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ARTICLE

Experimental Method for Neutron Elastic Scattering Cross-Section Measurement in Intermediate Energy Region at RCNP

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The applicability of an experimental method for neutron elastic scattering cross-section measurement using liquid organic scintillators and time-of-flight (TOF) technique was examined for quasi-monoenergetic neutron beams in the intermediate energy region above 100 MeV at the Research Center for Nuclear Physics (RCNP) of Osaka University, Japan. The elastic scattering neutrons were discriminated from the inelastic ones by the difference of their TOF. The results for carbon at 134 MeV were compared with the other experimental data obtained by a proton-recoil telescope. It was found that the experimental method proposed in this study is applicable to the measurement of elastic scattering cross sections with sufficient precision.

KEYWORDS: neutron, elastic scattering cross section, time-of-flight (TOF), liquid organic scintillator, intermediate energy region

I. Introduction

Thanks to recent advances in accelerator technology, applications of particle accelerators are rapidly expanding in various fields, not only in particle and nuclear physics but also in medical and material sciences. These accelerators have higher acceleration energy and greater beam intensity than previous ones. Neutrons generated at these accelerators have a strong penetrability through shielding material and dominate the radiation dose outside the shielding. In order to achieve reasonable radiation protection for workers and the general public, the interactions and transport characteristics of the neutrons must be well understood.

Elastic scattering cross section is one of the most important quantities in determining the particle behaviour inside a medium, and this parameter is also indispensable in establishing and determining Optical Model Potential (OMP), a basis for the evaluation of nuclear data used in design calculations of accelerator shielding. In fact, many proton elastic scattering experiments have been performed, and a systematic set of data has been constructed[1)]. However, for neutron elastic scattering in the intermediate energy region, experimental data are very scarce because of the experimental difficulties. An experiment with 96-MeV neutrons was reported by the group of Uppsala University using a quasi-monoenergetic neutron source and a proton-recoil telescope[2,3)]. Although the data have good resolutions in both energy and angle, the detection system used is not applicable to measurements with higher energy neutrons without modification of the detectors. A group at University of California Davis (UC Davis) obtained data with neutrons from 65 to 225 MeV using a continuous energy neutron source and a proton-recoil telescope at WNR of Los Alamos National Laboratory[4)]. The experiments, however, required a complicated detection system and a strong beam intensity to compensate for the low detection efficiency of the detection system.

A group at Tohoku University has successfully measured the neutron elastic scattering cross sections using a quasi-monoenergetic neutron source in the energy region from 40 to 90 MeV at TIARA of Japan Atomic Energy Agency[5)]. In this experiment, liquid organic scintillators were used as the neutron detector, employing a time-of-flight (TOF) technique. The neutron-detection efficiency of this scintillator is 10^4 times greater than that of a typical recoil-proton telescope, and the relatively long flight-path length makes possible to obtain very forward angle data with sufficient angular resolution. By using this scintillator and the TOF technique instead of the proton-recoil telescope, statistically accurate data could be measured even with a weak beam at TIARA.

In this paper, we describe an experimental method and data processing procedure for neutron elastic scattering cross-section measurement, using liquid organic scintillators and TOF technique, upon incidence of quasi-monoenergetic neutron beam above 100 MeV at the Research Center for Nuclear Physics (RCNP) of Osaka University. The measurements for carbon upon 134-MeV incidence are compared with the data of UC Davis and the evaluated nuclear data of JENDL/He-2007[6)] and ENDF/B-VII.0[7)].

II. Experimental method

The experiment was performed at the neutron-TOF course in RCNP. A proton beam supplied by a ring cyclotron whose

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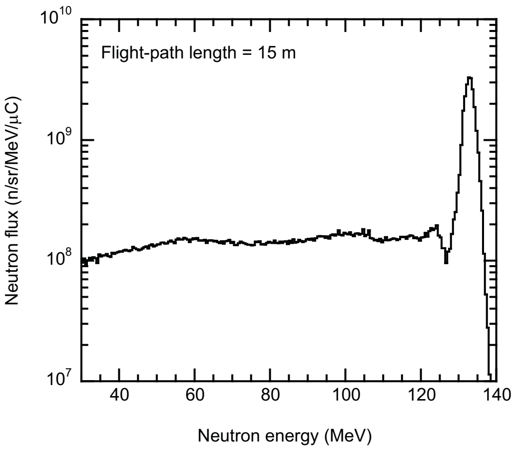

Fig. 1 Energy spectrum of source neutrons generated by ^{7}Li(p,n) reaction using 137-MeV protons.

maximum energy is 400 MeV was transported to a lithium target placed in a beam-swinger magnet. The thickness of the lithium target was 1.0 cm, which causes 137-MeV protons to lose 2.5 MeV. The protons transmitted through the target were bent by the magnetic field, and guided to a Faraday cup mounted inside a beam dump to monitor the beam current bombarding the target. The proton-beam current was set at 700 nA during the measurement of elastic scattering cross sections.

The intensity and energy spectrum of the source neutrons produced from the ^{7}Li(p,n) reaction were measured by an NE213 liquid organic scintillator located in the 0° direction and 15 m downstream from the target, with the TOF method. In the source-neutron measurement, the current was changed from 700 nA, and the beam was thinned out by 1/5 with a beam chopper. The current monitored by the Faraday cup was around 10 nA during the measurement. The energy spectrum upon 137-MeV proton bombardment is depicted in **Fig. 1**. A peak of quasi-monoenergetic neutrons was observed around 134 MeV. The FWHM of the peak was 3.0 MeV, and the intensity was 1.05×10^{10} neutrons/sr/μC.

Figure 2 illustrates a schematic of the experimental setup for the measurement of neutron elastic scattering cross section. The quasi-monoenergetic neutron beam was guided to a scattering sample passing through collimators. An additional collimator, which consists of iron 100 cm long and 5.5 cm in diameter at the exit side, was placed in front of a preinstalled collimator for more aggressive beam collimation. The scattering sample was set 10 m downstream from the lithium target by hanging it from the ceiling with a polyethylene line to suppress scattering by the material mounting the sample. Cylindrical samples of natural carbon (5 cmø× 5 cm) were bombarded with the 134-MeV neutrons.

NE213 liquid organic scintillators were employed to detect the scattering neutrons. The size of the scintillators was 12.7 cm in diameter and 12.7 cm in thickness. The neutrons were measured at three angles concurrently. By measuring TOF, elastic scattering neutrons were distinguished from inelastic ones, that have a relatively long TOF. For the measurement

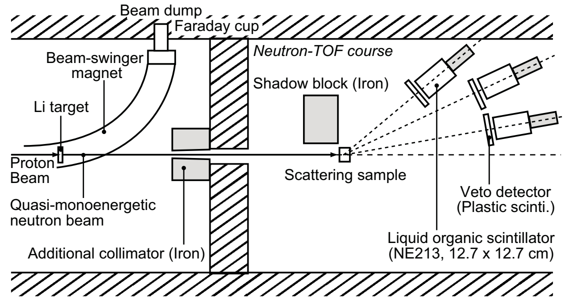

Fig. 2 Experimental setup for measurement of neutron elastic scattering cross section at RCNP.

of 134-MeV neutron scattering, the scintillators were placed at 6°, 8°, and 15°, with 560-, 500-, and 400-cm flight-path lengths, respectively.

Thin plastic scintillators were mounted in front of the NE213 scintillators as veto detectors to tag the charged particles from the sample. In order to prevent entering the neutrons produced at the collimator into the detectors, iron blocks were mounted between the collimator and the scintillators as a shadow block. The size of the shadow block was 60 cm along the beam axis, 100 cm horizontally orthogonal to the beam axis, and 20 cm in height centered on the beam. Background measurements were also performed without the sample to subtract the sample-independent background.

III. Electronic circuit

The data on the pulse height, pulse shape, and TOF were acquired event by event via an electronic circuit connected to a personal computer. **Figure 3** shows the block diagram of the electronic circuit, which consisted of NIM and CAMAC modules. An anode signal from a photomultiplier tube combined with the NE213 scintillator was divided into two branches. One of them was fed into a constant-fraction discriminator (CFD) to generate a logic pulse. The logic pulses from the each NE213 were joined at a fan-in module (FAN IN/OUT), and start pulses were generated to actuate the CAMAC modules. Once the data acquisition was started, the processes for new events were inhibited until the computer gave a busy out signal. A time-to-digital converter (TDC) was used to measure the TOF corresponding to the time difference between the signals from NE213 and the radio frequency (RF) signals for acceleration.

The other branch from NE213 was further divided into two, and sent to charge-sensitive analog-to-digital converters (ADCs). Two different gates, a 45 ns wide fast gate and a 350 ns slow gate with 50-ns delay, were set at the ADCs to execute the pulse-shape discrimination (PSD) by a two-gate integration method for the elimination of the events induced by gamma rays.

The proton beam current measured by the Faraday cup was fed into a current integrator, and the output pulses were

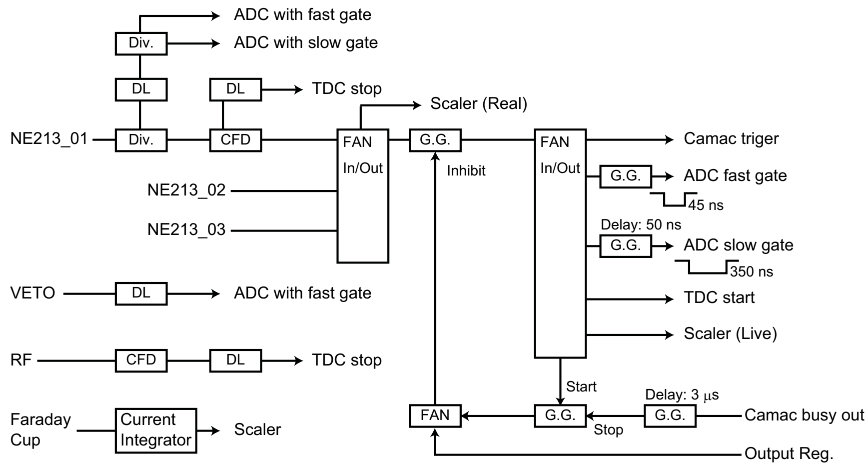

Fig. 3 Block diagram of electronic circuit.

counted by a digital scaler. All data were normalized to the integrated charge found in each measurement.

IV. Data analysis

1. Deduction of elastic scattering cross section

The experimental data were analyzed off-line. The gamma-ray events were segregated from the neutron events by PSD. Since the protons were accelerated with a typical RF cycle, *e.g.* 11.64 MHz for 137 MeV protons, pulse-height bias was set to cut off the low-energy neutrons of the preceding acceleration cycle. The events caused by charged particles were eliminated by using the pulse-height spectrum of the veto detectors.

After the discriminations, the TOF spectra for neutrons were obtained at each scattering angle. **Figure 4** shows an example of the TOF spectra obtained from foreground and background measurement at 15° of the carbon sample upon 134-MeV neutron incidence. The horizontal axis of the TOF spectra was reversed, because the start signal for the TOF measurement was taken from the NE213 scintillator. Thus, the events of higher energy neutrons appeared in the higher TOF channels. The peak observed in the foreground spectrum is constructed from the elastic scattering neutrons at the carbon sample, and the continuum component of the spectra is originated from the inelastic scattering. By subtracting the background spectrum and cutting off the low-TOF channels corresponding to the inelastic events, the elastic scattering neutrons were extracted.

The elastic scattering cross sections were deduced by the following equation,

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{Y(E',\theta)}{Y(E_0,0)} \cdot \frac{d^2}{N} \cdot \frac{D^2(\theta)}{D^2(0)} \cdot \frac{\varepsilon(E_0)}{\varepsilon(E')} \qquad (1)$$

where $d\sigma/d\Omega(\theta)$ is the elastic scattering cross section at θ in laboratory system, $Y(E',\theta)$ and $Y(E_0,0)$ are the peak neutron yields in the elastic scattering cross-section and the source-neutron measurements, respectively, normalized to the integrated charge of the proton beam, E' and E_0 are respectively

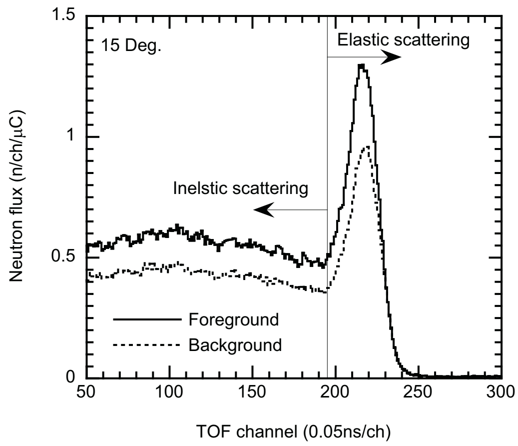

Fig. 4 TOF spectra at 15° from carbon for 134-MeV neutron.

the peak energies of the elastic scattering neutrons and the incident neutrons, d denotes the distance between the lithium target and the scattering sample, N is the number of nuclei in the sample, $D(\theta)$ and $D(0)$ are the flight-path lengths in the cross-section measurement and the neutron-source measurement respectively, and $\varepsilon(E)$ is the neutron-detection efficiency of the NE213 liquid organic scintillator at the energy E. The detection efficiencies were calculated with the SCINFUL-QMD code[8]. The ratio $\varepsilon(E_0)/\varepsilon(E')$ was almost equal to 1, because the E' and E_0 energies were similar.

The cross sections were finally described in a Center-of-Mass (CM) system, converting from the laboratory system.

2. Data correction

While the energy resolution of the TOF measurement was enough to separate the continuum component of inelastic neutrons with a TOF gate, it was impossible to discriminate the neutrons that come from low-excitation states of a sample nucleus, *e.g.* 2^+ state at 4.44 MeV and 3^- state at 9.64 MeV for carbon. Correction factors for this contribution were estimated by a coupled-channels calculation[9]. The cross sections were corrected by 4.0%, 5.0%, and 10% at 6°, 8°, and 15°,

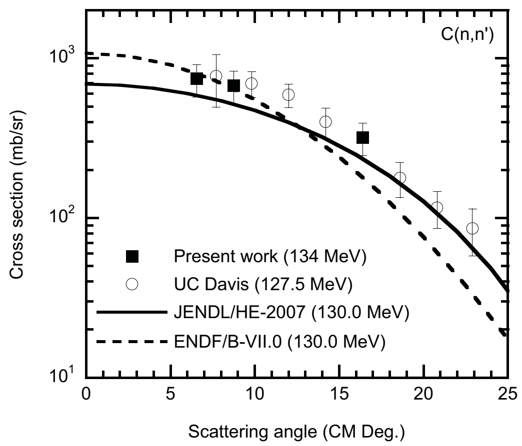

Fig. 5 Comparison of present measurements of $\mathrm{C}(n,n')$ differential cross sections with the experimental data of UC Davis and the evaluated nuclear data, JENDL/HE-2007 and ENDF/B-VII.0.

respectively, for carbon upon 134-MeV incidence. The effect of the inelastic neutron was insignificant for the results at forward angles due to the strong forward peak of elastic neutron.

V. Results

Figure 5 depicts a typical example of the present measurements for carbon upon 134-MeV incidence, together with the data of UC Davis[4)] upon 127.5-MeV incidence, and the evaluated nuclear data from JNEDL/HE-2007[6)] and ENDF/B-VII.0[7)] upon 130-MeV incidence. The present results exhibits overall agreement with the UC Davis data obtained with a recoil-proton telescope. This indicates that the experimental procedure proposed in this study is applicable to the measurement of neutron elastic scattering cross sections in the intermediate energy region above 100 MeV.

Comparing the nuclear-data libraries, ENDF/B-VII.0 agrees well with the experimental data in the forward angular region below 10 degrees in CM system, while JENDL/HE-2007 gives about 30% lower values. At angles over 10 degrees, ENDF/B-VII.0 underestimates the experimental data, and JENDL/HE-2007 agrees well. This discrepancy between the predictions of these nuclear-data libraries may be due to the difference in the OMP used.

VI. Conclusion

Neutron elastic scattering cross sections upon incidence of quasi-monoenergetic neutron beam above 100 MeV at RCNP have been measured with liquid organic scintillators and TOF techniques. The experimental method proposed in this study was validated for $\mathrm{C}(n,n')$ scattering at 134 MeV by comparison with the data of UC Davis comprising measurements with a recoil-proton telescope. With the advantages of higher detection efficiency and a simpler experimental procedure, our experimental method could be applied to systematic measurements of cross sections in the intermediate energy region, even in accelerator facilities with relatively weak beam intensity.

Measurements at RCNP will be continued to construct a set of neutron cross-section data in the energy region up to 400 MeV. The experimental method will be examined at larger scattering angles and higher incident energies. The scattering samples will be chosen from through out the periodic table to analyze the atomic mass dependence, and establish global OMP for nuclear-data evaluation.

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