Development of monoenergetic neutron calibration fields between 8 keV and 15 MeV

M. Baba\textsuperscript{a,*}, M. Takada\textsuperscript{b}, T. Iwasaki\textsuperscript{a}, S. Matsuyama\textsuperscript{a}, T. Nakamura\textsuperscript{b}, H. Ohguchi\textsuperscript{b,1}, T. Nakao\textsuperscript{b,2}, T. Sanami\textsuperscript{a}, N. Hirakawa\textsuperscript{a}

\textsuperscript{a}Department of Nuclear Engineering, Tohoku University, Sendai 980-77, Japan
\textsuperscript{b}Cyclotron Radioisotope Centre, Tohoku University, Sendai 980-77, Japan

Received 12 December 1995; revised form received 29 January 1995

Abstract

For characterization and calibration of neutron dosimeters and spectrometers, monoenergetic neutron calibration fields have been developed at eight energy points between 8 keV and 15 MeV (8 and 27 keV, 0.25, 0.55, 1.0, 2.0, 5.0 and 15 MeV). Monoenergetic neutrons are obtained by the Sc(p, n) reactions for 8 and 27 keV, and by the \textsuperscript{6}Li(p, n), T(p, n), D(d, n) and T(d, n) reactions between 0.25 and 15 MeV. Care was taken to reduce background neutrons by parasitic reactions and the scattering of primary neutrons at the target.

The neutron spectrum was characterized by the time-of-flight technique, and the neutron fluence was measured with two independent methods within ±5%. The field has been applied successfully for calibration and characterization of various neutron dosimeters and spectrometers.

1. Introduction

A neutron calibration field with well-known intensity and spectrum is indispensable for the establishment and improvement of the neutron dosimetry technique. In particular, a monoenergetic field is of special importance for obtaining energy responses of neutron dosimeters which vary strongly with neutron energy. Therefore, the recent development of accelerator facilities, experimental fusion facilities and nuclear-fuel processing plants demands monoenergetic fields over a wide range of neutron energy, tens of MeV to thermal energy to measure the energy response of neutron dosimeters.

Several national standard fields have been established and applied to the calibration work [1]. However, the number of monoenergetic neutron fields and the energy points is limited all over the world. Especially in the energy region below ~140 keV, the sources are very few in spite of the importance for reactor dosimetry [1,2]. In this region, monoenergetic fields based on the V(p, n) and Sc(p, n) sources were developed but applied only to a limited number of cases [1–3], and a moderate continuous field or a filtered reactor beam has mainly been employed. The filtered beam has a significant contamination of higher energy neutrons. Thus, a monenergetic field is highly required to measure the point-wise energy response of dosimeters.

We have developed neutron calibration fields at 10 energy points between 8 keV and 32 MeV at the Tohoku University 4.5 MV Dynamitron facility (8 keV–15 MeV) and the Cyclotron Radioisotope Center (CYRIC) (22, 32 MeV) by combining various neutron production reactions. The field at CYRIC is presented in our companion paper [4].

This paper describes the field between 8 keV and 15 MeV at the Dynamitron facility. The energy points and the neutron source properties are summarized in Table 1. The monoenergetic fields below ~100 keV were established using a \textsuperscript{45}Sc(p, n) source which is promising owing to its relatively strong intensity [1–3].

The energy spectra of the field were characterized using the time-of-flight (TOF) technique. Neutron fluences were determined within ±5% by two independent methods (a parallel-plate \textsuperscript{235}U fission chamber and a recoil-proton counter or a \textsuperscript{6}Li counter). The pulsed beam and stable DC beam delivered by the Dynamitron provided neutron beams appropriate for the present purpose.

The neutron field was designed to achieve a clean
Table 1

Neutron sources

<table>
<thead>
<tr>
<th>Neutron energy</th>
<th>Source reaction</th>
<th>Target/ backing</th>
<th>Energy spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 keV</td>
<td>$^{45}$Sc(p, n)$^{44}$Ti</td>
<td>$^{45}$Sc/Pt</td>
<td>&lt;1 keV</td>
</tr>
<tr>
<td>27 keV</td>
<td>$^{45}$Sc(p, n)$^{44}$Ti</td>
<td>$^{45}$Sc/Pt</td>
<td>&lt;1 keV</td>
</tr>
<tr>
<td>0.25 MeV</td>
<td>$^7$Li(p, n)$^7$Be</td>
<td>LiF/Pt</td>
<td>~50 keV</td>
</tr>
<tr>
<td>0.55 MeV</td>
<td>$^7$Li(p, n)$^7$Be</td>
<td>LiF/Pt</td>
<td>~50 keV</td>
</tr>
<tr>
<td>1.0 MeV</td>
<td>T(p, n)$^7$He</td>
<td>T-Ti/Cu</td>
<td>~100 keV</td>
</tr>
<tr>
<td>2.0 MeV</td>
<td>T(p, n)$^7$He</td>
<td>T-Ti/Cu</td>
<td>~80 keV</td>
</tr>
<tr>
<td>5.0 MeV</td>
<td>D(d, n)$^7$He</td>
<td>D$_2$gas/Pt</td>
<td>~250 keV</td>
</tr>
<tr>
<td>15 MeV</td>
<td>T(d, n)$^7$He*</td>
<td>T-Ti/Cu</td>
<td>~500 keV</td>
</tr>
</tbody>
</table>

* $^7$D$_2^+$ beam (1.5 MeV).

spectrum by reducing background neutrons due to neutron scattering from the target and parasitic reactions, as well as room-scattered neutrons. The presently developed field has been applied to measure the energy response of neutron dosimeters and spectrometers.

2. Neutron field

The layout of the Dynamiton laboratory and the experimental arrangement are illustrated in Figs. 1 and 2, respectively. The 8 keV to 15 MeV neutron field was set up at the 30°-target which is located in the central part of the experimental room, about 20 m by 25 m [5,6]. The location...
is advantageous for the present purpose owing to low room-scattered backgrounds and a wide space for the TOF measurement of neutron spectrum. The neutron target is ~1.5 m high from the ground floor, and room-scattered backgrounds are not so serious, as described in the following. As shown in Fig. 2, devices to calibrate are placed at a few to tens of cm from the target along the O°-line with respect to the incident beam. The distance was chosen according to the sensitivity and volume (size) of the device. The utilization of O° neutrons minimizes the effect of neutron scattering by the target which might distort the neutron spectrum substantially in particular for low energy neutrons [7,8]. The neutron fluence on the devices is determined by a relative fluence monitor that has been calibrated by a flux detector described in Section 4.

The neutron production reactions and targets are listed in Table 1. The Sc and LiF targets were prepared by vacuum evaporation on platinum backings, ~0.2 mm thick. As a lithium target, LiF was preferred to metal because of easier handling and stable performance although it is inferior in the neutron yield per unit energy interval. The tritium-loaded titanium (T-Ti) targets for the T(p, n) and T(d, n) sources were commercially available ones with nominal thickness of ~0.75 or ~2.5 mg/cm². The deuterium target was a gas cell with a window foil of Mo (~5 μm thick) or Havar (~2.2 μm thick), and a Pt beam stop (0.3 mm thick). The gas pressure was ~1 atm. A gas target provides neutrons with a much cleaner spectrum and a higher yield compared with a metal target, while the beam current is limited to around ~4 μA. The target thicknesses were chosen as a compromise between neutron yields and the energy spread. The energy spread deduced from the TOF measurement (Section 3) is generally less than 10% as presented in Table 1. The relatively large energy spread of 15 MeV neutrons is because they are obtained at 0° with respect to the incident beam (D²⁰) of 1.5 MeV (0.5 MeV per D²⁰). It can be reduced to less than ~100 keV by using neutrons emitted around 90°, if needed.

The neutron production targets were mounted in thin-walled (<0.5 mm thick) Cu chambers to reduce the scattering of primary neutrons by the chamber, and cooled by an air jet to avoid neutron moderation. The backing plates and beam stop were soldered to the chamber to eliminate a massive flange from the vicinity of the target. Similarly, the T-Ti target was encased in a dual-walled chamber shown in Fig. 3. Besides, the beam lines were pumped by turbo-molecular pumps and sputter-ion pumps to avoid hydrocarbon contaminants on the target. The ion beam from the Dynamitron was defined to ~7-mm-diameter with an aperture of Ta having a high reaction “threshold”. The utilization of Ta was important especially for the Sc(p, n) source because the proton energy for the source (~3 MeV) is high enough to produce neutrons from the beam tube elements, Fe and Cu.

Except for the D₂ gas cell, the targets could be bombarded by a beam current up to 10 μA without noticeable reduction of neutron yields. The source strengths are high enough to make a calibration of devices within a few hours.

3. Neutron source and spectrum

3.1. 0.25–15 MeV neutrons

Neutrons higher than 0.25 MeV could be obtained easily by using the conventional source reactions in Table 1 [1]. The neutron energy was adjusted as desired by tuning the energy of the proton or deuteron beam with observing a TOF spectrum of the produced neutrons. The neutron energy could be reproduced by only a slight adjustment of the beam energy. The TOF measurement was done using an NE213 scintillation detector, 5.08 cm-diameter and 5.08 cm-thick, coupled to a fast photomultiplier. The detector bias was set lower than 0.3 MeV proton energy to clarify the amount of low energy contaminant components. The flight path was 2 to 12 m depending on the neutron energy.

Typical examples of energy spectra are shown in Fig. 4. (The peak widths in the figure are larger than those in Table 1 because of a time resolution effect.) The spectrum is clean enough with little backgrounds. Contaminants were most serious in the 15 MeV source because of low energy parasitic neutrons via the D(d, n) and C, O(d, n) reactions, while the amount of contaminants was ~2–3% at most relative to primary neutrons. For lower energy sources, especially for (p, n) sources, the contaminant component was less. The measured contaminant components were taken into account in the correction of neutron fluence data. The intensity and spectrum of scattered neutrons at the target were estimated using the Monte Carlo method [6,9]. The fraction of scattered neutrons was less than ~2% (highest at 15 MeV).

3.2. 8 and 27 keV neutrons

To obtain monoenergetic neutrons of 8 keV or 27 keV by the Sc(p, n) reaction, some preparatory work was needed since very fine tuning of the proton energy is required. Fig.
5a shows the energy spectrum from a thick (∼500 μg/cm²) Sc target bombarded by a proton beam about 40 keV higher than the threshold. This spectrum was obtained by the TOF method using $^7$Li and $^8$Li glass scintillators (NE912 and NE913) for foreground and background measurements, respectively. The detectors were 5.08-cm-diameter by 0.127-cm-thick and placed at a flight path around 80 cm. Neutron peaks corresponding to the resonances in the $^{48}$Ti compound nucleus are observed with a structure similar to that by Cosack et al. [2]. By adjusting the proton energy and employing a thin target with an energy loss close to the resonance spacing, monoenergetic neutrons can be obtained. The 8 keV and 27 keV neutrons are attractive as a neutron source owing to the prominent strength.

For selection of the neutrons of interest, however, we have to tune the beam energy in the hundreds eV interval. To enable fine control of the beam energy, we installed a new potentiometer in the high-voltage control system of the Dynamitron. This system was preferred to a slit-feedback system since it is not affected by the beam path in the switching magnet in Fig. 1. Then, we took a calibration curve for the potentiometer vs. neutron energy using the TOF spectra by a thick Sc target. In this method, the neutron energy can be determined directly and related to the potentiometer setting. Using the calibration curve obtained and replacing the target with a thinner one (∼70 μg/cm², ∼4.2 keV), neutrons of ∼8 and ∼27 keV were selected. The spectra of 8 and 27 keV neutrons are shown in Fig. 5b (including background). The peaks of these neutron groups are confirmed while the spectra include
extraneous peaks. The extraneous peaks are due to the energy spread of the proton beam which was introduced by the operation of the beam bunched, and should disappear in the DC beam mode for irradiation.

By the procedure described above, we can get the monoenergetic neutrons of interest. However, we observed that the proton (neutron) energy changed beyond the resonance interval when the beam was switched from pulsed mode for TOF to DC mode for irradiation. Hence, the proton energy was readjusted to be appropriate for each neutron group by taking a neutron yield curve vs. potentiometer using a $^3$He-proportional neutron counter. The calibration curve was helpful for the procedure.

The proton beam energy should be stable enough for reliable operation of the Sc(p, n) source. We confirmed the stability of the proton beam energy to be around 200 eV, from the dispersion of the neutron yields at the beam energy around the half-height of the 8 keV resonance peak.

4. Neutron fluence determination

For determination of the neutron fluence, neutron detectors with known detection efficiency are indispensable. In this study, we employed the neutron detectors in Table 2. Those are based on the $^{235}$U(n, f), H(n, p) and $^6$Li(n, t) reactions best suited for neutron flux measurement owing to their well known cross sections. The number of atoms in sample foils of $^{235}$U, polyethylene and $^6$LiF can be measured precisely, and the counters were designed so that the detection efficiencies of the reaction products can be determined accurately by calculations. Further, at five energy points (0.55, 1.0, 2.0, 5.0, and 15 MeV), we made an intercomparison of flux measurements with two different devices, a fission chamber and the other one, for cross checking of the experiment and data analysis.

Above 200 keV, we employed a $^{235}$U fission chamber (FC) as a primary flux detector, and a proton recoil-telescope (PRT), a CH$_3$-SSD (Si surface barrier detector) counter and a $^6$LiF-SSD counter as secondary detectors. For the p-Sc source, only the $^6$LiF-SSD counter was used since the efficiency of the FC is uncertain in the keV region because of large fluctuations of the $^{235}$U fission cross section due to resonances. The validity of the $^6$LiF-SSD counter was confirmed by the comparison with the FC at 0.55 MeV. The chambers of these counters were fabricated to be low-mass to avoid neutron attenuation and scattering.

The neutron fluence was measured relative to a monitor detector and/or target current for normalization between counters (cf. Section 5).

4.1. Fission chamber

Fig. 6a illustrates a schematic view of the FC [5,6]. It is a parallel plate ionization chamber of back-to-back type and is operated in a gas flow mode. Its detection efficiency is close to 100% and can be known very precisely [5,6]. Furthermore, the FC has the great advantage that it can be applied over a wide range of neutron energy without changing the electronics setting because the pulse-height distribution is almost independent of the neutron energy. The deficiency that is sensitive to room-scattered neutrons could be covered by making measurements using a shadow bar. The back-to-back structure allowed two fission foils to

![Schematic view of the $^{235}$U fission chamber (FC).](image)

![Pulse height distribution of FC: A shows the threshold level.](image)

**Fig. 6.** (a) Schematic view of the $^{235}$U fission chamber (FC). (b) Pulse height distribution of FC: A shows the threshold level.
be measured concurrently. Two fission foils with different thicknesses and isotopic compositions were used; one is 99.9\% 235U and 90 \mu g/cm² thick, and the other is 93.3\% 235U and \(\sim\)600 \mu g/cm² thick. The flux measurement was made using the thinner one owing to the well known number of atoms and the good separation between fission fragments and \(\alpha\)-particles (Fig. 6b). The latter foil was employed to increase the counting efficiency for application work, and as a subsidiary device to check the systematic error in flux measurement.

The neutron flux \(\phi_n\) is determined by the following equation:

\[
\phi_n = \frac{C_{FC} \cdot f_{cor}}{\sum_i N_i \sigma_i \cdot C_{mon}},
\]

where, \(C_{FC}\) is the counts of fission fragments, \(N_i\) and \(\sigma_i\) are the number of atoms and fission cross section of nuclide \(i\), respectively, \(f_{cor}\) the correction factor, \(C_{mon}\) the monitor counts. \(N_i\) was determined by \(\alpha\)-counting of the foil with a well-defined geometry (low-geometry counter) [5,6]. The factor \(f_{cor}\) includes the corrections for the effects of 1) self-absorption of fission fragments (\(f_{abs}\)), 2) extrapolation to zero-pulse height of fission fragments (\(f_{ext}\)), 3) neutron attenuation by the chamber (\(f_{att}\)), 4) room-scattered neutrons (\(f_{rsn}\)), 5) parasitic neutrons (\(f_{pan}\)), 6) neutrons scattered at the target and chamber (\(f_{scn}\)). The details of the correction are described in Refs. [5,6,9]. The contribution of room-scattered neutrons was measured by placing a shadow-bar between the target and the fission chamber [5], and was less than \(\sim\)2\% at \(\sim\)10 cm from the target. The factors \(f_{att}\) and \(f_{scn}\) were estimated by Monte Carlo calculations and proved to nearly cancel out each other, since the main scattering source is the elastic-scattering which does not change the neutron energy significantly. Consequently, for the secondary counters described in Section 4.2, \(f_{att}\) was estimated using non-elastic cross sections, and the factor \(f_{scn}\) was assumed to be unity. The effect of parasitic neutrons were estimated to be \(\sim\)2\% at most (15 MeV) based on the neutron spectrum data. The overall correction factor for the thinner 235U foil was 0.97 to 1.0 as summarized in Table 3.

4.2. Proton-recoil telescope, CH₂-SSD, ⁶LiF-SSD counters

Schematic views and typical pulse-height distributions of the PRT [9], CH₂SSD and ⁶LiF-SSD counter are shown, respectively, in Figs. 7–9. The PRT and CH₂-SSD detect recoil-protons from a proton radiator and the ⁶LiF-SSD counts tritons from a ⁶LiF film by the ⁶Li(n, t)³He reaction. PRT employs \(\Delta E\) (transmission SSD: 450 mm², 150 \mu m thick) and \(E\) (BaF₂; 2 cm diameter, 2 mm thick) detectors in coincidence for background suppression, while the latter two counters employ a single Si SSD (300 mm², 100–500 \mu m thick). The geometries between the sample foils and the detectors were defined tightly by two apertures between them. The aperture was made of Al or Ta with small cross sections for charged particle production. At \(E_p\) ≤ 2 MeV, Al was used because of lower electron backgrounds, while Ta was used at higher energies.

The proton radiator was a high purity film of polyethylene (≥10 \mu m thick) or polypropylene of 4 \mu m thickness from Good Fellow Inc. The thickness were 4, 10, 20 and 660 \mu m for 1, 2, 5 and 15 MeV neutrons, respectively. The ⁶LiF films were fabricated by vacuum evaporation on Al foils (10 \mu m thick) and were 360 to 789 \mu g/cm² thick. The foil thicknesses were chosen to obtain peak responses without excessive energy loss, and determined by weighing within 2–3\%.

To reduce backgrounds in the CH₂-SSD and ⁶LiF-SSD counters, it was important to operate the SSDs at the minimum bias-voltages required to stop protons and

<table>
<thead>
<tr>
<th>(f_{abs})</th>
<th>(f_{ext})</th>
<th>(f_{att})</th>
<th>(f_{rsn})</th>
<th>(f_{pan})</th>
<th>(f_{scn})</th>
<th>(f_{cor})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.02–1.00</td>
<td>1.04–1.02</td>
<td>1.03–1.02</td>
<td>0.99–0.95</td>
<td>1.00–0.98</td>
<td>0.97–0.95</td>
<td>1.00–0.97</td>
</tr>
</tbody>
</table>
tritons. The decrease of bias voltage was very effective to reduce the pulse height of background electrons.

The neutron fluence was deduced by the equation

$$\phi_a = \frac{C_p}{\varepsilon} \frac{f_{cor}}{C_{mon}},$$  \hspace{1cm} (2)

where $C_p$ is the counts of protons or tritons, $\varepsilon$ is the detection efficiency, $f_{cor}$ is a correction factor, and $C_{mon}$ is the monitor counts. Detection efficiencies and response functions were calculated using an analytic method ($\varepsilon$ for PRT) [9,10] and Monte Carlo technique (others) on the basis of measured cross section data. The angular distributions were assumed to be isotropic in the center-of-mass system.

The correction factor takes account of the effects of 1) sample-out backgrounds ($f_{out}$), 2) backgrounds due to room-scattered neutrons ($f_{ran}$), and 3) extrapolation of particle yields to zero pulse height ($f_{ext}$). The factor $f_{ran}$ was determined by a shadow-bar method. For the PRT and CH$_2$-SSD counter, the factors other than $f_{out}$ were very small ($\ll 1\%$), since they have clear peak responses (Figs. 7, 8, 9b) and low sensitivity to room-scattered neutrons. In the case of the *Li-SSD counter, on the other hand, the factor $f_{ext}$ at 0.55 MeV was fairly large (Table 4) because of overlaps of $\alpha$-events on triton events (Fig. 9b). The extrapolation was done using the calculated response function for tritons as shown in Fig. 9b.

**Table 4**

<table>
<thead>
<tr>
<th>Neutron energy</th>
<th>$f_{out}$</th>
<th>$f_{ran}$</th>
<th>$f_{ext}$</th>
<th>$f_{cor}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55 MeV</td>
<td>0.99</td>
<td>0.97</td>
<td>1.15</td>
<td>1.10</td>
</tr>
<tr>
<td>8, 27 keV</td>
<td>0.99</td>
<td>1.00</td>
<td>1.00</td>
<td>0.99</td>
</tr>
</tbody>
</table>
The correction factor for the p-Sc source was very small owing to the clean spectrum shown in Fig. 9c. As noted in Section 4.1, $f_{scn}$ was assumed to be unity and $f_{str}$ was estimated using a non-elastic cross section (~1.0).

4.3. Comparison of neutron fluence measurement

The neutron fluences measured by the FC and by secondary detectors are compared in Table 5. The values of the two detectors agree within ±4%. Therefore, it is concluded that the neutron flux measured by the primary detector, the FC for $\geq 0.25$ MeV and the $^6$Li-SSD counter for 8 and 27 keV, are accurate within 4%. The experimental uncertainties were estimated considering errors in counting statistics, sample thickness, geometry, and correction factors. The uncertainty of the FC result is mainly due to statistical error because of the low sensitivity to fast neutrons. Therefore, in view of counting efficiency and insensitivity to backgrounds, the PRT and the CH$_2$-SSD are preferable to the FC. However, they were not applicable to neutrons lower than ~1 MeV without further reduction of backgrounds. To improve the counting efficiency of the FC, we calibrated the sensitivity of the thick $^{252}$U foil relative to the thin foil during the flux measurements. Hence, in practical application to dosimeter calibration, we can measure the neutron flux with much higher counting efficiency using the thicker foil.

By the procedure described above, we have characterized the monoenergetic neutron field with a sufficient accuracy both for neutron fluence and spectrum.

5. Application procedure

The present neutron field has been applied successfully for response measurements of several neutron dosimeters and spectrometers by the arrangement shown in Fig. 2 [11–13]. In the application, we first measure the neutron energy and spectrum by the TOF method, and then normalize the counts of the relative fluence monitor to those of the fluence detectors, the FC for $E_n \geq 0.25$ MeV and $^6$Li-SSD for the p-Sc source. The FC was placed around 8 cm from the target and $^6$Li-SSD a few cm. The correction factors determined above are applied to flux derivation.

Devices to calibrate are placed ~20 cm to ~1.5 m away from the target depending on their sensitivities and sizes. The neutron fluence at the device position can be estimated from that measured by the fission chamber according to the $1/r^2$ law, where $r$ is the distance from the target.

The neutron flux during irradiation is monitored by a relative fluence monitor. It is a spherical hydrogen proportional-counter (Nippon Radiation Eng., 3.5 cm diameter, H$_2$ 4.5 atm + CH$_4$ 0.5 atm) for $E_n \geq 0.25$ MeV. The hydrogen counter is placed around 45° relative to the incident beam axis and around 1.5 m away from the target. The counter proved to be insensitive to neutrons scattered from the devices. In the cases of large scattering devices, nevertheless, a shadow-bar is placed between the monitor and the device.

In the case of the p-Sc source, the low neutron flux made it necessary to place the device at a few cm from the target. In such an arrangement, neutrons scattered by the device gave perturbations to the relative monitor. In these cases, the target current proved to be a reliable measure of the neutron fluence owing to the uniform and stable thickness of the target. An additional $^3$He proportional counter placed around 90° was also employed to monitor the stability of the proton beam energy. The target current was a good relative monitor too in the higher energy region except for the cases of Ti-Ti targets whose thicknesses were not uniform enough.

Backgrounds due to room-scattered neutrons are measured using a shadow-bar method. The contribution of other background neutrons can be generally ignored as noted in Section 4.

By the procedure, the energy response or integral sensitivity of the devices can be calibrated at various neutron energies. The irradiation time is generally within a few hours including background measurements. For the p-Sc source, however, it is desirable to increase the neutron intensity by improving the cooling method of the target.
6. Summary

A monoenergetic neutron calibration field was developed at eight energy points between 8 keV and 15 MeV by combining various neutron production reactions. Such a wide range of neutron fields in the first one in the world which is applied routinely. In particular, the p-Sc field will be invaluable since it provides new neutron field at 8 and 27 keV where only continuous or filtered beams have been available. Therefore, the present calibration field will provide a useful means for calibration and development of neutron dosimeters and spectrometers. Besides, the method of neutron fluence measurement over a wide energy range established in the present study will be applicable in various fields.

Acknowledgement

The present work was partly supported by Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture in Japan. The authors wish to thank Drs. K. Kudo and A. Takeda of Electro-Technical Laboratory of Japan for valuable discussions. They also appreciate Mr. M. Kato for his preparation of the Sc foil and useful information on target preparation techniques. They thank Messrs. T. Kiyosumi, Y. Nauchi, M. Fujisawa and R. Sakamoto for their cooperation in the experiments.

References