NEUTRON MEASUREMENTS BY IN-SITU GAMMA-RAY SPECTROMETRY USING CADMIUM CONVERTERS

Matjaž Korun, Rafael Martinčič, Bogdan Pucelj

J. Stefan Institute, Ljubljana, Slovenia

Abstract. *Ambient fast neutron fluxes were measured with a neutron-gamma ray converter consisting of an aqueous solution of cadmium nitrate. The gamma rays were detected by a portable gamma-ray spectrometer. For fission neutrons with an asymptotic energy spectrum fair agreement between the flux density measured with the cadmium converter and converters containing boron was achieved. Also for the natural neutron background agreement between the measured and predicted flux density was established.*

INTRODUCTION

The presence of neutrons is reflected in gamma-ray spectra in peaks belonging to neutron capture and inelastic scattering on materials in the vicinity of the sensitive volume of the detector. These peaks are usually present in low-level background measurements and contribute to the background [1]. In in-situ measurements neutron-induced peaks cannot be observed in the spectra because of the high background. However, the sensitivity of the measurements to neutron induced radiation can be enhanced by surrounding the sensitive volume of the detector by a neutron-gamma ray converter. Such converters are most effective at thermal neutron energies because of the high cross sections for neutron reactions. The best materials boron and cadmium [2]. ^{11}B has a high cross section for the n,α reaction. After α particle emission the residual nucleus is formed in its first excited state with a probability of 0.94 and emits deexcitation gamma rays at 477 keV which are Doppler broadened. In case of a cadmium absorber neutrons are captured by the isotope ^{113}Cd. If the converter is mixed with a moderating material, the measurements are also sensitive to fast neutrons. This offers the opportunity to measure thermal and fast neutron fluxes separately.

Ambient neutron fluxes were measured on-site in a nuclear power plant using boron converters [2]. Also the natural cosmic-ray induced neutron background at an altitude of 300 m was measured [3]. However, measurements to determine the natural background with a relative uncertainty of some tens of percent last approximately one day. To improve the sensitivity of the measurements, boron in the converter was exchanged by cadmium. From the point of view of sensitivity, boron exhibits several disadvantages as compared to cadmium:

- Its line is Doppler broadened to about 14 keV;
- The energy of the gamma ray, characteristic of absorption of neutrons in boron, is the same as that belonging to the decay of cosmic-ray produced ^{7}Be and
- The Compton edge of gamma rays belonging to the decay of ^{137}Cs induces an uneven background at the energy of 477 keV.

All these effects contribute to the uncertainty of the peak area and the sensitivity. Therefore, cadmium converters are more suitable for measurements of small neutron fluxes. The line at 558 keV from the capture of neutrons on ^{113}Cd is not interfered by lines from naturally occurring radionuclei and is not Doppler broadened.

METHODS AND MEASUREMENTS

The measurements were performed with a 25% semiconductor detector and a cadmium converter with a volume of approximately 2 litres. The converter thickness was 5 cm at the front of the detector and 4 cm at the side of the detector. The converter was prepared as an aqueous solution of cadmium nitrate. The amount of cadmium dissolved in the converter is about 255 g. The count rate in the 558 keV line is given by:

$$n(558) = b(558)\,[\eta_T(558)\,\Phi_T + \eta_F(558)\,P_F\,\Phi_F] \quad .$$

Here $b(558)$ denotes the probability for the emission of gamma rays of energy 558 keV which is 0.73, $\eta_T(558)$ the probability for the detection of gamma rays with the energy of 558 keV from capture of thermal neutrons, $\eta_F(558)$ the probability for the detection of gamma rays from capture of fast neutrons, P_F the probability for thermalization of fast neutrons and Φ and Φ the fluxes of thermal and fast neutrons through the converter surface. Since the average free path of thermal neutrons in the converter is about 1.7 cm, thermal neutrons entering the converter through the surface are absorbed far from the detector sensitive area. Therefore, the probability for the registration of the corresponding gamma rays in the detector is small. On the other hand, since the diffusion length of fast neutrons during moderation is larger than the thickness of the converter [4], the source of gamma rays from fast neutrons is homogeneous. Neglecting the contribution of thermal neutrons, the flux density of fast neutrons is expressed as:

$$\phi_F = \frac{n(558)}{b(558)\,\eta(558)\,P_F\,S} \quad ,$$

where S denotes the cross section of the converter.

The response of the converter-spectrometer system to neutrons was determined from the response of the same spectrometer to neutrons using two borated paraffin converters. The first had the same geometry as the cadmium converter, and for the second the thermalization probability was calculated with the ANISN code for asymptotic fission neutron spectrum [2]. The ratio of count rates in the 477 keV line in the measurement with the two converters is:

$$\frac{n_1(477)}{n_2(477)} = \frac{\eta_1(477)}{\eta_2(477)}\,\frac{P_{F1}}{P_{F2}}\,\frac{S_1}{S_2} \quad .$$

Since $S{=}S_1$ and assuming $P_F{=}P_{F1}$, because the converters are of equal dimensions, the flux density can be expressed as:

$$\phi_F = \frac{n(558)}{b(558)\;\eta_2(447)\,\dfrac{\eta(558)}{\eta_1(477)}\,\dfrac{n_1(477)}{n_2(477)}\;P_{F2}\,S_2} \quad .$$

The efficiency of the second converter $\eta_2(477)$ was calculated from the measurement of an internal soil standard in the same geometry [2] and found to be 1.70 (1 ± 0.03). The efficiencies $\eta(558)$ and $\eta_1(477)$ refer to the same geometry. Their ratio was determined from the measurement of another internal standard in the geometry of the cadmium converter to be 0.88 (1 ± 0.02). This value was used for the calculation of the neutron flux density, and therefore the differences in the self-absorption of the cadmium converter, the borated paraffin converter and the internal standard were neglected. Near the reactor building the ratio of the count rates in the 477 keV line from the two borated paraffin converters was measured as 1.20 (1 ± 0.05). The probability for the thermalization of fast neutrons, calculated by the ANISN code, and the cross section of the corresponding converter are 0.42 (1 ± 0.02) and 104 cm^2 respectively [2]. Finally, the relation between the count rate in the 558 keV line and the flux density of fast neutrons is:

$$\phi_F = \frac{n(558)}{0.57(1 \pm 0.08)\;cm^2} \quad .$$

To test the response of the spectrometer to small neutron fluxes measurements were performed in the vicinity of a nuclear power reactor at two distances from the reactor building. The measurements lasted approximately 50 and 500 minutes respectively. The flux densities of fast neutrons at the two locations were found to be 0.068 (1 ± 0.17) cm^{-2} s^{-1} and 0.006 (1 ± 0.5) cm^{-2} s^{-1}, respectively.

To test the reliability of the neutron flux measurements with the cadmium converter a measurement was performed at a location where the thermal and fast neutron fluxes had also been measured using boron converters [2]. The measurements gave 0.13 (1 ± 0.08) cm^{-2} s^{-1} and 0.86 (1 ± 0.06) cm^{-2} s^{-1} respectively. The measurement with the cadmium converter gave a slightly lower value of 0.76 (1 ± 0.09) cm^{-2} s^{-1} for the flux of fast neutrons.

DISCUSSION

It should be noted that in an asymptotic fission spectrum, as well as in the spectrum of naturally occurring neutrons, the flux density of thermal neutrons is much smaller than the flux density of fast neutrons [2,5]. Only in this case can the contribution of thermal neutrons to the 558 keV line be neglected. The results show fair agreement between the fast neutron flux density measured by boron converters, where the thermal neutron flux is accounted for, and the flux density measured with the cadmium converter.

The time required to measure the natural neutron background flux is about ten hours. This time may be shortened by using a larger semiconductor detector and by shielding the spectrometer against background gamma-ray radiation.

CONCLUSION

It was shown that a high-resolution gamma-ray spectrometer can be converted to a neutron flux meter by using a suitable cadmium converter. A converter containing neutron moderating and absorbing materials, in the present case water and cadmium, is sensitive to fast neutrons. It should be noted that for a quantitative relation between the neutron flux and the count rate in the 558 keV line the neutron spectrum must be supposed. The agreement between the flux measured with the cadmium and boron converters near the reactor building, as well as the agreement between the natural neutron background and the flux measured further away reflects the fact that the spectra of fast neutrons far from a fission source and of natural neutrons are similar [2,6].

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