Nuclear Instruments and Methods in Physics Research A 618 (2010) 153–159

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A facility for measurements of (n,γ) cross-sections of a nucleus in the range $0.008 \leq E_n < 20$ MeV

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ARTICLE INFO

Article history:
Received 19 December 2008
Received in revised form
17 March 2010
Accepted 19 March 2010
Available online 8 April 2010

Keywords:
Radiative capture
Spectroscopy with light ions
Neutron spectroscopy
X- and γ-ray spectroscopy
Scintillation detectors

ABSTRACT

A new measurement system to determine the neutron-capture cross-sections of a nucleus at $0.008 \leq E_n < 20$ MeV has been installed at the 4 MV Pelletron accelerator laboratory at the facility of radiation standards at Japan Atomic Energy Agency. The performance of the new system was studied by measuring the neutron-capture reaction cross-section of ^{nat}Pb using pulsed neutrons from ^{7}Li(p,n)^{7}Be at $12 \leq E_n \leq 103$ keV. Prompt γ-rays from the reaction were detected by means of a highly sensitive anti-Compton NaI(Tl) spectrometer combined with a time-of-flight method. The obtained result demonstrated good sensitivity of the new system to determine the neutron-capture cross-sections of a nucleus at kiloelectron volt neutron energy.

1. Introduction

Fast neutrons in the energy region $E_n > 1$ keV have been used as a unique probe in science fields, such as nuclear astrophysics, nuclear physics, and nuclear engineering. In nuclear astrophysics, models of stellar nucleosynthesis play an important role in tracing the history of the Galaxy by studying the abundance of various elements as a function of the metallicity of stars [1]. The neutron-capture cross-section of a nucleus at an astrophysics relevant energy, $1 < E_n < 500$ keV, is one of the fundamental input parameters for constructing models of stellar nucleosynthesis of heavy elements, which were produced via slow (s-) and rapid (r-) neutron-capture processes [2,3]. In nuclear physics, many interesting phenomena, such as non-resonant s- and/or p-wave direct capture processes [4–6], doorway states [7,8], Pigmy [9], magnetic dipole (M1) [10], and electric quadrupole (E2) resonances [11,12], were observed by fast neutron-capture reaction of a nucleus. These phenomena provided crucial information to understand the nuclear reaction mechanism and the nuclear structure relevant to the reactions. In applications of nuclear engineering, the precise nuclear data of the cross-section of a nucleus, of fission yields, and of an emitted number of neutrons are required in the neutron energy range from thermal to several megaelectron volt. As far as astrophysics interest is concerned, the neutron-capture cross-sections have been measured at astrophysics relevant energy by using quasi mono-energetic [13] and/or continuous energetic pulsed neutrons [14]. The quasi mono-energetic pulsed neutrons can be obtained by the ^{7}Li(p,n)^{7}Be reaction using protons of about 1.9–2.5 MeV, in which only two reaction channels, such as ^{7}Li(p,n)^{7}Be and ^{7}Li(p,γ)^{8}Be, are open when one uses a Li metal as neutron production target. Intense γ-ray events due to ^{7}Li(p,γ)^{8}Be can be discriminated from true events due to neutron-capture by a sample nucleus with a time-of-flight (TOF) method, which allows us to install a low-background measurement system to accurately determine the small neutron-capture cross-section of a nucleus with a mass number A, $\sigma_\gamma(A)$, on the order of a few microbarn. The continuous energetic pulsed neutrons have been produced by bombarding a heavy element, such as Hg, Ta, and Pb, with high-energy electrons [14] and/or protons [15]. Using thus-produced neutrons with a continuous energy spectrum, one can measure $\sigma_\gamma(A)$ by using the same experimental setup in a wide energy range, which could allow us to determine the cross-section with a small systematic uncertainty. Recent progress using a high intensity proton beam accelerator could allow us to measure $\sigma_\gamma(A)$ of a rare abundant nucleus and/or a radioactive nucleus [16].

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doi:10.1016/j.nima.2010.03.127

However, the continuous energetic pulsed neutrons are produced together with various background particles, such as high-energy γ-rays, muons, and pions by spallation reactions. One needs to prepare well-designed heavy shields against these background particles to obtain true events from (n,γ) of a sample nucleus with a good *signal-to-noise* ratio. Despite the progresses so far made, further progress is required to reduce these background events for measuring neutron-capture cross-sections as small as a few microbarn. In order to accurately measure not only the $\sigma_\gamma(A)$, but also a neutron inelastic scattering cross-section of a nucleus with a mass number A, $\sigma_{n'\gamma}(A)$, using quasi mono-energetic neutrons in the energy range of $8\ \mathrm{keV} \leq E_n < 20$ MeV from the mentioned interesting points of view, we installed a new measurement system at the 4 MV Pelletron accelerator laboratory in the facility of radiation standards (FRS) of Japan Atomic Energy Agency (JAEA). A new system is described in Section 2, its performance study by measuring the neutron-capture cross-section of ^{nat}Pb is described in Section 3, the present result is given in Section 4, and we conclude our description of the present study in Section 5.

2. Measurement system

The 4 MV Pelletron accelerator (4UH-HC) was made by the National Electrostatics Corp. and is equipped with a Duoplasmatron ion source. A pulsed beam was generated using a sweep and a klystron buncher. Quasi mono-energetic pulsed neutrons in the neutron energy range from 8 keV to 14.8 MeV were already produced using ^{45}Sc(p,n)^{45}Ti, ^{7}Li(p,n)^{7}Be, ^{2}H(d,n)^{3}He, and ^{3}H(d,n)^{4}He reactions. So far, these neutrons have been mostly used to test properties of various types of neutron counters. The accelerated proton beam energy was calibrated using the ^{7}Li(p,n)^{7}Be reaction at the threshold energy within an uncertainty of 1 keV. The typical averaged proton beam current was about 5 μA at the repetition rate of 4 MHz. The pulse width of the proton beam was measured to be 3.3 ns (FWHM), as discussed later. Although the proton beam current was smaller by a factor two and the pulse width was about two times wider than the beam qualities of the 3 MV Pelletron accelerator at the Tokyo Institute of Technology (TIT), the mentioned beam qualities should be improved in near future.

2.1. γ-ray detector

We used an anti-Compton NaI(Tl) spectrometer to detect discrete γ-rays promptly emitted from the neutron-capture of a nucleus, since the electromagnetic multipolarity of a discrete γ-ray provides direct insight into the reaction mechanism of neutron-capture as well as nuclear structure. Such information is essential to improve the prediction of a theoretical model to calculate the (n,γ) cross-section of an unstable nucleus from nuclear astrophysics interest. It should be added that when one knows level schemes of a neutron capturing nucleus, a discrete γ-ray emitted from a neutron capturing state to low-lying states including the ground state uniquely characterizes a final nucleus, which could allow one to determine the $\sigma_\gamma(A)$ with a small systematic uncertainty.

An anti-Compton NaI(Tl) spectrometer used in the present study was developed by Ohsaki et al. [17] including one of the present authors to measure a neutron-capture cross-section of a nucleus at $5 < E_n < 600$ keV at TIT. Since we plan to measure the $\sigma_\gamma(A)$ above 600 keV in near future, we moved the spectrometer from TIT to the FRS.

The spectrometer consisted of a central NaI(Tl) detector with a diameter of 22.9 cm and a length of 20.3 cm and an annular NaI(Tl) detector with an outer diameter of 33.0 cm and a length of 27.9 cm to detect a discrete γ-ray with a good *signal-to-noise* ratio [17]. Low-background photomultiplier tubes were used for the anti-Compton NaI(Tl) spectrometer to reduce any background events due to the γ-rays from the β-decay of ^{40}K (at 1.461 MeV). Here four (eight) photomultiplier tubes were used for the central (annular) NaI(Tl) detector. Since a NaI(Tl) detector is known to be quite sensitive to neutrons, the spectrometer was heavily shielded with ^{6}LiH and borated polyethylene blocks to prevent neutrons scattered by a sample from entering into the central NaI(Tl) detector, and Pb against γ-rays produced by thermalized neutron-capture reactions by various materials placed in the measurement room. Concerning scattered neutrons mentioned above, it should be mentioned that ^{6}LiH with a thickness of 30 cm played an essential role to attenuate scattered neutrons via the ^{6}Li(n,α)^{3}H reaction without emitting any extra γ-rays. The thickness was also determined by considering the attenuation of intensities of γ-rays from the neutron-capture reaction of a nucleus.

The energy resolution of the central NaI(Tl) detector was 7% at 662 keV. The threshold energy level of an annular detector and the discrimination level of the constant fraction discriminator for the γ-rays detected by the central NaI(Tl) detector were respectively set at ~30 keV to effectively suppress any Compton background γ-rays escaping from the central NaI(Tl) detector and at about 600 keV to reduce the total count rate of the data-taking system.

The spectrometer was set at 100° with respect to the proton beam direction. The distance between the sample position and the front face of the central NaI(Tl) detector was 119 cm. Note that since the low energy neutrons were emitted from the ^{7}Li neutron production target within a narrow cone of about 50° with respect to the proton beam direction, they did not hit the spectrometer directly. A schematic view of the experimental setup is shown in Fig. 1. The floor of the measurement room was made of an Al grating to reduce any background due to scattered neutrons from the floor.

3. Performance of the new measurement system

The performance of the new system was studied by measuring the neutron-capture cross-section of a natural lead sample, $\sigma_\gamma(^{nat}\mathrm{Pb})$, using neutrons from ^{7}Li(p,n)^{7}Be in the neutron energy $12 \leq E_n \leq 103$ keV. We used a ^{nat}Pb sample, since a high sensitive measurement system could allow us to detect a discrete γ-ray from a state populated by ^{nat}Pb(n,γ) to a low-lying state of a neutron capturing nucleus and thereby to determine a small $\sigma_\gamma(^{nat}\mathrm{Pb})$ at non-resonance neutron energy. Note that the neutron-capture cross-sections of ^{206}Pb [18–23], ^{207}Pb [18,19,21, 24–26], and ^{208}Pb [27,28] at resonance energies were measured using neutrons with high energy resolution, although there remain discrepancies of the neutron-capture cross-sections of ^{206}Pb and ^{207}Pb between the different data sets, as discussed in Refs. [20,24]. The cross-sections between the resonances, however, are poorly studied [22,29,30]. Note that the broad-energy-average cross-section, including that at non-resonance neutron energy, is of importance for nucleosynthesis application. Hence, an evaluated cross-section of a nucleus, which is given in JENDL [31] and/or in ENDF [32] has been used in stellar nucleosynthesis calculations. However, an evaluation would be quite difficult, especially when there are many resonances, which interfere with the non-resonant capture reaction process.

In the present study, therefore, we aimed at determining the neutron-capture cross-sections of ^{nat}Pb in the mentioned neutron energy using a ^{nat}Pb sample with a diameter of 90 mm and a thickness of 8 mm. A gold sample with a diameter of 90 mm and a