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From dripline to dripline: Nuclear astrophysics in the laboratory

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Abstract. For the better part of a century the field of nuclear astrophysics has aimed to answer fundamental questions about nature, such as the origin of the elements and the behavior of high-density, low-temperature matter. Sustained and concerted efforts in nuclear experiment have been key to achieving progress in these areas and will continue to be so. Here I will briefly review recent accomplishments and open questions in experimental nuclear astrophysics.

1. Nearly 100 years of nuclear astrophysics

With Eddington's brilliant conjecture in 1920 that the Sun's energy reservoir "can scarcely be other than sub-atomic energy", based on ground-breaking experimental work by Aston and Rutherford, the field of nuclear astrophysics was born [1]. Work accomplished in the following decades demonstrated that nuclear physics was not only key to describing how stars lived and died, but also how they made the elements we see (and are made of) today [2, 3]. To date, great strides have been made in a worldwide effort (See Fig. 1.) toward answering fundamental questions about our universe, chief among them: *Where were the elements made?*, *How does nuclear energy generation impact stars and stellar explosions?*, and *How does matter behave at high density and low temperature?*. This progress has relied on the study of atomic nuclei over nearly the entire nuclear landscape, the region bounded by the so-called proton and neutron driplines, where protons or neutrons 'drip' out of the nucleus due to the extreme mismatch in their respective numbers.

The dramatic enhancements of experimental capabilities offered by next generation radioactive ion beam facilities such as the Facility for Rare Isotope Beams (FRIB) [4] and the NuSTAR experiments at the Facility for Antiproton and Ion Research (FAIR) [5], coupled with advances in observational and computational capabilities (e.g. Refs. [6, 7]), are certain to deepen our understanding of nature and likely yield more than a few surprises. The following sections will briefly touch on recent accomplishments in experimental nuclear astrophysics and outstanding questions across the nuclear landscape. Due to space limitations, many exciting works and research topics have been omitted. For more comprehensive reviews, see Refs. [8–10].

2. Progress on the proton-rich side

Various astrophysical environments feature nuclear reactions on the neutron-deficient side of the valley of β-stability that are responsible for nuclear energy generation and element formation. These proton-rich conditions, caused by an injection of large amounts of hydrogen from a stellar

Figure 1. Global census of radioactive ion beam facilities.

envelope or transmutation of neutrons into protons via neutrino capture, enable sequences of proton-capture reactions to proceed at high-temperature. These reactions drive the rapid proton-capture (rp)-process that largely powers type-I x-ray bursts [11] and classical novae [12] and are a main player in the reaction network leading to nucleosynthesis via the neutrino-p (νp)-process in core-collapse supernovae [13].

Classical novae are thermonuclear explosions on the surfaces of white dwarf stars that recur due to the reaccumulation of hydrogen fuel from a binary companion star [12]. These explosions, aside from generating astronomical displays occasionally visible to the naked eye, contribute to the creation of light elements in the universe. Even though these objects have been a focus of intense study for decades, including numerous observational, theoretical, and experimental efforts, their exact contribution to the cosmic abundances is still unknown. Major advances have been made recently by using the power of pure, exotic radioactive ion beams to investigate the origins of presolar dust grains that may have been produced by novae (e.g. Ref. [14]). In fact, studies such as the aforementioned work make novae one of the few astrophysical phenomena for which most nuclear reaction rates are based on experimental data.

Type-I x-ray bursts are similar but much more powerful explosions recurring on the surfaces of hydrogen and helium accreting neutron stars, where the larger surface gravity of the neutron star relative to the white dwarf ultimately leads to the enhanced energy release [11]. These observables are one of the main tools used for understanding neutron stars, unique astronomical laboratories that provide insight into the behavior of dense matter at low temperature. Recent work has focused on understanding reactions that trigger the rp-process (e.g. Ref. [15]) and the locations of the nuclear landscape where the rp-process reaction sequence is significantly stalled, termed waiting-point nuclides (e.g. Ref. [16]). Though the strengths of all waiting-points are soon to be well constrained, theoretical work has shown that a host of other nuclear uncertainties remain that must ultimately be removed or reduced by future experiments [17].

3. New and old directions for neutron-rich nuclides

On the opposite side of the nuclear chart, an array of nuclear reaction sequences operate in astronomical environments to various ends, such as the forging of new elements and the alteration of dense objects' thermal and compositional structures. The oldest and most well known of these is the rapid neutron-capture (r)-process that is responsible for creating roughly half of the elements heavier than iron in as-yet undetermined astrophysical sites [18]. However, other reaction sequences such as the α-process [19] and i-process [20] have recently joined the club of potential mechanisms for nucleosynthesis on the neutron-rich side of stability. Equally exciting are the new developments that have shown individual nuclear properties are critical to understanding the various observables from neutron stars that provide unique windows into the behavior of high-density, low-temperature matter [21].

The r-process, the rapid neutron-capture sequence likely operating in core-collapse supernovae and/or neutron star mergers, has long been out of reach of even the most advanced radioactive ion beam facilities. To date, much of the relevant experimental work has focused on constraining key nuclear quantities nearer to stability so that these results can guide theoretical estimates for nuclides on the r-process path [18]. However, recent innovative techniques have allowed some of the first experimental constraints to be made for nuclear reactions on the path itself (e.g. Ref. [22]). This and other approaches will be particularly powerful when coupled with the extended reach toward the neutron dripline anticipated for FRIB (See Fig. 2.) and FAIR and promise to dramatically advance our understanding of this long-studied problem.

In the past decade other avenues for nucleosynthesis have been identified that likely operate nearer to stability on the neutron-rich side. The α-process, which may operate via a sequence of α-capture, neutron-emission reactions [23], and i-process, a reaction sequence similar in spirit to the r-process but at lower neutron densities, have only just begun to be investigated. Numerous experimental studies are anticipated in the near future that will drastically expand our knowledge of these processes and provide critical tests of their viability as mechanisms of element formation.

Lately it has been shown that neutron-rich nuclides are just as important as their proton-rich cousins with regards to their impact on our understanding of dense matter. When the proton-rich ashes of the rp-process are compressed on the neutron star surface by subsequent accretion from a binary companion, electrons are forced into nuclei, converting protons into neutrons and fundamentally altering the neutron star thermal and compositional outer structure [21]. It has been shown that it is critical to determine the properties of individual neutron-rich nuclides in order to accurately describe the accreted neutron star ocean and crust [24–26]. Efforts in the near future are planned to focus on nuclides which have been identified to have the greatest potential impact on astronomical observables [27].

4. Nuclear astrophysics near stability

Although most nuclides in and near the valley of β-stability have been accessible in the laboratory for some time, several outstanding questions in nuclear astrophysics require their further study. These involve quiescent and explosive stellar environments and require experimental approaches using both indirect and direct techniques to study the most important reactions [28]. Open questions include the extent to which photodisintegration reactions impact the cosmic elemental abundances [29], the exact abundance yield from slow neutron capture in stellar envelopes [30], and the role of electron captures in high-density astrophysical environments [31]. Progress in these areas has been driven by several nuclear physics labs around the world, especially the many stable-ion beam facilities which are far too numerous to include in Fig. 1.

Precisely describing the nuclear reaction sequences of stars has remained a challenge since Eddington first approached the subject [1]. Partially due to triumphs of astrophysical modeling and observations, such as asteroseismology and measurements of neutrinos from our sun, high precision experimental studies are needed to advance our understanding of quiescent nuclear burning in stars [28]. Specialized equipment such as recoil mass separators and underground laboratories (e.g. Refs.[32] and [33], respectively) have played and will continue to play a major role in this effort. When direct measurements via these and other methods are not possible, as is the case for some branch-point nuclides in the slow neutron-capture (s)-process reaction network, indirect techniques will be required to experimentally constrain important reactions [30].

In spite of their association with the most exotic nuclides, models of stellar explosions require a thorough understanding of nearly the entire nuclear landscape, including nuclides along and near stability. A case-in-point is the photodisintegration-driven *p*-process operating in supernovae, which is currently the favored creation mechanism of the so-called *p*-nuclides whose origins cannot be explained by the *s* and *r* processes [29]. Sustained efforts have reduced the nuclear physics uncertainties of this process, where the focus has generally been on constraining the Wolfenstein-Hauser-Feshbach reaction theory that provides essential input to astrophysics models in the absence of experimental data (e.g. Refs. [34, 35]). Additional measurements on and near stability have focused on reducing the uncertainties in nuclear weak rates that limit the ability to describe the mechanisms through which supernovae operate (e.g. Ref. [36]). Here theory calculations have provided important guidance, identifying the most essential nuclear data and filling in the large gaps left by insufficient experimental information [31].

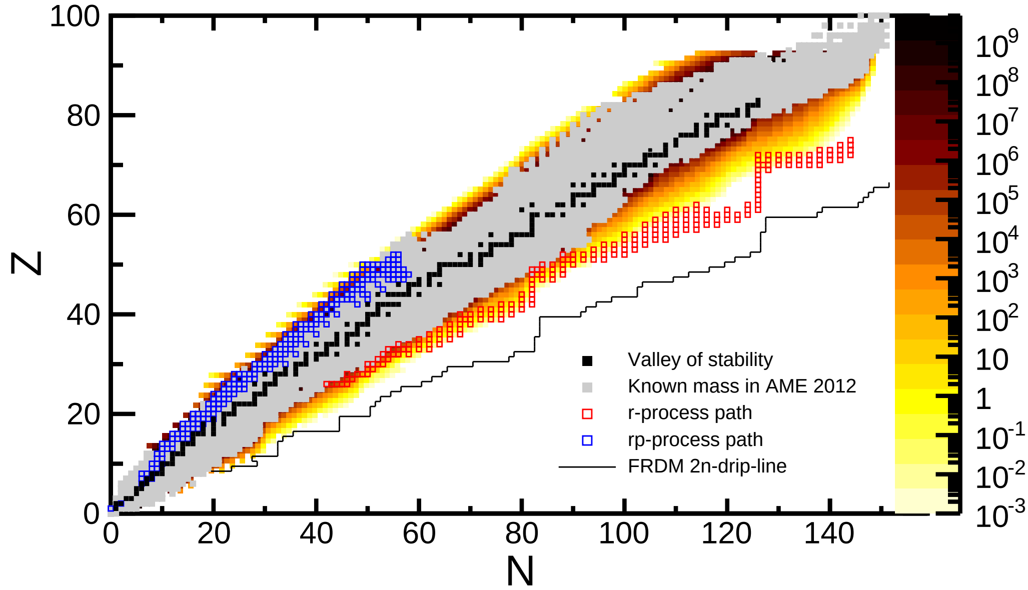

Figure 2. Predicted FRIB production rates in particles per second [37]. See Ref. [38] for a similar prediction for FAIR.

5. FRIB, FAIR, and the future

Roughly 100 years after its inception, nuclear astrophysics research continues to enhance our understanding of nature. At present the field is poised to build upon our current body of knowledge by leaps and bounds, in no small part due to upcoming developments such as new recoil separators [32, 39], underground laboratories [33], and storage rings dedicated to nuclear physics studies [38]. Frontier nuclear physics facilities such as FRIB and the NuSTAR experiments at FAIR will play a central role in this advancement by providing unprecedented access to ever more exotic nuclides (See Fig. 2.). Meanwhile, stable beam facilities will continue to play a complementary role in answering astrophysical questions both new and old. In the near future, together with advances in observation and theory, experimental nuclear astrophysics studies from dripline to dripline promise to offer profound insight into how our universe operates.

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