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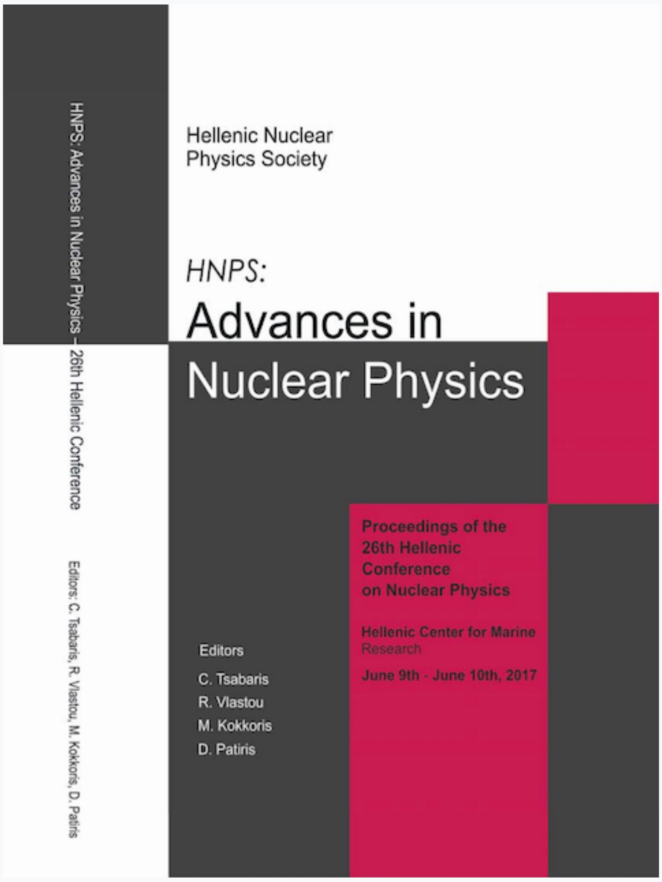

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Measurement and theoretical calculations for the cross section of the $^{197}Au(n,2n)^{196}Au$ reaction

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Abstract The cross section of the reaction $^{197}Au(n,2n)$ was experimentally determined relative to the $^{27}Al(n,\alpha)^{24}Na$ reaction at 17.9 MeV incident neutron energy using the activation technique. The quasi-monoenergetic neutron beam was produced at the 5.5 MV Tandem accelerator of NCSR "Demokritos" via the $^{3}H(d,n)^{4}He$ reaction. Following the irradiations the activity induced by the neutron beam at the targets and reference foils was measured by HPGe detectors. The cross sections for the population of the second isomeric state (m2) of ^{196}Au and the sum of the ground and isomeric states (g+m1+m2) population cross sections were independently determined. Theoretical calculations of the above cross sections were carried out using the TALYS code.

Keywords neutron, gold, cross section, TALYS

INTRODUCTION

The (n,2n) reaction on Au is proposed as a standard for high energy neutron dosimetry and is also important as monitor reaction. Due to the formation of a high spin isomeric state (12^-) of the residual nucleus ^{196}Au that presents a large spin difference with the ground state (2^-), constitutes a sensitive test case for many nuclear reaction model codes [1-4]. Moreover, the experimental data that exist in the literature [5] for the second isomeric state above 15 MeV are sparse and discrepant.

Thus, the purpose of this work was to experimentally determine the cross section of the $^{197}Au(n,2n)^{196}Au$ and $^{197}Au(n,2n)^{196}Au^{m2}$ reactions at incident neutron energy 17.9 MeV and to perform theoretical calculations for the cross section of the two studied reactions implementing the TALYS 1.8 code. This work is complementary to previous ones from our group [6,7].

EXPERIMENTAL PROCEDURE

The measurement was performed at the 5.5 MeV Tandem T11/25 Accelerator of NCSR "Demokritos" by means of the activation technique, relative to the $^{27}Al(n,\alpha)^{24}Na$ reference reaction cross section. The quasi-monoenergetic neutron beam was produced via the $^{3}H(d,n)^{4}He$ reaction when the 2 MeV incident deuteron beam impinged on the solid Ti-T target, at a deuteron beam current of ~ 0.3 μA. The samples were placed at a distance of ~ 2 cm from the Ti-T target so that the neutrons irradiating the samples be practically monoenergetic (±19º). The high purity gold sample of 0.5 mm thickness and 14 mm diameter, was placed between two aluminum foils of the same dimensions in order to determine the neutron flux using the mean value of the front and back Al fluxes and the corresponding result was found to be of the order of $\sim 2\cdot 10^{6}$ n/cm^{2} s. The irradiation lasted for 9.7 h, during which the neutron beam was monitored by means of a BF_3 counter and this information on the beam variation was used in the off-line analysis to account for the decay of the product nuclei during the irradiation time. For the neutron beam study the NeuSDesc [8] and MCNP5 [9] codes were implemented and the results for the neutron flux at the same distance from the Ti-T target are presented in Fig. 1. Thus, the mean neutron energy was estimated to be 17.9 ± 0.3 MeV.

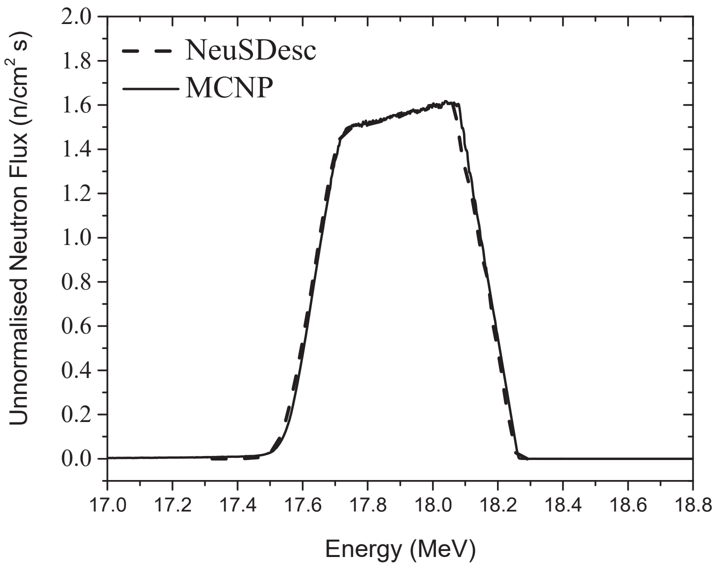


Fig. 1. Neutron flux with NeuSDesc and MCNP codes at 21 mm distance from the Ti-T target.

After the end of the irradiation, the induced activity on the target and reference foils was measured using HPGe detectors. The calibration and the absolute efficiency of the detectors were determined via a ^{152}Eu point source, which was placed at a distance of 10 cm from the detector window, as was done with the irradiated targets, in order to avoid pile up or coincidence summing corrections. Moreover, self-absorption effects were taken into account via MCNP5 simulations and found to be crucial especially for the low energy γ-rays of $^{196}Au^{m2}$.

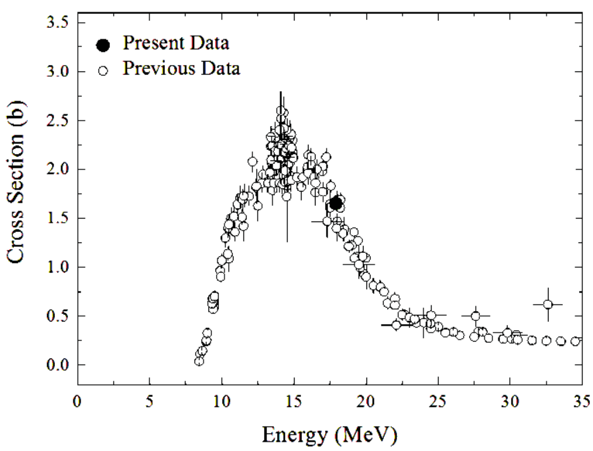
EXPERIMENTAL RESULTS AND UNCERTAINTIES

The cross section of the second isomeric state was determined independently and the decay properties of the daughter nuclei that were used in the analysis are presented in Table 1. From each γ- ray a different cross section value was obtained and the weighted average of the three and two cross section values, for the $^{197}Au(n,2n)^{196}Au$ and $^{197}Au(n,2n)^{196}Au^{m2}$ reactions respectively, was considered as the preliminary result for the cross section of the two reactions.

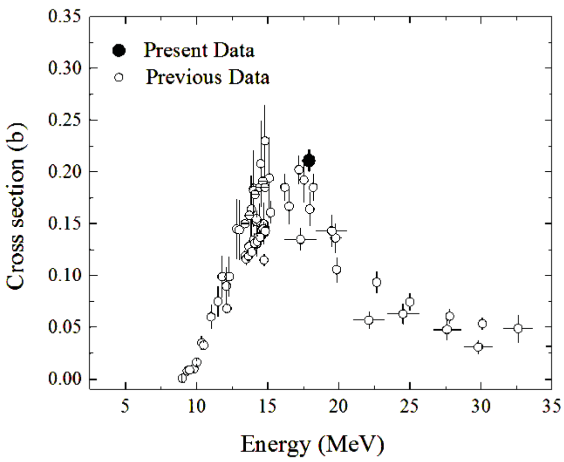
Reaction	Half – life	Energy (keV)	Intensity per decay (%)
$^{197}Au(n,2n)^{196}Au$	6.18 d	355.7	87.0
		333.0	22.9
		426.0	7.0
$^{197}Au(n,2n)^{196}Au^{m2}$	9.6 h	147.8	43.0
		188.3	37.4

Table. 1. Decay properties for every reaction and every γ-ray of interest.

The preliminary results for the cross sections of the $^{197}Au(n,2n)^{196}Au$ and $^{197}Au(n,2n)^{196}Au^{m2}$ reactions are presented in Figs. 2(a) and 2(b), respectively, as a solid circle.



(a)



(b)

Fig. 2. Preliminary cross section values, along with the existing experimental data in literature [5], for (a) the $^{197}Au(n,2n)^{196}Au$ reaction, (b) the $^{197}Au(n,2n)^{196}Au^{m2}$ reaction

A detailed list of all the uncertainties taken into account in order to estimate the cross section uncertainty obtained from each γ-ray is given in Table 2. The uncertainties of counts are uncorrelated, while the rest ones are fully correlated.

Reaction	Energy (keV)	Uncertainty (%)					
		Counts		# of Target nuclei		Absolute efficiency	
		Au	Al	Au	Al	Au	Al
$^{197}Au(n,2n)^{196}Au$	355.7	1.7	1.6	0.013	0.09	2.7	2.7
	333.0	1.4	1.6	0.013	0.09	2.6	2.7
	426.0	4.2	1.6	0.013	0.09	2.5	2.7
$^{197}Au(n,2n)^{196}Au^{m2}$	147.8	2.8	1.6	0.013	0.09	3.4	2.7
	188.3	3.0	1.6	0.013	0.09	2.7	2.7

Table. 2. Uncertainties taken into account in order to estimate the total uncertainty of the cross section obtained from each γ-ray for the $^{197}Au(n,2n)^{196}Au$ and $^{197}Au(n,2n)^{196}Au^{m2}$ reactions.

THEORETICAL CALCULATIONS AND RESULTS

Theoretical cross section calculations were performed in the energy range between 7 and 50 MeV by means of the TALYS 1.8 code [10,11]. In the framework of the Hauser-Feshbach theory, the level denisties of the compound nucleus were described via the Generalised Superfluid Model and additional width fluctuation corrections were taken into account according to the HRTW model [12]. The optical model parameters for outgoing particles were taken from RIPL-3 [13] using the data by Koning and Delaroche [14] for neutrons and protons and the ones by Avrigeanu et. al. [15] for alphas. Moreover, in order to achieve a fair reproduction of the cross section of the second isomeric state, which is the most significant constraint of the theoretical calculations, the spin cut-off paremeter was multiplied by a factor of 1.5 and the asymptotic level density parameters were taken from literature [16] as mentioned in reference [4].

The preequuilibrium emission was taken into account according to the exciton model [17], while the spin distribution for the preequilibrium population of the residual nuclei was based on the particle-hole state densities. Furthermore, an additional adjustment was made for the pick-up and stripping preequilibrium processes for α particle emission.

As far as direct reactions are concerned, the coupled-channels method [18] was implemented, combined with a deformed optical model potential.

The results obtained by using the aforementioned parametrization in TALYS, reproduced fairly well not only the existing experimental data in (n,2n) channels (Figs. 3 and 4), but also five more reaction channels, namely the (n,3n), (n,p), (n,α), (n,elastic) and (n, total).

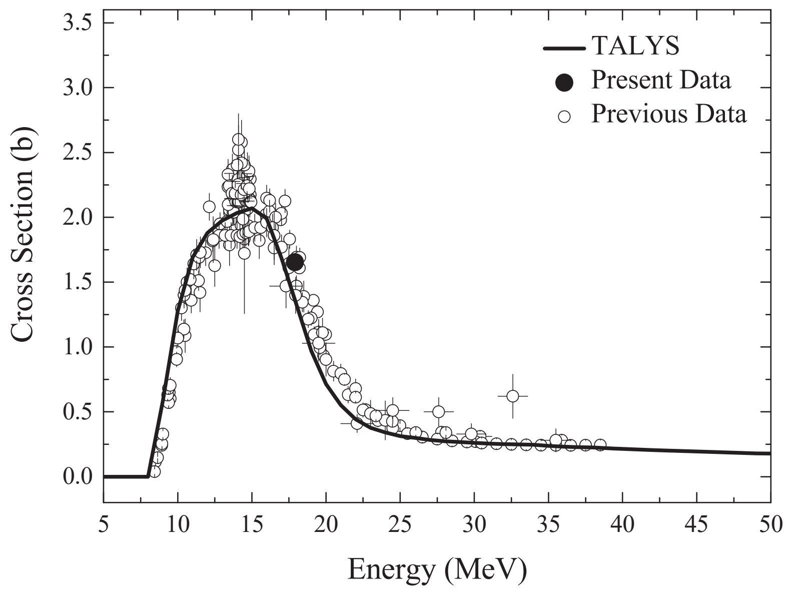


Fig. 3. Cross section theoretical calculations for the $^{197}Au(n,2n)^{196}Au$ reaction obtained with TALYS 1.8 code, along with the data point of this work at 17.9 MeV and EXFOR data [5].

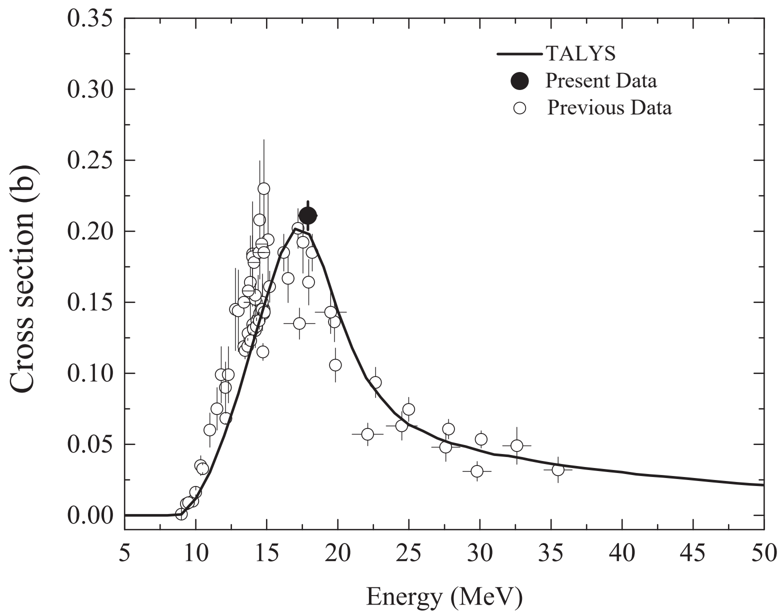


Fig. 4. Cross section theoretical calculations for the $^{197}Au(n,2n)^{196}Au^{m2}$ reaction obtained with TALYS 1.8 code, along with the data point of this work at 17.9 MeV and EXFOR data [5].

SUMMARY

The cross section of the (n,2n) reaction on Au was measured at 17.9 MeV independently for the population of the second isomeric state and for the sum of the population of ground, first and second isomeric states. The measurement performed at the 5.5 MV Tandem accelerator of NCSR "Demokritos" implementing the activation technique, relative to the $^{27}Al(n,\alpha)^{24}Na$ reference reaction cross section. The quasi-monoenergetic neutron beam was produced by means of the $^{3}H(d,n)^{4}He$ reaction and the preliminary experimental results are presented in Figs. 2(a) and 2(b) for the $^{197}Au(n,2n)^{196}Au$ and the $^{197}Au(n,2n)^{196}Au^{m2}$ reaction, respectively. The new data point for the cross section of the $^{197}Au(n,2n)^{196}Au$ reaction follows the general trend of existing data, while the other one for the cross section of the $^{197}Au(n,2n)^{196}Au^{m2}$ reaction indicates that the maximum cross section lies at a slightly higher cross section value than the previous data and at a neutron energy of ~ 17 MeV. Furthermore, cross section theoretical calculations were carried out using the TALYS 1.8 code and the results are quite satisfying the two studied (n,2n) reaction channels and five more, namely the: the (n,3n), (n,p), (n,α), (n,elastic) and (n, total) ones.

Acknowledgments

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