Designer Atomic Nuclei an Emerging Tool for Science

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Abstract. The field of nuclear science is in the middle of several revolutions. One is centered on the availability of a much wider range of isotopes than was previously obtainable. A range of isotopes creates the possibility to devise experiments where specific features of the nuclear many-body problem are isolated and hence model assumptions tested and approximations refined or changed. The new isotope tools allow us to search for the fundamental physics underlying apparent regularities found in atomic nuclei. The revolution extends to astrophysical modeling where, finally, a vast majority of the key nuclear data can be measured and used in astrophysical models. This will allow observations, such element abundances in stars, to be used to infer conditions in stellar explosions, or in the environment in which the star formed. This paper discusses some of the advances and potential other benefits of a wider range of isotopes.

1. Introduction
The frontiers of nuclear science involve the quest to study many-body aspects of QCD in regimes of the highest temperatures at RHIC [1] and LHC [2], and the highest densities as occur in neutron stars [3]. The frontiers extend to the effort to understand the QCD underpinning of atomic nuclei and the force that binds nucleons together. Key open questions remain on the nature of quark confinement, the origin of the nucleon-nucleon force in terms of QCD, and how to predicatively model atomic nuclei and their interactions.

Central to meeting the challenge of modeling atomic nuclei is the experimental quest to synthesize atoms made of arbitrary combinations of neutrons and protons. The ability to specify a given proton and neutron number and then study that system is similar to the capability to produce designer materials for nanoscience; hence, nuclear science has entered an age of designer atomic nuclei. However, isotopes are a synthesis problem on the femtoscale, and the difficulty of producing nuclei with widely different numbers of neutrons and protons has meant that nuclear scientists normally work in a limited range of proton and neutron numbers. The interest in producing a wider range is that certain combinations highlight particular aspects of the nuclear many-body problem and allow specific parts of the nuclear interaction or specific forces to be studied. Insight will also come from the novel quantum structures of certain exotic isotopes with low binding energies that exhibit phenomena such as haloes and skins [4]. These features are illustrated schematically in figure 1.

In part, based on the current capabilities for creating new nuclides at facilities such as the RIBF accelerator at RIKEN [5], our understanding of atomic nuclei has changed dramatically. Many of the so called basic properties of atomic nuclei turn out to not be as universal as we thought. For example, we now understand the standard shell model of atomic nuclei must be modified to include three-body and tensor forces [6,7]. New theoretical approaches and computational techniques have also been...
important in the development of a more complete picture. Over that last decade we have developed new theoretical approaches inspired by QCD and benefiting from the emergence of computational tools that allow modeling the nuclear many-body system with far fewer approximations.

Figure 1. Schematic examples of halo (left) and skin nuclei (right). The weak binding of the last two neutrons of $^{11}\text{Li}$ allow their wave function to penetrate beyond the central $^9\text{Li}$ core to a size similar to that of a $^{208}\text{Pb}$ nucleus. Nuclei such as $^{80}\text{Ni}$ (28 protons and 52 neutrons) are predicted to have surface of neutron matter due to the large difference in Fermi energies of the neutrons and protons. The Coulomb force constraints the protons but the neutrons can extend to larger radii.

2. Understanding the nuclear many body system
An ultimate goal of nuclear physics would be to describe atomic nuclei from QCD. This is however an extremely difficult problem. Lattice QCD is now able to calculate the relative masses of hadrons and heavy mesons at the scale of 1 GeV [8]. However nuclear features, such as the rotational bands in $^{220}\text{Rn}$ are at a scale 20 times lower in energy. There is no fundamental theory of QCD that can explain these features.

2.1. Origins of the nuclear force
One approach to solving the nuclear many-body problem is to study nucleon-nucleon scattering and use this data to construct two-body potentials such as the Argonne V18 potential [9], add three-body potentials [10], and then use these along with modern computational power to calculate the lightest nuclei up to $^{12}\text{C}$ [10] using Greens Function Monte Carlo (GFMC) methods. These techniques, referred to as *ab initio*, are remarkably successful and can calculate the binding energy of $^{12}\text{C}$ to better than 1 MeV [10]. A review of *ab initio* techniques can be found in reference [11]. A particularly important insight from the GFMC work came from comparison of calculated and measured binding energies of very neutron-rich helium isotopes. This led to the refinement of the three body forces used and a significant overall improvement in the accuracy of the technique. This example demonstrates how rare isotopes are often the only way to test and refine certain aspects of nuclear models.

Other recent attempts to model the nuclear force start from QCD [12] or string theory [13] to construct the nuclear potentials. Lattice QCD may be able to constrain parameters for the nuclear three-body force and three-body systems [14], which can then be tested against what is learned from rare isotopes [7]. Another promising approach is the development of effective field theories based on the symmetries of QCD, such as chiral symmetry [15]. These approaches naturally introduce three body forces in third order and also hint that four-body forces will be important in nuclei at some level.

2.2. A roadmap to a predictive model of atomic nuclei and their reactions
The nuclear theory community has developed a road map for how to construct a comprehensive and predictive model of atomic nuclei [16]. This involves starting with *ab initio* models for the lightest nuclei (here, study of neutron-rich, light nuclei helps determine the force to use in models). Mid-mass nuclei are modeled by configuration-interaction theory such as the shell model [6] (here, study of key nuclei such as $^{48}\text{Ca}$, $^{50}\text{Ca}$, $^{122}\text{Zr}$ will be important to determine the correct degrees of freedom such as shell closures and effective interactions). The heaviest nuclei will be modeled with improved density functional theory (here new measurements to provide a broad view of the nuclear mass surface,
deformation and vibrational modes as a function of $Z$ and $N$, the nuclear fission barrier mass surface, and other basic quantities are important).

The improved nuclear models and computational tools will advance our ability to calculate the reactions of nuclei. This will provide the ability to, for example, reliably calculate all the reactions important for Big Bang nucleosynthesis and develop models for nuclear decay. Understanding the role of the continuum is a key to these developments. Halo nuclei (left side of figure 1) are also sensitive to proper treatment of the continuum and hence provide a testing ground for reaction theory. Next generation facilities will allow drip line nuclei up to around mass number 100 to be studied. A prediction to illustrate the extreme extent for one such case, $^{42}$Mg, is shown in figure 2. The proton and neutron densities were calculated with HFB theory with the separation energy constrained to 100 keV (the predicted value).

![Figure 2. Radial density calculated for the nucleus $^{42}$Mg, illustrating the extreme halo nuclei that can be produced at rare isotope facilities. The inset shows the predicted change in the core proton distribution caused the valence two neutrons.](image)

3. Advances in nuclear astrophysics

3.1. Measurement of isotope abundances in stellar objects

The measurement of elemental abundances in stars is at the forefront of astronomical observation. Detailed abundance measurements are made possible by large area telescopes such as Subaru, Hubble Space Telescope, LBT, and the Keck telescopes, due to their high resolving power. A wealth of new data is available from detailed sky surveys that provide elemental abundance data in hundreds of thousands of stars [17]. A sample of the type of data available is shown in figure 3; taken from the Hamburg/ESO r-process star survey [18]. The figure shows the logarithmic ratios (defined by equation 1) of one element to another compared to the Solar value. In the figure barium to iron and iron to hydrogen ratios are shown. In general there are more than 30 elemental abundances heavier than iron that can be determined for stars in our galaxy. The study of rare isotopes is needed to provide the underlying nuclear physics to allow this evolution to be accurately modeled, or inversely to use models to infer the conditions in the universe over time. One of the goals would be to use the elemental ashes from the second and third generations of stars to let us infer the conditions that existed for the first stars in the universe.

$$[\text{Fe/H}] = \text{LOG} \left[ \frac{\text{Fe abundance}}{\text{H abundance}} \right]_{\text{Sun}} \left[ \frac{\text{Fe abundance}}{\text{H abundance}} \right]_{\text{Star}}$$

(1)

This is one of the main goals of future space telescope missions such as the James Webb Space Telescope - “is specifically designed for discovering and understanding the formation of the first stars and galaxies, measuring the geometry of the Universe and the distribution of dark matter, investigating the evolution of galaxies and the production of elements by stars, and the process of star and planet formation [19].”

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3.2. Modeling of explosive astrophysical environments

Another key area of astrophysics where rare isotopes are important is in explosive environments and in modeling neutron stars. More than half of the elements heavier than iron are produced in a rapid neutron capture process, the r-process. In order to match observations with models nuclear data is needed on very neutron-rich isotopes [20] that up to now have been largely unavailable. Data are also needed on electron capture rates to model the process before and during supernovae explosions and to model process on the surface of neutron stars that lead to X-ray busts [21].

Figure 3. Relative log abundances for sample stars measured in the HERES survey [18]. The figure illustrates the chemical evolution that measurements with rare isotopes will help unravel. Because stars create Fe over time while H is close to constant, the horizontal axis is related to time. The variance among individual stars of Ba/Fe tell us about the history of those stars. Currently we do not understand what that is.

4. Other uses of rare isotopes

4.1. Tests of fundamental symmetries

Rare isotopes can be used to test the fundamental symmetries and search for the ingredients of the New Standard Model [for a review see reference 22]. Use of isotopes from facilities like FRIB will allow tests of parity and time reversal symmetries and searches for potential new contributions to the weak interactions. For example, the isotopes produced at FRIB would allow an improved measurement of parity-non-conserving (PNC) effects in atomic systems and a determination of the weak charge, \( Q_w \), of the nucleus [23]. In atoms, PNC observables are proportional to \( Q_w \) times an atomic structure function that depends upon the distribution of neutrons in the nucleus. Determination of the latter limits the accuracy of the determination of \( Q_w \). The uncertainty from atomic calculations can be greatly reduced by using ratios of PNC observables in a series of isotopes–but this method requires a precise knowledge of the isotopic dependence of the neutron skin, which may come from the improved density functional theory resulting from FRIB. Another area where facilities like FRIB may contribute is to provide samples of isotopes such as \(^{229}\)Pa where the presentence sensitivity to and atomic EDM may be 10,000 greater than in current tests. An atomic EDM would be evidence for violation of time-reversal symmetry and provide tests for supersymmetric models and string theory [22].

4.2. Isotope applications in other sciences

Radioactive isotopes are used in a wide variety of applications ranging from medical diagnostics to the tracing of groundwater migration patterns. They serve as sensitive probes in materials science studies of nano-scale devices or in the study of mechanical wear of novel materials. In medical imaging, they form the basis of a multi-billion dollar industry. FRIB will have the capability to provide access to the full spectrum of known, important radioisotopes, such as \(^{7}\)Be, \(^{8}\)Li, \(^{11}\)Be, \(^{32}\)Si, \(^{221}\)Rn and others. However, more broadly, FRIB can endow future advances in the applied sciences by providing scientists access to thousands of new isotopes that are not normally available.
Table 1 shows some examples that have been identified as examples of interesting isotopes that a facility such as FRIB would produce well and that could be harvested parasitically to normal operation [24].

Table 1. Sample applications of isotopes.

| Nuclide       | Half-life | Use                                      |
|---------------|-----------|------------------------------------------|
| Silicon-32    | 153 y     | Oceanographic studies; climate change     |
| Radon-221     | 25 m      | Targeted alpha therapy                   |
| Protactinium-229 | 15 d   | Electric dipole moment search             |
| Radium-225    | 15 d      | Electric dipole moment search             |
| Krypton-85    | 11 y      | High specific activity for s-process studies and homeland security |
| Titanium-44   | 60 y      | Target and ion source material           |
| Copper-67     | 62 h      | Imaging and therapy for hypoxic tumours  |

*a These are representative uses discussed at the Workshop on Isotope Harvesting September 2010 at Santa Fe [24], New Mexico. Other uses are likely as well.

5. Rare isotope production facilities and the next steps

The dramatic next steps are being taken at new facilities such as RIBF at RIKEN, and will be taken will be the construction of new facilities such as the Facility for Rare Isotope Beams, FRIB, in the United States [25], FAIR in Germany [26], and SPIRAL2 in France [27]. These facilities will be able to produce most of the astrophysically interesting isotopes needed to model element formation in the universe, neutron stars, and stellar explosions [25]. They will also allow specific, key measurements of nuclear properties needed for progress in nuclear theory. Finally, the new capability promises to provide a range of interesting isotopes of use for fields from condensed matter science to human health. [25].

Figure 4. FRIB production rates indicated by shades of gray. Similar production yields will be possible at other modern facilities such as RIBF and FAIR.

The range of new isotopes that can be produced at one of these facilities, FRIB is illustrated in figure 4. The approximate limit of the current isotopes is marked by the jagged black line. FRIB (along with the other new facilities world-wide) will be able to produce more than 1000 new isotopes and allow detailed study of nearly 5000 isotopes compared to the 1700 or so studied in some detail.
today. It will allow the neutron drip line to be studied up to \( A = 120 \) (compared to \( A = 24 \) today) and production of most of the key nuclei for astrophysical modeling. The solid band shows a prediction for the range of isotopes that would be important for modeling the r-process, which is responsible for producing more than half of the elements heavier than iron, including making most of the gold atoms and all of the uranium we find on Earth.

6. Conclusions

Nuclear science has entered an age of designer isotopes, when arbitrary combinations of neutrons and protons can be assembled and used in experiments. The research with these isotopes is carried out at facilities such as RIBF at RIKEN and will be advanced at a number of facilities under construction world-wide such as FRIB. With the new tools of isotope production there is a pathway to develop a comprehensive and predictive model of atomic nuclei. This and the experiments with new, rare isotopes will allow researchers to understand the nuclear force, more accurately model astrophysical objects, test nature’s symmetries and provide isotopes over a wide range for other sciences.

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