Neutron Reactions Relevant to s-Process Nucleosynthesis

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Abstract. The last decades have seen an enormous progress in modeling astrophysical objects, which lead to a significantly improved understanding of various nucleosynthesis scenarios. This applies in particular for asymptotic giant branch (AGB) stars where about half of the heavy elements are synthesised by the main component of the s process. In order to test these models and to compare the model predictions with observational data accurate neutron capture cross sections of isotopes with mass numbers A > 90 are indispensable. This holds especially for nuclei near closed neutron shells and in the vicinity of branch points since the analysis of s-process branchings yields important information on stellar parameters like temperature, neutron density, mass density and even convection time scales during the s process. Within this picture neutron reactions on abundant light elements are also important since these act as neutron poisons, hence affecting the neutron balance in the star. Finally, also the most important neutron sources for the s process, $^{13}$C($\alpha$,n)$^{16}$O and $^{22}$Ne($\alpha$,n)$^{25}$Mg, will be discussed.

INTRODUCTION

It was not before the late 50’s when it became apparent that the chemical elements are synthesized in stars. While the light elements up to iron are produced by fusion reactions during the various stellar burning phases, three different processes (see Fig. 1) are necessary to explain the observed abundances of the heavy elements; the slow neutron capture process (s process), the rapid neutron capture process (r process), and the proton capture process (p process). The names originate from the fundamental paper by Burbidge, Burbidge, Fowler, and Hoyle (B²FH) [1] on the synthesis of the elements in stars. In the s and the r process the elements are build up by successive neutron captures followed by beta decays. They differ only by the time scales for neutron capture reactions. In the s process the time between two successive neutron captures is of the order of years and the produced unstable nuclei have time to undergo beta decay. Therefore, the s-process path runs along the valley of stability, producing about half of the elements from iron up to $^{209}$Bi where it terminates because of alpha-unbound nuclei. In the r process, which presumably takes place in an explosive environment, neutron capture times are of the order of ms, driving the r process path to the very neutron-rich nuclei. After the explosion, the produced neutron-rich nuclei decay back to the valley of stability by a series of beta decays forming the second half of the element abundances up to uranium and thorium. As can be seen in Fig. 1 there are some nuclei, which are produced by the s or r process exclusively. These nuclei are called s-only and r-only, respectively. Furthermore, Fig. 1 shows that there are some very rare proton-rich nuclei, which can neither be produced by the s nor by the r process. They are attributed to the p process and contribute less than 1% to the overall elemental abundance distribution.

FIGURE 1. Section of the chart of nuclei showing the s-process reaction path (black line). s-only and r-only isotopes are marked with “s” and “r” respectively.
This contribution focuses on the s process. An overview about recent developments in stellar modeling and observational information to constrain these models will be given. Thereafter, neutron capture cross sections important for s-process nucleosynthesis will be discussed.

**OBSERVATIONAL CONSTRAINTS**

The qualitative understanding of the nucleosynthesis processes requires the close collaboration between various fields in physics. Stellar models, which describe stellar evolution and nucleosynthesis occurring in the deep stellar interior, are the starting point. The task of the experimentalists is to provide the nuclear data input needed in the models and in case no experimental information is available theoreticians can help to provide these. Finally the models have to be tested and validated with the information obtained by the observers. There are several observations, which help to constrain stellar models. First, there is the solar abundance distribution [2] and it is clear that every theory about the formation of the elements must explain the solar abundance pattern and all its features. Although, s-, r-, and p-only nuclei help to disentangle the various contributions from the different processes one has to keep in mind that the solar abundance distribution is a mixture of many generations of stars with different evolution times, masses, metallicities, mass loss rates, etc. In contrast, stellar spectroscopy delivers information on single stars and by looking at stellar objects with different age/metallicity valuable information on galactic chemical evolution is obtained [3]. However, in most spectroscopic surveys only elemental but no isotopic abundances are determined. New constraints on s process models came from analyses of presolar grains [4], e.g., of SiC grains, which originate from the expanding envelopes of AGB stars and are captured by meteors, which bring them to earth. These grains of micrometer size contain trace amounts of heavy elements, showing the signature of the s process. They can be analyzed in the laboratory by high precision measurements of isotopic abundance ratios.

**Stellar Model of the s Process**

In order to explain the solar abundance distribution two s-process contributions, the weak and the main component, are necessary. The weak component is responsible for the production of nuclei between iron and yttrium (56<A<90) while the main component accounts for the heavier nuclei up to bismuth (90<A<209). The two components are connected with different stellar sites and physical conditions. In the current picture, the weak s process takes place during core He burning in massive stars (M_⊙ > 8) where for a short time temperatures of 2.2-3.5·10^8 K are reached and neutrons are liberated by the activation of the \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\) reaction. Since the neutron exposure is small the s-process flow cannot overcome the bottleneck at the closed neutron shell N=50 [2,3]. The stellar sites of the main component are the so-called thermally pulsing asymptotic branch (TP-AGB) stars [4]. These evolved Red Giants have burned already all the H and He in the core to carbon and oxygen. The energy generation occurs in the H- and He-burning shells, which are separated by a thin He-rich intershell. Figure 2 shows the time evolution of such a star. During the H-burning phase the intershell becomes more and more enriched in He until the concentration is high enough to ignite He-burning at the bottom of the inter-shell. The He-shell flash spreads out through the full intershell. Due to the heat generation the He-intershell becomes convective and the star expands and cools in the outer layers with the consequence that H-burning is temporarily terminated. The He-shell flash ends after about 200 years when most of the He is consumed; the star contracts again and H-burning is reactivated. These alternate H-and He-burning phases are repeated up to 40 times.

![FIGURE 2. Time evolution of a TP-AGB star. The star generates its energy by alternate H- and He-burning in two thin shells. The s-process nuclei are mainly produced during H-burning when the \(^{13}\text{C}(\alpha,n)^{16}\text{O}\) neutron source is active. A second, weaker neutron exposure takes place during the He-shell flash when for a short time the \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\) reaction becomes operative. Concerning the s process, current models have to assume, that protons are mixed after the thermal pulses from the convective envelope into the He-intershell. This mixing mechanism is not yet fully understood and](image-url)
is subject of current investigations. The protons are then captured by \(^{12}\text{C}\) and \(^{13}\text{C}\) is formed by the reaction sequence \(^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta,\nu)^{13}\text{C}\). This leads to the formation of the so-called \(^{13}\text{C}\) pocket, a thin layer enriched in \(^{13}\text{C}\). After some time, the temperature is high enough to produce neutrons by the \(^{12}\text{C}(\alpha,n)^{16}\text{O}\) reaction and the s process takes place. Since there are not many seed nuclei in this thin shell the neutron/seed ratio is high and the s process operates very efficiently over a long period of time. Later, during the convective He-flash, the freshly synthesized material is mixed and diluted with the other material in the He-intershell and again exposed to neutrons at the end of the pulse when the temperature is high enough to liberate neutrons by the \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\) reaction. The second neutron exposure is rather weak and not sufficient to produce s-isotopes on a grand scale but strong enough to alter the ratios of branch point nuclei. After the He-flash, part of the freshly synthesized material is mixed with the envelope and brought to the surface of the star where it is detectable by spectroscopy. Figure 3 illustrates how well the stellar model of TP-AGB stars reproduces the solar abundance of s-only isotopes [5].

**FIGURE 3.** Comparison of the isotopic abundances calculated by the stellar model for TP-AGB stars relative to the solar abundance distribution. For a perfect model the s-only isotopes (black points) would lie on the dotted line (overproduction factor =1). One can see that isotopes with A<90 are significantly underproduced since only the main component of the s process occurs in TP-AGB stars. An underproduction is also expected for isotopes, which are partly synthesized in the r process (crosses).

**NUCLEAR DATA NEEDS**

The most important nuclear data input for the stellar s-process models are neutron capture cross sections. There are also other ingredients like stellar enhancement factors (SEF) [6] and stellar beta-decay rates [7], which are important but are not discussed in this paper.

Since the neutron energy spectrum in the stellar interior can be described by a Maxwell-Boltzmann distribution at the corresponding thermal energy \(kT\) the experimentalists have to provide the corresponding Maxwellian averaged capture cross sections (MACS). The s process operates at typical thermal energies between \(kT=8\) and \(kT=30\) keV, which means that the cross sections have to be measured in an energy range between 0.1 keV and 500 keV. In the previous section it was shown how well the model predictions agree with observational data. Although the s abundances are in general quantitatively understood there are numerous remaining quests, which still need to be solved. In this section neutron capture cross sections and their relevance for yet open problems in s-process nucleosynthesis will be discussed.

A great number of these quests are related to the branchings in the s-process reaction path. There are about 20 isotopes along the s path, which exhibit comparable neutron capture and beta-decay rates. In these cases the competition between capture and decay leads to a branching of the s-process path as sketched in Fig. 5. Branchings are most important because the resulting abundance pattern carries information on the physical conditions during the s process.

**FIGURE 4.** The s-process reaction path with a branching at isotope A.

The branching probability \(f_\beta\) can be expressed by the beta decay rate \(\lambda_\beta = \ln 2/\tau_{1/2}\) and by the neutron capture rate

\[
\lambda_n = n_n \langle \sigma \rangle v_T
\]

where \(n_n\) denotes the neutron density, and \(v_T\) the mean thermal neutron velocity. Alternatively, \(f_\beta\) can be written in terms of the \(\sigma N\) values

\[
f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n} = \frac{\left(\langle \sigma \rangle N_A\right)}{\left(\langle \sigma \rangle N_A + \lambda_n\right)}.
\]
since most branchings are found in mass regions, where the local approximation $\sigma N_s = \text{const.}$ holds.

This equation can for example be solved for the neutron density $n_n$ and in cases where the beta-decay rate depends on temperature it can also be used to determine the temperature during the $s$ process. The important quantities that need to be known are the $s$-process abundances of the relevant isotopes and the MACSs of the involved stable $s$-only isotopes as well as of the radioactive branch point nuclei (Table 1). For the branch points along the $s$-process path complete experimental information on the neutron capture cross section exists only for a single case, the branch point $^{151}\text{Sm}$. For most other unstable branch point nuclei only theoretically calculated information is available. Capture cross section measurements on these branch point nuclei have high priority since the uncertainties of the physical parameters deduced by the analysis are mostly dominated by the uncertainties of these data.

**TABLE 1.** Status of $s$-process branch points.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Available Information</th>
<th>Uncertainty in % at $kT=30$ keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{63}\text{Ni}$</td>
<td>Only theoretical</td>
<td>19</td>
</tr>
<tr>
<td>$^{79}\text{Se}$</td>
<td>Only theoretical</td>
<td>18</td>
</tr>
<tr>
<td>$^{81}\text{Kr}$</td>
<td>Only theoretical</td>
<td>17</td>
</tr>
<tr>
<td>$^{85}\text{Kr}$</td>
<td>Only theoretical</td>
<td>16</td>
</tr>
<tr>
<td>$^{95}\text{Zr}$</td>
<td>Only theoretical</td>
<td>26</td>
</tr>
<tr>
<td>$^{103}\text{Cs}$</td>
<td>Partial information by activation measurement</td>
<td>9</td>
</tr>
<tr>
<td>$^{147}\text{Nd}$</td>
<td>Only theoretical</td>
<td>17</td>
</tr>
<tr>
<td>$^{147}\text{Pm}$</td>
<td>Partial information by activation measurement</td>
<td>10</td>
</tr>
<tr>
<td>$^{154}\text{Eu}$</td>
<td>Only theoretical</td>
<td>15</td>
</tr>
<tr>
<td>$^{154}\text{Eu}$</td>
<td>Partial information by activation measurement</td>
<td>6</td>
</tr>
<tr>
<td>$^{154}\text{Sm}$</td>
<td>Full information by TOF measurement</td>
<td>5</td>
</tr>
<tr>
<td>$^{170}\text{Tm}$</td>
<td>Only theoretical</td>
<td>18</td>
</tr>
<tr>
<td>$^{170}\text{Tm}$</td>
<td>Only theoretical</td>
<td>30</td>
</tr>
<tr>
<td>$^{170}\text{Ta}$</td>
<td>Only theoretical</td>
<td>32</td>
</tr>
<tr>
<td>$^{170}\text{W}$</td>
<td>Only theoretical</td>
<td>16</td>
</tr>
<tr>
<td>$^{204}\text{TI}$</td>
<td>Only theoretical</td>
<td>18</td>
</tr>
<tr>
<td>$^{204}\text{Pb}$</td>
<td>Only theoretical</td>
<td>18</td>
</tr>
</tbody>
</table>

It was already mentioned, that analyses of presolar grains provide stringent constrains on the $s$-process models [4]. Because these grains are only a few $\mu$m in size and because the abundances of heavy elements are rather low their isotopic abundance components in the grains are difficult to analyze. Lighter elements are more abundant and, therefore, easier to measure but in order to interpret the isotopic ratios reliable neutron capture cross sections are necessary. Fig 5 shows the present uncertainties of the MACSs at $kT=30$ keV. While there are many accurate measurements for heavy nuclei, especially in the rare earth region, the uncertainties are rather large for practically all light nuclei. For some elements like selenium and germanium experimental information is not available at all. For the comprehensive interpretation of the isotopic patterns in presolar SiC grains accurate $(n,\gamma)$ cross sections for the light elements (C,N,O, Ne, Mg, Si, Ca, Ti, noble gases) are mandatory.

The cross sections of light elements are also important to calculate the neutron balance inside the stars. Although their cross sections are small these elements are much more abundant than those in the mass region above Fe. Therefore, light elements constitute potential neutron poisons and may consume neutrons, which are then not available for the $s$ process. Especially important in this respect are the CNO elements and the neon and magnesium isotopes.

**FIGURE 5.** Uncertainties of Maxwellian averaged neutron capture cross sections at a thermal energy of $kT=30$ keV.

The weak $s$-process component is assumed to take place during core helium burning in more massive stars ($15<\text{M}<25$). In general, the models show a significant production in the mass range $70 \leq A \leq 90$. Apart from the key reactions $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ and $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ related to He burning the $(n,\gamma)$ cross sections need substantial improvement for deriving a reliable description of the abundance contributions from massive stars. This is especially important since the local approximation is not valid during the weak $s$ process. Therefore, any change in the cross section for a light isotope, e.g., $^{62}\text{Ni}$ [11], can affect the abundances of all the heavier isotopes up to zirconium. This underlines again that the neutron capture cross sections of the light isotopes in the mass range $A=50-90$ have to be measured with higher accuracy.
COMPOSITION OF SOLAR MATERIAL

The mass region between Fe and the actinides is dominated by abundance contributions from the s and r processes. The s-process abundance component can be described quantitatively on the basis of experimental data and rather advanced stellar models for the He burning phase of stellar evolution. Accordingly, the solar r-process component is defined by the difference,

\[ N_r = N_\odot - N_s \]

as plotted in Figure 6. It turns out that this distribution is fairly robust and exhibits almost no dependence on a particular s-process model [12].

The uncertainties in the s abundances are, however, directly linked to those of the stellar neutron capture rates. Therefore, these quantities are most important whenever the solar abundance is dominated by the s process, i.e., at the neutron magic isotopes around \(^{138}\text{Ba}\) and \(^{208}\text{Pb}\).

The decomposition of the solar abundance distribution plays an important role in characterizing the yet largely unknown site of the r process. In this context the remarkable agreement between the heavy element pattern observed in ultra metal-poor halo stars and the solar r distribution provides fascinating evidence for a robust r process [13]. In Figure 7 the surface composition of the star CS22892-052 – which belongs to a sufficiently old stellar population where no s-process material is to be expected – is compared to the solar r-abundance distribution normalized at the europium, an element of almost pure r-process origin. The fact that this agreement holds only for the elements heavier than barium indicates the existence of at least two different r-process mechanisms. In order to evaluate these differences in more detail, the s-process abundances - and hence the stellar neutron capture rates - need to be further improved in the mass region \(A<120\).

The need for better cross section data for a quantitative discussion of the discrepancies observed in the comparison of Fig. 7 becomes strikingly apparent if one compares the uncertainties in the solar r-abundances and the uncertainties of the spectroscopic data for CS 22892-052 (see Fig. 8).
capture cross section has an error of 7% the resulting r-abundance is uncertain by almost 100%.

**SUMMARY**

In general it is fair to say that the s-process component of the heavy element abundances can be quantitatively reproduced. This provides a unique possibility to obtain rather detailed information on the stellar interior for probing stellar and galactic evolution.

However, any such study has to rely on accurate neutron capture cross sections. Though the necessary accuracy has been locally achieved, further improvements are clearly required in the mass region below $A = 120$ and above $A = 180$. The remaining requests concentrate on $(n,\gamma)$ measurements in the following areas:

- The cross sections of the key s-only isotopes - in particular of those defining the s-process branchings - should be determined with uncertainties of ~1%. This goal has been reached only for half of the 33 s-only nuclei between $^{70}\text{Ge}$ and $^{208}\text{Pb}$.

- Meaningful analyses of the characteristic signatures preserved in presolar grains require accurate cross sections with uncertainties of ~1%. The present status is far from being adequate, especially for the lighter elements, where about 70 isotopes are concerned.

- Nuclei at or near magic neutron numbers $N=50$, 82, and 126 act as bottlenecks for the reaction flow in the main s-process region between Fe and Bi. For the majority of these data the necessary uncertainties of 3% have not been reached.

- The cross sections of abundant light isotopes below Fe, which may constitute crucial neutron poisons for the s-process, need to be improved. Of particular importance are $^{16}\text{O}$, $^{18}\text{O}$, and $^{22}\text{Ne}$.

- Cases where Direct Radiative Capture (DRC) contributes significantly to the astrophysical reaction rate are important for predicting this contribution in neutron-rich nuclei. Interesting examples are $^{14}\text{C}$, $^{16}\text{O}$, $^{88}\text{Sr}$, $^{138}\text{Ba}$, and $^{208}\text{Pb}$.

- Nuclei, which still constitute white spots in the s-process chain or which exhibit very uncertain cross sections, are found in the mass region below Fe, around $A=100$, and near the end of the s-process region.

- Complementary investigations of competing reaction channels are crucial for an improved assessment of the SEFs.

- Last, but not least, enhanced efforts should be directed to measurements on unstable nuclei. In addition to the activation technique, the very high fluxes available at spallation neutron sources appear to be promising options for such studies. Priority should be given to the important branch points $^{79}\text{Se}$, $^{147}\text{Pm}$, $^{154}\text{Eu}$, $^{161}\text{Ho}$, $^{176}\text{Tm}$, $^{171}\text{Tm}$, $^{179}\text{Ta}$, $^{204}\text{TI}$, and $^{205}\text{Pb}$.

**REFERENCES**