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Status of nuclear physics behind nucleosynthesis processes: The role of exotic neutron-rich nuclei

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Abstract. We give a brief overview of the current status of important nuclear physics inputs, like reaction rates, in hydrostatic and explosive nucleosynthesis. Recently, it has been proposed that exotic neutron-rich nuclei play an important role even in the formation of heavy elements via the r-process. The main problems here are identification, abundance estimation of seed nuclei in these processes, and their pathways. We will try to highlight how improved nuclear structure and reaction calculations can affect our present understanding of radiative capture rates of light-mass and medium-mass nuclei, which in turn can drastically influence the abundance of heavier-mass elements.

Keywords. Exotic nuclei—radiative capture reactions—r-process.

1. Introduction

A quantitative direction to the origin of matter around us came when it was realized that it was low-energy nuclear reactions that were responsible for creation and transmutation of elements in stars (Burbidge *et al.* 1957). This field involves calculating key nuclear reaction rates during the evolution of stars and in stellar explosions like in supernovae and neutron-star mergers (Wallerstein *et al.* 1997; José & Iliadis 2011).

Recently, advances made in accelerator and related technologies have provided us with a unique opportunity to produce and work with nuclei having very short half-lives and very small one-nucleon or two-nucleon separation energies. These nuclei lie very close to the drip lines (the limit of neutron or proton binding) and can exhibit behavior which is quite different from those of the stable isotopes. We still lack a fully microscopic understanding of the stability of these unique many-body systems. These nuclei are important also from the point of view of nuclear astrophysics. The rapid neutron capture (the r-process) together with the slow neutron capture (the s-process) are dominant mechanisms for the nucleosynthesis of heavy elements above iron. While the s-process creates elements at or near the valley of stability, the r-process passes mostly through the neutron-rich region of the nuclear chart. The properties of these nuclei are essential inputs to theoretical calculations on stellar burning which otherwise are often forced to rely on global assumptions about nuclear masses, decays and level structures extracted from stable nuclei. Some interesting aspects of exotic nuclei are dealt with in section 2.

Radiative-capture reactions play an important role not only in the production of light elements in the pp-chain but also in the r-process. It is imperative, therefore, to have robust nuclear inputs while calculating radiative-capture reaction rates.

A brief description of radiative-capture reactions is given in section 3. Given the problems of measuring them at low energies an alternative method based on ‘Coulomb dissociation as an indirect method in nuclear astrophysics’ is also introduced. This relates the Coulomb dissociation cross-section to the photo-dissociation cross-section and, subsequently, invoking the principle of detailed balance, the rate of the

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radiative-capture reaction at astrophysical energies is calculated. An important upshot of this method is that it is free from the uncertainties associated with the multipole strength distributions of the projectile, which are a bane in many other theories. Subsequently, several applications of radiative-neutron-capture reactions are described, involving low-mass exotic nuclei.

2. Exotic nuclei

Our current understanding of nuclear physics is to a large extent based on the study of stable isotopes, which are only about 300 out of nearly 7000 nuclei that can exist. With increasing experimental sophistication in the past few decades, it has now been possible to produce and initiate reactions with nuclei with very short lifetimes and also with small one(two)-nucleon separation energies. Compared to their stable counterparts, nuclei at the limits of low binding energy can have very different properties. Some have a halo structure in their ground states in which loosely bound valence nucleon(s) has (have) a large spatial extension with respect to the respective core. Halo nuclei, in most cases, have only one bound state (the ground state) and a broad featureless continuum. Indeed, first-generation radioactive ion-beam facilities have confirmed the existence of neutron halo in ^{11}Be,^{14}B and ^{19}C (one-neutron halo), and ^{6}He and ^{11}Li ,^{14}Be and ^{17}B (two-neutron halo). Proton halos, which are understandably rarer, have been found in ^{8}B,^{17}Ne,^{20}Mg and ^{26,27,28}P. Breakup reactions involving these nuclei, given their low binding energies, are thus a natural choice for investigating their structure and reactions. Therefore, it is a challenge to construct a purely quantum-mechanical theory which would take into account their microscopic structure and also describe their reactions. One such attempt in developing theoretical tools to investigate the structure and reactions of nuclei away from the valley of stability, by studying their breakup in the Coulomb and nuclear field of a nuclear target, can be found in Chatterjee and Shyam (2018). One is able to add the Coulomb and the nuclear amplitudes coherently within the same fully quantum-mechanical theory and thereby, as an upshot, also extract the interference terms.

More recently, with upgrades in radioactive ion-beam experimental facilities around the world, it is now possible to produce and work with neutron-rich medium-mass nuclei like ^{31}Ne and ^{37}Mg. This is a new development which involves expanding the field of ‘light exotic nuclei’ to the ‘deformed medium mass’ region of the nuclear chart. Specifically, ^{31}Ne and ^{37}Mg lie in the so-called ’island-of-inversion’, where an inversion between normal-*sd* and intruder-*pf* shell has been noted. This strongly suggests an evolution of nuclear-shell structure and a presence of deformation in these exotic nuclei. Naturally, when these properties are properly incorporated in nuclear inputs for astrophysical calculations they could lead to effects which may not be anticipated from mere statistical-model nuclear inputs.

Recent reviews of experimental and theoretical aspects of exotic nuclei are presented in Tanihata *et al.* (2013); Nakamura *et al.* (2017) and Chatterjee & Shyam (2018).

2.1 *Breakdown of magic numbers*

Another aspect of present-day nuclear physics, which may have consequences in abundance calculations based on shell evolution, is the concept of ‘magic numbers’. Mostly from the study of stable nuclei, if large gaps occur between groups of single-particle orbits that are completely filled with nucleons (neutrons or protons), then these nucleon numbers are called ‘magic’. The numbers 2, 8, 20, 28, 50, 82 and 126 were treated as sacrosanct. This was one of the most enduring concepts in nuclear-structure physics, especially the shell model. However, as one moves away from the valley of stability towards the neutron drip line, conventional shell gaps may disappear while new ones emerge. Indeed the vanishing of shell gaps at neutron numbers N = 8 and N = 20 has been observed in ^{12}Be, and ^{32}Mg and ^{30,32}Ne, respectively . The reason for this behavior has been traced to the characteristic nature of the spin-isospin interaction between the proton and neutron orbits in nuclei far from stability (Otsuka *et al.* 2001; Sorlin & Porquet 2008).

The breakdown of magic numbers, away from stability, may also be investigated using breakup reactions – the favorite tool to investigate exotic nuclei. It is known that full width at half maxima (FWHM) of the parallel momentum distribution for the breakup of stable isotopes is of the order of 140 MeV/c, while those involving exotic one-neutron halo nuclei is around 44 MeV/c. Furthermore, it was also observed

Table 1. Breakdown of N (neutron number) = 8 magic number in Be isotopes. S_n is the corresponding one-neutron separation energy of the isotope. Note that the maximum FWHM is for N = 6 and not for N = 8. For more details see text.

Be isotope	N	S_n (MeV)	FWHM (MeV/c)
^{9}Be	5	1.665	112
^{10}Be	6	6.812	191
^{11}Be	7	0.501	43
^{12}Be	8	3.169	89

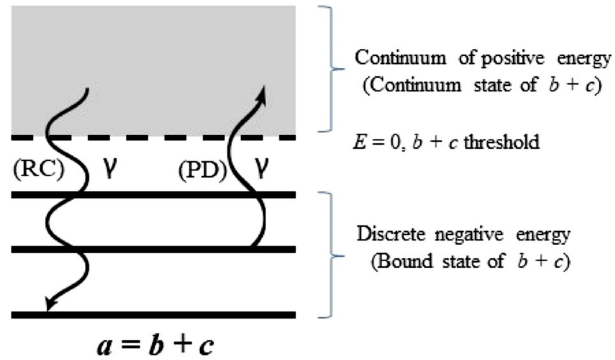

Figure 1. Schematic diagram of a radiative capture (RC) and its time-reversed counterpart, the photo-dissociation (PD).

that the width of the FWHM was independent of the target and was nearly constant for a range of experimental beam energies ranging from 50 MeV/nucleon to 2 GeV/nucleon. The essence of this information can be used to hypothesize that a projectile with a magic number of nucleons, on account of being more stable than its neighbors, will have a comparatively larger FWHM than its neighbors.

Indeed, this idea was first applied on Be isotopes in Shubhchintak & Chatterjee (2014) to study the breakdown of neutron number N = 8. They calculated the FWHM of the parallel momentum distribution in the breakup of (N = 5, 6, 7, 8) Be isotopes on a heavy target (gold) at beam energy of 100 MeV/nucleon. The results, summarized in Table 1, clearly show that in the Be chain of isotopes, ^{10}Be with N = 6 has the highest FWHM and not ^{12}Be with N = 8. This gives a clear indication of the breakdown of N = 8 magic number and the possible emergence of a new magic number at N = 6 near the neutron drip line.

We now turn our attention to radiative-capture reactions involving these exotic nuclei. In fact, the path towards the production of r-process seed nuclei follows a course where the neutron-rich light-mass and medium-mass nuclei play a crucial role. Therefore, it is of utmost importance that instead of relying on global assumptions extracted from stable nuclei, radiative-capture rates are calculated from a reaction theory which takes into account the intricacies of the structure of exotic nuclei.

3. Low-energy radiative-capture reactions

Consider the two-body $(a = b + c)$ particle-induced reaction $b + c \rightarrow a + \gamma$. The precise definition of a radiative-capture reaction is that it is an electromagnetic transition from a continuum state (ϕ_i) of a to a bound state (ϕ_f) of a (as shown in Figure 1). The transition rate for the process is given by $\mathcal{T} \sim |<\phi_f|\hat{O}(\pi, \lambda m)|\phi_i>|^2$, where $\hat{O}(\pi, \lambda m)$ is the electromagnetic operator of π : Electric/Magnetic type and λ the multipolarity of the transition with projection m. The cross-section for the process is given by $\sigma = \mathcal{T}/v$, where v is the relative velocity of the $b - c$ system with reduced mass μ. The modeling of the nuclear states (ϕ_i and ϕ_f) is the crux of the problem and the first step in any model calculation.

The nonresonant reaction rate per mole $N_A < \sigma v >$ (N_A being Avogadro's constant) is given by (see e.g. Iliadis (2007))

$$N_A < \sigma v > = N_A \sqrt{\frac{8}{(k_{\rm B}T)^3 \pi \mu}} \int_0^\infty dE \sigma(E) E \exp\left(-\frac{E}{k_{\rm B}T}\right), \quad (1)$$

where $k_{\rm B}$ is the Boltzmann constant, E is the centre of mass energy of the $b - c$ system, and T is the temperature in Kelvin (K).

In most cases, the the radiative capture cross-section is required in the sub-MeV range or even lower, given the temperature of the stellar environment. Thus measuring them in terrestrial laboratories becomes a problem because of extremely low counts or cross-sections. This difficulty can be overcome by use of indirect methods, like that of the Coulomb dissociation method.

In this method a projectile a consisting of the substructures $(b + c)$ is made to break up in the Coulomb field of a heavy target (t) and the elastic breakup cross-section (like the relative-energy spectrum $d\sigma/dE$) corresponding to the process $a + t \rightarrow b + c + t$ is measured. It is then related to the cross-section σ_γ of the photo-dissociation process $(a + \gamma \rightarrow b + c)$ via the virtual photon number $(n_{\pi\lambda})$,

$$\frac{d\sigma}{dE} = \frac{1}{E_\gamma} n_{\pi\lambda}\sigma_\gamma, \qquad (2)$$

provided only a single multipolarity ($\pi\lambda$) dominates the reaction. E_γ is the photon energy and is related to the $Q-$ value of the reaction by $E_\gamma = E + Q$. Note that the virtual photon number is fully dependent on the $a - t$ system. The photo-dissociation cross-section, on the other hand, is independent of the target and depends on the $b - c$ system. The radiative capture cross-section can then be calculated by using the principle of detailed balance. Of course, an element of theory enters into the experimental cross-section, but an upshot of this is that the radiative capture cross-section becomes available at very low energies. Thus one is able to connect a stellar reaction rate with a measurement done in a terrestrial laboratory. For more details see (Banerjee *et al.* 2008) and (Bertulani & Gade 2010).

We will now turn our attention to select radiative-neutron-capture reactions involving exotic nuclei.

3.1 *The* $^{8}Li(n,\gamma)^{9}Li$

The ^{8}Li$(n,\gamma)^{9}$Li reaction plays an important role in inhomogeneous big bang nucleosynthesis and type II supernova. In the former it was conjectured that ^{8}Li$(n,\gamma)^{9}$Li could compete with ^{8}Li$(\alpha,n)^{11}$B and may affect the production of $A > 12$ by as much as $40 - 50\%$. In the post-collapse phase of a type II supernova there is a possibility that this reaction can bridge the $A = 8$ gap via the $\alpha(2n,\gamma)^{6}$He$(2n,\gamma)^{8}$He$(\beta^-)^{8}$Li$(n,\gamma)^{9}$Li$(\beta^-)^{9}$Be reaction chain. This could open up a path to produce neutron-rich heavier isotopes like ^{36}S, ^{40}Ar, ^{46}Ca and ^{48}Ca, the origin of which is still under debate. However, this is again under competition with ^{8}Li$(\beta^-)^{8}$Be(2α).

The above reaction chains could also be expected in material ejected from neutron-star mergers which again underlines the importance of accurately measuring the ^{8}Li$(n,\gamma)^{9}$Li reaction rate.

Banerjee *et al.* (2008) calculated the reaction rate with proper nuclear-structure information, including updated spectroscopic factors. Their method was also able to avoid the usual uncertainties associated with the multipole strength distributions of the ^{9}Li nucleus, present in many other theories. They concluded that their reaction rate of 2900 cm^{3}mole^{-1}s^{-1}, at a temperature of 10^9 K, was not sufficiently large enough as to significantly reduce the formation of $A > 12$ elements. However, a more precise comparison of this rate with the ^{8}Li$(\beta^-)^{8}$Be(2α) channel would be very welcome.

3.2 *The* $^{15}N(n,\gamma)^{16}N$

The radiative neutron capture of ^{15}N is important in red-giant stars and is also considered to be a breakout reaction from the CNO cycle. Given that this leak-out is in competition with other charged-particle reactions involving ^{15}N, CNO abundances and by extension abundances of heavier-mass elements can be affected. In particular, its competition with ^{15}N$(\alpha,\gamma)^{19}$F can have consequences in determining fluorine abundances.

Given that the temperature where it operates is of the order of 0.2 GK, determining the capture cross-section at the corresponding low energies is quite challenging. In a direct capture measurement (Meissner *et al.* 1996) measured this reaction at 25, 152 and 370 keV. However, the challenge also comes from the fact that the cross-section is dominated by capture to the excited states of ^{16}N and not only to its ground state. The first four low-lying levels of ^{16}N are with spin-parity $J^\pi = 2^-, 0^-, 3^-, 1^-$, and the capture is dominated by the transition to the $J^\pi = 1^-, 0^-$ levels.

The other important nuclear-structure information that goes into the analysis are the spectroscopic factors (C^2S) of these four states. Bardayan *et al.* (2008) estimated them from the angular distributions of ^{15}N$(d,p)^{16}$N and concluded that they were close to unity and also agreed with those predicted from the shell model. Their results suggested that the first four levels in ^{16}N were essentially single-particle in nature. However, using a different transfer reaction, ^{15}N$(^{7}$Li$,^{6}$Li$)^{16}$N, (Guo *et al.* 2014) contradicted the above findings and concluded that the $J^\pi = 1^-, 0^-$ did not have a single-particle character. That would imply a very different cross-section and in turn a different rate of the ^{15}N$(n,\gamma)^{16}$N reaction.

To address this anomaly, (Neelam *et al.* 2015) recalculated the rates by considering the Coulomb dissociation of ^{16}N, and showed that they agree with the measurements of Bardayan *et al.* (2008) and (Meissner *et al.* 1996). This gave credence to the interpretation that the first four levels in ^{16}N could have a single-particle character. From the point of view of nucleosythesis in AGB stars and the inhomogeneous big-bang model, at the relevant temperatures that would favor the destruction of ^{15}N by the $^{15}N(n,\gamma)^{16}N$ reaction over charged-particle capture.

3.3 *The* $^{18}C(n,\gamma)^{19}C$

We now turn our attention to the critical role played by neutron-rich nuclei in the r-process (Terasawa *et al.* 2001; Sasaqui *et al.* 2005). The post-collapse phase of a type II or type Ib supernova and, analogously, neutron-star mergers could be such sites.

In the early expanding phase of a supernova alpha capture dominates and continues till temperature and density are relatively low. Then synthesis of elements can be possible by radiative neutron capture. Once the radiative neutron capture and the photo-dissociation reach an equilibrium, then, in principle, the largest abundance (for a given atomic or proton number, Z) could be on or very close to the corresponding neutron drip line. Terasawa *et al.* (2001) showed that the only exception to this was at ^{18}C and ^{36}Mg, where the (α,n) rates trump the (n,γ) rates. This assertion is, of course, open to interpretation, as (Terasawa *et al.* 2001) further commented in the conclusion of their paper. In fact, if one takes into account proper nuclear-structure effects in $^{18}C(n,\gamma)^{19}C$ or $^{36}Mg(n,\gamma)^{37}Mg$, the results might be different.

^{19}C is a classic one-neutron halo nucleus with a one-neutron separation energy of just 0.53 MeV and a spin parity $J^{\pi}=1/2^{+}$. Recently, (Dan *et al.* 2019) calculated the neutron capture cross-section and compared it with the statistical-model Hauser-Feshbach (HF) estimates of (α,n) and (n,γ) rates (Sasaqui *et al.* 2005), which are summarized in the following figures.

In Figure 2, the solid circles are data points generated from the measurement of relative-energy spectra in the breakup of ^{19}C from Nakamura *et al.* (1999). The solid line shows the $^{18}C(n,\gamma)^{19}C$ neutron capture cross-section which takes into account the halo nature of ^{19}C and the dot-dash line shows the statistical-model Hauser-Feshbach estimates, which were used in earlier calculations.

The effect on the reaction rate is quite dramatic and is shown in Figure 3. The solid line, which incorporates the proper structure effects in ^{19}C, is almost two orders of magnitude larger than the Hauser-Feshbach estimates (dot-dash line). The dotted line shows the

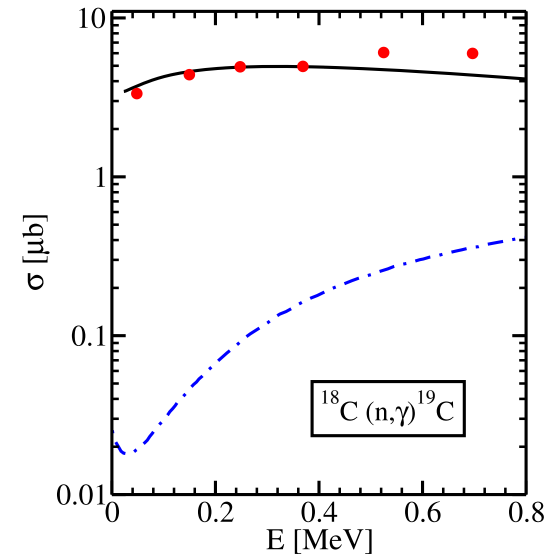

Figure 2. The $^{18}C(n,\gamma)^{19}C$ capture cross-sections taking into consideration the halo structure of ^{19}C (solid line) and statistical-model estimates (dot-dash line). The data are adapted from Dan *et al.* (2019). For more details refer to text.

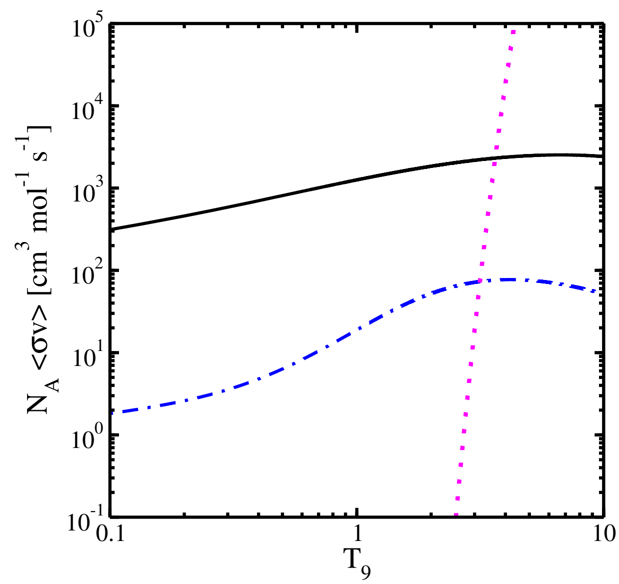

Figure 3. Reaction rates of $^{18}C(n,\gamma)^{19}C$ as a function of temperature in units of 10^{9}K (T_9). The solid line takes the halo nature of ^{19}C into account, while the dot-dash line shows the statistical-model estimates. The dotted line shows the statistical-model estimates of the $^{18}C(\alpha,n)^{21}O$ reaction rate. The data are adapted from Dan *et al.* (2019). For more details refer to text.

statistical-model estimates of the $^{18}C(\alpha,n)^{21}O$ reaction rate, which would not be able to compete with the neutron capture for $T_9 < 3$. This prompted (Dan *et al.*

2019) to conclude that the carbon abundances would be pushed to the neutron drip line. Nevertheless, it will be a welcome step to calculate the $^{18}C(\alpha, n)^{21}O$ transfer cross-section and subsequently its rate from a direct reaction theory.

4. Conclusions

A large number of inputs from low-energy nuclear physics to astrophysics are either based on the study of stable nuclei or are stochastic in nature. However, for the past few decades we have entered a paradigm where the effects of individual quantum states in nuclei are prominently being seen in nuclear-reaction observables. Long-held concepts like those of 'magic numbers' have been seen to fail while accounting for structure and reactions away from stability. This makes it all the more imperative that the detailed structure of nuclei away from stability be accounted for while calculating nuclear inputs for astrophysics.

We have tried to give some examples of how accounting for structure of light exotic nuclei can affect rates in both stellar and explosive nucleosynthesis. Singh *et al.* (2016) and Shubhchintak *et al.* (2017) have also shown that this trend is apparent in deformed medium-mass exotic nuclei like ^{34}Na and ^{37}Mg, which also lie at or near the island of inversion in the nuclear chart.

In retrospect, one looks back at the sesquicentennial of Mendeleev's periodic table, which was perhaps one of the most successful attempts to classify and understand the properties of the chemical elements, as a milestone in our quest to discover the origin of these elements. It is also a happy coincidence that this is shared with the centennial of the Saha equation, which was instrumental in unlocking the secrets of stellar spectra among its myriad other applications.

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