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Recent Experimental Progress in Nuclear Astrophysics

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Abstract

Experimental nuclear astrophysics aims at determining the nuclear properties and reaction rates that impact our understanding of past and ongoing processes in the Universe. Owing to the large number of unique sites, conditions, and environments in which nuclear physics plays an important, if not dominant role, a wide variety of complementary experimental approaches are required. This in turn requires utilization of multiple facilities throughout the world in order to obtain the nuclear data of interest. Some recent experimental approaches and results are reviewed with an eye towards future facilities and emerging frontiers of nuclear astrophysics.

Keywords: gas target, radioactive beams, transfer reactions

1. Introduction

Our daily lives and the world we live in are continuously impacted by the properties of nuclei and their reactions. The tranquil beauty of the night sky owes its slowly changing, almost stationary, nature to the relatively rare and slow process of fusing hydrogen one by one into helium in the cores of main sequence stars. This relatively slow process has the fortunate consequence that stars like our Sun are expected to live on the order of 10 billion years. Not all stars will live this long, however. The more massive, hotly burning stars can die explosively in only tens of millions of years. What determines whether a star will die in a cataclysmic explosion instead of just slowly fading away? The answer lies in the nuclear physics that can be measured in the laboratory and then extrapolated and adapted to describe stellar and explosive nucleosynthesis.

Nuclear physics provides the empirical foundation upon which our understanding of multiple topics in nuclear astrophysics relies. This includes understanding the inner workings of stars and their evolution, how stars explode such as in novae and supernovae, how the elements are synthesized in these stellar environments, how γ radiation streaming through space was generated,

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the composition and evolution of the early Universe, and the age and ultimate fate of the Universe. Using accelerators on Earth, nuclear scientists can generate and study many of the same (in some cases exotic) nuclei and nuclear reactions that are controlling the behavior of these extreme astrophysical systems and environments.

Ultimately, one would like to know the rates and processes by which all nuclei can be transformed into other nuclei, releasing or absorbing energy in the process. These include transformations by way of reactions or decays and knowledge of the particle/radiation types that are created and destroyed. Nuclear reaction rates depend on the temperature of the environment, and thus some care must be taken to extrapolate measured reaction rates to astrophysical conditions. For instance, consider a process in which a projectile nucleus *X* reacts with a target nucleus *Y* ($X + Y \rightarrow$ some reaction products). This nuclear reaction rate per unit volume is then given by

$$R_{xy} = \frac{1}{1+\delta_{xy}} N_x N_y \langle \sigma(v) v \rangle$$

where $\sigma(v)$ is the nuclear cross section of the reaction of interest at relative velocity v, N_x and N_y are the number densities of species X and Y respectively in the stellar environment, and the brackets indicate that the product $\sigma(v)v$ must be averaged over the distribution of target and projectile velocities, which will in turn depend upon the temperature at which the reaction rate is being calculated. The Kronecker delta is to avoid double counting for identical projectile and target nuclei. The distribution of target and projectile velocities are usually well described by a Maxwell-Boltzmann distribution at astrophysical temperature *T*. The relative velocity can be replaced by the center of mass energy (i.e., $E=1/2\ \mu v^2$ where μ is the reduced mass) and then one obtains

$$\langle \sigma(v) v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE .$$

The net result is that an expression determining the astrophysical reaction rate at temperature *T* can be obtained if the nuclear cross section is known as a function of energy. In practice for charged-particle reactions, the cross section does not need to be measured at all energies but instead in a smaller energy range (i.e., the Gamow window) for the particular reaction at a given temperature. This is a result of the cross section for charged-particle fusion dropping rapidly at low energies and the Maxwell-Boltzmann distribution falling off at high energies. The product of the two probabilities can be approximated as a Gaussian called the Gamow window with a peak at E_o and full width half maximum Δ given by

$$E_o = 1.22 (Z_x Z_Y \mu T_6^2)^{1/3} [\text{keV}]$$
$$\Delta = 0.749 (Z_X^2 Z_Y^2 \mu T_6^5)^{1/6} [\text{keV}]$$

where T_6 is the temperature in MK, μ is the reduced mass in amu, and $Z_X(Z_Y)$ is the atomic number of species X(Y) (Langanke and Barnes 1996).

A variety of experimental tools exist in order to determine the nuclear cross section, see for example (Smith and Rehm 2001). In some cases, the cross section can be measured directly in the nuclear laboratory. Rarely, however, are these measurements complete, and typically the cross sections must be extrapolated to the energies of astrophysical interest. In other cases, it is not currently possible to directly measure the cross section. This could be, for example, because the reaction of interest involves exotic nuclei for which beams of sufficient intensities do not currently exist or that the astrophysics reaction involves neutron interactions with short-lived nuclei, neither of which can be targets of experimental measurements. In such circumstances, indirect techniques are required to estimate the nuclear cross section as a function of energy. Examples of these techniques are described in further detail below.

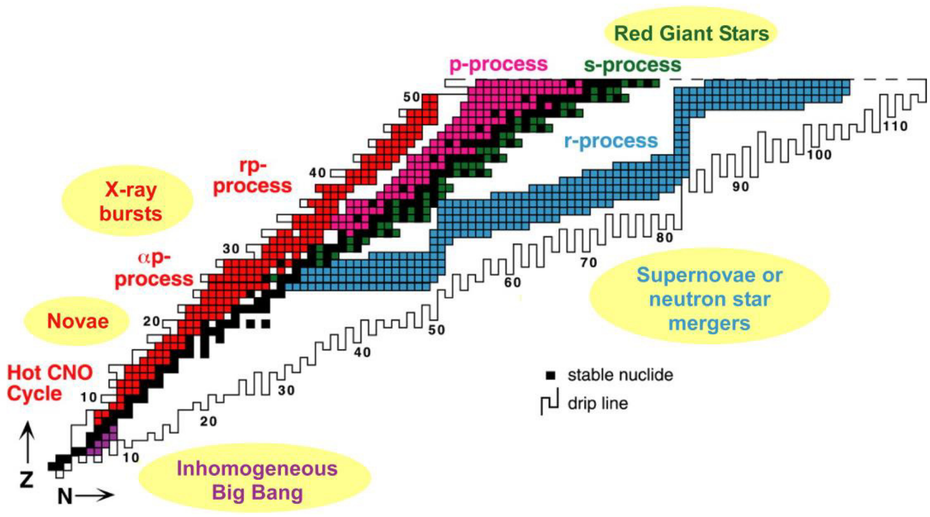

Figure 1: A chart of the nuclides with selected nucleosynthetic processes along with possible production sites. Figure adopted from (Smith and Rehm 2001).

2. Origin of the Elements

The elements have been or are continuing to be created in a variety of astrophysical scenarios (see Fig. 1) (Rolfs and Rodney 1988, Clayton 1983). These nucleosynthesis events can range in duration from billions of years in stars like the Sun to only a few seconds in explosive environments. The Big Bang is believed to have created mostly hydrogen, helium, and lithium and thus the rest of the elements had to be created in later astrophysical events. As mentioned above, stellar hydrogen burning has the net effect of fusing four hydrogen nuclei into a single helium nucleus. The energy released in this process is sufficient to prevent gravitational collapse and the star can stably burn hydrogen for billions of years. This process can occur by either the pp chains or CNO burning in stars slightly more massive than the Sun presuming that some CNO material is present. After core hydrogen exhaustion, contraction can heat the material further until helium is ignited, and the star greatly expands becoming a red giant. Such helium burning can lead to the production of carbon and oxygen, which can serve as fuel for advanced burning in more massive stars. Finally, carbon, oxygen, and silicon burning lead to the production of ^{56}Fe and the end of hydrostatic burning. Since the binding energy per nucleon peaks around ^{56}Fe, subsequent fusion reactions do not liberate energy and thus the fusion process ends. The result of stellar hydrogen burning is the production of nuclei around stability up to Fe and Ni with abundance peaks at nuclei composed of even numbers of alpha particles.

The helium burning stage of a red giant may also create the conditions necessary for the slow neutron-capture process (s process). Reactions such as ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg are possible sources for free neutrons that may be captured by heavy seed nuclei. Heavy elements are then built by a sequence of neutron captures and β decays, which transform material from iron peak elements to heavy elements such as Pb and Bi. The time scale for neutron captures is much longer than the subsequent β-decay lifetimes and thus the reaction flow stays within 1 or 2 units of β stability (Fowler 1984).

Explosions resulting from the accretion of hydrogen from one object to a degenerate companion in a binary system can lead to novae or X-ray bursts. The mechanism is similar in that hydrogen is accreted from one star onto a white dwarf in the case of a nova explosions or a neutron star in the case of an X-ray burst. Temperatures and densities are somewhat lower in novae and the nucleosynthesis is primarily limited to proton-rich nuclei produced by the Hot-CNO cycle and a limited rapid proton (rp) capture process (subsequent proton captures followed by β decay). Nuclei up to about the mass of Ca can be produced in a nova explosion. X-ray bursts are somewhat more extreme. The full rp process is produced after having been triggered by the αp process [subsequent (α,p),(p,γ) reactions beginning with ^{14}O]. Nuclei up to roughly the mass of Sn can be created in the rp process (Parikh 2014).

Finally, the last process discussed in this manuscript is the rapid neutron capture process (r process). While the site of the r process is not known, it is believed to create roughly half of the elements heavier than iron with the rest having been created in the s process. Leading candidates that produce the appropriate conditions to initiate the r process are supernovae and neutron star mergers

(Surman 2008). The process occurs in such high-neutron-density environments that very exotic neutron-rich nuclei are produced by subsequent neutron captures before β decay brings the flow back towards stability. Thousands of exotic neutron-rich nuclei are believed to be produced in the r process and many of them have never been experimentally studied in the laboratory. Recent progress in studying these processes is discussed further below.

3. Stellar Nucleosynthesis

Quiescent hydrogen and helium burning (stellar nucleosynthesis) occurs at much lower temperatures than explosive nucleosynthesis, and thus the Maxwell-Boltzmann distribution of particle energies is shifted to much lower energies (tens of keV compared to hundreds of keV for explosive environments) (Langanke and Barnes 1996). Since the probability of Coulomb barrier penetration is greatly reduced between nuclei at lower energies, the cross sections for nuclear fusion drop precipitously at the relevant energies for stellar nucleosynthesis (recall the peak of the Gamow window is much larger than the product kT). This low probability of fusion means that very few stellar nucleosynthesis reaction cross sections have actually been measured at the most important energies and extraordinary means are necessary to make measurements at these low counting rates.

One approach to measuring such small cross sections is to place the experimental accelerator far underground where the cosmic radiation background is greatly reduced. The Laboratory for Underground Nuclear Astrophysics (LUNA) Collaboration has been performing such measurements in the Gran Sasso laboratory in Italy for over a decade (Prati 2008). The first measurement, which was published in 1999, was a study of the ^{3}He(^{3}He,2p)^{4}He reaction (Bonetti 1999). This was the first stellar nucleosynthesis reaction actually measured in the Gamow window. More recent measurements by LUNA include studies of the ^{17}O(p,γ)^{18}F (Di Leva 2014) and ^{2}H(α,γ)^{6}Li (Anders 2014) reactions. The laboratory has recently started an upgrade to allow for reaction measurements at higher energies.

In the United States, a similar approach is being pursued at the Sanford Underground Research Facility (SURF) in the Homestake mine in South Dakota (Best 2013). The initial effort to demonstrate the feasibility is called CASPAR (Compact Accelerator System for Performing Astrophysical Research) and is repurposing a small accelerator from the University of Notre Dame. Hydrogen and helium beams from 100-1000 keV with intensities of up to 150 μA will be used to bombard solid and gas targets. The initial thrust will be to study the s-process neutron sources: ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg.

An alternative approach for the measurement of these small cross sections is to greatly increase the number of reaction events by significantly raising the beam current. This approach has been successfully pursued at numerous locations throughout the world including, in the U.S., the Laboratory for Experimental Nuclear Astrophysics (LENA) (Champagne 2014) and at the Notre Dame Nuclear Science Laboratory (NSL) (Aprahamian and Wiescher 2007). Recently, a high-current single-ended 5MV machine has been installed at the NSL that can produce beams of gaseous elements up to A~40 at intensities up to 100 μA. The new accelerator has been coupled to the St. George (Couder 2008) recoil separator to make direct measurements of astrophysical interest in inverse kinematics. The separator system is being optimized for direct (α,γ) reaction measurements and is expected to reach the final commissioning stage during 2014.

4. Accretion-Driven Explosions

Roughly half of all stars are contained in some sort of binary system, and under certain circumstances, there can be mass transfer from one star to the other. If one member of the pair happens to be an advanced degenerate star, then the conditions are appropriate to produce spectacular thermonuclear explosions such as novae, X-ray bursts, or type Ia supernovae. In this case, the electron degeneracy pressure prevents the collapse of the advanced star. As hydrogen and helium rich material is accreted from its companion, the temperature and density will rise without an accompanying increase in pressure and volume that would tend to cool a normal star. The result is a thermonuclear runaway on the surface that can lead to total disruption of the system, or may even repeat at regular intervals. The distinguishing feature between the different types of events depends primarily on the type of degenerate star and the accretion rate. For example, it is believed that accretion onto a white dwarf is responsible for nova explosions while accretion onto a neutron star is responsible for X-ray bursts (Parikh 2014).

The nucleosynthesis in such events is determined by the properties of the proton-rich exotic nuclei produced in the process. Stable seed nuclei (typically C and O) are converted to radioactive proton-rich nuclei by nuclear reactions from the accreted hydrogen. Owing to the high temperatures and densities involved, these radioactive nuclei can undergo subsequent reactions before they decay. The reaction flow passes through several exotic nuclei, and the reaction rates and properties of these nuclei determine the properties of the produced explosions. Producing beams of exotic nuclei has become the emphasis of many laboratories throughout the world, and utilization of such beams is a primary method by which our knowledge of these explosive events are advanced (Smith and Rehm 2001).

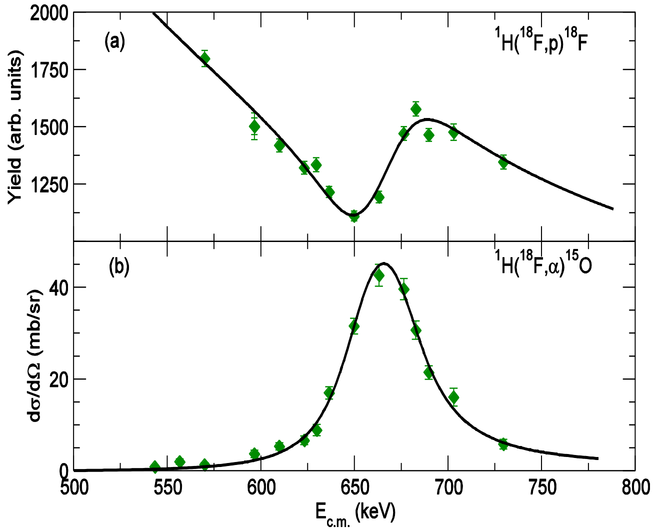

Figure 2: $^{1}H(^{18}F,p)^{18}F$ and $^{1}H(^{18}F,\alpha)^{15}O$ excitation functions measured in panels (a) and (b), respectively for an important resonance at $E_{c.m.}$=665 keV. Figure adopted from (Bardayan 2001).

Of particular importance is to determine the reactions affecting radioisotope production such as ^{18}F and ^{22}Na in novae (Hernanz 2002). These radioisotopes live long enough to survive the explosive event and their abundances provide important clues as to the conditions that must have been present during their nucleosynthesis. To understand and interpret these observations, however, it is necessary to know the rates of reactions creating and destroying the radioisotopes at astrophysical temperatures.

The $^{18}F(p,\alpha)^{15}O$ reaction is the primary destruction channel of ^{18}F in the novae. ^{18}F beams from several exotic beam facilities worldwide have been used to directly measure the rate (Bardayan 2001, Graulich 2001, Chae 2006, Beer 2011), and recent advances in radioactive beam science have created opportunities to precisely determine the resonant behavior of the reaction (see Fig. 2). Additional information has come from elastic scattering (Bardayan 2000, Mountford 2012), proton-transfer (Adekola 2011), and indirect measurements populating ^{19}Ne levels of interest (Laird 2013). Despite these advances, the reaction has still not been measured over most of the energy range relevant for novae. As described in (Beer 2011), interference between low-energy resonances could have a significant impact, and more direct measurements at lower energies are needed.

Also tied to observable radionuclides, the DRAGON collaboration at TRIUMF has made several direct measurements of proton-capture reactions on exotic nuclei. Their first measurements were studies of the $^{21}Na(p,\gamma)^{22}Mg$ (Bishop 2003) reaction where the strengths of several resonances were characterized. Numerous other studies have been completed since then including the measurements of resonances strengths in the $^{26}Al(p,\gamma)^{27}Si$ (Ruiz 2006) and $^{18}F(p,\gamma)^{19}Ne$ (Akers 2013) reactions.

X-ray bursts are similar to novae with the exception that the degenerate star is a neutron star instead of a white dwarf. Typically, such events are observed to emit short (~1-10 s) bursts of x-ray radiation, and they may repeat at regular time intervals. Recently, new phenomena called superbursts have been observed where the x-ray emission may last for hours instead of seconds. While the precise mechanism is not understood, it has been postulated that the fusion of light nuclei (e.g., C+C) may be in some way responsible. In fact, the fusion of extremely neutron-rich isotopes of C may have significance. In response to this recognized importance, the systematic characterization of fusion of C isotopes has been recently studied at ATLAS (Carnelli 2014). Agreement with certain classes of barrier-penetration models was obtained.

5. Rapid Neutron Capture Process Nucleosynthesis

While the astrophysical site of the r-process is not known, it must occur in environments with sufficient neutron densities and temperatures that initial seed nuclei around Fe are transformed into extremely neutron-rich nuclei approaching the neutron drip line. Neutron captures occur until nuclei with small neutron separation energies are reached and neutron capture/photodisintegration equilibrium is reached. At this point, the reaction flow must wait for β decays to occur before moving on to heavier regions. These equilibrium points tend to cluster near the neutron closed shells so large amounts of near closed-shell nuclei are produced.

The flow of material during the main r-process is largely controlled by the masses (Aprahamian 2014) and half-lives (Mumpower 2014) of the nuclei involved. Great advances have been made over the past decade or so in mass-measurement technology. Trapping exotic nuclei has allowed mass measurements with astonishing precision ($\sim 10^{-8}$) (e.g., Mukherjee 2008). The coupling of fission sources with ion traps has greatly increased the number of neutron-rich nuclei for which measured masses now exist. Recent trap measurements with the CARIBU source reported the new measurement of 40 masses approaching nuclei on the r-process path (Van Schelt 2012).

Half-lives are also an important ingredient in r-process models. The primary challenge is to produce sufficient numbers of exotic r-process nuclei to make a significant number of half-life measurements. A recent breakthrough was made at RIKEN where half-lives of several r-process nuclei were measured (Xu 2014). Many of these where the first measurements of a given nucleus's half-life while others represented significant improvements in precision.

During late times as the temperature decreases (i.e., freezeout), the path moves closer to stability, and the β decay and β-delayed neutron emission probabilities become more important in shaping the final abundances (Madurga 2012). Owing to the large abundances of near closed neutron shell nuclei (and their daughters), the neutron-capture rates on these nuclei can also be important (Surman 2014). For instance if the neutron capture rate of a nucleus with a large abundance is increased in r-process nucleosynthesis calculations, the number of free neutrons may be greatly decreased, which in turn, affects late-time processing of the material. While direct measurements of neutron-capture rates on exotic nuclei are rarely possible (Dashdorj 2009), it is still critical to have reasonable estimates of these rates. One possibility is to make measurements of the nuclear structure of nuclei near the closed neutron shells, where the r-process abundances peak. Significant progress has been made via the study of (d,p) reactions on accelerated fission-fragment beams (Jones 2010, Kozub 2012). The measurements of excitation energies, spins, and spectroscopic factors can significantly decrease the uncertainty of the estimated neutron-capture rates. Combining neutron transfer with the measurement of subsequent γ emission has also been fruitful (Allmond 2014).

6. Outlook and Conclusions

Worldwide numerous facilities have recently come online, are in construction, or are in some stage of development. Exploitation of these investments and efforts will clearly lead to significant progress in answering many open questions in nuclear astrophysics. In the United States, the Facility for Rare Isotope Beams (FRIB) is eagerly anticipated (Bollen 2010). The facility will take beams up to U from a high-power driver LINAC at energies up to 200 MeV/u. These beams will be fragmented on production targets to produce copious amounts of exotic nuclei. From there the beams can be directed to fast-beam experimental systems which run near the full driver beam energies or can be directed to stopping systems for subsequent reacceleration to beam energies appropriate for different types of experiments. It is anticipated that FRIB will nearly double the availability of rare isotopes for study.

Of critical importance to the direct measurement of astrophysical proton capture reactions is the construction of a gas target system/recoil separator for use with exotic beams at FRIB. The JENSA gas jet target has been constructed at ORNL and installed at the ReA3 hall at NSCL to facilitate proton-transfer and capture measurements on proton-rich nuclei (Chipps 2014). A recoil separator SECAR (Berg 2010) is currently under design for coupling to the JENSA target when the National Superconducting Cyclotron Laboratory transitions to FRIB.

Understanding the nucleosynthesis of elements in the Universe continues to remain one of the most compelling issues in science. The dizzying array of astrophysical processes that are responsible for this production requires a world-wide effort (see for example the review by Blumenfeld, Nilsson, and Van Duppen 2013) to engage in complementary approaches for measuring the nuclear data that are critical to understanding element synthesis. Numerous breakthroughs have occurred over the last decade but the science horizon appears bright with many future experiments and facilities under development or construction.

Acknowledgements

This manuscript describes some recent progress in experimental nuclear astrophysics. In no way should this description be interpreted as complete or all encompassing. The author would like to apologize for the glaring omissions that are surely present. The author would also like to thank K. A. Chipps, R. L. Kozub, and P. D. O'Malley for their careful reading of this manuscript and K. E. Rehm for helpful suggestions. This work was supported by the U.S. Department of Energy Office of Nuclear Physics and the National Science Foundation.

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