PROCEEDINGS OF SCIENCE

Are there only 30 p nuclei?

I. Dillmann[*]
Physik Department E12, Technische Universität München, D-85748 Garching, Germany
Excellence Cluster Universe, Technische Universität München, D-85748, Garching, Germany
E-mail: `iris.dillmann@ph.tum.de`

Franz Käppeler
Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, D-76021 Karlsruhe, Germany

Thomas Rauscher and F.-K. Thielemann
Departement Physik, Universität Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

Roberto Gallino and Sara Bisterzo
Dipartimento di Fisica Generale, Università di Torino, I-10125 Torino, Italy

We have performed p-process simulations with the most recent stellar (n,γ) cross sections from the "Karlsruhe Astrophysical Database of Nucleosynthesis in Stars" project (version v0.2, http://www.kadonis.org). The simulations were carried out with a parametrized supernova type II shock front model ("γ process") of a 25 solar mass star. The four isotopes ^{113}In, ^{115}Sn, ^{152}Gd, and ^{164}Er were not produced in these simulations, consistent with prior findings. Whereas for ^{152}Gd and ^{164}Er large s-process contributions were found, the origin of the observed solar ^{113}In and ^{115}Sn abundance is still under discussion.

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[*]Speaker.

1. The "*p* processes"

A "*p* process" was postulated to produce 35 stable but rare isotopes between ^{74}Se and ^{196}Hg on the proton-rich side of the valley of stability. Unlike the remaining 99% of the heavy elements beyond iron these isotopes cannot be created by (slow or rapid) neutron captures [1], and their solar and isotopic abundances are 1-2 orders of magnitude lower than the respective *s*- and *r*-process nuclei [2, 3]. However, so far it seems to be impossible to reproduce the solar abundances of all *p* isotopes by one single process. In current understanding several (independently operating) processes seem to contribute.

The largest fraction of *p* isotopes is created in the "γ process" by sequences of photodissociations and β^+ decays [4, 5, 6]. This occurs in explosive O/Ne burning during SNII explosions and reproduces the solar abundances for the bulk of *p* isotopes within a factor of $\approx$3 [6, 7]. The SN shock wave induces temperatures of 2-3 GK in the outer (C, Ne, O) layers, sufficient for triggering the required photodisintegrations. More massive stellar models (M$\geq$20 M$_\odot$) seem to reach the required temperatures for efficient photodisintegration already at the end of hydrostatic O/Ne burning [8]. The decrease in temperature after passage of the shock leads to a freeze-out via neutron captures and mainly β^+ decays, resulting in the typical *p*-process abundance pattern with maxima at ^{92}Mo (N=50) and ^{144}Sm (N=82).

However, the γ process scenario suffers from a strong underproduction of the most abundant *p* isotopes, ^{92,94}Mo and ^{96,98}Ru, due to lack of seed nuclei with $A > 90$. For these missing abundances, alternative processes and sites have been proposed, either using strong neutrino fluxes in the deepest ejected layers of a SNII (νp process [9]), or rapid proton-captures in proton-rich, hot matter accreted on the surface of a neutron star (rp process [10, 11]). A few *p* nuclides may also be produced by neutrino-induced reactions during the γ-process. This "ν process" [12] was additionally introduced because the γ process alone strongly underproduces the odd-odd isotopes ^{138}La and ^{180m}Ta. These two isotopes could be the result of excitation by neutrino scattering on pre-existing *s*-process seed nuclei, depending on the still uncertain underlying nuclear physics.

Modern, self-consistent studies of the γ-process have problems to synthesize *p* nuclei in the regions $A < 124$ and $150 \leq A \leq 165$ [8]. It is not yet clear whether the observed underproductions are only due to a problem with astrophysical models or also with the nuclear physics input, i.e. the reaction rates used. Thus, the reduction of uncertainties in nuclear data is strictly necessary for a consistent understanding of the *p* process. Experimental data can improve the situation in two ways, either by directly replacing predictions with measured cross sections in the relevant energy range or by testing the reliability of predictions at other energies when the relevant energy range is not experimentally accessible. In this context we have carried out *p*-process network calculations with a modified reaction library which uses the most recent experimental and semi-empirical (n,γ) cross sections from the "Karlsruhe Astrophysical Database of Nucleosynthesis in Stars" project, KADoNiS v0.2 [13]. This aims to be a step towards an improved reaction library for the *p* process, containing more experimental data. However, it has to be kept in mind that the largest fraction of the *p*-process network contains proton-rich, unstable isotopes which are not accessible for cross section measurements with present experimental techniques. Hence there is no alternative to employing theoretical predictions for a large number of reactions. Typically, these come from Hauser-Feshbach statistical model calculations [14] performed with the codes NON-

SMOKER [15, 16] or MOST [17].

2. *p*-process network calculations

We studied the *p* process in its manifestation as a γ process. The network calculations were carried out with the program "PPROSIM" [18] and a full reaction library from Basel university [19] which was updated with the most recent version of the "Karlsruhe Astrophysical Database of Nucleosynthesis in Stars" (KADoNiS v0.2) [13]. The abundance evolution was tracked with a parameterized reaction network, based on a model of a supernova type II explosion of a 25 $M_\odot$ star [7]. For a more detailed description of the simulation and parameters, see [18, 20].

One result of these *p*-process simulation was that the nuclides ^{152}Gd and ^{164}Er are not produced. This is consistent with previous work finding large *s*-process contributions to these nuclei [21]. Also, the two odd-*A* isotopes ^{113}In and ^{115}Sn are more destroyed than produced. The latter underproduction problem is known since a long time [6, 7]. The initial seed abundances of ^{113}In and ^{115}Sn are destroyed by the γ process, since the destruction channel is much stronger than the production channel. Thus, it appears as if the nuclides ^{152}Gd, ^{164}Er, ^{113}In, and ^{115}Sn have strong contributions from other processes and it is conceivable that they even may not be assigned to the group of *p* nuclei.

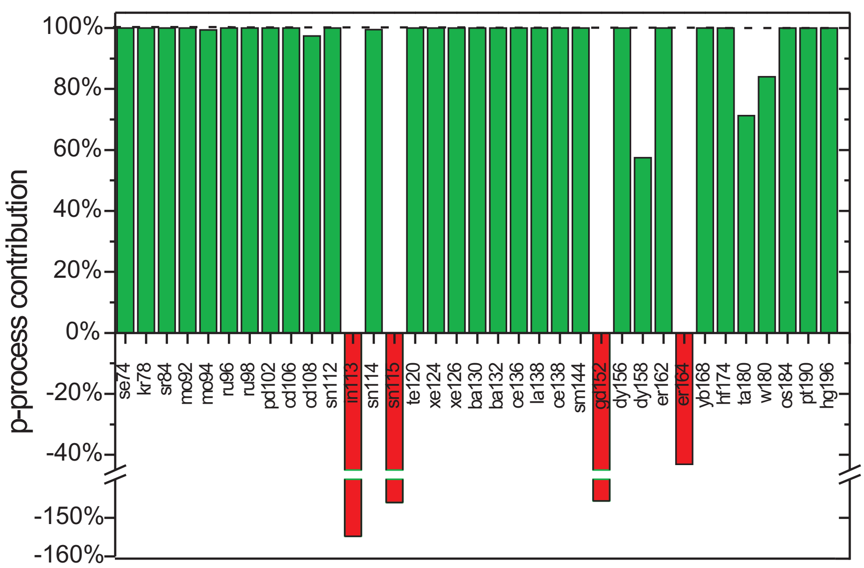

Figure 1: *p*-process contributions of all 35 "*p* nuclei" as deduced from the simulation of a supernova type II explosion of a 25 $M_\odot$ star. ^{152}Gd, ^{164}Er, as well as ^{113}In, and ^{115}Sn are destroyed during the γ process.

3. Where do the solar ^{113}In and ^{115}Sn abundances come from?

Calculations in the Cd-In-Sn region are complicated since many isomeric states have to be considered. Nemeth et al. [22] determined the contributions for ^{113}In, and ^{115}Sn with the (outdated) classical *s*-process approach to be very small (less than 1% for both cases). A recalculation of the main *s*-process contributions in the Cd-In-Sn region with the low mass TP-AGB star model [21] was performed with the recent reaction network "bab8" from Torino university. This network uses the most updated cross sections from KADoNiS v0.2 [13] and yielded *s*-contributions of 0.41% (^{108}Cd), 0.0013% (^{113}In), 0.023% (^{114}Sn), and 3.36% (^{115}Sn).

One solution could be contributions from the *r* process. Although ^{113}Cd and ^{115}In have quasi-stable ground-states, the β-decays of *r*-process progenitor nuclei can proceed via isomeric states: $^{113g}Ag \rightarrow {}^{113m}Cd \rightarrow {}^{113}$In and ^{115g}Cd $\rightarrow {}^{115m}In \rightarrow {}^{115}$Sn. In this way Nemeth [22] could ascribe only part (<16% and 58% for ^{113}In and ^{115}Sn, respectively) of the missing abundances to post-*r*-process β-decay chains, leaving rather large residues for other production mechanisms (83% and 41%). Other recently developed solutions for the *p* process, such as the *rp* process [10, 11] or the νp process [9] can be excluded since their reaction chains do not reach beyond *A*=110. Another alternative explanation discussed in [22] was a *"thermally enhanced β-decay"* by an accelerated decay of the quasi-stable ^{113}Cd and ^{115}In during the *s* process.

In fact, both ground-states show very strong temperature-dependencies [23]. At temperatures of 250 MK (as for He shell flashes) ^{113}Cd ($t_{1/2}$= 7.7×10^{15}y) and ^{115}In ($t_{1/2}$= 4.41×10^{14}y) decay faster by 11 and 9 orders of magnitude, respectively. Recently, the stellar neutron capture cross section to the isomeric state of ^{113}Cd was determined by our group to be $<\sigma>_{30keV}$=13 mb, resulting in a isomeric ratio $\frac{\sigma_m}{\sigma_{m+g}}$ of ≈7%. This value is consistent with the 6.4% assumed by Ward and Beer [24]. Thus, if ^{113}Cd^m ($t_{1/2}$=14.1 y) is also affected by this acceleration of the β-decay, the missing ^{113}In abundance could be ascribed to fast β-decays from this isomeric state.

However, ground, isomeric, and low-lying excited states in ^{113}Cd and ^{115}In are already fully equilibrated at temperatures of the main *s*-process (see Table 1 in [22]). This means that the isomeric states are immediately depopulated by (γ,γ') into the ground state via intermediate states [22, 24, 25], and the question of the possible production mechanism remains still unclear.

4. Conclusions

The interpretation of the nucleosynthesis in the Cd-In-Sn region is complicated due to multiple isomeric branchings. The origin of ^{113}In and ^{115}Sn, originally assigned as "*p* nuclei", is still unclear. Contributions from the *s* process can be excluded, and also the different the *p* process mechanisms (γ-, *rp*-, and νp-processes). The most promising scenario are still post-*r*-process decay chains, although previous calculations could not reproduce the complete missing abundances.

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PoS(NIC X)091