Stellar neutron capture on $^{180}Ta^m$. II. Defining the *s*-process contribution to nature's rarest isotope

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The contribution of the slow neutron capture process (*s* process) to the solar $^{180}Ta^m$ abundance has been investigated on the basis of new experimental information. Measured neutron capture cross sections of $^{180}Ta^m$ and the corresponding Maxwellian averaged (n,γ) rates were important for defining the *s* abundance of $^{180}Ta^m$, and the result of a recent photoactivation experiment was providing an estimate of its half-life at the temperatures of the *s*-process site. Following the *s*-process network with stellar evolutionary models from the premain sequence through the asymptotic giant branch phase, it was found that the produced $^{180}Ta^m$ survives the high temperatures during He shell flashes because of the fast convective mixing, which provides an efficient means for transporting freshly synthesized matter into cooler, outer zones. Accordingly, $^{180}Ta^m$ appears to be predominantly of *s*-process origin.

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I. INTRODUCTION

$^{180}Ta^m$ is the rarest stable isotope found in the solar system, representing only 0.012% of natural tantalum (which in turn is the rarest chemical element in nature [1]), and it is the only isotope that is stable in the isomeric state. The attempt to understand how this isotope was produced in the universe has encountered numerous difficulties, triggering a tantalizing series of investigations. In the course of these studies, all common processes for synthesizing the heavy elements, the *s*, *r*, *p*, and eventually the ν process, have been investigated with varying success.

Apart from the difficulties to model the different scenarios, the production of $^{180}Ta^m$ was also questioned by the possibility that it may be easily destroyed in the hot stellar interior by thermally induced depopulation to the short-lived ground state. Since the final $^{180}Ta^m$ abundance reflects a fine balance between nuclear and stellar parameters, it is considered to represent an important test for nucleosynthesis models of the heavy elements.

Among the various nucleosynthesis mechanisms, the *s* process is certainly most suited for a quantitative description of the corresponding $^{180}Ta^m$ yield, since the reaction path follows the valley of β stability and is, therefore, directly accessible to laboratory studies. Also from the astrophysical side the associated He burning scenarios are comparably stable and easier to model than the explosive scenarios responsible for the *r* and *p* processes.

The *s*-process reaction path in the region of $^{180}Ta^m$ is sketched in Fig. 1 and shows that the main reaction flow (thick arrows) is completely bypassing $^{180}Ta^m$, since ^{181}Hf appears to be the first unstable hafnium isotope. Nevertheless, marginal feeding of $^{180}Ta^m$ can be achieved in two weak branchings of the main reaction path. The decay of the 8^- isomeric state in ^{180}Hf, which is weakly populated in neutron capture of ^{179}Hf, has been suggested by Beer and Ward [2] and has been shown by Kellogg and Norman [3] to account for about 20% of the $^{180}Ta^m$ abundance. The population of this ^{180}Hf isomer at the termination of the β-decay chain at $A=180$ was found negligibly small, thus excluding a possible additional *r*-process contribution [4].

While the *s* contribution via the ^{180}Hf decay is fixed by the partial cross section of ^{179}Hf feeding the 8^- isomer, the second branching suggested by Yokoi and Takahashi [5] is mostly determined by the stellar conditions of the *s*-process site. These authors pointed out that the $7/2^-$ state at 214 keV in ^{179}Hf, which is thermally populated in the hot stellar photon bath, is unstable and β-decays to ^{179}Ta. In spite of the

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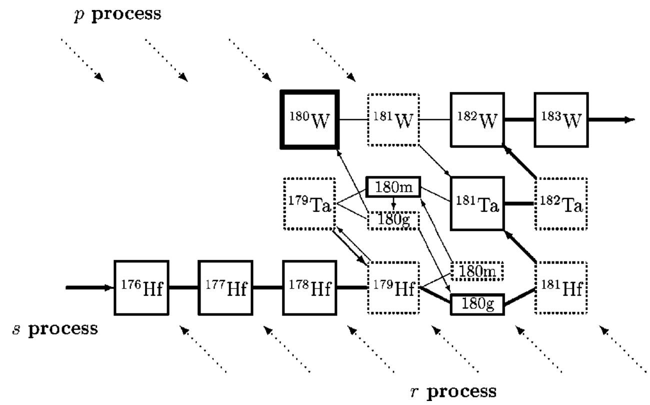

FIG. 1. The reaction path of the *s* process in the Hf/Ta/W region. Though the main reaction path (thick arrows) is bypassing ^{180}Ta^m this rare isotope is produced via minor branchings due to neutron captures on ^{179}Ta and β decays of a weakly populated isomer in ^{180}Hf. The sketch refers to the stellar situation, when ^{179}Hf becomes unstable against β decays from thermally excited states.

back decay to ^{179}Hf, this leads to a small but significant ^{179}Ta abundance that acts as a seed for neutron captures to ^{180}Ta^m. In contrast to the first branching, this route depends strongly on temperature, indicating that the ^{180}Ta^m abundance may be interpreted as a sensitive stellar thermometer [6]. The uncertainty of this second route to ^{180}Ta^m is difficult to quantify but should not be larger than a factor of 2 (see below). Since the second branching opens only at relatively high temperatures, its efficiency for producing ^{180}Ta^m is jeopardized by the possibility that the freshly produced ^{180}Ta^m may be immediately destroyed by thermally induced depopulation to the short-lived ground state [6]. Direct decays being strictly forbidden by selection rules, this depopulation can only be achieved by excitation of an intermediate state with decay channels to the ground state. Many attempts have been made to locate the position of the lowest intermediate state because this determines the fate of ^{180}Ta^m: Only if this state appears above or near 1 MeV excitation energy, ^{180}Ta^m may well survive at typical *s*-process temperatures.

A variety of photoactivation experiments have been performed, either by exposing natural Ta to photon fields of bremsstrahlung facilities [7–10] and strong γ-ray sources [6,11] or by using Coulomb excitation techniques [12,13]. However, these efforts were hampered by the use of natural Ta samples, resulting in limitations of the experimental sensitivity that did not allow one to identify any mediating state below an excitation energy of 1.5 MeV. Experimental data were also missing for the neutron capture rates that determine the neutron induced destruction and production of ^{180}Ta^m in the *s* process. The available theoretical cross sections differed by factors of 2–3 [6,14,15].

In an attempt to improve the nuclear physics part of this pending situation a Munich-Stuttgart-Darmstadt-Karlsruhe collaboration shared the loan of the world supply of enriched ^{180}Ta^m. This sample consisted of 150 mg tantalum oxide powder with a ^{180}Ta^m content of only 5.5%. Nevertheless, it allowed to improve the sensitivity of previous photoactivation experiments by a factor of 5000, resulting in the discovery of several new mediating states [16,17]. The same sample could afterwards be used for the measurement of the neutron capture cross section in the energy range from 10 to 100 keV described in Ref. [18] and in the accompanying Paper I [19].

The results of both experiments bear important consequences for the origin of ^{180}Ta^m and for testing current *s*-process models. Since the schematic classical approach [20] turned out to fail in describing the *s* abundances near magic neutron numbers and in certain branchings [21], it became obvious that this heuristic model is particularly unfit to account for the weak and delicate branchings to ^{180}Ta^m: While the production via the ^{180}Hf^m isomer is not affected by the stellar environment, the second branching depends strongly on temperature because the population of the β-unstable excited states in ^{179}Hf is determined by thermally induced transitions. The improved photoactivation experiment [16,17] showed that the half-life of ^{180}Ta^m is reduced to less than 10 yr for temperatures in excess of $T_8=2$ (T_8=temperature in units of 10^8 K). Nevertheless, ^{180}Ta^m could—in principle—be produced in spite of the unfavorable physical conditions characteristic for the classical approach, i.e., temperatures of $T_8=2.5\pm0.4$ and a duration of 10^4 yr, because ^{180}Ta^m is sufficiently populated in thermal equilibrium [22]. In order for ^{180}Ta^m to survive, however, the abrupt freeze-out of temperature and neutron density assumed in the classical approach appears to be not realistic.

For the more complex stellar *s*-process model, however, the fate of ^{180}Ta^m is completely different. It is currently accepted that the main *s*-process component in the solar system between $A=90$ and 200 is produced during recurrent thermal instabilities during the asymptotic giant branch (AGB) phase in the evolution of $(1.5–3)M_\odot$ mass stars [23–25]. In this scenario, about 95% of the neutron irradiation occurs under radiative conditions during the interpulse phase between thermal instabilities via the ^{13}C$(\alpha,n)^{16}$O reaction at comparably low temperatures of $T_8=1$, when ^{179}Hf and ^{180}Ta^m are both stable. Accordingly, only a minor fraction of ^{180}Ta^m is produced via the decay of ^{180}Hf^m.

During thermal instabilities, however, temperatures of $T_8=2.5–2.8$ are reached for a few years, resulting in a second neutron burst due to the activation of the ^{22}Ne$(\alpha,n)^{25}$Mg reaction. At these higher temperatures, ^{179}Hf becomes unstable, thus opening the neutron capture sequence from ^{179}Ta to ^{180}Ta^m. Since the prolific energy production in these He shell flashes creates a convective zone with turnover times of less than a week [26], freshly produced ^{180}Ta^m is effectively mixed into cooler regions where it survives and from where it is eventually mixed into the stellar envelope.

Calculations using theoretically calculated Ta cross sections and neglecting a possible thermal destruction of ^{180}Ta^m find that about 50% of the solar ^{180}Ta^m abundance can be accounted for by this stellar model [21]. Obviously, any attempt for a more realistic and quantitative description of the *s*-process origin of this isotope has to consider the important thermal effect on the lifetime of ^{180}Ta^m and must be based on a reliable experimental value for the stellar (n,γ) cross section. This improved nuclear physics input is mandatory for solving this long-standing astrophysical puzzle and for interpreting the ^{180}Ta^m abundance as a constraint for the temperature profile and the convective turnover time scale during He shell flashes on the AGB.

Apart from the negligible *r*-process yields mentioned before, the *p* and/or ν process may have contributed to the production of $^{180}Ta^m$ as well. Since both processes are related to supernovae, thermal depopulation is of minor importance in these cases due the short time scale of the explosion. The *p* process is related to the explosive Ne-O burning phase where temperatures of $T_9=2-3$ are reached. The high energy part of the thermal photon distribution gives rise to successive (γ,n) reactions, driving the reaction path to the proton-rich side by about 5 mass units until the rapidly increasing neutron separation energies favor the competing (γ,p) and (γ,α) channels.

Hence, the *p*-process reaction network remains relatively close to stability. At freeze-out, the primary reaction products decay by β^+ and electron capture transitions and account for the rare proton-rich species.

Though the *p* process contributes an almost negligible fraction of the heavy element abundances and though $^{180}Ta^m$ is shielded from the main *p*-process yields by its stable isobar ^{180}W, a small but significant $^{180}Ta^m$ abundance may result from direct (γ,n) reactions on the abundant ^{181}Ta. Studies of this scenario led to somewhat contradictory results. While Rayet *et al.* [27] found that $^{180}Ta^m$ is depleted under the conditions of explosive Ne/O burning, a significant overproduction of $^{180}Ta^m$ was calculated with models describing the *p* process in SN1987A [28] and in type II supernovae in general [29].

The ν process suggested by Woosley *et al.* [30] considers that inelastic neutrino scattering and subsequent neutron evaporation may affect the abundance pattern when the intense neutrino flux of a supernova explosion interacts with the outer layers. Though first results indicated that this mechanism may fully account for the origin of $^{180}Ta^m$, a more comprehensive analysis of the nuclear reaction aspects, e.g., by considering the relative population of short-lived ground state and quasistable isomer, showed that only a small fraction could be produced in this way [17].

II. *s*-PROCESS ANALYSES

A. The nuclear physics

The Maxwellian averaged cross sections of $^{180}Ta^m$ determined in Paper I represent the most crucial input for the following analyses (see also Refs. [18,31]). These data are complemented by stellar (n,γ) rates adopted from Ref. [32]. The required β-decay rates are from Takahashi and Yokoi [33], and the temperature-dependent half-life of $^{180}Ta^m$ is treated according to the results of Belic *et al.* [16,17].

B. Classical approach

The phenomenological or classical picture of the *s* process [34,35] provided an appealing analytic solution based on the assumption of a steady *s* process with constant temperature and neutron density. By assuming an exponential distribution of neutron exposures the set of differential equations describing the neutron capture chain could be solved analytically [36], yielding a simple expression for the product of *s* abundance and stellar cross section, which characterizes the unbranched reaction flow in the mass region $90<A<209$ of the so-called *main s*-process component:

$$\sigma^i N_s^i = \frac{G N_\odot^{56}}{\tau_0} \prod_{j=56}^{i} [1 + (\sigma^j \tau_0)^{-1}]^{-1}.$$

In this way, the solar system $\langle\sigma\rangle N_s$ curve could be successfully reproduced with the fit of only two parameters, the fraction G of the solar iron abundance $N_\odot^{56}$ required as a seed, and the mean neutron exposure τ_0 [37]. The assumption, that the neutron exposure follows an exponential distribution appeared justified since it was shown to result as the natural consequence of repeated He-shell flashes during the AGB phase due to the partial overlap of subsequent thermal pulses [38].

The model was also modified to account for branchings in the neutron capture path [39]. Such branchings occur at unstable nuclei that exhibit comparable neutron capture and β-decay rates. Apart from the respective stellar (n,γ) rates, the branchings are described by two parameters, a constant neutron density n_n and the respective β-decay rate. Therefore, the resulting abundance patterns are determined by the stellar neutron flux $n_n \times v_T$ and/or by the effective stellar half-lives. Since the latter are known to depend on temperature T and electron density n_e in many cases, branching analyses are important for constraining these main parameters of the *s*-process site [20,33].

With respect to the origin of $^{180}Ta^m$, increasingly refined attempts were made using information derived from analyses of several other branchings [21,40,41] for a quantitative description of the flow pattern of Fig. 1 and, hence, for the *s*-process abundances of the $A=180$ isobars. At first, these attempts seemed to be superseded by the result of the Stuttgart photoactivation experiment [16], which yields a $^{180}Ta^m$ half-life of less than 1 day in the temperature range obtained with the classical model, i.e., between thermal energies of $kT=28$ and 33 keV [21,42]. Nevertheless, Loewe [22] showed in a detailed study of the Hf-Ta-W branchings that considerable amounts of $^{180}Ta^m$ could, actually, be explained by the classical model since a sufficient population probability of $^{180}Ta^m$ is always maintained by thermally induced transitions.

Over the past years, there was, however, increasing evidence that the classical approach failed to provide a consistent description of the investigated branchings [21,40,41,43], obviously because the time dependence of neutron density and temperature at freeze-out was completely neglected. This led to an overestimation of the *s*-process temperature, resulting in an enhancement of the β-decay branch from ^{179}Hf to ^{179}Ta [33] and consequently not only to a high $^{180}Ta^m$ abundance but also to unacceptably high ^{180}W yields.

If the classical model was found to reproduce the $^{180}Ta^m$ abundance, the concomitant *s*-process contribution to ^{180}W [5,6,21] was always much too high to comply either with a smooth *p*-process pattern or with recently calculated *p*-process yields, which are reported to range between 50% [28] and 100% [29,44,45]. If these yields are considered as well, the resulting *s*-process contribution to solar ^{180}W

should not exceed about 30%, a limit very hard to reconcile with the reproduction of the $^{180}Ta^m$ abundance by the classical *s* process.

This dilemma remains if the temperature would be constrained to keep the *s* contribution to ^{180}W below 30%. In this case the classical model would require an electron density of $n_e^{26} > 10$ (in units of 10^{26} cm^{-3}), in contradiction to the allowed range $4 < n_e^{26} < 10$ obtained from the Dy-Ho-Er region [21].

C. Stellar *s*-process scenarios for the production of $^{180}Ta^m$

Detailed stellar model calculations have shown that substantial amounts of $^{180}Ta^m$ can be produced in low mass, thermally pulsing stars on the asymptotic giant branch (TP-AGB stars) [16,21,31]. In agreement with observations, He shell burning in such stars with masses between $1.5M_\odot$ and $3M_\odot$ accounts for the main *s*-process component [20,26,46]. The necessary neutron supply results from the interplay of the dominant $^{13}C(\alpha,n)^{16}O$ reaction and a comparably weak contribution from the $^{22}Ne(\alpha,n)^{25}Mg$ reaction.

The spectra of TP-AGB stars show an excess of *s*-process elements but do not exhibit the Mg excess expected if $^{22}Ne(\alpha,n)^{25}Mg$ were the main source of neutrons [47]. Therefore, most neutrons are assumed to originate from a thin, ^{13}C enriched layer of about $10^{-3}M_\odot$ in mass and containing $(2\times10^{-6})M_\odot$ of ^{13}C [25]. This ^{13}C *pocket* results from the injection of a small amount of protons $(\sim10^{-6}M_\odot)$ into the He shell at the epoch of the third dredge up. After a few hundred years, the He shell heats up and these protons are captured by the abundant ^{12}C in the reaction sequence $^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C$.

Since attempts for modeling the formation of the ^{13}C pocket on the basis of a fully hydrodynamical treatment are yet not quantitative enough [48,49], the parametrized prescription of the convective region outlined in Ref. [25] has been adopted. Though this approximation may be too schematic in some respects, it provides a consistent description of the *s*-process abundance pattern [21,50,51].

All ^{13}C nuclei in the pocket are consumed under radiative conditions during the interpulse time of a few 10^4 years, thus providing about 95% of the *s*-process neutron exposure at comparably low temperatures ($kT \simeq 8$ keV) and neutron densities ($n_n \leqslant 10^7$ cm^{-3}). When this *s*-process enriched layer is engulfed into the next convective instability, a sufficiently high temperature is reached at the bottom of the He burning zone ($T_8 \approx 3$) to marginally activate the ^{22}Ne source. This short burst of ≈ 5 yr reaches peak neutron densities of $n_n \leqslant 10^{10}$cm^{-3}. Though this second burst represents only a few percent of the total neutron exposure, it is crucial for defining the observed abundance pattern of several *s*-process branchings. In particular, the time dependence of this second burst determines the freeze-out of the final abundances.

In this scenario, the production of $^{180}Ta^m$ becomes rather complex because of the two phases of *s*-process nucleosynthesis, which are characterized by significantly different physical conditions. At the low temperatures during the interpulse period, when neutrons are produced by the $^{13}C(\alpha,n)^{16}O$ reaction, ^{179}Hf remains stable. Hence, the ^{179}Hf branching is closed and $^{180}Ta^m$ is depleted to the level defined by the branching at $^{180}Hf^m$. The final neutron burst from the $^{22}Ne(\alpha,n)^{25}Mg$ source occurs subsequently during a relatively short period ($\Delta t < 10$ yr) at a peak temperature of $T_8 \approx 3$ reached in the bottom layers of the convective pulse during the maximum extension of the thermal instability. The enormous energy produced by the 3α reaction causes large temperature and density gradients in the convective zone ($0.2 \leqslant T_8 \leqslant 3$ and $10 \leqslant \rho \leqslant 10^4$g cm^{-3}, respectively).

This strong gradient implies that—according to the result of the photoactivation measurement [16]—the effective lifetime of $^{180}Ta^m$ varies by more than 15 orders of magnitude between the top and the bottom of the convective zone. It is evident that high temperatures prevail only in a relatively small zone near the bottom of the convective He shell, where the *s* process takes place. It is only there that $^{180}Ta^m$ can be efficiently destroyed via thermally induced transitions to the short-lived ground state. As long as the turnover time is short compared with the actual half-life, most of the produced $^{180}Ta^m$ resides in the outer and cooler zones of the convective region. This fraction survives unaltered until it is mixed into the stellar envelope by the subsequent third dredge-up episode.

D. Convection in He shell flashes

So far, this important question has not been addressed in sufficient detail [26]. For a more reliable answer, extensive calculations were performed using the stellar evolution code FRANEC [24,52] for describing the appropriate physical conditions in the convective pulse.

These calculations describe the evolution of the internal structure of AGB stars with initial masses ranging between $1M_\odot$ and $3M_\odot$. The most recent updates of the microphysics (e.g., opacity, equation of state) have been included. In particular, a time-dependent mixing algorithm is used to treat mixing episodes characterized by short time scales, as those generated by thermal pulses along the AGB. Convective velocities are evaluated by means of the mixing length theory.

The corresponding results are displayed in Fig. 2, where the upper panel exhibits the temperature in the convective shell of a typical thermal pulse in a $3M_\odot$ star of solar composition. This figure refers to the epoch of maximum power production in the He shell flash. The calculated convective velocities presented in the lower panel show that the convective turnover time is somewhat less than 1 h. After maximum, the temperature in the convective zone decreases, while the convective turnover time increases. When the bottom temperature drops down to 2.5×10^8 K, the mixing time scale is still less than few hours.

Hence, the crucial transport time from the hot synthesis zone to cooler layers is found to be always much shorter than the enhanced decay rate of $^{180}Ta^m$ suggested in Ref. [16] (which approaches the 8.15 h half-life of the ground state only at even higher temperatures of $T_8 \geqslant 3.3$). Therefore, the thermal coupling of isomer and ground state via the intermediate state at $E_x = 1.0$ MeV reported in Refs. [16,17] has practically no consequence for the *s*-process production of $^{180}Ta^m$ in thermally pulsing, low-mass AGB stars.

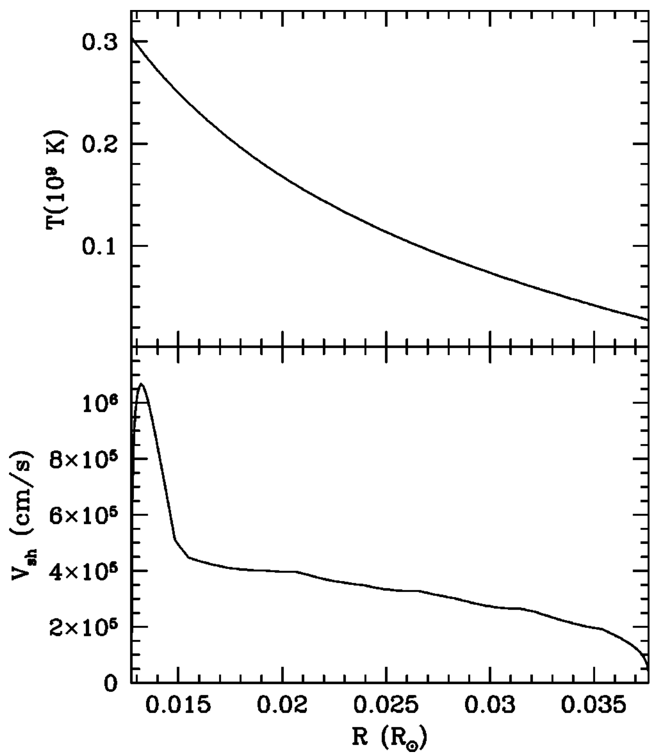

FIG. 2. The temperature in the convective shell of a typical thermal pulse in a $3M_\odot$ star of solar composition. The corresponding calculated convective velocities in the lower panel show that the convective turnover time is a few hours only. The scale on the abscissa starts at the bottom of the convective shell.

E. ^{180}Ta^m production in TP-AGB stars

The production and survival of ^{180}Ta^m was followed in detail during the He shell flashes of the AGB phase by dividing the convective zone into 25 meshes of equal extension, where the physical conditions could be considered constant per each time step. The time behavior of each mesh was obtained from the stellar evolution model, which accounts also for the respective changes from pulse to pulse along the AGB evolution [25]. The nucleosynthesis was followed in each mesh separately, and the resulting abundances were periodically mixed according to the typical turnover times of the convective zone. The effective half-life of ^{180}Ta^m was adopted from Refs. [16,17] since the inverse population of the isomer by thermal excitation of the ground state was shown to contribute only at temperatures above $kT \approx 27$ keV [22], i.e., above the temperature range of the stellar model considered.

As expected from the short turnover time, these calculations showed that—in contrast to the half-life problem—the experimental (n,γ) rate of ^{180}Ta^m has a much deeper impact on the final abundance. Since the *s*-process yields in the mass region around $A=180$ are to good approximation inversely proportional to the respective Maxwellian-averaged cross sections, the smaller experimental rate implies a corresponding increase of the ^{180}Ta^m production as compared with the previous study based on theoretical cross sections [21].

The contribution to the ^{180}Ta^m abundance resulting from the neutron burst by the ^{22}Ne source averaged over a typical

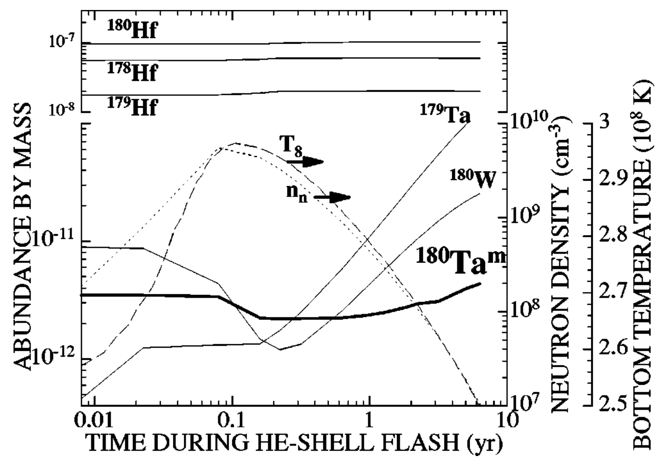

FIG. 3. Time evolution of abundances (as mass fractions) during the ^{22}Ne$(\alpha,n)^{25}$Mg neutron burst for a typical advanced pulse of the standard model star [$2M_\odot, Z=(1/2)Z_\odot$, solid lines]. Compared to the evolution of the neighboring Hf isotopes, which are in reaction equilibrium, the variations of ^{179}Ta, ^{180}Ta^m, and ^{180}W are due to the branching at ^{179}Hf. Since the ^{180}Ta^m yields for stars of different mass and metallicity are very similar, the average over Galactic chemical evolution is not expected to differ significantly from these results (see text). The dashed line corresponds to the bottom temperature of the convective region (right scale), which reflects also the behavior of the neutron density.

He shell flash is illustrated in Fig. 3. While the neighboring Hf isotopes are in reaction equilibrium and remain almost unchanged, the branching at ^{179}Hf causes the ^{179}Ta and ^{180}W abundances to follow the temperature and neutron density profiles (with a certain delay due to the β-decay half-life of the 214 keV level in ^{179}Hf). As a consequence of the complex interplay between temperature, neutron density, and β decay, this behavior is less evident for the ^{180}Ta^m abundance. Nevertheless, the initial ^{180}Ta^m abundance, which results from the neutron exposure by the ^{13}C source during the interpulse phase and from previous He shell flash episodes, increases during the flash from 57% to 80% as shown in Fig. 3.

Starting from the situation illustrated in Fig. 3 the *s*-process production of ^{180}Ta^m has been studied for a range of stellar masses $(1.5 \leqslant M/M_\odot \leqslant 3)$ and metallicities $(0.01 \leqslant Z/Z_\odot \leqslant 1)$. It turned out that the ^{180}Ta^m yields are fairly independent of stellar mass and metallicity, in particular for stars with $Z \approx 0.01$, which are known to contribute most efficiently to the solar *s* abundances between Ba and Pb [53,54]. Since all investigated models predicted ^{180}Ta^m abundances between 80% and 86% of the solar value, this range determines the average over galactic chemical evolution.

It is important to note that the ^{180}W problem is completely avoided in this model. Because the branching at ^{179}Hf is closed at the low temperatures during the interpulse period when the ^{13}C source is operating, it is completely bypassed by 95% of the total neutron exposure. Accordingly, only $\approx$5% of solar ^{180}W are produced in AGB stars on average.

The remaining uncertainties for the production of ^{180}Ta^m in thermally pulsing low-mass AGB stars originate essentially from the temperature-dependent β-decay rate of ^{179}Hf and from the theoretically calculated (n,γ) cross section of ^{179}Ta. Reducing the β-decay rate of ^{179}Hf by a generous factor of 2 translates into a reduction of the final ^{180}Ta^m abundance of 26%, which means that the ^{179}Hf branching would be practically negligible. On the other hand, doubling the rate yields already a strong overproduction. The 32% uncertainty quoted for the recommended cross section of ^{179}Ta [32] was found to cause a 25% change of the final ^{180}Ta^m abundance. Clearly, an experimental access to both quantities remains a challenge for an improved description of the *s*-process nucleosynthesis of ^{180}Ta^m.

Nevertheless, already the present results strongly suggest a dominant *s*-process origin of ^{180}Ta^m related to He shell burning in low-mass AGB stars.

III. OTHER PRODUCTION MECHANISMS

Alternative production mechanisms for ^{180}Ta^m have been discussed for scenarios of explosive nucleosynthesis. In the ν process, ^{180}Ta^m can be formed from ^{181}Ta in the strong neutrino wind from core collapse supernovae [30]. The original claim that all ^{180}Ta^m can be accounted for by excitation of ^{181}Ta above the neutron threshold due to inelastic neutrino scattering was significantly reduced after the involved reaction channels were considered in detail [17]. The remaining contribution is less than 20% and is compatible with the *s*-process predictions. However, this result is still affected by the highly uncertain ν temperatures of this scenario. The second alternative is related to the *p* process, which is expected to occur in supernova envelopes, when the outgoing shock front is heating the Ne-O layer beyond the ignition temperature for explosive burning. Complete production of ^{180}Ta^m has been claimed [29] from (γ,n) reactions on ^{181}Ta, but significantly smaller yields were found when all partial cross sections were considered consistently [45]. The difficulty with the *p*-process yields is the fairly large uncertainties of the involved reaction rates of a factor of 3 on average.

IV. SUMMARY

Based on first experimental results for the stellar neutron capture rate, the *s*-process origin of ^{180}Ta^m has been studied by using the classical approach as well as the stellar scenario related to He-shell burning in thermally pulsing, low-mass AGB stars.

Attempts to model the abundance of ^{180}Ta^m in the *s* process must properly account for the complex interplay of temperature, density, and neutron flux on the various reaction chains. Therefore, the phenomenological or classical approach, which neglects the important freeze-out effects of the stellar environment by assuming constant temperature and neutron flux, is not sufficient for this purpose. This picture is also problematic because it leads to unacceptably high *s* contributions to ^{180}W, which is known to be of almost pure *p* origin.

These difficulties are avoided if the *s*-process yield of ^{180}Ta^m is studied by means of a stellar model for He shell burning in thermally pulsing low-mass AGB stars. By due consideration of the physical environment during He shell flashes, including the convective turnover time and the related temperature gradient, the abundance evolution of ^{180}Ta^m was followed on a fine grid throughout the duration of the He shell flashes. In this way, it turned out that typically 80% of the observed ^{180}Ta^m can be produced by this scenario. While the final ^{180}Ta^m abundance is still somewhat dependent on the theoretical ^{179}Ta cross section, the calculated low *s* abundance of ^{180}W is well compatible with the dominant *p*-process origin of this isotope.

With respect to alternative production sites of ^{180}Ta^m, we find recently reduced yield from the ν process related to explosive nucleosynthesis in core collapse supernovae as well as the small *r*-process component to be in fair agreement with the *s*-process prediction. With respect to the full reproduction of the ^{180}Ta^m abundance in the *p* process, there are discrepant claims from recent calculations, which need to be investigated further [29,45]. Given the intriguing sensitivity of the ^{180}Ta^m abundance with respect to the physical conditions of the various scenarios, the origin of this isotope continues to challenge the respective models, now that the nuclear physics part [besides the ^{179}Ta$(n,\gamma)^{180}$Ta^m rate] seems to be settled satisfactorily.

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