Photon-induced Reactions
in Stars and in the Laboratory:
A Critical Comparison

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Abstract. Photon-induced reactions during the astrophysical $p$-(or $\gamma$-) process occur at typical temperatures of $1.8 \leq T_9 \leq 3.3$. Experimental data of ($\gamma$,n), ($\gamma$,p), or ($\gamma$,\alpha) reactions – if available in the relevant energy region – cannot be used directly to measure astrophysical ($\gamma$,n), ($\gamma$,p), or ($\gamma$,\alpha) reaction rates because of the thermal excitation of target nuclei at these high temperatures. Usually, statistical model calculations are used to predict photon-induced reaction rates. The relations between experimental reaction cross sections, theoretical predictions, and astrophysical reaction rates will be critically discussed.

I INTRODUCTION

The nucleosynthesis of heavy neutron-deficient nuclei, so-called $p$-nuclei, proceeds mainly via a series of photon-induced ($\gamma$,n), ($\gamma$,p), and ($\gamma$,\alpha) reactions in the thermal photon bath of an explosive astrophysical event. Type II supernovae are good candidates to provide the required astrophysical environment (e.g., temperatures of $1.8 \leq T_9 \leq 3.3$) [1–4].

Calculations of the astrophysical reaction rates and cross sections are based on the statistical model; input parameters for photon-induced reactions are $\gamma$-ray strength functions, optical potentials, and level densities. Recent results are summarized in [5–7].

Experimental data for photon-induced cross sections in the astrophysically relevant energy region have been obtained using two different techniques. Monochromatic photons from Compton backscattering of a Laser beam were used by [8], and a quasi-thermal photon spectrum was obtained by a superposition of bremsstrahlung spectra [9–11].

In this paper the astrophysically relevant energy window for ($\gamma$,n), ($\gamma$,p), and ($\gamma$,\alpha) reactions [12,13] will be analyzed taking into account that the target nuclei may be thermally excited at the typical temperatures of $1.8 \leq T_9 \leq 3.3$. A critical comparison between experimental data in the laboratory and data for thermally
excited nuclei in stars will be given, and relevant input parameters for the statistical model will be clearly defined.

II  GAMOW WINDOW FOR (γ,n) AND (γ,α) REACTIONS

For simplicity, the following discussion will be restricted to (γ,n) and (γ,α) reactions. (γ,p) reactions play only a minor role in the reaction network for p-process nucleosynthesis. Additionally, most of the arguments given for (γ,α) reactions are valid for (γ,p) reactions, too.

The nucleus $^{148}$Gd and the reactions $^{148}$Gd(γ,n)$^{147}$Gd and $^{148}$Gd(γ,α)$^{144}$Sm will be chosen as an example because the nucleosynthesis path of the p-process shows a branching point between (γ,n) and (γ,α) reactions which defines the production ratio between $^{146}$Sm and $^{144}$Sm. This ratio may be used as a chronometer for the p-process [1,4,14] because it can be measured at the time of the formation of the solar system from correlations between the $^{144}$Sm abundance and isotopic anomalies in $^{142,144}$Nd in meteorites [15].

The astrophysical reaction rate $\lambda(T)$ of a photon-induced reaction is given by

$$\lambda(T) = \int_0^\infty c \ n_\gamma(E, T) \ \sigma_{\gamma,x}(E) \ dE$$

(1)

with the speed of light $c$ and the cross section of the $\gamma$-induced reaction $\sigma_{\gamma,x}(E)$. The thermal photon density $n_\gamma(E, T)$ is given by the Planck distribution

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

(2)

where $n_\gamma(E, T)$ is the number of $\gamma$-rays at energy $E$ per unit of volume and energy interval. The integrand in Eq. (1) is defined by the product of the cross section which increases with energy and the photon density which decreases exponentially with energy. This leads to a well-defined energy window which is astrophysically relevant (the so-called Gamow window). A comparison of typical Gamow windows for (γ,n) and (γ,α) reactions for target nuclei in their ground states is given in [13].

A  $^{148}$Gd(γ,n)$^{147}$Gd

The Gamow window for (γ,n) reactions is located close above the neutron threshold. The maximum of the integrand in Eq. (1) is located at $E_0^\gamma = S_n + kT/2 \approx 9200$keV for $T_\gamma = 2.5$ where $S_n$ is the neutron separation energy $S_n(^{148}$Gd) = 8984keV. The typical width of this window is about 1 MeV. Therefore, the astrophysically relevant window for the excitation energy $E_x$ is located between $S_n$ and $S_n + 1$MeV (see Fig. 1). The position of the Gamow window for (γ,n) reactions depends only weakly on the temperature.
If the nucleus $^{148}$Gd is in its $0^+$ ground state, the dominating $E1$ transitions lead to $1^-$ states in the Gamow window (left part of Fig. 1, gray shaded area). These $1^-$ states may decay by neutron emission to low-lying states in $^{147}$Gd with $E_x(^{147}$Gd) < 1 MeV. Note that there is no Coulomb barrier for neutrons, and because of the small centrifugal barrier transitions to states with low $J^\pi$ in $^{147}$Gd are preferred. The cross section for this process can be measured in the laboratory. A statistical model prediction of this cross section requires the $E1$ $\gamma$-ray strength function around the energy $E_{n0}$ for the excitation process. Neutron and $\alpha$ optical potentials, the $\gamma$-ray strength function at $E < E_{n0}^\gamma$, and the level density of the residual nuclei above experimentally known levels are required for the calculation of the possible decays of excited $^{148}$Gd by neutron, $\alpha$, or $\gamma$ emission.

The situation changes if the nucleus $^{148}$Gd is not in the ground state, but thermally excited to its low-lying levels. For simplicity, the discussion is restricted to the first two levels at $E_x = 784$ keV ($2^+$) and 1273 keV ($3^-$). A significant contribution of these levels is already obtained at temperatures $kT < E_x$ because the ratio of population $n_x/n_0$ is given by the Boltzmann factor $\exp (-E_x/kT)$ and by the statistical weight of the spins

$$\frac{n_x}{n_0} = \frac{2J_x + 1}{2J_0 + 1} \exp (-E_x/kT) = (2J_x + 1) \exp (-E_x/kT)$$  \hspace{1cm} (3)

for even-even nuclei with $J_0^\pi = 0^+$. Assuming a similar energy dependence of the $(\gamma,n)$ cross section of the excited state, one finds again a Gamow window close
above the threshold at excitation energies around $E_0^n$. However, the required photon energy for a ($\gamma,n$) reaction is reduced by the excitation energy of the populated low-lying state: $E_\gamma = E_0^n - E_x(2^+) \approx 8400$ keV and $E_\gamma = E_0^n - E_x(3^-) \approx 7900$ keV. Starting from the $2^+ (3^-)$ state, $E1$ transitions may populate states with $J^\pi = 1^-, 2^-, 3^- (J^\pi = 2^+, 3^+, 4^+)$ as shown in Fig. 1, middle and right. These states may decay by neutron emission to low-lying states in $^{147}\text{Gd}$, again preferring final states with small spin differences. This process cannot be measured in the laboratory. A statistical model calculation for these processes starting from the thermally excited $2^+ (3^-)$ state requires the $E1$ $\gamma$-ray strength function around the energy $E_\gamma = E_0^n - E_x(2^+) \approx 8400$ keV resp. $E_\gamma = E_0^n - E_x(3^-) \approx 7900$ keV for the excitation. For the decay the same ingredients as in the previous case are required.

The important results for the $^{148}\text{Gd}(\gamma,n)^{147}\text{Gd}$ reaction are that (i) excitation energies around $E_0^n \approx 9200$ keV are the relevant region independent of the thermal excitation of $^{148}\text{Gd}$, and (ii) the $E1$ $\gamma$-ray strength function has to be known at the energy $E_0^n \approx 9200$ keV for $^{148}\text{Gd}$ in the ground state and at lower energies $E_0^n - E_x$ for $^{148}\text{Gd}$ in thermally excited states. Note that the $E1$ $\gamma$-ray strength function at energies $E_0^n - E_x < S_n$ cannot be measured by ($\gamma,n$) reactions because this strength is located below threshold! A similar phenomenon of important $\gamma$-ray strength below threshold has been found for neutron capture cross sections relevant for the $\tau$-process [17]. Usually, one extrapolates the $E1$ $\gamma$-ray strength function from the giant dipole resonance (GDR) to lower energies, and one assumes, following the Brink-Axel hypothesis [18–20], that a similar GDR and $E1$ $\gamma$-ray strength distribution can be found above each excited state. Such extrapolations of the $\gamma$-ray strength function towards lower energies are extensively discussed in [21].

### B $^{148}\text{Gd}(\gamma,\alpha)^{144}\text{Sm}$

The position of the Gamow window for ($\gamma,\alpha$) reactions is mainly defined by the Coulomb barrier. The maximum of the integrand in Eq. (1) for ($\gamma,\alpha$) reactions is shifted by the $\alpha$ separation energy $S_\alpha$ compared to the ($\alpha,\gamma$) reaction:

$$E_0^\alpha = 1.22 \left( Z_f^2 Z_T^2 A_{\text{red}} T_0^2 \right)^{1/3} \text{keV} + S_\alpha \tag{4}$$

The Gamow window for ($\gamma,\alpha$) reactions is much broader compared to the ($\gamma,n$) reaction, and because many heavy neutron-deficient nuclei are $\alpha$ unbound ($S_\alpha < 0$) the energy $E_0^\alpha$ is often smaller than $E_0^n$. The position of the Gamow window depends sensitively on the temperature $T$. For $T_0 = 2.5$ one finds the Gamow window at $E_0^\alpha = 5520$ keV (with $S_\alpha = -3271$ keV) and with a width of about 3180 keV. $T_0 = 2.0$ (3.0) leads to $E_0^\alpha = 4300$ keV (6660 keV).

If the nucleus $^{148}\text{Gd}$ is in its $0^+$ ground state, the dominating $E1$ transitions lead to $1^-$ states in the Gamow window (left part of Fig. 2, gray shaded area). These $1^-$ states may decay by $\alpha$ emission to low-lying states in $^{144}\text{Sm}$. Because of the Coulomb barrier for $\alpha$ particles, the decay to the ground state of $^{144}\text{Sm}$ will be preferred; transitions to excited states in $^{144}\text{Sm}$ are suppressed because of the
reduced tunneling probability; they are shown as dashed lines in Fig. 2. The cross section for this process can be measured in the laboratory. A statistical model prediction of this cross section requires the $E1\gamma$-ray strength function around the energy $E_0^\alpha$ for the excitation. The $\alpha$ optical potential, the $\gamma$-ray strength function at $E < E_0^\alpha$, and the level density of the residual nuclei above experimentally known levels are required for the calculation of the possible decays of excited $^{148}$Gd by $\alpha$ or $\gamma$ emission; the neutron channel is not open at the low excitation energies.

Again, the situation changes if the nucleus $^{148}$Gd is not in the ground state, but thermally excited to its low-lying levels. Assuming a similar energy dependence of the $(\gamma,\alpha)$ cross section of the excited state, one finds again a Gamow window at excitation energies around $E_0^\alpha \approx 5520$ keV. However, the required photon energy for a $(\gamma,\alpha)$ reaction is reduced by the excitation energy of the populated low-lying state: $E_\gamma = E_0^\alpha - E_x(2^+) \approx 4700$ keV and $E_\gamma = E_0^\alpha - E_x(3^-) \approx 4250$ keV. Starting from the $2^+ (3^-)$ state, $E1$ transitions may populate states with $J^\pi = 1^-, 2^-, 3^-$ ($J^\pi = 2^+, 3^+, 4^+$) as shown in Fig. 2, middle and right. These states may decay by $\alpha$ emission to low-lying states in $^{144}$Sm, again preferring the ground state of $^{144}$Sm because of the Coulomb barrier (with the exception of the unnatural parity states with $J^\pi = 2^-$ and $3^+$). This process cannot be measured in the laboratory. A statistical model calculation for these processes starting from the thermally excited $2^+ (3^-)$ state requires the $E1\gamma$-ray strength function around the energy $E_\gamma = E_0^\alpha - E_x(2^+) \approx 4700$ keV resp. $E_\gamma = E_0^\alpha - E_x(3^-) \approx 4250$ keV for the excitation. For the decay the same ingredients as in the previous case are required.
The important results for the $^{148}$Gd($\gamma$,\alpha)$^{144}$Sm reaction at $T_\gamma = 2.5$ are that (i) the excitation energies around $E_0^\alpha \approx 5520$ keV are the relevant region independent of the thermal excitation of $^{148}$Gd (but $E_0^\alpha$ itself depends sensitively on the temperature!), and (ii) the $E1 \gamma$-ray strength function has to be known at the energy $E_0^\alpha$ for $^{148}$Gd in the ground state and at lower energies $E_0^\alpha - E_x$ for $^{148}$Gd in thermally excited states. Note that the $E1 \gamma$-ray strength function has now to be known at relatively low energies.

C The ratio $(\gamma,n)/(\gamma,\alpha)$

As stated above, the branching ratio between $(\gamma,n)$ and $(\gamma,\alpha)$ reactions defines the nucleosynthesis in the $p$-process. For a reliable prediction of branchings between $(\gamma,n)$ and $(\gamma,\alpha)$ reactions from statistical model calculations, various ingredients have to be known accurately. Besides the optical potentials for neutrons and $\alpha$ particles and the level densities, $E1 \gamma$-ray strength functions have to be known at different energies for the $(\gamma,n)$ and $(\gamma,\alpha)$ reactions. Therefore a precise knowledge of the energy dependence of the $\gamma$-ray strength function at low energies is essential for the prediction of the ratio of $(\gamma,n)/(\gamma,\alpha)$ cross sections. It is highly desirable to check all ingredients of the model calculations by experimental data including the Brink-Axel hypothesis [18–20] where a partial breakdown was discussed in [21].

III COMPARISON WITH EXPERIMENTAL DATA

It is found that discrepancies between different statistical model calculations are mainly caused by different extrapolations of the $E1 \gamma$-ray strength function and by different $\alpha$ optical potentials whereas various parametrizations of level densities and neutron optical potentials lead to almost identical predictions for the cross section. The study of a global $\alpha$ optical potential has been described elsewhere (see Refs. [22–26]).

The $E1 \gamma$-ray strength function was determined for many nuclei from photoabsorption data around the GDR [27]. However, the astrophysically relevant energy region for $(\gamma,n)$ and $(\gamma,\alpha)$ reactions is located at significantly lower energies. $(\gamma,n)$ data close above the neutron threshold [8–11] help to restrict the $E1 \gamma$-ray strength function at energies around $E_0^n$. Experimental data with monochromatic photons [8] should be preferred because such data can be directly compared to theoretical predictions. The method of the quasi-thermal photon spectrum using a superposition of bremsstrahlung spectra [9] provides averaged cross sections which cannot be compared to theoretical predictions directly.

A standard technique to measure $E1 \gamma$-ray strength functions at low energies is photon scattering [28]. Bremsstrahlung experiments with unpolarized photons have no sufficient sensitivity to distinguish between $E1$ and $M1$ transitions [29] and are not well-suited for the precise determination of the $E1 \gamma$-ray strength function and its energy dependence. Off-axis bremsstrahlung may provide a limited
photon polarization. However, the best solution would be photon scattering experiments using 100% polarized photons from Laser-Compton scattering. Especially the SPring-8 facility with a high electron energy of several GeV and a long Laser wavelength of several µm provides an almost white spectrum with photon energies of several MeV, huge intensities, and almost 100% polarization [30]. Alternatively, γ-ray spectra in neutron capture reactions have been used to extract the γ-ray strength function at low energies [31].

A special problem has to be mentioned. The γ-ray strength function is continuous above the neutron threshold but the measured E1 strength below neutron threshold consists of discrete levels. A direct comparison remains difficult. In the case of (γ,α) reactions the Gamow window is typically found at energies below the neutron threshold. Therefore, the relevant E1 strength is again concentrated in discrete levels, and the (γ,α) reaction rate may depend sensitively on the excitation energies of the corresponding levels.

Experimental data for the inverse capture reactions may provide further insight into the photodisintegration reaction rates. The reaction $^{144}$Sm(α,γ)$^{148}$Gd was measured close above the astrophysically relevant energies [32]. Under laboratory conditions the nucleus $^{144}$Sm is in its ground state, and the (α,γ) reaction populates many levels in $^{148}$Gd. These experimental conditions for the (α,γ) reaction are very close to the (γ,α) reaction under stellar conditions. Here many levels of $^{148}$Gd are thermally populated, and because of tunneling probabilities through the Coulomb barrier mainly the $^{144}$Sm ground state is populated in the (γ,α) reaction (see Fig. 2). However, laboratory conditions for the (γ,α) reaction with $^{148}$Gd in its ground state differ significantly from stellar conditions for the (γ,α) reaction. Therefore, a measurement of the (α,γ) reaction provides the best test for statistical model predictions of astrophysical (γ,α) reaction rates. This argument does not hold for (γ,n) reactions: under stellar conditions excited states in the target and residual nucleus have to be taken into account (see Fig. 1) whereas in laboratory (γ,n) [(n,γ)] experiments the target [residual] nucleus is in its ground state.

IV CONCLUSIONS

Reaction networks for the nucleosynthesis of heavy nuclei require a huge number of reaction cross sections and reaction rates at high temperatures which are calculated using the statistical model. Experimental data are rare in the astrophysically relevant energy region; additionally, astrophysical reaction rates cannot be derived directly from experimental data in the laboratory because of the thermal excitation of target nuclei under stellar conditions. However, experimental data can provide systematic input parameters for the statistical model calculations. Improved γ-ray strength functions and a global α-nucleus potential are needed.

Although present photodisintegration experiments at astrophysically relevant energies (e.g., [8–11]) can provide valuable information for the theoretical prediction of reaction rates, there are limitations to the extent of information because only
few relevant transitions are tested experimentally. Especially for the prediction of astrophysical ($\gamma, \alpha$) reaction rates, a measurement of the inverse ($\alpha, \gamma$) cross section seems to be a better test for the ingredients of the statistical model than a measurement of the ($\gamma, \alpha$) reaction.

The nice idea of producing a quasi-thermal photon spectrum in the laboratory [9–11] is unfortunately in many cases not really useful because the measured laboratory reaction rates may differ significantly from the reaction rates at typical stellar conditions with temperatures of about $1.8 \leq T_9 \leq 3.3$ [10]. The relevant ingredients of statistical model calculations, namely the $E_1 \gamma$-ray strength function, can be extracted with improved precision and reliability from experiments with monochromatic photons [8].

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