

Understanding the origin of the elements: experiments at the dripline

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Abstract. The field of Nuclear Astrophysics deals with the question of the origin of the elements. Nuclear physics plays a major role in the understanding and modeling of different processes of heavy element production and therefore, experimental and theoretical studies on nuclear systems are needed.

By means of two important explosive astrophysical scenarios, current selected experimental progress, achieved at the GSI facility in Darmstadt, Germany, and at the NSCL at MSU, USA, will be reviewed. A short outlook on future developments will be given at the end.

1. Introduction

In an impressive publication by M. Burbidge, G. Burbidge, W. Fowler and F. Hoyle (*B²FH*) from 1957 [1] the authors suggested an answer to the long-standing question: what is the origin of the heavy elements in the universe? Their remarkable argument is based on the very promising idea, that nucleosynthesis is linked with (ongoing) processes inside stars and in stellar explosions. Nuclear physics plays a key role in the understanding and modeling of the complex processes taking place in stars. Besides astrophysical processes involving stable isotopes or isotopes close to stability (which will not be subject of this review), short-lived radioactive nuclei with large proton-to-neutron ratios (and vice versa) are considered to be important in the different nucleosynthesis processes proposed in *B²FH*.

With the advent of radioactive beam facilities it became possible to gain experimental access to nuclei far away from stability. This has enabled a variety of studies of basic properties of the complex many-body quantum system, like *e.g.* the mass and level structure, which in turn stimulates the development and improvement of the underlying nuclear theory. Huge progress has been made over the last decades and the astrophysical models have benefited from reliable input provided from nuclear physics. Recent experimental efforts and results motivated by two different nucleosynthesis processes will be discussed in Sec. 2 and 3. A short outlook will be given in Sec. 4.

2. The rapid proton-capture process

The rp process is an extended series of fast (p, γ) reactions along isotonic chains, interspersed with slower β^+ -decays and electron-capture reactions. Within typically 10-100 s, the rp process spans a nuclear reaction network of up to the $A \approx 100$ region [2, 3]. The high densities and high temperatures involved indicate an explosive astrophysical site like a type I x-ray burst.



A type I x-ray burst is a thermonuclear explosion ignited in the outer envelope of an accreting neutron star, situated in a binary system with a relatively unevolved companion star. Mainly H/He-rich material is transferred onto the accretion disk formed around the neutron star and in most cases, the accreted material is burned unstably on very regular timescales. Around a hundred of such x-ray bursters have been identified in the Galaxy, thus being the most frequently observed explosion, see *e.g.* Refs. [4, 5].

Accurate modeling of type I x-ray bursts still exhibits large uncertainties mainly owing to many unconstrained proton-capture reaction rates. In order to eliminate nuclear physics uncertainties induced into the astrophysical models, reaction studies involving exotic proton-rich nuclei are necessary. Since most of the involved nuclei are very short-lived, and, thus, can not be fabricated into targets, the reaction studies are performed in inverse kinematics (unstable nuclei are used as projectiles, not as targets). Moreover, direct (p, γ) and (α, γ) reactions usually have extremely small cross sections making the direct measurement extremely difficult if not impossible with current radioactive beam facilities. To overcome this problem, indirect studies have been used in many cases to constrain experimentally important reaction rates identified in sensitivity studies [6]. As an example: the astrophysical temperature-dependent capture-reaction rate, when proceeding through a narrow isolated resonance, can be approximated by

$$\langle \sigma v \rangle \propto \Sigma_r (\omega \gamma)_r \cdot e^{-\frac{E_r}{k_B T}}, \quad (1)$$

with σ being the cross section, v the relative velocity of the particles, $(\omega \gamma)_r$ the resonance strength (depending on the spins and partial widths of the resonance and the particle), E_r the energy of the resonance, and $k_B T$ the Boltzmann constant multiplied with the temperature T . As can be seen from this equation, experimental extraction of spectroscopic properties (like *e.g.* the resonance energy E_r) can be used to indirectly obtain stellar reaction rates.

A powerful indirect reaction method is Coulomb breakup. It can be used to extract properties like *e.g.* spectroscopic information and radiative-capture cross sections via detailed balance (*i.e.* the time-reversed reaction is measured), see *e.g.* Refs. [7, 8]. Versatile setups are used to measure the reaction residues and γ -rays after decay of the excited states, and the extracted kinematical information can be combined to reconstruct the excitation energy spectrum or the momentum distributions.

In a recent experiment at the R³B-LAND setup at GSI, the excitation energies of low-lying levels in proton-rich ³¹Cl have been extracted by employing the Coulomb-breakup method and reconstruction of the excitation energy spectrum. The ³⁰S(p, γ)³¹Cl reaction is considered to be an important reaction during the rp process due to its low Q-value of ~ 300 keV. The rate had been determined by theoretical calculations [9], and an unambiguous experimental confirmation, especially of the important first low-lying state, was still missing. The left part of Fig. 1 shows the energy-differential excitation spectrum of ³¹Cl [10]. The two-lying peaks can be clearly identified and are in good agreement with the theoretical calculations in [9].

In-flight γ -ray spectroscopy is another powerful tool to gain spectroscopic information on exotic nuclei. In this experimental approach, mainly γ -decaying states are populated via a variety of different possible reaction mechanisms, like *e.g.* nucleon transfer, knock-out, and Coulomb excitation, at corresponding beam energies. The emitted γ -rays are subsequently detected in dedicated detector systems (usually in coincidence with the reaction residue) and detailed spectroscopic information of excited states can be deduced. Especially new instrumental tools, like *e.g.* the GRETINA array in the US [12] and AGATA in Europe [13], enable studies with unprecedented sensitivity involving nuclei so far out of reach.

The right part of Fig. 1 shows a preliminary spectrum of Doppler-corrected γ -ray transitions in proton-rich ⁵⁸Zn, populated in a ⁵⁷Cu(d, n) transfer reaction at 75 MeV/ u , measured with GRETINA in conjunction with the S800 spectrometer [14] at the NSCL. Similar to ³¹Cl, ⁵⁸Zn is considered to be an important nucleus during rp-process nucleosynthesis [6], and X-ray burst

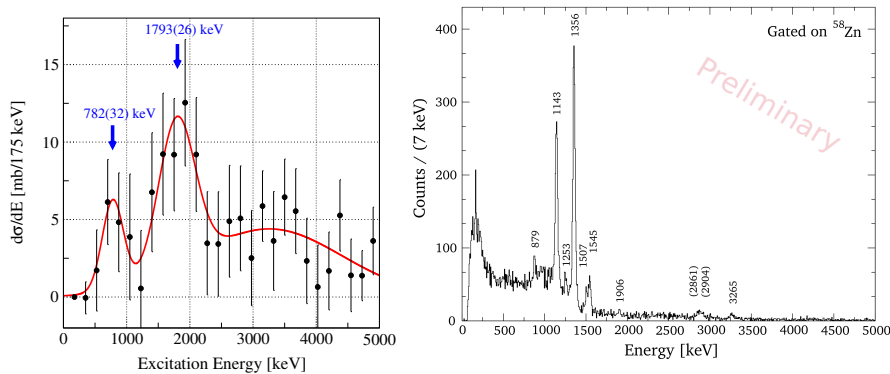


Figure 1. Left: Results of a Coulomb-breakup experiment carried out at the R³B-LAND setup at GSI using ³¹Cl as an incoming beam. The excitation spectrum reveals two important resonances (energies marked with arrows), which play a crucial role for the ³⁰S(*p*, γ)³¹Cl reaction during rp-process nucleosynthesis [10]. Right: A Doppler-corrected γ -ray spectrum of ⁵⁸Zn, measured with GREINA at the NSCL [11]. The reaction ⁵⁷Cu(*p*, γ)⁵⁸Zn is of major interest for x-ray burst models.

models predicting the light curve and the composition of the ashes rely on accurate input for this particular reaction. So far it was not possible to extract experimentally spectroscopic information for ⁵⁸Zn, which mainly determines the ⁵⁷Cu(*p*, γ)⁵⁸Zn reaction rate. Using the improved sensitivity of the GREINA array, it was subsequently possible to extract the information needed to improve the reaction rate by orders of magnitude [11].

Measurements studying the capture reactions directly are in most cases favorable in comparison to indirect methods since any dependence on theory is minimized. In a recent proof-of-principle experiment performed at the storage ring ESR at GSI the ⁹⁶Ru(*p*, γ) reaction cross section was successfully measured [15] at the relevant stellar (low) energies. In that experiment a ⁹⁶Ru beam was injected into the ring, where a liquid hydrogen target was installed. Because of the many circulations of the ions in the ring, a high target luminosity of 10²⁵ cm⁻²s⁻¹ was achieved overcoming the low cross sections. First results are in good agreement with theory and the whole concept is, thus, very promising.

3. The rapid neutron-capture process

About half of the elements heavier than iron are created during the rapid neutron-capture process (r process). Up to now, the astrophysical site of the r process remains unclear, partly because the involved nuclear physics is still uncertain and relies on theoretical input parameters, such as masses, β -decay half-lives, and neutron-capture reaction rates far away from stability [16, 17].

Mass measurements employing new techniques [18] provide a powerful tool to experimentally constrain atomic masses, which are crucial input parameters for r-process models. In a recent experiment utilizing the Canadian Penning Trap (CPT) at the ATLAS facility at Argonne National Lab, the masses of 33 r-process nuclides were measured, ranging from ¹³⁰In to very neutron-rich ¹⁴⁶Cs [19]. The authors used different r-process simulations implementing the newly measured masses for the involved nuclei. According to their models, a significant increase of processing time through that region is obtained when comparing the results of the simulations using state-of-the-art mass models. This points towards insufficiently constrained mass models for accurate r-process simulations. New facilities and techniques are needed to further improve the existing mass models.

The r-process reaction flow and the overall processing time also depends on the β -decay half-lives of certain important isotopes. Huge experimental effort is therefore put into lifetime measurements, and recent progress has been achieved to constrain global models and to accurately predict the reaction flow, see *e.g.* Refs. [20, 21].

In order to calculate neutron-capture reaction rates, precise knowledge of the evolution of nuclear shell structure towards very neutron-rich systems is required. Similar to the rp-process reaction studies, different experimental techniques can be employed to study the structure of most exotic neutron-rich nuclei.

One of the major changes in the evolution of shell structure are the observed dramatic changes in the well-known magic numbers (2, 8, 20, 28, ..). This involves *e.g.* the disappearance of the $N = 20$ magic number, and the appearance of a new magic number with $N = 16$, resulting in a new doubly magic nucleus ^{24}O (see Ref. [22] and references therein for a good overview). A key role in the theoretical understanding of these phenomena is played by the tensor short-range interaction of the nuclear force, and here especially by the monopole interaction [23].

Moreover, inclusion of 3N-forces seems to be able to resolve some still standing open questions, like the abrupt change of the dripline behavior going from oxygen isotopes to the fluorine chain. In a recent experiment at the R³B-LAND setup at GSI, the authors of [24] measured the excitation energy spectrum of unbound ^{26}O . In order to understand the data, they explicitly included 3N-forces into their model, with which they are able to quantitatively explain the abrupt change of the dripline behavior and the structure of ^{26}O . Although ^{26}O is not situated on the standard r-process reaction path, the result improved the structural description and understanding of very neutron-rich nuclei, especially in the light region. This can be modified and used for nuclei which are relevant for modern r-process calculations, and shows nicely the interplay between Nuclear Structure Physics and Nuclear Astrophysics. Experiments like these are needed in the future to get a more complete picture of the nuclear force, and thus, being able to predict neutron-capture rates with high accuracy, making astrophysical model predictions eventually more reliable.

4. Outlook

Radioactive beam facilities play a crucial role in the understanding of the origin of the elements. For certain studies, however, the present available facilities do not have enough beam intensity and major upgrades are needed in order to pursue studies involving nuclei so far unreachable. Most of the neutron-rich isotopes situated on the assumed r-process path can not be produced with the current facilities. To overcome this problem, many astrophysical nuclear physics input parameters need to be extrapolated, which, in turn, carries large uncertainties. With future facilities currently under construction or already in the commissioning phase, a new era will be possible using most exotic beams with high intensities and beam quality.

Direct reaction rate measurements can also benefit from new facilities such as the proposed storage ring at the future NuSTAR experiment (see *e.g.* Refs. [25, 26] and references therein). Based on the high target luminosity achieved through the circulation of a cooled radioactive beam in the storage ring, direct reactions like (p, γ) or (α, γ) involving the most exotic nuclei can be studied.

Complementary, the ReA3 experiment at the NSCL (right now in the commissioning phase) provides high-intensity stopped and re-accelerated radioactive beams at around 3 MeV/ u and, thus, enables reaction studies at highest intensities. In a later driver accelerator upgrade (*FRIB*, see [27]) coupled to ReA3, even the most exotic nuclei can be produced, stopped and re-accelerated, and subsequently used for reaction studies. In this facility the *Separator for Capture Reactions* (SECAR) will be used for direct reaction rate studies related to Nuclear Astrophysics. The recoil separator, the *SuN* (Summing NaI) detector, ANASEN, and the gas-jet target JENSA will be extremely powerful for further, so far unreachable, studies (see [28] for more information).

The author is therefore very much looking forward into the bright and exciting future in the field of Nuclear Physics and Nuclear Astrophysics.

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