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Modification of nuclear transitions in stellar plasma by electronic processes: *K* isomers in ^{176}Lu and ^{180}Ta under *s*-process conditions

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The influence of the stellar plasma on the production and destruction of K isomers is studied for the examples ^{176}Lu and ^{180}Ta. Individual electromagnetic transitions are enhanced predominantly by nuclear excitation by electron capture, whereas the other mechanisms of electron scattering and nuclear excitation by electron transition give only minor contributions. It is found that individual transitions can be enhanced significantly for low transition energies below 100 keV. Transitions with higher energies above 200 keV are practically not affected. Although one low-energy transition in ^{180}Ta is enhanced by up to a factor of 10, the stellar transition rates from low-K to high-K states via so-called intermediate states in ^{176}Lu and ^{180}Ta do not change significantly under s-process conditions. The s-process nucleosynthesis of ^{176}Lu and ^{180}Ta remains essentially unchanged.

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I. INTRODUCTION

In general, nuclear properties like decay half-lives and radiation widths do not depend on the electronic environment of the atomic nucleus. However, there are several well-known exceptions. Obviously, electron capture decays are affected by the number of available electrons, in particular K electrons, and thus the K-capture half-life depends on the ionization of the atom. A second example are low-energy γ transitions where the decay widths are enhanced by additional conversion electrons. The present study focuses on further effects that may affect nuclear transitions in a hot and dense plasma that is found in the interior of stars: inelastic and superelastic electron scattering and nuclear excitation by electron capture (NEEC) [1,2]; NEEC is the inverse process of the above-mentioned internal conversion (IC). Furthermore, even nuclear excitation by electron transition (NEET) [3] may be important if matching conditions can be achieved.

As will be shown in this study, γ transitions with relatively low energies far below 1 MeV are most affected by the surrounding hot and dense plasma. Typical γ-transition energies for (n,γ), (p,γ), and (α,γ) capture reactions are of the order of 1 MeV and higher and are thus not significantly affected by the stellar plasma. However, low-energy γ transitions play an important role in the production and destruction of low-lying isomers in the astrophysical s process. There are two astrophysically relevant examples for heavy odd-odd nuclei where low-lying isomers exist because of the huge difference of the K quantum number between the ground state and the isomer: ^{176}Lu and ^{180}Ta. The astrophysical transition rates between the low-K and high-K states in ^{176}Lu and ^{180}Ta may be affected by the temperature dependence of the individual transitions.

The interesting astrophysical properties of ^{176}Lu and ^{180}Ta will not be repeated here. The s-process nucleosynthesis of ^{176}Lu and ^{176}Hf and the interpretation of the ^{176}Hf/^{176}Lu ratio as s-process thermometer are discussed in several recent articles (see Refs. [4–6] and references therein). The open question on the nucleosynthetic origin of ^{180}Ta in various processes (s process, r process, p process or γ process or ν process) and the survival probability of the 9^- isomer under the corresponding conditions was also studied recently (see Refs. [7,8] and references therein).

The main subject of the present study is the temperature dependence of individual transitions from an initial state i to a final state f. This general temperature dependence should not be mixed up with the temperature dependence of the stellar transition rates between low-K states and high-K states in ^{176}Lu and ^{180}Ta that are defined by low-lying so-called intermediate states and their decay properties; i.e., all possible transitions from these intermediate states. It is obvious that changes in the individual transitions—as studied in this work—do also affect the stellar transition rates.

The article is organized as follows. In Sec. II some introductory remarks on the nuclear structure of isomers are given, and the stellar reaction rate between low-K states and high-K states is defined. In Sec. III the temperature dependence of individual transitions is discussed. Results for selected individual transitions in ^{176}Lu and ^{180}Ta are presented in Sec. IV, and their influence on the stellar transition rate is discussed. Finally, conclusions are drawn in Sec. V. As usual, we will give the "temperature" in units of keV, i.e., the temperature T is multiplied by the Boltzmann constant k leading to the thermal energy kT.

II. STELLAR REACTION RATES

A. Nuclear structure

The approximate conservation of the K-quantum number leads to a strong suppression of direct transitions between

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so-called low-K and high-K states in heavy nuclei. As a consequence, the low-K $J^\pi = 1^-; K = 0$ state in ^{176}Lu at $E_x = 123$ keV practically cannot decay to the high-K $7^-;7$ ground state. Instead, the low-K $1^-;0$ state forms an isomer that β decays with a half-life of $t_{1/2} = 3.66$ h to ^{176}Hf. The β decay of the $7^-;7$ ground state is also highly suppressed and has a long half-life of about 38 gigayears, i.e., it is practically stable for the time scale of the astrophysical s process. In ^{180}Ta the roles of the ground state and the isomer are exchanged: the low-K $1^+;1$ state is the ground state and has a short β-decay half-life of about 8.15 h, whereas the high-K $9^-;9$ isomer at $E_x = 77$ keV is quasistable with $t_{1/2} > 7.1 \times 10^{15}$ yr [9]. Excitation energies, spins and parities, half-lives, and decay properties are in most cases taken from the online database ENSDF [10] that is based on Ref. [11] for ^{176}Lu and Ref. [12] for ^{180}Ta; other data sources are stated explicitly.

Because of the strong suppression of direct transitions between the low-K and the high-K states, two species (a low-K one and a high-K one) of such nuclei like ^{176}Lu and ^{180}Ta have to be considered in nucleosynthesis calculations (see, e.g., Ref. [4]). Within each species, thermal equilibrium is obtained on time scales of far below 1 s (e.g., explicitly shown in Ref. [6] for ^{176}Lu). However, indirect transitions between the low-K and the high-K states are possible via so-called intermediate states (IMS) that are located at higher excitation energies and have intermediate K quantum numbers. Such IMS have been detected experimentally by high-resolution γ-ray spectroscopy for ^{176}Lu [13–17], and an indirect proof for the existence of IMS was obtained from various photoactivation studies [18–27]. A review of the results for ^{176}Lu is given in Ref. [5]. For ^{180}Ta only indirect evidence for the existence of IMS was derived from photoactivation [28–41]. A direct detection of IMS by γ spectroscopy was not possible up to now; see, e.g., Refs. [42–45].

B. Definition of astrophysical reaction rates

The stellar transition rate λ^* for transitions from the low-K to the high-K species of heavy nuclei is approximately given by

$$\lambda^*(T) = \int c\, n_\gamma(E,T)\,\sigma(E)\,dE \approx c \sum_i n_\gamma(E_{\mathrm{IMS},i},T)\, I_\sigma^*(E_{\mathrm{IMS},i}) \qquad (2.1)$$

with the thermal photon density

$$n_\gamma(E,T) = \left(\frac{1}{\pi}\right)^2 \left(\frac{1}{\hbar c}\right)^3 \frac{E^2}{\exp(E/kT) - 1} \qquad (2.2)$$

and the energy-integrated cross section I_σ^* under stellar conditions for an IMS at excitation energy E_{IMS}

$$I_\sigma^* = \int \sigma(E)\,dE = \frac{2J_{\mathrm{IMS}}+1}{2J_0+1}\left(\frac{\pi\hbar c}{E_{\mathrm{IMS}}}\right)^2 \times \frac{\Gamma^*_{\mathrm{IMS}\to\mathrm{low}-K}\,\Gamma^*_{\mathrm{IMS}\to\mathrm{high}-K}}{\Gamma^*}, \qquad (2.3)$$

where $\Gamma^*_{\mathrm{IMS}\to\mathrm{low}-K}$ and $\Gamma^*_{\mathrm{IMS}\to\mathrm{high}-K}$ are the total decay widths from the IMS to low-K and to high-K states under stellar conditions (including all cascades), $\Gamma^* = \Gamma^*_{\mathrm{IMS}\to\mathrm{low}-K} + \Gamma^*_{\mathrm{IMS}\to\mathrm{high}-K}$ is the total decay width, J_{IMS} and J_0 are the spins of the IMS and the initial state, and the energy E_{IMS} is given by the difference between the excitation energies of the IMS and the initial state: $E_{\mathrm{IMS}} = E_x(\mathrm{IMS}) - E_0$. The factor $\Gamma^*_{\mathrm{IMS}\to\mathrm{low}-K} \times \Gamma^*_{\mathrm{IMS}\to\mathrm{high}-K}/\Gamma^*$ in Eq. (2.3) may also be written as $b^*_{\mathrm{IMS}\to\mathrm{low}-K} \times b^*_{\mathrm{IMS}\to\mathrm{high}-K} \times \Gamma^*$, where $b^*_{\mathrm{IMS}\to\mathrm{low}-K}$ and $b^*_{\mathrm{IMS}\to\mathrm{high}-K}$ are the total decay branchings of the IMS under stellar conditions.

It is important to point out that the total decay widths (including all cascades) to low-K and high-K states enter into Eq. (2.3). This is a consequence of the thermal population of excited states under stellar conditions; for details, see Refs. [7,46].

The stellar reaction rate λ^* in Eq. (2.1) is given by the sum over the integrated cross sections I_σ^* of all IMS where the contribution of each IMS is weighted by the number of thermal photons at the corresponding excitation energy. Because of the exponential dependence of the thermal photon density in Eq. (2.2), only very few low-lying IMS contribute to the sum in Eq. (2.1). In the present study we restrict ourselves to the experimentally confirmed IMS in ^{176}Lu at 839 keV and a further candidate at 725 keV [6]; for ^{180}Ta we analyze the lowest IMS candidate at 594 keV [7].

The stellar reaction rate $\lambda^*(T)$ is strongly temperature dependent because of the roughly exponential factor $E^2/[\exp(E/kT) - 1]$ in Eq. (2.2). In addition to this explicit temperature dependence there is further implicit temperature dependence of $\lambda^*(T)$ because the widths Γ^* in Eq. (2.3) also depend on temperature. This further temperature dependence will be discussed in detail in the next Sect. III; see also Eq. (3.5).

For the sake of clarity we will use the symbol λ^* in units of s^{-1} only for the stellar reaction rate between low-K and high-K states in Eq. (2.1); the symbol λ will be used for transition rates between levels or groups of levels (in the same K group). Levels will be further characterized by their lifetimes τ instead of their decay constants $\lambda = 1/\tau$. All energies are given in keV.

C. Transitions in ^{176}Lu and ^{180}Ta

1. ^{176}*Lu*

A simplified level scheme of ^{176}Lu is shown in Fig. 1. There is an experimentally confirmed IMS at 839 keV, and a further candidate for an IMS at 725 keV has been suggested from the almost degeneracy of a low-K 7^- level and a high-K 7^- level [6]. Very recently, new low-lying IMS have been found by coincidence γ spectroscopy [17].

Here we analyze the experimentally confirmed IMS at 839 keV and its decays to the low-K levels at 723, 657, 635, and 596 keV and to the high-K levels at 564 and 0 keV (ground state). Further details of the transitions are listed in Table I. There are transitions in a wide range of energies for this IMS at 839 keV. Thus, conclusions can also be drawn for transitions from other IMS [6,17] without a further detailed analysis.

A candidate for an IMS at 725 keV has been suggested by Ref. [6]; the suggestion is based on a theoretical study of K mixing of two 7^- states at 724.7 and 725.2 keV with $K = 0$

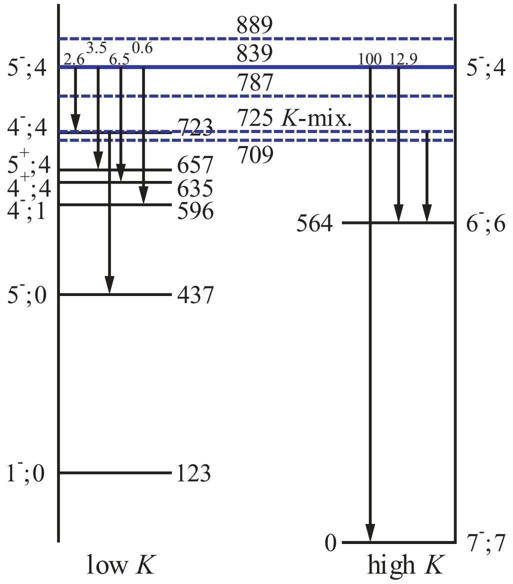

FIG. 1. (Color online) Partial level scheme of ^{176}Lu with low-K states on the left and high-K states on the right. IMSs are indicated by blue lines over the full width of the diagram. The IMS at 839 keV (full line) decays to low-K and to high-K states. Relative γ-ray branches $b^{\gamma,\mathrm{rel}}$ normalized to the dominating ground state branching $b^{\gamma,\mathrm{rel}}_{839\to 0} = 100$ are given for the IMS at 839 keV. K mixing of two neighboring 7^- levels at 724.7 and 725.2 keV may lead to a further IMS [6]. New low-lying IMS have been identified in a $K = 4$ band at 709, 787, and 889 keV [17]. The dashed lines indicate IMS that are not studied in detail in this work.

and $K = 6$. The 725-keV states decay to the low-K state at 437 keV and to the high-K state at 564 keV.

Members of the $K = 4$ band with its 4^+ band head at 635 keV have been identified as IMS recently [17]. Weak branches to the high-K $7^-; 7$ ground state have been found for the 6^+, 7^+, and 8^+ members of this band at 709, 787, and 889 keV. The main decay branch from this band goes to the low-K side. From the estimated transition strengths in [17] it results that only the lowest IMS at 709 keV may have significant influence on the stellar transition rate λ^*.

TABLE I. Transitions in ^{176}Lu (from Ref. [10]).

$J_i^\pi; K$	$E_{x,i}$ (keV)	$J_f^\pi; K$	$E_{x,f}$ (keV)	Transition	$\Gamma^\gamma_{i\to f}$ (μeV)
$5^-; 4$	839	$4^-; 4$	723	$(M1)$	1.3[a]
$5^-; 4$	839	$5^+; 4$	657	$(E1)$[b]	1.8[a]
$5^-; 4$	839	$4^+; 4$	635	$(E1)$[b]	3.3[a]
$5^-; 4$	839	$4^-; 1$	596	$(M1,E2)$[b]	0.3[a]
$5^-; 4$	839	$6^-; 6$	564	$M1$	6.5[a]
$5^-; 4$	839	$7^-; 7$	0	$E2$	50.0[c]
$7^-; 0$	725	$5^-; 0$	437	$E2$	27.3[d]
$7^-; 6$	725	$6^-; 6$	564	$(M1)$	15.8[d]

[a] From $\Gamma^\gamma_{839\to 0}$ and measured branching.
[b] Tentative assignment.
[c] Assumed within the experimental errors; see text.
[d] Calculated value [6].

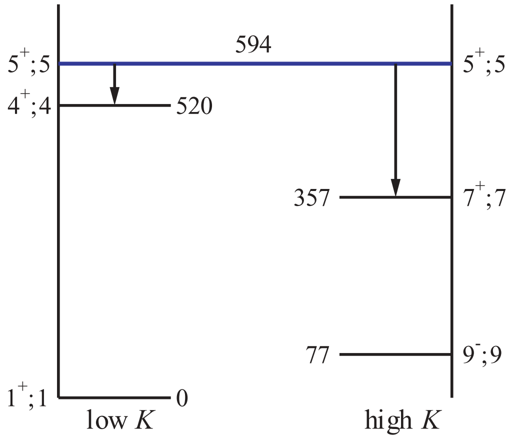

FIG. 2. (Color online) Partial level scheme of ^{180}Ta with low-K states on the left and high-K states on the right. The IMS is indicated by a blue line over the full width of the diagram.

Unfortunately, the lifetimes of the two 7^- states at 725 keV are unknown, and only lower and upper limits for the lifetime of the 5^- state at 839 keV are available in the literature. For the following discussion we take $\Gamma^\gamma_{839\to 0} = 50$ μeV that corresponds to a partial lifetime of $\tau_{839\to 0} = 13.2$ ps. This value is in the experimental limits $10\,\mathrm{ps} \leqslant \tau \leqslant 433\,\mathrm{ps}$ for the lifetime of the 839 keV state because this state predominantly (branching $\gtrsim 80\%$) decays by the $839 \to 0$ transition. In agreement with the theoretical arguments in Ref. [48] and the experimental photoactivation yields [26,27] (see discussion in Ref. [5], where $\tau \approx 12$ ps is suggested with an uncertainty of about a factor of 2) we use a value close to the upper experimental limit of the width (or lower limit of the lifetime).

2. ^{180}Ta

Following Ref. [7], the lowest IMS in ^{180}Ta is located at 594 keV. It is the band head of a $K = 5$ rotational band, and also the higher members of this band have been assigned as IMS [47]. The 594-keV level has a half-life of $t_{1/2} = 16.1 \pm 1.9$ ns and decays by a 72.2-keV transition [42,43], probably by an $M1$ transition to the 520-keV level on the low-K side. (Note that there is a surprising 2-keV discrepancy in the transition energy and the excitation energies that may be related to the 2-keV shift of the 9^- isomer from $E_x = 75$ keV in earlier compilations to $E_x = 77$ keV in the latest database [10].) Based on reasonable assumptions for the transition strength of the $E2$ transition from the 594-keV state to the 7^- state at 357 keV on the high-K side, it has been concluded in Ref. [7] that the 594-keV state is the lowest IMS in ^{180}Ta. A simplified level scheme of ^{180}Ta is shown in Fig. 2.

III. MODIFICATIONS OF TRANSITIONS BY THE STELLAR PLASMA

A. Stellar transition rates and detailed balance theorem

In this chapter, we have changed notations to have indices I, L, and H to designate IMS, low-K, and high-K states, respectively. The stellar reaction rate expression in Eqs. (2.1) to (2.3) only includes radiative excitation and spontaneous photon emission. In a stellar plasma at thermodynamic equilibrium, induced photon emission has also to be included. This can be easily done by changing Eq. (2.3) for a transition from a high-K state to a low-K state into:

$$I_\sigma^* = \frac{2J_I+1}{2J_H+1}\left(\frac{\pi\hbar c}{E_I-E_H}\right)^2 \times \frac{\Gamma^*_{IL}\Gamma^*_{IH}\frac{\exp\left(\frac{E_I-E_H}{kT}\right)}{\exp\left(\frac{E_I-E_H}{kT}\right)-1}}{\Gamma^*_{IL}\frac{\exp\left(\frac{E_I-E_L}{kT}\right)}{\exp\left(\frac{E_I-E_L}{kT}\right)-1}+\Gamma^*_{IH}\frac{\exp\left(\frac{E_I-E_H}{kT}\right)}{\exp\left(\frac{E_I-E_H}{kT}\right)-1}}. \tag{3.1}$$

However, it should be noted that L and H must designate single levels here. When several high-K levels or several low-K levels are involved, each stellar transition rate must be dealt with separately.

Adding induced photon emission is relevant only when transition energies are not too much larger than the plasma temperature kT. In the worst case that will be presented below, a 72-keV transition in ^{180}Ta at a temperature of 25 keV, the correction is only 5%. Thus, the approximation for the stellar reaction rate in Eq. (2.1) remains valid for typical astrophysical conditions.

In a plasma at local thermodynamic equilibrium (LTE), transition rates are related to their corresponding inverse transition rates by the detailed balance theorem. It can be easily proved that this still stands when dealing with indirect (through the IMS) transition rates, so we can write:

$$\frac{\lambda^*_{HL}}{\lambda^*_{LH}} = \frac{2J_L+1}{2J_H+1}\exp\left(\frac{E_L-E_H}{kT}\right). \tag{3.2}$$

It is possible to define a global excitation and deexcitation rate when the IMS state is excited from, or decays down to, a group of levels by summing over the contributing levels j [2]:

$$\lambda_{IL} = \sum_j \lambda_{IL_j} \tag{3.3}$$

and

$$\lambda_{HI} = \frac{\sum_j (2J_{H_j}+1)e^{-\frac{E_{H_j}}{kT}}\lambda_{H_jI}}{\sum_j (2J_{H_j}+1)e^{-\frac{E_{H_j}}{kT}}}. \tag{3.4}$$

These global rates do not verify the detailed balance theorem, as no single energy and spin can be associated to the "global level." The detailed balance theorem can only be verified for a transition between two individual levels and not when some are grouped together into a global level.

However, in the case where one transition dominates all the other transitions from its group, the detailed balance theorem is approximately verified. In particular, such is the case for ^{176}Lu in this work.

B. Modifications of transition rates by electronic environment

Electronic environment in stellar plasmas may influence decay or excitation properties of nuclei. Internal conversion is strongly dependent on the number of bound electrons, and nuclear transitions may be excited by its inverse process NEEC [49,50].

The huge number of low-energy free electrons may also play a role in decay or excitation by electron scattering [51] even though the transition rate is usually quite small for high-energy nuclear transitions. In the particular cases where an atomic transition matches in energy a nuclear transition, NEET and its reverse process BIC (bound internal conversion) become possible [3,52]. However, this last phenomenon is absent for the nuclear transitions in ^{180}Ta or ^{176}Lu of this study as no atomic transition matches the high-energy nuclear transitions of interest.

The net effect of all these processes is a modification of the excitation and deexcitation rates leading to modifications of nuclear level lifetimes [2]. All these processes have been dealt with under the LTE hypothesis, which means that the detailed balance theorem can be used for each individual process as well as for the total transition rate between two levels.

The width $\Gamma^*_{i\to f}(T)$ for a transition from an initial state i to a final state f under stellar conditions depends on temperature and is given be the sum over several contributions:

$$\begin{aligned}\Gamma^*_{i\to f}(T) &= \Gamma^\gamma_{i\to f} + \Gamma^{\mathrm{IC}}_{i\to f}(T) + \Gamma^{(e',e)}_{i\to f}(T)\\ &= \Gamma^\gamma_{i\to f}\left[1+\alpha^{\mathrm{IC}}_{i\to f}(T)+\alpha^{(e',e)}_{i\to f}(T)\right]\end{aligned} \tag{3.5}$$

$\Gamma^\gamma_{i\to f}$ is the temperature-independent γ-radiation width that is enhanced by the temperature-dependent widths of conversion electrons $\Gamma^{\mathrm{IC}}_{i\to f}(T)$ and of electron scattering $\Gamma^{(e',e)}_{i\to f}(T)$. The α are the corresponding dimensionless enhancement factors normalized to the radiation width $\Gamma^\gamma_{i\to f}$. The $\alpha^{\mathrm{IC}}_{i\to f}$ is the well-known internal conversion coefficient modified to take into account the partial ionization of the atom and the modifications it induces on the electronic wave functions.

The explanation of Eq. (3.5) uses the standard wording for the decay case. Although the underlying physics is exactly the same, the usual wordings for the excitation case are "nuclear excitation by electron capture" Γ^{NEEC} instead of "internal conversion" Γ^{IC} and "inelastic electron scattering" $\Gamma^{(e,e')}$ instead of "superelastic electron scattering" $\Gamma^{(e',e)}$.

For completeness and clarification of the figures in Sec. IV it must be pointed out that the radiation width Γ^γ itself is temperature independent. However, the half-life (or decay rate) of a given state becomes temperature dependent at high temperatures because of induced photon emission (see also Sec. III A), even in the absence of the further contributions of IC/NEEC and electron scattering in Eq. (3.5).

IV. RESULTS

As already mentioned in the Introduction, plasma effects are important mainly for transitions with low energies. Thus, capture reactions with typical energies far above 1 MeV are practically not affected in any astrophysical scenario, whereas the production and destruction of isomers in the astrophysical s process has to be studied in detail.

It is generally accepted that the astrophysical s process operates in thermally pulsing AGB stars [53–55]. In the so-called interpulse phase neutrons are produced by the

^{13}C(α,n)^{16}O reaction at relatively low temperatures around $kT \approx 8$ keV for about 10^4–10^5 years; this temperature is too low to affect isomer production and destruction [5,7]. During thermal pulses the ^{22}Ne(α,n)^{25}Mg neutron source is activated for a few years at temperatures around 25 keV and densities of the order of 10^3 g/cm^3 [53]. For the present analysis we adopt this density, and we study the temperature dependence of various transitions in the chosen examples ^{176}Lu and ^{180}Ta.

The results are presented as temperature-dependent enhancement factors $\mathcal{F}(T)$ that relate the plasma effects (mainly NEEC and electron scattering) to the effective radiative transition width

$$\mathcal{F}^X(T) = \frac{\Gamma^X(T)}{\Gamma^{\gamma}_{\rm eff}(T)}, \qquad (4.1)$$

where the index X stands for IC/NEEC, electron scattering, or NEET. The presentation of the relative enhancement factor $\mathcal{F}$ instead of $\Gamma^X(T)$ avoids complications for transitions with unknown radiation widths Γ^{γ}. For $T \rightarrow 0$ the enhancement factors $\mathcal{F}$ in Eq. (4.1) are identical to the usual factors α in Eq. (3.5).

It has to be kept in mind that the radiative width Γ^{γ} in Eq. (3.5) is temperature independent; but the radiative part is enhanced by induced photon transitions at high temperatures, leading to the temperature-dependent effective radiation width $\Gamma^{\gamma}_{\rm eff}(T)$ in the denominator in Eq. (4.1):

$$\Gamma^{\gamma}_{\rm eff}(T) = \Gamma^{\gamma}\left[1 + \frac{1}{\exp(\Delta E/kT) - 1}\right]. \qquad (4.2)$$

The second part in the parenthesis is the enhancement due to induced photon emission for a transition with energy ΔE; see also Eq. (3.1) where the same factor was already used for the definition of the integrated cross section I^*_{σ}. Obviously this enhancement remains small at low temperatures and high transition energies, i.e., $\Delta E \gg kT$.

All following results are presented within a range of temperatures from 1 keV to 1 MeV. However, it should be noted that the results are nonrelativistic estimates, which can lead to some errors for temperatures above a few hundred keV.

A. Modification of widths in ^{176}Lu and ^{180}Ta

1. ^{176}Lu

The lowest transition energy between the $5^-;4$ IMS state in ^{176}Lu at 839 keV and a lower state is 116 keV. For such a high energy, one should not expect the electrons to have a large influence on the transition rates.

First, we study the excitation of the $5^-;4$ IMS at 839 keV from the high-K side, i.e., from the $7^-;7$ ground state and the $6^-;6$ state at 564 keV. We plot the plasma enhancement factor as a function of temperature for the chosen density of 1000 g/cm^3 in Fig. 3. Only NEEC is not totally negligible against radiative excitation, but it never amounts to more than a few percentages.

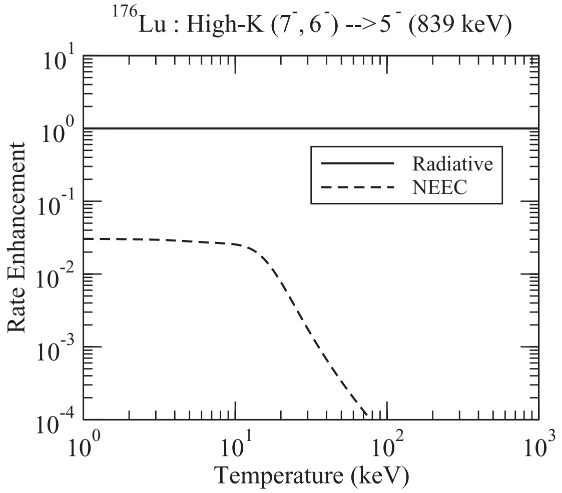

FIG. 3. Transition rate enhancement factor for NEEC from high-K levels to the IMS level of ^{176}Lu at 1000 g/cm^3.

Excitations of the $5^-;4$ IMS at 839 keV from the low-K side are somewhat more strongly affected. This is not surprising because of the lower transition energies from the $4^-;1$, $4^+;4$, $5^+;4$, and $4^-;4$ states located between 596 and 723 keV. We find NEEC rates nearly equal to radiative rates for temperatures lower than 10 keV as shown in Fig. 4. NEEC accounts for a global excitation rate increase by a factor around 1.6 in this temperature range.

This enhancement translates into the same factor on the stellar transition rate Eq. (2.1) shown on Fig. 5. However, at temperatures below about 15 keV the stellar transition rate from high-K to low-K states in ^{176}Lu drops below 10^{-15}/s or 3×10^{-8} per year [4,5]; i.e., it becomes negligible on the above mentioned time scale of a thermal pulse. Consequently, the plasma modification of the stellar transition rate does not affect the nucleosynthesis of ^{176}Lu in the s process.

The enhancement of the stellar transition rate is directly related to the decrease of the partial half-life of the IMS level down to low-K levels as shown in Fig. 6. The dominating branch to the high-K side is practically not affected.

Two almost degenerate 7^- states around 725 keV and their K mixing have been suggested as a further candidate for a low-lying IMS in ^{176}Lu [6]. The influence of the plasma

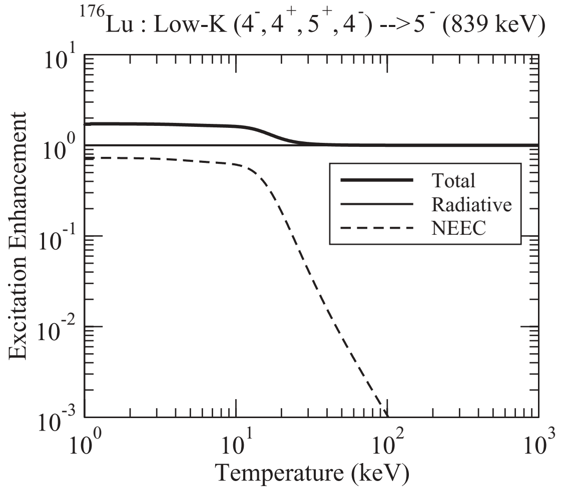

FIG. 4. Transition rate enhancement factor for NEEC from low-K levels to the IMS level of ^{176}Lu at 1000 g/cm^3.

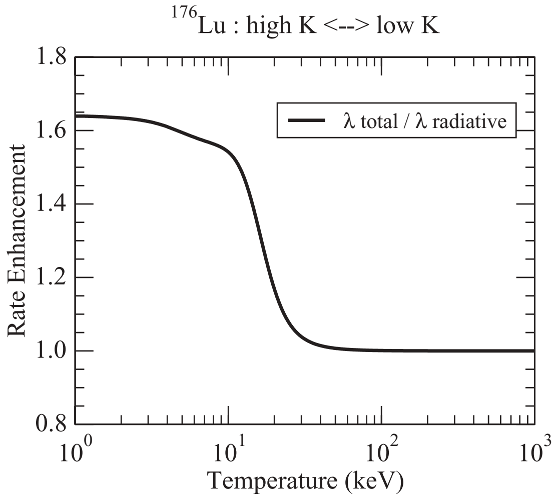

FIG. 5. Stellar transition rate enhancement factor due to NEEC for ^{176}Lu at 1000 g/cm^3. The enhancement at temperatures below 15 keV does not affect the nucleosynthesis of ^{176}Lu in the *s* process because the stellar rate drops below 10^{-15}/s at 15 keV.

environment on these two almost degenerate 7^- states is small. The decay energies are 288 keV for the low-K branch and 161 keV for the high-K branch. These transition energies are higher or at least similar to the transition energies in the low-K branch of the $5^-;4$ IMS at 839 keV that are enhanced only at very low temperatures (see Fig. 4 and discussion above). Thus, it can be concluded that the IMS properties of the two 7^- states are not affected by the plasma environment.

2. ^{180}*Ta*

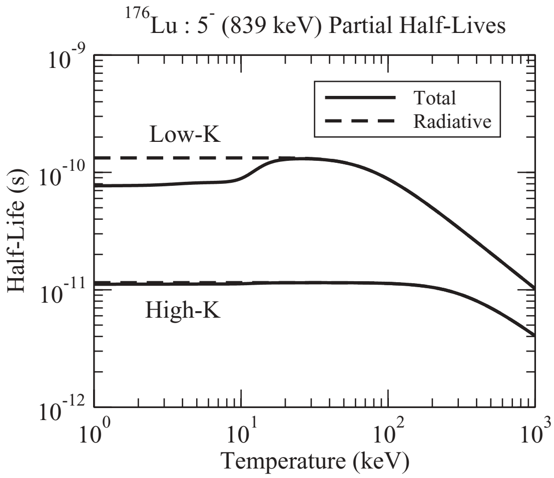

FIG. 6. Partial half-lives of the $5^-;4$ IMS level of ^{176}Lu toward low-K and high-K levels at 1000 g/cm^3. At low temperatures the branch to low-K states is enhanced by NEEC/IC. At high temperatures above 100 keV induced photon emission shortens the half-lives.

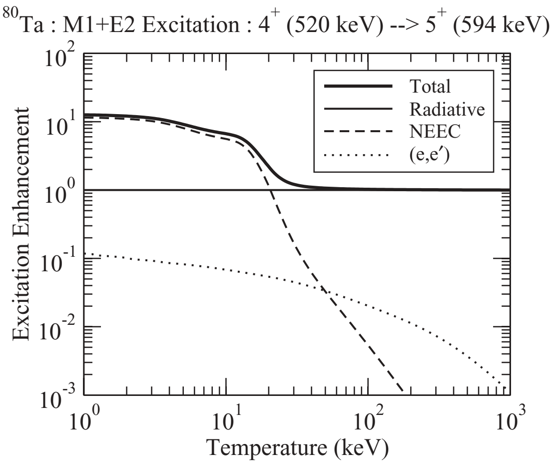

FIG. 7. Transition rate enhancement factor for NEEC from the low-K 4^+ level to the 5^+ IMS level of ^{180}Ta at 1000 g/cm^3.

The candidate for the lowest IMS in ^{180}Ta is a 5^+ state at 594 keV that decays to the low-K branch by a 72 keV ($M1$) transition; the laboratory half-life is $t_{1/2} = 16.1 \pm 1.9$ ns. Thus, at first glance, effects on ^{180}Ta appear to be stronger because of the relatively low transition energy of only 72 keV. Indeed, the excitation rate from the low-K 520 keV state exhibits a large influence of electrons shown in Fig. 7. For temperatures below 10 keV, electron inelastic scattering reaches 10% of the radiative rate and NEEC is 10 times higher than the radiative rate. This factor can also be observed in Fig. 8 with a factor of 10 decrease on the half-life of the IMS level.

The excitation rate enhancement for the 237 keV $E2$ transition from the 5^+ IMS to the high-K 7^+ state at 357 keV is very small, even though in this case NEEC is not the only contributor as electron inelastic scattering makes an appearance as can be seen on Fig. 9.

Contrary to the ^{176}Lu case, the rate enhancement of the low-K branch of the IMS does not translate into a similar increase on the stellar transition rate between low-K and high-K states. Figure 10 shows that a 20% increase can at best be expected for the lowest temperatures because the excitation from the high-K level is the relevant term in the stellar transition rate.

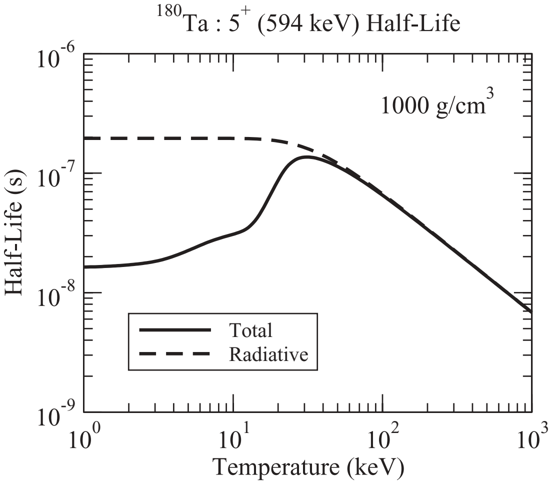

FIG. 8. Partial half-life of the 5^+ IMS level of ^{180}Ta toward the 4^+ low-K level at 1000 g/cm^3. The reduction of the half-life at low temperatures results from enhanced transitions by NEEC. The reduction at high temperatures is due to induced transitions.

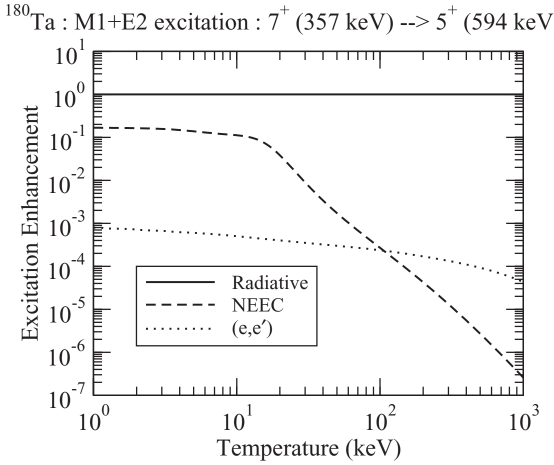

FIG. 9. Transition rate enhancement factor for NEEC from the 7^+ high-K level to the 5^+ IMS level of ^{180}Ta at 1000 g/cm^3.

Similar to ^{176}Lu, the small enhancement of the stellar reaction rate at low temperatures below about 15 keV does not affect the nucleosynthesis in the s process because the absolute rates are too small at such low temperatures.

B. Discussion of the results

From the above shown examples it can be concluded that transitions with energies above 200 keV are practically not affected by the plasma environment that is present under stellar s process conditions. The influence of the stellar plasma increases for lower transition energies and may reach about a factor of 2 for transition energies above 100 keV. Low-energy transitions below 100 keV may change dramatically; e.g., a factor of about 10 has been found for the 72-keV transition in ^{180}Ta.

NEEC is the main contributor to this increase with capture onto the 1s shell amounting to the larger part. This effect disappears when the temperature increases as free electrons have too much energy to be captured onto an atomic shell. The only other influence of electrons is inelastic scattering. However, it is never greater than 10% of the radiative excitation rate or more than 1% of the total transition rate. NEET remains negligible as long as no matching transitions are present.

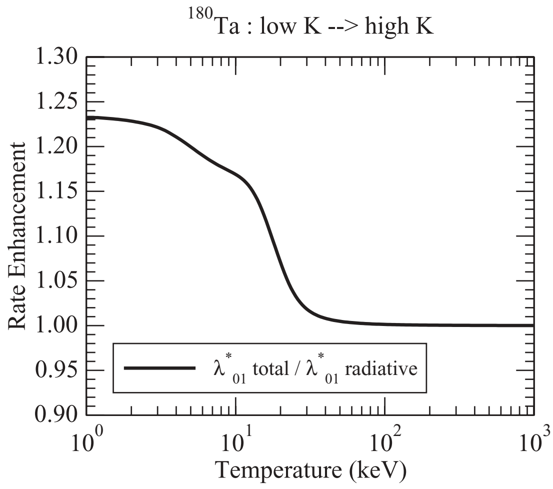

FIG. 10. Stellar transition rate enhancement factor due to NEEC for ^{180}Ta at 1000 g/cm^3.

Changes in the strength of a particular transition do not directly translate into modifications of the stellar reaction rate λ^* for transitions from the low-K to the high-K levels. The stellar reaction rate λ^* is proportional to the integrated cross section I_σ^* in Eq. (2.3) and thus proportional to a width factor

$$\lambda^* \sim I_\sigma^* \sim \frac{\Gamma_1 \Gamma_2}{\Gamma_1 + \Gamma_2}, \tag{4.3}$$

where the Γ_i represent the low-K and high-K branches under stellar conditions. As long as one of the partial widths dominates—e.g., $\Gamma_1 \gg \Gamma_2$ and thus $\Gamma = \Gamma_1 + \Gamma_2 \approx \Gamma_1$ – this dominating width Γ_1 cancels out in Eq. (4.3), and the stellar rate is approximately proportional to the smaller width Γ_2. If the smaller width corresponds to a K-forbidden transition with relatively high energies above 200 keV, then the stellar reaction rate λ^* is practically not affected by the plasma environment. This is the case for the decay of the lowest IMS in ^{180}Ta [46] and also for the recently identified lowest IMS in ^{176}Lu [17].

Although ^{176}Lu and ^{180}Ta appear to have a very different behavior in terms of modification of individual excitation rates by electrons, the global effects on the stellar transition rates are very similar: a 20% to 60% increase of the stellar rate is found for temperatures lower than 20 keV. The major change of the 72-keV transition in ^{180}Ta does not appear as a major modification of the stellar reaction rate because this 72-keV transition is the dominating decay branch of the IMS in ^{180}Ta.

V. SUMMARY AND CONCLUSIONS

Under stellar conditions the radiative transition width Γ^γ for an individual transition from an initial state i to a final state f is enhanced by electronic transitions which are induced by the surrounding stellar plasma. The enhancement factor $\mathcal{F} = \Gamma^*/\Gamma^\gamma_{\text{eff}}$ is composed of several effects. Under typical s-process conditions the dominating effect is NEEC. Electron scattering plays a very minor role, and NEET remains completely negligible for all practical purposes.

Typical s-process conditions are temperatures around $kT \approx$ 23 keV and $\rho \approx 10^3$ g/cm^3 for the helium shell flashes in thermally pulsing AGB stars. Under these conditions we find negligible enhancement factors $\mathcal{F} \approx 1$ for transitions with energies above $\Delta E = 150$ keV. At energies around 100 keV, $\mathcal{F}$ increases but remains below a factor of 2. Further lowering of the transition energy down to about 50 keV leads to dramatic enhancement factors up to one order of magnitude ($\mathcal{F} \approx 10$). Transitions with energies below 50 keV are even further enhanced; but nuclear transitions with such low transition energies are very rare.

The nucleosynthesis of ^{176}Lu and ^{180}Ta is affected by low-lying K isomers in these nuclei and the production and destruction of these isomers via transitions to IMS. The stellar transition rates λ^* for transitions from high-K to low-K states are defined by the decay properties of the IMS, i.e., by a combination of the individual transition strengths. For ^{176}Lu the stellar plasma does not lead to a significant modification of the stellar transition rate λ^* because the lowest transition energy of 116 keV is sufficiently high, and thus all individual transitions remain unaffected by the plasma. For ^{180}Ta a significant enhancement of more than a factor of 2 is found for the low-energy $\Delta E = 72$ keV transition from the lowest IMS at 594 keV. This low-energy transition is the dominating decay branch of the IMS; but the stellar rate λ^* is essentially defined by the weak decay branch to the 357-keV state (as suggested in Ref. [7]) which remains unaffected because of its larger transition energy. Thus, more or less by accident, the stellar rate λ^* for ^{180}Ta is not modified significantly although one individual decay branch is modified by more than a factor of 2.

In summary, due to the plasma environment the stellar reaction rate λ^* for the production or destruction of K isomers in ^{176}Lu and ^{180}Ta does not change by more than about 20% at s-process temperatures around 25 keV and less than about 60% at very low temperatures below 10 keV. However, at these low temperatures the absolute rates are too low to have influence on s-process nucleosynthesis; under these conditions, corresponding to the long-lasting interpulse phase with $kT \approx 8$ keV, the low-K and high-K states have to be treated as two separate species that are practically decoupled because the IMS cannot be reached by thermal excitations.

Within the present knowledge of IMS in ^{176}Lu and ^{180}Ta it may be concluded that electronic effects due to the plasma environment do not play a relevant role in the s-process nucleosynthesis of ^{176}Lu and ^{180}Ta. However, it should be kept in mind that three new IMS (or a group of IMS) have been suggested in the past few years: 725 keV [6] and 709 keV, 787 keV, and 889 keV [17] in ^{176}Lu and 594 keV in ^{180}Ta [7]. Each newly suggested IMS has its individual decay pattern which has to be studied. It may have a weak low-energy branch that may be significantly enhanced by the plasma environment. This low-energy branch may finally define the stellar rate λ^* according to Eq. (4.3). So we conclude here that the plasma enhancement should be taken into account for any low-energy transition below about 100 keV.

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