PHOTONEUTRON CROSS-SECTION MEASUREMENTS FOR ^{165}Ho BY THE DIRECT NEUTRON-MULTIPLICITY SORTING AT NEWSUBARU*

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The Coordinated Research Project of the International Atomic Energy Agency (IAEA CRP-F41032) was launched with a goal to publish two compilations of an updated photonuclear data library and a reference database of photon strength functions. The PHOENIX (PHOto-Excitation and Neutron emIssion cross [X] sections) Collaboration has been established for the IAEA-CRP in the γ-ray beam line GACKO (GAmma Collaboration hutch of KOnan university) of the NewSUBARU synchrotron radiation facility in Japan. The collaboration provides (γ, xn) cross-section data to resolve

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the long-standing discrepancy between the Livermore and Saclay data on partial photoneutron cross sections. For the IAEA-CRP, a flat-efficiency neutron detector (FED) for (γ, xn) cross-section measurements was developed. The detector consists of ^{3}He counters arranged in three concentric rings embedded in a polyethylene moderator. Due to the fact that the efficiency of the detector is constant for the neutron energies up to several MeV, it is possible to determine the partial photoneutron reactions cross sections using direct neutron-multiplicity sorting technique. The paper gives details of the experimental setup and data analysis, and preliminary results of total neutron-production cross sections in monochromatic approximation for ^{165}Ho nucleus.

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1. Introduction

Partial (γ, xn), with $x > 1$, and total photoneutron reaction cross-section data are important for many applications including: (1) radiation shielding and radiation transport analyses; (2) calculation of absorbed doses in the human body during radiotherapy; (3) activation analyses; (4) safeguards and inspection technologies; (4) nuclear waste transmutation; (5) fission and fusion reactor technologies and (6) astrophysical nucleosynthesis. The majority of photoneutron reactions were investigated using quasi-monoenergetic photon beams from in-flight positron annihilation at the Lawrence Livermore National Laboratory (USA) and France Centre d'Etudes Nucleaires de Saclay.

Significant discrepancies between the cross sections measured at the two facilities were observed that cannot be resolved in a systematic manner [1, 2]. In order to solve this issue, a direct neutron multiplicity (DNM) sorting technique has been developed [3]. The DNM method is based on the constant neutron detection efficiency with no dependence on the energy of the neutrons. The method, with a recently developed detector, was applied for the first time to ^{209}Bi [4] at the experimental hutch GACKO of the laser-Compton scattering (LCS) γ-ray beam line of the NewSUBARU synchrotron radiation facility [5].

Similar detection system is planned to be used at Extreme Light Infrastructure–Nuclear Physics (ELI–NP) [6], which is a facility under development, aiming to provide a very brilliant γ-beam source [7].

This paper presents a measurement of the ^{165}Ho nucleus in the series of experiments dedicated to partial photoneutron cross-section measurements for the IAEA Coordinated Research Project (CRP-F41032) on Photonuclear Data and Photon Strength Functions. In this paper, the experimental technique, data analysis and preliminary results are reported.

2. Experimental procedure

Photoneutron ^{165}Ho(γ, xn) with $x = 1$–4 reaction cross-section measurements have been performed by using γ-ray beams at the NewSUBARU synchrotron radiation facility. Gamma-ray beam production and characterization as well as the neutron detection system are presented in this section.

2.1. Gamma-ray beam production and characterization

LCS γ-ray beams were produced via the interaction of a high power Nd:YVO4 laser and relativistic electron beams. The (γ, n) reaction was investigated starting from the vicinity of the neutron emission threshold (S_n = 7.99 MeV) up to 11.5 MeV using electron beams of 680 to 810 MeV energy and the INAZUMA laser [8] operated in the first harmonic (λ = 1064 nm; power = 40 W). The energies from 11.5 up to 43.2 MeV (S_{2n} = 14.66 MeV, S_{3n} = 23.07 MeV, S_{4n} = 29.99 MeV) were obtained using electron beams of 560 to 1110 MeV energy and the TALON laser [9] operated in the second harmonic (λ = 532 nm; power = 20 W). For the purpose of DNM sorting technique, neutrons recorded between two consecutive gamma bunches have to be generated in the same reaction, therefore, to avoid event mixture, the time between bunches should be long enough for neutrons to be moderated. For this, 1 ms clock was used.

The γ-ray beam flux was monitored during each neutron measurement run with an $8'' \times 12''$ NaI(Tl) detector placed at the end of the LCS γ-ray beam line and also used as a gamma beamdump. The left panel of Fig. 1 shows a 43.2 MeV maximum energy incident LCS γ-ray beam time spectrum, where the time is relative to the previous clock signal. The first peak represents a so-called "prepulse", while the high amplitude peak in the vicinity of 80 μs represents the main LCS γ-ray bunches, corresponding to the allowed laser pulses. The continuous background component is related to the bremsstrahlung and cosmic γ rays. The total energy spectrum of the recorded γ rays during the measurement for 43.2-MeV energy point is displayed in the bottom right panel of Fig. 1 by the black line. The three components described above are selected by applying gates on the time spectrum.

The LCS γ rays are generated in bunches corresponding to each laser light pulse following a Poisson probability distribution. The main LCS γ-ray spectrum displays a pile-up structure with average of 6.2 photons per bunch, while the "prepulse" component is characterized by a lower average of 1.4 photons per bunch. The number of recorded LCS γ-ray photons were obtained with the pile-up method described in Ref. [10], where the pile-up spectra are deconvoluted using single-photon spectra (see the right panel of Fig. 1), which are recorded before or after each neutron measurement run by operating the laser at reduced power, where it is most likely to measure only one photon at a time.

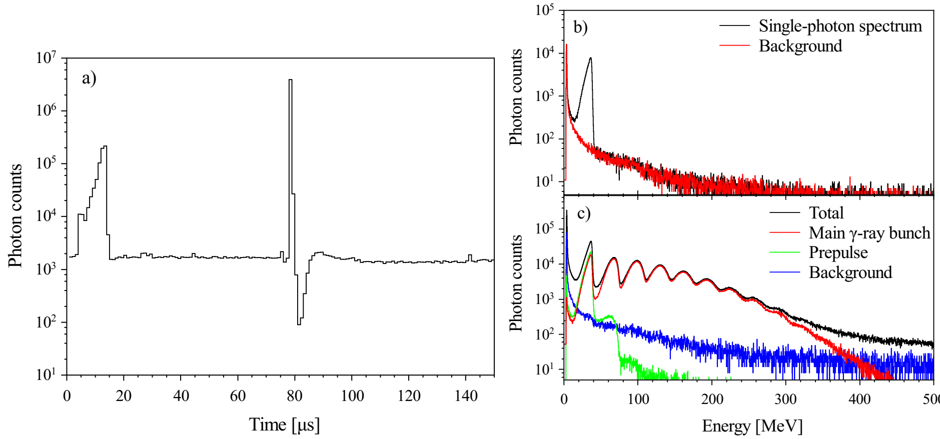

Fig. 1. (Color online) Left panel: (a) Incident LCS γ-ray beam time spectrum, relative to the previous clock signal recorded using the NaI(Tl) detector. Right panel: Energy spectrum measured with NaI(Tl) of 43.2 MeV maximum energy LCS γ-ray beam. (b) represents the single photon (black) and background (gray/red) spectra taken before the measurement. In (b), there is represented the total γ-ray spectrum acquired during the measurement (black) and its three components: main γ-ray bunch (gray/red) the "prepulse" photons (light gray/green) and background (dark gray/blue).

The γ-ray beam energy profile was measured with a $3.5'' \times 4''$ $LaBr_3$:Ce detector as described in Ref. [11]. The left panel of Fig. 2 shows the experimental detector response (solid red line) to 43.2 MeV maximum energy LCS γ-rays along with Geant4 [12] simulations of the detector response function (solid red line) and incident γ-ray beam (dotted black line). The energy spread in full width at half maximum is at the level of 6%. The incident beam parameters are adjusted in the simulations until the experimental response function is well reproduced.

2.2. Neutron detection system

A flat efficiency neutron detection array [3] has been developed recently. The detection is based on the conversion of neutrons into charged particles through the ^{3}He$(n,p)t$ reaction. As the cross section of the reaction is very high for thermal neutrons, they are slowed down in the moderator. Such type of a detector is mandatory for the DNM sorting technique applied to obtain absolute (γ,xn) reaction cross sections, as described in details in Ref. [3].

The flat efficiency detector (FED) consists of three rings of 4, 9 and 18 ^{3}He counters (10 atm pressure) located at 5.5 cm, 13 cm and 18 cm from the γ-ray beam axis, respectively. The counters are embedded in a

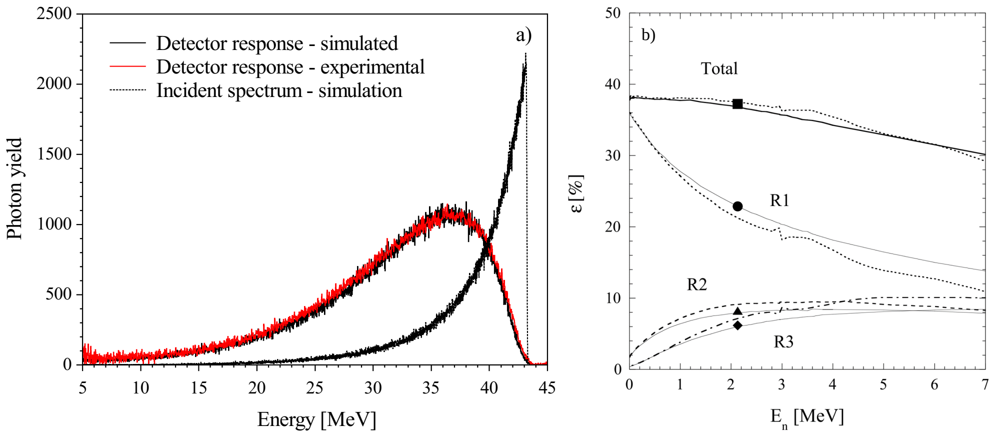

Fig. 2. (Color online) (a) LCS γ-ray beam spectrum recorded with the $LaBr_3$:Ce detector (solid black line) and detector the response function (solid gray/red line) and incident γ-ray beam (dotted black line) simulations. (b) The total detection efficiency and of each individual rings of the FED. Results of the calibration with a ^{252}Cf source are shown by the filled symbols. Results of the MCNP Monte Carlo simulations for monochromatic neutrons are shown by the broken lines, while those for the neutron-evaporation spectra by the solid lines. Figure taken from [3].

polyethylene moderator shielded by additional borated polyethylene plates for background neutron suppression. In order to find best configuration to obtain flat efficiency, an extensive MCNP [13] simulations have been performed considering s-wave evaporation neutron sources placed in the centre of the moderator. The evaporation spectra were obtained by applying the Weisskopf–Ewing model.

The calibration measurement was performed with a ^{252}Cf source and the detection efficiency was estimated to be $37.27 \pm 0.82\%$ at 2.13 MeV (the average energy of the neutron spectrum). As shown in the right panel of Fig. 2, the experimental calibration (filled symbols) is well-reproduced by the simulations (broken lines) and also 1.42 MeV temperature Maxwell fission spectra (solid lines).

All simulation results are displayed for the average energy of the neutron spectra. The total efficiency is 38.0–35.7% over a neutron energy up to 5 MeV. Based on Monte Carlo (MC) statistical model calculations on ^{209}Bi provided by Kawano [3], we confirmed that the average energy of the emission spectra is below 2–3 MeV, thus more than 90% of the emission spectrum is in the flat efficiency energy range of the detector. We applied the analysis procedure on the simulated data and reproduced the input cross sections for the MC simulations with a $< 1\%$ uncertainty.

3. Data analysis and preliminary results

First step of the DNM sorting technique [3], which allows to compute the numbers of (γ, xn) reactions, is to determine the number of single (N_1), double (N_2), triple (N_3) and quadruple (N_4) neutron coincident events registered by the FED. The left panel of Fig. 3 shows examples of neutron time moderation spectra for N_1, N_2, N_3 and N_4 events, in the case of 43.2 MeV maximum energy LCS γ rays. The spectra were constructed for the first arriving neutron out of one to four neutrons. These structures present a very sharp rise time followed by an exponential curve. One can observe that during 1 ms time interval, all the neutrons are detected. The number of neutrons generated in reactions induced by the main γ-ray bunches, for each measurement point and for each type of events, was computed by subtracting the background. The numbers of (γ, xn) induced reactions, R_i, where $i = 1, \ldots, n$, are obtained from the number of single N_1, double $N_2, \ldots, n$-events N_n, where an n-event is defined as the interval between two consecutive γ-ray bunches in which n neutrons were recorded by the neutron detection system. For this, the following set of n equations is applied:

$$N_j = \Sigma_{i=j}^{m} C_j^i \, R_i \, \epsilon^j (1-\epsilon)^{i-j} \,, \tag{1}$$

where $j = 1, \ldots n$.

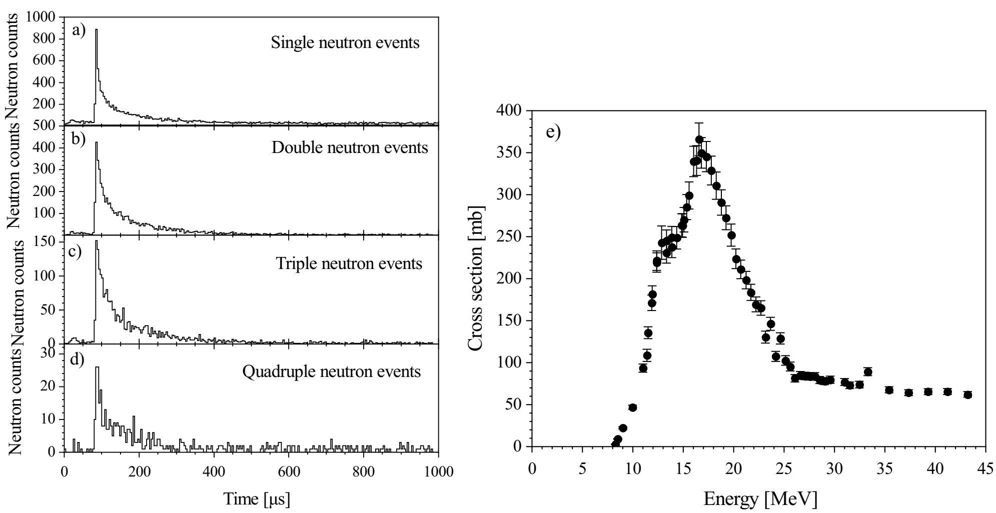

Fig. 3. Left panel: Neutron moderation time spectra of single (a), double (b), triple (c) and quadruple (d) neutron events generated in $^{165}\mathrm{Ho}(\gamma, xn)$ reactions induced by 43.2 MeV maximum energy LCS γ-rays. Right panel: (e) Total neutron production cross section in monochromatic approximation.

One can see that this system of equations is possible to solve because of efficiency being independent from the neutron energy. This is the reason why FED is necessary. Then, the cross section in monochromatic approximation is expressed by

$$\sigma_{\gamma xn}^{\rm mono} = R_x/(N_{\rm t} N_\gamma \xi f_x)\,,$$

where R_x is the number of induced reaction, $N_{\rm t}$ is the number of target nuclei per unit surface, N_γ is the number of γ rays hitting the target, ξ is the thick target correction factor and f_x is the fraction of photons above S_{xn}.

The right panel of Fig. 3 presents the total neutron production cross section in monochromatic approximation. Such cross sections cannot be compared directly to the existing data as they are folded with the incident γ-beam spectra. The cross sections need to be unfolded using an iterative method of reproducing the monochromatic cross sections by folding a trial cross section with the incident γ-beam energy spectrum. Therefore, the next steps of the analysis will be to estimate the partial (γ, xn) cross sections in monochromatic approximation and unfolding.

4. Summary

A new direct neutron multiplicity sorting method which employs a constant neutron detection efficiency system has been developed for IAEA-CRP F41032 on Photonuclear Data and Photon Strength Functions. The first measured test case was ^{209}Bi nucleus [4] and the measurements continued for ^{197}Au, ^{169}Tm, ^{89}Y, ^{181}Ta, ^{165}Ho, ^{59}Co, ^{159}Tb, ^{139}La, ^{103}Rh.

The case of ^{165}Ho is discussed in this paper. Photoneutron reactions (with neutron emission multiplicity 1–4) have been investigated within the 8.2–43.2 MeV energy range. The data analysis starting from the beam characterization was presented as well as the idea of neutron multiplicity sorting method with flat-efficiency detector. Preliminary total neutron production cross sections were presented. Further steps, including computation of partial cross sections as well as unfolding taking into account initial gamma-beam spectra are on-going.

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REFERENCES

[1] V.V. Varlamov *et al.*, *Eur. Phys. J. A* **50**, 114 (2014).

[2] V.V. Varlamov *et al.*, INDC(CCP) **433** (2002).

[3] H. Utsunomiya *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **871**, 135 (2017).

[4] I. Gheorghe *et al.*, *Phys. Rev. C* **96**, 044604 (2017).

[5] S. Amano *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **602**, 337 (2009).

[6] `www.eli-np.ro`

[7] O. Adriani *et al.*, `arXiv:1407.3669 [physics.acc-ph]`.

[8] R. Szweda, Diode Laser Materials and Devices — A Worldwide Market and Technology Overview to 2005, Elsevier Science Ltd, 2001.

[9] `https://www.spectra-physics.com`

[10] T. Kondo *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **659**, 462 (2011).

[11] D. Filipescu *et al.*, *Phys. Rev. C* **90**, 064616 (2014).

[12] J. Allison *et al.*, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).

[13] J.F. Briesmeister, computer code MCNP, Version 4C, Los Alamos National Laboratory, Los Alamos, 2000.