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Photodisintegration of ^{181}Ta leading to the isomeric state ^{180}Ta^m

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Partial photoneutron cross sections for ^{181}Ta$(\gamma,n)^{180}$Ta$^m(9^-)$ were measured with laser Compton scattering γ rays. The partial cross section, which reflects selective γ transitions in ^{180}Ta leading to the isomeric state, cast new light into the spin- and parity-dependent nuclear level density of ^{180}Ta. Essentially the same selective γ transition is expected in neutron capture on ^{179}Ta leading to ^{180}Ta$^m(9^-)$. The weak s-process branching to the only naturally occurring isomer ^{180}Ta^m is discussed.

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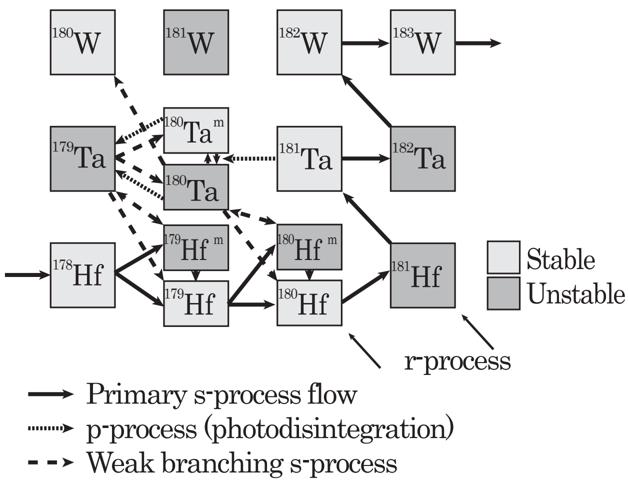

Figure 1: The s-, r- and p-process flows around ^{180}Ta^m

1. p- and s-process origins of ^{180}Ta^m

Understanding the origin of ^{180}Ta^m is one of most intriguing subjects in nuclear astrophysics because of its unique character as the only naturally occurring isomer and the rarest isotope in the solar system. ^{180}Ta^m is classified as one of p-nuclei that are found on the neutron-deficient side of the chart of nuclides [1]. As shown in Fig. 1, ^{180}Ta^m is bypassed by the main s-process path and shielded from the β^- decay by a stable nucleus ^{180}Hf after the rapid neutron capture. In the p-process, photodisintegration of pre-existing ^{181}Ta of the s- and r-process origin is a primary contributor for the production of ^{180}Ta^m. The most promising astrophysical site which can provide a suitable hot stellar photon bath is the O/Ne layers of massive stars in the presupernova phase [2, 3, 4] or during their explosions as type-II supernovae [3, 4, 5, 6, 7]. Photoneutron cross sections were measured for ^{181}Ta [8] to study photoproduction of ^{180}Ta^m. The stellar photon bath of the order of 10^9 K is hot enough to achieve thermal equilibrium in ^{180}Ta between the ground state and the isomeric state through mediating excited states [1, 9]. The total photoneutron cross section and its thermal partition to the isomeric state determine photoproduction of ^{180}Ta^m. It is shown in the Z = $Z_\odot$ M = $25M_\odot$ model calculation that ^{180}Ta^m is a natural p-process product [8]. The remaining uncertainty is largely attributed to photodestruction of ^{180}Ta^m which is a challenge to experimentalists. It is to be noted that the final ^{180}Ta production may be increased by the neutrino nucleosynthesis, where ν_e capture (charged current capture) on ^{180}Hf is the major contributor rather than the neutral current on ^{181}Ta. This extra production is still subject to all the uncertainties related to the neutrino physics, in particular, the neutrino luminosity, temperature, oscillation and interaction cross section.

Besides the p-process, a different origin can be found in the weak s-process branching at ^{179}Hf in ABG stars [10]. β^- decay of ^{179}Hf in the isomeric state ($7/2^-$ at 214 keV) has access to a radioactive ^{179}Ta; a subsequent neutron capture on ^{179}Ta with the half life 1.82 y can produce ^{180}Ta^m. Neutron capture in AGB stars takes place at temperatures of the order of 10^8 K. Since it is most likely that the thermal equilibrium is no longer achieved at these low temperatures, partial

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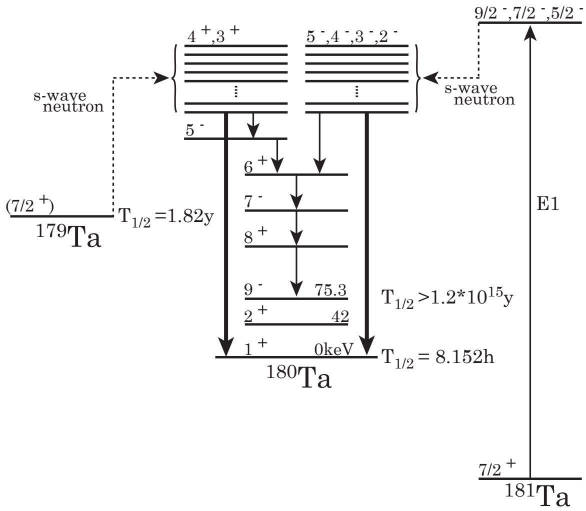

Figure 2: γ transitions leading to the isomeric state ^{180}Ta^m in photodisintegration of ^{181}Ta and neutron capture on ^{179}Ta.

neutron capture cross sections leading to the isomeric state are of critical importance in the s-process origin of ^{180}Ta^m.

At present, the partial neutron capture cross section is experimentally unknown. Therefore, one has to reply on model calculations in which a large uncertainty stems from the nuclear level density. Fig. 2 depicts a naive picture of γ transitions leading to the isomeric state of ^{180}Ta both in photodisintegration of ^{181}Ta and in neutron capture on ^{179}Ta. In the s-wave neutron capture on ^{179}Ta in the ground state (7/2$^+$), 3$^+$ and 4$^+$ states can be populated in ^{180}Ta. To reach the isomeric state ^{180}Ta^m (9$^-$), very selective γ transitions are required; for instance, if they are E1 transitions starting 4$^+$, γ transitions proceed as $4^+ \rightarrow 5^- \rightarrow 6^+ \rightarrow 7^- \rightarrow 8^+ \rightarrow 9^-$. Note that the spin increases in γ transitions, while the excitation energy decreases. The excitation energy up to some 5 MeV is of our interest. The partial neutron cross cross section represents selective multi-step transitions that are sensitive to the distribution of relatively high-spin states in the nuclear level density (NLD) of ^{180}Ta.

The NLD of ^{180}Ta can be investigated in photodisintegration of ^{181}Ta. In the E1 excitation of ^{181}Ta in the ground state (7/2$^+$ state) followed by an s-wave neutron emission, states in ^{180}Ta with the spin and parity of 5$^-$, 4$^-$, 3$^-$ and 2$^-$ can be populated. Therefore, the essentially same multi-step γ transitions, e.g. $5^- \rightarrow 6^+ \rightarrow 7^- \rightarrow 8^+ \rightarrow 9^-$ are expected in photodisintegration.

In what follows, the experimental result and its impact on the NLD of ^{180}Ta are given in conjunction with the s-process origin of ^{180}Ta^m. One can refer to [11] for the experimental procedure and the data analysis.

2. Partial photoneutron cross sections and the s-process origin of ^{180}Ta^m

Fig. 3 shows partial photoneutron cross sections with the statistical and systematic uncertainties (10 - 26%) combined linearly. The present simultaneous measurements of total and partial

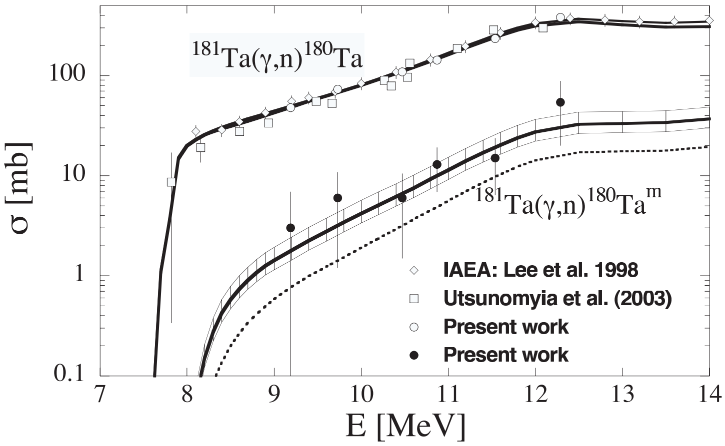

Figure 3: The present result of total and partial photoneutron cross sections for ^{181}Ta [11]. Results of the statistical model calculation with the Talys code are shown by the dotted line for the statistical NLD and the solid line for the combinatorial NLD. Uncertainties associated with the combinatorial prediction were estimated by a least-squares analysis of the experimental data, where error bars between the thin solid lines correspond to an increase of 1 from the χ^2 minimum.

cross sections allowed us to reduce the systematic uncertainty to large extent (for details, see [11]). The Talys code [12] for the statistical model calculation was used to predict the partial cross section. Two different models of the NLD were adopted. The first one used a statistical calculation that takes into account the discrete structure of the single-particle spectra associated with the HFBCS potential [13](dotted line), while the second one is based on the combinatorial approach using the single-particle scheme and pairing strength derived from an HFB calculation [14, 15](solid line). The E1 γ-strength function based on the HFBCS + QRPA model is adjusted to reproduce the total cross section which is insensitive to the adopted NLD model. In contrast, the partial cross section is sensitive to the NLD as expected. While the combinatorial NLD satisfactorily reproduces the partial cross section, the statistical NLD significantly underestimates it. This difference originates from the large NLD obtained with the combinatorial approach for spins J $>$ 5 at low energies, where the number of intermediate states feeding to the isomeric state increases.

Neutron capture cross sections for ^{179}Ta was evaluated with the combinatorial NLD. As expected, a large reaction flow to the isomeric state resulted not only in photodisintegration of ^{181}Ta but also in neutron capture on ^{179}Ta, giving a partial neutron capture cross section 90 $\pm$ 20 mb at 30 keV. This cross section is twice as large as the previous prediction (44 mb [16]), while the branching ratio (0.04 $\pm$ 0.01) is in good agreement.

3. Concluding remarks

The present study indicates that the cross section for neutron capture on ^{179}Ta leading to ^{180}Ta^m is enhanced from the previous standard value by a factor of two. However, this does not necessarily mean that the contribution of the weak branching at ^{179}Hf to the production of ^{180}Ta^m increases by the same factor because uncertainties still remain in the β decay rates of ^{179}Hf in stellar conditions as well as in the detailed temperature history in which the s-process takes place in AGB stars.

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References

[1] M. Arnould, and S. Goriely, Phys. Rep. **384**, 1 (2003).

[2] M. Arnould, Astron. Astrophys. **46**, 117 (1976).

[3] M. Rayet *et al.*, Astron. Astrophys. **298**, 517 (1995).

[4] T. Rauscher *et al.*, Astrophys. J. **576**, 323 (2002).

[5] S.E. Woosley and W.M. Howard, Astrophys. J. Suppl. **36**, 285 (1978).

[6] S.E. Woosley *et al.*, Astroph. J. **356**, 272 (1990).

[7] S. Goriely *et al.*, Astron. Astrophys. **375**, L35 (2001).

[8] H. Utsunomiya *et al.*, Phys. Rev. C **67**, 015807 (2003).

[9] D. Belic *et al.*, Phys. Rev. Lett. **83**, 5242 (1999).

[10] K. Yokoi and K. Takahashi, Nature **305**, 198 (1983).

[11] S. Goko *et al.*, Phys. Rev. Lett. **96**, 192501 (2006).

[12] A.J. Koning, S. Hilaire and M.C. Duijvestijn, Proc. Int. Conf. on Nuclear Data for Science and Technology (eds. C. Haight et al.) AIP Conference Vol. 769, p. 1154, 2005.

[13] P. Demetriou, and S. Goriely, Nucl. Phys. **A695**, 95 (2001).

[14] S. Hilaire and S. Goriely, Nucl. Phys. A (2006) submitted.

[15] S. Hilaire *et al.*, Eur. Phys. J. **A12**, 169 (2001).

[16] Zs. Németh *et al.*, Astroph. J. **392**, 277 (1992).