Neutron detection using a Gadolinium-covered CdZnTe sensor

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***Abstract* – Gain in efficiency and miniaturization is an issue for portable neutron detectors. ^{157}Gd, ^{155}Gd and ^{113}Cd nuclei show the highest neutron capture cross-sections available in the stable element list. They are then a subject of interest for neutron detection and could be considered as suitable competitors with regards to detectors using ^{3}He, ^{10}B, ^{6}Li or proton recoils.**

A neutron detector using a Gd converter and a CdZnTe diode is studied to address portable neutron detection. To exploit the low energy signature from the Gd, a reliable compensation technique with a guard sensor has been designed. Some innovations have been done on algorithmic part and sensor part of the system. The concept has been experimentally proved. It has notably been demonstrated that a Tb cover on the guard sensor allows a reduction of the overcompensation and then a maximization of the sensitivity of the detector.

***Index Terms* — CdZnTe; Gadolinium; Neutron; Compensation; Algorithm.**

I. Introduction

NEUTRON measurement is an active subject of research driven by the necessity to find solutions to the ^{3}He shortage and portable neutron dosimeters [1, 2]. The detectors usually take advantages of high cross-section capture reactions, inducing charged ions easily separable from recoil electrons. The evolution of the cross-section as a function of the incident neutron energy is presented in Fig. 1 for the ^{3}He(n,p), ^{10}B(n,α), ^{6}Li(n,α), ^{1}H(n,n'), ^{113}Cd(n,γ), and ^{157}Gd(n,γ) reactions. Though Gadolinium and Cadmium isotopes have the highest capture cross-sections for thermal neutrons, prompt gamma rays from the radioactive capture cannot be easily discriminated from natural background gamma rays. Indeed, the capture of a neutron by ^{157}Gd forms a ^{158}Gd* nucleus within an excited state. The return to a fundamental state of energy is promptly mediated by the emission of gamma rays.

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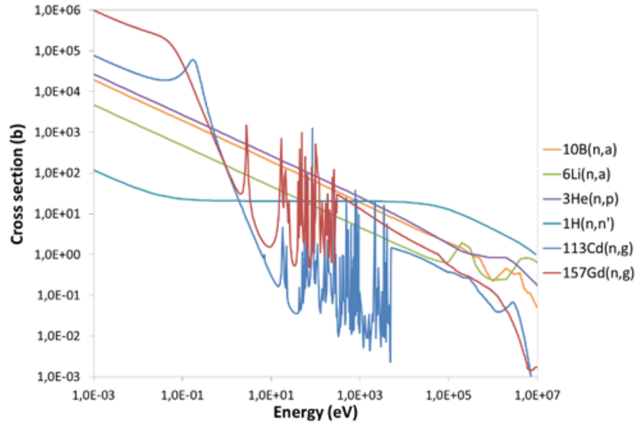

Fig. 1 Cross-sections of different isotopes used for neutron detection.

However, Gadolinium-based detectors have been developed to address alternative neutron measurement. The first approach consists in loading gadolinium into scintillation detectors. In this framework, inorganic scintillators as the Gd-doped Hf02 or the LGB crystals [3-4], together with organic scintillators [5-7] must be mentioned. Robust gamma rejection and promising neutron sensitivity have been obtained in scintillation technology addressing large sensor applications [8-9].

The second approach consists in covering a detector by a gadolinium layer. Gadolinium-covered gas detectors have notably been studied in details by D.A. Abdushukurov [10]. As a representative example, S. Masaoka has developed a micro-strip gas chamber with gadolinium converters for neutron position-sensitive detectors associated to neutron scattering experiments [11].

To develop portable detectors addressing personal neutron dosimetry, semi-conductor technologies are preferable due to the high photon stopping power into condensed matter. A Gd converter has been incorporated into a MOSFET component to develop a neutron dosimeter [12]. A relationship between the output current and the neutron dose has been described. The intrinsic properties of CdTe for neutrons detection have been studied in [13]. CdTe sensors contain neutron-sensitive cadmium, which has led to the observation of a characteristic signature at 96 keV and 560 keV, resulting from neutron capture in ^{113}Cd isotopes. A Gadolinium-covered CdTe diode has been developed and tested by Miyake et al., making use of both ^{113}Cd and ^{157}Gd isotopes [14]. The small CdTe pixel detector ensures the identification of the characteristic X-ray peaks from Gd at 43 keV and 49 keV, prompt gamma-ray peaks from Gd at 79.5 keV, 89 keV, 182 keV, 199 keV, and from Cd at 95 keV. Signatures from Cadminium and Gadolinium have been measured but the peak area estimation is not a reliable technique to ensure a neutron metrology due to possible gamma rays interferences. A compensation system has been design and presented in the present article.

II. Source term

The source term associated with the de-excitation of a Gd or Cd nucleus following the absorption of a thermal neutron is subdivided into a prompt photon source term and a prompt electron source term. The complete equations of the nuclear reactions read:

$$^{113}_{48}\text{Cd} + ^{1}_{0}\text{n} \rightarrow ^{114}_{48}\text{Cd}^{*} \rightarrow ^{114}_{48}\text{Cd} + \gamma + XR + ICe^{-} + Ae^{-} \quad (1)$$

$$^{155}_{64}\text{Gd} + ^{1}_{0}\text{n} \rightarrow ^{156}_{64}\text{Gd}^{*} \rightarrow ^{156}_{64}\text{Gd} + \gamma + XR + ICe^{-} + Ae^{-} \quad (2)$$

$$^{157}_{64}\text{Gd} + ^{1}_{0}\text{n} \rightarrow ^{158}_{64}\text{Gd}^{*} \rightarrow ^{158}_{64}\text{Gd} + \gamma + XR + ICe^{-} + Ae^{-} \quad (3)$$

where the sum of the gamma rays labeled γ and the X rays noted XR forms the photon source term, and the sum of internal conversion electrons noted ICe^{-} and the labeled Auger electrons Ae^{-} forms the electron source term.

Prompt gamma rays produced as a result of a neutron capture into Cd or Gd nuclei are extracted from the IAEA data bank [15] and displayed in Fig.2 and 3, and internal conversion electron spectra are calculated by the BrIcc calculator [16] form Australian National University and presented in Fig. 4. Cross-sections for the most significant terms (above 1000 b) are summarized in Tab. 1. It appears that the signature of the ^{157}Gd is largely prominent. Given the size of the sensor, the signal of interest will lie below 200 keV. The measurement will specifically target 79.5 keV and 182 keV rays.

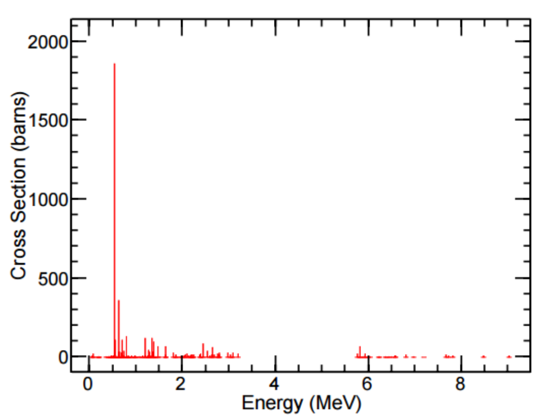

Fig. 2 Prompt gamma-ray emission spectrum of ^{113}Cd (extracted from IAEA data base [15]).

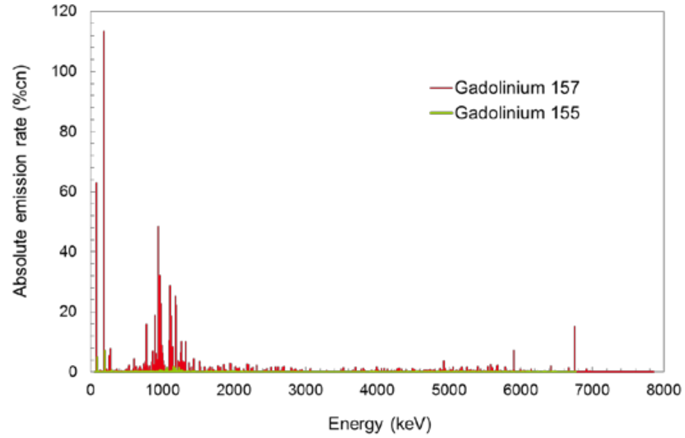

Fig. 3 Prompt gamma-ray emission spectrum of ^{155}Gd and ^{157}Gd (extracted from IAEA data base [15]).

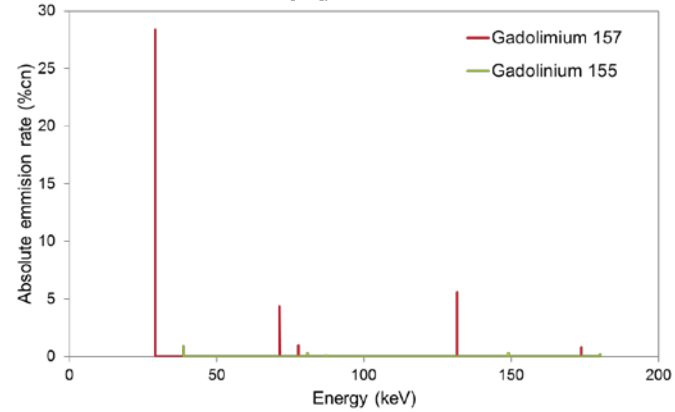

Fig. 4 Internal conversion electron spectrum of ^{155}Gd and ^{157}Gd (extracted from IAEA data base [15] and BrIcc conversion coefficient calculator [16]).

Tab. 1 Main gamma-ray and electron emissions induced by radiative capture in Gd and Cd. The emission rate is expressed in emission probability per neutron captures (%cn).

Nuclide [ref.]	Particle	Energy (keV)	Cross-section (b)	Emission rate (%cn)
^{113}Cd [15]	γ rays	558	1860	29.2
^{155}Gd [15]	γ rays	89	1380	21.7
^{155}Gd [15]	γ rays	199	2020	31.7
^{157}Gd [16]	*IC* e^{-}	29.3	1807	28.4
^{157}Gd [16]	*IC* e^{-}	71.4	280	4.4
^{157}Gd [15]	**γ rays**	**79.5**	**4010**	**63.0**
^{157}Gd [16]	*IC* e^{-}	131.7	356	5.6
^{157}Gd [15]	**γ rays**	**182**	**7210**	**113.3**
^{157}Gd [15]	γ rays	898	3290	51.7
^{157}Gd [15]	γ rays	944	3090	48.5
^{157}Gd [15]	γ rays	962	2050	32.2
^{157}Gd [15]	γ rays	977	1440	22.6
^{157}Gd [15]	γ rays	1108	1830	28.8
^{157}Gd [15]	γ rays	1186	1600	25.1

III. Method

We consider two CdZnTe diodes covered by a Gadolinium converter for the first one and a compensation cover (as Terbium) for the second one. Each diode is coupled to a charge sensitive preamplifier and a signal processing allowing counting, every time step Δt, pulses comprise between two energy boundaries. The number N_1 and N_2 of counts for respectively the reference and the guard channels have to be smoothed in order to reduce the shot noise associated with counting estimations. A nonlinear filter CST optimizing the tradeoff between response time and precision has to be implemented [17] and use to provide accurate and precise values of $\widehat{N}_1, \widehat{N}_2$ and their associated variances $\sigma^2(N_1)$ and $\sigma^2(N_2)$.

$$\begin{cases} [\widehat{N}_1; \sigma^2(N_1)] = CST(N_1) & (4) \\ [\widehat{N}_2; \sigma^2(N_2)] = CST(N_2) & (5) \end{cases}$$

The algorithm for the estimation of the neutron count rate $\hat{S}_n$ is based on a hypothesis test where K is a coverage factor governing the risk of false detection.

Algorithm. 1 Estimation of the neutron count rate.

$$\begin{array}{ll} If & \widehat{N}_1 - \widehat{N}_2 > K\sqrt{\sigma^2(N_1) + \sigma^2(N_2)} \\ Then & \hat{S}_n = \widehat{N}_1 - \widehat{N}_2 \\ Else & \hat{S}_n = 0 \end{array}$$

It can be noted here that smoothing is a critical point because the variance reduction will directly impact the detection limit.

IV. Experimental Results

The experimental set-up is composed with a 500 mm^3 CdZnTe diode mounted on a dedicated card [18]. The diode is used successively without convertor, with a Gd convertor and with a Tb convertor. The Fig. 5 shows the diode cover by the Terbium foil. The foils of Gadolinium and Terbium have a thickness equal to 25 µm; this value is known as an optimal value as mentioned in previous study [10].

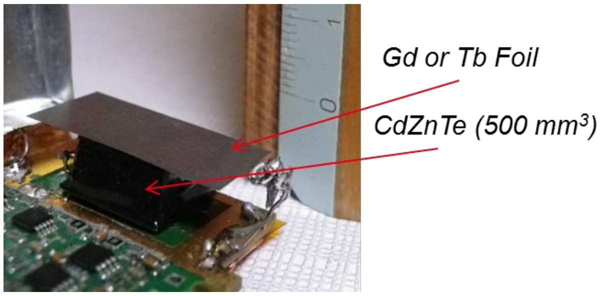

Fig. 5 CdZnTe diode covered by a Tb foil.

A source of Californium 252 is placed at 15.2 cm from the detector. A screen composed by 5 cm of Lead and 2 mm of Copper limits the gamma flux impinging the sensor. In the first configuration, a bloc of 10 cm of High Density Polyethylene PEHD is set between the source and the Lead in order to maximize the thermal neutron flux (*cf.* Fig. 6). In the second configuration, a bloc of borated wood replaces the PEHD in order to minimize the thermal neutron flux while maintaining an equivalent gamma flux on the detector (*cf.* Fig. 7).

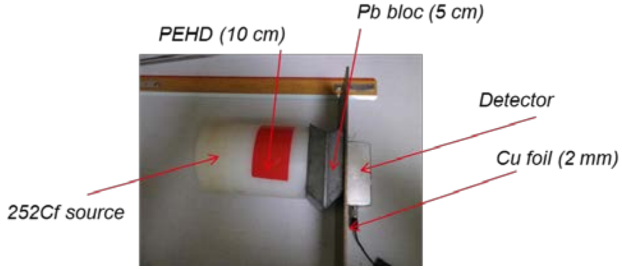

Fig. 5 Experimental configuration maximizing the thermal neutron flux.

Fig. 6 Experimental configuration minimizing the thermal neutron flux.

Spectra obtained by the subtraction of the spectrum measured respectively with the gadolinium converter and without any converters are presented in Fi.g 7. We can observe an overcompensation on the spectra below 200 keV. This phenomenon is explained by the screen effect due to the Gd foil itself. As seen in the PEHD case (red curve), the neutron increases the signal in this energy range but not enough to become significant in the range [60; 200] keV. As already observed in [19], a signal coming from X-rays at 43-44 keV is measured. To increase the signal in the range [60; 200] keV, we have then decided to cover the guard sensor by a Terbium foil with the same thickness. Terbium has been chosen because of its charge number (Z=65) nearby Gadolinium one. Fig. 8 shows subtracted spectra obtain with the use of the Terbium cover on the guard sensor. The neutron signal becomes significant with the contribution in:

- the range 70-80 keV containing the 79 keV gamma rays from ^{158}Gd* and the summation between the 29 keV internal conversion electron and 43 keV X rays,
- the range 120-140 keV containing the 132 keV internal conversion electron from ^{158}Gd* and the summation between the 29 keV internal conversion electron and the 79 keV gamma rays,
- the 558 keV gamma rays from ^{114}Cd*.

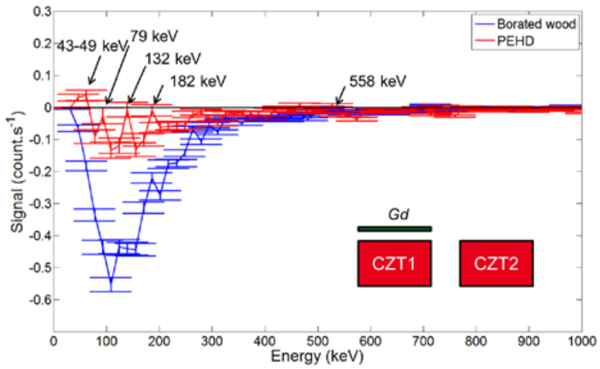

Fig. 7 Subtracted spectra measured without cover on the guard sensor.

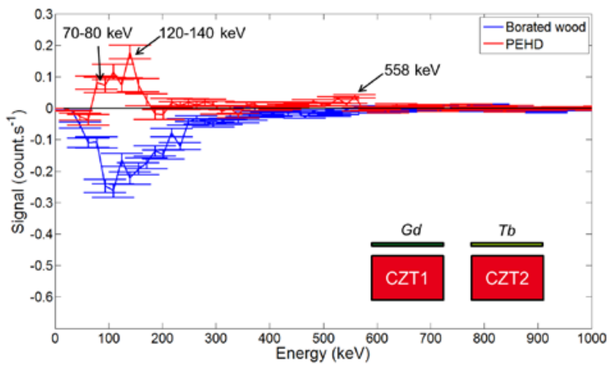

Fig. 8 Subtracted spectra measured with a Terbium cover on the guard sensor.

The Tab. 2 displays the integrated values within the range [60; 200] keV (related to gadolinium) and the range [500; 600] keV (related to cadmium). The significantly positive values measured when the neutrons are cooled by the PEHD prove the efficiency of the concept.

Tab. 2 Count rates measure in the different configurations

	PEHD Count rates (couts.s^{-1})	**Borated wood Count rates (couts.s^{-1})**
Gd / void [60; 200] keV	-0.65 ± 0.34	-3.64 ± 0.30
Gd / Tb [60; 200] keV	**+0.55 ± 0.33**	-1.76 ± 0.29
Gd / void [500; 600] keV	-0.13 ± 0.07	-0.098 ± 0.052
Gd / Tb [500; 600] keV	**+0.102 ± 0.066**	-0.070 ± 0.051
Gd / void [60; 600] keV	-1.23 ± 0.39	-4.88 ± 0.34
Gd / Tb [60; 600] keV	**+0.79 ± 0.38**	-2.45 ± 0.33

V. CONCLUSION

R&D works are in progress for the development of neutron detector based on a Gadolinium covered CdZnTe diode. This detector is particularly suitable to measure the low energy signature emitted by the radiative capture on Gd nuclei.

It has been conceived a signal processing permitting a reliable and sensitive neutron count rate metrology. Moreover the implementation of a Terbium cover on the guard sensor has permitted to reduce the overcompensation phenomenon and then to provide a significant signal coming from the prompt gamma rays between 60 to 200 keV.

The concept has been proven and future works will be engaged to optimize the design, develop a prototype and to benchmark it with competitor solutions.

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