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学 位 論 文 題 目	Study on neutron anisotropic emission from photonuclear reaction in giant dipole resonance energy region
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(Form 3)

Summary of Doctoral Thesis

Name in full: Tran Kim Tuyet

Title

Study on neutron anisotropic emission from photonuclear reaction in giant dipole resonance energy region

For energy of photon ranging from 10 to 30 MeV, the nucleus absorbs the photon, and this results in the relative displacement of neutrons and protons included in the nucleus that results nucleon emission. The data of the photon induced nucleon emission, photonuclear reaction, are important for developing nuclear reaction models, designing radiation shielding, analyzing radiation transport, and evaluating dosimetry of radiotherapy in applications of electron accelerators. Until now, data of photonuclear reaction were obtained for the (γ,xn) reaction cross section through plenty of experiments with different photon sources. Recently, energy spectrum of neutrons and its angular distribution are obtained for Au target at 17 MeV photon energy. The data show large amount of low energy isotropic and small amount of high energy anisotropic neutron emission. The energy distribution should be considered for evaluation of radiation effects due to electron accelerators. The experimental data for describing cross section with neutron energy and angular distribution, double differential cross-section (DDX), are scarce. The DDX enable us to not only evaluate nuclear data library used in radiation transport but also developing the physics model. Thus, measurement of the DDXs photoneutron should be carried out for various target materials and using the different incident photon energies. The objective of this thesis is development of experimental method for the measurement of DDXs of photoneutron to reveal nature of the reaction and its impact on application.

In this research, a beam of linearly polarized mono-energetic photons was generated at the NewSUBARU facility (Spring-8, Japan) by using the laser Compton scattering (LCS) technique. The LCS photons were generated by the collisions of the laser photons with wavelength of 1.064 μm and a beam of high-energy electrons, whose energy were adjusted to produce LCS photons with maximum energies of 14 MeV, 17 MeV and 20 MeV. The LCS photon beam was collimated by lead blocks to approach a cylindrical target at its circular center. The target was made of different materials, including ^{nat}Pb, Au, ^{nat}Sn, ^{nat}Cu, ^{nat}Fe, and ^{nat}Ti, and each material was respectively placed on the LCS beam direction for measurement. Owing to the photonuclear reactions, neutrons were generated in the target. Surrounding the target, the neutron detectors filled with the organic liquid scintillator NE213 (a product of Nuclear Enterprises Ltd., U.K., or equivalent) were placed to detect neutrons. An event-by-event data acquisition (DAQ)

system consisted of Versa Module Europa (VME) and Nuclear Instrument Module (NIM) modules was assembled with the time-of-flight (ToF) function to measure the neutron energy, and the pulse shape discrimination (PSD) function to distinguish neutrons and background γ-rays. The raw data were stored in a Linux computer, and interpreted by C++ and ROOT framework.

The DDXs of photoneutrons were determined by normalizing neutron yield with number of LCS photons, the attenuations of neutron and photon, neutron detection efficiency, target atom and solid angle. Neutron and gamma events were distinguished using the PSD parameter that was the ratio of the tail integral to the total integral. Neutron energy was determined by the time of flight that was obtained as a sum of the gamma flight time and the time difference between the neutron data and the prompt gamma peak. The number of counts by the plastic scintillator (PLS) was used with the consideration of its photon detection efficiency to evaluate the number of LCS photons. Using PHITS calculation, the photon attenuation was determined by taking the ratio of the average track length of photons to the target thickness. As the LCS photons, the photoneutrons emitted from the target were also attenuated when penetrating through the target to reach the NE213 detectors, the neutron attenuation was also taken into account and calculated by the PHITS. The neutron detection efficiency was determined by combining efficiency data from ^{252}Cf measurement and SCINFUL-QMD calculation.

The DDXs for Pb, Au, Sn, Cu, Fe and Ti targets were calculated by PHITS. Geometry of the DDXs calculation conducted in PHITS was similar to the experiment. Target thickness of 5 μm was chosen in the DDXs calculation to reduce the target thickness effect. The PHITS results did not express the angular distribution of the photoneutron. In addition, The DDXs were extracted from JENDL/PD-2004 and JENDL/PD-2016.1 libraries by a python-based software. The cascade exciton model, CoH_3, was also used to calculate DDXs. The all three DDX results were considered for the abundances of isotopes in target, the width of the incident photon energy within 14 MeV - 17 MeV and the neutron energy resolution.

The DDXs of photoneutron was obtained for Pb, Au, Sn, Cu, Fe and Ti targets at polar angles of 30°, 60°, 90°, 120°, 150° and azimuthal angle of 90° for 14, 17 and 20 MeV linearly polarized photons. There were two components shown in all the DDXs, one component occupied in the energy range 2-4 MeV, and the second component occupies from 4 MeV to the maximum energy. To determine the energy for separation these two components, the low-energy component was fitted with Maxwellian distribution, which can well explain the evaporation process of low-energy neutrons. Afterwards, ratio of experimental points to fitting data was used to separate the two components. To discuss angular distribution of the photoneutron, it is needed to consider the angular differential cross sections (ADXs) and the angles of the incident photons and the emitted neutrons.

The angular dependence of the neutrons in low and high-energy components can be well explained by the fitting function $ADX(\Theta)=a+b\cos(2\Theta)$, Θ was angle between directions of the photon polarization and neutron emission. The angular distribution of high-energy neutron was studied in previous experiment measured with unpolarized photons. The a_2 is the anisotropy parameter in Legendre polynomial expansion and is used to compared angular distributions between researches. In this research, I calculate the a_2 parameter using my data measured with mono-energetic polarized photons and compared it with other experiments. The numerical data of a_2 in Ti and Sn targets were measured the first time in this research. The a_2 values in Cu and Fe were consistent with the results obtained in the previous studies; while the a_2 values of Pb and Au were smaller than the previous results. For comparison of the experiment DDXs and the calculations, PHITS simulation does not produce the high energy component that was obtained by the experiment, and there is a slight disagreement between the DDXs from the evaluated nuclear data files with the experimental data. Studying target mass dependence of photo-neutron, the neutron yield and maximum energy increase with increasing target mass number. A relatively large high energy component was observed in the spectra for heavy nuclei (Pb, Au, Sn); however, the component was relatively small for the other targets (Cu, Fe, Ti). Dependence of the photoneutron on the photon energy, the maximum energy of photon-neutrons increases and the slopes of energy distribution of evaporation shaped component becomes gentle with the photon energy.

The effect of the photo-neutron spectrum shape for the Pb(γ,xn) using 17 MeV of the incident photon on the shielding calculation was studied by considering leakage dose rate using PHITS code. The geometry for the concrete shielding calculation was a sphere geometry. The thickness of shielding concrete was varied from 0 cm to 180 cm. The two neutron spectra of the Maxwellian shaped and experimental based that consist of Maxwellian and preequilibrium component were applied for shielding calculations. After penetrating the shield, the neutrons in the high energy component region lose their energy and make differences in the lower energy part with increasing the shielding thickness. The result shows the dose could be underestimated almost three times with increasing shielding thickness if we use Maxwellian shaped spectrum for shielding calculation. Because I used neutron spectrum obtained for the horizontal polarized photon that gives large preequilibrium component, the underestimation will be mitigated in actual shielding design that was performed for the Bremsstrahlung un-polarized photon.

I used the mono-energetic linearly polarized photon beam and time of flight technique on the experiment. I obtained the DDXs of photoneutron for six medium-heavy target nuclei at six different angles for three photon energies. I successfully identified low energy and high energy components, which were previously observed for Au target, on DDXs for photonuclear reactions on Pb, Au, Sn,Cu, Fe, and Ti targets. Through the DDX data, target mass dependence on the photo-neutron spectrum and the photon energy dependence were discussed.

The angular distributions of photoneutron are parameterized to compare that with the previous data for checking consistency. The factor of the second-order Legendre polynomial a_2, which describes the component of angular dependence from photonuclear reactions with Bremsstrahlung photons, were deduced from the DDXs. The numerical data of a_2 in Ti and Sn targets were measured the first time in this research. The a_2 values in Cu and Fe were consistent with the results obtained in the previous studies; while the a_2 values of Pb and Au were smaller than the results reported in previous studies.

To understand the current status of photoneutron production in particle transport simulation, the DDXs were compared with that from Monte Carlo code, the nuclear data files and cascade exciton model. This comparison indicates the anisotropy in high energy component are not reproduced in MC code and theoretical models. Improvement of physical models should be studied to generate the neutron spectrum which is consistent with the experimental data.

Finally, the impact of anisotropic high energy neutron that was observed in the experimental neutron spectrum was demonstrate through calculation of the leakage dose for a simple shielding structure. The ratio of doses for the total component to the Maxwellian only component increased with shielding thickness and reached 2.9 for a concrete thickness of 180 cm. This result implies either a nuclear reaction model or database to reproduce a photo neutron spectrum including the anisotropy high energy component must be used for the shielding calculation of an electron accelerator facility.

Form8・Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　名　Tran Kim Tuyet

Title
論文題目　Study on neutron anisotropic emission from photonuclear reaction in giant dipole resonance energy region

10-20 MeVの光子から発生する光中性子のエネルギー・角度二重微分断面積は、電子加速器の遮へい設計において極めて重要である。しかし、単一エネルギーの光子源が少ないため、これまで限られた情報しか得られていない。

Tuyet氏は、NewSUBARU加速器においてレーザー逆コンプトンの方法により、10-20 MeVの単一エネルギー光子を発生させ、Pb, Cuなど加速器コンポーネントとして重要な6種類のターゲットにそれを入射させ、発生する中性子をNE213液体シンチレータで測定した。測定にはTOF法が用いられ、立ち下がり時間と飛行時間の関係を利用して中性子とガンマ線によるバックグラウンドをはっきりと弁別している。ターゲット内での光子と中性子の減衰を補正し、二重微分断面積を得ている。得られた中性子のエネルギースペクトルは前平衡過程による成分と、蒸発過程による成分からなり、両成分のターゲット、角度依存性を論じている。前平衡成分の角度分布については、入射光子の偏光ベクトルの方向を中心とする分布として整理しており、角度分布の強さのターゲット依存性を論じている。また、PHITSコード、JENDL/PD-2004、JENDL-PD-2016, CoH_3コードによる計算との比較を行っている。この際、光子エネルギーの広がり、中性子検出器の特性による見かけ上の中性子エネルギーの広がりを考慮して計算値のエネルギー分解能を下げ、実験と計算値を詳しく比較している。PHITSコードが前平衡成分を再現できないことが分かったため、その実際の電子加速器の遮へい計算結果への影響の程度を見積もった。前平衡成分が最も多い実験条件のデータを用い、コンクリート遮蔽体透過後の中性子のエネルギー分布と線量の変化を厚みの関数として試算した。審査会では、Tuyet氏は研究内容を明瞭かつ簡潔に発表し、質疑に対しても的確に回答した。また、英語で投稿論文を執筆し掲載済みであること、学位論文を英語で執筆していること、審査会でも英語での発表、質疑応答を行っていることから博士として十分な英語の能力を持つと判断した。論文の主旨及び研究内容は博士論文として妥当であり十分な完成度であると判断し、審査委員全員一致で本審査を合格とした。