Designer Nuclei — Making Atoms that Barely Exist

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Designer Nuclei – Making Atoms that Barely Exist

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The physics of nuclei is not a democratic field. It has to be said, some nuclei are just more interesting than others. And some are more useful than others, either to explain the origins of the elements, or the nature of matter itself, or for uses in medicine and other applied fields. The trick is to work out which nuclei are going to be the most important, and then go out and make them. Nuclear physicists are getting increasingly better in fabricating and characterizing short-lived nuclei with desired properties, the designer nuclei. This paper describes selected frontiers of this research. For an in-depth overview, the reader is referred to the recent report.[1]

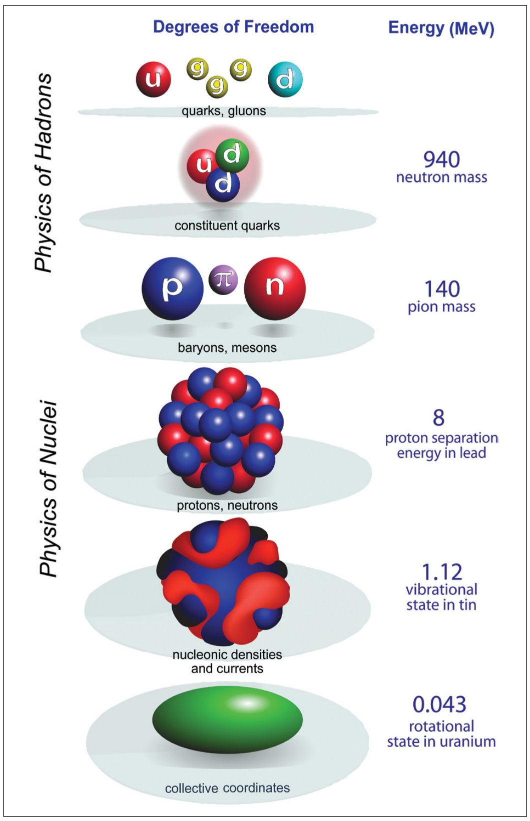

Fig. 1. The basic elements (degrees of freedom) that strongly interacting matter is made of depend on the energy of the experimental probe. The building blocks of the theory of strong interactions, quantum chromodynamics, are quarks and gluons, which are lurking inside mesons and baryons. In low-energy nuclear physics experiments, quarks are invisible and nuclei can be well described in terms of individual protons and neutrons, their densities and currents, or – for certain nuclear excitations – collective coordinates describing rotations and vibrations of the nucleus as a whole.

Nuclear building blocks

Existing in the realm of the microscopic world on the femtometer scale, (1 fm = 10^{-15} m), the nuclei that reside in the heart of atoms are made up of neutrons and protons, collectively called *nucleons* (see Fig. 1). And even nucleons have structure, being composed of smaller building blocks—quarks and gluons. The fundamental theory of strongly interacting matter, quantum chromodynamics (QCD), should in principle be able to predict the properties and interactions of particles at the nuclear scale. However, the equations of QCD are extremely difficult to crack even for a single proton, and this still makes it practically impossible to describe the nature of nuclei from first principles. Hence, other strategies have to be used.[2] Important insights come from the realization that the choice of building blocks (degrees of freedom) always depends on the resolution of experimental microscopes, i.e., the energy of the probe. For example, experiments performed at energies around 1000 MeV, the mass of the proton, are sensitive to the internal quark-gluon structure of the nucleons; however, those performed at energies of 100 MeV will see a nucleus as an aggregation of nucleons interacting through complex forces (not unlike van der Waals forces between protein molecules). At even lower energies, 10 MeV and below, other degrees of freedom, such as collective rotations and vibrations of the nucleus as a whole, come into play. Designer nuclei live in the low-energy world in which protons and neutrons are fundamental entities.

Nuclear landscape

To date around 3000 nuclei have been synthesized in the laboratory, but this represents only a fraction of the nuclei that are expected to exist. The nuclear landscape is most easily depicted on the chart of the nuclei, which shows each nucleus as a square representing the number of neutrons and protons it consists of (see Fig. 2). The black squares are the stable nuclei, those that live forever or practically forever, and constitute more than 99.9% of the mass of matter around us. There are around 288 such species forming the so-called valley of stability. By adding neutrons or protons to a stable nucleus, we enter the territory of radioactive nuclei, first long-lived, then short-lived, until we finally reach the nuclear "drip line," where there is no longer enough binding to prevent the last nucleons from dripping off the nuclei. The proton drip line is already relatively well determined experimentally up to bismuth (with 83 protons, that is $Z = 83$). In contrast, the neutron drip line is considerably further from the valley of stability and harder

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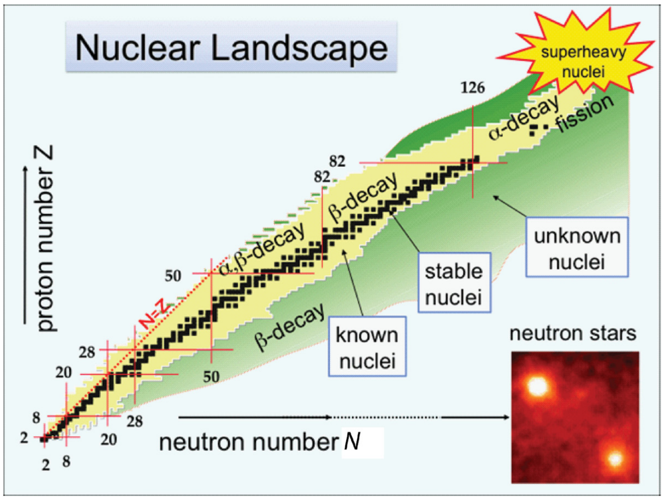

Fig. 2. Nuclear landscape. Map of bound nuclear systems as a function of the proton number *Z* (vertical axis) and the neutron number *N* (horizontal axis). The black squares show stable, or nonradioactive, nuclei, which form the "valley of stability." There are 256 such species, to which 32 "primordial" nuclei can be added with extremely long half-lives. The yellow color indicates short-lived nuclei that have been found in nature or produced in nuclear laboratories. Many thousands of exotic radioactive nuclei with very small or very large neutron-proton imbalance await discovery in the "unknown territory" indicated in green. The red lines show the magic numbers (cf. Fig. 3) known around the valley of stability. The main decay modes (β, α, fission) in various areas of the landscape are indicated. The study of very neutron rich nuclei may improve our understanding of the crusts of neutron stars, composed almost entirely of neutrons.

to approach. Except for the lightest nuclei (around oxygen with $Z = 8$), the neutron drip line is estimated on the basis of nuclear models; hence, it is very uncertain due to the dramatic extrapolations involved. The proton and neutron drip lines form the borders of nuclear existence. The third frontier, at the limit of stability in mass and charge, is formed by the super heavy nuclei with atomic numbers greater than that of lawrencium ($Z = 103$), the last of the actinides. The territory of the superheavies is poorly mapped, and its extent is unknown.

The shortest-lived, most exotic nuclei that abide at this edge of existence we refer to as *rare isotopes.* These nuclei are truly exotic in two meanings of the word. Firstly they are "not native to the place where they are found,"[3] meaning that we cannot find these nuclei naturally occurring anywhere on the Earth. Corresponding to extreme ratios of protons to neutrons, either very small or very large, these elusive systems reside far away from the stability valley. Any exotic nuclei that may have existed in the material making up the Earth in the distant past would have long since decayed. Secondly, they are "strikingly, excitingly, or mysteriously different or unusual."[3] Indeed, these nuclei can have exotic properties such as sizes many times larger than their nearest stable nuclei, or exotic decay modes whereby they emit one or more particles in an attempt to return to stability as quickly and efficiently as possible.

Fragile nuclear shells

The properties of exotic nuclei are not solely determined by their proximity to the stability region or drip lines. Just as atoms have a well-defined structure of orbits containing fixed numbers of electrons, displayed by the inertness of the noble gases versus the volatility of the alkali metals, nucleons in nuclei also move in quantum shells. The cornerstone of our description of the nucleus for more than a half a century has been the shell model, in which each neutron or proton is assumed to move in an average potential generated by all of the other nucleons.[4] This picture of nucleon motion explains a host of phenomena, such as the existence of particularly well-bound "magic" nuclei corresponding to completely filled shells with particle numbers 2, 8, 20, 28, 50, 82, and, for neutrons, 126. The structure of nuclear shells, shown on the left-hand side of Fig. 3, has been a paradigm for more than 60 years in nuclear structure research.[5] However, as demonstrated by recent experiments, the structure of shells in exotic nuclei is markedly different to that for mere stable nuclear species.[6] For instance, the well-known magic numbers such as neutron numbers 20 and 28 disappear altogether as we approach the drip lines, and new shell gaps seem to emerge (see the right side of Fig. 3). Also, there is no consensus among theorists with regard to what should be the next magic nucleus beyond ^{208}Pb (82 protons and 126 neutrons): the regions of enhanced shell effects in the super-heavy region are generally expected to be fairly broad, with no well-defined magic gaps. As we are able to synthesize and study more exotic nuclei, the new paradigm of fragile nuclear shells can be explored and characterized.

Halos, skins, and neutron stars

Protons and neutrons in nuclei close to the neutron drip line experience a very different environment than their cousins in stable nuclei. The neutron drip line diverges very quickly from the valley of stability as we go up in mass. Looking back at Fig. 2 we see that the green area to the right of the stable nuclei extends to very large neutron numbers. In neutron-rich nuclei, the well-bound protons occupy very different shell-model orbits than the last neutrons that are much closer to the top of the potential well, meaning that they are not as well bound. In light nuclei, this weak binding can lead to the formation of a diffuse halo of neutron matter surrounding the nucleus. The effect can be dramatic. For instance, the nucleus ^{11}Li, with just three protons and eight neutrons, has a spatial extent close to that of a heavy ^{208}Pb nucleus. In heavier neutron-rich nuclei, the excess of neutrons predominantly collects at the nuclear surface, creating a skin, a region of weakly bound neutron matter that is our best laboratory access to the diluted matter existing in the crusts of neutron stars. Figure 4 depicts the calculated[7] neutron and proton density distributions for ^{100}Sn (50 protons, 50 neutrons) and ^{100}Zn (30 protons and 70 neutrons), both having a total of 100 nucleons. The neutron skin is clearly seen in the extended neutron distribution in ^{100}Zn. Measurements of neutron skin properties in rare isotopes, including the size of the skin and properties of "pygmy" skin oscillations with respect to a well-

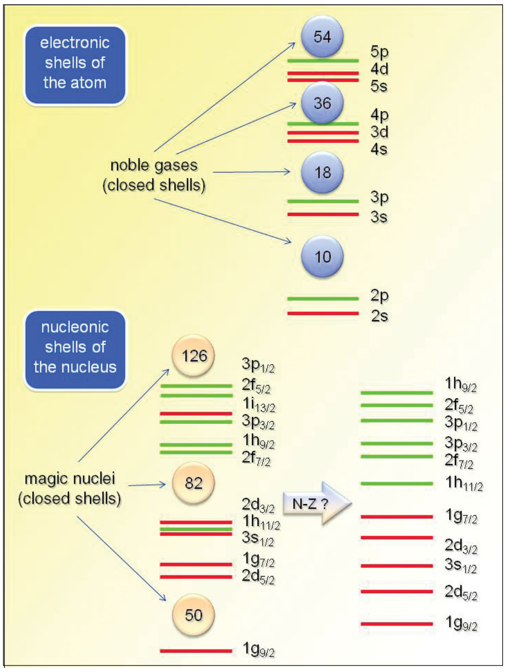

Fig. 3. Shell structure in atoms and nuclei. Top: electron energy levels forming the atomic shell structure. In the noble gases, outer shells of valence electrons are completely filled. Bottom: the nuclear shell structure. In the "magic" nuclei, which are analogous to noble gases, proton and/or neutron shells are completely filled. The left-hand side of the diagram shows the shell structure characteristic of stable or long-lived nuclei close to the valley of stability. Here, the known magic numbers are 2, 8, 20, 28, 50, 82, and 126. The right-hand side of the diagram shows schematically the shell structure predicted in very neutron-rich nuclei with $N>>Z$, which corresponds to a different distribution of energy levels and different magic gaps. Some new data on such nuclei confirm such modifications.[6]

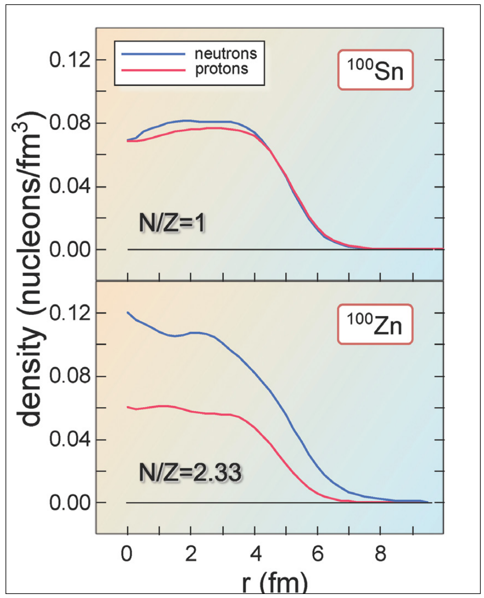

Fig. 4. Distributions of nucleons in exotic nuclei. Calculated densities of protons and neutrons in two extreme nuclei, each with 100 nucleons.[12] The top panel shows the situation characteristic of a proton rich nucleus ^{100}Sn. Here, the numbers of protons (Z = 50) and neutrons (N = 50) are the same, and this implies very similar proton and neutron distributions (they are not identical because of the weak Coulomb repulsion between protons). The bottom panel shows the prediction for a neutron-rich nucleus ^{100}Zn (Z = 30, N = 70). Note how the neutrons extend much further out in ^{100}Zn, forming the low-density "neutron skin." Occurrence of neutron skins is believed to give rise to new kinds of modes, such as vibration of the skin with respect to the rest of the nucleus.

bound core, will inform us about the mass-to-radius ratio of neutron stars.[8]

Cooking elements in stars: astrophysics in the nuclear landscape

Nuclear physics has become increasingly intertwined with nuclear astrophysics, the study of nuclear reactions in stars and explosive cosmic events. Our understanding of how elements are produced in the cosmos, and how nuclear processes fuel stars, relies heavily on knowledge of the structure of nuclei and reactions between them.[9]

All the elements in the world around us were synthesized either in the Big Bang, or cooked in stars and explosive cosmic events such as novae and supernovae. For instance, the iron found in our blood comes from the decay of radioactive ^{56}Ni, a doubly magic nucleus initially made in supernovae. Today, we have a pretty good idea about how the nucleosynthesis processes work, their pathways through the nuclear chart (see Fig. 5), and the places in the cosmos where they occur. For instance, the accretion of matter from a heavy star, such as a red giant, onto a white dwarf or a neutron star in a binary system can lead to novae and x-ray bursts. The extremely high temperatures in novae—around 20 MK—drive nucleosynthesis initially in the light nuclei, carbon, nitrogen, and oxygen, in the so-called CNO cycles. At these high temperatures it is also possible to capture protons and the rapid proton-capture, or rp-process, comes into play.

Elements up to iron (with 26 protons) can be produced in stars by fusing lighter nuclei. However, once iron is reached, energy is required to keep fusion going. At this point element production ceases and the star begins to collapse. One way to make heavier nuclei is to fuse neutrons instead of protons. Heavier elements can be synthesized by fusing neutrons to heavy nuclei in either the slow (s-), or rapid (r-) neutron capture process. The s-process, located in giant stars, winds its way slowly through nuclei close to stability, whereas the extremely high temperatures and superfluity of neutrons found in supernovae allow the r-process to occur much more quickly utilizing very short-lived, neutron-rich nuclei.

Since element production often takes place far from stability, understanding nucleosynthesis and energy generation in a particular astrophysical environment requires measurements of key reactions involving short-lived nuclei. Such measure-

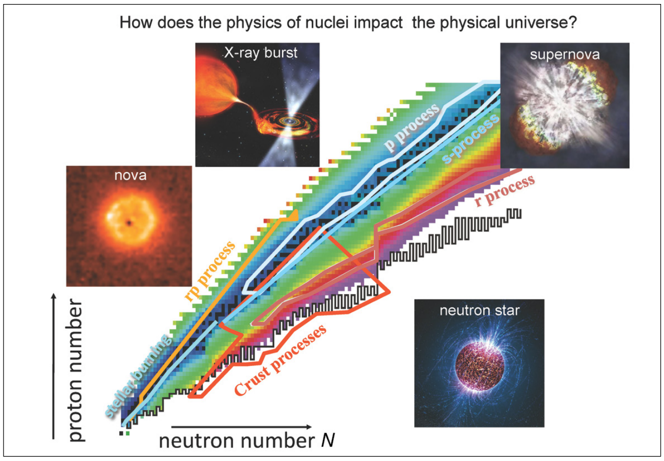

Fig. 5. Astrophysics on the nuclear landscape.[1,8] The synthesis of elements in giant stars and explosive cosmic events follow various pathways through the nuclear landscape. The rapid-proton-capture, or rp-process, is believed to occur in novae or x-ray bursts, while the rapid-neutron-capture, or r-process, may occur in supernova explosions. The elements from iron to uranium found in nature are thought to be mainly synthesized by neutron capture processes – about one half by slow neutron captures (the s-process) and the other half by the r-process. X-ray bursts are thought to occur on the surface of neutron stars. The ashes of the bursts undergo a series of nuclear reactions, the so-called crust processes. (Photos courtesy of NASA.)

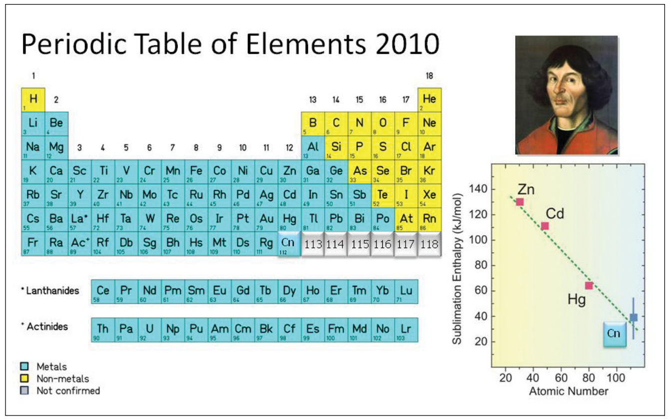

Fig. 6. Left: Periodic table of elements as of 2010. The element *Z* = 112 has recently had the permanent name copernicium (chemical symbol Cn) proposed in honor of scientist and astronomer Nicolaus Copernicus. Element 112 is currently the highest-numbered element to be officially recognized. Right: Recent experiments strongly suggest that copernicium behaves as a typical member of group 12, demonstrating properties consistent with a volatile metal.[12]

ments provide crucial data for calculations of nuclear reaction networks.[9]

Upper limit of the periodic table: super-heavy elements

The mass-charge extreme of nuclear existence is in the realm of the super-heavy elements. The fact that these extremely highly charged nuclei do not tear themselves apart by the Coulomb repulsion between all those protons is a wonder in itself. To explain the mere existence of these remarkable nuclei, we need to return to the shell model. It was recognized as early as the 1960s that the extra binding that comes from the nucleonic shells can tip the balance in favor of existence for the heaviest nuclei. Calculating the extra energy from nearby shell closures, or even locating where these shell closures are, is extremely difficult. The latest predictions for the next shell closures are $Z = 120$, 124, or 126, and $N = 184$, or 172.[10] Despite the huge Coulomb repulsion, some of these nuclei are predicted to have very long lifetimes, reaching 10^5-10^7 years.[11]

To produce super-heavy nuclei, scientists from the laboratories at GSI in Germany and RIKEN in Japan used low-energy fusion reactions on targets of stable heavy nuclei such as lead or bismuth. In this way they produced elements up to $Z =$ 113. Synthesizing even heavier elements becomes increasingly difficult as the probability of producing the nucleus, and of the nucleus surviving long enough to be measured, both drop precipitously. For instance, after 241 days of experimentation, scientists at RIKEN succeeded in producing two alpha-decay chains of a new isotope of element 113.[12] Scientists in Dubna, Russia, used an alternative approach of fusing heavier targets of actinides with a very neutron-rich beam of ^{48}Ca, in what are termed "hot"-fusion reactions.[11] Together with their collaborators from the U.S. National Laboratories at Livermore and Oak Ridge, they reported the synthesis of nuclei with $Z =$ 113-118, having increased lifetimes, in accord with theoretical expectations. Research in this area is ongoing, and reaching the new "island of stability" is in sight.

Another exciting avenue are atom-at-a-time chemistry studies of the superheavy elements. Recently, by using individual atoms of copernicium (Cn, $Z = 112$) it has been possible to place Cn in group 12 of the periodic table, under mercury, cadmium, and zinc.[13] That Cn is a very volatile noble metal was a surprise to some quantum chemists who, because of relativistic shrinking of electron wave functions, expected it to be a noble gas. Because the elements produced in hot-fusion reactions are not directly attached to the region of known isotopes, such chemical studies may also help to support element discovery claims from purely physics experiments.

Perspectives

These are truly exciting times for nuclear physicists. In experimentation, worldwide radioactive beams initiatives promise to create designer nuclei with novel properties. In nuclear theory, major progress will be achieved due to the advent of terascale, and soon exascale, computing platforms.

In the United States rare isotopes are produced at major dedicated radioactive ion beam facilities, such as the NSCL at Michigan State University (MSU),[14] HRIBF at Oak Ridge National Laboratory,[15] as well as at other national and university nuclear laboratories. The Department of Energy is embarking on the construction of the Facility for Radioactive Ion Beams (FRIB),[16] which will greatly expand the variety and intensity of exotic nuclei, allowing studies of hitherto unmeasured nuclei, excitation modes, and reactions. This opportunity will lead to breakthroughs in understanding the nature of nuclear matter, the chemical evolution of the cosmos, and the fundamental symmetry laws of nature, as well as the production of a variety of rare isotopes for applied research in medicine, materials science, and strategic areas.[1,16]

The aim of medieval alchemy was to make substances possessing unusual properties, including the transmutation of common metals into gold and the creation of the elixir of life that would cure all diseases. In the research with designer nuclei, the alchemist dream comes true. Over the last decade, tremendous progress has been made in techniques to produce designer nuclei, rare atomic nuclei far more valuable than gold, with characteristics adjusted to specific research needs. Those rare isotopes are the key to answering questions in many areas of science and they provide society with numerous opportunities, in particular in medicine. But this is another story!

Bringing nuclear physics into the classroom can be fun for the students and rewarding for the teacher. One approach[17] developed at the National Superconducting Cyclotron Laboratory uses magnetic marbles to represent neutrons and protons. This program has proven to be engaging to students (there are lesson plans available for grades 7-12) and general members of the public. Many resources exist on the web describing the basics of nuclear structure[18,19] as well as its connection to astrophysics.[20] Outreach efforts from the national laboratories,[21-24] including tours (advance registration will usually apply as well as certain restrictions), provide a way to bring students to nuclear science. If your school or college is close to a nuclear research laboratory, be sure to check their website. For more specialized reading, we recommend the *Decadal Study on Nuclear Physics* (open book) by the Board on Physics and Astronomy, NAS.[25]

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