (Experimental data taken from ref. 2.)

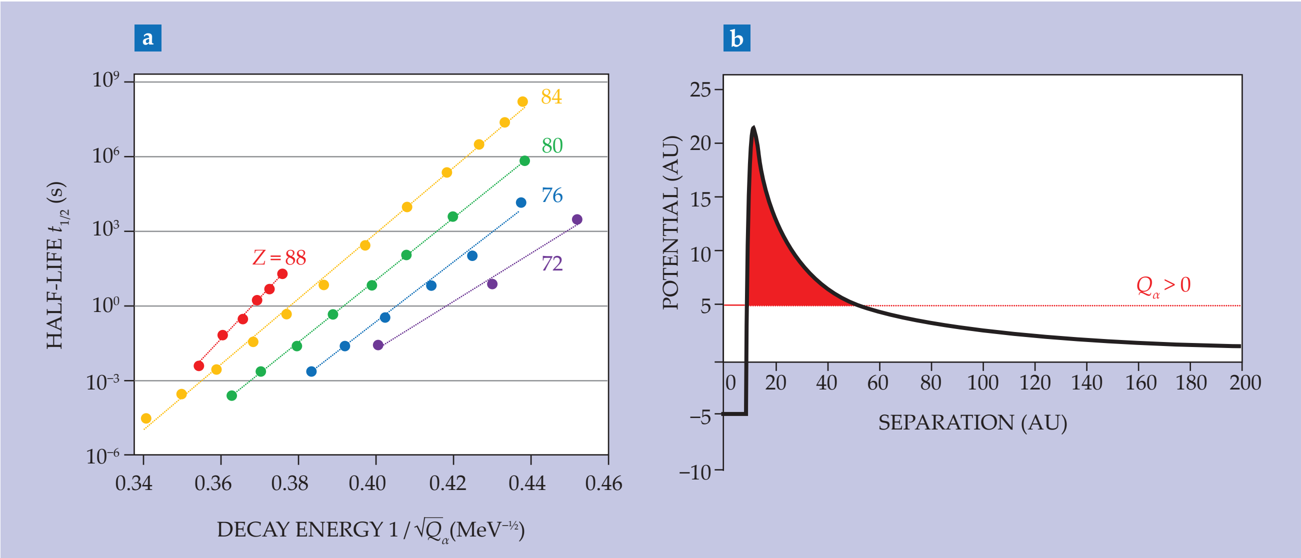

FIGURE 2. ALPHA DECAY. (a) The Geiger–Nuttall law states that alpha-decay half-lives (colored lines) increase exponentially with the inverse square root of the decay energy Q_α and with atomic number Z (labels). The data confirm that alpha particles can decay by tunneling through a potential energy barrier that behaves according to $1/r$ at large distances and that increases with Z, where r is the distance from the center of the nucleus. **(b)** For $Q_\alpha > 0$ (red horizontal line), which is different for each nucleus, the decay rate is determined by the size and range of the potential barrier (shaded region) and the detailed nuclear structure of the parent and daughter nuclides. (Experimental data taken from ref. 2.)

The next lesson is that the stability valley separates two regions of weak nuclear decays: Nuclei decay by β^- emission in the eastern region of the chart and β^+ emission and electron capture in the western region. In the extreme northeast region, where the superheavy elements are found, no long-lived, stable nuclei exist because of alpha-particle decay and spontaneous fission.

A pattern for the stable nuclei emerges when the focus is on isobars, which are defined by nuclides with a constant mass number $A = N + Z$. Usually, only one stable nuclide exists for odd-A systems. For even-A isobars, most often two stable nuclides exist, both of which have even numbers of protons and neutrons. Such observations are perhaps the clearest evidence that like nucleons tend to pair up—the phenomenon of nucleonic superconductivity—and the result is a more tightly bound nucleus.

The boundaries of the chart are more challenging to explain, and the study of nuclei at the boundaries is a subject of active investigations.[4] With enough excess protons or neutrons, the nuclear binding energy decreases to the point that the nucleus can decay by emitting the excess nucleons. The positions on the chart where nucleon emission becomes energetically favorable are called drip lines—the proton drip line to the west and the neutron drip line to the east. The drip lines do not, however, define the chart boundaries rigidly. On the proton-rich side, where the Coulomb repulsion is strongest, the drip line merely denotes a transition from a region that's energetically stable to proton emission to one that's metastable with respect to such emission.

That realization compels the question: When does an assemblage of nucleons constitute a nucleus? By studying ephemeral nuclei, we can begin to answer that question. Such nuclei can also be useful for understanding processes in nuclear astrophysics and various exotic environments.

What is a nucleus?

To answer the question of what constitutes a nucleus, it is helpful to consider the case of the long-known nuclear decay mode in which the nucleus emits an alpha particle. In 1912, Hans Geiger and John Mitchell Nuttall published a paper that showed that the half-lives $t_{1/2}$ of nuclides that emit helium-4 nuclei increase exponentially with the atomic number of the radioactive nucleus Z and with the inverse square root of the decay energy Q_α.[5] The latter is the difference between the energy of the parent atom and the summed energies of the daughter and helium atoms (see figure 2a). The Geiger–Nuttall law remained unexplained until the development of quantum mechanics more than a decade later.

A key element of the explanation was provided in 1928. An alpha particle, which can transiently form inside the parent nucleus because of the exceptionally strong binding of two protons and two neutrons, is subject to an average potential dominated at short distances by the attractive nuclear force and at long distances by the repulsive Coulomb force.[6,7] The competition between the short-range attraction and the long-range repulsion gives rise to a net effective potential with a barrier similar to what is schematically illustrated in figure 2b.

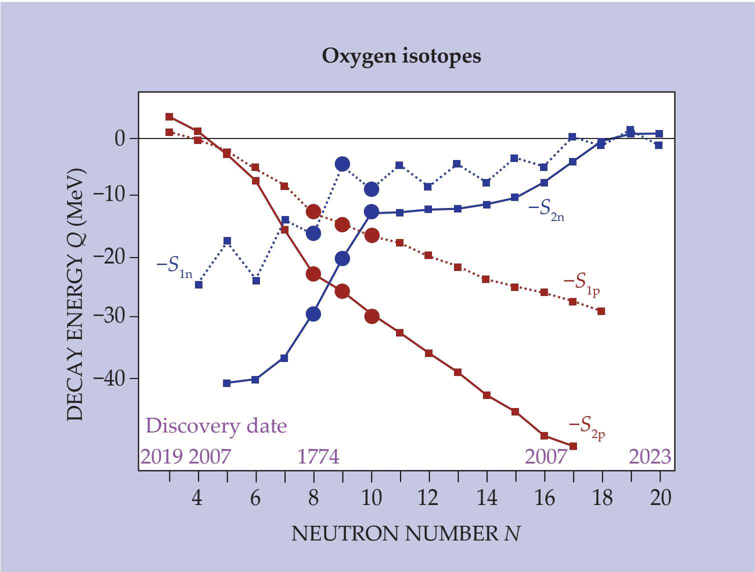

FIGURE 3. THE ENERGY REQUIRED to remove one (S_{1n}, S_{1p}) or two (S_{2n}, S_{2p}) nucleons for each of oxygen's isotopes. The nuclides ^{16}O, ^{17}O, and ^{18}O (largest dots) are the only truly stable isotopes of oxygen because they are also stable to the weak interaction. Oxygen isotopes at lower and higher neutron numbers are unstable to weak decays. On the neutron-deficient side (left), the isotopes ^{11}O and ^{12}O are unbound to 1p and 2p decay. Below the solid horizontal line, the nuclei are stable with respect to particle emission, and some energy—quantified by the *Q* value—is needed to remove a nucleon from the nucleus. On the neutron-rich side, without a Coulomb barrier, the nuclei beyond ^{24}O are ephemeral. Neutron-unstable ^{26}O and ^{28}O isotopes have small neutron separation energies and emit multiple neutrons. Only in recent years, with the discovery of ^{11}O, ^{12}O, and ^{28}O, have researchers begun to study the zone of nuclear ephemera. (Experimental data taken from ref. 2.)

According to classical theory, if the energy of the potential barrier is higher than that of the alpha particle, decay is impossible. But because of its wavelike behavior, an alpha particle can leave the nucleus by quantum mechanical tunneling. If the tunneling probability is low, then the nucleus is metastable to alpha decay. The fact that the experimental Geiger–Nuttall systematics were consistent with the picture of tunneling through a potential barrier constituted an early triumph of quantum mechanics.

Since the discovery of the Geiger–Nuttall law, nuclear scientists have mapped where alpha decay is the dominant decay mode. The territory is shown in yellow in figure 1. The number of nuclei for which alpha decay is energetically possible ($Q_\alpha > 0$), however, is much greater. (In figure 1, those nuclei lie above the yellow line.) If not for the robust alpha-decay barrier, the region of stable nuclei would end with atomic numbers in the low 60s. Using the same argument, one can conclude that all nuclides heavier than $A = 110$ are energetically unstable to the division into two lighter nuclei through fission. (Alpha decay can be viewed as an extremely asymmetric fission.) The elements in the upper half of the periodic table exist not because of their absolute stability against decay but because of an imposing barrier that prevents them from partitioning into smaller nuclei.

Thus, any reasonable answer to the question of what constitutes a nucleus must not come from whether an assembly of nucleons is energetically bound. Instead, the answer must be based on lifetime considerations. That applies to the light nuclei discussed in this article as well as the heaviest nuclei that define the upper northeast boundary of the chart. In the northeast territory, the nuclei can decay by both fission and alpha emission, but they can be studied as long as they possess an imposing barrier to decay. The situation for neutron-rich nuclei is a bit different than for proton-rich nuclei. Closer to the neutron drip line, beta decay times decrease until neutrons become unbound. Without the Coulomb contribution to the potential, and thus no imposing barrier inhibiting neutron emission, neutron-decay metastability is far more limited, and nuclei rapidly transition from particle-stable to unstable. The long-sought-after tetraneutron sits near that transition.[8]

Confronted with the reality that metastability presents a continuum of lifetimes that depends largely on the effective potential barrier, is there a sensible definition for a nucleus? One measure that makes physical sense is that an assemblage of nucleons possesses a mean lifetime $\tau = t_{1/2} / \ln(2)$, which is long enough for nucleons, moving with velocities characteristic of the internal kinetic energies of the weakest-bound nucleons, to traverse nuclear dimensions at least several times. The result is a characteristic single-particle time scale τ_{SP} of about 1.5×10^{-22} s.

Consequently, if a nuclear state lasts for a long time compared with τ_{SP}, it should be considered a nucleus. Fleeting nuclei that are barely kept together by a potential barrier are referred to as ephemeral. With that definition, a collection of nucleons—including some extremely neutron-poor oxygen isotopes and other light nuclei with an unusually high proton-to-neutron ratio—builds an effective average potential barrier like the one shown in figure 2b. For such nuclei, which are on the western side of the figure 1 inset, the barrier generates metastability similar in form to that which inhibits alpha decay and fission.

A family of nuclei

Oxygen isotopes ($Z = 8$) offer a complete set of possible collections of nucleons that satisfy any reasonable definition of a nucleus. Figure 3 shows the experimental mass difference between an oxygen parent nucleus and a daughter nucleus, with one or two nucleons removed, and the separated nucleons. The decay value Q is the negative of the energy required to separate one or two nucleons from the parent system.

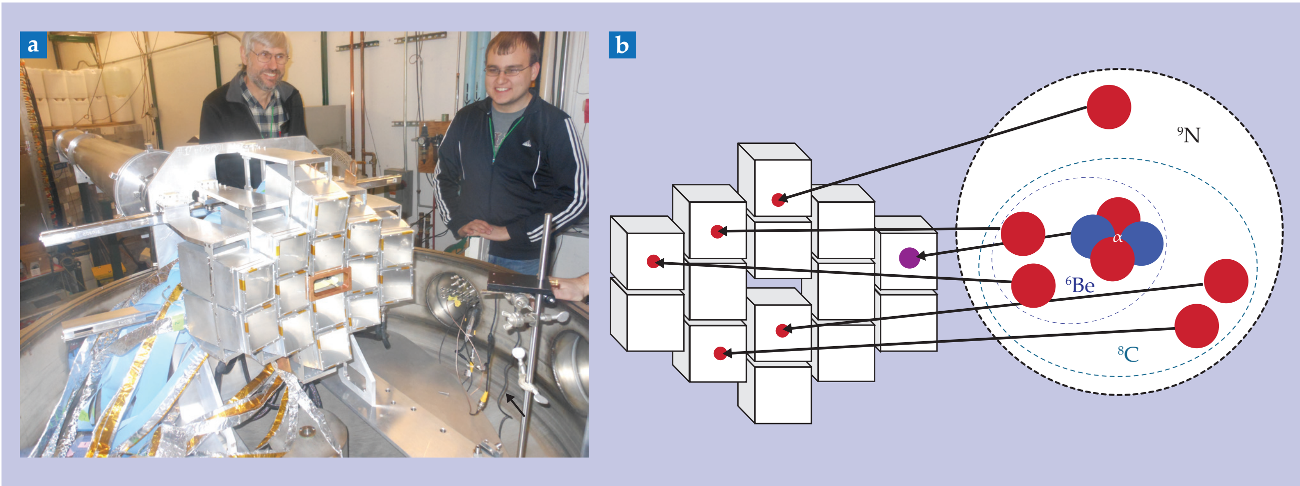

FIGURE 4. INVARIANT-MASS SPECTROSCOPY. (a) A high-resolution array is used by (from left) Robert Charity (Washington University in St. Louis) and Kyle Brown (Michigan State University) to detect the nitrogen-9 nucleus.[12] **(b)** The particle type (proton or alpha in this case), position, and energy of all the fragments from the decay of a ^{9}N parent nucleus are detected by the high-resolution array. Each of the 14 detector elements has multi-hit capability and 1024 location pixels. In the case of the ^{9}N decay, five protons (red) and one alpha particle (the cluster of two red and two blue dots) hit the detector simultaneously and are associated with one decay event. The total decay energy of a ^{9}N nucleus can be reconstructed from each alpha + 5p event, as can the decay energy of intermediates such as carbon-8 from the five possible alpha + 4p subevents. (Image by Jason Keisling.)

When a separation energy is positive (and when Q is negative), some energy is required to remove the designated number and type of nucleons from the nucleus. Hence, if all the nucleon separation energies are positive, the nucleus cannot emit nucleons. All the oxygen isotopes, at least in their ground states, also have positive alpha separation energies and are, therefore, stable to alpha decay. The same cannot be said of excited states, where alpha decay and the fission of oxygen-16 into two beryllium-8 nuclei have been observed.

The ^{16}O, ^{17}O, and ^{18}O nuclides are also stable to weak decays. They are, therefore, the only nonradioactive oxygen isotopes. The nuclei near the three stable oxygen isotopes cannot emit particles but are unstable to weak decays. When Q becomes positive—the uppermost region in figure 3—the oxygen nuclei are metastable.

On the proton-rich side, ^{11}O and ^{12}O are not only unstable to beta decay, they are also unbound to proton emission. For light nuclei, particle emission dominates over beta decay. But for the heavier elements—and deep in the proton metastable region, especially when Z is even—weak decays can prevail. On the neutron-rich side, nuclei heavier than ^{24}O ($N = 16$) strain the definition of a nucleus. Only the presence of finite angular momentum, which generates small potential barriers, and subtle many-body correlations among the nucleons can save the collections of nucleons from prompt disassembly.

Figure 3 shows two even–odd features. First, only the one-neutron separation energy S_{1n} shows even–odd staggering: More energy is required to remove a neutron when a neutron pair must be broken—a signature of neutron pairing. The second is that for the metastable neutron-deficient isotopes, less energy is needed to remove two protons than to remove one. Both ^{11}O and ^{12}O are simultaneous two-proton emitters.

In fact, throughout the proton-rich metastable region, one-proton emission dominates for odd-Z values and two-proton emission for even Z (see the figure 1 inset). The zigzag pattern of the proton drip line results from the relative ease with which elements with an odd number of protons shed one proton. Elements with even Z are relatively resilient—their primary particle decay mode is to shed two protons.[9]

A similar zigzag behavior is seen for the neutron drip line. Odd-N nuclei are often unbound, and their even-N neighbors are bound to neutron emission. Again, the phenomenon of neutron pairing is to blame. Only during the last decade have researchers discovered the extreme isotopes, which are unbound in their ground states to proton and neutron emission. The discoveries were made possible by advances in the production of radioactive beams, which are required to probe the outer reaches of the chart, and by advances in technology that simultaneously detect the many decay products of a metastable nucleus as it disassembles.

Unraveling complex decay sequences

As shown in the inset of figure 1, the proton metastable region has been probed deep enough to find cases for which up to five protons are emitted. The decays always seem to proceed sequentially in steps of one- and two-proton emission. Two-proton nuclear decay usually occurs when no energetically allowed one-proton emission is possible. The situation occurs regularly for even-Z elements because of the pairing energy.[10] If the atomic number of the parent nucleus is odd, the first emission step is always one-proton decay.

The ultra-exotic nucleus nitrogen-9 is a spectacular example of a nuclide that lies west of the proton drip line and approaches the point at which nuclear existence is questionable.[11] The ^{9}N nucleus decays initially by the emission of a single proton and then by two sequential steps of two-proton emission: $^{9}N \rightarrow [^{8}C] + p \rightarrow [(^{6}Be) + 2p] + p \rightarrow [(^{4}He + 2p) + 2p] + p$. The decay sequence may conjure an image of nested dolls, in which the disassembly of the parent generates a smaller, unstable daughter that eventually decays.

The complicated decay sequence can be unraveled with invariant-mass (IM) spectroscopy, a technique that is borrowed from high-energy physics but that has many refinements specific to the study of exotic nuclei. IM spectroscopy is applicable to situations with many particles in the decay sequence. The technique measures the mass of the decomposed parent relative to the stable, final decay products, each of which has a well-known mass. In IM spectroscopy, a beam composed of nuclei that are unstable to beta decay but are particle-bound is directed toward a target that's in front of a detector capable of identifying and measuring the energy of many particles at the same time. Figure 4a shows an example of an IM spectroscopy system.[12]

The ability to generate such beams is possible at only a few facilities, which use primary reactions to generate radioactive species that themselves can be made into usable beams. A second reaction produces the metastable nucleus that decays, and its progeny fly into the detector system, as seen in figure 4b. From the energies of all the progeny, researchers measure Q for multistep decays and the decay energies of all the subsystems, which represent possible intermediates in the decay sequence. State-of-the-art multiparticle IM spectroscopy can determine absolute masses of the decaying species, or any of the possible intermediates in the decay sequence, with uncertainties of about one part in a million for a nucleus of $A = 10$.

IM spectroscopy is the essential tool for dissecting the multistep decay of ^{9}N. To do so, a bootstrap search looks for the possible decay intermediates within the six particles found in the final state.[11,13] In the case of ^{9}N, if it's formed and ultimately decays to a ^{4}He nucleus and five protons, one must search for the intermediate ^{8}C resonance in the five possible $^{4}He + 4p$ subevents of the complete $^{4}He + 5p$ event. Similarly, the ^{6}Be resonances must be searched for in the six possible $^{4}He + 2p$ subevents of the $^{4}He + 4p$ subevents.

Beyond nuclear physics

In recent years, nuclear scientists have studied regions of the nuclear landscape beyond the limits of nucleon binding. Nuclei such as ^{11}O, ^{12}O, ^{25}O, ^{26}O, ^{27}O, ^{28}O, and ^{9}N live in an ephemeral region beyond the drip lines. To better understand the regions at the extreme border of the nuclear landscape, experiments are being planned at radioactive-ion-beam facilities, such as the Facility for Rare Isotope Beams at Michigan State University, the Radioactive Isotope Beam Factory at RIKEN in Japan, and the GSI Helmholtz Centre for Heavy Ion Research in Germany.

The goal of the experiments is to discover exotic nuclides with extreme neutron-to-proton ratios. The work will revolutionize our knowledge about nuclear science and nuclear astrophysics. Violent astrophysical events, such as neutron star mergers and supernovae, synthesize many nuclei via nuclear reaction sequences that proceed through particle-unbound regions and, in some cases, metastable regions of the chart of the nuclides. The methods developed to produce nuclei at the edge of the chart also improve the ability to create much longer lived unstable nuclei that lie closer to the valley of stability, which may have significant applications for society's benefits.[14]

The presence of unbound, very short lived states, which approach the nuclear ephemeral zone, poses fascinating challenges for nuclear theory. Such nuclei cannot be described by the quantum framework found in a textbook. Instead, an open quantum system description must be used that allows for the incorporation of scattering states into a coherent description of the full many-body system.[15,16] The situation parallels the need to include the electromagnetic field in a quantum description of unbound atoms or molecules. With that analogy in mind, researchers have predicted that the interaction between the bound states of a system and the scattering environment will give rise to effects such as superradiance, which enhances alpha decay and is caused by quantum many-body dynamics,[17] and nonexponential decays.[18]

The study of nuclei in the ephemeral zone is closely related to investigations of other small open quantum systems, whose properties are profoundly affected by the environment. In the nuclear context, experimental data, such as that of the ephemeral ^{9}N nucleus, are putting open quantum system treatments of nature to an exacting test. The lessons learned from the study of nuclei with fleeting lifetimes can be applied to atomic, molecular, and reduced-dimensionality open quantum systems.

REFERENCES

1. L. Neufcourt et al., *Phys. Rev. C* **101**, 044307 (2020).
2. Data are from the National Nuclear Data Center, Evaluated Nuclear Structure Data File, http://www.nndc.bnl.gov/ensdf.
3. M. Thoennessen, *Rep. Prog. Phys.* **67**, 1187 (2004).
4. O. R. Smits et al., *Nat. Rev. Phys.* **6**, 86 (2024).
5. H. Geiger, J. M. Nuttall, *Lond., Edinb., Dublin Philos. Mag. J. Sci.* **23**, 439 (1912).
6. G. Gamow, *Z. Phys.* **51**, 204 (1928).
7. R. W. Gurney, E. U. Condon, *Nature* **122**, 439 (1928).
8. M. Duer et al., *Nature* **606**, 678 (2022).
9. M. Pfützner, I. Mukha, S. M. Wang, *Prog. Part. Nucl. Phys.* **132**, 104050 (2023).
10. V. I. Goldansky, *Nucl. Phys.* **19**, 482 (1960).
11. R. J. Charity et al., *Phys. Rev. Lett.* **131**, 172501 (2023).
12. M. S. Wallace et al., *Nucl. Instrum. Methods Phys. Res. A* **583**, 302 (2007).
13. R. J. Charity, L. G. Sobotka, *Phys. Rev. C* **108**, 044318 (2023).
14. K. Matheny, "At this lab, the secrets of the atom—and the universe—are being discovered," *USA Today*, 8 August 2023.
15. C. W. Johnson et al., *J. Phys. G* **47**, 123001 (2020).
16. N. Michel, M. Płoszajczak, *Gamow Shell Model: The Unified Theory of Nuclear Structure and Reactions*, Springer (2021).
17. A. Volya et al., *Commun. Phys.* **5**, 322 (2022).
18. S. M. Wang et al., *Phys. Rev. Res.* **5**, 023183 (2023).