Neutron-Rich Isotopes and the Boundaries of Nuclear Physics

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Abstract

Neutron-rich isotopes are extremely important for the improved understanding of nuclear structure and reactions. The neutron drip line has currently not been probed past a proton number of 8, and knowledge of where it lies helps answer the question of what combinations of nucleons can form a stable nucleus. Neutron-rich nuclei form exotic structures such as neutron skins and halos, and are not accurately described by current models such as the shell model. The improvement of current models and development of new models for describing the behavior of neutron-rich nuclei is essential for the field of nuclear physics. In my review paper, I will investigate our current knowledge about how nuclei are organized, what nucleon combinations can form a bound nucleus, and how those properties relate to structure and dynamical phenomena in the universe.

Introduction

The stability of neutron-rich nuclei is one of the biggest open questions in nuclear physics today. Lurking at the edges of stability, exotic nuclei allow us to test our theories on nuclear structure and probe the properties of nuclei far from naturally occurring nuclear configurations. More generally, nuclear effects are at play at both the smallest and largest scales of the universe. Nucleosynthesis reactions in the hearts of stars and beyond are driven by neutron-rich isotopes, and a more detailed understanding of these nuclei can help us understand how these reactions are driven. Nucleosynthesis reactions are responsible for the formation of every element observed in nature. In addition, neutron-rich matter makes up over 90% of a typical neutron star, the densest form of matter that we can detect in the electromagnetic spectrum. Rare isotopes illuminate nuclear structure at the extremes, and allow us to push our understanding of how the nucleus works past the current limits.

Before we can begin our discussion on rare isotopes, it is useful to define some background and terminology. A key quantity that characterizes a nucleus is the binding energy per nucleon, which is the energy cost to remove a nucleon from a nucleus. In general, a nucleus can be uniquely specified by its number of protons and number of neutrons. An element is determined by the number of protons and an isotope is associated with the number of neutrons in the nucleus. How a nucleus is bound determines whether it is stable or radioactive.

Another very important facet of nuclear physics is the nuclear drip lines. Nuclei within the drip lines are bound to the extent that they will not spontaneously decay via the emission of nucleons. Beyond the drip lines, nuclei cannot bind another nucleon, and will spontaneously emit either protons or neutrons, or in some cases two nucleons at once. The neutron drip line, where extremely neutron-rich isotopes lie, is currently not very well known. However, the proton drip line, where extremely neutron-deficient nuclei lie, is known up to bismuth, with 83 protons.

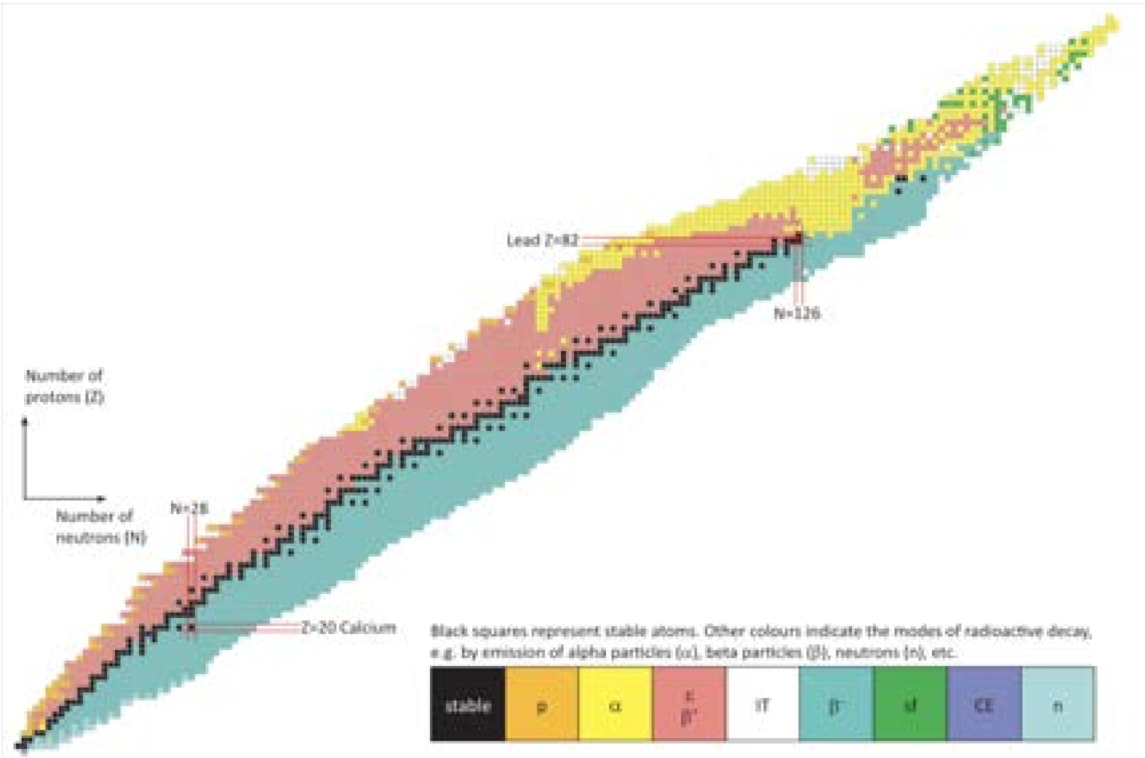

Fig. 1: The chart of nuclides (Sóti et al 2). The number of neutrons (N) is on the x axis, and the number of protons (Z) is on the y axis.

Fig. 1 shows the Chart of Nuclides, which organizes all known nuclei with their number of neutrons (N) on the horizontal axis and number of protons (Z) on the vertical axis. It displays the line of stability, and how isotopes located away from the line will decay. While the drip lines are not marked, isotopes past the drip lines will decay via proton or neutron emission, shown in orange and light blue, respectively. From the decay modes, it is clear that the proton drip line has been reached far up the chart, while the neutron drip line has only been achieved for light elements. Neutron-rich heavier elements decay via β^- decay. Currently, about 3000 stable and radioactive nuclei have been produced in laboratories or been observed in nature. Theoretical calculations predict that there are around 7000 possible nuclides within the drip lines (Watanabe 1).

Another important phenomenon related to the stability of nuclei is that of magic numbers. This concept will be explained more thoroughly in the next section, but it is intrinsically related to binding energy of nuclei and how nuclei with specific numbers of nucleons have relatively high binding energies compared to neighboring isotopes. Nuclei with magic numbers of nucleons also tend to be especially abundant. For nuclei far from the drip lines, these numbers are 2, 8, 20, 28, 50, 82, and 126. At the moment, 126 is a magic number for neutrons only. Elements past 118 protons have not been experimentally created.

Magic Numbers	Element	Binding energy per nucleon (keV)	Binding energy per nucleon of neighboring isotope (-1 N) (keV)	Binding energy per nucleon of neighboring isotope (+1 N) (keV)
Z=2, N=2	Helium	7073.9038(6)	2572.6650(24)	5481.2(50)
Z=8, N=8	Oxygen	7976.0832981(16)	7463.56(5)	7750.6153(11)
Z=20, N=20	Calcium	8550.8428(21)	8369.197(6)	8546.2563(24)
Z=82, N=126	Lead	7864.725(12)	7867.1251(12)	7845.9335(18)

Table 1: Binding energies of doubly magic isotopes and their neighboring isotopes. Data from Nuclear Binding Energies and Atomic Masses (Schopper a,b).

Table 1 shows the binding energy of several well-known elements with doubly magic isotopes and neighboring isotopes. Helium-4 is a very clear example of higher binding as compared to its neighbors. 4He has a binding energy of over 7000 keV per nucleon, while its neighboring isotopes are only 2572.6650 keV and 5481.2 keV respectively. While the differences are not as pronounced for oxygen and calcium, they are still clear. However, as shown in Table 1, lead-208 does not match the binding energy pattern exactly. This deviation shows the nontrivial nature of nuclear structure.

Beyond nuclear structure, it is also interesting to study bulk properties of nuclear matter, which govern the behavior of a sufficiently large system of nuclear matter in thermal equilibrium. Thermal properties are studied via the Equation of State (EOS). The EOS relates variables such as pressure, volume, and temperature in order to describe the equilibrium state of a substance. A well-known example of an EOS is the ideal gas law, $PV = nRT$, where P is pressure in atmospheres (atm), V is volume in liters (L), n is number of moles, R = 0.082057$\frac{L\cdot atm}{mol\cdot K}$, and T is temperature in kelvin (K). The EOS for nuclear matter is essential for understanding the bulk structures of nuclear systems, such as the cores of neutron stars. The EOS for nuclear matter can be expressed as the symmetry energy-which measures the change in binding energy in a system as neutron and proton ratios are changed at a fixed number of nucleons (Baldo and Burgio 1)-as a function of density. This quantity also relates to nuclear internal structure properties such as the emergence of deformed nuclei and neutron skins. Thus, the EOS connects two massively different regimes: from the smallest nuclei to neutron stars many times heavier than the sun.

Structure

The structure of exotic isotopes is a very interesting field of study at the moment. While we do not know everything, a substantial amount of progress has been made over the past years. From the original nuclear shell model to neutron skins and halos, many unique structures exist in neutron-rich isotopes. In this section we will discuss the basics of nuclear shell structure, then move on to more complex phenomena such as neutron skins, halos, and clusters.

Nuclear Shell Structure

A pronounced shell structure is observed in electron orbitals, with the probabilities of the locations of electrons following a clear pattern. The quantum state of an electron is determined by four quantum numbers: n, the principal quantum number; l, the orbital momentum quantum number; m, the magnetic quantum number; and s, the spin quantum number. The quantum number n is what is referred to when talking about the energy levels of shells: 4p, 3s, et cetera. The values of l and m both depend on the value of n, but the value of s is always ½ or -½ . Spin is an intrinsic quality of a particle. Particles with a spin of ½ are called fermions. The value of l is what determines the type of electron orbital: 0 for an s orbital, 1 for a p orbital, 2 for a d orbital, and 3 for an f orbital. S orbitals are spherical, but p, d, and f have more complex shapes. P orbitals are often compared to dumbbells. Orbitals are nested within each other, with the final incomplete energy level containing valence electrons. Similar to electrons, the nuclei of atoms also show a shell structure. The reason for this shell structure is the same as for electrons; the Pauli Exclusion Principle prevents two fermions from occupying the same quantum state. As electrons, protons, and neutrons are all fermions, this applies. For electrons, the shell structure is quite straightforward.

However, for nucleons, the shell structure is much more complex. There are many more possible types of shells for nucleons than for electrons, and strong spin-orbit coupling is a feature of the nuclear shell structure. Spin-orbit coupling is the reaction between the orbital momentum (l) and the spin (s). The result of this is the splitting of energy levels into multiple sublevels with slightly different energies.

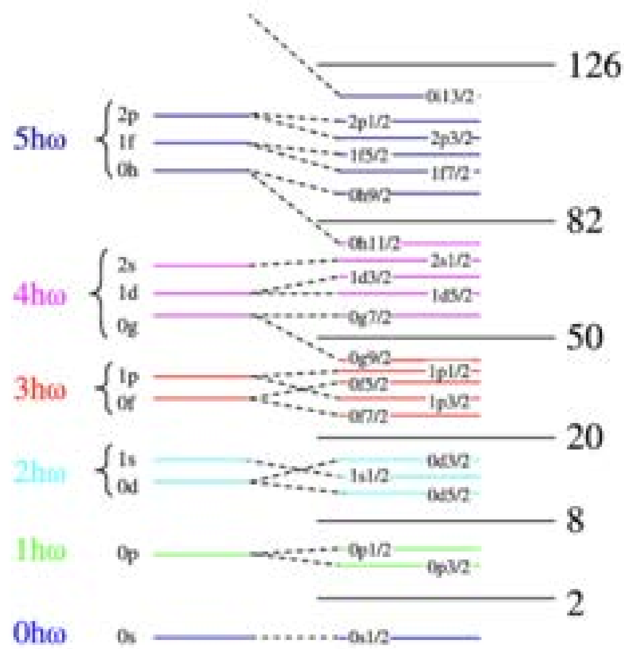

Fig. 2: A schematic representation of nuclear shell structure (Walet). Shells with similar energy levels are grouped together, with gaps shown at magic numbers.

Fig. 2 shows a representation of nuclear shell structure. The splitting of energy levels is clearly shown, for example with the splitting of the 2p shell into 2p1/2 and 2p3/2. The filling of nuclear shells also does not follow as simple a pattern as electron shells, and must be determined experimentally. Fig. 2 also divides energy levels by magic numbers of nucleons. There is a significant energy gap located at each magic number. As noted above, nuclei with magic numbers of nucleons tend to be particularly stable and abundant. Nuclear shell structure can explain this, by showing how nuclei with magic numbers have complete shells of nucleons.

Harmonic Oscillator

A remarkable quality of the nuclear shell model is that its simple assumptions can predict experimentally observed phenomena with a high degree of accuracy. One of these assumptions is that the energy potential which confines nucleons in shells can be modeled as a quantum harmonic oscillator potential. A quantum harmonic oscillator describes motion which follows a parabolic potential, such as a particle oscillating in a parabolic well or a mass attached to a string. The motion of this particle can be described with the wavefunction, Ψ(x), which encodes the probability that the particle is at the point x.

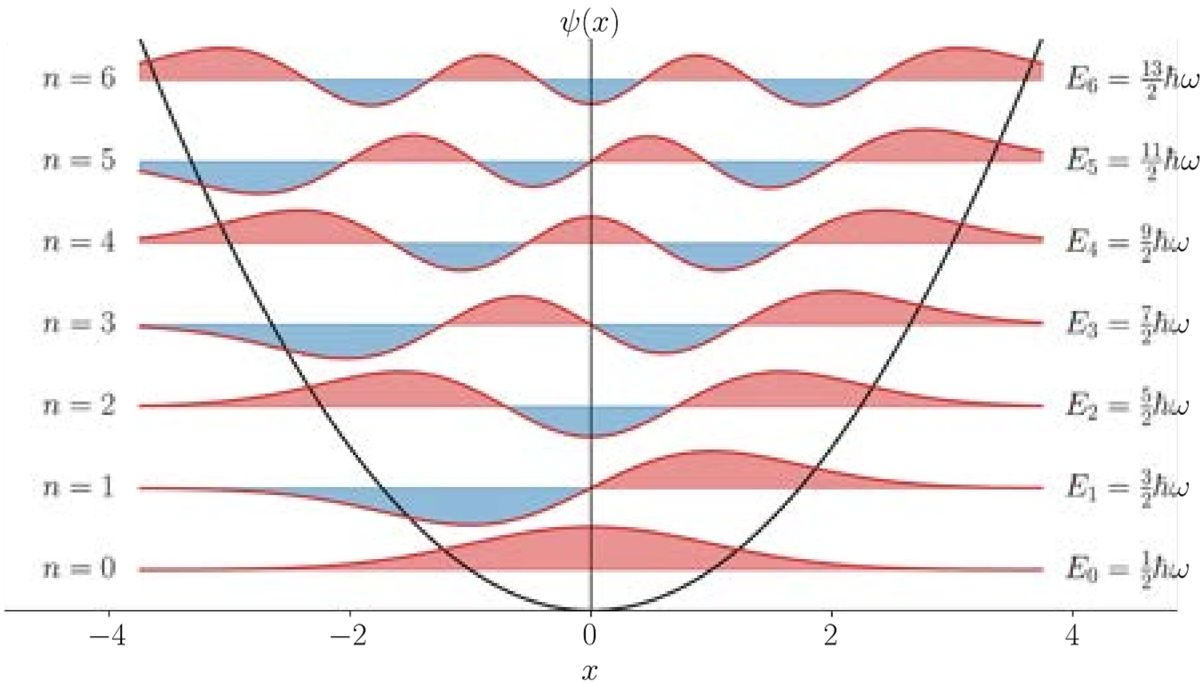

Fig. 3: A plot of the harmonic oscillator wavefunctions (Jackson). The vertical direction represents the energy of the quantized energy levels, and the horizontal direction represents the direction of motion.

The exact form of the wavefunction will depend on the energy of the particle. Fig. 3 shows a plot of harmonic oscillator wavefunctions. The x-axis is the direction of motion, and the y-axis shows the energy levels, with the trapping parabolic potential shown in black. Most importantly, Fig. 3 shows that energy levels do not occur at every possible location. This is due to the quantization of energy, and is also the case with electron orbitals. A particle must gain enough energy to “jump” up to the next energy level. An ideal quantum harmonic oscillator would have infinite energy levels, but in reality they only extend a finite distance and a particle will be able to escape. Fig. 3 also shows how only an integer number of wavelengths can fit within the energy well. Note, however, the boundary of the harmonic oscillator potential is not a hard boundary – it is more of a soft or spread-out boundary. The quantized energy levels of the quantum harmonic oscillator potential are very useful for describing the shell structures that appear in the nuclei of atoms.

The Nuclear Shell Model

Now that we have explained the concept of a quantum harmonic oscillator, we can now move on to the nuclear shell model. The history and shortcomings of the nuclear shell model are a key topic for understanding the current state of knowledge of nuclear structure. In this section, we will discuss the development of the nuclear shell model, its successes and failures, and attempts to improve it.

The original nuclear shell model, developed simultaneously in 1949 by Maria Goeppert-Mayer in the United states and Hans Suess, Hans Jensen, and Otto Haxel in Germany has been crucial for determining properties of nuclei and explaining the magic number phenomenon. It simplifies calculations, treating a nucleus as a two-body system instead of a many-body system containing potentially dozens of particles. One of the core assumptions of the nuclear shell model is strong spin-orbit coupling (Mayer 1). The nuclear shell model uses a harmonic oscillator potential, which can be solved analytically. However, this treats the nucleus as spherical and therefore cannot be used for many nuclei. The original shell model can become quite complex and computationally demanding for many nuclei, requiring calculations far beyond the capabilities of shell-model codes (Otsuka 2). Though today its flaws are clear, the shell model's successes cannot be understated. The nuclear shell model's explanation of magic numbers helped to explain why some isotopes were particularly stable or abundant. It also explains why all known isotopes with 39 neutrons are unstable, due to the closing of a p shell at Z = 40 (Feenberg and Hammack 3).

There have been multiple attempts to improve the shell model, one being the No Core Shell Model (NCSM). The basic idea of the NCSM is to treat all nucleons as active and solve the equation for that, rather than treating the nucleus as having an inert core forming a closed shell. The NCSM approach avoids issues related to the excitation of nucleons from the core (Barrett et al. 3). In addition, it also correctly predicts the extremely small quadrupole moment of lithium-6, which nearly all other models struggle with (Barrett et al. 19). While it is a significant improvement from the original shell model, the NCSM is only solving a three-body problem. This does not take into account the individual behaviors of all the nucleons in a nucleus.

The Monte Carlo Shell Model (MCSM) is also often used. The main advantages of the Monte Carlo Shell model are that it can describe excitations within the nucleus, and that it can handle many valence particles. The second point is essential for calculations involving heavy elements (Otsuka 7-8). The MCSM simplifies calculations by only considering a few important vectors (particularly for low-lying states) that are dominant in terms of key nuclear properties, making calculations possible (Otsuka et al. 2-3). The major advantage of the MCSM is that dimensions grow gradually with increasing complexity, so it can describe the behavior of nuclei including full valence shells (Otsuka et al. 17). This allows more insight into nuclear structure. Unfortunately, as with all nuclear calculations, significant amounts of computing power and time must be used.

One of the other reasons why the nuclear shell model fails is that the concept of shells tends to break down for some nuclei. For superheavy nuclei, it's not known whether shells work in quite the same way as in lighter, more stable elements (Heßberger 2). For a more detailed and complete understanding of exotic nuclei, sophisticated many-body treatments and experimental programs are necessary.

In reality, nuclei are complex many-body quantum systems, and the non-trivial nature of the interactions between protons and neutrons inside a nucleus can lead to non-spherical nuclear shapes, especially in the case of neutron-rich and heavy nuclei. A comprehensive theory of the many-body interactions within nuclei does not currently exist and none of the methods described in this section have a well-defined regime of applicability beyond spherical nuclei. The quantum theories that are available are computationally demanding and calculations are often limited by hardware. Therefore significant effort is being directed towards not only the development of new theories that can incorporate the relevant physics, but also hardware and software design. Even current theories which have limited regimes of applicability require experimental input due to free parameters in the theory. Millions of dollars have been put into the Facility for Rare Isotope Beams (FRIB) and other experimental facilities to address this issue.

Neutron Skins

Neutron skins are another major aspect of more complex structure in nuclei, and are common in heavier isotopes. Neutron skin thickness is dependent upon the pressure of neutron-rich matter. With high pressure, neutrons are pushed out to form a thick neutron skin (Horowitz and Piekarewicz 1). Essentially, the neutron radius is larger than the proton radius, so for some, especially neutron rich nuclei, it might be energetically favorable to form a neutron skin due to the complex interplay between coulomb and strong nuclear force interactions. Neutron skins can occur in non-exotic nuclei (such as lead-208), but are significantly pronounced primarily in unstable exotic nuclei (Baldo and Burgio 15).

Two nuclei shown to have neutron skins are calcium-48 and lead-208. Calcium-48, probed with parity-violating electron scattering in the CREX experiment, has been shown to have a thin neutron skin. Lead-208 was shown to have a thick neutron skin in the PREX-II experiment. Due to the small length scales required to describe nuclei, length is typically measured in femtometers (fm), where 1 fm = 10^{-15} m. The width of 208Pb's neutron skin was measured to be 0.283±0.071 fm (PREX Collaboration 5). Calcium-48's neutron skin was measured to be 0.121±0.026 fm (CREX Collaboration 5). Note that 48Ca has a radius of 3.4771 fm, while 208Pb has a radius of 5.5012 fm (Angeli and Marinova 78, 88).

Neutron Halos

Much less understood than neutron skins, neutron halos also pop up in neutron-rich isotopes. Halos appear in very light nuclei because neutrons are more strongly bound in heavier isotopes, causing neutron skins to appear instead of halos. Indeed, as halo structures appear very close to the drip lines, only very light neutron halo isotopes are known.

The halo structure means that these nuclei will present a more tightly bound core with a much more loosely bound valence nucleon or nucleons, resulting in a significantly larger radius than other nuclei with the same number of nucleons. These particles form a low density diffuse "halo" around the core, as they have a higher probability of being farther away from the other nucleons.

The halo occurs due to the quantum tunneling of a few loosely bound nucleons (Shyam and Chatterjee 3). Quantum tunneling describes the observed phenomenon of particles moving through a potential barrier. Classical mechanics cannot describe this phenomenon, which occurs purely due to the quantum nature of nucleons. This is shown very clearly in a halo nucleus, where there is an area near the core with a high nucleon probability density, an area slightly farther away with a very low probability density, and then the "halo" area with a higher probability density again. The nucleon "tunnels" through the low probability density area between the two high probability density regions to form the halo. Beryllium-11 is an example of a one-neutron halo nucleus, while lithium-11 is a two-neutron halo nucleus (Capel 1-2).

Halo nuclei have very short half-lives, since they are very close to the drip line. For that same reason, halo nuclei are difficult to create and measure experimentally. Facilities like FRIB will help further our understanding of halo nuclei in the coming years.

Clustering

Another important aspect of structure is the clustering of particles in a region of space, giving rise to substructure in nuclei. Alpha-clusters are one of the most common forms of clustering in nuclei, which occurs when two neutrons and two protons form a bound state. This happens due to the very high binding energy of the helium-4 nucleus. 12C and 16O have been modeled as being composed of three and four α-clusters, respectively. This model succeeded in explaining electromagnetic properties that the typical shell model could not (Horiuchi and Itagaki 1). It has been suggested that one state of 12C may be three α-particles arranged linearly, while another has the three particles in an equilateral triangle (Freer et al. 3). Beryllium-8 has also been found to be highly clustered. The isotopes 9Be and 10Be appear to preserve this cluster structure.

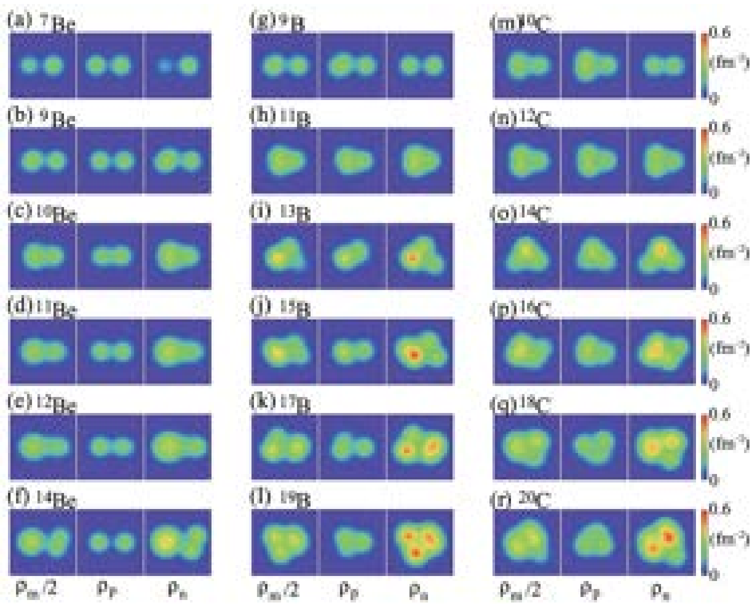

Fig. 4: From left to right in each panel: distributions of proton, neutron, and matter densities for several beryllium, boron, and carbon isotopes (Kanada-En'yo).

Fig. 4 shows multiple excellent examples of clustering from theoretical molecular dynamics calculations. It is a chart of proton, neutron, and matter densities for isotopes of beryllium, boron, and carbon. Note how carbon isotopes appear to form triangular structures at isotopes with 6 or more neutrons. Beryllium displays an elliptical or "peanut-like" shape, caused by the emergence of two regions of higher matter density. Similarly, the lighter isotopes of boron display elliptical shapes, while heavier isotopes are more triangular due to the emergence of a third cluster. While this prediction is specific to one theoretical framework, the uneven distributions clearly point to strong clustering in these nuclei, a promising signature that can be searched for experimentally.

Shell Gaps and Shell Evolution

Shell gaps are incredibly important in the discussion of nuclear structure, as they encode the energy difference between different shells. At magic numbers, there are very large gaps between energy levels, which points to an intrinsic connection between shell gaps and magic numbers and, thus, the stability of nuclei.

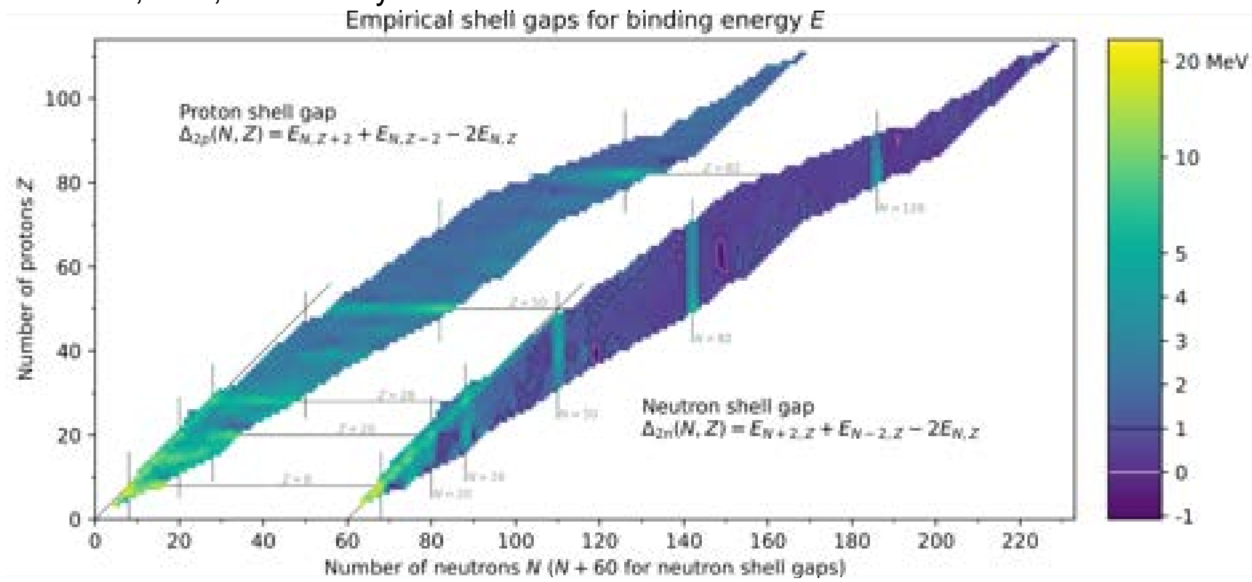

Fig. 5: A chart of proton and neutron shell gaps (Dobson). The left chart shows proton shell gaps, with vertical lines where neutron shell gaps are located as well. The right chart shows neutron shell gaps, with vertical lines marking where each shell gap occurs. Horizontal lines show the locations of proton shell gaps. The line N = Z is marked on both charts.

Fig. 5 is a chart of both proton and neutron shell gaps as function of the number of neutrons (N) and protons (Z), and demonstrates how large shell gaps appear at magic numbers and at the line N = Z. Note that the line N = Z occurs quite close to the edge of each chart, and as it does not line up with the line of stability for long heavier magic isotopes will not lay on this line. However, as previously discussed, magic numbers only tend to hold at isotopes relatively far from drip lines. In less conventional isotopes, more complex effects come into play.

In exotic isotopes, traditional magic numbers tend to disappear and large shell gaps are observed at new energy levels. This is known as shell evolution. For neutron-rich calcium isotopes, magicity has been observed at N = 32 and N = 34 (Brown 2). These are not traditional magic numbers, but due to the phenomenon of shell evolution, these isotopes are unexpectedly stable. The N = 32 sub-shell gap has also appeared in neutron-rich titanium and chromium isotopes. Heavy beryllium isotopes are another example of shell evolution in neutron-rich nuclei. In 11Be and 12Be, the N = 8 shell gap disappeared (Freer et al. 11). These isotopes also show evidence of the appearance of a new magic number at N = 6 due to the abnormally small charge radius (Freer et al. 12).

Away from the drip line, shell gaps and shell evolution are poorly understood due to both theoretical and experimental uncertainties. Once again, FRIB is expected to make measurements which will help determine the shell structure of neutron-rich nuclei.

Reactions

Nuclear reactions are extremely important tools for examining the structure of neutron-rich isotopes. For instance, knowledge of halo nuclei would be impossible to acquire without the help of nuclear reactions. That is because individual atoms are too small to be probed by anything in the visible light spectrum (and nuclei are miniscule compared to atoms). In order to access smaller length scales we need high-energy collisions between nuclei, which allow us to resolve individual protons and neutrons inside the nucleus. This section will discuss different types of reactions, the decay of drip-line nuclei, and new facilities that will improve the understanding of nuclear reactions.

Breakup Reactions

Breakup reactions can be described with a participant-spectator model, where one part of the nucleus goes on to interact with a target nucleus but the other continues on in its original trajectory. This type of reaction is well-suited to study nuclei with short lives, such as halo nuclei. In breakup reactions of halo nuclei, the weakly bound halo dissociates from the core by interacting with the target (Valiolda et al. 2). The two mechanisms by which breakup occurs are Coulomb and nuclear interactions, which are distinct fundamental forces. For an accurate model of the breakup of nuclei, both need to be taken into account. This requirement poses a fundamental challenge for the theoretical modeling of these reactions.

Nucleon Emission

Nucleon emission occurs far from the line of stability, where the excess neutrons or protons become very weakly bound and can escape the nucleus. This type of decay contributes to the understanding of which nuclei can exist in bound states, as well as whether states are bound for specific types of nucleon emission.

In neutron-rich isotopes, the induced emission of a neutron following a previous β decay has been observed when the β decay populates excited states where the neutron is not bound. This is also observed in proton-rich isotopes with induced proton emission (Godoy 25).

When the energy required to remove a nucleon becomes negative, nuclei will spontaneously emit a neutron or proton at their ground state. Proton emitters display longer lifetimes than neutron emitters due to the Coulomb barrier constraining valence protons. While proton emission competes with β decay due to its slower pace, neutron emission is the dominant decay mechanism for unstable neutron-rich nuclei (Godoy 26).

Beyond the drip lines, two-nucleon emission at the ground state often happens. Interestingly, near the drip lines even-N beryllium isotopes are bound for single nucleon emission and odd-N isotopes are unbound. Some systems can exist that are bound for single nucleon emission and unbound for two-nucleon emission. Oxygen-26 and beryllium-16 are good candidates for spontaneous two-neutron emission (Godoy 27, 35).

Other Reactions

Other types of reactions are possible, such as knockout, inelastic scattering, and transfer reactions. Knockout reactions allow for the investigation of a nucleus by removing one or a few nucleons from the beam nucleus via its collision with a target light stable nucleus. In inelastic scattering, a nucleus of interest in the beam collides with a stable target (just as in knockout reactions), but no nucleons are removed, which allows us to measure the excited states of a nucleus. Transfer reactions are when nucleons are transferred from one nucleus to another. These reactions are especially useful for determining the structure of halo nuclei.

Facilities

There are many facilities currently studying the reactions of rare and exotic isotopes. Two major facilities active at the moment are the Radioactive Isotope Beam Factory (RIBF) and the Facility for Rare Isotope Beams (FRIB).

RIBF is located at RIKEN Nishina Center, Japan. One of its major advantages is that it can collect widely spread reaction products. FRIB is located at Michigan State University in the United States. It recently became functional, replacing the previous facility at MSU, NSCL (the National Superconducting Cyclotron Laboratory). FRIB is expected to produce about 5000 isotopes, while RIBF can produce about 4000. As well as improving the understanding of nuclei, the study of neutron-rich isotopes helps to illuminate large-scale structures.

Nuclear Structure and Astrophysics

Neutron-rich isotopes have many applications to large-scale structures in the universe. Neutron stars, supernovae, and nucleosynthesis are some of the major areas of study where the study of neutron-rich isotopes applies. In this section we will discuss nuclear matter's relation to neutron stars, supernovae, and nucleosynthesis, as well as the equation of state (EOS) that governs its behavior.

One of the clearest connections between subatomic structures and large-scale phenomena is revealed in neutron stars. Neutron stars consist of a solid non-homogenous crust above a liquid core. The crusts of neutron stars and the skins of heavy neutron-rich nuclei are made of the same essential material: neutron-rich matter at roughly the same density (Horowitz and Piekarewicz 1). In addition, the size of the radii of neutron skins of heavy elements have profound implications on the structure of neutron stars, such as the stellar mass and equatorial radius (Fattoyev and Piekarewicz 12). In addition, the thicker the neutron skin is determined to be, the lower the density of the transition from crust to liquid of a neutron star (Horowitz and Piekarewicz 9).

As stated above, exotic extremely neutron-rich nuclei are present in the crusts of neutron stars. The environment of a neutron star prevents these asymmetric nuclei from β-decaying due to the presence of electrons (Baldo and Burgio 3). Towards the core of a neutron star, the atomic number increases and the nuclei become increasingly neutron-rich. Such nuclei are extremely unstable and are not available in laboratory environments on Earth. However, in the inner crust of a neutron star, the neutron excess becomes so large that neutrons begin to "drip" from the nuclei and form a neutron gas (Baldo and Burgio 26). The drip point is dependent on the symmetry energy, shell effects, and single particle effects, all of which are key properties of exotic nuclei that we study with experiments on Earth.

In addition to neutron stars, supernovae are also intrinsically connected with exotic nuclear matter. As massive stars collapse during a supernova, their cores collapse until the density reaches the point where nuclear matter is the most strongly bound. After that point, the binding energy starts to decrease with increasing density, the collapse stops as matter bounces, leading to an explosion of massive proportions. The nuclear matter EOS (and symmetry energy in particular) determines at what point in the supernova matter "bounces." The environment of a supernova is quite different from a neutron star in terms of temperature and proton-to-neutron ratios, but both these structures are governed by the nuclear matter EOS.

Neutron-rich matter is also relevant to nucleosynthesis. Reactions and decays of neutron-rich rare isotopes are what drive the processes that synthesize elements. The rapid neutron capture process (r-process) is the process that creates about 50% of naturally occurring isotopes past iron. It is currently poorly understood, but thought to happen at extreme temperatures with a very high density of neutrons (Watanabe 35).

The EOS for nuclear matter is essential for the understanding of the structure and stability of nuclei, the structure of neutron stars, element formation, and whether the core-collapse of massive stars result in neutron stars or black holes (Adhikari et al. 1). Currently, the EOS at high densities (multiple times the densities in heavy nuclei) is not very well known. Constraining the EOS in many different regimes is one of the major goals of nuclear physics and will require input from astronomical observations and terrestrial experiments.

Conclusion

The continued research into neutron-rich isotopes is one of the most important topics in the field of nuclear physics. In this review, we have explored currently known aspects of structure, reactions, and how these apply to the greater universe. More specifically, we discussed that many aspects of neutron-rich nuclei are poorly understood, such as deformed nuclei, clustering, halos, shell structures, and ground states. Though not much is known from either theory or experiment, there are major efforts towards developing new theoretical frameworks (and hardware to support demanding calculations) as well as reaction studies at state-of-the-art facilities like FRIB and RIBF that will offer novel experimental insight in the near future. The improved understanding of neutron-rich nuclear matter will help us to learn about how the world works at the smallest and largest levels of the universe. Therefore, it is important to support future research to push this understanding even further.

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