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PHOTONEUTRON CROSS SECTIONS MEASUREMENTS IN ^{13}C WITH THERMAL NEUTRON CAPTURE GAMMA-RAYS

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ABSTRACT

Photoneutrons cross sections measurements of ^{13}C have been obtained in energy interval between 5,3 and 10,8MeV, using neutron capture gamma-rays with high resolution in energy (3 - 21eV), produced by 21 target materials, placed inside a tangential beam port, near the core of the IPEN/CNEN-SP IEA-R1 (2MW) research reactor. The sample have been irradiated inside a 4π geometry neutron detector system "Long Counter", 520,5cm away from the capture target. The capture gamma-ray flux was determined by means of the analysis of the gamma spectrum obtained by using a Ge(Li) solid-state detector (EG&G ORTEC, 25cm^3, 5%), previously calibrated with capture gamma-rays from a standard target of Nitrogen (Melamine). The neutron photoproduction cross section has been measured for each target capture gamma-ray spectrum (compound cross section). A methodology for unfolding the set of experimental compound cross sections, have been used in order to obtain the cross sections at specific excitation energy values (principal gamma lines energies of the capture targets). The cross sections were compared with experimental data, reported by other authors, using different gamma-ray sources. A good agreement was observed between in this work and reported in the literature.

1. INTRODUCTION

The use of electromagnetic probes, such as photons, for studies of ground and excited nuclear states, has the advantage to be a very known nuclear interaction with well established spin selection rules [1]. As a consequence of these selection rules, the photoabsorption by a nucleus is predominantly of the type E1, with high selectivity of angular momentum in the entrance channel, resulting in a restricted number of compound nucleus states.

Photonuclear reaction studies with thermal neutron capture gamma-rays of high energy resolution (between 4 and 20 eV), have been undertaken at this laboratory [2-6] for some heavy nuclei using a limited number (not more than 12) of excitation energies. As a consequence, the number of experimental data obtained in these experiments has not been appropriated for the extraction and interpretation of nuclear parameters from nuclear models. In order to improve the studies of photonuclear reactions at low energies, an experimental apparatus for production and utilization of up to 30 capture gamma-ray lines, with discrete energies ranging from 5 to 11 MeV, was installed at a tangential beam hole of the IEA-R1 research reactor [7-9].

In this work, we report new measurements of photoneutron cross sections for ^{13}C, in 21 discrete energy values ranging from 5.27 to 10.83 MeV, using gamma rays of high resolution in energy (few eV) produced by thermal neutron capture. It is expected that further experimental data on photoneutron cross section for ^{13}C are important to reduce the uncertainties in the contemporary knowledge of these parameters, to provide new informations at excitation energies not explored in previous measurements and also as a mean to understanding the origin of the discrepancies between the data reported in the literature.

2. EXPERIMENTAL PROCEDURES

The measurements have been carried out in an experimental arrangement installed at the tangential beam hole BH4-12 of the IPEN-IEA-R1 (2MW) pool-type research reactor. A detailed description of this arrangement can be found elsewhere [9]. In summary, gamma radiation with discrete energies ranging from threshold to 10.83 MeV are produced by thermal neutron capture in 21 target materials, when they are placed near the reactor core, in the center of the tangential channel. The capture gamma-rays are directed to the experimental area by means of an assembly of conic lead collimators, 2m long and 3cm internal diameter, mounted inside the beam tube at the opposite side from the extremity by which the targets are placed (or taken off) for irradiation. Sample of ^{13}C (8.2 g) was inside an aluminum cylinder, 2.54cm internal diameter and 2.5cm high.

Neutrons produced in (γ,n) reactions were detected by a 4π sr long-counter detector system with high efficiency, similar to that proposed by Dowdy and Caldwell [10]. This long-counter system is formed by 48 ^{3}He proportional detectors (Harshaw model He-3-8-24S) distributed into three concentric rings inside a polyethylene cube where neutrons are slowed down. In the center of the long-counter system there is a copper tube 2mm thick, 7.6cm internal diameter and 130cm long, where the sample was placed for irradiation, 520.5cm away from the capture target. Between the output extremity of the beam tube and the long-counter entrance, hydrogenated materials were used in order to remove neutrons coming from the reactor core by scattering effects on the target material and beam tube walls. The best combination of neutron filters, experimentally determined by optimizing the signal (photoproduced neutrons) to background (scattered neutrons) ratio, was 58.2cm polyethylene and 8.4cm borated paraffin. The efficiency of the long-counter was measured by employing a calibrated ^{252}Cf source having, on April 27/1993, an activity of (477.9 ± 1.8%) Bq. In the whole period of this experiment, the detector efficiency was practically constant and equal to (0.4497 ± 0.0036).

The gamma-ray flux was measured with a Ge(Li) (EG&G ORTEC, 25 cm^3, 5%) coaxial detector positioned along the beam path at 823cm from the capture target. Even at this distance, the gamma-ray flux had to be attenuated with lead plates, in order to avoid detector saturation. It was experimentally observed that the gamma beam extracted from the reactor channel is homogeneous at any point of its path, within an area of 3cm diameter around the center, and its intensity decreases with the inverse square of the distance from the internal extremity of the conic lead collimator. This characteristic of the experimental arrangement allowed easily to obtain the gamma-ray flux intensities at the sample irradiation position.

A pulser with known frequency, connected to the Ge(Li) detector pre-amplifier, was used to correct counting losses due to dead time and pile-up effects. The detector calibration factor, as a function of the gamma-ray energy, was obtained by submitting all the detector volume to a standard gamma beam with known intensity. This standard gamma-ray flux was produced by irradiating at the capture target position a known mass of nitrogen (melamine $C_3N_6H_6$) and measuring the local thermal neutron flux by means of activation technique with cobalt wires. In order to calculate the capture gamma-ray production rate it was used a thermal neutron capture cross section for nitrogen integrated over a Maxwellian type spectrum, corrected for a moderator temperature of 30°C. The mass attenuation coefficients for the neutron filters and lead plates were determined by a log-log type linear interpolation from the data reported by Storm and Israel [11]. It was used the calibration standard values recommended by IAEA for nitrogen capture gamma-rays intensities. The gamma-ray spectra measured with a multichannel analyzer (PCA 8000 from Nucleus Inc.) were analyzed by means of the computer code REGULUS [12]. Calibration curves, in the energy interval from 3.5 to 11.0 MeV, were obtained for the full energy absorption, single and double escape peaks, using least square fitting and the methodology of covariance matrix [13]. A second degree polynomial function in a log-log scale was fitted to the data points [14].

During all measurements carried through this experiment, the reactor power was monitored by a self-powered neutron detector (SPND) with silver converter, installed near the capture target at the external wall of the tangential beam tube.

^{13}C sample was several times irradiated inside the neutron detector long-counter with the capture gamma-rays produced by each one of the 21 target materials. An equivalent mass of aluminum oxide, packed as the sample, played the role of a blank. This blank was irradiated in order to determine the neutron background contribution from two main sources: 1. neutrons coming from the reactor together with the gamma beam, which are scattered to the interior of the long counter. 2. neutrons generated by the neighboring experiments in the experimental area of the reactor. Besides these sources of background, another important contribution which has been taken into account in this work was the neutron production in the samples by gamma radiation from neutron capture in air, reactor structural materials, target carrier and target packing. This background was measured by placing an empty target packing at the capture target position.

3. RESULTS AND DISCUSSION

The experimental photoneutron cross sections (S_i), for each capture gamma-ray spectrum, is a composition of the contributions from all gamma-lines emitted by the target (i) and may be expressed as:

$$S_i = \sum_{j=1}^{n_i} I(E_{ij})\sigma_{\gamma n}(E_{ij}) = \frac{R_i}{N\varepsilon\phi(E_{ip})} \tag{1}$$

where,

$I(E_{ij})$ = relative intensity of each gamma-ray line,

n_i = number of gamma-ray lines emitted by the target i,

$\sigma_{\gamma n}(E_{ij})$ = photoneutron cross section at the energy E_{ij},

R_i = photoneutron count rate for target i, corrected for background contributions,

N = number of ^{13}C nuclei in the sample,

ε = neutron detector efficiency,

$\phi(E_{ip})$ = flux of the main gamma-ray line.

The photoneutron cross section as a function of the excitation energy was determined employing the methodology described in reference [8] to unfold the set of experimental data for S_i. In summary, the system of equations (1) obtained for the 21 capture targets, is reduced to a quadratic form (*NxN*) by using an adequate procedure for approximating all the secondary gamma line intensities, at each energy of the set of 21 main gamma rays. The set of equations (1) can now be expressed in matrix notation as:

$$S = M\sigma \tag{2}$$

which has a exact solution given by:

$$\sigma = M^{-1}S \tag{3}$$

where the column vector S is the compound photoneutron cross sections and the matrix M corresponds to the gamma line intensities.

Considering the covariance matrix V for the uncertainties in the measured compound photoneutron cross sections, the solution of equation (3), by least-squares methods is:

$$\sigma = PM^{t}V^{-1}S \tag{4}$$

The symbols "*t*" and "*-1*", as superscripts in equation (4), denote matrix transposition and inverse matrix respetively. The covariance matrix P for the solution parameters σ_i is given by the formula:

$$P = \left(M^{t}V^{-1}M\right)^{-1} \tag{5}$$

The elements of the column vector σ were calculated by means of a computer program named SIGMAP4 [8].

The ^{13}C photoneutron cross sections obtained in this work are listed in Table 1. The relative errors in the measured photoneutron cross sections and the uncertainty correlations for the present data are provided in Table 2. This correlation matrix generated by the SIGMALP4 code shows the correlation between the overall photoneutron cross sections errors calculated by the least-squares method at energies related to the main gamma lines for 21 targets. In figure 1, the calculated photoneutron cross section for ^{13}C are compared with previous measurements reported in the literature [15, 16, 17].

Table 1 The ^{13}C Photoneutron Cross Sections Obtained in This Work.

Capture Target	Main Gamma-Ray Line Energy (MeV)	^{13}C Photoneutron Cross Section (mb) This Work
Yb	5.27	0.04 ± 0.01
S	5.42	0.012 ± 0.005
K	5.69	0.11 ± 0.04
Hf	5.72	0.10 ± 0.02
In	5.89	0.21 ± 0.03
Y	6.08	0.18 ± 0.02
Si	6.38	0.03 ± 0.01
V	6.52	0.12 ± 0.03
Se	6.60	0.05 ± 0.02
Ti	6.76	0.25 ± 0.03
Sm	7.21	0.30 ± 0.05
Mn	7.24	0.54 ± 0.08
Pb	7.34	0.40 ± 0.04
Fe	7.63	0.84 ± 0.09
Al	7.72	0.73 ± 0.06
Zn	7.86	0.57 ± 0.06
Cu	7.91	0.54 ± 0.07
Cd	8.48	0.08 ± 0.06
Ni	8.99	0.46 ± 0.05
Cr	9.72	1.13 ± 0.16
N	10.80	1.27 ± 0.11

Table 2 Relative Errors and The Correlation Matrix for the Measured ^{13}C Photoneutron Cross Sections Generated by The SIGMALP4 Code.

E (MeV)	Error (%)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
5.27	25.00	**1**	1000																				
5.42	40.00	**2**	-354	1000																			
5.69	36.36	**3**	123	532	1000																		
5.72	20.00	**4**	145	312	232	1000																	
5.89	14.29	**5**	-56	-245	345	367	1000																
6.08	11.11	**6**	54	-342	-234	21	-35	1000															
6.38	33.33	**7**	78	132	-211	-221	356	481	1000														
6.52	25.00	**8**	279	233	145	245	657	-68	236	1000													
6.60	40.00	**9**	60	421	321	541	-233	-345	465	324	1000												
6.76	12.00	**10**	214	80	89	478	432	205	356	543	453	1000											
7.21	16.67	**11**	43	-173	26	485	490	27	365	226	354	402	1000										
7.24	14,00	**12**	209	211	-12	646	631	-19	700	324	548	23	354	1000									
7.34	14.81	**13**	335	130	-67	45	32	42	67	87	34	67	252	54	1000								
7.63	10.71	**14**	-71	67	46	-156	154	58	143	243	109	23	76	45	-29	1000							
7.72	8.22	**15**	65	-21	254	466	376	-135	291	233	-32	322	246	324	32	342	1000						
7.86	10.53	**16**	-19	32	267	33	143	254	164	278	246	56	233	165	41	53	213	1000					
7.91	12.96	**17**	220	87	-45	623	576	278	256	354	287	-34	376	356	52	678	-234	299	1000				
8.48	75.00	**18**	145	156	-88	234	600	21	-257	545	467	54	436	422	-34	208	452	213	432	1000			
8.99	10.87	**19**	45	172	278	-34	132	-390	145	97	23	67	57	345	52	23	276	43	65	88	1000		
9.72	14.16	**20**	-89	54	32	453	-43	112	356	548	254	345	24	53	4	-98	243	254	433	504	-34	1000	
10.80	8.66	**21**	58	165	342	287	250	43	144	318	267	753	370	33	-31	12	45	133	44	23	-23	457	1000

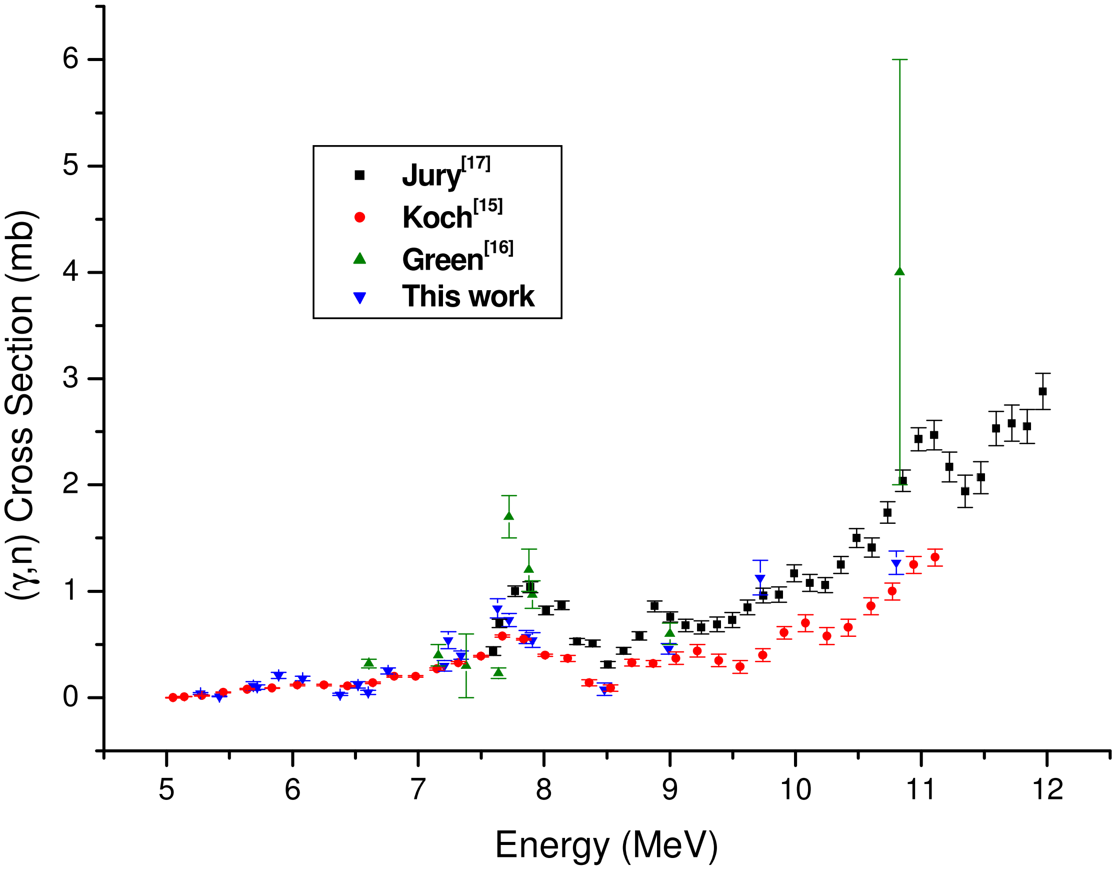

Figure 1 Comparison of Experimental Photoneutron Cross Sections for ^{13}C with Evaluated Data from References 15, 16 and 17.

4. CONCLUSION

We have measured the ^{13}C photoneutron cross section in 21 discrete energies between 5.27 to 10.83 MeV, using photons of high resolution in energy (4 to 20 eV), produced by thermal neutron capture.

In the present work was employed a appropriate methology to unfold the set of experimental data, envolving covariance matrix and least-squares methods. The new experimental information are provided in several energies not yet explored with capture gamma-rays.

The photoneutron cross sections values are compared with experimental data from the literature [15, 16, 17]. The overall agreement between the present results and the data of authors is reasonable. Some results were obtained with an excessively large overall error, and this could be explained by the contribution of a high number of secondary gamma-lines distributed within a large energy interval, in the capture gamma-ray spectra. The results compare favorably with measurements carried out with different gamma radiation sources.

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