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The s-process branching at ^{186}Re revised

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Recent experimental data for the ^{187}Re(γ,n)^{186}Re reaction are reviewed, and the contribution of the (8^+) isomer in ^{186}Re is discussed. Statistical model calculations are used to derive the ^{186}Re(n,γ)^{187}Re capture cross section from the photodisintegration data, and $\sigma_{\mathrm{MACS}} = 1070 \pm 370$ mb is obtained at $kT = 30$ keV. The s-process branching at ^{186}Re remains small.

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1. Introduction

The s-process branching at ^{186}Re is important for the understanding of the s-process nucleosynthesis pattern in this mass region, and it affects the ^{187}Re-^{187}Os cosmochronology [1, 2]. A direct measurement of the neutron capture cross section of ^{186}Re is extremely difficult because of its short half-life of $t_{1/2} = 3.72$ d. Instead, two recent experiments have measured the inverse photodisintegration cross section of ^{187}Re(γ,n)^{186}Re, and statistical model calculations were used to derive the ^{186}Re(n,γ)^{187}Re capture cross section [2, 3]. Here we compare the experimental approaches and discuss the reliability of the extraction of (n,γ) cross sections from experimental (γ,n) data. Special attention is given to the role of the (8^+) isomer in the photodisintegration reaction which is located in ^{186}Re at $E = 149$ keV with the much longer half-life of $t_{1/2} = 2.0 \times 10^5$ y. It has been shown that the role of the (8^+) isomer in the ^{185}Re(n,γ)^{186}Re capture reaction remains negligible because of the minor population in the (n,γ) reaction [4].

2. Available experimental data of ^{187}Re(γ,n)^{186}Re

Three data sets exist for the ^{187}Re(γ,n)^{186}Re reaction: bremsstrahlung photons and direct neutron detection were used for measurements around the giant dipole resonance (GDR) by [5]. Measurements above the threshold at $S_n = 7.363$ MeV up to about 11 MeV were performed using monochromatic photons and direct neutron detection [2], and [3, 6] have used bremsstrahlung for photoactivation measurements from threshold to about 10 MeV. The results are shown in Fig. 1.

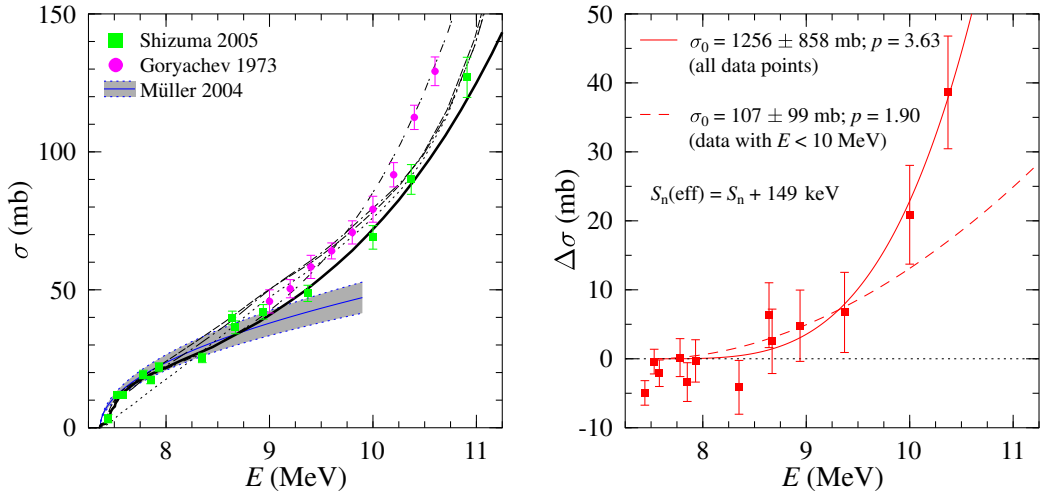

Figure 1: Experimental data for the ^{187}Re(γ,n)^{186}Re reaction (cross section data [2, 5] and a parametrization of the cross section [6]) compared to statistical model calculations (black lines) with various parameter sets from [2, 7] (left). Difference $\Delta\sigma$ between the direct measurements of [2] and the photoactivation data of [6] (right); the difference may be attributed to the population of the (8^+) isomer in ^{186}Re (see text). The analysis of [3] combines the direct data of [5] (including the isomer contribution) and photoactivation data (excluding the isomer contribution); it is thus questionable and not shown in this figure.

There are *a priori* two arguments for a noticeable contribution of the (8^+) isomer in the ^{187}Re(γ,n)^{186}Re reaction. (*i*) In the ^{185}Re(γ,n)^{184}Re reaction a significant isomer population of

about 20 % around 10 MeV has been reported in [6]; the same spins and parities are involved in both reactions: $J^\pi(^{187}\mathrm{Re}_{\mathrm{g.s.}}) = J^\pi(^{185}\mathrm{Re}_{\mathrm{g.s.}}) = 5/2^+$, the lowest states in ^{184}Re and ^{186}Re have low spins and negative parity, and there is a $8^{(+)}$ isomer at $E = 188$ keV in ^{184}Re and a (8^+) isomer in ^{186}Re at $E = 149$ keV. So one expects a similar isomer contribution in both reactions. (*ii*) The measured average neutron energy remains below 1 MeV in the ^{187}Re(γ,n)^{186}Re reaction [2] up to $E_\gamma = 11$ MeV, and thus ^{186}Re is produced at excitation energies of a few MeV at higher photon energies. Here a sufficient number of states with higher spins and significant decay branches to the (8^+) isomer can be expected.

In [6] an upper limit for the decay activity of the (8^+) isomer of $r_{\mathrm{act}} = A_{\mathrm{iso}}/A_{\mathrm{g.s.}} = 10^{-5}$ is derived from the measured spectra. Using the half-lives of the ground state and the (8^+) isomer, this upper limit for the activity translates to an upper limit of the production yield of $r_{\mathrm{yield}} = Y_{\mathrm{iso}}/Y_{\mathrm{g.s.}} \approx 200$; nevertheless, the (8^+) isomer in ^{186}Re has been ignored in [6, 3].

The isomer contribution can be determined from the difference between measurements with direct neutron detection and photoactivation. Unfortunately, the error bars prevent a precise determination but a clear trend can be seen in Fig. 1. If one uses the parametrization

$$\sigma(E) = \sigma_0 \times \left(\frac{E - S_{\mathrm{n}}^{\mathrm{eff}}}{S_{\mathrm{n}}^{\mathrm{eff}}} \right)^p \tag{2.1}$$

one can fit the isomer contribution in Fig. 1 (right part) by adjusting σ_0 and p and with $S_{\mathrm{n}}^{\mathrm{eff}} = S_{\mathrm{n}} + 149$ keV. Depending on the treatment of the data points close above threshold (where one finds unphysically negative cross sections) and depending on the number of data points which are taken into account (see below), one finds in any case values for σ_0 which are significantly positive and values for p between 1.9 and 3.6 which are typical for large involved angular momenta ($p \approx l + 1/2$) for the states feeding the (8^+) isomer.

The experimental result of [3, 6] is a parametrization of the cross section which also uses Eq. (2.1) with $S_{\mathrm{n}}^{\mathrm{eff}} = S_{\mathrm{n}} = 7.363$ MeV: $\sigma_0 = 80.4 \pm 9.6$ mb and $p = 0.5$; the validity is restricted to $E < 8.55$ MeV in [3] because the lowest directly measured data points of [5] around 9 MeV are higher than the parametrization of [3]. It is concluded in [3] that this difference is due to the tail of the GDR. However, the measured values of σ_0 in [3] (see their Fig. 5) do not increase with energy. Therefore, the deviation between the photoactivation data of [3] and the data of [5] must probably – at least partly – be attributed to a noticeable isomer contribution. Unfortunately, [3] do not compare their data to the precise data of [2]; surprisingly, [2] is not even referenced in [3].

3. Theoretical predictions of isomer contributions of (γ,n) reactions

The theoretical prediction of isomer contributions in (γ,n) reactions is difficult because of several reasons: (*i*) The isomer contribution depends sensitively on the level density of high-spin states in the residual nucleus. At low energies, it is particularly difficult to estimate the level density especially for high-spin states, since the statistical approach is not valid anymore. Combinatorial or shell-model models are therefore required. In addition, there is a clear lack of experimental data that can be used to constrain such models. It has been suggested to use experimental data of the isomer contribution in (γ,n) reactions to study the high-spin level density [8]. (*ii*) Small branching ratios of low-spin states to the isomer may contribute noticeably to the total isomer cross section.

(*iii*) The neutron emission probability with large angular momenta l depends on the interplay of the attractive nuclear potential and the repulsive centrifugal barrier.

For the ^{187}Re(γ,n)^{186}Re reaction the theoretical isomer contribution increases from about 1 % to 15 % in the energy range of about 10 MeV to 20 MeV. As expected from the similarity of the involved spins and parities (see above), a similar result is obtained for the isomer contribution of the ^{185}Re(γ,n)^{184}Re reaction.

The comparison of the experimental result and the theoretical prediction of the ^{185}Re(γ,n)^{184}Re reaction [6] shows that the theoretical prediction underestimates the experimental data significantly. In contrast, for the isomer contribution in the ^{181}Ta(γ,n)^{180}Ta reaction theoretical and experimental results agree very well [8]. Only very few experimental data are available at energies close above the relevant thresholds, e.g. for the $13/2^+$ isomer in the ^{198}Hg(γ,n)^{197}Hg reaction [9].

At the present stage there is a clear discrepancy between the theoretical isomeric contribution predicted for the ^{185}Re(γ,n)^{184}Re reaction (around 1 % at 10 MeV) and the experimental results in [6], and a similar discrepancy is found for the ^{187}Re(γ,n)^{186}Re reaction as shown in Fig. 1 (right part). Further theoretical studies and improved and extended experimental data for isomer contributions in (γ,n) reactions are urgently needed to shed light on this issue.

4. Relation between (γ,n) and (n,γ) data in the lab and under stellar conditions

It has been stated in [3] that "the ^{187}Re(γ,n)^{186}Re cross section and the cross section of the inverse reaction ^{186}Re(n,γ)^{187}Re are related via the principle of detailed balance". However, the detailed balance (as usually defined in nuclear astrophysics) relates reaction rates (not cross sections):

$$\frac{\lambda^\star}{\langle\sigma v\rangle} \sim \left(\frac{G_1 G_2}{G_3}\right)\left(\frac{A_1 A_2}{A_3}\right)^{3/2} T^{3/2} \exp\left(-\frac{Q}{kT}\right) \tag{4.1}$$

The total neutron capture cross section $\sigma(n,\gamma)$ in the lab is given by the sum over all final states i in ^{187}Re:

$$\sigma(n,\gamma) = \sum_i \sigma(n_0,\gamma_i) \tag{4.2}$$

whereas the photodisintegration cross section $\sigma(\gamma,n)$ in the lab has to be summed over all final states j in ^{186}Re:

$$\sigma(\gamma,n) = \sum_j \sigma(\gamma_0,n_j) \tag{4.3}$$

Time reversal symmetry links the cross sections

$$\sigma(n_j,\gamma_i) \text{ and } \sigma(\gamma_i,n_j) \tag{4.4}$$

From the relation in Eq. (4.4) the detailed balance principle for reaction rates in Eq. (4.1) can be derived; for the example of the ^{16}O(α,γ)^{20}Ne reaction this has been shown explicitly in [10]. However, there is no simple way to relate the capture and photodisintegration cross sections in the lab as defined in Eqs. (4.2) and (4.3).

Photodisintegration data of the ^{187}Re(γ,n)^{186}Re reaction can be used to test statistical model calculations and/or to adjust the parameters of the calculations. It has been shown in [2] that different parameter sets lead to comparable agreement with the experimental data (see also Fig. 1).

A careful comparison between experimental ^{187}Re(γ,n)^{186}Re data and theoretical predictions is also given in [11].

It turns out that the predicted neutron capture cross sections of the ^{186}Re(n,γ)^{187}Re reaction show significant variations from 560 mb to 1460 mb [2, 7, 12, 13] at $kT = 30$ keV. This leads to an average cross section of $\sigma = 1070 \pm 370$ mb which is slightly lower than the adopted value of 1550 ± 250 mb [12, 13]. This result is based on statistical model calculations using parameter sets which are able to reproduce the ^{187}Re(γ,n)^{186}Re cross section. Note that the large value in the list of calculations in [13] of $\sigma = 2011$ mb is based on a parameter set which is not able to describe the recent ^{187}Re(γ,n)^{186}Re data [2] and should not be used for the ^{186}Re(n,γ)^{187}Re reaction.

5. Conclusions

The (8^+) isomer in ^{186}Re plays a significant role in the ^{187}Re(γ,n)^{186}Re photodisintegration reaction and has to be taken into account in the analysis of photoactivation data. The parameters of statistical model calculations can be restricted using the experimental ^{187}Re(γ,n)^{186}Re data; this leads to an improved neutron capture cross section of ^{186}Re at $kT = 30$ keV of $\sigma = 1070 \pm 370$ mb. Further experimental data are required for isomer contributions in (γ,n) reactions to improve the theoretical description of high-spin level densities and isomer cross sections. Using the very simplistic assumption of a constant neutron density of $N_\mathrm{n} = 4 \times 10^8$ cm^{-3} the s-process path proceeds mainly via β-decay of ^{186}Re (95 %), and the neutron capture branch via ^{186}Re(n,γ)^{187}Re remains small (5 %). Extremely small branching ratios of $(2.1 - 5.4) \times 10^{-4}$ as quoted in [3] are not understandable because any definition of the astrophysical s-process parameters is missing in [3]. Further details and information on the Re/Os chronometer can be found in the contributions of [14, 15, 16] to this conference.

Acknowledgments

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Notes added in Proof:

In a recent experiment Hayakawa *et al.* [17] have measured the half-life of ^{184}Re populated by the the ^{185}Re(γ,n)^{184}Re reaction at energies around the giant dipole resonance using the photoactivation technique. By a careful analysis of the decay curve they find an exponential decay of the activity with a half-life of $t_{1/2}(^{184}\mathrm{Re}) = 35.4 \pm 0.7$ days which is somewhat smaller than the adopted value of 38.0 ± 0.5 days. No long-living component was found, and an upper limit of about 3 % for the isomer contribution in the ^{185}Re(γ,n)^{184}Re cross section is derived in [17]. In addition, the result of [6] has been revised by the author: the stated isomer contribution of 20.8 % should be read as an upper limit [18]. Thus, the theoretical predictions for the isomer contribution of the order of a few per cent in the ^{185}Re(γ,n)^{184}Re reaction are in agreement now with the available experimental data.

The similarity of the ^{187}Re(γ,n)^{186}Re and ^{185}Re(γ,n)^{184}Re reactions is confirmed by an additional Hauser-Feshbach calculation [19]. This similarity indicates that the isomer contribution in the ^{187}Re(γ,n)^{186}Re reaction may be smaller than derived in Sect. 2 although low-lying levels in ^{186}Re with decay branches to the (8^+)isomer have been identified [16]. The origin of the discrepancy between the directly measured data of [2, 5] and the photoactivation data of [3, 6] (as shown in Fig. 1) remains unclear.