\(^{197}\text{Au}(n, \gamma)\) - towards a new standard for energies relevant to stellar nucleosynthesis

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Abstract. Two experiments were performed to resolve a discrepancy of the \(^{197}\text{Au}(n, \gamma)\) cross section between the IAEA standard evaluation and the reference cross section for astrophysical experiments in the lower keV energy region. We measured the \(^{197}\text{Au}(n, \gamma)\) reaction by means of the time-of-flight technique with n\(_{\text{TOF}}\) at CERN and extracted the cross section in the unresolved resonance region between 5-400 keV with an overall uncertainty from 3.9-6.7\% for a resolution of 20 bins per energy decade. Additionally, we remeasured the neutron spectrum of the \(^{7}\text{Li}(p, n)^{7}\text{Be}\) reaction with \(E_p=1912\) keV, which was used as a neutron source for determining the astrophysical reference cross section. The n\(_{\text{TOF}}\) data are already fully analyzed and published. The results are in good agreement with the ENDF standard evaluation, but uncertainties don’t allow to draw definite conclusions. The analysis of the neutron spectrum of \(^{7}\text{Li}(p, n)^{7}\text{Be}\) is underway, preliminary results will be reported here.

1. Introduction

The \(^{197}\text{Au}(n, \gamma)\) cross section is an accepted standard for thermal neutron energies and for neutron energies from 200 keV to 2.8 MeV [1]. The standard evaluation, based on several experimental datasets also covers the lower keV region starting from 2.5 keV, where the \(^{197}\text{Au}(n, \gamma)\) is not considered as standard due to discrepancies of 6-8\% relative to the Au cross section used as a reference in astrophysical experiments. This latter cross section is based on an activation measurement by Ratynski and Käppeler [2] in combination with a time-of-flight
The activation study was performed using the $^7$Li($p$, $n$)$^7$Be reaction as a neutron source with a proton energy, $E_p = 1912$ keV. Under these conditions, the emitted neutron spectrum resembles closely the spectrum required for measuring the Maxwellian Averaged Cross Section (MACS, energy dependent cross section averaged over the stellar neutron spectrum) at $kT \sim 25$ keV, thus simulating stellar conditions. Since the proton energy is only slightly above the reaction threshold of 1881 keV, neutrons are emitted in a forward peaked cone with 120 degrees opening angle. The Au sample was chosen to cover the entire neutron beam, allowing to directly determine the neutron flux by measuring the activity of the product $^7$Be. The energy dependence of the cross section by Macklin et al. was used to correct for differences between the laboratory neutron distribution and a true Maxwellian spectrum. Ratynski and Käppeler found a MACS at $kT = 30$ keV of $(582 \pm 9)$ mb, in good agreement with the results obtained via the time-of-flight technique by Macklin et al.

In the following we report on recent experiments aimed at resolving the discrepancies mentioned above. One of them is the measurement of the $^{197}$Au($n$, $\gamma$) cross section at the time-of-flight facility n_TOF at CERN in the keV region [5]. As a second approach, we remeasured the neutron spectrum at Physikalisch-Technische Bundesanstalt Braunschweig (PTB) produced under the same conditions as the Ratynski and Käppeler experiment [6].

2. Measurement of $^{197}$Au($n$, $\gamma$) at n_TOF

The neutron time-of-flight facility n_TOF installed at CERN produces a highly intense, pulsed neutron beam by spallation reactions of 20 GeV/c protons provided by the CERN PS impinging on a massive, water moderated and cooled lead target. The short proton pulse width of 7 ns and the large neutron flight path of 185 m guarantee a high energy resolution. More information can be found elsewhere [7]. Neutron captures on $^{197}$Au were studied for neutron energies from 1 eV-400 keV using a pair of C$_6$D$_6$ liquid scintillation detectors, detecting the prompt $\gamma$-emission following a neutron capture event. For energies up to 5 keV a resonance analysis was performed by Massimi et al. [8]. Here we will concentrate on the results of the unresolved resonance region covering neutron energies from 5 to 400 keV [5].

Using the C$_6$D$_6$ detection system, the efficiency to detect a capture event, which depends on the details in the deexcitation path of the nucleus can be taken into account using the pulse-height-weighting-technique [9]. After applying this correction, the capture yield in the unresolved resonance region is obtained as

$$Y = f_{corr} \times \frac{C_W}{\Phi \times E_C}$$

where $C_W$ denotes the weighted, background subtracted count-rate, $\Phi$ the neutron flux, $E_C$ the excitation energy and $f_{corr}$ takes into account corrections for the sample size. A careful analysis of the background components was performed by measurements and verified by Monte Carlo simulations including an extensive description of the experimental setup. The neutron flux was measured using a $^{235}$U loaded parallel plate fission chamber from PTB [10] and continuously monitored by placing a Mylar foil deposited with Li in the beam and detecting the reaction products of $^6$Li($n$, $\alpha$)$^3$H with surrounding Si detectors. Furthermore, the yield was corrected for the fact that the sample is smaller than the neutron beam by normalizing the reaction yield to the 4.9 eV saturated resonance in Au. Multiple scattering and self shielding effects were calculated using the code SESH [11].

The neutron capture cross section could be extracted with a total uncertainty of 3.9-6.7% for a neutron energy resolution of 20 bins per decade. The results show good agreement with the ENDF standard evaluation as shown in Fig. 1. We also calculated the MACS from $kT = 5$ keV to $kT = 100$ keV. The MACS at 30 keV is in very good agreement with the MACS of the ENDF
standard evaluation. Our result is also in fair agreement with the value obtained by Ratynski and Käppeler (see Table 1).

![Figure 1](image.png)

**Figure 1.** The $^{197}$Au($n, \gamma$) cross section measured at n$_{TOF}$ [5] compared to the ENDF/B-VII standard evaluation [12]

| Author                                    | $<\sigma>_{30keV}$ (mb) |
|-------------------------------------------|-------------------------|
| ENDF/B-VII [12, 13]                       | 614.1                   |
| Ratynski and Käppeler, 1988 [2]           | 582 ± 9                 |
| Lederer et al., 2011 [5]                  | 611 ± 22                |

3. Measurement of the $^7$Li($p, n$)$^7$Be neutron spectrum at PTB

The neutron spectrum of the reaction $^7$Li($p, n$)$^7$Be was measured at PTB Braunschweig via the time-of-flight technique. A pulsed proton beam, 3 ns in width and $(1912 \pm 1)$ keV in energy was provided by the Van de Graaff Accelerator of the PTB Ion Accelerator Facility PIAF. The metallic Li target, evaporated onto a Ta backing was 565 $\mu$g/cm$^2$ in thickness, sufficient to slow down all protons below the reaction threshold. The time-of-flight spectra were recorded in steps of 5 degrees with a moveable Li-glass detector at angular positions from 0-65 degrees with respect to the proton beam. Two runs were performed using different flight paths of 35 cm and 70 cm. The shorter flight path provided a more detailed investigation of the low energy end of the spectra because of the reduction of wrap-around effects. A long counter at an angular position of 16 degrees relative to the proton beam and a distance of approximately 6 m from the target served as fluence monitor. The stability of the setup was checked by regular measurements at a reference position of 70 cm flight path and 0 degree angle.

The background and dead-time corrected time-of-flight spectra were transformed to an energy grid and normalized for the neutron fluence provided by the long counter. We applied corrections for the detection efficiency performing Monte Carlo simulations, taking into account the details of the experimental setup. The individual angular spectra were scaled for their solid angle and
summed. Figure 2 shows the summed spectrum at a flight path of 70 cm compared to the measurement by Ratynski and Kappeler. The agreement is fairly well, our measurement shows deviations specifically in the high neutron energy range and around 20 keV. However, the effect on the averaged Au cross section due to these differences is negligibly small.

![Neutron Spectrum](image)

**Figure 2.** Angle integrated neutron spectrum measured at PTB compared to the results of Ratynski and Kappeler [2]. Both spectra are normalized to an area of 1.

4. Summary

We performed two different experiments to resolve the discrepancy of the $^{197}$Au($n, \gamma$) cross section between the ENDF standard evaluation and the reference cross section used for astrophysical experiments below 200 keV. Our results for the $^{197}$Au($n, \gamma$) cross section measured at n_TOF are in good agreement with the ENDF/B-VII standard evaluation, and, within the quoted uncertainty with the activation study by Ratynski and Kappeler and the time-of-flight measurement performed by Macklin *et al.* Preliminary results on the neutron spectrum of the $^7$Li($p, n$)$^7$Be reaction show only small deviations from the Ratynski and Kappeler measurement and thus this aspect cannot be regarded as a reason for a discrepancy of $6−8\%$ to the ENDF/B-VII standard evaluation. Currently, further activities are being pursued like a time-of-flight measurement of the Au cross section at the Geel-Electron-Linear-Accelerator at IRMM [14] and a study describing an independent definition of the $^7$Li($p, n$)$^7$Be spectrum and an activation measurement of the Au cross section in that spectrum [15]. Additional systematic studies concerning the $^7$Li($p, n$)$^7$Be spectrum and spectrum averaged cross sections are planned in framework of EUFRAT2010 [16].

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[1] A.D. Carlson *et al.*, Nucl. Data Sheets, 110, 3215 (2009).
[2] W. Ratynski and F. Kappeler, Phys. Rev. C 37, 595 (1988).
[3] R.L. Macklin, J. Halperin, and R.R. Winters, Phys. Rev. C., 11, 1270 (1975).
[4] R. Macklin, private communication to Mughabghab, S.F. (1982), see also www.nndc.bnl.gov/nndc/EXFOR 12720.002 (unpublished).
[5] C. Lederer, and the n_TOF collaboration, Phys. Rev. C, 83 034608 (2011).
[6] C. Lederer *et al.*, in preparation.
[7] U. Abbondanno *et al.*, Technical report CERN-SL-2002-053 ECT, CERN n_TOF Facility: Performance Report, CERN, Geneva (2003).
[8] C. Massini, C. Domingo Pardo, and the $n$-TOF collaboration, Phys. Rev. C, 81, 044616 (2010).
[9] R.L. Macklin and R.H. Gibbons, Phys. Rev. 159, 1007 (1967).
[10] C. Borcea et al., Nucl. Instrum. Methods Phys. Res. A, 513, 524 (2003).
[11] F.H. Fröhner, SESH computer code, GA-8380, Gulf General Atomic, (1968).
[12] M.B. Chadwick et al., ENDF/B-VII.0: Next generation evaluated nuclear data library for nuclear science and technology, Nucl. Data Sheets, 107, 2931 (2006).
[13] I. Dillmann, M. Heil, F. Käppeler, R. Plag, T. Rauscher, and F.-K. Thielemann, KADoNiS - The Karlsruhe Astrophysical Database of Nucleosynthesis in Stars, AIP Conf. Proc., 819, 123; online at http://www.kadonis.org.
[14] C. Lampoudis, et al., IRMM, Private Communication (2011).
[15] G. Feinberg, et al., Quasi-stellar neutrons from the $^7$Li(p,n) reaction with an energy-broadened proton beam, publication in preparation.
[16] F. Käppeler, et al., Neutron capture cross section of $^{197}$Au(n,$\gamma$) at the VdG using a $^7$Li(p,n) neutron beam, EUFRAT proposal, 2010.