Analysis of the impact of the ^{204}Tl neutron capture cross section on the *s*-process only isotope ^{204}Pb

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Abstract. In the study of the slow (s) process of nucleosynthesis branching nuclei become of particular interest. These nuclei have half-lives of the order of 1-100 years, and in the stellar environment their decay rate can compete with the neutron capture rate, which effectively leads to a split of the *s*-process path. Due to the dependence of the decay and the neutron capture rates on the the physical conditions -temperature and neutron density- of the nucleosynthesis environment, variations in these conditions lead to a change in the abundances of the immediately following nuclei. A very interesting branching point is the *s*-process only ^{204}Tl, which decays to ^{204}Pb. In this work we show how the capture cross section of ^{204}Tl is a key nuclear input which, in addition to being crucial in fixing the ultimate ^{204}Pb *s*-process abundance, makes the latter sensible to the temperature and neutron density of the stellar environment where the *s*-process takes place.

1 Introduction

Approximately half of the solar elemental abundances heavier than iron are produced by the so-called slow (s) process of stellar nucleosynthesis. This process is characterized by successive neutron capture and beta decay reactions, following the path of the valley of nuclear stability. Elements with $A > 90$ are mainly produced by the *main s*-process, which takes place in the Asymptotic Giant Branch (AGB) phase of low mass ($1.5 - 3\ M_{\odot}$), thermally pulsing stars. During the AGB phase, *s*-process happens in two main stages, characterized by different physical conditions. Between two Thermal Pulse (TP) episodes, H is burned radiatively in a shell at the bottom of the convective envelope of the star. In the ashes of the H-burning shell, conditions are such that a ^{13}C pocket forms, and neutrons are released by the ^{13}C(α,n) reaction. When temperature approaches $\sim 0.9 \cdot 10^8$ K (corresponding to a thermal energy of $kT \sim 8$ keV), neutron densities of $\sim 10^7$ cm^{-3} trigger the *s*-process chain. After some 40,000 years, the partially degenerated helium that has accumulated in a thin He intershell finally ignites fusion, leading to a short and intense increase in star luminosity –hence the TP name. During the TP, temperature in the H and He shells can rise up to $\sim 3 \cdot 10^8$ K (corresponding to $kT \sim 26$ keV) and a large convection zone is created. At the bottom of this convective zone the increase in temperature leads to a release of neutrons by the partial activation of the

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^{22}Ne(α,n) reaction. Although these events last for a few years, neutron densities can reach up to $\sim 10^{10}$ cm^{-3}, changing the isotopic patterns around some particular isotopes. An up to date review of the *s*-process, including a more detailed analysis of the stellar scenarios, can be found in [1].

Along the *s*-process path, some unstable nuclei are produced, with half-lives from a few years to thousands of years. At these isotopes the neutron capture reactions may compete with beta-decays. In some cases, the high temperature reached during the TP can change considerably the capture-to-decay ratio. When this occurs, the usual path of the nucleosynthesis process is changed, thus leaving its fingerprint on the abundances of the neighbouring stable nuclei. Hence, by affecting the local isotopic ratios, these branching-point nuclei become probes of the stellar conditions where they are produced. For a quantitative study of the branching nuclei one needs to know both their β-decay half-lives and the neutron capture cross sections. While the former are quite straight-forward to measure, the determination of the cross section is very challenging. This is due to difficulties in producing a sufficiently large amount of sample material with a significant enrichment on the isotope of interest, and also to the background induced in most cases by the decay of the sample material itself during the experiment.

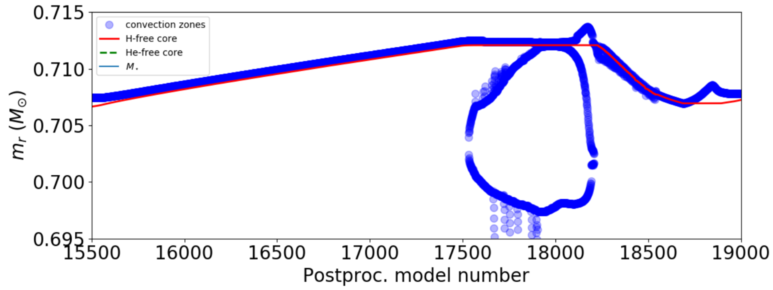
2 The ^{204}Tl branching point

^{204}Tl is a relevant branching point because it crucially determines the abundance of its daughter isotope, ^{204}Pb, and of the radioactive ^{205}Pb. Both isotopes are sheltered from any contribution from the *r*-process, and thus are largely (>90%) produced by the *s*-process [2][3]. ^{205}Pb, with a half-life of 17.3 My, has several cosmochemical applications [4]. In addition it has the potential to be used as a chronometer of the last *s*-process events that contributed to the Solar System composition[5][6]. The strength of a branching point like ^{204}Tl can be quantified by the *branching factor* f_β,

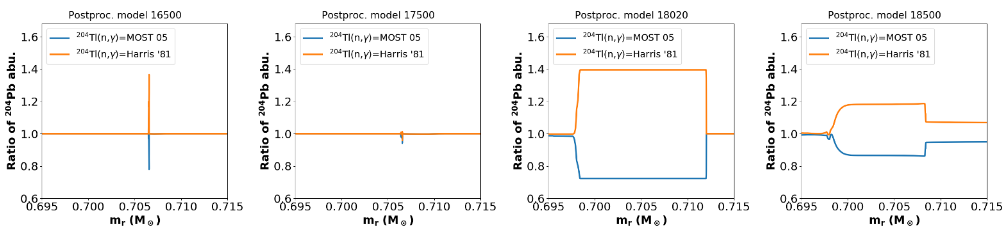
$$f_\beta = \frac{\lambda_\beta}{\lambda_n + \lambda_\beta}, \tag{1}$$

where $\lambda_\beta = \ln(2)/t_{1/2}$ is the beta decay rate, and $\lambda_n = n_n \langle\sigma_A\rangle v_T$ is the neutron capture rate. The quantity $\langle\sigma_A\rangle$ is defined as the capture cross section averaged by the Maxwellian spectrum of the neutrons with thermal velocity v_T, or MACS. For values close to 1 of f_β, most of ^{204}Tl will decay to ^{204}Pb whereas for low f_B values neutron capture will dominate, leading to a decrease in the production of ^{204}Pb. Hence, the abundance of the latter is directly related to the strength of the branching ratio. More interestingly, the branching ratio itself is very sensitive to the physical conditions, that is, temperature and neutron density, that characterize the *s*-process. In the first place, the half-life of the decay of ^{204}Tl is predicted to decrease dramatically as temperature rises [7]. On the other hand, the strength of the neutron sources, especially the ^{22}Ne(α,n) reaction, is also strongly dependent on temperature. However, in order to extract information on the *s*-process physical conditions, it is necessary to know as accurately as possible the nuclear inputs associated to the decay and capture rates, that is, the stellar half-life of ^{204}Tl and the MACS.

In order to understand the *s*-process behaviour at the ^{204}Tl branching, we carried out a sensitivity study using previously available theoretical estimates of the ^{204}Tl cross section. In this first step we could study the dynamics of the ^{204}Tl branching –and the ^{204}Pb resulting abundance– as a function of the ^{204}Tl cross section during the two stages of the *s*-process. For that, we have employed the post-processing nucleosynthesis tools and AGB models provided by the NuGrid Collaboration [8]. The calculation has been performed for a full sequence of a ^{13}C pocket and the following TP events. Concerning the input data for the ^{204}Tl cross section



(a)



(b) (c) (d) (e)

Figure 1: (a) Kippenhahn diagram of the evolution of the structure of the $3M_\odot$, $Z = 0.006$ star model employed in the analysis of the ^{204}Tl branching provided in the text. The bottom panels show the ^{204}Pb abundance profile of the star for the two extreme cases of the ^{204}Tl(n, γ) cross section mentioned in the text, which have been normalized to the Kadonis reference value. The profiles are taken at four specific moments of the star evolution: (b) during the ^{13}C-pocket (cycle 16500), (c) at the end of it and prior to the TP event (cycle 17500), (d) at the time of the highest neutron irradiation in the TP (cycle 18020), and (e) during the Third Dredge-up (cycle 18500).

for the calculations, theoretical values were employed since there was no experimental data before the results reported later in this contribution. As reported in the Kadonis database [9], the theoretical calculations of the cross section differ by more than a factor of three, spanning between 97 mb [10] and 328 mb [11]. This situation is in contrast with the ∼18% relative uncertainty ascribed to this cross section in Kadonis, and most probably indicates a large underestimation of the true uncertainty. We have selected these values as extreme cases in our nucleosynthesis calculations, with the recommended value by Kadonis as the reference value. Results of a nucleosynthesis calculation of a full ^{13}C-pocket and the following TP event are depicted in Figure 1 for a stellar model with 3 $M_\odot$ and a metallicity of $Z = 0.006$, approximately equivalent to half solar. In particular, the plot in figure 1a, known as Kippenhahn diagram, shows the time evolution of the structure of the star; the y-axis values correspond to its radius, expressed by the mass that they enclose (in units of solar masses), and the values of the x-axis correspond to post-processing cycles. Figures 1b to 1e show the stellar profile of the abundance of ^{204}Pb at different times during the ^{13}C-pocket event and the subsequent TP for the different ^{204}Tl cross sections mentioned before, and normalized to the reference value of Kadonis. During the first stages of the ^{13}C-pocket event (Figure 1b), important variations in the ^{204}Pb abundance due to the different cross section are observed. A lower ^{204}Tl(n, γ) cross section leads to a ^{204}Tl buildup and consequently a higher ^{204}Pb abundance. However, the long time span and low neutron exposure during the ^{13}C-pocket event ensures that the equilibrium of nucleosynthesis flow is maintained, and any excess –or defect– of the ^{204}Pb abundance tends to be counterbalanced (Figure 1c). On the other hand, in the TP *s*-process episodes, and despite the predicted reduction in the ^{204}Tl half-life, the neutron density is high enough to lead to values of $f_\beta \sim 0.5$. The high neutron capture rate makes the abundance of ^{204}Pb during these episodes especially sensitive to the capture cross section of ^{204}Tl, as can be seen in Figure 1d. Finally, when the TP is over and the subsequent third dredge-up occurs, the material synthesized during the preceding TP is directly injected into the stellar envelope (Figure 1e). Since the AGB phase is characterized by several ^{13}C leading to a differentiation of the ^{204}Pb abundance as a function of the ^{204}Tl capture cross section. At the end of the AGB phase the cumulative effect of the contributions of the successive ^{13}Cplus TP events (10 for the model employed in this work) leads to a differentiation of around 30%. for the two extreme cases of the ^{204}Tl cross section analyzed here.

The same analysis has been carried out for a star model of the same metallicity, but a lower mass of 1.65 $M_\odot$. The differentiation in the abundance of ^{204}Pb obtained is lower, which we ascribe not only to the possible different number of TP events, but also to the much higher intensity of the thermal pulses –in terms of temperatures and neutron density– in the more massive star. A more detailed analysis of the differentiation of the ^{204}Pb abundance as a function of the stellar model is being currently performed, and is expected to be published in the near future. In any case, the crucial role of the ^{204}Tl neutron capture cross section in determining the abundance of ^{204}Pb has been highlighted. Up to now, a more accurate and precise determination of the *s*-process dominant contribution to the ^{204}Pb abundance has been hampered by the unknown ^{204}Tl neutron capture cross section. The first experimental measurement of the ^{204}Tl(n, γ) cross section was performed at the neutron Time-of-flight facility, n_TOF, at CERN, in the year 2015. Details of the sample production, the experimental methods and the analysis procedure can be found in [12] and in [13]. This experiment has provided the first ever direct measurement of neutron capture cross resonances on ^{204}Tl. The first experimental determination of the MACS, based on these new results, is currently under way. The new MACS will be employed to constrain the *s*-process contribution to the primordial ^{204}Pb abundance. Current nucleosynthesis models predict a deficiency in the *s*-process abundance of ^{204}Pb [14]. If this deficiency is confirmed, it could be an indication of additional processes contributing to the observed abundance of ^{204}Pb, such as fractionation effects [15] and/or contributions from the γ-process [16].

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