

Survival of nature's rarest isotope  $^{180}\text{Ta}$  under stellar conditionsP. Mohr,<sup>1,\*</sup> F. Käppeler,<sup>2</sup> and R. Gallino<sup>3</sup><sup>1</sup>Diakoniekrankenhaus Schwäbisch Hall, D-74523 Schwäbisch Hall, Germany<sup>2</sup>Forschungszentrum Karlsruhe, Institut für Kernphysik, P.O. Box 3640, D-76021 Karlsruhe, Germany<sup>3</sup>Dipartimento di Fisica Generale, Università di Torino, Via P. Giuria 1, I-10125 Torino, Italy

(Received 11 May 2006; published 8 January 2007)

The nucleosynthesis of nature's rarest isotope  $^{180}\text{Ta}$  depends sensitively on the temperature of the astrophysical environment because of depopulation of the long-living isomeric state via intermediate states to the short-living ground state by thermal photons. Reaction rates for this transition have been measured in the laboratory. These ground state rates underestimate the stellar rates dramatically because under stellar conditions intermediate states are mainly populated by excitations from thermally excited states in  $^{180\text{m}}\text{Ta}$ . Full thermalization of  $^{180}\text{Ta}$  is already achieved for typical s-process temperatures around  $kT = 25$  keV. Consequently, for the survival of  $^{180}\text{Ta}$  in the s-process fast convective mixing is required which has to transport freshly synthesized  $^{180}\text{Ta}$  to cooler regions. In supernova explosions  $^{180}\text{Ta}$  is synthesized by photon- or neutrino-induced reactions at temperatures above  $T_9 = 1$  in thermal equilibrium; independent of the production mechanism, freeze-out from thermal equilibrium occurs at  $kT \approx 40$  keV, and only  $35 \pm 4\%$  of the synthesized  $^{180}\text{Ta}$  survive in the isomeric state.

DOI: 10.1103/PhysRevC.75.012802

PACS number(s): 25.20.Dc, 26.20.+f, 26.30.+k, 27.70.+q

The nucleosynthesis of nature's rarest isotope and only naturally occurring isomer  $^{180}\text{Ta}$  has been studied intensively over the last years. In a simplified view, there seems to be no production path to  $^{180}\text{Ta}$  in the slow and rapid neutron capture processes (s-process, r-process), and it has been pointed out that  $^{180}\text{Ta}$  is a natural product of the p-process without neutrino interactions [1–3] or with neutrino interactions [4,5].  $^{181}\text{Ta}(\gamma, n)$   $^{180}\text{Ta}$  photoproduction cross sections have been measured in Refs. [2,6]. But the s-process may also contribute to the production of  $^{180}\text{Ta}$  via  $\beta$ -decay of thermally excited  $^{179}\text{Hf}$  to  $^{179}\text{Ta}$  and subsequent  $^{179}\text{Ta}(n, \gamma)$   $^{180}\text{Ta}$  neutron capture [7], or via  $^{179}\text{Hf}(n, \gamma)$   $^{180\text{m}}\text{Hf}(\beta^-)$   $^{180}\text{Ta}$  [8]. Even the r-process might produce  $^{180}\text{Ta}$  via the  $^{180\text{m}}\text{Hf}(\beta^-)$   $^{180}\text{Ta}$  decay [8,9]; however, the isomer decay branches in  $A = 180$  nuclei are too small to explain the stellar abundance of  $^{180}\text{Ta}$  [10–13]. The astrophysical sites for the nucleosynthesis of  $^{180}\text{Ta}$  are still uncertain. A combination of the above processes seems to be most likely.

The s-process production of  $^{180}\text{Ta}$  depends on the neutron capture cross sections of  $^{179}\text{Ta}$  [7] and  $^{180}\text{Ta}$  [14–16] and the photodestruction of the  $9^-$  isomeric state in  $^{180}\text{Ta}$  which has been studied using real photons from bremsstrahlung and from radioactive sources and virtual photons in Coulomb excitation experiments [17–30]. It is the scope of the present paper to improve the analysis of the above experimental data and to calculate the effective half-life of  $^{180}\text{Ta}$  under s-process conditions and the survival probability of  $^{180}\text{Ta}$  in supernova explosions after production by photon- and neutrino-induced reactions. The results are essential to explain the extremely low abundances of  $^{180}\text{Ta}$  (isotopic:  $0.01201 \pm 0.00008\%$ ; solar:  $2.49 \times 10^{-6}$  relative to Si =  $10^6$ ) [31].

The effective half-life  $t_{1/2}^{\text{eff}}$  of  $^{180}\text{Ta}$  depends sensitively on temperature because the  $1^+$  ground state of  $^{180}\text{Ta}$  has a short half-life of only  $t_{1/2, \text{g.s.}} = 8.154$  h, whereas the  $9^-$  isomeric

state ( $J = 9$  confirmed very recently in Ref. [32]) at  $E_x = 77.1$  keV has a very long half-life  $t_{1/2, \text{iso}} > 1.2 \times 10^{15}$  yr; very recently, this value has been improved by a factor of six to  $t_{1/2, \text{iso}} > 7.1 \times 10^{15}$  yr [33]. Photoexcitation from the  $9^-$  isomer to intermediate states (IMS) in the thermal photon bath at energies around 25 keV couples the long-living isomer to the short-living ground state.

Realistic stellar models of s-process nucleosynthesis have shown that the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  and  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reactions are the neutron sources for the s-process. The  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  reaction operates at thermal energies around  $kT \approx 8$  keV for about  $10^4$ – $10^5$  years, but does not contribute significantly to the  $^{180}\text{Ta}$  production. The higher energy of  $kT \approx 26$  keV of the  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reaction is required for the production path via  $\beta$ -decay of thermally excited  $^{179}\text{Hf}$  to  $^{179}\text{Ta}$  and subsequent  $^{179}\text{Ta}(n, \gamma)$   $^{180}\text{Ta}$  neutron capture. The  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  neutron source operates during convective helium shell flashes which last of the order of a few years [34–36]. Convective mixing transports freshly synthesized  $^{180}\text{Ta}$  to cooler regions with a turnover time of less than one hour [37]. Thus, for a survival of  $^{180}\text{Ta}$  in the s-process the effective half-life of  $^{180}\text{Ta}$  has to be (i) of the order of the mixing time scale at  $kT = 26$  keV to survive the mixing in the flash and (ii) of the order of  $10^5$  years at  $kT = 8$  keV to survive the s-process conditions between the shell flashes. It will be shown that the second condition (ii) is always fulfilled; however, the result of the present work shows that convective mixing has to occur on timescales shorter than a few hours—as calculated in Ref. [37]—to fulfill condition (i).

In a big number of  $\gamma$ -spectroscopic studies no IMS in  $^{180}\text{Ta}$  has been identified which mixes the  $K$  quantum number and has simultaneous  $\gamma$ -ray branches to the low- $K$  ground state and to the high- $K$  isomeric state (see, e.g., Refs. [38–41]). However, at higher excitation energies the  $K$  quantum number is eroded. It is clear that IMS must exist because of the measured yield in the photoactivation experiments. This is schematically shown in Fig. 1 where states with low  $K$

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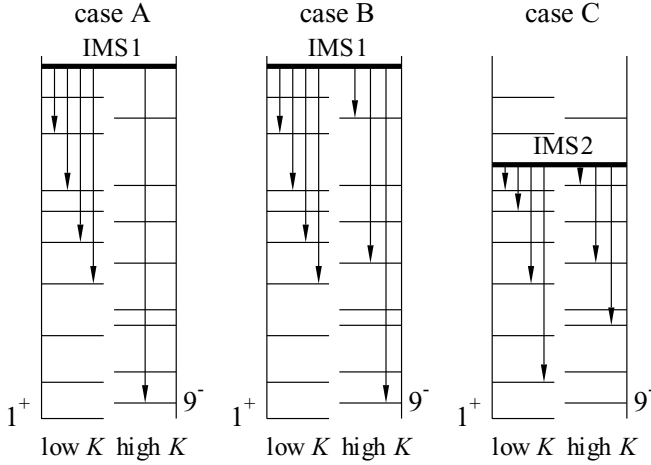


FIG. 1. Simplified level scheme of  $^{180}\text{Ta}$  with low- $K$  (left) and high- $K$  (right) states and two IMS. The high- $K$  branch of the IMS1 may decay directly to the  $9^-$  isomer (case A, experimentally confirmed [17,18]) or via different branches (case B, not measured yet). For another IMS2 the high- $K$  branch may decay only to excited states of the high- $K$  bands (case C, not measured yet). The latter case C will dramatically reduce the effective half-life of  $^{180}\text{Ta}$  under s-process conditions whereas case B leads only to a minor reduction of  $t_{1/2}^{\text{eff}}$  but may affect the freeze-out in the p-process (see text).

(high  $K$ ) decaying to the ground state (isomeric) band are shown on the left (right) hand side.

Photodestruction of  $^{180\text{m}}\text{Ta}$  has been identified down to an energy of about 1010 keV above the  $9^-$  isomer [17,18], and an energy-integrated cross section of  $I_{\sigma}^{\text{lab}} = 5.7 \text{ eV fm}^2$  for the transition from the isomer to the ground state band has been derived. The experimental data do not exclude that the IMS is located at lower energies and has a smaller cross section. A tentative assignment for the IMS is given in [42] with  $J^{\pi}(\text{IMS}) = (8^+)$  and  $E_x = 1076 \text{ keV}$ ; this IMS belongs to the  $K^{\pi} = 5^+$  band with the band head at  $E_x = 594 \text{ keV}$ . The given  $I_{\sigma}^{\text{lab}}$  leads to the effective half-life as shown in Fig. 2, case A.

Up to now, the effective half-life  $t_{1/2}^{\text{eff}}$  has been calculated from a three-level model taking into account the long half-life of the isomeric state, the short half-life of the ground state, and the integrated cross section  $I_{\sigma}^{\text{lab}}$  for the direct transition from the  $9^-$  isomeric state via the IMS to the ground state band [17, 18]. However, the integrated cross section has been measured under laboratory conditions. Under stellar conditions the direct transition from the  $9^-$  isomer to the IMS is only a minor contribution to the stellar integrated cross section  $I_{\sigma}^*$ ; this has not been taken into account up to now.

It is a general feature of photon-induced reactions that cross sections under stellar and laboratory conditions show noticeable differences. The cross section in the laboratory for a resonance with  $J_R$  at  $E_x$  in the reaction  $(\gamma, X)$  with the target in a defined state with spin  $J_0$  and excitation energy  $E_0$  is given by

$$\sigma^{\text{lab}}(E_{\gamma}) = \frac{g}{2} \frac{\pi}{k_{\gamma}^2} \frac{\Gamma_{\gamma}^{J_R \rightarrow J_0} \Gamma_X}{[E_{\gamma} - (E_x - E_0)]^2 + \Gamma^2/4} \quad (1)$$

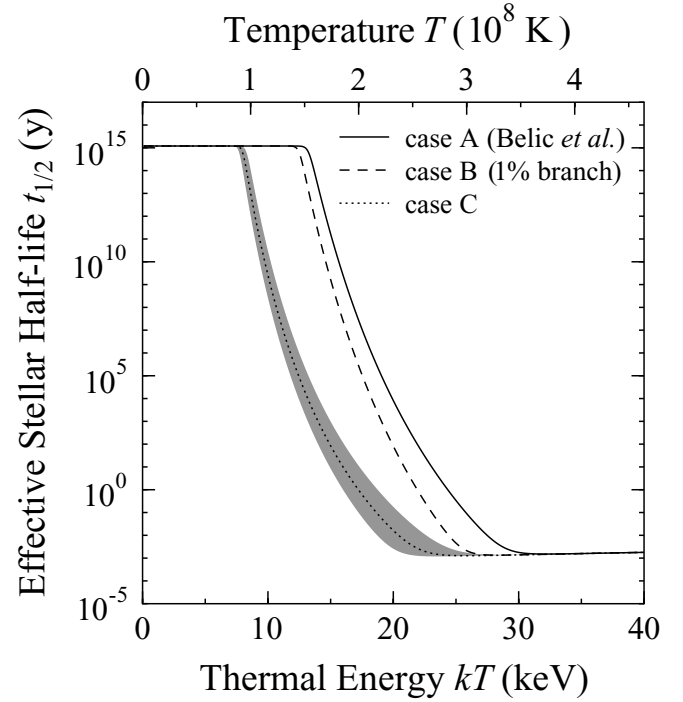


FIG. 2. Effective stellar half-life  $t_{1/2}$  of  $^{180}\text{Ta}$  calculated from the half-lives of the  $1^+$  ground state and  $9^-$  isomer and the integrated cross section  $I_{\sigma}$ . The effective half-life of  $^{180}\text{Ta}$  at  $kT = 26 \text{ keV}$  is around 11 h (case C). For further discussion see text.

with the statistical factor  $g = (2J_R + 1)/(2J_0 + 1)$ , the photon energy  $E_{\gamma} = \hbar c k_{\gamma}$ , the partial radiation width  $\Gamma_{\gamma}^{J_R \rightarrow J_0}$  for the direct transition from  $J_R$  to  $J_0$ , the partial width  $\Gamma_X$  for the decay into the  $X$  channel, and the total width  $\Gamma$ . The energy-integrated cross section is obtained by integration over  $E_{\gamma}$ :

$$I_{\sigma}^{\text{lab}} = g \left( \frac{\pi \hbar c}{E_x - E_0} \right)^2 \frac{\Gamma_{\gamma}^{J_R \rightarrow J_0} \Gamma_X}{\Gamma}. \quad (2)$$

The reaction rate  $\lambda^{\text{lab}}$  is given by

$$\lambda^{\text{lab}}(T) = c \int n_{\gamma}(E_{\gamma}, T) \sigma^{\text{lab}}(E_{\gamma}) dE_{\gamma} \approx c n_{\gamma}(E_x - E_0, T) I_{\sigma}^{\text{lab}} \quad (3)$$

with the thermal photon density

$$n_{\gamma}(E_{\gamma}, T) dE_{\gamma} = \frac{1}{\pi^2} \frac{1}{(\hbar c)^3} \frac{E_{\gamma}^2}{\exp(E_{\gamma}/kT) - 1} dE_{\gamma}. \quad (4)$$

Let us now for simplicity assume in the next paragraph that there is one excited state with  $J_1$  at energy  $E_1$ . The thermal population ratio is given by

$$\frac{n_1}{n_0} = \frac{(2J_1 + 1)}{(2J_0 + 1)} \exp\left(-\frac{E_1 - E_0}{kT}\right) \quad (5)$$

and decreases exponentially with the factor  $\exp(-E_1/kT)$ . However, the reaction rate  $\lambda_1$  from this state is comparable to  $\lambda^{\text{lab}}$  because the required photon energy  $E_{\gamma}$  for excitation of the resonance at  $E_x$  is reduced by  $E_1$  and thus the photon density in Eq. (4) is enhanced by the same exponential factor.

After summing over all properly weighted contributions from all thermally excited states the integrated cross section  $I_\sigma^*$  for one IMS under stellar conditions is given by

$$I_\sigma^* = g \left( \frac{\pi \hbar c}{E_x - E_0} \right)^2 \frac{\Gamma_\gamma^{\Sigma J_R \rightarrow J_i \rightarrow J_0} \Gamma_X}{\Gamma} \quad (6)$$

with the partial radiation width  $\Gamma_\gamma^{\Sigma J_R \rightarrow J_i \rightarrow J_0}$  summed over all partial widths  $\Gamma_\gamma^{J_R \rightarrow J_i}$  leading finally to the initial state with  $J_0$ . Note that the properties of the thermally excited states with  $J_i$  cancel out in Eq. (6). Thermal equilibrium is maintained by strong, i.e., mainly dipole and quadrupole, transitions with  $\Delta J = 1$  or  $2$ ; thermalization between states with large  $\Delta J$  is achieved by multiple transitions with low  $\Delta J$ .

The ratio between the reaction rates and integrated cross sections under stellar and laboratory conditions is given by the branching ratio:

$$\frac{\lambda^*}{\lambda^{\text{lab}}} = \frac{I_\sigma^*}{I_\sigma^{\text{lab}}} = \frac{\Gamma_\gamma^{\Sigma J_R \rightarrow J_i \rightarrow J_0}}{\Gamma_\gamma^{J_R \rightarrow J_0}}. \quad (7)$$

For the example of an isolated resonance in the  $^{20}\text{Ne}(\gamma, \alpha)^{16}\text{O}$  reaction the contributions of thermally excited states have been calculated explicitly in [43].

For the case of  $^{180}\text{Ta}$  this means that the integrated cross section is dramatically enhanced under stellar conditions compared to the laboratory results [17,18]. The stellar integrated cross section  $I_\sigma^*$  is given by

$$I_\sigma^* = g \left( \frac{\pi \hbar c}{E_{\text{IMS}} - E(9^-)} \right)^2 \frac{\Gamma_\gamma^{\Sigma \text{IMS} \rightarrow 9^-} \Gamma_\gamma^{\Sigma \text{IMS} \rightarrow 1^+}}{\Gamma} \quad (8)$$

with the summed partial widths  $\Gamma_\gamma^{\Sigma \text{IMS} \rightarrow 9^-}$  to the  $9^-$  isomer at  $E(9^-) = 77.1$  keV,  $\Gamma_\gamma^{\Sigma \text{IMS} \rightarrow 1^+}$  to the  $1^+$  ground state, and the total width  $\Gamma = \Gamma_\gamma^{\Sigma \text{IMS} \rightarrow 9^-} + \Gamma_\gamma^{\Sigma \text{IMS} \rightarrow 1^+}$ . The effective stellar half-life under s-process conditions is mainly defined by the lowest IMS.

Let us first show the influence of various decay branches of the experimentally known IMS1 via excited states to the  $9^-$  isomer. Case A in Figs. 1 and 2 repeats the result of [17,18] and takes into account only the direct decay from IMS1 to the  $9^-$  isomer. If one makes the hypothetical assumption that the direct decay of the ISM1 to the  $9^-$  isomer contributes only with 1% to the total decay to the isomer (case B in Figs. 1 and 2), one can calculate  $I_\sigma^* = 100 I_\sigma^{\text{lab}}$  and a reduced effective stellar half-life as shown in Fig. 2 (dashed line). Note that almost all states in  $^{180}\text{Ta}$  do not directly decay to the ground state or to the  $9^-$  isomer but via  $\gamma$ -ray cascades (see adopted level scheme and adopted  $\gamma$ -rays in [44]).

In the following paragraph we try to identify the lowest IMS which defines the effective half-life of  $^{180}\text{Ta}$  under s-process conditions. The experimental results for IMS in [17,18] have been tentatively assigned to members of an intermediate  $K$  band with  $K^\pi = 5^+$  and the band head at  $E_x = 594$  keV [42]. A careful inspection of the level scheme of  $^{180}\text{Ta}$  in [44] shows that this band head is an excellent candidate for the lowest IMS (IMS2 in Fig. 1). The half-life of this  $5^+$  isomer is  $t_{1/2} = 16.1 \pm 1.9$  ns [44], and it decays via 72 keV  $M1$  (or  $E2$ ) decay to the  $4^+$  state at  $E_x = 520$  keV. The half-life of the  $5^+$  isomer corresponds to  $3.7 \times 10^{-3}$  W.u. ( $M1$ ) or about 300 W.u. ( $E2$ ).

Let us now assume that there is a weak 1% branching of this  $5^+$  isomer to the  $7^+$  state at  $E_x = 357$  keV which is the band head of the  $K^\pi = 7^+$  band and decays via two subsequent  $\gamma$ -transitions to the  $9^-$  isomer at  $E_x = 77.1$  keV. Such  $E2$  transitions with  $\Delta K = 2$  have indeed been observed in  $^{180}\text{Ta}$  and also in neighboring  $^{176}\text{Lu}$  [44]. The direct transition from the  $5^+$  state to the  $9^-$  isomer ( $M4$  or  $E5$ ) is extremely weak. This is illustrated as case C in Fig. 1.

The  $E2$  transition from the  $5^+$  to the  $7^+$  state with a 1% branching corresponds to  $7.5 \times 10^{-3}$  W.u. which is of the same order of magnitude as the  $M1$  transition. Such a transition leads to an integrated stellar cross section of  $I_\sigma^* = 2.3 \times 10^{-4}$  eV fm<sup>2</sup>. The effective stellar half-life is dramatically reduced (see case C, shown as dotted line in Fig. 2). The grey shaded error bar in Fig. 2 is obtained if one increases or reduces the  $E2$  transition strength by a factor of 10. The assumed lower limit of less than  $10^{-3}$  W.u. for a  $E2$  transition from a  $K^\pi = 5^+$  to a  $K^\pi = 7^+$  band is much lower than typical hindrance factors for such a  $\Delta K = 2$  transition. Even larger transition strengths have been reported for a direct  $E2$  or  $E3$  transition from the  $9^-$  isomer to an unidentified IMS in a Coulomb excitation experiment [26].

The 72 keV decay of the  $5^+$  level at  $E_x = 594$  keV has not been confirmed in [41]. It is interesting to note that the results for the effective stellar half-life of  $^{180}\text{Ta}$  are not affected if the  $5^+$  state decays preferentially by the above discussed  $E2$  transition to the  $7^+$  state—provided that there is a 1% branching to states which decay finally to the ground state because of the symmetric roles of the  $9^-$  isomer and  $1^+$  ground state in the stellar integrated cross section  $I_\sigma^*$  in Eq. (8).

At the relevant thermal energy of  $kT = 26$  keV one finds that the effective stellar half-life of  $^{180}\text{Ta}$  is about 11 h from the above mentioned model which includes the  $1^+$  ground state, the  $9^-$  isomer, and the IMS which connects the ground state and the isomer. This short half-life is no longer defined by the transition rate from the isomer via the IMS to the ground state (as assumed in all previous work). Instead, such short half-lives correspond to full thermalization of  $^{180}\text{Ta}$  at the relevant temperature, and the effective half-life can simply be calculated from the properly weighted decay rates of low-lying states in  $^{180}\text{Ta}$ . At  $kT = 26$  keV one finds about 57% of  $^{180}\text{Ta}$  in the  $1^+$  ground state, 21% in the  $2^+$  state at  $E_x = 40$  keV, 19% in the  $9^-$  isomer at  $E_x = 77$  keV, and about 3% in higher-lying states. The half-lives of the  $1^+$  ground state and the  $9^-$  isomer are well-known experimentally. However, the  $\beta$ -decay half-life of the  $2^+$  state is experimentally unknown because the  $2^+$  state decays by  $M1$  or  $E2$   $\gamma$ -rays to the  $1^+$  ground state. It has been estimated in [45] that thermal population of low- $K$  states slightly increases the half-life of  $^{180}\text{Ta}$ . A further increase of the effective half-life of  $^{180}\text{Ta}$  by up to a factor of three at temperatures around  $kT = 10$ – $30$  keV comes from the ionization at high temperatures which reduces the electron capture probability of  $^{180}\text{Ta}_{\text{g.s.}}$  [24,45].

It has been shown recently [37] that the convective turnover time in helium shell flashes of AGB stars is of the order of one hour, and the time required for the transport of freshly synthesized nuclei to cooler regions may even be shorter of the order of minutes. Consequently, a reasonable amount of  $^{180}\text{Ta}$

can survive under s-process conditions. A precise calculation of the s-process production of  $^{180}\text{Ta}$  requires the knowledge of production and destruction cross sections of the ground state and the  $9^-$  isomer in  $^{180}\text{Ta}$  and coupling of ground state and  $9^-$  isomer via the IMS [16]. These nuclear physics ingredients have to be combined with a time-dependent model of the helium shell flashes in AGB stars.

As an alternative to the s-process nucleosynthesis, photon-induced reactions or neutrino-induced reactions during type II supernova explosions have been suggested for the production of  $^{180}\text{Ta}$  [1–6]. For photon-induced reactions the lower end of the adopted temperature region around  $T_9 = 2\text{--}3$  is required because of possible production and destruction by  $^{181}\text{Ta}(\gamma, n)$   $^{180}\text{Ta}$  ( $\gamma, n$ )  $^{179}\text{Ta}$  reactions. Neutrino nucleosynthesis of  $^{180}\text{Ta}$ , mainly by the charged current reaction  $^{180}\text{Hf}(\nu_e, e^-)^{180}\text{Ta}$ , occurs also at high temperatures above  $T_9 = 1$  [4,46,47]. The stellar reaction rates  $\lambda^*$  for the transition from the isomer to the ground state and its inverse are linked together by detailed balance and exceed  $\lambda^* = 10^5/\text{s}$  at  $T_9 = 1$ ; thus,  $^{180}\text{Ta}$  is completely thermalized independent of the production mechanism by photons or neutrinos. As soon as the reaction rate  $\lambda^*$  drops below the time scale of the supernova explosion,  $^{180}\text{Ta}$  freezes out in the thermal composition at freeze-out temperature  $kT_f$ . We calculate the freeze-out temperature  $kT_f = 40.4 \pm 5.5$  keV from the reaction rate  $\lambda^* = 1/\text{s}$ ; the uncertainties are carefully estimated using  $\lambda^* = 10/\text{s}$  (0.1/s) for the upper (lower) limit of  $kT_f$ . Taking into account all known levels of  $^{180}\text{Ta}$ , one finds that  $34.8_{-4.6}^{+3.6}\%$  of the synthesized  $^{180}\text{Ta}$  is in states with high  $K$  at  $kT_f$  and survives

finally in the  $9^-$  isomer. This is at the lower end of previous estimates of about 30%–50% for the survival probability [1,3].

It is interesting to note that the stellar reaction rate  $\lambda^*$  above  $T_9 > 1$  is dominated by the properties of the lowest experimentally known IMS at  $E_x = 1076$  keV from [17,18] and further higher-lying IMS. Thus, full thermalization of  $^{180}\text{Ta}$  under p-process conditions is inevitable and based on experimental data. The reaction rate  $\lambda^*(594)$  of the new IMS at  $E_x = 594$  keV is the same as  $\lambda^*(1076)$  at a temperature of 0.50 or 43 keV:  $\lambda^*(594) = \lambda^*(1076) \approx 1.5/\text{s}$ . The new IMS at  $E_x = 594$  keV shifts the freeze-out temperature  $kT_f$  only slightly down by about 2 keV and reduces the survival probability of the  $9^-$  isomer from 36.1% to 34.8%. A slightly stronger shift of  $kT_f$  is found for the hypothetical case B in Fig. 1.

In conclusion, it has been shown that thermal excitation from the long-living  $9^-$  isomer in  $^{180}\text{Ta}$  leads to an enhanced stellar cross section  $I_\sigma^*$  for transitions from the  $9^-$  isomer to the  $1^+$  ground state via an intermediate state. At  $kT = 26$  keV which is required for the s-process production of  $^{180}\text{Ta}$  we find that  $^{180}\text{Ta}$  is fully thermalized. Fast convective mixing is required for the survival of  $^{180}\text{Ta}$  because of the short effective half-life of  $t_{1/2}^{\text{eff}} = 11$  h. In supernovae  $^{180}\text{Ta}$  is produced above  $T_9 = 1$  in thermal equilibrium. Freeze-out at  $kT \approx 40$  keV leads to survival of 35% of the synthesized  $^{180}\text{Ta}$  independent of the production mechanism by photons or neutrinos.

We thank T. Rauscher and K. Takahashi for encouraging discussions.

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