Measurements of Photo-Neutron Energy Spectra from Thick Targets Produced by Irradiation of 2.0 GeV Electron Beam

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ABSTRACT

Photo-neutron spectra produced by 2.04 GeV electron incident on thick Al, Cu, Sn and Pb targets were measured by TOF method. A Pb attenuator was placed at the middle point of the flight path to suppress γ-flash signals. The thickness of the attenuator was changed from 10 cm to 30 cm for each target, and the effects of the attenuator on the neutron spectra were calculated by a combination of small changed LAHET2.7 code and ENDF-HE/VI data. Obtained neutron spectra are larger than calculated values predicted by a combination of EGS4, our modified PICA95 and LAHET2.7 codes.

1 Introduction

Recently high-energy electrons have been used rather widely for Synchrotron Orbital Radiation and other purposes. They produce high-energy photons as bremsstrahlung, and induce photospallation reactions in a beam stop. Therefore, photo-neutron spectra data are indispensable not only for a better understanding of the reaction mechanisms but also for the safety of electron accelerators.

Over the years, a lot of measurements of photo-neutron yield above the giant resonance region were carried out. However, only a few experiments [1]–[4] were to measure their energy spectra. Bremsstrahlung induced by striking electron beams into thick targets were used as photon source. Most of the other photo-neutron measurements were for evaluating total cross section of photo-nuclear reaction by summing up cross section of all neutron emitted channels. Pseudo mono-energetic photons were usually used for these cases.

In general, time of flight (TOF) method is adopted to measure neutron energy spectrum emitted from a beam bombarded target. However, it is difficult to measure the photo-neutron spectrum because of too large electromagnetic background. Especially, photo-neutrons with high energies are very hard to be measured because those neutrons tend to reach a detector within the detector dead time caused by strong γ-flash signals.

On the other hand, several calculation codes (CEM95, [5] DINREG, [6] FLUKA, [7] MARS, [8] and PICA95 [9] etc.), which are able to predict high energy photo-neutron spectrum, have been developed. These codes are based on the intra-nuclear cascade evaporation model except for DINREG. However, there is large discrepancy between calculated spectra by those codes because detail calculation models are different from code by code. Therefore, it is very hard to decide the most sophisticated model because of the lacking of the experimental data.

From these considerations, a photo-neutron spectra produced by 2.04 GeV electron incident on thick targets were measured by TOF method. A Pb attenuator was placed at the middle point of the flight path to suppress the electromagnetic background, and the effects of the attenuator on the spectra were calculated by a combination of LAHET2.7 code [10] with small modification and

ENDF-HE/VI data. [11] The obtained results are compared with calculated spectra by a combination of EGS4, [12] our modified PICA95, [13] and LAHET2.7 codes. The detail experimental procedures are described in Section 2. Analyses and discussions about the obtained results are given in Section 4. The final section is for conclusions.

2 Experimental Procedures

1. Geometry

The experiments were performed at the injection linac in Pohang Accelerator Laboratory. A simplified schematic diagram of the experimental set-up is shown in fig.1. An Al, Cu, Sn and Pb target was placed in front of the accelerator tube window, and its thickness was 8.0, 14.0, 12.1 and 5.5 cm, respectively. The distance between the window and the center of the targets was 21.0 cm.

2. Beam Status

The 2.04 GeV electron beam from the accelerator is focused on a center of the target about 2 cm diameter. The beam frequency was 10 Hz and the pulse width was 1 nsec. The beam intensity measured by a wall-current monitor was approximately 500 pC/pulse. The integrated currents during each measurement were monitored by current integrator. The accuracy of the integrator was confirmed by an activation measurement of Au foils, which were inserted in the Pb target. The foils were irradiated by the electron beam for 22 minutes. After the irradiation, yields of ^{196}Au in the Au foils were determined by measuring their activities. Comparing these values with calculated ones which were evaluated by EGS4 and our modified PICA95, it was found out that the error associated with the current integrator was less than 5 %. The detail description of this checking method was written in our previous paper. [14]

3. Detector Efficiency

A detector of PILOT-U (2 inchϕ $\times$2 inch) was located at a fixed angle of 90 degrees to the beam axis and 557.5 cm separation from the target. The detector was surrounded by a Pb collimator whose outside and inside diameter are 30 cm and 6 cm, respectively. Since the discriminate level was set to 4.2 MeVee checked by an Am-Be reference source, the lower limit of measurable neutron energy was approximately 9 MeV. The higher limit was approximately 300 MeV.

The detector efficiency was calculated by SCINFUL [15] for neutron energy below 80 MeV, and Cecil's code [16] for above the energy. It should be noted that the calculated values by SCINFUL were for NE110 efficiencies, and the values by Cecil's were for NE213 values because the calculation codes were not adapted to PILOT-U. The results by Cecil's code were normalized to those by SCINFUL at the neutron energy 80 MeV because the performance of PILOT-U was closer to that of NE110 compared with NE213. For a determination of the effect of the surrounded collimator, and also for a confirmation of the calculated results, the efficiency of the detector with the collimator were measured for neutron energies 14.9, 33.0, 64.7, 66.0, 86.5, and 132.0 MeV. The measurements were performed by using quasi-monoenergetic neutron sources of four different facilities, OKTAVIAN [17] for neutron energy 14.9 MeV, CYRIC [18] for 33.0 MeV, TIARA [19] for 64.7 MeV, and RIKEN [20] for other energies. The obtained efficiencies were shown in fig.2.

From the figure, it is obvious that the experimental values agree with the calculated ones well.(within 15%) It means that the effects of the Pb collimator surrounded the detector are almost negligible to the detector efficiency. This results are consistent with Bahr's result. [21] From these consideration, we can say the calculated efficiency is enough precise to be used in the analysis of the photo-neutron spectra.

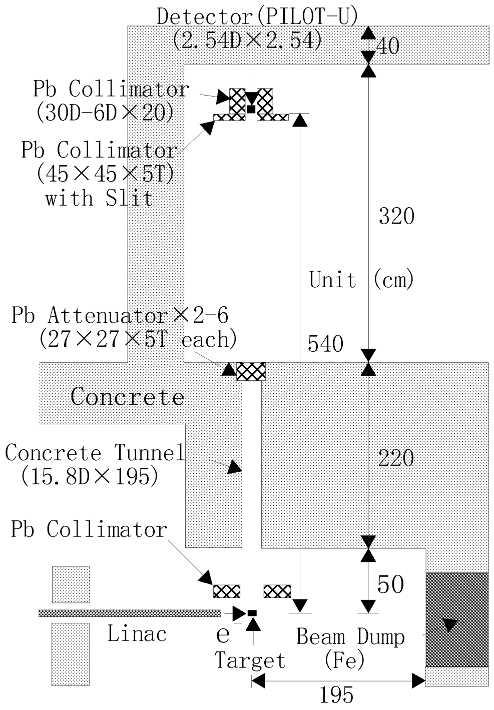

Fig.1 Experimental arrangement.

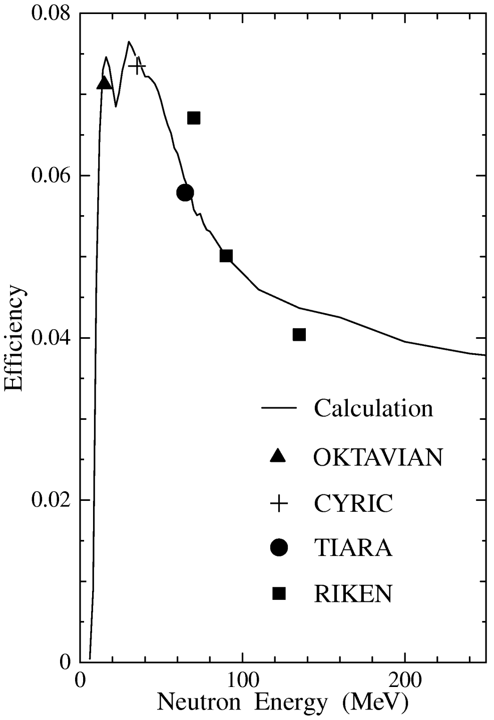

Fig.2 Measured and calculated detector efficiency.

4. Attenuator Effect

Neutrons emitted from the target were collimated by passing through a lead and concrete collimator of 10 cm and 220 cm thickness, respectively. A lead attenuator was placed at the end of the concrete collimator to suppress the electromagnetic background. The thicknesses of the attenuator for the cases of the Cu, Sn and Pb targets were changed from 15 cm to 30 cm at an interval of 5 cm. However, the data of high and low neutron energy part for 15 cm attenuator case were not reliable due to too large electromagnetic background. The thicknesses for the Al target case were 5 cm or 10 cm because radiation length of the Al target was much smaller than those of the other targets.

The effects of the attenuator on the neutron spectra were determined by calculating probabilities of neutrons getting to the detector after passing through the attenuator. The detail calculation method of the probability was described in other paper. [22] The neutron spectra at the target surface can be evaluated from the probabilities and detected neutron spectra.

3 Results and Discussion

For a confirmation of the attenuator effects, and checking an accuracy of the experiment, the yields at the Sn target surface for several neutron energy bins are plotted in fig. 3 as a function of the attenuator thickness. Those yields are normalized to the values for 25 cm attenuator cases. The errors are only associated with the counting statistics. From the figure, it is found out that the yields are almost independent of the attenuator thickness for neutron energy between 10 MeV and 300 MeV.

Since neutrons with energies above 300 MeV tend to reach the detector within the detector dead time caused by the strong γ-flash specially for thinner attenuator cases, the yield for the energy region becomes larger by increasing of the attenuator thickness. On the contrary, the yields of neutrons with energies below 10 MeV become smaller by increasing of the thickness. It is due to an increasing of the number of the neutron whose light output is above the threshold level by decreasing of the attenuator thickness, since light outputs from the electro-magnetic background are added to the value from the neutron.

Obtained photo-neutron spectra at the Al and Pb targets surfaces are shown in fig. 4. The attenuator thickness is 10 cm and 25 cm for the case of the Al and Pb target, respectively. The errors are also associated with the counting statistics only. There may be an additional 10 % and 15 % of systematic errors at maximum in the value of the current monitor and the detector efficiency, respectively. Calculated values corresponding to the experimental data evaluated by a combination of EGS4, our modified PICA95, and LAHET2.7 were also shown in the figures.

The photon, electron and positron track length in the targets were calculated by EGS4. Photo-neutron production cross sections were evaluated by our modified PICA95. Neutron production cross sections of electron-nuclear or positron-nuclear reactions were deduced from those of photo-nuclear ones. The detail methods of the evaluation were described in ref. [14]. However, almost all the neutrons were produced by photo-nuclear reaction, and the effects of other reactions were only a few percents of the total neutron yields. The transports of produced neutrons, protons, and pions in the targets were calculated by LAHET2.7.

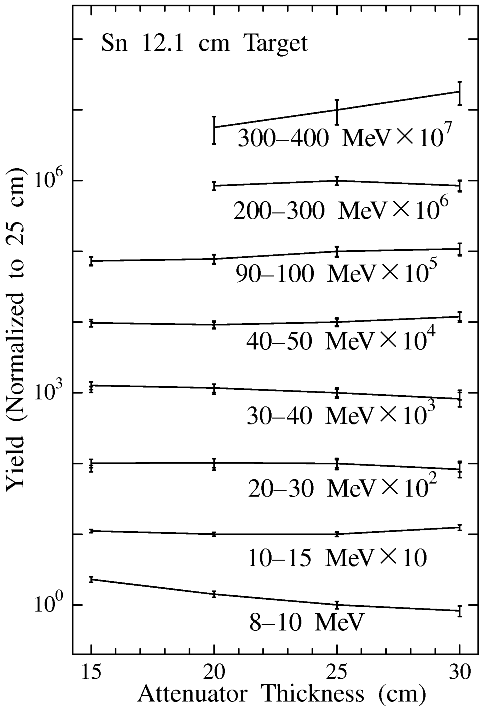

Fig.3 Photo-neutron yields of the Sn target as a function of the attenuator thickness. Those yields are normalized to the values for 25 cm attenuator cases.

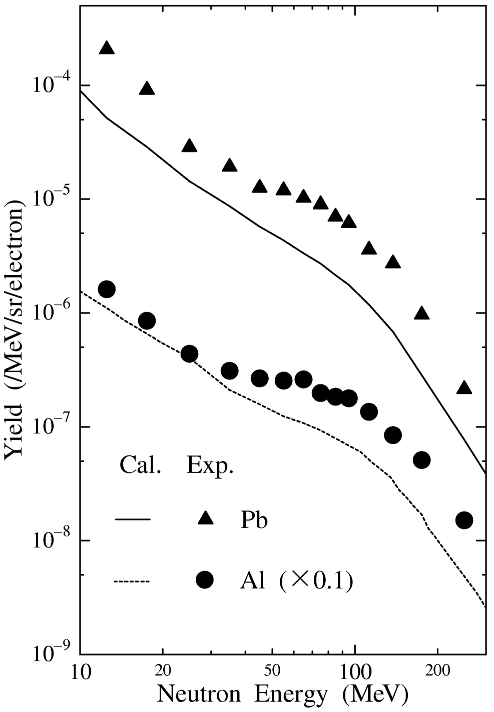

Fig.4 Photo-neutron spectra at the Al and Pb targets surfaces

Comparing experimental data with the calculated ones, it is obvious that the calculated values underestimate the experimental ones. This discrepancy is clearly seen for neutron energy less than 20 MeV, and greater than 50 MeV. This tendency is also observed for the other targets' cases.

One reason of the discrepancy for lower energy neutron yields is an ignorance of pre-equilibrium process in the PICA95 calculation. Neutrons having an intermediate energy (greater than an average energy of neutron produced by evaporation process, and less than that by direct process) are mainly produced by the pre-equilibrium process. Therefore, the ignorance of the process causes an underestimation of the neutron yields below 20 MeV.

The reason of the discrepancy for higher energy neutron yields has not been figured out. One considerable reason is an underestimation of quasi-deuteron disintegration (QDD) for incident photon energies above 150 MeV, because the average kinetic energy of emitted neutrons produced by the reaction is higher than the value by Δ resonance. The QDD reaction mechanism proposed by Levinger [23] is the dominant photo-nuclear reaction for incident photon energies between 30 MeV and 150 MeV. The modified PICA95, which adopts the model, can reproduce the experimental total photo-nuclear reaction cross section for the energy region very well. [13] However, there is no experimental data to prove the accuracy of the model above 150 MeV because Δ resonance become a dominant reaction for the energy region, and it is very hard to extract the QDD reaction contribution from experimental data. Another considerable reason is a difference between experimental and calculated angular distributions of emitted neutrons. However, both of them can not explain such a large discrepancy sufficiently.

4 Conclusions

The photo-neutron spectra produced by striking 2.04 GeV electron into various thick targets were measured by placing a Pb attenuator at the middle point of the TOF flight path, and the obtained spectra are almost independent of the attenuator thickness for neutron energies between 10 MeV and 300 MeV.

The neutron spectra calculated by a combination of EGS4, our modified PICA95, and LAHET2.7 underestimate the experimental ones. This discrepancy is clearly seen for neutron energy less than 20 MeV, and greater than 50 MeV. One reason of the discrepancy for lower energy neutron yields is an ignorance of pre-equilibrium process in the PICA95 calculation. The reason for higher energy neutron yields has not been figured out.

More experimental data, especially the yields for higher and lower neutron energies which can not be measured in these experiments, are required. The spectra for other angles are also needed because the angular distribution of emitted neutron may become a key to solve the discrepancy between experimental and calculated results. Recently, we have performed a similar experiments by using longer flight path (10.4 m) to obtain the spectra with better energy resolution. The results of the experiments will be published soon.

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