PROCEEDINGS OF SCIENCE

K-Isomers in odd-odd nuclei on the s-process path: ^{176}Lu, ^{180}Ta, and ^{186}Re

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Peter Mohr[*]
Diakonie-Klinikum, D-74523 Schwäbisch Hall, Germany
E-mail: `WidmaierMohr@t-online.de`

The thermal coupling between low-K and high-K states via so-called intermediate states (IS) in a stellar photon bath is analyzed. The transition rates depend linearly on the integrated cross sections of IS and exponentially on temperature. These transitions may affect the effective half-life of nuclei under stellar conditions dramatically. Three examples are studied in detail: ^{176}Lu, ^{180}Ta, and ^{186}Re. ^{176}Lu acts as a thermometer for the s-process; however, there are discrepancies for the integrated cross section of the lowest IS at 839 keV. ^{180}Ta is thermalized under s-process conditions within hours and may be interpreted as a "mixometer" for the fast convective mixing in AGB stars. In the p(γ)-process and ν-process ^{180}Ta is produced in thermal equlibrium leading to survival of about one third of the synthesized ^{180}Ta in the 9^- isomeric state. The (8^+) isomer in ^{186}Re does not have significant influence on the s-process branching at ^{186}Re.

10th Symposium on Nuclei in the Cosmos
July 27 - August 1 2008
Mackinac Island, Michigan, USA

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[*] Speaker.

1. Introduction

Low-lying isomers may affect the nucleosynthesis path in various nucleosynthesis processes dramatically. In particular, the synthesis of heavy nuclei is influenced by so-called K-isomers. The K quantum number is the projection of the angular momentum on the intrinsic symmetry axis of a nucleus; it is approximately conserved. Especially in heavy odd-odd nuclei the angular momenta $\vec{j}_p$ and $\vec{j}_n$ of the unpaired proton and neutron may couple to states with high $K \approx |\vec{j}_p| + |\vec{j}_n|$ and low $K \approx |\vec{j}_p| - |\vec{j}_n| \approx 0$. Transitions between low-K and high-K states are strongly suppressed by approximately a factor of 100 per degree of K-forbiddenness which is defined as $\nu = |\Delta K - \mathscr{L}|$ where $\mathscr{L}$ is the multipole order of the electromagnetic transition [1]. E.g., for ^{180}Ta this increases the lifetime τ of an E2 transition with $\Delta E = 100\,\mathrm{keV}$ from about $1\,\mu$s without K-suppression by twelve orders of magnitude to about ten days for a transition with $\nu = 6$, $K_i = 9 \rightarrow K_f = 1$.

Direct transitions between low-K and high-K states are strongly suppressed. However, a coupling between low-K and high-K states may be realized by higher-lying states with intermediate K which may decay directly or via cascades to the low-lying low-K and high-K states. The properties of these so-called intermediate states (IS) have to be analyzed carefully. IS may be excited in the thermal photon bath of the respective stellar environment, e.g. at thermal energies kT of about 8 keV and 26 keV for the neutron sources ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg in the s-process, or about $150 - 300$ keV in the p(γ)-process. The transition rate λ between low-K and high-K states via an IS at energy E_{IS} depends on the energy-integrated cross section:

$$\lambda(T) = \int c\, n_\gamma(E,T)\, \sigma(E)\, dE \approx c\, n_\gamma(E_{IS},T)\, I_\sigma(E_{IS}) \tag{1.1}$$

with the thermal photon density

$$n_\gamma(E,T) = \left(\frac{1}{\pi}\right)^2 \left(\frac{1}{\hbar c}\right)^3 \frac{E^2}{\exp\left(E/kT\right) - 1} \tag{1.2}$$

and the energy-integrated cross section

$$I_\sigma = \int \sigma(E)\, dE = \frac{2J_{IS}+1}{2J_0+1} \left(\frac{\pi\hbar c}{E_{IS}}\right)^2 \frac{\Gamma_{IS\rightarrow\mathrm{low}-K}\,\Gamma_{IS\rightarrow\mathrm{high}-K}}{\Gamma} \tag{1.3}$$

$\Gamma_{IS\rightarrow\mathrm{low}-K}$ and $\Gamma_{IS\rightarrow\mathrm{high}-K}$ are the total decay widths from the IS to low-K and high-K states (including all cascades), $\Gamma = \Gamma_{IS\rightarrow\mathrm{low}-K} + \Gamma_{IS\rightarrow\mathrm{high}-K}$ is the total decay width, J_{IS} and J_0 are the spins of the IS and the initial state, and the energy E_{IS} is given by the difference between the excitation energies of the IS and the initial state: $E_{IS} = E_x(IS) - E_0$. The factor $\Gamma_{IS\rightarrow\mathrm{low}-K} \times \Gamma_{IS\rightarrow\mathrm{high}-K}/\Gamma$ in Eq. (1.3) may also be written as $b_{IS\rightarrow\mathrm{low}-K} \times b_{IS\rightarrow\mathrm{high}-K} \times \Gamma$ where $b_{IS\rightarrow\mathrm{low}-K}$ and $b_{IS\rightarrow\mathrm{high}-K}$ are the total decay branchings of the IS. The total stellar transition rate is given by the sum over all IS; however, from the exponential dependence of the photon density in Eq. (1.2) it is obvious that only very few low-lying IS – and often only the lowest IS – dominate the stellar transition rate.

There is a significant enhancement for the stellar transition rate λ between low-K and high-K states in Eq. (1.1) because laboratory measurements (e.g. photoactivation or Coulomb excitation [2, 3]) of the integrated cross section I_σ determine only the minor direct transition $\Gamma_{IS\rightarrow\mathrm{initial}}$ from the IS to the initial state in the experiment (excluding cascades) instead of the total decay width to the low-K or high-K initial state in Eq. (1.3) [4]. In particular, the lowest IS cannot be found in the experiment if there is no direct decay from the IS to the initial state in the experiment [4].

2. Nucleosynthesis of ^{180}Ta: s-process, p(γ)-process, r-process, ν-process?

The nucleosynthesis of the rarest quasi-stable nucleus ^{180}Ta is still an open question. Whereas the 1^+ ground state of ^{180}Ta is unstable with a half-life of about 8 h, there is a 9^- isomer at $E_x = 77$ keV with a half-life of more than 10^{15} y. At first view, it is bypassed in the s-process and shielded from the r-process. Consequently, ^{180}Ta has been assigned to the p(γ)-process, and a small temperature window has been found to produce a significant amount of ^{180}Ta by the ^{181}Ta(γ,n)^{180}Ta reaction [5, 6]. However, ^{180}Ta may also be produced in two branches of the s-process (*i*) via the decay of thermally excited ^{179}Hf to ^{179}Ta and subsequent neutron capture or (*ii*) via isomer population and decay in the ^{179}Hf(n,γ)$^{180\mathrm{m}}$Hf(β^-)$^{180\mathrm{m}}$Ta chain [7], or by neutrino interactions, e.g. in the ^{180}Hf(ν_e,e)^{180}Ta reaction [8]; r-process synthesis of ^{180}Ta remains indeed excluded because of very weak isomer-to-isomer decay branches in the $A = 180$ decay chain [9].

Based on the photoactivation data [2] and the interpretation [10] of the experimentally determined IS as high-lying members of the $K^\pi = 5^+$ band at $E_x = 594$ keV, a recent analysis [4] has shown that the 5^+ band head acts as lowest IS in ^{180}Ta. The observed activation after Coulomb excitation [11] may also be assigned to this band by an E3 transition from the 9^- isomer to the 6^+ state at 735 keV. Because the nucleosynthesis of ^{180}Ta was studied in detail in [4], here I only repeat the main conclusions. They are based on reasonable theoretical estimates for the decay strengths of the new IS at 594 keV and on the measured integrated cross sections of higher-lying IS [2].

The new low-lying IS at 594 keV does not affect the nucleosynthesis of ^{180}Ta at $kT \approx 8$ keV which is typical for the ^{13}C(α,n)^{16}O neutron source which burns for ten thousands of years in AGB stars. However, at $kT \approx 26$ keV which is typical for the ^{22}Ne(α,n)^{25}Mg neutron source which burns for a few years, ^{180}Ta is thermalized within a few hours. Thus, ^{180}Ta can survive s-process conditions only because of fast convective mixing with its timescale of the order of several hours. If the s-process production of ^{180}Ta could be measured, e.g. from an isotope analysis of meteorites, ^{180}Ta may be used as “mixometer” for the convective mixing in AGB stars.

Nucleosynthesis of ^{180}Ta in the p(γ)-process or ν-process occurs at much higher temperatures $kT \gg 100$ keV where ^{180}Ta is thermalized within less than microseconds. The isomer abundance freezes out when the coupling via IS becomes slower than the supernova time scale of about one second. This leads to a (35 ± 4) % survival of ^{180}Ta in its long-living isomeric 9^- state – independent of the production by photon-induced or neutrino-induced reactions [4].

Although the abundance of ^{180}Ta is the lowest of all naturally occurring nuclei, the above conclusions indicate that three nucleosynthesis processes – the s-process, the p(γ)-process, and the ν-process – are required which synthesize ^{180}Ta with almost similar contributions.

3. Nucleosynthesis of ^{176}Lu: thermometer for the s-process

The 7^- ground state of ^{176}Lu decays with a long half-life of about 40 Gy to stable ^{176}Hf. Both ^{176}Lu and ^{176}Hf are s-only nuclei. Their abundance ratio seems to be a perfect chronometer for the s-process. However, there is a low-lying 1^- isomer in ^{176}Lu with a much shorter half-life of 3.7 h for the decay to ^{176}Hf. The coupling of isomer and ground state via IS shortens the effective stellar halflife of ^{176}Lu and turns the chronometer into a thermometer for the s-process.

It is generally accepted that the lowest IS in ^{176}Lu is a 5^- state at $E_x = 839$ keV. Its decay properties have been measured [12, 13, 14], and it has been found that the IS decays predominantly to the ground state. Thus, an experimental determination of the integrated cross section I_σ is possible, and such experiments have been performed using Coulomb excitation [3] and photoactivation with bremsstrahlung [15].

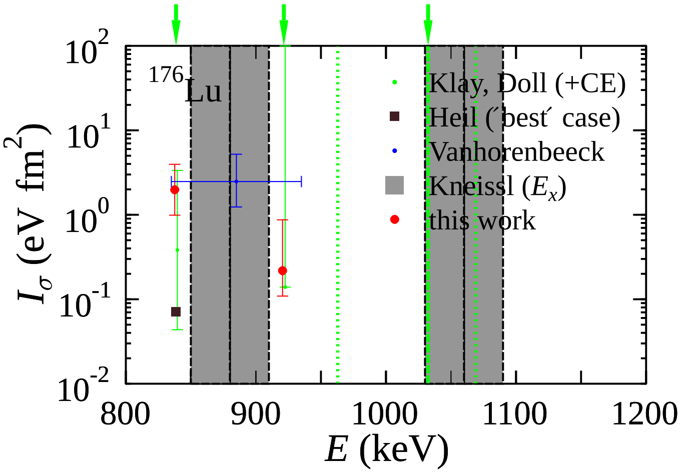

Figure 1: Integrated cross section I_σ for various IS in neutral atomic ^{176}Lu. The combined analysis of all avaliable experimental data for the lowest IS at 839 keV [3, 12, 13, 14, 15] (red) is about a factor of 10 higher than a recent astrophysical determination [16] (brown). Further discussion see text.

The results of the various experiments are summarized in Fig. 1. IS with γ-spectroscopically confirmed decay branches to low-K and high-K states are marked in green [12, 13, 14]. For the lowest IS at 839 keV upper and lower limits for the lifetime are available leading to the shown error bar for $I_\sigma(839)$. An upper limit for the lifetime is known for the IS at 922 keV leading to a lower limit of $I_\sigma(922)$. No lifetimes are known for the other IS; thus, I_σ remains unknown (indicated by vertical lines). IS with dominating ground state transitions, i.e. IS which should be seen in photoactivation or Coulomb excitation, are additionally marked by green arrows on top of Fig. 1.

The Coulomb excitation [3] experiment cannot resolve individual IS. Instead, it provides a sum of I_σ of the low-lying IS (blue). The analysis of the photoactivation data [15] is not finished, i.e. the I_σ are not yet determined. However, the excitation energies of IS can be taken from the photoactivation yield curve in [15] (grey bars). An energy difference of about 180 keV is found between the two lowest IS, corresponding to the IS at 839 and 1032 keV. Combining all available experimental data, one finds that $I_\sigma(839)$ is close to its upper limit (in agreement with theroretical considerations in [14]), and $I_\sigma(922)$ is close to its lower limit (red). The result for $I_\sigma(839)$ is about a factor of 10 higher than the so-called 'best case' of [16] (brown) which is based on an analysis of lutetium and hafnium abundances from a realistic s-process model in AGB stars.

The I_σ of IS in ^{176}Lu are shown for atomic natural ^{176}Lu. The small transition energy of the M1 transition from the 5^- state at 839 keV to the 4^- state at 723 keV leads to a significant enhancement of $I_\sigma(839)$ under laboratory(!) conditions because this transition is enhanced by conversion electrons. At s-process temperatures one finds $n_K \approx 0.4$ electrons in the K-shell [17] instead of $n_K = 2$ leading to an effective conversion coefficient $\alpha^{\rm eff} \approx 0.4$ instead of $\alpha = 2.42$ for neutral atoms [18]. In total, $I_\sigma(839)$ is about a factor of two larger in laboratory experiments than under s-process conditions. This cannot resolve the shown discrepancy to the result of [16], see Fig. 1.

4. The s-process branching at ^{186}Re and the Re/Os cosmochronometer

The ground state of ^{186}Re has $J^\pi = 1^-$ with a short half-life of 3.7 days. An (8^+) isomer is found at $E_x = 149\,\mathrm{keV}$ with a half-life of 2×10^5 y, and a candidate for an IS is the $(6)^-$ state at 186 keV. Decay properties of the candidate for an IS are unknown. Nevertheless, it can be stated that the influence of the isomer on the s-process branching at ^{186}Re and the Re/Os-cosmochronometer is negligible. The isomer is only weakly populated in neutron capture [19] with $(1.3 \pm 0.8)\,\%$. If the $(6)^-$ state acts as IS, this weak population of the isomer is further reduced to the thermal equilibrium value below 1 %. Under any realistic circumstances the s-process branching at ^{186}Re remains weak, especially when compared to the neighboring branching at ^{185}W.

5. Conclusions

Isomers may affect nucleosynthesis dramatically. Because of their low-lying isomers, ^{176}Lu is a thermometer for the s-process, and ^{180}Ta may act as “mixometer” for the s-process. Additionally, only one third of the synthesized ^{180}Ta survives p(γ)-process- or ν-process-conditions. Contrary to ^{180}Ta and ^{176}Lu, the isomer in ^{186}Re has no significant influence on the ^{186}Re s-process branching. A significant discrepancy for the integrated cross section of the lowest IS in ^{176}Lu between the experimental data and an astrophysical determination [16] remains to be solved.

I thank R. Gallino, F. Käppeler, U. Kneissl, K.-L. Kratz for encouraging and fruitful discussions.

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