Experimental simulation of a stellar photon bath by bremsstrahlung: the astrophysical $\gamma$-process

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The nucleosynthesis of heavy proton-rich nuclei in a stellar photon bath at temperatures of the astrophysical $\gamma$-process was investigated where the photon bath was simulated by the superposition of bremsstrahlung spectra with different endpoint energies. The method was applied to derive $(\gamma, n)$ cross sections and reaction rates for several platinum isotopes.

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The trans-iron nuclei have been synthesized by neutron capture in the $s$- and $r$-processes, except the $p$-nuclei ($p$ for proton-rich), with relative abundances of the order of 0.01 to 1% [1–6]. The main production mechanism of the $p$-nuclei is assumed to be photodisintegration in the $\gamma$-process, i.e. by $(\gamma, n)$, $(\gamma, p)$, and $(\gamma, \alpha)$ reactions induced on heavier seed nuclei synthesized in the $s$- and $r$-processes. Typical parameters for the $\gamma$-process are temperatures of $2 \leq T \leq 3$ (in the temperature in units of $10^9$ K), densities $\rho \approx 10^6$ g/cm$^3$, and time scales $\tau$ in the order of seconds. Several astrophysical sites for the $\gamma$-process have been proposed, whereby the oxygen- and neon-rich layers of type II supernovae seem to be good candidates. However, no definite conclusions have been reached yet [1–6], predominantly due to the lack of experimental data for the cross sections and reaction rates of the $\gamma$-induced reactions at astrophysically relevant energies. All reaction rates have been derived theoretically using statistical model calculations [1–6].

The energy distribution of a thermal photon bath at a temperature $T$ is given by the Planck distribution

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

where $n_\gamma(E, T)$ is the number of $\gamma$-rays at energy $E$ per unit of volume and energy interval. In a photon-induced reaction $B(\gamma,x)A$ the distribution leads to a temperature dependent decay rate $\lambda(T)$ of the initial nucleus $B$

$$\lambda(T) = \int_0^\infty c \cdot n_\gamma(E, T) \cdot \sigma(\gamma,x)(E) \cdot dE$$

with the speed of light $c$ and the cross section of the $\gamma$-induced reaction $\sigma(\gamma,x)(E)$. Obviously, $\lambda$ is also the production rate of the residual nucleus $A$. In the following we will focus on photodisintegration by the $(\gamma, n)$ reactions.

A large number of $(\gamma, n)$ cross sections has been measured over the years [1–6]. However, most of the data have been obtained around the giant dipole resonance (GDR), i.e. at energies much higher than those in stars, and practically no data exist for the $p$-nuclei. The integrand in Eq. (2) is given by the product of the $\gamma$ flux $c \cdot n_\gamma(E, T)$, which decreases steeply with increasing energy $E$, and the cross section $\sigma(\gamma,x)(E)$, which increases with $E$ approaching the GDR region. The product leads then to a window at an effective energy $E_{\text{eff}}$ with a width $\Delta$ similar to the Gamow window for charged-particle-induced reactions. If one assumes a typical threshold behavior of the $(\gamma, n)$ cross section close to the threshold energy $E_{\text{thr}}$, the effective energy is approximately given by $E_{\text{eff}} = E_{\text{thr}} + \frac{1}{2}kT$, and the typical width $\Delta$ is in the order of 1 MeV (Fig. 1).

FIG. 1. Astrophysically relevant energy window for the $^{192}\text{Pt}(\gamma,n)^{191}\text{Pt}$ reaction ($E_{\text{thr}} = 8676$ keV) in a thermal photon bath with temperature $T_0 = 2.5$. The Planck distribution $n_\gamma(E, T)$ (dotted line) and the $(\gamma, n)$ cross section $\sigma(E)$ (dashed line) are given in relative units. The product $c \cdot n_\gamma(E) \cdot \sigma(E)$ shows a maximum at the effective energy $E_{\text{eff}} \approx E_{\text{thr}} + \frac{1}{2}kT$ (full line). The GDR parameters were taken from experimental data [1–6] and the threshold behavior $\sigma \sim \sqrt{E - E_{\text{thr}}}$ was matched to the Lorentzian shaped GDR cross section 1 MeV above the threshold.

The energy distribution of bremsstrahlung is approximately described by the Schiff formula [6]. Close to the endpoint energy $E_0$ (which is also the energy of the incoming electron beam) the bremsstrahlung spectrum decreases steeply with increasing energy. We found that...
over a narrow energy region the bremsstrahlung spectrum has a similar shape as the Planck spectrum. However, a superposition of several bremsstrahlung spectra \( \Phi_{\text{brems}}(E_{0,i}) \) with different endpoint energies \( E_{0,i} \) leads to a quasi-thermal spectrum \( \Phi_{\text{brems}}^q(T) \) which has nearly the same shape as the Planck spectrum over a relatively broad energy range (Fig. 2):

\[
c n(E, T) \approx \Phi_{\text{brems}}^q(T) = \sum_i a_i(T) \cdot \Phi_{\text{brems}}(E_{0,i})
\]

where the strength coefficients \( a_i(T) \) must be adjusted for each temperature \( T \). The example shown in Fig. 3 demonstrates that a reasonable agreement between quasi-thermal and thermal spectrum in the astrophysically relevant energy range from 6 to 10 MeV is already obtained by the superposition of six bremsstrahlung spectra. The bremsstrahlung spectra have been calculated from GEANT simulations [10], which compare well with the observed photon flux of the \( ^{11}\text{B}\,(\gamma,\gamma') \) reaction (see below). However, close to the endpoint energy the simulated spectra had to be slightly reduced. Details of the calculated bremsstrahlung spectra will be given elsewhere [11].

For an application of the quasi-thermal bremsstrahlung spectrum we have chosen to measure the \( (\gamma,n) \) cross sections of several platinum isotopes using the activation technique. The high sensitivity of this technique allows for a concurrent measurement of the \( (\gamma,n) \) cross sections for \(^{190}\text{Pt} \) (natural abundance = 0.014%), \(^{192}\text{Pt} \) (0.782%), and \(^{198}\text{Pt} \) (7.163%) due to similar half-lives of the residual nuclei \(^{189}\text{Pt}, \, \, ^{191}\text{Pt}, \) and \(^{197}\text{Pt} \) [e.g. \( T_1/2^{191}\text{Pt} = 2.862 \text{ d} \)].

The experiment was performed at the real photon facility of the superconducting Darmstadt linear electron accelerator S–DALINAC [12–14]. The electron beam with a typical beam current up to 40 \( \mu \text{A} \) was stopped in a massive copper disk leading to a photon flux of about \( 10^3 \text{ (keV cm}^2\text{s)} \) at the irradiation position. For the irradiation platinum disks (20 mm diameter, 0.125 mm thickness) of natural isotopic composition were mounted at the target position of the \( (\gamma,\gamma') \) setup [13]. The disks were sandwiched between two boron layers with masses of about 650 mg each. For normalization of the photon flux, spectra of resonantly scattered photons from nuclear levels of \(^{11}\text{B} \) were obtained during the activation with two high purity germanium (HPGe) detectors (100% relative efficiency) placed at 90° and 130° relative to the incoming photon beam (for details, see also [13]). The platinum disks were irradiated for about one day, and then they were mounted in front of a third HPGe detector (30% relative efficiency), where the \( \gamma \)-activity was observed for one day. A typical spectrum is shown in Fig. 3: \( \gamma \)-ray lines from the decay of the platinum isotopes \(^{189}\text{Pt}, \, \, ^{191}\text{Pt}, \) and \(^{197}\text{Pt} \) can clearly be identified. Additionally, two lines from the decay of \(^{193m}\text{Pt} \) were detected; this isomer is mainly populated by the \( (\gamma,\gamma') \) reaction. In another experiment [10], the decay curves of several lines were measured and found to be in excellent agreement with the recommended half-lives [7].

Irradiations were performed using seven endpoint energies from \( E_{0,\text{min}} = 7200 \text{ keV} \) to \( E_{0,\text{max}} = 9900 \text{ keV} \) in steps of 450 keV. In the conventional analysis of the data the shape of the \( (\gamma,n) \) cross section was assumed to exhibit a typical threshold behavior:

\[
\sigma = \sigma_0 \cdot \sqrt{(E - E_{\text{thr}})/E_{\text{thr}}} \quad .
\]
The average deviation between the Planck distribution decay rate to the experimental yields is 10% in the relevant energy region around $E_{\text{thr}} = E_{\text{thr}} + \frac{1}{2} kT$. The results of the analysis with the quasi-thermal spectrum are also presented in Table I together with results from statistical model calculations using the code NON-SMOKER [19].

For the future study of $(\gamma,n)$ reactions on $p$-nuclei with their low abundances the sensitivity of the experiments can be improved with enriched samples. These $(\gamma,n)$ data might restrict the relevant parameters of $\gamma$ process models leading eventually to definite conclusions for the astrophysical site of the $\gamma$ process.

Finally, under stellar conditions the target nucleus can be excited in the thermal photon bath reducing the effective neutron threshold by the respective excitation energy. This two-step process must be taken into account in model calculations [19], because in our experiment the target nucleus is always in the ground state.

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### TABLE I. Summary of the $(\gamma,n)$ results for the platinum isotopes $^{190}$Pt, $^{192}$Pt, and $^{198}$Pt.

| Target $E_{\text{thr}}$ (keV) | $\sigma_0$ (mb) | $\lambda_{\text{conv}}$ (s$^{-1}$) | $\lambda_{\text{q}}$ (s$^{-1}$) | $\lambda_{\text{tho}}$ (s$^{-1}$) |
|-----------------------------|----------------|-------------------------------|----------------|----------------|
| $^{190}$Pt                   | 8911           | 350 ± 150                     | 0.38 ± 0.16   | --             | 0.18           |
| $^{192}$Pt                   | 8676           | 120 ± 25                      | 0.37 ± 0.08   | 0.37 ± 0.07    | 0.58           |
| $^{198}$Pt                   | 7556           | 155 ± 25                      | 72 ± 6        | 62 ± 9         | 50 ± 9         |

$^a$ The $^{190}$Pt$(\gamma,n)^{190}$Pt reaction could be measured only at the highest endpoint energy $E_0 = 9900$ keV because of the low natural abundance of $^{190}$Pt (0.014%).

$^b$ Our new experimental result for $\sigma_0$ of the reaction $^{198}$Pt$(\gamma,n)^{197}$Pt is in good agreement with the data from [15], where the neutron yield has been measured from the GDR region down to about 500 keV above the $(\gamma,n)$ threshold.

$^c$ The high rate of $^{198}$Pt is a consequence of the lower threshold energy.