The intermediate neutron-capture process in AGB stars

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Abstract. The intermediate neutron-capture process is thought to arise when protons are mixed in a convective helium-burning zone. This can happen during the early Thermally-Pulsing (TP) Asymptotic Giant Branch (AGB) phase of low-mass, low-metallicity stars. After discussing the differences between the s- and i-processes in AGB stars, we highlight some critical \((n,\gamma)\) reactions for i-process nucleosynthesis that may be experimentally constrained by the \(\beta\)-Oslo method. We then compare our s- and i-process nucleosynthesis predictions to the abundances of the Carbon-Enhanced Metal-Poor star HE2258-6358, which shows a composition pattern midway between the s- and r-process.

1 Introduction

Most of the elements heavier than iron were synthesized by neutron-capture processes. In addition to the slow and rapid neutron-capture processes, an intermediate neutron-capture process (i-process) is thought to arise when protons are mixed in a convective helium-burning zone (proton ingestion event or PIE). One possible astrophysical site is the early Thermally-Pulsing (TP) Asymptotic Giant Branch (AGB) phase of low-mass, low-metallicity stars ([1] and references therein). Very few AGB models have consistently followed the possible i-process nucleosynthesis. In this proceedings paper, after discussing the differences between the s- and i-processes in AGB stars, we highlight critical \((n,\gamma)\) rates, which are unknown experimentally, and compare our AGB nucleosynthesis predictions to the Carbon-Enhanced Metal-Poor star HE2258-6358 whose abundance pattern is in-between s and r (CEMP-r/s star).

2 Differences between the s- and the i-process in AGB stars

The Thermally-Pulsing AGB star are evolved low-and intermediate mass stars and the site of a very rich nucleosynthesis [2–5]. Their degenerate carbon-oxygen core is surrounded by an unstable helium-burning shell, surrounded by a hydrogen-burning shell and an extended convective envelope. The two burning shells are separated by the intershell region. The energy is alternatively produced by hydrogen burning (during interpulses) and helium-burning (during thermal pulses).

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2.1 The radiative s-process

After a thermal pulse, the inner boundary of the convective envelope moves inwards (third dredge up). Depending on mixing parameters (e.g., those controlling the overshoot below the envelope), protons from the envelope can be partially mixed in the intershell region, react with $^{12}\text{C}$ via $^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta^+)^{13}\text{C}$ and form the so-called $^{13}\text{C}$-pocket. Neutrons are then released by the reaction $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and the s-process takes place during the interpulse in radiative conditions. The temperature is about 100 MK, the timescale of the order of $10^4$ yr (duration of an interpulse) and the neutron density $\sim 10^8$ cm$^{-3}$. The radiative s-process is usually thought to be the main mechanism in AGB stars to synthesize trans-iron elements, and in particular the heavy (Ba, La, Ce, Pr, Nd) and very heavy (Pb) s-elements.

2.2 The convective s-process

When the H-burning ashes are engulfed in the convective pulse, $^{14}\text{N}$ is quickly converted to $^{22}\text{Ne}$ by $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(e^+,\nu_e)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$. If the temperature at the bottom of the pulse is greater than 300 MK (i.e. for an initial stellar mass $M_{\text{ini}} \gtrsim 3 \, M_\odot$), the $^{22}\text{Ne}(\alpha,n)$ reaction is activated and leads to a short burst of neutron with neutron density of $10^{10} - 10^{14}$ cm$^{-3}$ during typically one year [6]. Due to its convective nature, the s-process in such conditions is not expected to contribute as much as the radiative s-process but can significantly affect the light s-elements (Sr, Y, Zr), as well as the relative abundances around branching points.

2.3 The i-process

It was shown that during a thermal pulse, the entropy barrier at the bottom of the H-burning shell in low metallicities stars can be surmounted by the energy released by the pulse [7, 8].
these conditions, the top of the helium-convective zone reaches the hydrogen-rich layers, so that protons can be engulfed (in a PIE) and mixed down to high temperatures in a convective timescale of typically 1 hr. The protons burn on the fly by $^{12}\text{C}(p,\gamma)^{13}\text{N}$ and do not reach the bottom of the pulse. The $^{13}\text{N}$ isotope beta-decays to $^{13}\text{C}$ in 10 min and $^{13}\text{C}(\alpha,\gamma)^{16}\text{O}$ is activated. At the bottom of the pulse, the temperature is typically 250 MK and the $^{13}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction leads to neutron densities of $10^{15}$ cm$^{-3}$ during $\sim$ 1 day. During the peak neutron emission, the neutron-capture timescale $\tau_n$ is of the order of 1 min. For instance, in the i-process model shown in Fig. 1, $\tau_n$ for the $^{129}\text{Sn}$ isotope is 46 s.

The s- and i-processes use the same neutron source $^{13}\text{C}(\alpha,\gamma)^{16}\text{O}$ but they operate at very different temperatures ($\sim$ 100 vs 250 MK, respectively) and environment (radiative vs convective). Also due to the large amount of nuclear energy released during the proton injection by $^{12}\text{C}(p,\gamma)^{13}\text{N}$, the structure, surface composition and evolution of the AGB star can be substantially impacted [1].

### 3 Nuclear uncertainties

The abundances resulting from i-process nucleosynthesis are affected by nuclear uncertainties. About 70% of the neutron-capture rates involved during i-process nucleosynthesis are not known experimentally. To study the impact of nuclear uncertainties, we calculated the i-process nucleosynthesis during a PIE using three different sets of theoretical $(n,\gamma)$ rates, as detailed in Ref. [9]:

- Model A: the fiducial rates obtained with TALYS reaction code [10].
- Model B: same as model A but considering the photon strength functions from [11], instead of [12] as in model A.
- Model C: same as model A but adding the direct capture mechanism [13].

We chose models B and C out of the ten sets included in [9] since they give the lower and upper limits for the heavy element production. According to these three nuclear models, we identified the most critical and uncertain $(n,\gamma)$ reactions for the nuclei between Ba and Pb located along the i-process path (or nearby) at $N_n \sim 10^{15}$ cm$^{-3}$ (Table 1). This value of the neutron density is reached at the bottom of the thermal pulse of our 1 $M_\odot$, [Fe/H] = $-2.5$ model star. The different nuclear models give rise to differences of typically 0.4 dex in the surface abundance enrichment of the AGB star. The impact is

<table>
<thead>
<tr>
<th>reaction</th>
<th>$\langle\sigma\rangle_B/\langle\sigma\rangle_A$</th>
<th>$\langle\sigma\rangle_C/\langle\sigma\rangle_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{159}\text{Pr}(n,\gamma)$</td>
<td>2.13e+0</td>
<td>1.42e+1</td>
</tr>
<tr>
<td>$^{158}\text{Pm}(n,\gamma)$</td>
<td>5.91e+0</td>
<td>1.53e+1</td>
</tr>
<tr>
<td>$^{159}\text{Sm}(n,\gamma)$</td>
<td>4.61e+0</td>
<td>2.86e+1</td>
</tr>
<tr>
<td>$^{163}\text{Eu}(n,\gamma)$</td>
<td>9.86e-1</td>
<td>1.88e+1</td>
</tr>
<tr>
<td>$^{165}\text{Eu}(n,\gamma)$</td>
<td>1.16e+0</td>
<td>2.83e+1</td>
</tr>
<tr>
<td>$^{161}\text{Gd}(n,\gamma)$</td>
<td>1.95e+0</td>
<td>1.80e+1</td>
</tr>
<tr>
<td>$^{165}\text{Gd}(n,\gamma)$</td>
<td>2.03e+0</td>
<td>1.45e+1</td>
</tr>
<tr>
<td>$^{167}\text{Dy}(n,\gamma)$</td>
<td>2.40e+0</td>
<td>1.01e+1</td>
</tr>
</tbody>
</table>

Table 1. Most uncertain $(n,\gamma)$ reactions (from Ba to Pb) along the i-process path (at a neutron density of $\sim 10^{15}$ cm$^{-3}$), according to the three different nuclear models A, B and C. Reactions are included when at least one of the ratios of the Maxwellian-averaged cross sections from different models (at $T = 250$ MK, given in the table) is higher than 10.
the highest in the $75 \lesssim Z \lesssim 80$ region with differences of up to $\sim 1$ dex (Figure 6 in [9]). An accurate rate determination of these reaction rates is therefore desired to reduce the uncertainties affecting i-process nucleosynthesis in low-metallicity AGB stars. Although the involved isotopes are generally away from the valley of stability, it may be possible to constrain experimentally some of these reactions using the $\beta$–Oslo method [14].

4 The i-process and the CEMP-r/s stars

The CEMP-r/s stars are main-sequence or red giant stars that show abundance patterns midway between the s- and r-processes. Because they are not sufficiently evolved, they could not have enriched their surface by themselves. Instead, one (or more) external stellar source(s) should have polluted their surface. A possibility is that these stars have acquired their heavy element pattern from at least two distinct astrophysical sources that produced the s- and r-processes separately. A difficulty with this scenario is to explain the correlation that seems to exist between Ba (mostly formed by s-process) and Eu (mostly formed by r-process) [6]. An alternative paradigm is that the CEMP-r/s stars acquired their chemical pattern by mass accretion from an AGB companion that experienced the i-process [16]. This scenario is supported by the fact that most CEMP-r/s stars are in binary systems [17].

As shown in Fig. 2, the heavy element abundance pattern of the CEMP-r/s star HE2258-6358 is well reproduced by the yields of an AGB star that experienced i-process nucleosynthesis (red pattern). By contrast, a standard radiative s-process in an AGB cannot account for the high abundances in the Eu region and overestimates Sr, Y and Zr (blue pattern).

Another issue with the radiative s-process models is that the level of enrichment may be too small to explain the CEMP-r/s stars, although it strongly depends on the efficiency of the third dredge-up, which is very uncertain (e.g. section 4 in [5]). When fitting the abundances of a CEMP-r/s star, the dilution factor $f$ is freely varied so as to minimize the $\chi^2$ value. A dilution factor of 0.87, for instance, means that 13 % of the AGB material was mixed with 87 % of the envelope of the accreting star (details can be found in Sect. 6.2 of [1] and in [18]). The dilution factor can also be linked to physical quantities related to the binary
system properties:

\[ f = \frac{M_{\text{env}}}{M_{\text{env}} + M_{\text{acc}}}, \]

where \( M_{\text{env}} \) is the envelope mass of the r/s star before the accretion episode and \( M_{\text{acc}} \) the mass accreted by the r/s star from the AGB companion.

For the s-process AGB model, the dilution factor is \( f = 0.41 \), which gives \( M_{\text{acc}} = 0.54 M_\odot \). Accreting this much mass is likely not realistic and if happening, will possibly boost the evolution of the r/s-star to the white dwarf stage, thereby making it unobservable today. In the case of the i-process AGB model, the dilution factor of \( f = 0.87 \) leads to the more realistic value of \( M_{\text{acc}} = 0.06 M_\odot \). Noticing that \( M_{\text{acc}} = \beta M_{\text{wind}} \) with \( M_{\text{wind}} \) the mass lost by the AGB star during its lifetime (\( \sim 0.5 M_\odot \) in this case), and \( \beta \) the accretion efficiency parameter, we obtain \( \beta \sim 0.1 \), which is compatible with 3D hydrodynamical simulations of wind mass transfer in AGB binary systems [19].

5 Conclusions

We discussed the i-process in low-mass, low-metallicity AGB stars. Although the i-process in AGB shows similarities with the radiative s-process in AGB, the i-process arises at much higher temperatures and in convective conditions. Using three different nuclear models, we extracted 17 critical \((n, \gamma)\) reactions for i-process nucleosynthesis (between Ba and Pb) whose rates are the most uncertain (Table 1). Finally, we have shown the ability of i-process AGB models to explain the CEMP-r/s star HE2258-6358. This suggests that low-mass, low-metallicity AGB stars are a viable site for the i-process.

Acknowledgments

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References