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Development of experimental technique for measurement of (*n*,*xn*) double-differential cross sections above 20 MeV

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The experimental technique for measurement of (*n*,*xn*) double differential cross sections above 20 MeV has been developed with continuous-energy neutrons up to 400 MeV. Neutrons were produced in the spallation reaction by the 800-MeV proton beam, which was incident on a thick, heavily shielded tungsten target at the WNR facility at Los Alamos National Laboratory. The energies of incident neutrons were determined by the time-of-flight method. Emitted neutrons were detected by the recoil proton method at 15°, 30° and 90°. A phoswich detector consisting of NaI(Tl) and NE102A plastic scintillators was used for detecting recoil protons. We obtained the neutron energy spectra by use of the unfolding code, FERDO. The response functions of the NaI(Tl) scintillator for protons were calculated by the calculation code of Particle and Heavy Ion Trasnport code System (PHITS). We compared the experimental cross section data with the calculations by the PHITS and QMD codes.

KEYWORDS: inclusive (n,xn) double differential cross sections, continuous-energy neutrons, recoil proton method, phoswich detector, unfolding

I. Introduction

In progress of intermediate energy proton-accelerator technology, a highly intense neutron source by spallation reactions became usable for scientific researches and industrial developments. In nuclear technology, Accelerator-Driven-Systems (ADS) for energy production and long-lived nuclear-waste transmutation[1] have been proposed and the development therefore has raised the practical need for neutron nuclear reaction data such as neutron-production double differential cross sections in the intermediate energy region. Some experimental data of (*n*,*xn*) double-differential cross sections were reported[2,3] for incident neutron energies above 20 MeV. These measurements were conducted by using the monoenergetic neutron beam produced by either $T(d,n)^4He$ or $^7Li(p,n)^7Be$ reaction. However, experimental data have never been obtained above 100 MeV because of the lack of the monoenergetic neutron field.

We attempted to use continuous-energy neutrons for measuring inclusive (*n*,*xn*) double differential cross sections above 20 MeV. A continuous energy spectrum of incident neutrons did not allow us to perform the time-of-flight (TOF)[4] measurement. The recoil proton method, therefore, was adopted for measuring emitted neutrons. To detect the recoil protons as full stop events, a phoswich detector composed of an inorganic crystal and plastic scintillators was considered to be suited as a recoil proton detector. The neutron energy spectra were obtained by the unfolding technique with the FERDO[5] code from the measured pulse height spectra and response functions of the NaI(Tl) scintillator for protons. The response fuctions of NaI(Tl) were determined by the calculation code, Particle and Heavy Ion Transport code System (PHITS)[6] upgraded from NMTC/JAM[7] based on the intranuclear cascade evaporation (INCE)[8] model.

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In this paper, we report the experimental technique for measuring (*n*,*xn*) double differential cross sections above 20 MeV and compare the preliminary data with the results calculated by the PHITS and QMD[9] codes to know the applicability of this technique.

II. Experimental arrangement

The experimental arrangement is schematically illustrated in **Fig.1**. Neutrons were produced by the 800-MeV proton beam from the linear accelerator through the spallation reaction at Los Alamos National Neutron Science Center (LANSCE). Generated neutrons traveled about 90 m to be incident on our sample target. The time of flight was obtained as the time difference between the pulses from a d*E* detector and the accelerator time pick-off to determine the incident neutron energy. The d*E* detector pulses served as the start pulse for the TOF measurement. The neutron flux was monitored by a fission ionization chamber.[10] This chamber was placed in front of the sample and the signal was taken in the TOF mode.

For neutron energy measurement, we adopted the recoil proton method, where a phoswich detector measured the recoil protons generated by the elastic scattering of neutrons. The radiator was a 20-mm thick polyethylene disk. We also performed the repeated measurements with a carbon disk to eliminate the contribution of carbon reaction. We selected full-stop proton events by the function of phoswich configuration explained later. A veto counter was set in front of the

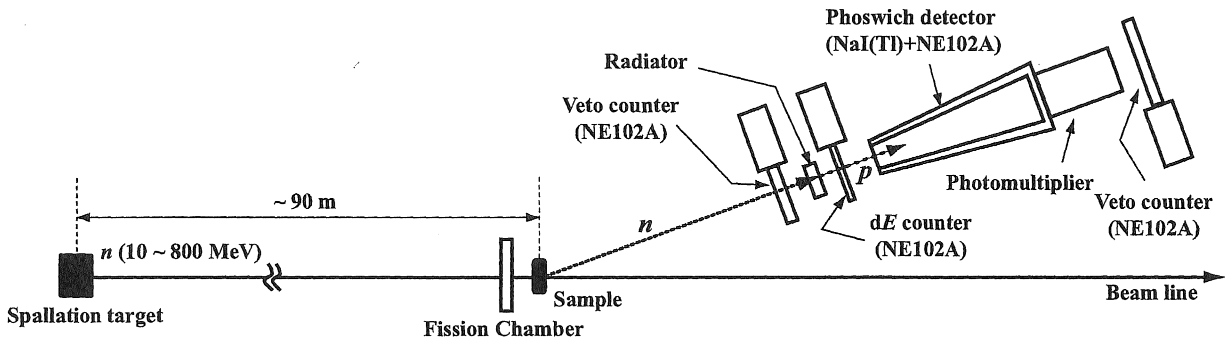

Fig. 1 Typical scheme of experimental area

radiator to eliminate the charged particles from the sample. The veto counter was 10-mm thick NE102A plastic scintillator. The dE counter was located between the radiator and the phoswich detector to identify the charged particles produced in the radiator. The dE detector was a 5-mm thick NE102A plastic scintillator. The distance between the sample and the phoswich detector was about 0.7 m.

The energy of recoil proton from the radiator was measured by the phoswich detector. The configuration of the detector is seen in Fig.1. It consisted of a NaI(Tl) crystal and NE102A plastic scintillators, optically connected to a single photomultiplier tube. The NaI(Tl) crystal was wrapped with 1-cm thick NE102A plastic scintillators, except for the entrance plane. The phoswich detector length was 360 mm to stop protons of energies up to 400 MeV. The decay times of NaI(Tl) and NE102A scintillation lights were 230 and 2.4 ns, respectively. A single photomultiplier tube received the light from both NaI(Tl) and plastic scintillators. Pulse-shape discrimination was performed by the two-gate integration method, and it allowed us to separate the events of charged particles passing through outer scintillators from full stop events in NaI(Tl). The total and fast gates in the integration method were 300 ns and 100 ns long, respectively. The phoswich configuration serves to reduce accidental background events. To identify the events in which recoil protons penetrate the detector straightly, a plastic scintillator was set up behind each phoswich detector except in the direction of 90°.

III. Data Analysis

Figure 2 shows a typical TOF spectrum. The events in the sharp peak on the right-hand side of Fig.2 are indicated by an arrow. They were induced by photons originating at the neutron production target. This prompt gamma-ray peak provides a useful time reference to convert the TOF into incident neutron energy; its full width at half maximum (FWHM) is approximately 3 ns. In this experiment, the energy of incident neutrons was simply derived from the arrival time to the dE detector because the flight time from the sample to the dE detector was negligible in comparison to that of incident neutrons flying over 90 m. This simple treatment gives the incident neutron energy resolution of 6.1% at maximum, for

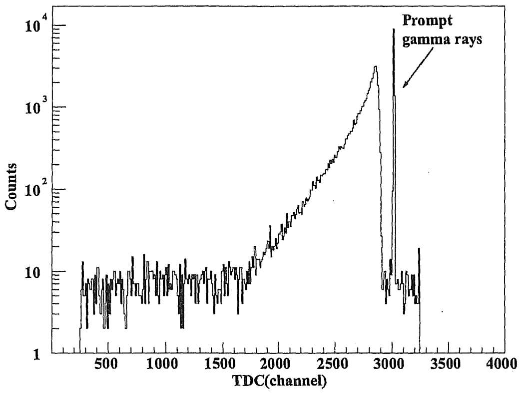

Fig. 2 Typical time-of-flight (TOF) spectrum for incident neutrons.

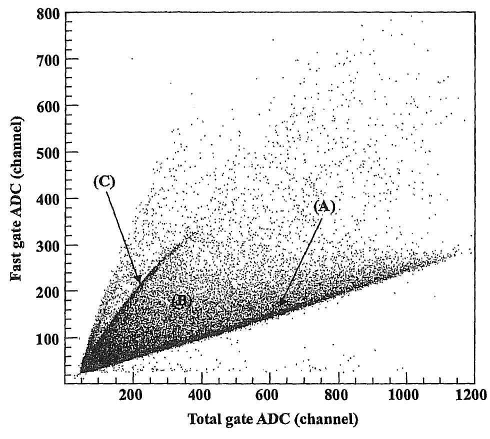

Fig. 3 Pulse-shape discrimination for the phoswich detector by two-gate integration method.

instance, 24.4 MeV for 400 MeV incident neutrons. The influence of the flight time of the emitted neutrons should be correctted at the final data processing.

By use of signals of the veto counters in front of the ra-

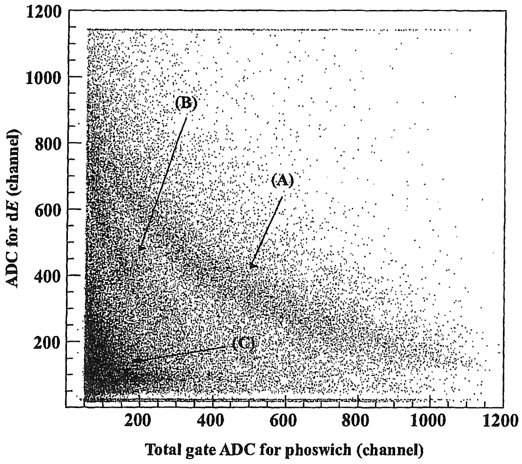

Fig. 4 Typical two-dimensional spectrum of the total gate signal for the phoswich detector versus the dE signal.

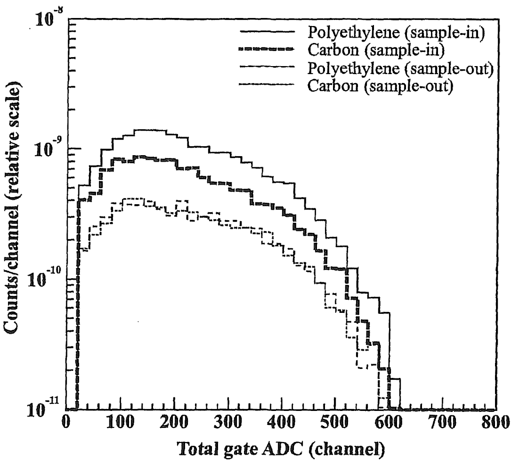

Fig. 5 Typical ADC spectra of the sample-in and -out measurements using polyethylene or carbon.

diator and behind the phoswich detector, we first removed the events that were ascribed to charged particles coming from the sample or upstream, or penetrating the detector. The result of the pulse shape discrimination is shown in **Fig.3**. One can see three types of events in Fig.3. The events in the region (A) indicate those in which the light came from the NaI(Tl) scintillator alone; they stand for full stop recoiled protons which are usable for derivation of (n,xn) cross sections. The events in the region (B) appear in a condition where the scintillation occurred in both NaI(Tl) and plastic scintillators. The events in the region (C) are generated when only the plastic scintillator emitted scintillation. The events in the regions of both (B) and (C) are discarded by choosing the full-stopping proton events in the region (A). **Figure 4** shows a two-dimensional pulse-height plot of the total gate signal for the phoswich detector versus the dE signal for the dE detector. In this figure, we

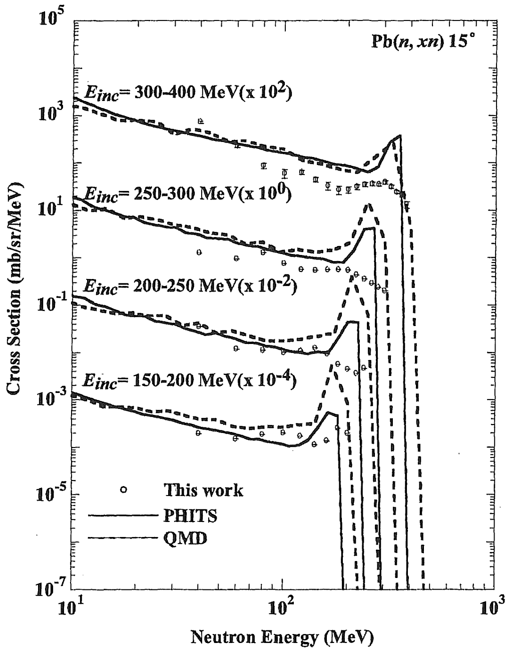

Fig. 6 (n,xn) double differential cross sections for neutrons of 150-200, 200-250, 250-300, and 300-400MeV incident on the natural lead at 15°.

identified three regions labeled as (A), (B) and (C). The events in the region (A) indicate that recoil protons deposited their energies in the NaI(Tl) scintillator. The region (B) indicates that the recoil protons penetrated the phoswich detector. As the dE counter does not scintillate by the neutron and gamma ray events, the region (C) presents emitted neutrons passing through the radiator, or background neutrons and gamma rays. We selected full-stopping recoil proton events in the region (A).

The experiments were also performed with a carbon disk as the radiator. They were used to eliminate the contribution of carbon in polyethylene by selecting only full-stop proton events of the H(n,p) reaction after normalization. In **Fig.5**, typical pulse-height spectra are shown for sample-in and sample-out with both the polyethylene and the carbon radiator. Counts for the polyethylene radiator were about twice as large as those for the carbon radiator.

The energy of emitted neutrons is nearly equal to the energy of recoil protons because the scattering angle of detected protons is within approximately 7°. The (n,p) elastic scattering cross sections were used for evaluating the neutron flux. The neutron energy spectrum was obtained with the FERDO unfolding code for the proton spectrum. The adoption of the recoil proton method forced us to obtain the response functions of the phoswich detector for protons up to 400 MeV. The response functions were calculated by PHITS. However, it is desired for the response functions of the detector system to be measured with neutrons, since it is difficult to obtain the correct response functions only by the calculation.

IV. Results

Figure 6 displays the preliminary result of (*n,xn*) double differential cross sections obtained for the natural lead target at 15°. The energy bin width of incident neutron is 50 MeV or 100 MeV. The results were compared with the calculated results of the PHITS and QMD codes. The representative energies for calculation were chosen as the maximum values of each energy bin. The aim of the comparison is not to make detailed discussion on the reaction mechanism but to test the applicability of this experimental technique. The measurement was also performed at 30° and 90°, but it suffered from large statistical uncertainties in these directions.

V. Conclusion

The experimental technique was developed for measurement of (*n,xn*) double differential cross sections with continuous-energy neutrons. The experiment was done by using the spallation neutron source at the WNR facility at LANL. From the experiment, we comfirmed that this experimental technique is applicable to measure the (*n,xn*) double differential cross sections above 20 MeV.

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