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First experimental (n, γ) cross sections of heavy p-process nuclei.

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J. Marganiec[*][†], **I. Dillmann**[‡], **C. Domingo Pardo**[§], **F. Käppeler, and S. Walter**
Forschungszentrum Karlsruhe, Institut für Kernphysik, 76344 Eggenstein-Leopoldshafen, Germany
E-mail: `justmarg@uni.lodz.pl`

First measurements of the stellar neutron capture cross sections are reported for the stable p isotopes ^{168}Yb, ^{184}Os, and ^{196}Hg. For ^{180}W and ^{190}Pt the uncertainties of 11% and 27% from previous measurements could be significantly reduced. Neutrons were produced at the Karlsruhe 3.7 MV Van de Graaff Accelerator via the $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ reaction. A series of activation measurements was carried out in a quasi-stellar neutron spectrum of $kT = 25$ keV. The stellar cross sections extrapolated to $kT = 30$ keV were found to be 1214 ± 49 mbarn, 660 ± 53 mbarn, 590 ± 38 mbarn, 508 ± 44 mbarn, 204 ± 8 mbarn, and 26.7 ± 1.3 mbarn for ^{168}Yb, ^{180}W, ^{184}Os, ^{190}Pt, ^{196}Hg, and $^{196}\mathrm{Hg}^{\mathrm{m}}$, respectively. These measurements are completing a systematic study of stellar (n, γ) cross sections of 14 stable p isotopes. The new results will be directly applied in p-process studies using a reaction library with all available experimental information.

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[*] Speaker.
[†] present address: Division of Nuclear Physics, University of Lodz, Pomorska 149/153, 90-236 Lodz, Poland
[‡] present address: Physik-Department E12, Technische Universität München, Garching, Germany
[§] present address: GSI Darmstadt, Planckstr. 1, 64291 Darmstadt, Germany

1. Introduction

The present measurements of the (n,γ) cross sections of ^{168}Yb, ^{180}W, ^{184}Os, ^{190}Pt, and ^{196}Hg are motivated by the fact that the neutron captures on proton-rich nuclei are an important aspect for the nucleosynthesis of the heavy elements in the *p* process. The importance of (n,γ) reactions in the *p* process refers to the competition with (γ,n) reactions, which affects the photodisintegration flux towards lighter nuclei, and to the formation of the final *p*-process abundances during the freeze-out phase. However, the knowledge of neutron capture cross sections of the rare proton-rich isotopes is rather limited or even still missing.

The experiment was carried out by the activation technique, taking advantage of the excellent sensitivity and selectivity of this method that allows one to determine the (n,γ) cross sections of very rare even with samples of natural composition, because the various reaction channels can unambiguously separated by the characteristic γ decay of the product nuclei. The activation technique consists of two steps, neutron irradiation of the sample in a well defined neutron spectrum and the subsequent determination of the induced activity [1].

2. Experiment

The activation measurements were performed at the Karlsruhe 3.7 MV Van de Graaff accelerator. Neutrons were produced with the ^{7}Li$(p,n)^{7}$Be reaction by bombarding thin layers of LiF on Cu backings with protons of $E_p = 1912$ keV. At this energy, the neutrons are kinematically collimated in a forward cone of 120° opening angle and with a maximum energy of 106 keV. Under these conditions, the angle-integrated neutron spectrum corresponds closely to a Maxwell-Boltzmann distribution for a thermal energy of $kT = 25.0 \pm 0.5$ keV. Hence, the Maxwellian averaged cross sections (MACSs) at 25 keV required for stellar *s*-process studies can be directly measured by activation in this neutron field [1, 2].

Apart from the Pt samples, which were cut from metal foils, the chemically stable compounds Yb_2O_3, OsO_2, and Hg_2Cl_2 have been used for pressing thin sample discs. All samples were prepared from materials of natural composition Ref. [3]. The only exception was the ^{180}W sample, which was made from metal powder with 91.4% enrichment. The samples were 6 and 10 mm in diameter, sandwiched between 0.03 mm thick gold foils of the same diameter, which served for neutron flux determination. Repeated activations have been carried out for each of the investigated reactions in order to verify the data analysis procedures.

Throughout the activations the Van de Graaff accelerator was operated in DC mode with beam currents between 80 and 100 μA, yielding an average neutron flux of $\sim 10^9$ n/s. The experimental setup shown in Figure 1 included a ^{6}Li-glass detector for monitoring the neutron flux in time steps of 30 s for the proper evaluation of the decay correction f_b described below.

After the irradiations, the induced activities of the investigated samples and of the gold foils were counted with high purity Ge detectors. In all cases, the most intense, pure γ-ray lines emitted in the decay of the product nuclei were used in the analysis. The decay properties of these lines are summarized in Table 1.

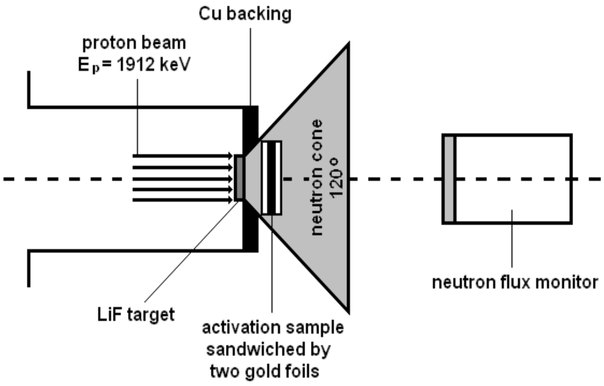

Figure 1: Schematic sketch of the experimental setup.

Table 1: Decay characteristics of the activated product nuclei.

Isotope	$t_{1/2}$	E_γ [keV]	I_γ [%]	Reference
^{169}Yb	32.026 (5) d	130,52368	11,31 (21)	[4]
		177.21402	22.2 (4)	
		197.95788	35.8 (7)	
		307.73757	10.05 (18)	
^{181}W	121.2 (2) d	136.28	0.0311 (10)	[5]
		152.32	0.083 (3)	
^{185}Os	93.6 (5) d	646.116	78.0 (31)	[5]
^{191}Pt	2.802 (25) d	359.88	6.4 (5)	[6]
		538.87	15.9 (12)	
^{197}Hg	64.14 (5) h	77.351	18.7 (4)	[7]
^{197}Hg^{m}	23.8 (1) h	133.98 (IT)	33.48 (26)	[7]
^{198}Au	2.69517 (21) d	411.8	95.58 (12)	[8]

3. Data analysis

The number of activated nuclei A at the end of irradiation is

$$A = \Phi_{tot} N \sigma f_b \tag{3.1}$$

where Φ_{tot} denotes the time integrated neutron flux, N the sample thickness, σ the spectrum averaged (n,γ)cross section, and f_b the correction factor for variations in the neutron flux and for the decay of activated nuclei during the irradiation time t_a [1].

The number of counts C in the respective γ-ray lines can be written as

$$C = A K_\gamma \varepsilon_\gamma I_\gamma (1 - e^{-\lambda t_m}) e^{-\lambda t_w}, \tag{3.2}$$

where A is the number of activated nuclei, K_γ the γ-ray self absorption in the sample, ε_γ the detector efficiency, I_γ the intensity per decay, t_m the measuring time, and t_w the waiting time between irradiation and activity measurement [1].

Since all measurements were performed relative to gold, one has

$$\frac{A}{A_{Au}} = \frac{\sigma}{\sigma_{Au}} \cdot \frac{N}{N_{Au}} \cdot \frac{f_b}{f_{b_{Au}}}. \tag{3.3}$$

The measured spectrum averaged cross section σ can be converted into a MACS for $kT = 25$ keV by applying a small modification, which is connected with the difference between the experimental neutron spectrum and the true Maxwellian shape. The extrapolation of these results to the values for $kT = 30$ keV given in Table 2 was based on the available shape of the energy differential capture cross sections.

4. Results

The MACSs obtained in a total of 19 activations are summarized in Table 2. The individual results exhibit uncertainties between 4.0% and 8.6%, which are mainly determined by uncertainties of the γ-ray intensities used. The comparison with previous data (Refs. [9] - [21]) in Fig. 2 shows in general fair agreement, except for the theoretical predictions of the ^{196}Hg cross section. In all cases, however, the uncertainties could be significantly improved.

Table 2: Present Maxwellian averaged cross sections for $kT = 30$ keV.

Isotope	MACS (mbarn)	Rel. uncertainty (%)
^{168}Yb	1214 ± 49	4.0
^{180}W	660 ± 53	8.0
^{184}Os	590 ± 39	6.6
^{190}Pt	508 ± 44	8.6
^{196}Hg	204 ± 8	4.0
^{196}Hg$^{\mathrm{m}}$	26.7 ± 1.3	4.7

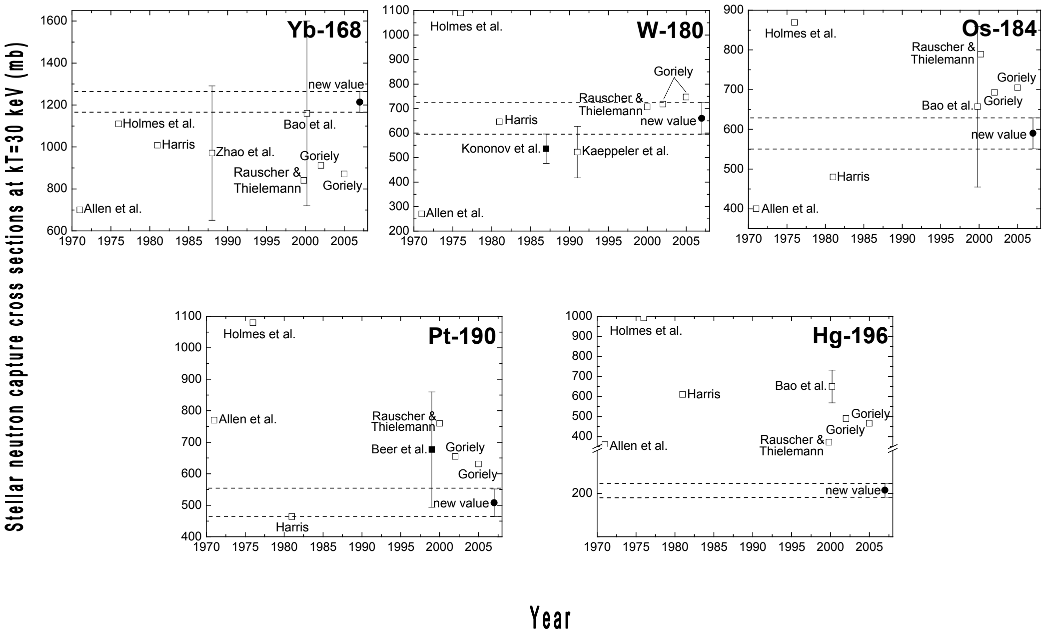

Figure 2: The present Maxwellian averaged cross sections for $kT = 30$ keV compared with previous data.

5. Summary

The (n,γ) cross sections of ^{168}Yb, ^{180}W, ^{184}Os, ^{190}Pt, ^{196}Hg, and ^{196}Hg$^{\mathrm{m}}$ have been measured by means of the activation technique, using a quasi-stellar neutron spectrum produced via the ^{7}Li$(n,p)^{7}$Be reaction, which is a good approximation of the Maxwell-Boltzmann distribution for a thermal energy of $kT = 25$ keV. The uncertainties between 4 and 8% - depending on the quality of the respective γ-ray intensities - represent a substantial improvement compared to previous data. With this study, a complete set of experimental stellar (n,γ) cross sections for the stable p nuclei could be established for the first time.

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