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Characterization of the 3 MeV Neutron Field for the Monoenergetic Fast Neutron Fluence Standard at the National Metrology Institute of Japan

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This paper describes the 3 MeV neutron field where the neutrons are generated in the $D(d,n)^3He$ reaction by bombardment of a deuterium-titanium target with a 230 keV deuteron beam from a Cockcroft-Walton accelerator. The neutron field is being prepared for a new national standard on neutron fluence in Japan. The neutron fluence was measured using a proton recoil neutron detector consisting of a silicon surface barrier detector with a polyethylene radiator and the results were compared with data obtained by measuring 3 MeV protons from the D(d,p)T reaction in the deuterium-titanium target in a manner similar to the associated particle method. Neutron spectra were measured using a newly developed recoil proton spectrometer composed of three position sensitive proportional counters and two silicon surface barrier detectors. The gamma rays existing in the field were also characterized using a liquid organic scintillation detector. The ambient dose equivalents were estimated to be of the order of a few μSv at a neutron fluence of 10^7 neutrons cm^{-2}.

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1. Introduction

The National Metrology Institute of Japan provides national standards for the fast monoenergetic neutron fluences at 144 keV, 565 keV, 5.0 MeV and 14.8 MeV. A Van de Graaff accelerator is used to produce the 144 keV and 565 keV neutrons by the $^{7}Li(p,n)^{7}Be$ reaction and the 5.0 MeV neutrons by the $D(d,n)^{3}He$ reaction. The 14.8 MeV neutrons are generated by the $T(d,n)^{4}He$ reaction through bombardment of a tritium-titanium target with a 230 keV deuteron beam from a Cockcroft-Walton accelerator. We are preparing a new neutron field at an energy region of 2-3 MeV using the $D(d,n)^{3}He$ reaction where neutrons are generated in the same way as the 14.8 MeV neutrons but a deuterium-titanium target is used instead of tritium-titanium. We are scheduled to establish a new neutron fluence standard and start a calibration service at this neutron field in 2006.

We describe characterization of the neutron field in the present paper. Neutron fluence determination was carried out using a silicon surface barrier detector with a polyethylene radiator [1] as previously performed in the 5.0 MeV neutron standard field. The results were compared with results obtained by measuring 3 MeV protons produced by a d-d reaction in a similar manner to the associate particle measurement performed for the 14.8 MeV neutron standard field. Neutron spectra were measured using a recoil proton spectrometer consisting of three position sensitive proportional counters and two silicon surface barrier detectors [2] and compared with calculation results obtained by a simulation of d-d neutron generation during deuteron beam transport in a target combined with an MCNP4C neutron transport calculation [3]. The gamma rays existing in the neutron field were also characterized using a liquid organic scintillation detector in a similar manner as performed in the previous studies for the thermal neutron field [4] and the 5.0 MeV neutron field [5]. The spectral fluences of the gamma rays were obtained by unfolding the measured spectra using the HEPRO and UMG program packages [6,7]. The ambient dose equivalents were estimated with a correction to take account of the self-induced gamma rays in the detector.

2. Experimental

The experimental configuration is shown in Figure 1. A Cockcroft-Walton accelerator was used to produce the 2-3 MeV neutrons by the $D(d,n)^{3}He$ reaction, where a 230 keV deuteron beam impinged on a target consisting of a 270 $\mu g/cm^2$ deuterium-titanium layer evaporated on a 0.5 mm thick copper backing. The target was mounted inclined by 45 degrees with respect to the deuteron beam axis. The beam current was between 15 and 25 μA at the target in the present condition. The beam line incorporates two silicon surface barrier detectors, called AP (Associated Particle) detectors in the present paper, installed at 90.7 and 131.9 degrees with respect to the deuteron beam axis which monitor the ions created by nuclear reactions in the target. The AP detectors have a 700 μm depletion depth with sensitive areas defined by apertures 5 mm in diameter mounted 1 m away from the target and just in front of

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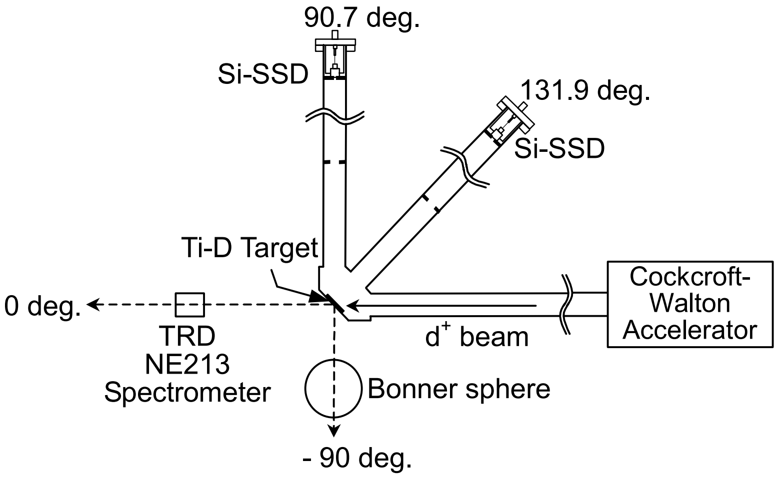

Figure 1: Layout of the 3 MeV neutron field

the detectors. Back-scattered deuterons are stopped with a thin absorber foil made of polyvinyl-acetate-chloride copolymer (VYNS) on the detectors. For the 14.8 MeV neutron standard, the AP detectors monitor the $T(d,n)^4He$ reaction rate and determine the neutron fluence by the associated particle method. Direct monitoring of the neutrons was also performed at 2 m away from the target in the -90 degree direction with a Bonner sphere consisting of a spherical ^3He proportional counter of 33 mm diameter mounted at the center of a 9.5 inch diameter polyethylene spherical moderator. The neutrons were generated in an irradiation room with dimensions of 11.5 m × 11.5 m × 11.5 m. The scattered neutrons from surrounding materials were reduced by placing the target assembly and the measuring instruments on an aluminum-grating floor supported at mid-height of the room.

We characterized the neutron field along the extension line of the deuteron beam from the Cockcroft-Walton accelerator. The neutron fluence was measured in a similar way as performed in our 5 MeV standard neutron field using a proton recoil neutron detector called TR (Thick Radiator) detector in the present paper. The TR detector consists of a 0.5 mm thick polyethylene radiator disk of 89 mm^2 area mounted in front of a totally depleted silicon surface barrier detector of 150 mm^2 area and 300 μm depletion depth. Neutron spectra were measured using a newly developed neutron spectrometer with the apparatus described in [2]. The spectrometer consists of three position sensitive proportional counters and two silicon surface barrier detectors installed in a tandem configuration and operates based on the recoil proton spectrometer principle, *i.e.* the recoil angle and the energy of recoil protons produced in n-p elastic scattering determine the incident neutron energy where the position sensitive proportional counters measure the recoil angle and the sum of all the detector outputs gives the energy. A polyethylene collimator 20 cm thick with a 20 mm diameter hole was placed in front of the spectrometer. The gamma rays existing in the neutron field were also characterized using a 2 inch diameter and 2 inch thick NE213 liquid scintillation detector. Pulse shape discrimination was performed based on differences in decay time of scintillation pulses to separate events induced by gamma rays from those induced by neutrons.

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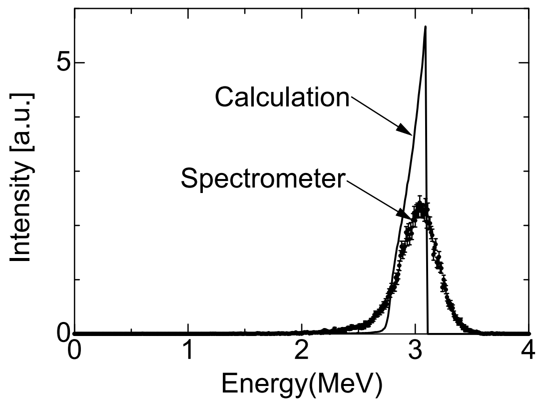

Figure 2: Neutron spectra measured with the spectrometer and obtained by calculation.

3. Results and Discussion

Figure 2 shows a neutron spectrum measured with the spectrometer at 0 degrees with respect to the deuteron beam axis. The spectrometer was placed so that the distance from the target to the collimator entrance was 5 cm. We simulated deuteron beam transport and d-d neutron generation in the target and calculated subsequent neutron transport with the MCNP4C code [3]. Figure 2 shows the calculated neutron spectrum at this position. In both spectra, the fluence-averaged energy is 3 MeV. The measured spectrum exhibits a broader peak than the calculated spectrum, which can not be explained by the intrinsic energy resolution of the spectrometer [2]. Since the collimator was located closed to the target to enhance the count rate of the spectrometer in the measurement, the broadening may be attributable to the angle of divergence of the incident neutrons.

Pulse height spectra were measured with the TR detector located at 0 degrees and 7.3 cm, 15 cm and 35 cm from the target. The neutron fluence at the TR detector positions was determined by the following procedure. The neutron spectral fluence was calculated for each TR detector position as detailed above, and normalized so that the total fluence was equal to unity. The pulse height responses of the TR detector to the normalized spectral fluences were computed by simulating the transport of recoil protons produced in the polyethylene radiator and tallying their energy deposition in the silicon detector. The scaling factor between the deposited energy (MeV) and the channel number was adjusted to achieve the best fit between the calculated responses and the measured spectra. The neutron fluences were given by the ratio between the measured and calculated TR detector counts in the deposited energy region above 1.5 MeV.

Table 1 summarizes the neutron fluences at 0 degrees and 7.3 cm, 15 cm and 35 cm from the target per unit count of the neutron fluence monitors, *i.e.* the AP detector at 90.7 degrees and the Bonner sphere at -90 degrees. For the counts of the AP detector, we used the area counts under the peak caused by the 3 MeV protons from the D(d,p)T reaction in the target. We determined the counts of the Bonner sphere from the area counts above the lower discrimination at 20 % of the peak channel in the spectra. Table 1 also shows the neutron fluences per unit count of the AP detectors determined by the following kinematics calculation in a similar manner as performed for our 14.8 MeV neutron standard by the associated particle method.

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Table 1: Neutron fluences per unit count of the Bonner sphere and the 90.7 degree AP detector. The fluences were determined using the TR detector and by kinematics calculation.

	ϕ/Bonner (cm^{-2})	ϕ/AP(90.7deg) (cm^{-2})	
	Fluence determination		
Position	TR	TR	Kinematics
7.3 cm	439.2±16.1	2430±86	2293±175
15 cm	102.4±4.1	585.7±22.5	546.7±41.6
35 cm	20.66±1.25	119.8±7.2	99.21±7.56

A Monte Carlo simulation was carried out on the deuteron beam transport, proton generation by the D(d,p)T reaction and proton transport in the target. The branching ratio between the D(d,p)T and D(d,n)^{3}He reactions was then evaluated using the ENDF/B-VI deuteron data [8]. The uncertainty of the ratio was adopted to be 7 % by considering the amount of scatter in the measurements on which the ENDF data was based. As seen in Table 1, the neutron fluences determined using the TR detector are 5-20 % larger than the values obtained by kinematics calculation. This may be ascribed to d-d neutrons originating from the deuterons implanted into the beam line components. The amount of the neutrons will be estimated in future measurements using a blank target.

We also characterized the gamma rays existing in the neutron field using the NE213 detector in a similar manner as in our previous study for the 5.0 MeV neutron standard field [5]. Gamma ray response spectra of the NE213 detector were measured using gamma ray reference sources of ^{88}Y, ^{60}Co, ^{22}Na, ^{54}Mn and ^{137}Cs. Energy scale calibration was performed and the energy resolution function was determined by comparing these spectra with the response functions calculated with the MCNP4C code. The energy resolution function dE/E (E in MeV) was found to be $(0.056^2 + 0.076^2/E + 0.014^2/E^2)^{1/2}$ under the present experimental conditions. Figure 3 shows pulse height spectra measured in the neutron field. The NE213 detector was located at 50 cm and 100 cm from the target. The spectra were normalized corresponding to the neutron fluence of 10^7 neutrons/cm^2 at the detector position for both case. Figure 3 indicates that the gamma ray intensity per unit neutron fluence was larger at the greater distance from the target. This may be attributable to gamma rays produced or scattered in the surroundings in the irradiation room.

The spectra were unfolded to obtain the spectral fluence of the gamma rays using the HEPRO and UMG program packages [6,7]. Response functions were prepared for the incident gamma rays up to 10 MeV using the MCNP4C code and Gaussian-broadened with the above resolution function to complete the response matrix for these unfolding codes. Figure 4 shows the unfolded spectra obtained with the MIEKE code in the HEPRO package, which agreed well with the results unfolded with the MAXED code in the UMG package. The ambient dose equivalents H*(10) were evaluated for the spectral fluences using the conversion coefficients [9]. Table 2 summarizes the results as well as the effective dose equivalents evaluated for the AP geometry (irradiation from front to back) and the LAT geometry (lateral irradiation from either side) [10]. Corrections were applied for gamma rays produced by neutrons in the detector

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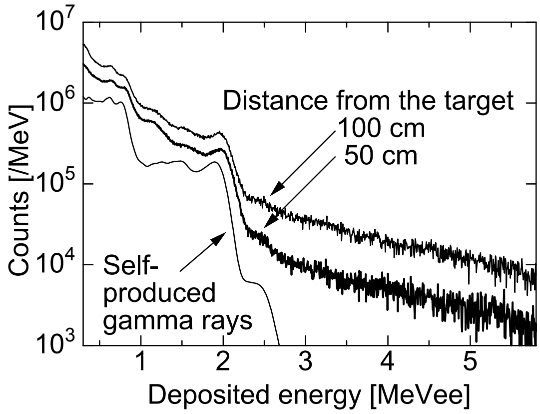

Figure 3: Pulse height spectra measured for the 3 MeV neutron field and the calculated response to the neutron-induced gamma rays in the detector.

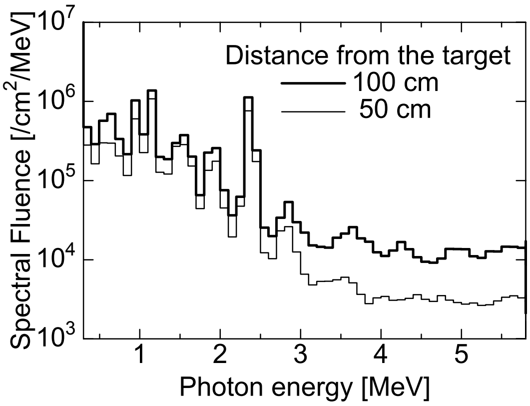

Figure 4: Photon energy spectra in the 3 MeV neutron field unfolded with the MIEKE code.

assembly using the MCNP4C code. Figure 3 also shows the detector response to self-produced gamma rays. The spectrum comprises the gamma rays produced by inelastic scattering and the capturing process of neutrons in the scintillator and the other constituent materials of the detector assembly. The overestimation due to this inner gamma-ray generation was about 2 μSv at 10^7 neutrons/cm^2 on the detector.

4. Conclusion

We have characterized the 3 MeV neutron field that is being prepared for a new national neutron fluence standard in Japan. The neutron spectrum was measured using a newly developed recoil proton spectrometer. The neutron fluence was measured using the TR detector and the calibration factors were determined between the neutron fluence and the count of the fluence monitors, *i.e.* the AP detector and the Bonner sphere. The gamma rays existing in the field were also characterized using a liquid organic scintillation detector. The ambient dose equivalents of the gamma rays were estimated with a correction to take account of self-induced gamma rays.

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Table 2: Dose equivalents of the gamma rays at 10^7 neutrons/cm^2.

Position	Unfolding code	H*(10) (μSv)	AP (μSv)	LAT (μSv)
50 cm	MIEKE	1.39	1.35	0.86
	MAXED	1.33	1.29	0.79
100 cm	MIEKE	3.82	3.54	2.56
	MAXED	3.71	3.42	2.45

Acknowledgements

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References

[1] N. Kobayashi, T. Kinoshita and T. Michikawa, *Correction factors of detector efficiency of proton recoil fast neutron detectors calculated by the Monte Carlo method*, Nucl. Instr. and Meth., **A 242** (1985) 164.
[2] T. Matsumoto, H. Harano, Y. Ito, A. Uritani, K. Emi and K. Kudo, *Development of fast neutron spectrometer composed of silicon-SSD and position-sensitive proportional counters*, Radiat. Prot. Dosim., **110** (2004) 223.
[3] J. F. Briesmeister, *MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C*, LA-13709-M, Los Alamos National Laboratory, 2000.
[4] K. Kudo, N. Takeda, S. Koshikawa, H. Toyokawa, H. Ohgaki, and M. Matzke, *Photon spectrometry in thermal neutron standard field*, Nucl. Instr. and Meth., **A 476** (2002) 213.
[5] H. Harano, T. Matsumoto, Y. Ito, A. Uritani, and K. Kudo, *Characterization of gamma rays existing in the NMIJ standard neutron field*, Radiat. Prot. Dosim., **110** (2004) 69.
[6] M. Matzke, *Unfolding of pulse height spectra: the HEPRO program system.* PTB Report PTB-N-19, Braunschweig, 1994.
[7] M. Reginatto, P. Goldhagen. and S. Neumann, *Spectrum unfolding, sensitivity analysis and propagation of uncertainties with the maximum entropy deconvolution code MAXED*, Nucl. Instr. and Meth., **A 476** (2002) 242.
[8] G. M. Hale, ENDF/B-VI deuteron data, T-2 Nuclear Information Service, [http://t2.lanl.gov/data/deuteron.html].
[9] *Conversion Coefficients for Use in Radiological Protection Against External Radiation*, ICRP Publication 74, Ann. ICRP, 26(3/4), Pergamon Press, Oxford, (1996).
[10] *ICRP Data for Use in Protection Against External Radiation.* ICRP Publication 51, Ann. ICRP, 17(2/3), Pergamon Press, Oxford, (1987).

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