A Multipurpose Spherical Neutron Counter

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Abstract

We have developed a unique neutron counter applicable to measurements of fluence, energy distribution and the dose equivalent of neutrons with very wide energy range, and to estimations of incident direction of neutron beams. This 4π sensitive neutron counter consists of a spherical polyethylene moderator and three charge-division-type Position-Sensitive Proportional Counters (PSPCs) inserted into the moderator orthogonally with each other. The three PSPCs give thermal neutron distributions in the spherical moderator that bring us the above information. The characteristics of this neutron counter have been studied with Monte Carlo simulations and with experiments using monoenergetic neutrons.

I. INTRODUCTION

Neutron counters are categorized into three groups [1]. One of them uses fast neutron scattering and the others are based on neutron induced reactions and neutron moderation. The neutron counters based on neutron moderation are of great advantage to an extended-energy response, typically from thermal to tens of MeV. Having the extended-energy response, these neutron counters are used at standard neutron field facilities and at nuclear reprocessing plants, where thermal to fast neutrons exist.

Because the moderating process eliminates most of the information on the original energy, special attempts are necessary if the energy information is to be extracted. Such an attempt is made on the measurement using the Bonner Sphere neutron counters (BS) [2,3]. One of the counters consists of a spherical moderator and a thermal neutron detector placed at the center of the moderator. From a series of measurements of count rates for a neutron source with a set of BS with different radii, information on the energy of the incident neutrons can be extracted with an unfolding process.

Different from the BS, the long counter [4,5], which is known as a neutron fluence monitor, is usually operated with only a single counter system. Therefore the energy information, in principle, can not be extracted from the conventional long counters.

We once developed the modified long counter, ESLOC [6], capable of extracting the energy information about a neutron beam with only a single counter system and a single measurement. The counter consisted of a cylindrical polyethylene moderator and a long PSPC inserted into the moderator. The PSPC gave a thermal neutron distribution in the moderator that brought the energy information on the incident neutrons [6,7]. Then the ESLOC can be used as an energy sensitive fluence monitor for a measurement of a beam of neutrons.

If the neutron fields where neutrons are from many directions are to be measured, a series of measurements by turning the counter for various directions should be necessary. Then we have developed a 4π sensitive neutron counter, as described here, consisted of a spherical moderator and PSPCs. The method of extracting the energy information is similar to that of the ESLOC. The present neutron counter is energy sensitive, hence, named as Energy sensitive SPHErical NEutron Counter (ESPHENEC).

II. DESCRIPTION OF THE ESPHENEC

A schematic view of the ESPHENEC is shown in fig. 1. The ESPHENEC consists of a spherical polyethylene moderator and three slender PSPCs inserted into the moderator orthogonally with each other. The radius of the moderator is 13 cm. It was designed with preliminary simulations so that the counter have relatively high detection efficiencies for neutrons with the energy about a few MeV. The outer diameter, the wall thickness and the effective length of the PSPCs are 1 cm, 0.5 mm and 35 cm, respectively. The counting gas is a mixture of ^{3}He (101 kPa) and CF_4 (70 kPa). Because the CF_4 gas shortens the ranges of the proton and triton produced in the ^{3}He(n,p)t reaction, its addition improves the position resolution [8]. The PSPC has the inherent position resolution of 0.7 cm and good integral linearity over the effective length.

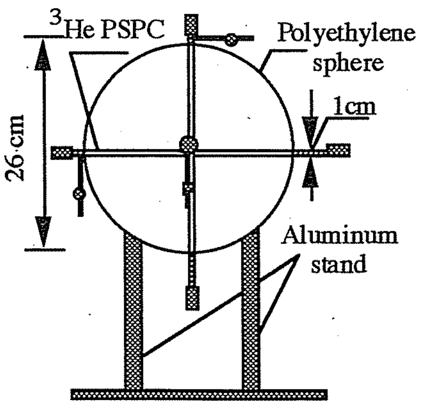

Fig. 1 A schematic drawing of the ESPHENEC

A Cartesian coordinate system at which the center of the moderator is specified (0, 0, 0) is used for the effective notation of the counter geometry and incident direction of beams of neutrons. The PSPCs are placed 0.7 cm away from the x-, y- and z-axes of the coordinate system so that the PSPCs do not intersect with each other. Each PSPC is called the x-, y- and z-PSPC. The incident directions of neutron beams are expressed by the direction cosines.

III. EXPERIMENT

A block diagram of the signal processing system is shown in fig. 2. The six signals from the three PSPCs were taken to an assembly of preamplifiers (CLEAR-PULSE CS507), and then to shaping amplifiers (ORTEC 570). The pulse heights of the outputs of the shaping amplifiers were analyzed by the ADCs (SEIKO EG&G 1821). All pulse height data together with the ADC numbers and coincidence information were processed by the multi-parameter data acquisition system (SEIKO EG&G 1910 LIST CNT) and stored as list mode data on a magneto optical disk (MO) through a personal computer (PC). The detection positions were calculated with the PC. The gamma-ray induced events were easily eliminated by pulse height discrimination.

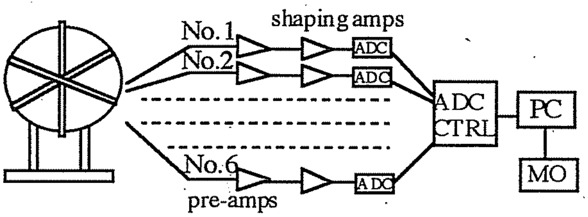

Fig. 2 A block diagram of signal processing system.

Four monoenergetic neutron beams, 165 keV, 3.0 MeV, 5.0 MeV and 14.9 MeV were generated by the Van de Graaff accelerator and the Cockcroft-Walton accelerator at Electrotechnical Laboratory [9]. The experiments were carried out for the four beams of monoenergetic neutrons from three directions: (1.00, 0.00, 0.00), (0.85, 0.50, 0.00) and (0.71, 0.71, 0.00), that is 0°, 30° and 45° from the x-axis, respectively. A schematic drawing of the experimental setup is shown in fig. 3. Background counts evaluated by the experiments using a shadow cone were subtracted from original data. The contribution of the background neutrons to the foreground ones was less than 20% at most.

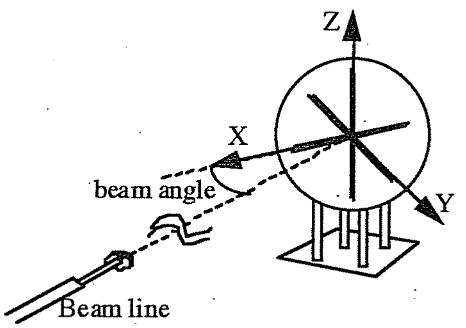

Fig. 3 A schematic drawing of the experimental setup.

IV. RESULTS AND DISCUSSIONS

A. Response function of the ESPHENEC

Figure 4 shows experimentally obtained detection position profiles for the x-, y- and z-PSPCs for (a) 165 keV, (b) 5.0 MeV and (c) 14.9 MeV neutron beams from (1.00, 0.00, 0.00). The abscissae, from -13 cm to 13 cm, correspond to the diameter of the moderator. With increasing energy of the incident neutrons; the fraction of neutron detection around the central region (about -3 cm to 3 cm) increased. Then accumulating the detection counts within any two different radii, or within any one of the spherical shell regions (shell region accumulation; SRA), we can get detection efficiency in the spherical shell region independently of those in other shell regions. Therefore each shell region of different thickness at different depth from

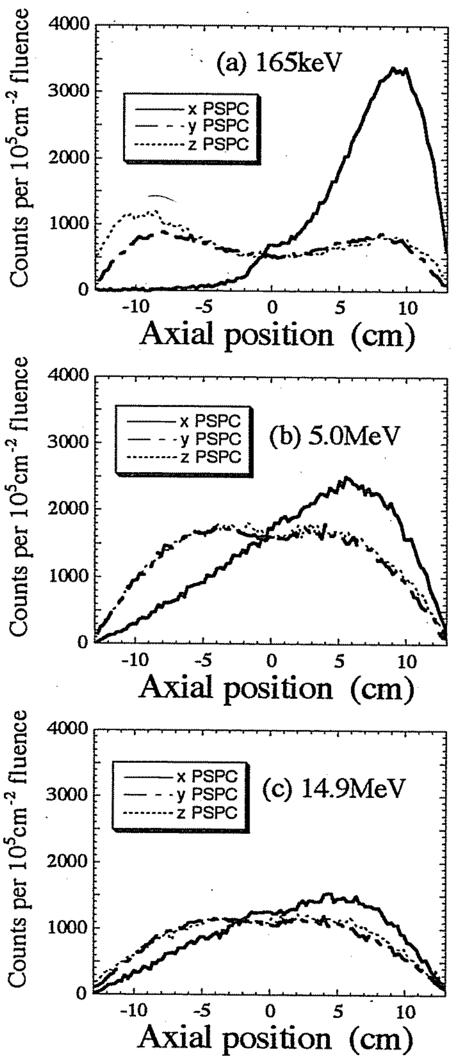

Fig. 4 Experimentally obtained detection position profiles for the monoenergetic neutron beams of (a) 165 keV, (b) 5.0 MeV and (c) 14.9 MeV from (1.00, 0.00, 0.00).

the surface can be assumed as the independent neutron counter having different moderator thickness.

The relation between moderator thickness and the detection efficiency is similar to that of the BS. A sphere with larger radius is much more sensitive to fast neutrons than to slow neutrons, because fast neutrons should be slowed down undergoing many collisions until they are detected by the central thermal neutron detector. Slow neutrons can escape out of the moderator surface without contributing to the detection counts when the radius of the moderator was large enough. On the other hand, a sphere with smaller radius is much more sensitive to slow neutrons than to fast neutrons because fast neutrons can easily penetrate the counter without producing any interactions.

By the same reason, the detection efficiency of the ESPHENEC at the central shell region is high for fast neutrons, and that at the outer shell region or near the surface region, is high for slow neutrons. Therefore, as seen in fig. 4, the fraction of the detection counts at the central region increases with the energy of the incident neutrons. Then the response function of the ESPHENEC can be made with introducing the SRA method.

The calculated SRA response curves with the Monte Carlo simulations are shown in fig. 5. The SRA was carried out for the three shell regions within the radii 0~3 cm, 6~8 cm, and 10~12 cm. Compared to the measurement with the BS, the present method requires, in principle, only a single counter system and a single measurement to obtain the similar information. The response function of the ESPHENEC can be optimized by selecting proper numbers of groupings or thicknesses of the shell regions. The unfolded energy spectra will be given in the next paper.

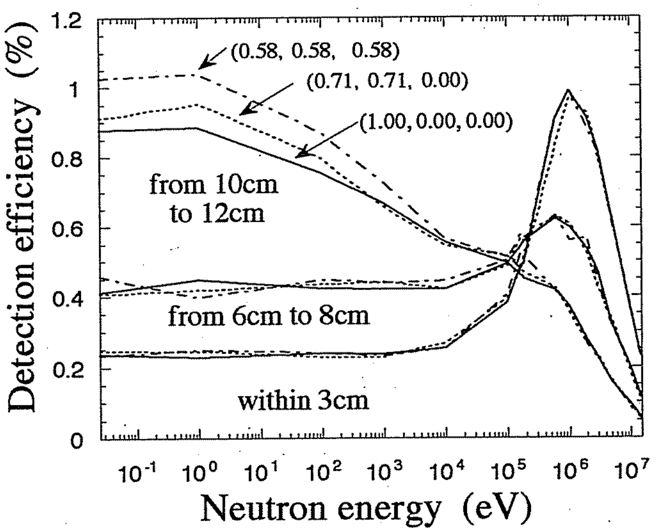

Fig. 5 Response curves obtained with the SRA method.

B. Integrated response of the ESPHENEC

The integrated response (IR), defined as the detection efficiency accumulated for overall moderator radius (from 0 cm to 13 cm), was calculated to examine the possibility of applying the ESPHENEC to the neutron fluence measurement. Simulated results of the IR curves for the parallel neutron beams from (1.00, 0.00, 0.00), (0.71, 0.71, 0.00) and (0.58, 0.58, 0.58), and for the quasi-isotropic neutron field are shown in fig. 6. The quasi-isotropic neutron field was composed of the three neutron beams with proper weighting factors. Each of the four IR curves gradually decreased with increasing the neutron energy up to about 10 keV, reached the local maximum at about 1 MeV and, then, continuously decreased.

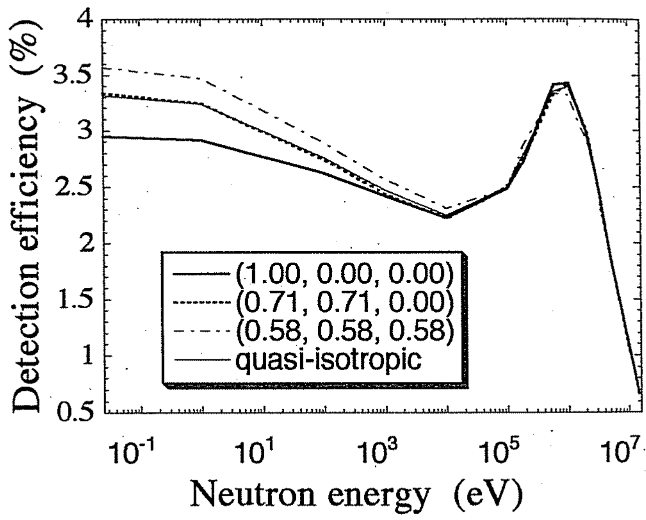

Fig. 6 The integrated response curves.

The energy-dependencies of the IRs for the three neutron beams and for the quasi-isotropic neutron field were evaluated by the Maximum value of relative Deviation from the Mean Efficiency (MDME) at the energy range from 0.025eV to 3.0 MeV. The minimum (Min.) and the maximum (Max.) efficiency, the mean efficiency (ME), and the MDME are shown in Table 1. For neutrons in the above energy range, the deviations of the IRs from the mean efficiencies are no greater than 0.24.

Table 1 The energy-dependency of the IR.

Incident direction	Min. (%)	Max. (%)	ME (%)	MDME
(1.00,0.00,0.00)	2.2	3.4	2.9	0.24
(0.71,0.71,0.00)	2.2	3.4	2.9	0.24
(0.58,0.58,0.58)	2.3	3.6	2.9	0.23
Quasi-Isotropic	2.3	3.4	2.9	0.24

At the lower energy region below about 10 keV, the direction-dependency of the IR can be seen. Table 2 summarizes the direction-dependencies of the IRs for the same energy range. It was evaluated by the Maximum value of relative Deviation of the IR from that of the Quasi-isotropic neutron Field (MDQF) for the three neutron beams. For example, the IR for 0.025 eV neutrons from (1.00, 0.00, 0.00) direction was 2.95 % and that for 0.025 eV neutrons from quasi-isotropic direction was 3.31 %. Then the relative deviation of the IR from that of the quasi-isotropic neutron field for (1.00, 0.00, 0.00) was 0.11. For the neutrons from the same direction, the relative deviation of the IR was less than this value, then the MDQF for (1.00, 0.00, 0.00) direction was evaluated as 0.11. The MDQFs for neutrons from other directions were less than this value. Therefore the ESPHENEC is applicable to the fluence measurement of parallel neutron beams and also of isotropic neutron field.

Table 2 The direction-dependency of the integrated response.

Incident direction	MDQF
(1.00,0.00,0.00)	0.11 (0.025 eV)
(0.71,0.71,0.00)	0.02 (1 keV)
(0.58,0.58,0.58)	0.07 (0.025 eV)

*The value in the parerenthesis is the energy that gives the MDQF.

C. Estimation of incident directions

Figures 7 (a)~(c) show the detection position profiles for the beams of 165 keV neutrons incident from (1.00, 0.00, 0.00), (0.87, 0.50, 0.00) and (0.71, 0.71, 0.00), respectively. Calculated position profiles, corresponding to the experimental ones, are shown in figs. 7 (d)~(f). From the fig. 7, we found that the position profiles were sensitive to the incident direction of neutrons.

In figs. 7 (a) and (d), most of the neutrons detected by the x-PSPC were in the extreme of the positive portion (peaked at about 9 cm) of the x-axis. The position profiles for the y- and z-axes were, on the other hand, nearly symmetrical, because the incident direction of the neutron beam was perpendicular to the axes (or 90° from the axes).

The slightly larger counts are found in the negative portions of the experimentally obtained position profiles for the z-axes in figs. 7 (a)~(c). We considered these counts were due to the reentering neutrons that were originally scattered from the counter itself and scattered back by the stand of the counter or the floor of the laboratory.

Queer bumps are found at about 0 cm in the same figures for the position profiles for the x-axes. We tried to explain the cause of the bumps with geometrical conditions, streaming of neutrons due to the PSPCs, and local increase of gas multiplication. Unfortunately we have not succeeded in reasoning the cause of the bumps yet.

Figures 7 (b) and (e) show the position profiles when the direction of the neutron beam was 30° from the x-axis or 60° from the y-axis. The fraction of the detection counts at the positive extreme (more than 7 cm) of the x-axis was much more than that of the y-axis. When the two angles between the incident direction of the neutron beam and the x-axis, and the y-axis were same (figs.7 (c) and (f)), the two position profiles for the x- and y-axes were also same.

A vector was introduced to evaluate the direction of the neutron incidence. The elements of the vector are the mean positions calculated fort the position profiles for the x-, y- and z-PSPCs. The norm of the vector or the distance from the origin to the point specified with the mean positions in the coordinate system can be used for the rough estimation of the neutron energy. It is useful, however, to get the information on the incident direction of the neutron beam independently of the energy with normalizing the norm of the vector to a unit length. Then the direction cosine was obtained that indicated the mean direction or the Center of Gravity of Angular distribution (CGA) of the beam axis of the incident neutrons.

Table 3 shows examples of the CGA vectors for the beams of 165 keV and 3.0 MeV neutrons from the three directions. The experimentally obtained vectors and the calculated (with Monte Carlo simulation) ones agreed with the direction cosines that indicated real directions from which the neutron beams were incident. Negative values of z-elements, found in experimentally obtained vectors for the beam of 165 keV neutrons, are due to the influence of the rescattered neutrons. Because the CGA vectors indicated only the mean directions of

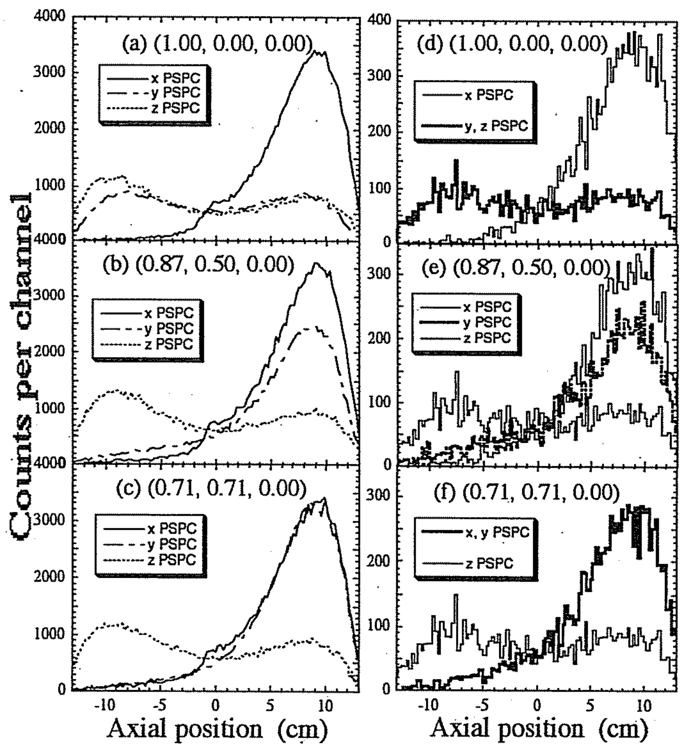

Fig. 7 Experimentally obtained detection position profiles for the 165 keV neutron beams from (a) (1.00, 0.00, 0.00), (b) (0.87, 0.50, 0.00) and (c) (0.71, 0.71, 0.00) are shown together with the simulated results (d)~(f), which correspond to the experimental ones.

neutron incidence, slightly lower directions than real ones were obtained. We concluded that the mean direction from which a neutron beam was incident was properly estimated with the CGA vector.

Table 3 The estimated direction of neutron incidence.

Energy (MeV)	CGA vector		
	Incident direction		
	(1.00, 0.00, 0.00)	(0.87, 0.50, 0.00)	(0.71, 0.71, 0.00)
0.165 (Experimental)	(0.98,-0.04,-0.18)	(0.77,0.62,-0.12)	(0.70,0.70,-0.11)
0.165 (Calculated)	(1.00,0.01,0.01)	(0.79,0.62,0.01)	(0.71,0.71,0.01)
3.0 (Experimental)	(1.00,-0.06,0.08)	(0.87,0.49,0.01)	(0.73,0.68,0.00)
3.0 (Calculated)	(1.00,-0.01,-0.01)	(0.83,0.56,-0.01)	(0.71,0.71,-0.01)

V. CONCLUSIONS

The multipurpose neutron counter, ESPHENEC, applicable to measurements of fluence, energy distribution and the dose equivalent was developed. The characteristics were studied with the Monte Carlo simulations and the experiments using monoenergetic neutrons.

The response function was obtained with the SRA method. The response at the central shell region was high for fast neutrons, and that at the outer shell region or near the surface region, was high for slow neutrons. Compared to the measurement with the BS, the present method requires, in principle, only a single counter system and a single measurement to obtain the similar information. The energy distribution and the dose equivalent of the incident neutrons will be obtained with an unfolding process.

The integrated response for the parallel neutron beams from (1.00, 0.00, 0.00), (0.71, 0.71, 0.00) and (0.58, 0.58, 0.58), and also that for the quasi-isotropic neutron field were calculated. The energy-dependency, evaluated with the MDME for each of the three neutron beams and also for the quasi-isotropic neutron field was less than 0.24 over the energy range from 0.025eV to 3.0 MeV. We concluded the detection efficiency was flat enough for the measurement of neutron fluence. The direction-dependency was evaluated with the MDQF. The maximum value of the MDQFs was 0.11 for the beam of 0.025eV neutrons from (1.00, 0.00, 0.00) direction. Therefore the ESPHENEC is applicable to the fluence measurement of parallel neutron beams and also of isotropic neutron fields.

We tried estimating the incident direction of a neutron beam with the CGA vector that indicated the mean direction. The elements of the vector were the normalized mean detection positions to a unit length calculated for the position profiles for the x-, y- and z-PSPCs. The experimentally obtained vectors and the simulated ones agreed with the direction cosines that indicated real directions from which the neutron beams were incident. The CGA vector was useful for indicating the incident direction of a neutron beam.

ACKNOWLEDGEMENTS

We wish to express our thanks to Dr. Hiroshi Miyahara at Department of Nuclear Engineering, Nagoya University, for his valuable discussions, and to Mr. Katsuo Yanagida at Department of Nuclear Engineering, Nagoya University, for his support to manufacturing the counter.

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