Photoneutron Cross Section Measurement for ^{94}Zr Using Laser Inverse Compton γ Rays

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Abstract

Quasi-monoenergetic γ rays produced in laser inverse Compton scattering (LCS) were used to measure photoneutron cross sections for ^{94}Zr near neutron threshold. The photodisintegration measurement is expected to probe neutron capture for ^{93}Zr (a long-lived fission product) within the framework of the statistical model. Measured cross sections are reported.

1. Introduction

In recent years, nuclear transmutation of minor actinides (MA) and long-lived fission products (LLFP) has promoted direct measurements of neutron capture cross sections for MA and LLFP [1,2]. However, the direct measurement is feasible only at dedicated facilities, for example, CERN n-TOF [1] and J-PARC [2], where strong neutron sources are/will be available. Yet preparation of radioactive samples is very difficult if not impossible.

Photodisintegration serves as an indirect probe of neutron capture because photoneutron cross sections can be used as constraints on the E1 γ strength function in the statistical model to predict neutron capture cross sections. Quasi-monoenergetic γ rays produced in laser inverse Compton scattering (LCS) at the National Institute of Advanced Industrial Science and Technology (AIST) are an ideal photon source for photodisintegration measurements. The present work represents a photodisintegration measurement for ^{94}Zr as a probe of neutron capture for ^{93}Zr ($t_{1/2} = 1.53 \times 10^6$ years) among other LLFP (^{80}Se, ^{108}Pd, etc.).

2. Experiment

Quasi-monoenergetic γ rays were generated in head-on collisions of laser photons from the INAZUMA laser system on relativistic electrons in the storage ring TERAS. The INAZUMA (a fiber-coupled diode-pumped Q-switch Nd: YVO_4 laser) was operated in the fundamental mode (λ = 1054 nm) at 20 kHz with the maximum power of 24 W. The beam line of the laser inverse Compton scattering (LCS) is shown in Fig. 1. Laser photons were led to a region of interaction with electrons through a laser optics consisting of an expander, a lens, and a mirror. The energy of the LCS γ rays was changed from 8.4 MeV to 9.8 MeV by adjusting the electron beam energy. Pencil-like beams of the LCS γ rays in 2mm diameter were produced with a 20cm lead collimator. A macro-time structure was generated in the LCS γ-ray beam by applying a 10 Hz external gate with 80 ms ON and 20 ms OFF to the laser system as shown in Fig. 2.

The LCS beam was used to irradiate a ^{94}Zr target mounted at the center of a neutron detector. The target was oxide powder (ZrO_2) with 99.60% in isotopic purity and 99.942% in chemical purity. The powder was encapsulated in an aluminum container. Fig. 3 shows the neutron detector consisting of twenty ^{3}He proportional counters (CANBERRA/ Dextray: Eurisys Mesures) embedded in a polyethylene moderator. The ^{3}He counter is 25mm in diameter and 500mm in length. The polyethylene moderator is 360mm in height, 360mm in width and 500mm in length. Three concentric rings of 4 (inner), 8 (middle), and 8 (outer) ^{3}He counters mounted at distances of 76mm, 140mm and 200mm from the beam axis, respectively, provide high detection efficiencies (60 – 70%)

for moderated neutrons. The electronic circuit for the triple-ring neutron detector is shown in Fig. 4. Signals from the ^{3}He counters in each ring were processed by an AMP-Discri module that is composed of 10 sets of pre-amplifiers, main amplifiers and pulse-height discriminators. The OR signal for the individual ring of ^{3}He counters was generated with a FANIN/OUT module. The beam ON and OFF gates were applied to the OR signals in a coincidence module to select events of reaction plus background neutrons and background neutrons, respectively.

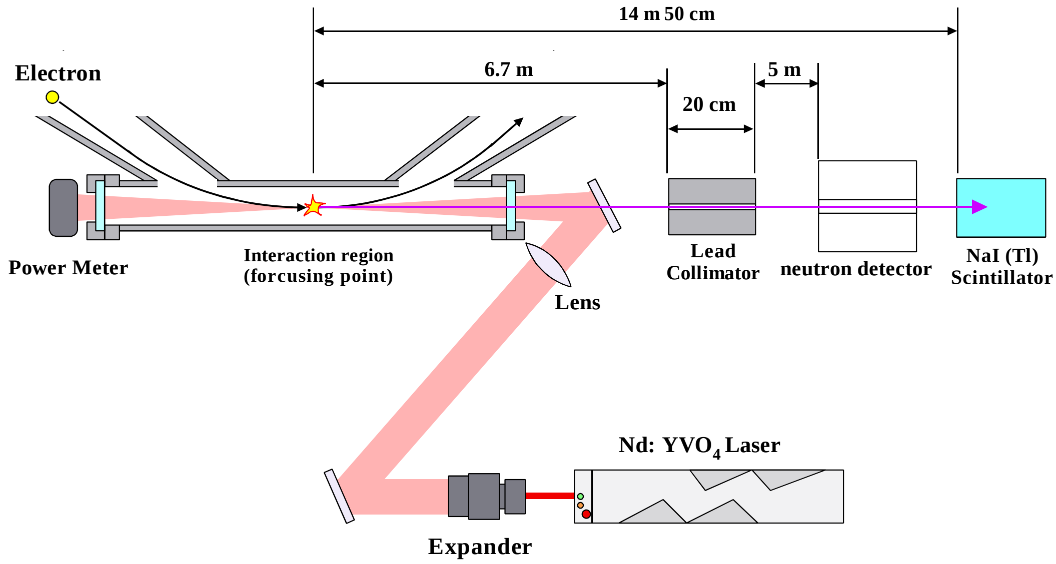

Fig. 1 Schematic view of the LCS γ-ray beam line.

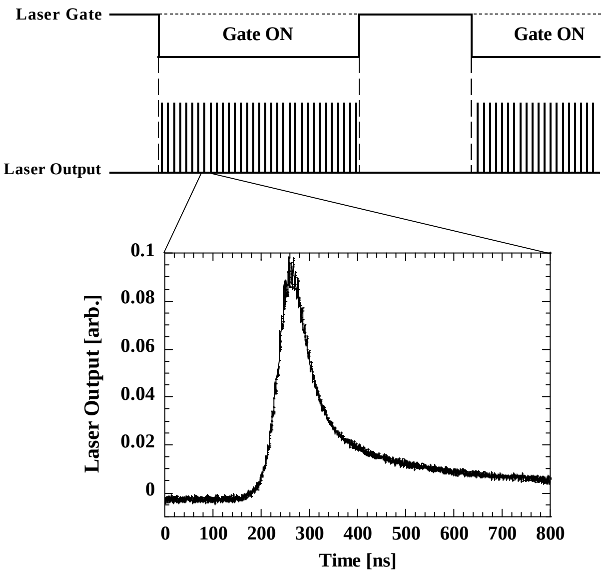

Fig. 2 Macro (upper) and micro (lower) time structures of the Nd: YVO_4 laser power (INAZUMA: Spectra-Physics)

The LCS γ ray was measured with a 120% high-purity germanium detector. The response function of the Ge detector to the LCS γ rays was analyzed in EGS4 Monte Carlo simulations to obtain the energy distribution of the LCS γ beam [3]. A typical response function of the Ge detector and energy spectrum of the LCS γ rays are shown in Fig. 5. Obviously γ rays above the neutron threshold induced photoreactions. The LCS γ beam was monitored with a large volume NaI(Tl) detector (20cm in diameter and 30cm in length). A pile-up spectrum of the LCS γ rays from the NaI(Tl) detector is shown in Fig. 6. The pile-up spectrum was analyzed to obtain the number of incident γ rays [3].

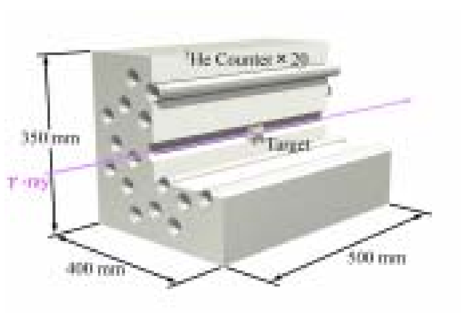

Fig. 3 Schematic view of the triple-ring neutron detector

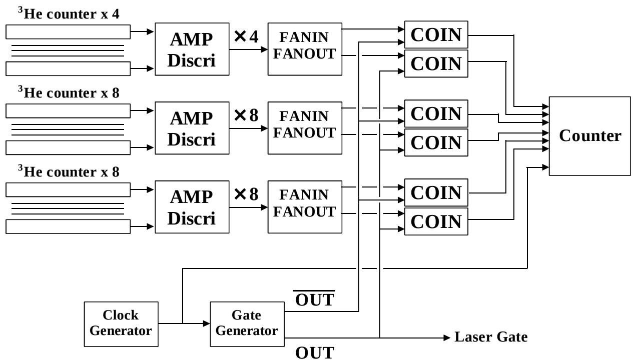

Fig. 4 Electronic circuit for the triple-ring neutron detector

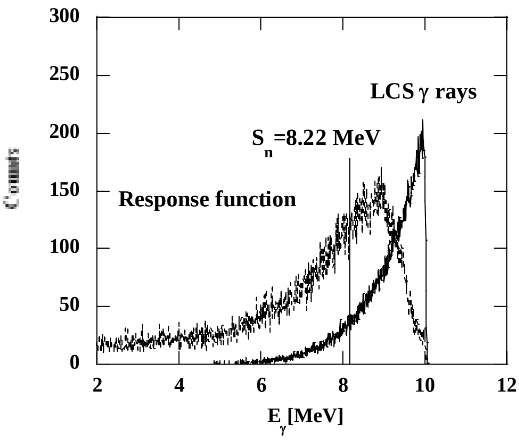

Fig. 5 Response function of the germanium detector and the energy distribution of the LCS γ rays

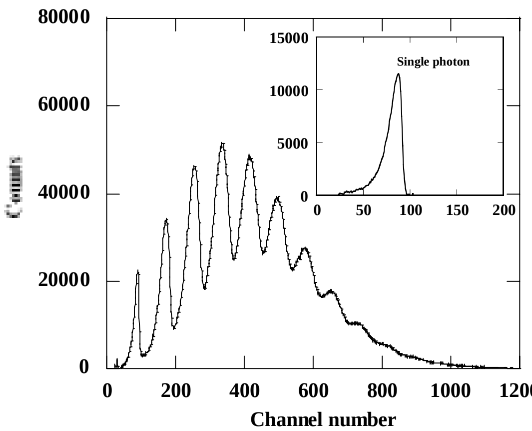

Fig. 6 Pile-up spectrum of the LCS γ-ray beam from the NaI(Tl) detector. A single photon response of the detector is also shown.

3. Analysis and Result

Photoneutron cross sections were experimentally determined at the average γ-ray energies in the monochromatic approximation from $\sigma(E_\gamma) = N_n/(N_t\ N_\gamma(E_\gamma)\ \varepsilon_n\ f)$, where N_n is the number of neutrons detected, N_t is the number of target nuclei per unit area, $N_\gamma(E_\gamma)$ is the number of incident γ rays, ε_n is the neutron detection efficiency, and f is a correction factor for the present thick-target measurement. The correction factor is given by $f = (1 - e^{-\mu t})/\mu t$ with the linear attenuation coefficient of γ rays μ and target thickness t [4]. The detection efficiency was determined from ring ratios [3,5], where three ring ratios were averaged with weights being proportional to the inverse of the square of associated statistical uncertainties. It is to be noted that the monochromatic approximation provides cross sections near the neutron threshold within typical uncertainties of a few percents [6].

Fig. 7 shows the present result of photoneutron cross sections for ^{94}Zr. The statistical error bars are smaller than the size of the data points. The data of Berman et al. [5] are also shown for comparison. The present data are consistent with the previous data above neutron threshold, whereas non-vanishing cross sections below neutron threshold obtained in the previous measurement are apparently problematic.

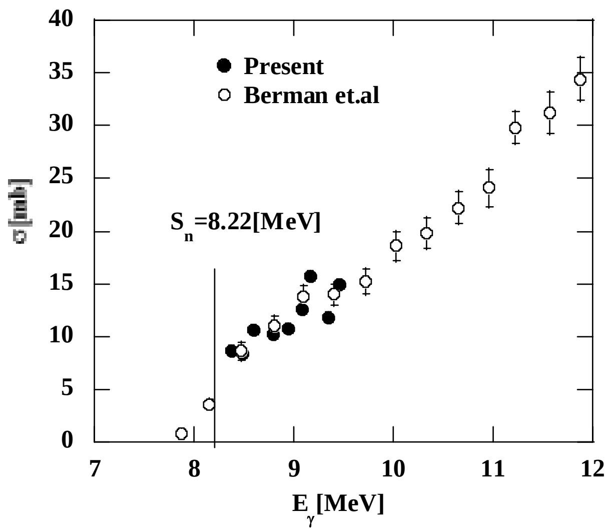

Fig. 7 Photoneutron cross sections for ^{94}Zr in comparison with those obtained previously [5].

4. Summary

We measured (γ, n) reaction cross section for ^{94}Zr with the LCS γ-ray beam at AIST. The present result is consistent with that of Berman et al. [5] above neutron threshold. However, the non-vanishing cross sections of the previous measurement below neutron threshold are apparently problematic. The present result exhibits a large cross section even at 8.36 MeV which is already very close to the threshold. The threshold behavior of the photoneutron cross section needs to be studied carefully further.

Reference

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