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DEVELOPMENT OF A QUASI-MONOENERGETIC NEUTRON FIELD USING THE ^{7}Li(p,n)^{7}Be REACTION IN THE ENERGY RANGE FROM 250 TO 390 MeV AT RCNP

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A quasi-monoenergetic neutron field using the ^{7}Li(p,n)^{7}Be reaction has been developed at the ring cyclotron facility at the Research Center for Nuclear Physics (RCNP), Osaka University. Neutrons were generated from a 10-mm-thick Li target injected by 250, 350 and 392 MeV protons and neutrons produced at 0° were extracted into the time-of-flight (TOF) room of 100-m length through the concrete collimator of 10 × 12 cm aperture and 150 cm thickness. The neutron energy spectra were measured by a 12.7-cm diam × 12.7-cm long NE213 organic liquid scintillator using the TOF method. The peak neutron fluence was 1.94×10^{10}, 1.07×10^{10} and 1.50×10^{10} n sr^{-1} per μC of 250, 350 and 392 MeV protons, respectively. The neutron spectra generated from various thick (stopping length) targets of carbon, aluminium, iron and lead, bombarded by 250 and 350 MeV protons, were also measured with the TOF method. Although these measurements were performed to obtain thick target neutron yields, they are also used as a continuous energy neutron field. These neutron fields are very useful for characterising neutron detectors, measuring neutron cross sections, testing irradiation effects for various materials and performing neutron shielding experiments.

OVERVIEW OF THE STUDY

There are several high-energy neutron fields for neutron experiments in the world. Among them, two quasi-monoenergetic neutron fields of energy higher than 200 MeV exist at the TRIUMF (Tri-University Meson Factory) facility, Canada(1) and the Research Center for Nuclear Physics (RCNP), Osaka University, Japan(2). A series of high-energy neutron experiments for accelerator shielding research has been performed at the neutron time-of-flight (TOF) beam course at RCNP. In this study, a quasi-monoenergetic neutron field was developed using the ^{7}Li(p,n)^{7}Be reaction in the energy range from 250 to 390 MeV in the ring cyclotron facility at RCNP. Proton beams of 250, 350 and 392 MeV energies extracted from the cyclotron were transported to the experimental hall and impinged onto a 10-mm-thick Li target placed in a vacuum chamber. Protons passing through the target were swept out towards the beam dump by the swinger magnet to measure the proton beam intensity with a Faraday cup. The proton beam intensity was also monitored with a plastic scintillator by scattering through a thin (100 μm) plastic film. Neutrons produced at 0° from the Li target were extracted into the TOF room of 100-m length through a concrete collimator of 10×12 cm aperture and 150 cm thickness, while charged particles were rejected by a vertical bending magnet located in the collimator. This field was used to perform the neutron shielding experiment and the neutron detector characterisation in this study.

The neutron spectra generated from various thick (stopping length) targets of carbon, aluminium, iron and lead, bombarded by 250, 350 and 392 MeV protons, were also measured with the TOF method. Although these measurements were performed to obtain the thick target neutron yields, they are also used as a continuous energy neutron field. For neutron production from thick targets by such high-energy protons, several experiments have been performed at several facilities(3–5), but only one experimental data exists at 0° for 210-MeV protons(6).

DEVELOPMENT OF QUASI-MONOENERGETIC NEUTRON FIELD

Quasi-monoenergetic neutrons produced from the Li target at 0° were measured by a 12.7-cm diameter × 12.7-cm long NE213 organic liquid scintillator

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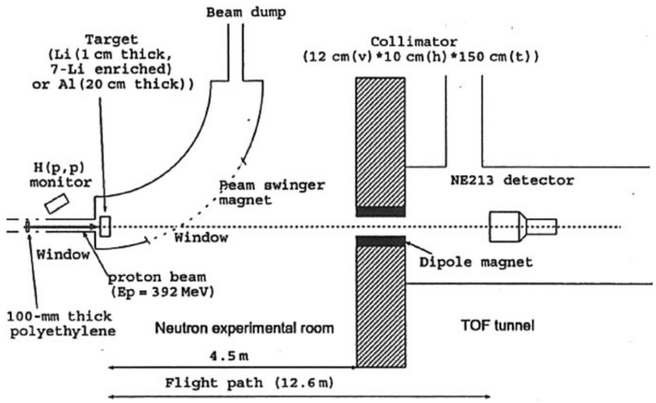

Figure 1. Experimental setup.

placed at two different distances, 11.4 and 95 m from the target in the TOF room, as shown in Figure 1. The repetition period of the incident proton beam from the cyclotron was extended to about 800 ns by using a beam chopper to avoid contamination from lower energy neutrons. The chopper trigger signal was used as the stop signal for the TOF measurement. The neutron energy spectra were measured using the TOF method between the chopper trigger signal and the detector signal. The long distance measurement at 95 m was used to get a good energy resolution in high-energy peak region. The output pulses of NE213 were sampled in two different gates, total gate and slow gate, to discriminate neutron events from photon events including escaping proton events. In this TOF analysis, the detection efficiency of NE213 was calculated with the CECIL code[7]. The resulting TOF spectrum is shown in Figure 2. The absolute peak neutron yields were obtained by measuring 478-keV gamma rays from ^{7}Be nuclei produced in a Li target through the ^{7}Li(p,n)^{7}Be reaction.

The energy spectra converted from the TOF spectra for three proton energies are shown in Figure 3. These spectra are obtained by combining two TOF spectra measured at two distances, 11.4 and 95 m. The long distance spectra with good energy resolution were combined at 120, 220 and 350 MeV with the short distance spectra for 250, 350 and 392 MeV incident proton energies. A sharp monoenergetic peak can clearly be seen at 248, 348 and 390 MeV, respectively, with an energy width (FWHM) of 2.5 MeV. The measured lowest energy end is $\sim$5 MeV for 250 and 350 MeV proton incidence, but $\sim$20 MeV for 392-MeV protons. At the low energy end, a small peak around 10 MeV can be seen, maybe a contribution of room-scattered or collimator-scattered components. The peak neutron fluences were 1.94×10^{10}, 1.07×10^{10} and 1.50×10^{10} n sr^{-1} per μC of 250, 350 and 392 MeV

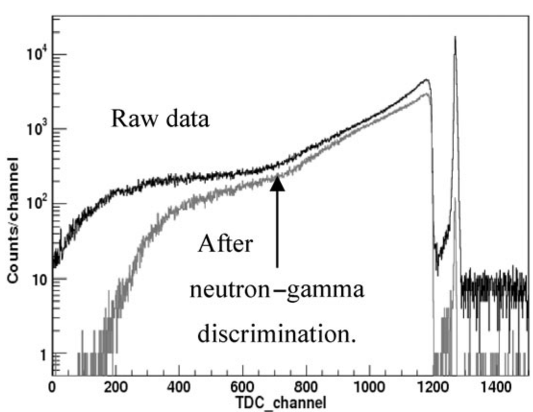

Figure 2. Neutron TOF spectra before and after neutron–gamma discrimination.

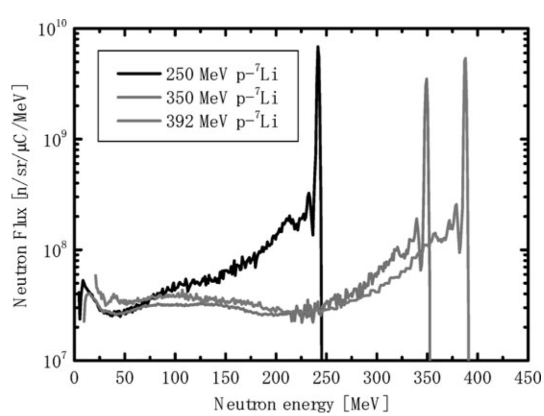

Figure 3. Quasi-monoenergetic neutron spectra for 250, 350 and 392 MeV p–Li reactions.

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Table 1. Characteristics of the quasi-monoenergetic neutron field at RCNP, Osaka University.

Proton energy [MeV]	250	350	392
Peak neutron energy [MeV]	248	348	390
Integration interval of peak neutron [MeV]	236–250	344–350	383–392
Peak neutron intensity [n/(sr μC)]	1.94×10^{10}	1.07×10^{10}	1.50×10^{10}
FWHM of peak neutron [MeV]	2.5	2.5	2.5
Integration interval of tail neutron [MeV]	4–236	6–344	21–383
Tail neutron intensity [n/(sr μC)]	1.70×10^{10}	1.35×10^{10}	1.76×10^{10}

protons. Table 1 gives the characteristics of the quasi-monoenergetic neutron field. The maximum proton beam intensity in this beam line is about 1 μA.

NEUTRON PRODUCTION YIELD AT 0° FROM THICK TARGET

The neutron spectra generated at 0° from thick (stopping length) targets of carbon, aluminium, iron and lead, bombarded by 250, 350 MeV protons, were also measured with the TOF method. Figure 4 exemplifies the neutron energy spectra at 0° for carbon and iron targets compared with the PHITS[8] and MCNPX[9] calculations for 250 and 350 MeV proton bombardments[10]. Calculated results of PHITS with Bertini/GEM and MCNPX with LA150 + Bertini underestimate the experimental results in the neutron energy range from 30 MeV to incident energy. In Figure 4, the underestimation of the calculations is also found in the thick iron target experiment at 0° for 210-MeV proton at RIKEN[6]. Those may result from the underestimation of neutron-production DDX (double differential cross sections) at small angles and the strong self-shielding in target nucleus. In contrast,

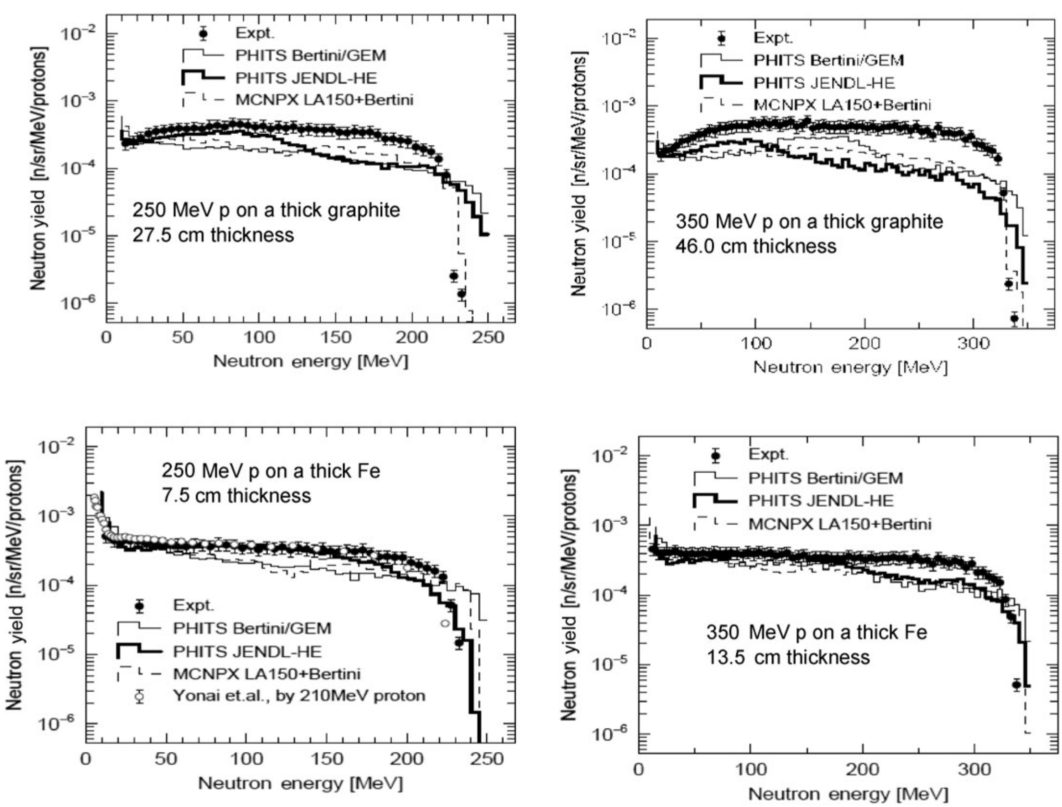

Figure 4. Measured and calculated neutron energy spectra at 0° from thick C and Fe targets bombarded by 250 and 350 MeV protons.

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the calculated result with the JENDL-HE file[11] gives good agreement with experimental results below 100 MeV on graphite and below 150 MeV on aluminium and iron.

The neutron spectra generated at 0° from thin and thick targets are very scarce and all calculations give largely underestimated results, so it is strongly required to get more experimental results and also to improve the calculation models and nuclear data in the forward direction.

MEASUREMENT OF NE213 SCINTILLATOR RESPONSE FUNCTION

By using this quasi-monoenergetic and continuous energy neutron fields, the response functions of a 12.7-cm diameter × 12.7-cm long NE213 organic liquid scintillator were measured with the TOF method in a wide energy range up to 390 MeV[12]. Absolute value of the response function only for the 390-MeV peak neutron energy was obtained from the ^{7}Be activity in the Li target. The response functions in other energies were normalised to the total detection efficiencies calculated by the original version of the CECIL code. Figure 5a exemplifies the response functions for neutrons of 95–200 MeV compared with the CECIL calculations (in solid lines)[12]. It can be seen that the calculation disagrees with the measurement in high light output regions. Figure 5b also gives the response function for 340–350 MeV neutrons compared with the SCINFUL-QMD calculation[13]. The SCINFUL-QMD code[14] developed by Satoh gives good agreement with the measured result.

SHIELDING EXPERIMENT THROUGH CONCRETE AND IRON

The shielding experiment was performed with 250 and 350 MeV p–Li quasi-monoenergetic neutrons. Concrete and iron shields of 120 × 120 cm sizes having 10 and 5 cm thickness, respectively, were added to change the total thickness up to 2 m for concrete and 1 m for iron. They were fixed just after the concrete collimator. The NE213 scintillator and the multi-moderator detector with ^{3}He counter, Bonner ball, were set behind the shield to get the neutron energy spectra down to thermal energy. We are now analysing the experimental results.

SUMMARY AND FUTURE PLAN

Quasi-monoenergetic neutron fields of 250, 350 and 392 MeV have been established at RCNP, Osaka University, on the TOF beam line. By using these quasi-monoenergetic neutrons, a shielding experiment through concrete and iron has been done with Bonner ball and NE213 detector. Neutron production yields from thick C, Al, Cu and Pb targets at 0°, and the response functions of NE213 and other neutron detectors were also measured.

We will perform the next experiment with a quasi-monoenergetic neutron field of 150 MeV and are now planning double-differential neutron production and elastic cross-section experiments. These neutron fields are very useful for characterising neutron detectors, measuring neutron cross sections, testing irradiation effects for various materials and performing neutron shielding experiments.

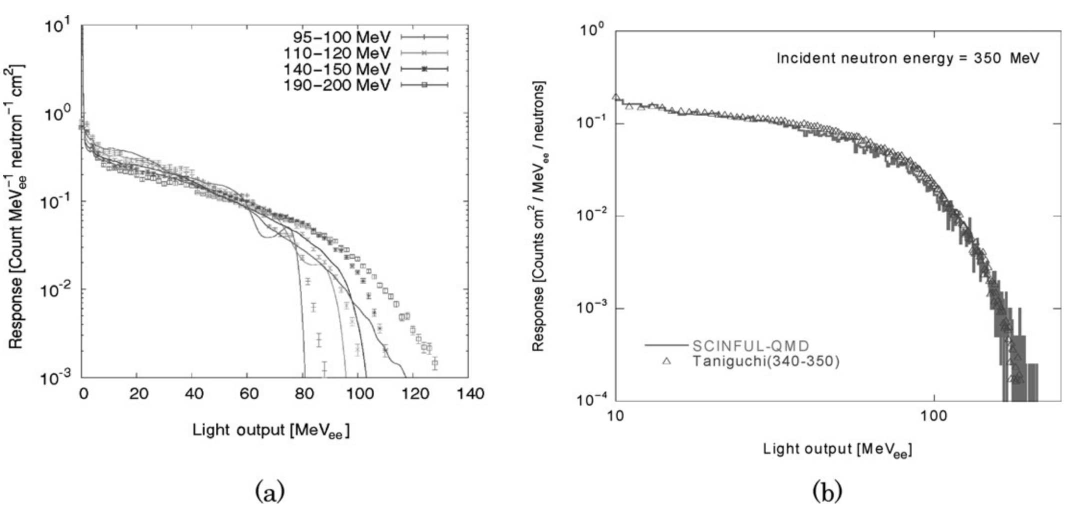

Figure 5. Response functions of 12.7-cm diameter by 12.7-cm long NE213 for several neutrons compared with the CECIL (a) and SCINFUL-QMD (b) codes.

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