PRODUCTION OF FOCUSED NEUTRON BEAM USING HEAVY ION REACTION

K. Hasegawa, K. Kotajima, M. Kitamura, T. Yamaya*, O. Satoh*, T. Shinozuka** and M. Fujioka**
Department of Nuclear Engineering, Tohoku University, Sendai 980, Japan
*Department of Physics, Tohoku University, **Cyclotron and Radioisotope Center, Tohoku University

Summary

Accurate measurements of the secondary neutrons originated from neutron induced processes are usually disturbed severely by the source neutrons themselves. The essential way to eliminate such a disturbance is to converge source neutrons into a small forward cone. This could be attained by utilizing the endoenergetic heavy ion reactions on light nuclei. When the bombarding energy is fixed slightly above the threshold, the velocity of generated neutron in the center-of-mass system becomes negligibly small compared to that of the centroid. Consequently, the generated neutrons are directed into the very forward angle. In the present work, the $^1H(^{13}C,n)^{13}N$ reaction (E_{th}=41.74 MeV) was employed taking into account the available heavy ions species and their acceleration energies[1] for the Tohoku University AVF Cyclotron[2] to study the feasibility of producing a focused neutron beam of 2.8 MeV.

The target was a 1.2 cm ϕ × 3.0 cm gas cell filled with 0.5-kg/cm^2 hydrogen. A 7.5-μm thick Ta foil was used as the beam entrance window to suppress the undesirable fusion neutron yield. The generated neutrons were detected with a 2" ϕ × 2" NE213 scintillation counter placed at 60-180 cm from the gas cell target. To obtain the energy spectra of neutrons, the unfolding code FERDOR[3] was used. The neutron energy spectra were also measured by TOF with a flight path of 180 cm. The measured angular distributions of neutrons are shown in Fig. 1. The neutron yield and the corresponding total reaction cross section turned out to be ∿7×10^3 n/10 enA and ∿5mb, respectively, for the bombarding energy of 45.0 MeV. The accelerated $^{13}C^{4+}$ beam current at the extraction radius of the cyclotron (R=65.0 cm) was ∿1 eμA,[4] which indicates a good possibility of providing a focused neutron beam of ∿10^6 n/sec.

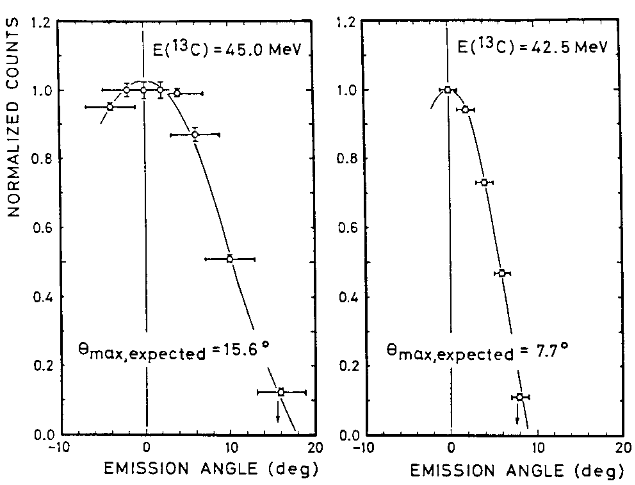

Fig. 1 Measured neutron angular distributions of the $^1H(^{13}C,n)^{13}N$ reaction for E(^{13}C) = 45.0 MeV (left) and E(^{13}C) = 42.5 MeV (right). The maximum emission angles of generated neutrons θ_{max} expected from Eq. (1) are shown with arrows.

Why we produce a FOCUSED NEUTRON BEAM

Neutrons and the related technologies are widely applied to various scientific and industrial fields such as medicine, biology, material science and so forth. On the other hand, fission reactors still have to be improved for higher level of efficiency and safety. With regard to this, accurate studies of the neutron interactions, namely, the neutron scattering and neutron-induced reaction processes in reactor materials have been strongly required. In fact, the thermal neutron cross sections are known close to the required degree of accuracy with the current experimental techniques, but for higher neutron energies, further measurements with improved precision should be performed.

Accurate measurements of the secondary neutrons originated from neutron-induced processes at such energies are usually disturbed severely by the source neutrons themselves, because they are emitted from the neutron target in every direction and scattered back from all quarters. Consequently, the experimental area is full of stray neutrons which will cause tremendous backgrounds to the neutron detectors installed in the same area (see Fig. 2a). Providing a heavy detector shield against these neutrons is quite effective but not satisfactory for excluding the backgrounds. It is thus not able to attain the required accuracy of the measurement in this way.

In principle, the essential way to eliminate the disturbance is to avoid production of any stray neutrons. To realize this, the source neutrons should be emitted into a very small forward cone (see Fig. 2b). If such a focused neutron beam is produced, the neutron detector can see only the neutrons from

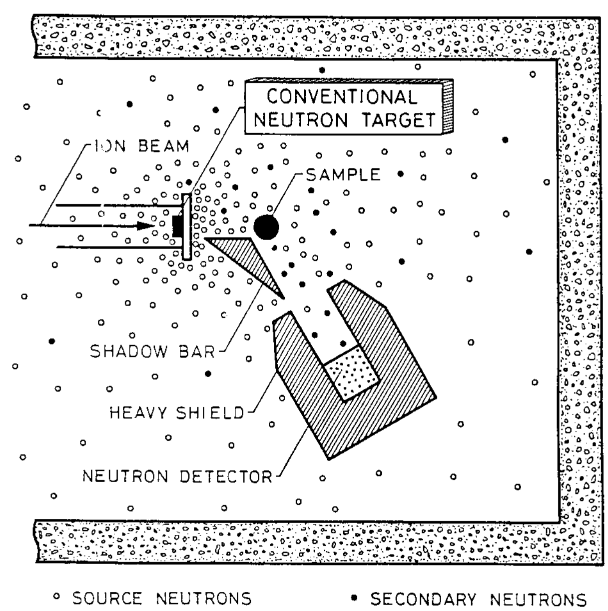

Fig. 2a Schematic drawing of a typical neutron measuring system using a conventional neutron source.

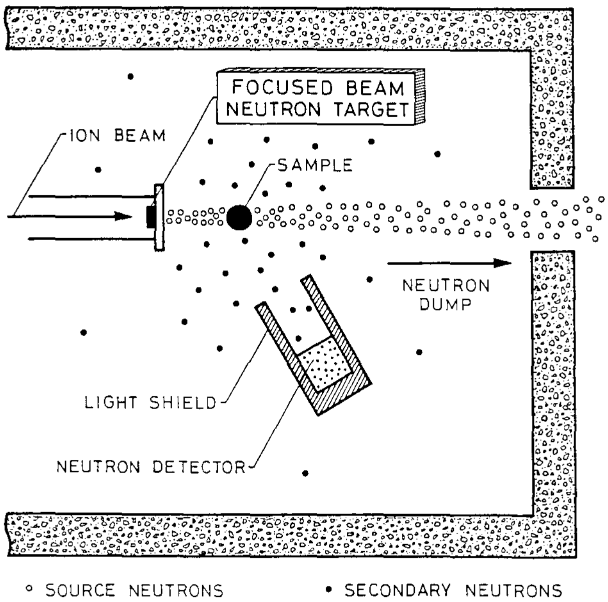

Fig. 2b Conceptional drawing of providing a high quality neutron measuring system using a focused neutron beam.

the sample to be measured (secondary neutron). The uninteracted source neutrons (primary neutrons) just transmitting through the sample could easily be led to a neutron dump prepared in the far distance from the experimental area, so that the area could be free from those background neutrons. The use of focused neutron beam could, therefore, improve the accuracy of the neutron interaction measurements, just as we can observe stars more clearly at night than in day time. In this sense, we have studied the feasibility of producing a monoenergetic focused neutron beam of 2.8 MeV using the Tohoku University K=50 AVF Cyclotron[2].

How to produce a FOCUSED NEUTRON BEAM

Practically, there are two ways of producing such a focused neutron beam by the heavy ion reaction of $^1H(HI,n)$ type, as illustrated in Fig. 3. The velocity of generated neutron in the laboratory system V_L (shown in the right side) is the vector sum of the neutron velocity in the center-of-mass system V_n (shown in the middle) and the velocity of the centroid V_G (shown in the left side). The first method so-called "momentum-focusing" is to take V_G as large as possible compared to V_n. When the projectile heavy ion energy (therefore, V_G also) is increased by a considerable amount, the excess energy will act mostly to increase the number of emitted nucleons, and their average energies (therefore, V_n also) stay rather constant. Therefore, the resultant V_L points more to the forward direction. Since V_n in this case is not definite, the maximum emission angle of the neutrons in the laboratory system θ_{max} can not be defined. The disadvantage of this method is that a very high-energy heavy ion accelerator (probably ∿100 MeV/A or more) is required.

The second method so-called "kinematic focusing" is to make V_n as small as possible compared to V_G, so that the resultant V_L points to the forward angle. To realize this, the projectile heavy ion energy E_{proj} should be taken slightly above the threshold energy

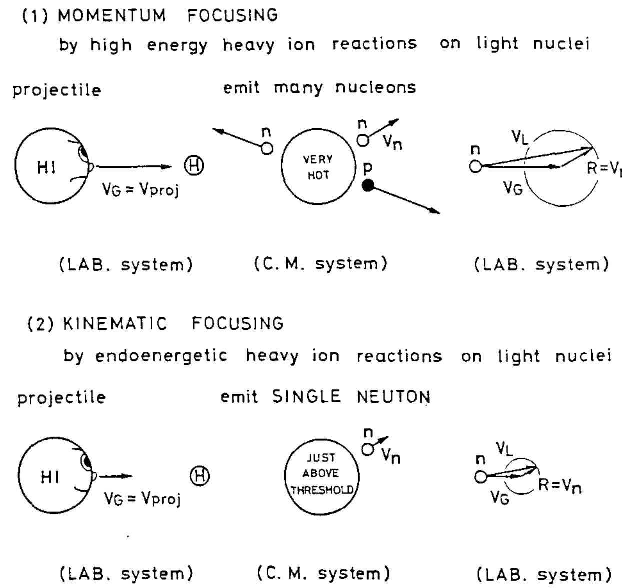

Fig. 3 Illustrations of producing the focused neutron beam by (1) MOMENTUM FOCUSING and by (2) KINEMATIC FOCUSING.

E_{th} of the endoenergetic reaction. Then the excess energy converted to V_n becomes very small. Based on this method, an experiment to produce neutron beam had been reported.[5] Since the V_n in this case is unique, the maximum emission angle of the neutron in the laboratory system θ_{max} is given by

$$\theta_{max} = \sin^{-1}(V_n/V_G) = \sin^{-1}\sqrt{1 - E_{th}/E_{proj}} \quad (1)$$

The advantage of this method is that the required bombarding energy of the heavy ion is much lower than that in the case of momentum focusing, and thus any presently operating heavy ion cyclotron can be used immediately. Moreover, the associated gamma-ray background yield in this case is expected to be extremely small compared to that using a conventional neutron target. These are the reasons of using kinematic focusing in the present study.

Table 1 shows a list of endoenergetic heavy ion reactions on hydrogen target for the production of a monoenergetic focused neutron beam by the kinematic focusing. In the present work, the $^1H(^{13}C,n)^{13}N$ reaction was used taking into account the available heavy ion species and acceleration energies[1] of the cyclotron[2].

Table 1 Candidates for producing the monoenergetic focused neutron beam with ^1H target

projectiles	E_{th} (MeV)	E_n (MeV)	projectiles	E_{th} (MeV)	E_n (MeV)
^7Li	13.09	1.44	^6Li	35.35	4.35
^9Be	18.40	1.67	^{14}N	88.30	5.53
^{11}B	32.97	2.53	⋮		
^{13}C	41.75	2.79	^{12}C	234.1	16.7
^{19}F	79.82	3.82	⋮		
^{10}B	48.49	4.03			

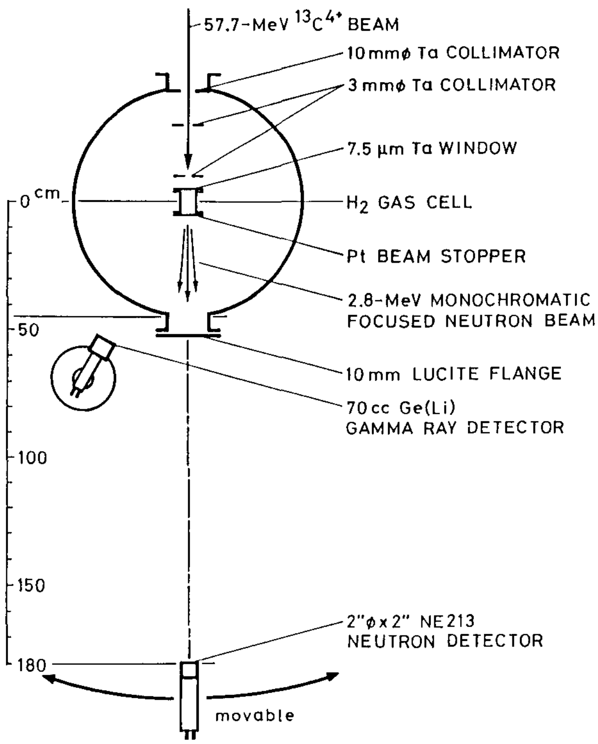

Fig. 4 Schematic drawing of the experimental setup to produce a monoenergetic focused neutron beam of 2.8 MeV by the $^1H(^{13}C,n)^{13}N$ reaction.

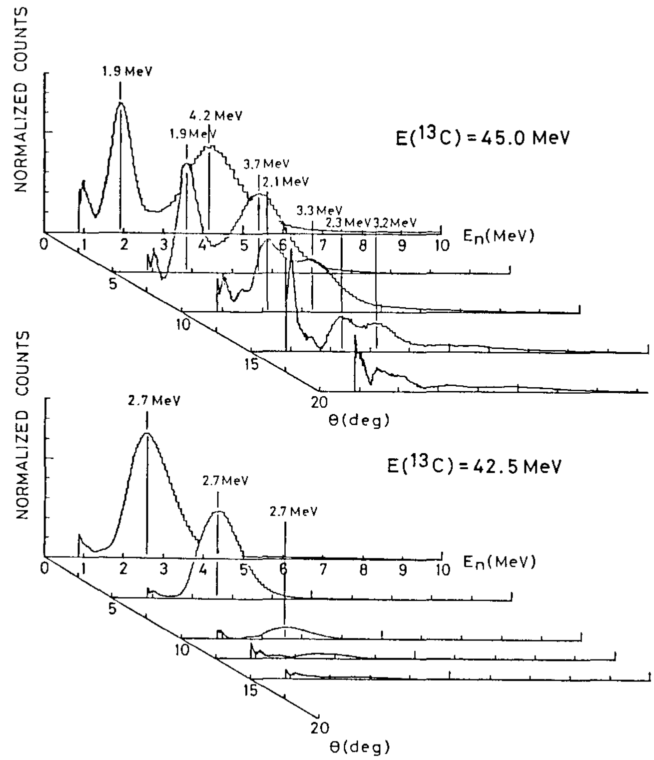

Fig. 5 Measured neutron spectra of the $^1H(^{13}C,n)^{13}N$ reaction by TOF for E(^{13}C) = 45.0 MeV (above) and E(^{13}C) = 42.5 MeV (below).

Properties of the FOCUSED NEUTRON BEAM

The experimental setup for measuring the energy spectra, angular distributions and production yields of the focused neutrons is schematically shown in Fig. 4. The $^{13}C^{4+}$ ion beam accelerated for 57.7–60.0 MeV was led through 0.3 cm ϕ Ta double collimators onto a 1.2 cm ϕ × 3.0 cm hydrogen gas cell with a 7.5-μm thick Ta foil as the beam entrance window. A 0.1-mm thick Pt plate was used as the beam stopper. The reason for using high-Z materials (Ta and Pt in our case) for the beam collimators, window and stopper, is mainly to suppress the fusion neutrons produced by the heavy ion bombardment on low-Z nuclei. During the measurements, the gas pressure was monitored with a semiconductor type pressure transducer of 0.5 % accuracy (Model P-3000S/102A, COPAL ELECTRONICS Co. Ltd., Japan) and adjusted manually to keep the preset pressure. The energy losses of the 57.7–60.0 MeV ^{13}C beam passing through the Ta window and H_2 gas were estimated to be 14.6–14.3 MeV and 1.13–1.07 MeV, respectively, using the tabulation by Northcliffe and Schilling.[6] From these figures, the actual bombarding energies were estimated to be 42.5–45.2 MeV. The whole gas cell assembly was electrically insulated from the ground to measure the $^{13}C^{4+}$ beam current.

A 2" ϕ × 2" NE213 liquid scintillation counter was mounted at the distance of 60–180 cm on a stand which could be moved along the concentric circumference of a circle centered at the gas cell position. The neutron energy spectra were also measured by time-of-flight with a flight pass length of 180 cm. In both cases, the NE213 detector signals were fed to the PDP-11/44 computer for analysis. The unfolding code FERDOR[3] was used to obtain neutron energy spectra from the detector output. A 70-cc Ge(Li) detector was fixed at 60 cm from the gas cell to evaluate the gamma-ray background.

Energy Spectra

Neutron energy spectra of the $^1H(^{13}C,n)^{13}N$ reaction measured by time-of-flight are shown as a function of the emission angle θ in Fig. 5 for the bombarding energies of 45.0 MeV (above) and 42.5 MeV (below). At 45.0 MeV bombarding energy, two neutron components (4.2 and 1.9 MeV at 0°), each corresponding to the forward and backward emissions in the center-of-mass system, were observed. As the emission angle becomes larger, the energy difference between the two components becomes smaller (see also Fig. 6). At 42.5 MeV, the only one component (2.7 MeV at 0°) was observed. As the emission angle becomes larger, this

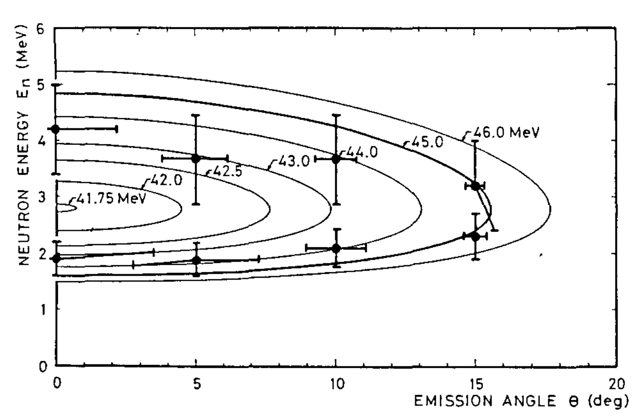

Fig. 6 Kinematics of the $^1H(^{13}C,n)^{13}N$ reaction near threshold taking the projectile energy as a parameter. The measured neutron energies vs. emission angle are also indicated for E(^{13}C) = 45.0 MeV.

component disappears very rapidly. These behaviors are exactly what we expect from the endoenergetic heavy ion reaction kinematics as shown graphically in Fig. 6.

Angular Distributions

Angular distributions of the generated neutrons are already shown in Fig. 1 for the bombarding energies of 45.0 MeV (left) and 42.5 MeV (right). When the bombarding energy became close to the reaction threshold, the angular distribution of the neutrons (maximum emission angle θ_{max}) was getting somewhat unstable. This is explained by the fact that the sensitivity of θ_{max} to the bombarding energy can be expressed as

$$d\theta_{max}/dE_{proj} = 1/(2E_{proj}\sqrt{(E_{proj}/E_{th})-1}\ ) \qquad (2)$$

by differentiating Eq. (1). Thus, for producing a stable focused neutron beam with a cyclotron, the stabilization of the bombarding energy as well as the beam intensity is required.

Neutron Yields

As mensioned earlier, the measured neutron yield was $\sim 7\times 10^3$ n/10 enA at the bombarding energy of 45.0 MeV. This gives a value of $\sim$5 mb for the corresponding total cross section of the $^1H(^{13}C,n)^{13}N$ reaction. The intensity of the accelerated $^{13}C^{4+}$ ion beam current just before the extraction radius (R=65.0 cm) of the cyclotron was $\sim$1 eμA,[4] which indicates a good possibility of producing a focused neutron beam of $\sim 10^6$ n/sec.

Neutron Backgrounds

Background neutrons created from origins other than the gas cell were measured by bombarding the empty gas cell with the ^{13}C ion beam of the same energy. In order to suppress neutron backgrounds, the beam transporting system had to be carefully adjusted so that the beam did hit nothing other than the slits or collimators. When this was attained, the amount of the neutron backgrounds at 0° turned out to be a few percent of the gas cell source neutrons. During the present experiments, the beam instability was monitored by inspecting the neutron and gamma-ray background spectra.

Gamma-ray Backgrounds

In order to evaluate the gamma-ray backgrounds associated with this neutron producing process, the gamma-ray spectra were measured with a 70-cc Ge(Li) detector (see Fig. 4) for the following cases.

A) Natural background was measured without ^{13}C ion beam.
B) Background due to the 60-MeV incident ^{13}C ion beam was measured with the empty gas cell.
C) Background due to the neutron production was measured with the 60-MeV incident ^{13}C ion beam on hydrogen filled gas cell.

The obtained spectra are shown in Fig. 7.

In the spectrum (A), all the observed gamma-ray peaks are identified to be due to the decay of natural activities such as ^{40}K, ^{208}Tl, $^{211,214}Pb$, ^{214}Bi and ^{228}Ac, and due to the decay of induced activities such as ^{54}Mn and $^{56,58}Co$ in the surrounding materials. Besides these activities, gamma rays due to the Coulomb excitation of Ta were recognized in the

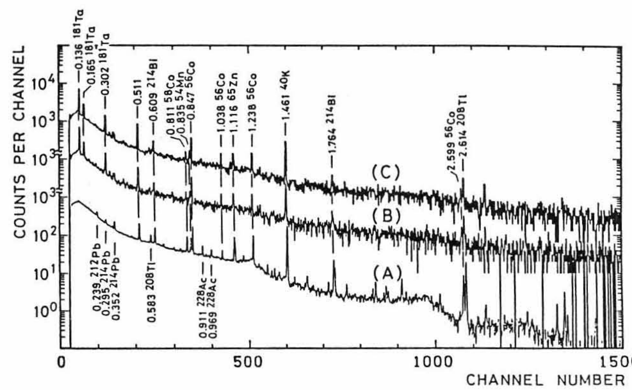

Fig. 7 Measured gamma ray spectra with a 70-cc Ge(Li) detector mounted at 60cm from the H_2 gas cell. Each corresponds to
(A) natural background spectrum
(B) background spectrum of the gas cell without H_2 gas bombarded by the 60-MeV ^{13}C beam
(C) background spectrum of the gas cell filled with 0.5-atm H_2 gas bombarded by the 60-MeV ^{13}C beam.
The ordinate is shifted by an order for easy inspection.

spectrum (B). It is clear from Fig. 7 that the spectra (B) and (C) are identical. This indicates a fact that there is practically no gamma-ray background associated with the focused neutron beam.

What we can do with a FOCUSED NEUTRON BEAM

As described above, a monoenergetic focused neutron beam of 2.8 MeV with a flux of $\sim 10^4$ n/sec was produced by bombarding the hydrogen gas cell with a $^{13}C^{4+}$ ion beam of 42.5-45.2 MeV and $\sim$10 enA. When an internal irradiation of the target in the cyclotron can be done or a high-intensity heavy ion linear accelerator can be used, we can expect a neutron flux of $\sim 10^6$ n/sec or more. This figure is still somewhat small for application of the present method to neutron dosimetry or neutron therapy. However, it should be noted that the focused neutron beam of this type has almost no associated neutron or gamma-ray backgrounds. Therefore, it is very suitable to apply this method for calibrating the detection efficiency of neutron detectors with a higher precision, which could considerably improve the present accuracy of the neutron experiments.

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