Preparatory Gamma Above Neutron Threshold experiments

Present study: Test and calibration of the ELIGANT-TN flat efficiency neutron detection system

T. Renstrøm,1 D. Filipescu,2 I. Gheorghe,2 T. Gledariu,2 M. Krzysiek,2,3 M. Boromiza,4 A. Negret,4 A. Olacel,4 C. Petrone,4 F.L. Bello Garrote,1 H. Berg,1 F. Furmyr,1 D. Gjestvang,1 G. Henriksen,1,5 V.W. Ingeberg,1 A.-C. Larsen,1 V. Modamio,1 L.G. Pedersen,1 S. Rose,3 S. Siem,3 G. Tveten,1 F. Zeiser,1 S. Belyshev,6 A. Kuznetsov,7 K. Stopani,7 P. van Beek,8 H. Scheit,8 D. Symochko,8 M. Ciemala,3 M. Kmiecik,3 A. Maj,3 F. Camera,9,10 G. Gosta,9 O. Wieland,9 T. Ari-izumi,11 and H. Utsunomiya11

1Department of Physics, University of Oslo, N-0316 Oslo, Norway
2ELI-NP, "Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului, 077125 Bucharest-Magurele, Romania
3Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland
4"Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului, 077125 Bucharest-Magurele, Romania
5Norwegian Medical Cyclotron Centre Ltd.
6Lomonosov Moscow State University, Department of Physics, Moscow, 119991, Russia
7Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics, Moscow, 119991, Russia
8Institut für Kernphysik Technische Universität Darmstadt, Germany
9University of Milano, Department of Physics, Via Celoria 16, 20133 Milano, Italy
10INFN Section of Milano, Via Celoria 16, 20133 Milano, Italy
11Department of Physics, Konan University, Okamoto 8-9-1, Higashinada, Kobe 658-8501, Japan

Abstract

Absolute photoneutron reaction cross sections are proposed to be measured at the upcoming $\gamma$-ray beam source of the Extreme Light Infrastructure - Nuclear Physics facility. A flat efficiency neutron detector dedicated for $(\gamma,xn)$ measurements with $x=1,2$ has been constructed. The detection system consists of 28 $^3$He proportional counters embedded in a polyethylene moderator block. It was designed based on Geant4 simulations in search of a flat-response geometrical configuration. We propose to test and calibrate the neutron detection system using charged particle beams provided by the 9 MV IFIN-HH Tandem accelerator.

I. SCIENTIFIC MOTIVATION

Our fundamental knowledge of the interaction of photons with the nuclei is mostly provided by the extensive photonuclear reaction measurements performed during the 1960 - 1980 period at the Lawrence Livermore National Laboratory (USA) and the Centre d’Etudes Nucléaires de Saclay (France). The complete compilation of the existing photonuclear reaction cross section data up to 2000 [1] has been generated by the International Atomic Energy Agency (IAEA). Currently, the IAEA has launched a coordinated research project (CRP) for updating the compilation of photonuclear reactions. This is mainly to the disagreements between existing data and because of the development of novel Laser Compton scattering (LCS) $\gamma$-ray beams as ELI-NP.

Within the Extreme Light Infrastructure - Nuclear Physics (ELI-NP) Gamma Above Neutron Threshold (ELIGNANT) research group, one of the proposed physics cases is the measurement of selected photoneutron reaction cross sections in order to contribute to the global effort of updating the current Photonuclear Data Library. Photoneutron $(\gamma,xn)$ cross sections with $x=1,2$ will be measured using a novel in-beam neutron multiplicity technique based on the dedicated ELIGNANT high-and-flat efficiency neutron detector, ELIGNANT-TN.

The present proposal aims to test and validate the flatness of the ELIGNANT-TN neutron detection efficiency. Using in beam calibration technique we will perform calibration at several average neutron energies (average of the neutron evaporation spectra) compared to standard PuBe, $^{252}$Cf, etc. sources which give only one calibration point.
II. THE ELIGANT-TN ARRAY

The neutron detection system is comprised of three concentric rings of 4, 8 and 16 $^3$He proportional counters respectively, placed in a polyethylene moderator block at 59 mm, 130 mm, and 155 mm from the beam line. A front view of the detection system is shown in Fig. 1(right). The counters are $\varnothing$ 25 mm × 500 mm cylinders containing $^3$He gas at 12 atm pressure. A similar detection system has been developed at the NewSUBARU $\gamma$-ray beam line using a different geometrical configuration, with three rings of 4, 9, and 18 counters with $^3$He gas at 10 atm pressure placed at 55 mm, 130 mm, and 160 mm respectively from the beam line, as described in Ref. [2].

The ELI-GANT-TN array is designed to count neutrons and to measure neutron multiplicity with high efficiency. Therefore, neutrons have to be thermalized using a moderator material placed between the target and the neutron counters. This is done at the price of losing completely the information of the energy and time of emission. The determination of the neutron emission multiplicity, described in Ref. [2], is based on the following hypotheses:

- the target is in the center of the neutron detection system
- the detection system (based on $^3$He counters embedded in a moderator) has a flat efficiency vs. neutron energy
- the distance between two events is long enough for most of the neutrons to be moderated (an event is the arrival of one $\gamma$-ray bunch)
- In one event more than one ($\gamma$,xn) induced reactions are highly improbable.

Figure 1 shows the neutron detection efficiency curves of the ELI-NP and NewSUBARU detection systems. The total efficiency and the individual efficiency values for each ring of counters are shown separately. The efficiency of the NewSUBARU detector has been calibrated using a $^{252}$Cf source with known neutron emission rate of $(1.62 \pm 0.04) \times 10^4$ neutrons per second, as described in Ref. [2]. A value of $37.27 \pm 0.82$ % has been obtained for the average neutron energy of 2.13 MeV. For both detection systems, the neutron detection efficiency was calculated using Geant4 simulations of the passage of neutrons through the detection system. A selection of the available physics processes and corresponding models has been made, with emphasis on neutron elastic and inelastic scattering and capture and including also the thermal neutron scattering on polyethylene molecules with the possible excitation of vibrational modes. As shown in Fig. 1, the NewSUBARU experimental calibration is well reproduced by the Geant4 simulations considering neutron evaporation spectra of the emitted neutrons described by the Weisskopf-Ewing model. The ELIGANT-TN neutron detection efficiency varies between 37 % and 32.5 % with an average of 36 % within the 10 keV - 5 MeV energy range, approximately 5 % below the NewSUBARU one.
III. OBJECTIVES OF PRESENT CAMPAIGN

As described above, the neutron multiplicity sorting method requires the precise measurement of the neutron detection efficiency. Although monochromatic neutron sources (such as (p,n) reactions on $^7$Li) would be useful for constructing a calibration curve with well defined energy points, for the first experimental campaign we will focus on cross checking the current integration procedure. For this, we will combine the direct neutron detection system with an auxiliary activation system for measuring the well studied proton induced reactions on natural Copper. The neutron detection efficiency values will be measured for the average neutron emission energy of the induced reactions.

We propose to irradiate $\sim 1\,\mu m$ thick natural Copper foils placed in the center of the neutron detection system with proton beams of energies between 4 and 10 MeV. For incident energies below 10 MeV, (p,n) reactions are induced on the two stable Copper isotopes $^{63}$Cu, and $^{65}$Cu, populating the unstable Zinc isotopes $^{63}$Zn, and respectively $^{65}$Zn, which decay by electron capture with half lives of 38.47 min, respectively 243.93 days. The two reactions are recommended as monitor reactions by the IAEA, having well studied cross sections with high values, ranging from 30 mb to 300 mb for incident energies below 10 MeV, as displayed in Fig. 2. For this first experimental campaign, we will use continuous incident proton beams with energies below the (p,2n) threshold values on $^{63,65}$Cu, of 13.48 MeV, respectively 10.27 MeV.

The induced activity of the irradiated targets will be measured using a low background, energy and efficiency calibrated $\gamma$ spectroscopy detection system currently in use at the IFIN-HH department. The system is comprised of a pair of large volume (60 %, respectively 100 % relative efficiency) High Purity Germanium (HPGe) detectors placed in close geometry to the measuring probe. The nuclear data used for the activation measurements are listed in Table I.

A graphite Faraday cup with a guard ring at -300 V will be used for current integration. The Faraday cup will be placed downstream from the neutron detection system and will be covered by polyethylene plates and Cadmium sheets, for background neutrons suppression. The current integration will be cross checked by performing two additional activation measurements on Cu targets placed inside the Faraday cup.

- **Objective 1. Validate neutron detection efficiency simulations.**

  Experimental values for the neutron detection efficiency $\varepsilon^{\text{exp}}$ will be obtained as:

  $$\varepsilon^{\text{exp}} = \frac{N_{\text{ns}}}{N_{\text{act}}},$$

  where $N_{\text{ns}}$ are the total number of neutrons recorded by the neutron detection system, and $N_{\text{act}}$ are the number of induced reactions obtained by applying the activation method on the irradiated targets. For single neutron emission reactions, the number of recorded neutrons $N_{\text{ns}}$ is the same with the number of recorded reactions. The proton beam energy will be varied by $\sim 0.5$ MeV for each irradiation point. The average energy of the reaction neutrons will be estimated using the statistical model codes Talys and Empire. The straggling of the incident proton beams in the targets will be calculated with the TRIM code.

- **Objective 2. Test the current integration process.**

  FIG. 2: Cross sections of the $^{nat}$Cu(p,x)$^{63}$Zn and $^{nat}$Cu(p,x)$^{65}$Zn reactions for incident energies starting from the reaction threshold up to 30 MeV, respectively 50 MeV. Figures taken from [3].
TABLE I: Nuclear data on proton induced reactions on Copper used in the activation method.

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<tbody>
<tr>
<td>$^{63}$Cu(p,n)</td>
<td>$^{63}$Zn</td>
<td>$\varepsilon$: 100 %</td>
<td>38.47 (5) min</td>
<td>4.2</td>
<td>669.62</td>
<td>8.2 (3) %</td>
</tr>
<tr>
<td>$^{65}$Cu(p,n)</td>
<td>$^{65}$Zn</td>
<td>$\varepsilon$: 100 %</td>
<td>243.93 (9) days</td>
<td>2.16</td>
<td>1115.54</td>
<td>50.04 (10) %</td>
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For two proton beam energy values, 4 MeV and 10 MeV, we will measure absolute cross sections of the $^{nat}$Cu(p,x)$^{63}$Zn and $^{nat}$Cu(p,x)$^{65}$Zn reactions using the activation technique. For each energy point, two measurements will be performed: with the irradiated target placed in the center of the neutron detection system and, respectively, in the Faraday cup. The targets placed in the Faraday cup will be irradiated individually, to avoid spreading the energy spectrum of the proton beam by straggling in target stacks. The resulting experimental cross sections will be compared with the literature ones in order to cross check the charge collection process in the Faraday cup, the integrity of the data acquisition system and the effect of recoiled reaction products.

IV. BEAM TIME REQUEST

Because this is a commissioning experiment with the ELIGANT-TN instrument, we must also consider the necessary beam time for aligning the detection system with the beam line. Several tests will be performed with and without target holder, to investigate and reduce the related background.

We want to measure the amount of reactions induced by irradiating $\sim 1 \mu$m thick natural Copper foils with proton beams in the 4 MeV to 10 MeV energy range. Each target will be irradiated individually. The beam energy will be varied by $\sim 0.5$ MeV for each irradiation point. The neutron detection efficiency of the new flat efficiency neutron detector ELIGANT-TN will be determined using the auxiliary activation method, for each irradiated target. The integrity of the charged collection performed using a Faraday cup will be checked using two additional activation measurements performed on targets irradiated inside the Faraday cup.

Considering proton beam current expected values based on previous experiments at the 9 MV Tandem facility, we estimate that 7 hours of irradiation will be necessary to obtain a 1% uncertainty level from the activation measurements, for 30 mb $^{65}$Cu(p,n) reaction cross section. We request 42 shifts (14 days) beam time. The proton beam should have an intensity of at least 20 nA, kept constant as much as possible, thus allowing a precise extraction of the absolute cross sections.

In this first commissioning test we will use a continuous proton beam, which will make possible only the measurement of (p,1n) cross sections. If this test experiment will be successful, we plan to follow with more complex experiments in which we plan to try pulsing the tandem in the ms range (for example 80-100 us beam on, the remaining time up to 1 ms - beam off). This will allow us to apply the neutron multiplicity sorting technique.