

1-1-2011

## What do (and don't) we understand about explosive nucleosynthesis?

J. C. Blackmon  
*Louisiana State University*

Follow this and additional works at: [https://digitalcommons.lsu.edu/physics\\_astronomy\\_pubs](https://digitalcommons.lsu.edu/physics_astronomy_pubs)

---

### Recommended Citation

Blackmon, J. (2011). What do (and don't) we understand about explosive nucleosynthesis?. *Journal of Physics: Conference Series*, 312 (SECTION 4) <https://doi.org/10.1088/1742-6596/312/4/042001>

This Conference Proceeding is brought to you for free and open access by the Department of Physics & Astronomy at LSU Digital Commons. It has been accepted for inclusion in Faculty Publications by an authorized administrator of LSU Digital Commons. For more information, please contact [ir@lsu.edu](mailto:ir@lsu.edu).

**OPEN ACCESS**

## What do (and don't) we understand about explosive nucleosynthesis?

To cite this article: J C Blackmon 2011 *J. Phys.: Conf. Ser.* **312** 042001

View the [article online](#) for updates and enhancements.

### You may also like

- [Nucleosynthesis in 2D core-collapse supernovae of 11.2 and 17.0 M progenitors: implications for Mo and Ru production](#)  
M Eichler, K Nakamura, T Takiwaki et al.
- [Trends in nuclear astrophysics](#)  
Hendrik Schatz
- [r-process nucleosynthesis: connecting rare-isotope beam facilities with the cosmos](#)  
C J Horowitz, A Arcones, B Côté et al.



**IOP | ebooks™**

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

# What do (and don't) we understand about explosive nucleosynthesis?

**J. C. Blackmon**

Dept. of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70808 USA

E-mail: [blackmon@lsu.edu](mailto:blackmon@lsu.edu)

**Abstract.** Isotopic abundances reflect both nuclear structure and environmental history. Observations are providing new evidence that is helping us to understand astrophysical phenomena, the chemical history of the Galaxy, and the origins of the diverse isotopic abundances found on earth. What we infer from observations, however, depends upon a robust understanding of the underlying nuclear physics. The difficulties involved in producing and studying short-lived isotopes are particularly problematic for understanding stellar explosions. While new facilities and experimental techniques have recently spurred significant progress in our understanding of the light, proton-rich nuclei that are important for understanding novae, studies of heavier exotic nuclei that are crucial for understanding more energetic explosions and the origins of the heavy elements are still quite challenging. We briefly survey recent progress in experimental nuclear physics that is important for understanding explosive nucleosynthesis and outline some of the major outstanding questions and the prospects for future advances.

## 1. Introduction

Stellar explosions account for mere instants amongst astronomical time scales, but these instants are important and challenging to understand. Explosions involve complicated, non-equilibrium conditions and nuclei that are unstable and not formed naturally in other environments anywhere in the cosmos. Stellar explosions can produce and disperse new isotopes into the interstellar medium, influencing the chemical evolution of the Galaxy. To understand these events and their role in the history of the Galaxy requires that we understand the underlying nuclear physics that plays a role. Recent advances in our ability to produce and study short-lived radioactive nuclei have had a great impact on our understanding, but there are also major outstanding questions. In this paper, we highlight some of the recent nuclear physics measurements that are having a significant impact on our understanding of stellar explosions and outline important questions that will be a focus of future research. The reader is cautioned that this brief paper is not exhaustive and is referred to the recent review by Bertulani and Gade [1] for a more thorough treatment.

## 2. Novae and X-ray bursts

Novae and X-ray bursts are the most common stellar explosions in the Galaxy. These events occur in binary systems when matter accretes onto a compact companion and ignites in a thermonuclear explosion. The explosions are not severe enough to completely disrupt the system and may recur. X-ray bursts are intense explosions on the surface of a neutron star that recur

on typical timescales of hours to days [2]. Over 100 such systems are known in the Galaxy, and repeated observations are now allowing the time evolution of the binary to be studied [3]. Novae are similar, though less energetic, explosions occurring on the surface of white dwarves [4, 5]. A few dozen novae are observed each year in our Galaxy, but only a few exceptional cases have been observed to recur as the recurrence time scales are believed to be quite long (more than  $10^3$  years). Thus, the prevalence of interacting binary systems that undergo nova explosions could be quite high.

While the most common stellar explosions, novae and X-ray bursts eject comparatively little matter into the interstellar medium and likely significantly influence the chemical evolution of only a few fragile isotopes with low natural abundance [6, 7]. However, nuclear reactions drive these events. The nuclear reactions that occur are crucial for understanding energy generation, the observed light curves and spectra, and the evolution of the system. High temperatures are reached in these explosions and the time scales for the events are short (seconds to minutes). Reactions involving radioactive nuclei that are themselves products of nuclear reactions can play an important role. Large uncertainties in reaction rates involving radioactive isotopes have hindered our understanding, but there has recently been experimental progress in improving important reaction rates including:  $^{17}\text{O}(p,\alpha)^{14}\text{N}$  [8, 9],  $^{17}\text{O}(p,\gamma)^{18}\text{F}$  [10, 8],  $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$  [11],  $^{18}\text{F}(p,\alpha)^{15}\text{O}$  [12],  $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$  [13],  $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$  [14],  $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$  [15],  $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$  [16, 17],  $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$  [18],  $^{26}\text{Si}(p,\gamma)^{27}\text{P}$  [19],  $^{29}\text{P}(p,\gamma)^{30}\text{S}$  [20],  $^{30}\text{P}(p,\gamma)^{31}\text{S}$  [21, 22, 23], and  $^{31}\text{S}(p,\gamma)^{32}\text{Cl}$  [24]. In the next sections we will briefly discuss a few representative examples from these studies.

### 2.1. Direct cross section measurements

In a nova explosion, hydrogen-rich gas ignites on a white dwarf whose composition is primarily carbon, oxygen, and in some cases, neon. Energy production is dominated by the hot-CNO cycles. Most reactions involving stable isotopes have been directly measured in the relevant energy range and are reasonably well understood. Some of the most important uncertainties involve the sequence of reactions initiated on  $^{16}\text{O}$ . Hydrogen fuses with  $^{16}\text{O}$  to make  $^{17}\text{F}$ , but does the  $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$  reaction bypass the relatively slow beta decay of  $^{17}\text{F}$ ? The question is important for understanding production of  $^{18}\text{F}$ , which is expected to be the largest source of potentially observable gamma rays from novae [25]. If  $^{17}\text{F}$  decays to  $^{17}\text{O}$ , then it is predominantly burned by the  $^{17}\text{O}(p,\alpha)^{14}\text{N}$  reaction, cycling back to the lower CN cycle and bypassing  $^{18}\text{F}$  production. If the  $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$  reaction is fast compared to the  $^{17}\text{F}$  beta decay rate, a high production rate of  $^{18}\text{F}$  may be achieved. However, how much  $^{18}\text{F}$  survives to later decay when the outer envelope is more transparent (allowing gamma rays to be more readily observable) also depends crucially on the rate of the  $^{18}\text{F}(p,\alpha)^{15}\text{O}$  reaction that destroys  $^{18}\text{F}$  and cycles material back to the lower CN cycle. This process is also important since the  $^{17}\text{F}$  and  $^{15}\text{O}$  that are produced in novae likely make major contributions to the  $^{17}\text{O}$  and  $^{15}\text{N}$  in our Galaxy. Reactions on  $^{17}\text{O}$  comprised the largest uncertainties involving stable isotopes, but recent direct cross section measurements have recently significantly improved our understanding of the  $^{17}\text{O}(p,\gamma)^{18}\text{F}$  and  $^{17}\text{O}(p,\alpha)^{14}\text{N}$  reaction rates [10, 9, 8, 26]. The  $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$  and  $^{18}\text{F}(p,\alpha)^{15}\text{O}$  reactions have been especially problematic but measurements with low energy radioactive ion beams of  $^{17}\text{F}$  and  $^{18}\text{F}$  are now allowing substantial improvements.

The rates of charged particle reactions at nova temperatures (up to  $4 \times 10^8$  K) are typically dominated by the contributions of just a few resonances corresponding to excited states just above the particle threshold in the compound nucleus. In the case of  $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ , a single *s*-wave resonance corresponding to the first  $3^+$  state in  $^{18}\text{Ne}$  is expected to be important and to increase the cross section by about 2 orders of magnitude. The  $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$  cross section near this important resonance was recently measured at the Holifield Radioactive Ion Beam Facility (HRIBF) [11]. A mixed beam of  $^{17}\text{F}$  and  $^{17}\text{O}$  from the HRIBF bombarded a windowless

hydrogen gas target. As gamma rays carry away little momentum, the recoiling nuclei continued forward with nearly identical momentum to the beam. The Daresbury Recoil Separator was used to separate the reaction products by mass, and a gas ionization chamber at the focal plane of the separator measured the energy and atomic number of the reaction products. The cross section was deduced from the number of  $^{18}\text{Ne}$  recoils, and the contribution of the most important  $3^+$  resonance to the reaction rate was determined. Measurements made off resonance were only able to set upper limits on the cross section that were not sufficient to allow meaningful constraints to be placed on the non-resonant contribution to the reaction rate. While this measurement has addressed one of the important components of the  $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$  reaction, a better constraint on the non-resonant contribution is needed, which will require either direct measurements with higher intensity  $^{17}\text{F}$  beams or indirect spectroscopic studies to constrain the low-energy Asymptotic Normalization Coefficient [27].

Some white dwarves contain substantial neon in their core as a product of helium burning. Many additional reactions occurring on neon and heavier nuclei are important in nova explosions occurring on such stars. Observations have shown significant enrichments of sulfur in some nova ejecta [28], and calculations indicate that nuclei as heavy as calcium may be synthesized in the explosion [29]. Experimental attention has been focused around reducing uncertainties in the production of the long-lived radionuclides  $^{22}\text{Na}$  and  $^{26}\text{Al}$  in novae. The abundance of  $^{26}\text{Al}$  has been mapped throughout the Galaxy, and the observed abundance has been used to estimate the rate of supernovae [30]. However, calculations predict significant production of  $^{26}\text{Al}$  in novae, which could alter interpretations. Observation of  $^{22}\text{Na}$  decay is particularly interesting since the half-life is short enough that any observation could be correlated with a particular astronomical event. While the decay of  $^{22}\text{Na}$  has not yet been observed in the Galaxy, the sensitivity of observations is close to expectations for nearby novae [31].

Direct measurements using intense low energy beams at TRIUMF-ISAC have led great progress in our understanding of ONe novae and production of  $^{22}\text{Na}$  and  $^{26}\text{Al}$ . The reaction sequence  $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}(p,\gamma)^{22}\text{Mg}(\beta^+)^{22}\text{Na}(p,\gamma)^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$  is particularly important, and both the  $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$  and  $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$  reactions were directly measured at TRIUMF using the DRAGON facility [32]. In these measurements beams of radioactive nuclei bombarded a windowless hydrogen gas target. Reaction products were separated by the DRAGON recoil separator and detected at the foil plane. One important feature of DRAGON is that an efficient array of BGO detectors surrounds the windowless hydrogen gas target and detects gamma rays in coincidence with heavy ions detected by the DRAGON recoil separator. Correlations between the gamma rays and recoils (especially time-of-flight), the gamma ray energy, local time-of-flight at the focal plan of DRAGON, and the relative timing to the ISAC accelerator combine to make DRAGON highly selective for these types of measurements. In the case of the  $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$  reaction, resonance strengths of all important resonances were measured down to  $E_{cm} = 206$  keV, including resonance strengths as weak as  $\omega\gamma \approx 1$  eV. These measurements reduced the uncertainty in the  $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$  reaction rate from several orders of magnitude down to only about 20% at nova temperatures [33]. In the case of the  $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$  reaction, the energy and resonance strength of the most important at  $E_{cm} = 486$  keV was measured [15]. The powerful selectivity of the DRAGON facility was particularly evident for this measurement as the measurement was conducted with a beam consisting of only 0.1-2.0%  $^{23}\text{Mg}$ .

The  $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$  reaction was also recently measured by a collaboration between the University of Washington (UW) and TRIUMF [13]. In this case, an intense, pure  $^{22}\text{Na}$  beam at TRIUMF was used to produce  $300\mu\text{Ci}$  radioactive targets by implanting the long-lived  $^{22}\text{Na}$  beam into a copper backing. The  $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$  reaction was then measured directly by irradiating the implanted target with low energy proton beams at the Center for Experimental Nuclear Physics and Astrophysics at UW. Gamma rays were detected by high-purity germanium detectors that were specially shielded to suppress the intense gamma background from the

radioactive targets while still allowing detection of the higher energy gamma rays from the  $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$  reaction with fair efficiency. The strengths of the most important resonances were accurately measured and found to be stronger than previously expected by factors of 2-3. Upper limits were also set on the contribution of some resonances that had been identified as being potentially important [34], leading to a substantial reduction in the uncertainty on the reaction rate, which was found to be about twice as large as previously believed.

## 2.2. Indirect measurements

It is often not feasible to directly measure important cross sections. Even if direct measurements are possible, indirect studies are still important to identifying resonance energies and guide direct measurements. Measurements using stable beams and targets have provided much of the experimental information on reactions involving radioactive nuclei. For example, transfer reactions have been used to populate states, and devices like high resolution spectrographs have been used to study the properties of states corresponding to important resonances. New technologies are expanding such capabilities. For example, large arrays of silicon-strip detectors have been combined with the Enge spectrograph at the Wright Nuclear Structure Laboratory at Yale University to identify proton-unbound states of interest and measure the proton-decay branching ratio by detecting charged particles emitted from unbound states in coincidence with the spectrometer [21, 35]. In other approaches, gamma decay schemes of states corresponding to low lying resonances are also now being measured with excellent sensitivity using high efficiency arrays like Gammasphere [23, 36]. The development of experimental techniques like these is allowing information to be extracted from stable beam measurements that was previously not accessible. Unfortunately, it is slowest channel (smallest decay width) that has the greatest influence on the astrophysical reaction rate, and the smaller partial width is more difficult to access by such indirect approaches.

New techniques are also now being developed for indirect studies with radioactive beams. Proton transfer reactions like (d,n) using large neutron detector arrays and ( $^3\text{He}$ ,d) using a gas jet target or a specialized spectrometer like HELIOS [37] may provide greater sensitivity to small proton widths that are important for low energy resonances but are difficult to access by other means. Two recent examples show the potential promise of such approaches. The  $^{56}\text{Ni}(^3\text{He},d)^{57}\text{Cu}$  reaction was studied at Argonne National Lab using a cryogenic  $^3\text{He}$  gas cell (with windows) [38]. Deuterons were detected in a silicon strip detector array and recoiling  $^{57}\text{Cu}$  ions in the Fragment Mass Analyzer. While the resolution was limited due primarily to geometrical considerations in the experiment, the experiment was able to show that the first and second excited states in  $^{57}\text{Cu}$  that are important resonances for the  $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$  reaction are single particle in nature with large proton widths that result in a reaction rate higher than predictions.

In another experiment, states in  $^{19}\text{Ne}$  that are important for the  $^{18}\text{F}(p,\alpha)^{15}\text{O}$  reaction were studied by the  $^{18}\text{F}(d,n)^{19}\text{Ne}$  proton transfer reaction [12]. While there have been direct cross section measurements of the  $^{18}\text{F}(p,\alpha)^{15}\text{O}$  reaction down to  $E_{cm} \approx 300$  keV, the contributions of lower energy resonances, and how they interfere with states at higher energies, still introduces substantial uncertainties into the reaction rate. In this measurement, a beam of pure beam of  $^{18}\text{F}$  from the HRIBF bombarded a  $\text{CD}_2$  target and breakup  $\alpha+^{15}\text{N}$  products from excited states produced in  $^{19}\text{Ne}$  were detected and identified using  $\Delta E - E$  silicon strip telescopes at forward angles. By accurately measuring the position and energy of both products in coincidence, the reaction angle and center of mass energy were reconstructed without detecting the emitted neutron. This approach is particularly powerful when all charged particles are detected, allowing cancellation of energy losses within the target, and allowing states in  $^{19}\text{Ne}$  to be reconstructed with good energy resolution (less than 100 keV) despite using a thick target ( $700 \mu\text{g}/\text{cm}^2$  in this case). The angular distribution of events allows the angular momentum

transfer and proton widths to be determined. From previous studies of the mirror nucleus, a strong  $J^\pi = 3/2^+$  resonance was expected near the proton threshold, but in this measurement it was found to lie 122 keV below the proton threshold in  $^{19}\text{Ne}$  and a relatively low limit was set on the contributions from any  $J^\pi = 3/2^+$  just above the proton threshold. This measurement significantly reduces uncertainties that arise from potential interference between states, though further direct measurements are needed to constrain the sign of interferences between levels that are not constrained by the transfer measurement.

For more energetic explosions like X-ray bursts and supernovae, reactions involving heavier, more proton-rich nuclei are important, but little experimental information is available. With a large number of uncertain reactions involved in the process, it is important to try to assess which reactions are most important. Sensitivity studies using astrophysical models are helping to identify reactions that have the greatest influence on astronomical observations [39, 40], though one has to be a bit cautious as the sensitivity to input parameters can depend upon hydrodynamical details of the particular model. The situation is more clear for reactions with low  $Q$  value at high temperatures, where direct and inverse reactions fall into equilibrium. In such cases, only the mass differences (reaction  $Q$  values) and decay properties are very important, not the detailed structure or reaction rates. As the relative abundances depend exponentially on the reaction  $Q$  value in such cases, an accurate determination of the mass differences between nuclei is the critical first step that is required in understanding reaction rates and nucleosynthesis.

Substantial progress is currently being made in our understanding of masses important for X-ray bursts led by six Penning trap mass measurement programs: the CPT at Argonne National Laboratory [41], LEBIT at the NSCL at Michigan State University [42], JYFLTRAP at Univ. of Jyväskylä [43], SHIPTRAP at GSI [44], ISOLTRAP at CERN [45], and TITAN at TRIUMF-ISAC [46]. The general approach is to produce short-lived isotopes via nuclear reactions, stop the ions in a buffer gas, extract, mass analyze, cool and bunch the ions, then trap them in a combination of electric and magnetic fields. Often two stages of trap are used for isobaric purification then for determination of the mass by measuring the cyclotron resonance frequency of the ions. Recent measurements of proton-rich nuclei in the region around the tin isotopes at JYFLTRAP and SHIPTRAP have determined proton-separation energies to a precision of about 10 keV [47, 48, 49]. These measurements show that strong cycling of material closed by  $(\gamma, \alpha)$  reactions can not occur in the region of the proton-rich tin isotopes as previously proposed, which has significant influence on X-ray burst light curves, the ashes of the burst, and the subsequent evolution of the system.

### 3. Origins of the heavy elements

About half of the heavy elements originate in Asymptotic Giant Branch (AGB) stars. These stars burn hydrogen and helium in shells outside the core, and neutrons produced by the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  and  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reactions result in a series of neutron captures and beta decays, the  $s$  process. Convective instability leads to the ejection of the outer layers with the newly synthesized elements into the interstellar medium [50]. There remain some important open questions regarding the complicated thermodynamic mechanism (mixing and convection) and the abundances around long-lived radioactive nuclei where the reaction sequence branches, but the contributions to heavy element synthesis from the  $s$  process are generally well understood [51, 52]. There are high quality neutron capture data on most stable isotopes and good constraints from astrophysical observations and isotopic abundance measurements on meteoritic grains originating in AGB stars. However, the  $s$  process only accounts for about half of the measured solar system abundances of heavy elements. Where do the rest of the heavy elements originate?

Based upon the pattern of the residual abundances not produced in the  $s$  process, it appears that most other isotopes originate as short-lived neutron-rich nuclei produced in a hot explosive environment, the  $r$  process [53], but recent astronomical observations are revolutionizing our

understanding. Spectroscopic surveys of stars in the Galactic halo have identified old stars (with low iron abundance) that are significantly enriched in heavy elements [54]. These halo stars presumably formed close to a site of heavy element production early in the history of the Galaxy, before AGB stars likely contribute to element production [55]. Such observations allow heavy element production to be compared at different times and locations throughout the history of the early Galaxy. The relative abundances of observed elements from tin to lead show an identical pattern in these old halo stars, a pattern that also matches the solar system pattern once the  $s$  process abundances have been subtracted [56]. The universal nature of the abundance pattern provides further evidence that these nuclei originate from a robust equilibrium process in an hot (explosive) environment. The frequency, ejected mass, and extreme conditions expected in core collapse supernovae make them a leading candidate for the site of the  $r$  process [57], but supernova models thus far produce explosions only in a limited range of progenitor conditions and do not produce the right hydrodynamic conditions to lead to formation of heavy elements by an  $r$  process [58]. The overall normalization of  $r$  process abundances in the halo stars does not correlate with the iron abundance. While this may arise from a lack of mixing in the early Galaxy [59], these all may be indications that supernovae are not the site of the  $r$  process.

Elements lighter than tin show substantial variations in abundance from star to star and are generally lower than expected compared to heavier elements [56]. This indicates that at least one process that is fundamentally different from the  $r$  process must contribute to the abundance of elements between iron and tin. Observations thus far are well described by adding just two unique patterns, an  $r$  process pattern resulting from a high neutron density environment and a pattern producing more predominantly lighter isotopes, the Light Element Primary Process (LEPP), with different relative mixing [60]. The abundance pattern produced by the LEPP is consistent with an origin in a low neutron density environment similar to the  $s$  process, but the astrophysical site that could produce such conditions early in the history of the Galaxy is unclear. The LEPP abundance pattern might also be produced in supernovae as proton-rich isotopes created from the interaction of neutrinos with iron group nuclei, the  $\nu p$  process [61]. The sequence of reactions involved in this process is more similar to that of the  $rp$  process, but neutrons produced through neutrino interactions help bypass the decays of long-lived beta emitters.

An important open question is the connection of the observed LEPP abundances in the halo stars with the stable isotopes in the Galaxy that lie on the proton-rich side of stability and have low abundances. These  $p$  process isotopes can not be produced by neutron capture reactions [53]. Their generally low abundance likely indicates a secondary processes, spallation reactions on  $s$  and  $r$  process nuclei in a hot environment like supernovae for example, might produce these isotopes, but the  $\nu p$  process provides an alternate mechanism that could lead to the lighter  $p$  process isotopes [61]. The low abundance, the extreme conditions where they might originate, and the lack of experimental data makes understanding the origins of the  $p$  process nuclei particularly challenging. While there have been important mass measurements (for example the Penning traps studies mentioned previously [47, 48, 49]) and measurements of decay properties (for example, see [62]) in the region, but almost no spectroscopic information is available. Even reactions on stable isotopes are not well understood. Complementary experimental programs are now providing data that are helping to improve theoretical models that form the basis of reaction rates in the  $p$  process. Direct measurements of photon induced cross sections using gamma-ray beams, produced for example at the National Institute of Advanced Industrial Science and Technology (Japan) [63] and at the S-DALINAC superconducting electron linear accelerator in Darmstadt [64], are directly measuring important cross sections relevant for the  $p$  process. Important constraints are also being provided though capture reaction measurements using intense low energy beams of protons and alphas, for example at ATOMKI [65, 66], and through neutron activation at Karlsruhe [67]. These experimental programs are challenging due to the

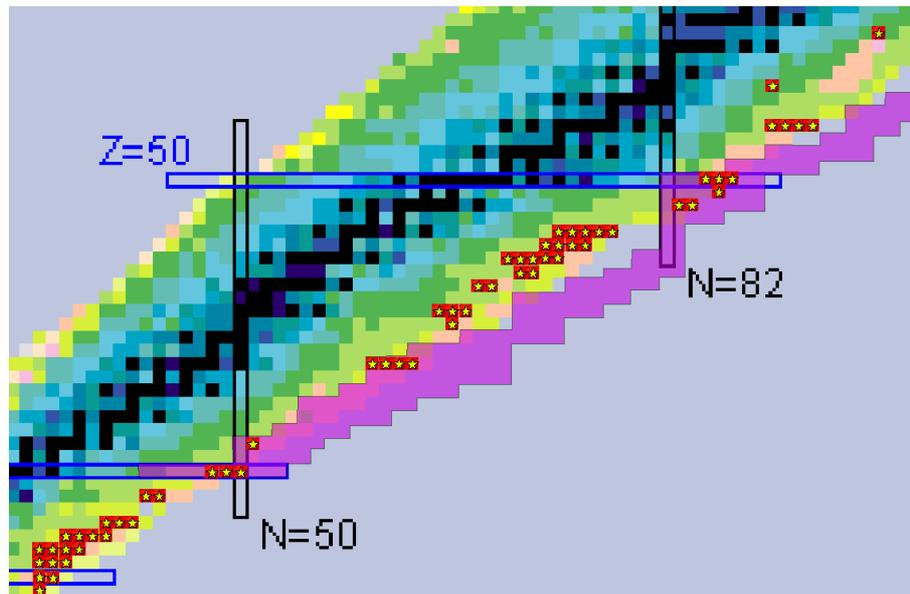
small cross sections of interest and the limited availability of enriched rare isotopes for target material. Measurements at lower energies and with rarer and radioactive isotopes are needed to provide stringent constraints on theoretical models over the wide mass range of interest, but such measurements will be even more difficult.

While supernova models do not seem to produce conditions that are favorable for the  $r$  process, there are substantial uncertainties regarding the supernova mechanism, and it is possible that supernovae might be the site of the  $r$  process, the LEPP and the  $p$  process [68]. The rates of weak interactions at finite temperature are one significant source of uncertainty in the supernova mechanism. Weak reaction rates affect the dynamics of core collapse (electron capture rates) [69] and in the interaction of the expanding shock with the outer layers of the star (neutrino cross sections) [70]. Rates are mostly based on theoretical calculations of Gamow-Teller strength distributions [71, 72]. Charge exchange reactions provide the best experimental probe, and recent measurements on stable nuclei have shown significant disagreement with theoretical models (e.g. see [73]). Techniques that are being developed to allow charge-exchange measurements in inverse kinematics with radioactive ion beams are particularly important to test the reliability of theoretical models away from stable isotopes. [74].

Given the current issues faced with supernova models, exploring other potential scenarios for the origins of the heavy elements is important [75, 76, 77]. While such scenarios may create conditions suitable for formation of heavy elements, achieving sufficient abundances to describe the chemical evolution of the Galaxy, particularly at early times, may be problematic [78]. Regardless of the site, the path towards understanding the origins of the heavy elements depends in part upon comparison of new observational data with more sophisticated multi-dimensional astrophysical models. However, any such comparison suffers from substantial uncertainties in the underlying nuclear physics. Only a few nuclei that are expected to be important in the  $r$  process have been accessible thus far in the laboratory, produced mostly via fragmentation or fission of heavier nuclei.

The most important quantities for understanding  $r$  process nucleosynthesis are masses and decay properties [79]. As the  $r$  process involves both high temperatures and high neutron densities, the rate of neutron capture and photodissociation are much faster than the rates for beta decay. The relative abundances of the isotopes of a given element maintain a statistical distribution of abundances until fairly late times when the temperature has dropped significantly and the abundances of nuclei have shifted closer to stability. Mass measurements are important not only as direct input for  $r$  process models but as a benchmark for improving theoretical models (see, for example, [80, 81]). Time-of-flight and storage ring techniques with fragmentation beams have allowed masses of many nuclei to be simultaneously measured in a short time, providing complementary capabilities to Penning Trap mass measurement programs [82]. In general, measurements of more neutron-rich nuclei have shown that theoretical predictions of atomic masses generally deviate more substantially as extrapolations are made further from the region of measured masses [81, 83]. This places an importance not only on new mass measurements but on understanding the evolution of nuclear structure away from stability.

Decay properties (half-lives and neutron-emission probabilities) also have a direct significant impact on  $r$  process abundances. The relatively slow progress in understanding the properties of neutron-rich nuclei is illustrated in Figure 1 where we compile beta-decay half-life measurements for nuclei near the  $r$  process path that have been published over about the last decade. While the half-lives of only a few  $r$  process nuclei have been measured, the measurements have had a substantial impact. The half-life of the one nucleus,  $^{78}\text{Ni}$ , was shown to significantly influence expected abundances [84]. Measurements between the closed shells have illustrated the important role that nuclear structure plays in understanding decay properties in non-spherical nuclei [85, 86]. Beta-delayed neutron emission probabilities are also especially important as they shift the abundances of nuclei produced. While there have been important measurements



**Figure 1.** A portion of the Chart of Nuclides indicating new half-life measurements over about the last decade (marked with star) for nuclei in the region of the *r* process (approximate location shaded in pink).

([87, 88], for example), data only exists for a few *r* process nuclei closest to stability.

Given the current state of experimental data and the large number of short-lived isotopes that are involved in the *r* process, an emphasis must be placed on improving nuclear structure models that will necessarily form the basis of our understanding of the astrophysical *r* process in the near term. Studies of basic properties like electromagnetic transition strengths (for example [89, 90]) and single particle structure near closed shells [91] are particularly valuable as they provide exacting tests of theoretical models that can improve the reliability of models to extrapolate away from stability. These measurements are also important for improving estimates of neutron capture rates for relatively abundant nuclei (typically closer to stability and near closed neutron shells) that can have a global impact on abundances by affecting the abundance of neutrons at late times [92].

#### 4. Outlook

Progress in our understanding of explosive nucleosynthesis is limited in large part by our ability to produce and study short-lived nuclei. New facilities are now under development around the world that are applying different approaches to expand our capabilities. The Radioactive Ion Beam Factory (RIBF) Facility in Japan and the Facility of Antiproton and Ion Research (FAIR) in Germany focus on fragmentation studies of heavy relativistic ion beams to push the reach to the most short-lived nuclei. The ARIEL project at TRIUMF-ISAC will use a high power electron beam to induce photofission in an actinide target to provide a intense beams of isotopes from uranium fission. The CARIBU project at Argonne National Lab will use spontaneous fission of  $^{252}\text{Cf}$  to produce beams of neutron-rich isotopes with complementary capabilities to ARIEL. The SPIRAL-2 facility uses both fragmentation and an ISOL-type approach [93] to produce beams at both relativistic and low energies. The Facility for Rare Isotope Beams (FRIB) in the US will couple a high power linac driver with gas stopping and reacceleration to produce beams intense beams of even short-lived nuclei at the energies that are important for stellar

explosions. The combined complementary capabilities of these facilities will have a great impact astrophysics by allowing access to the many of the nuclear properties that are important in our understanding of X-ray bursts, supernovae and the origins of the heavy elements.

#### 4.1. Acknowledgments

We thank our colleagues for many useful discussions and suggestions in preparing this brief overview. Thanks are due particularly to Jason Clark, Raph Hix, Dave Lunney, Milan Matoš, Hendrik Schatz and Remco Zegers.

#### References

- [1] Bertulani C A and Gade A 2010 *Phys. Rep.* **485** 195
- [2] Fisker J L, Schatz H and Thielemann F K 2008 *Astrophys. J. Suppl. Ser.* **174** 261
- [3] Galloway D K *et al.* 2004 *Astrophys. J.* **601** 466
- [4] Starrfield S 2002 *Classical Nova Explosions (American Institute of Physics Conference Series vol 637)* ed M Hernanz & J José p 89
- [5] Jos'e J and Hernanz M 2007 *J. Phys. G* **34** R431
- [6] Weinberg N N, Bildsten L and Schatz H 2006 *Astrophys. J.* **639** 1018
- [7] Romano D and Matteucci F 2003 *Mem. Soc. Astronom. Ital. Sup.* **3** 163
- [8] Chafa A *et al.* 2007 *Phys.Rev. C* **75** 035810
- [9] Moazen B H *et al.* 2007 *Phys.Rev. C* **75** 065801
- [10] Newton J R *et al.* 2010 *Phys.Rev. C* **81** 045801
- [11] Chipps K A *et al.* 2009 *Phys. Rev. Lett.* **102** 152502
- [12] Adekola A S *et al.* 2010 submitted to *Phys. Rev. Lett.*
- [13] Sallaska A L *et al.* 2010 *Phys. Rev. Lett.* **105** 152501
- [14] Al-Abdullah T *et al.* 2010 *Phys.Rev. C* **81** 035802
- [15] Erikson L *et al.* 2010 *Phys. Rev. C* **81** 045808
- [16] Peplowski P N *et al.* 2009 *Phys.Rev. C* **79** 032801
- [17] Wrede C 2009 *Phys.Rev. C* **79** 035803
- [18] Ruiz C *et al.* 2006 *Phys.Rev.Lett.* **96** 252501
- [19] Guo B *et al.* 2006 *Phys.Rev. C* **73** 048801
- [20] Bardayan D *et al.* 2007 *Phys. Rev. C* **76** 045803
- [21] Wrede C *et al.* 2009 *Phys. Rev. C* **79** 045803
- [22] Ma Z *et al.* 2007 *Phys.Rev. C* **76** 015803
- [23] Jenkins D G *et al.* 2006 *Phys.Rev. C* **73** 065802
- [24] Matoš M *et al.* 2010 submitted to *Proceedings of the 11th Symposium on Nuclei in the Cosmos (NIC XI)*
- [25] Senziani F, Skinner G K, Jean P and Hernanz M 2008 *Astron. Astrophys.* **485** 223
- [26] Newton J R, Iliadis C, Champagne A E, Longland R and Ugalde C 2007 *Phys.Rev. C* **75** 055808
- [27] Blackmon J C *et al.* 2004 *Nucl. Phys. A* **746** 365
- [28] Williams R E, Phillips M and Hamuy M 1994 *Astrophys. J. Sup. Ser.* **90** 297
- [29] Iliadis C, Champagne A, José J, Starrfield S and Tupper P 2002 *Astrophys. J. Suppl. Ser.* **142** 105
- [30] Diehl R *et al.* 2006 *Nature* **439** 45
- [31] Hernanz M and José J 2006 *New Astron. Rev.* **50** 504
- [32] Engel S *et al.* 2003 *Nucl. Instrum. Meth. Phys. Res. A* **553** 491
- [33] D'Auria J M *et al.* 2004 *Phys.Rev. C* **69** 065803
- [34] Jenkins D G *et al.* 2004 *Phys. Rev. Lett.* **92** 031101
- [35] Deibel C M *et al.* 2009 *Phys. Rev. C* **80** 035806
- [36] Lotay G *et al.* 2009 *Phys. Rev. Lett.* **102** 162502
- [37] Lighthall J C *et al.* 2010 *Nucl. Instrum. Meth. Phys. Res. A* **622** 97
- [38] Jiang C L *et al.* 2009 *Phys. Rev. C* **80** 044613
- [39] Smith K *et al.* 2008 *Nuclei in the Cosmos (NIC X)*
- [40] Parikh A, José J, Iliadis C, Moreno F and Rauscher T 2009 *Phys. Rev. C* **79** 045802
- [41] Savard G *et al.* 2001 *Hyperfine Interactions* **132** 223
- [42] Ringle R, Bollen G, Prinke A, Savory J, Schury P, Schwarz S and Sun T 2009 *Nucl. Instrum. Meth. Phys. Res. A* **604** 536
- [43] Elomaa V V *et al.* 2009 *Nucl. Instrum. Meth. Phys. Res. A* **612** 97
- [44] Rahaman S *et al.* 2006 *Int. J. Mass Spec.* **251** 146
- [45] Bollen G *et al.* 1996 *Nucl. Instrum. Meth. Phys. Res. A* **368** 675

- [46] Delheij P *et al.* 2006 *Hyperfine Interactions* **173** 123
- [47] Elomaa V V *et al.* 2009 *Phys. Rev. Lett.* **102** 252501
- [48] Weber C *et al.* 2008 *Phys. Rev. C* **78** 054310
- [49] Martin A *et al.* 2007 *Eur. Phys. J. A* **34**(4) 341 10.1140/epja/i2007-10520-5
- [50] Karakas A I, van Raai M A, Lugaro M, Sterling N C and Dinerstein H L 2009 *Astrophys. J.* **690** 1130
- [51] Lattanzio J C and Lugaro M A 2005 *Nuclear Physics A* **758** 477
- [52] Koehler P E 2005 *Nuclear Physics A* **758** 493
- [53] Burbidge E M, Burbidge G R, Fowler W A and Hoyle F 1957 *Rev. Modern Phys.* **29** 547
- [54] Beers T C and Christlieb N 2005 *Ann. Rev. Astron. Astrophys.* **43** 531
- [55] Trigo-Rodríguez J M *et al.* 2009 *Meteoritics and Planetary Science* **44** 627
- [56] Cowan J J and Sneden C 2006 *Nature* **440** 1151
- [57] Cowan J J and Thielemann F K 2004 *Physics Today* **57**
- [58] Hoffman R D, Müller B and Janka H T 2008 *Astrophys. J.* **676** 127L
- [59] Truran J W, Cowan J J, Pilachowski C A and Sneden C 2002 *PASP* **114** 1293
- [60] Montes F *et al.* 2007 *Astrophys. J.* **671** 1685
- [61] Fröhlich C *et al.* 2006 *Phys. Rev. Lett.* **96** 142502
- [62] Mazzocchi C *et al.* 2007 *Phys. Rev. Lett.* **98** 212501
- [63] Utsunomiya H *et al.* 2009 *Phys. Rev. C.* **81** 035801
- [64] Hasper J *et al.* 2009 *Phys. Rev. C* **79** 055807
- [65] Güray R T *et al.* 2009 *Phys. Rev. C.* **80** 035804
- [66] Kiss G G *et al.* 2009 *Phys. Rev. C.* **80** 045807
- [67] Marganiec J, Dillmann I, Pardo C D, Käppeler F and Walter S 2010 *Phys. Rev. C* **82** 035806
- [68] Arcones A, Janka H T and Scheck L 2007 *Astron. Astrophys.* **467** 1227
- [69] Hix W R *et al.* 2003 *Phys. Rev. Lett.* **91** 201102
- [70] Juodagalvis A *et al.* 2005 *Nucl. Phys. A* **747** 87
- [71] Dzhioev A A 2010 *Phys. Rev. C* **81** 015804
- [72] Langanke K *et al.* 2003 *Phys. Rev. Lett.* **90** 241102
- [73] Hitt G W *et al.* 2009 *Phys. Rev. C* **80** 014313
- [74] Zegers R G T *et al.* 2010 *Phys. Rev. Lett.* **104** 212504
- [75] Surman R, McLaughlin G C, Ruffert M, Janka H T and Hix W R 2008 *Astrophys. J.* **679** L117
- [76] McLaughlin G C and Surman R 2005 *Nucl. Phys. A* **758** 189
- [77] Freiburghaus C, Rosswog S and Thielemann F K 1999 *Astrophys. J.* **525** L121
- [78] Argast D, Samland M, Thielemann F K and Qian Y Z 2004 *Astron. and Astrophys.* **416** 997
- [79] Cameron A G W, Cowan J J and Truran J W 1983 *Astrophys. Space Sci.* **91** 235
- [80] Hager U *et al.* 2007 *Phys. Rev. C* **75** 064302
- [81] Hager U *et al.* 2006 *Phys. Rev. Lett.* **96** 042504
- [82] Matoš M *et al.* 2009 *Acta Phys. Pol. B* **40** 695
- [83] van Schelt J *et al.* 2010 in preparation, private communication
- [84] Hosmer P T *et al.* 2005 *Phys. Rev. Lett.* **94** 112501
- [85] Pereira J *et al.* 2009 *Phys. Rev. C* **79** 035806
- [86] Montes F *et al.* 2006 *Phys. Rev. C* **73** 035801
- [87] Hosmer P *et al.* 2010 *Phys. Rev. C* **82** 025806
- [88] Winger J A *et al.* 2009 *Phys. Rev. Lett.* **102** 142502
- [89] Padilla-Rodal E *et al.* 2005 *Phys. Rev. Lett.* **94** 122501
- [90] Radford D C *et al.* 2002 *Phys. Rev. Lett.* **88** 222501
- [91] Jones K L *et al.* 2010 *Nature* **465** 454
- [92] Surman R, Beun J, McLaughlin G C and Hix W R 2009 *Phys. Rev. C* **79** 045809
- [93] Ravn H L 1979 *Phys. Rep.* **54** 201