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Thermal neutron detection with cadmium$_{1-x}$ zinc$_x$ telluride semiconductor detectors

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Abstract

Cadmium zinc telluride (CdZnTe) detectors have been used to detect thermal neutrons. The CdZnTe detectors were placed in a double diffracted thermal neutron beam and the prompt gamma ray emissions from thermal neutron interactions in the Cd have been detected. The devices clearly show the 558.6 and 651.3 keV prompt gamma ray emission peaks from ^{113}Cd(n, γ)^{114}Cd reactions. The intrinsic detection sensitivity is dependent on the gamma ray absorption efficiency, which is measured to be approximately (3.7±1.9)% at 558.6 keV for a 3 mm × 10 mm × 10 mm CdZnTe device.

1. Introduction

A neutron detection system is generally based on measuring the reaction products from thermal neutron interactions. The reaction products may be charged particles (as observed with the ^{10}B(n, α)^{7}Li and ^{3}He(n, p)^{3}H reactions), conversion electrons (as observed with the ^{157}Gd(n, γ)^{158}Gd reaction), or prompt gamma rays (as observed with the ^{113}Cd(n, γ)^{114}Cd reaction). Gas detectors such as $^{10}BF_3$ and ^{3}He tubes are popularly used for thermal neutron detection [1]. Gas detectors have the advantage that the absorber material is also the ionizable medium, yet the devices are generally large to ensure that an adequate gas volume is present for good thermal neutron interaction efficiency. Reaction product producing films attached to solid state devices, such as ^{157}Gd or ^{10}B coated semiconductor detectors, offer the advantage of reasonable efficiency and compact size [2,3]. Yet, due to reaction product self-absorption in the thin film region, the devices suffer a physical limitation in sensitivity to thermal neutrons. An ideal thermal neutron detector is a solid state semiconductor device composed of a highly neutron absorbing material that releases ionizing radiation reaction products. The device therefore serves both as the absorber and the detector, hence the high density of absorber atoms in a solid state form allows for high thermal neutron absorption efficiency in a compact design. Also, reaction product self-absorption in a dead region is no longer an issue for such a device since the reaction products would be released inside the active region of the detector.

Cadmium based semiconductors seem to have the necessary properties for solid state thermal neutron detectors. The isotope ^{113}Cd has a relatively high thermal neutron absorption cross section of 20 000 b [4,5]. However, the natural abundance of ^{113}Cd is only 12.26%, which yields an absorption cross section of only 2450 b for natural cadmium [4,5]. Thermal neutron interactions with ^{113}Cd produce an abundance of prompt gamma ray emissions which are well catalogued [6–8]. Hence, a large Cd based semiconductor detector would be capable of both absorbing neutrons and the corresponding prompt gamma ray emissions [9]. The device should also be capable of high resolution such that the prompt gamma rays corresponding to a neutron absorption can be easily identified and distinguished from background gamma ray events. Recently, relatively large volume CdZnTe detectors have shown promise as high resolution gamma ray spectrometers [10–12], hence a CdZnTe device of respectably large size could serve as an alternative thermal neutron detector. Presented are preliminary results from thermal neutron measurements acquired with a commercial CdZnTe solid state semiconductor detector.

2. Experimental arrangement and results

The thermal neutron source was a 2 MW LEU thermal nuclear reactor. The neutrons from the reactor were moderated with a D_2O tank, and collimated out of the reactor area through neutron beam port tubes. The neutron

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beam port did not point directly at the core, therefore reducing the overall background gamma ray component of the beam. The neutrons were then diffracted with copper plates to remove the neutron beam from the remaining background gamma rays emitted through the beam port. The beam was collimated once more through a high density polyethylene tube encased in a highly absorbing thermal neutron beam stop material (Benelex) before reaching the working space. The basic experimental arrangement is shown in Fig. 1.

A commercial 3 mm × 10 mm × 10 mm $Cd_{0.8}Zn_{0.2}Te$ detector was used for the thermal neutron measurements. The composition of the material yields a ^{113}Cd atomic density of $1.49 \times 10^{21}/cm^3$ with a thermal neutron macroscopic cross section of 29.72/cm. Therefore, 3 mm of $Cd_{0.8}Zn_{0.2}Te$ is almost completely opaque to thermal neutrons, allowing only 0.013% of the thermal neutrons to pass entirely through the device. The detectors were coupled to an Ortec 142A charge sensitive preamplifier for all measurements reported in the following work. The detector and preamplifier were shielded in a lead encasement on all sides except the region directly in front of the thermal neutron beam working space. The lead shielding was used to reduce counts from background and scattered gamma rays. The open area was arranged such that different shielding and absorber materials could be placed in the thermal neutron beam directly in front of the CdZnTe detector. While in place, the pulse height spectra of the CdZnTe detector was calibrated using ^{133}Ba, ^{22}Na, and ^{60}Co calibration standards.

The thermal neutron beam port was blocked with a high density polyethylene and Cd plug, and a 10 min long measurement was performed with the CdZnTe detector in order to acquire a background count rate and spectrum. The plug was then removed and different absorber materials were placed directly in front of the CdZnTe detector (at the location shown in Fig. 1), including 1 in. of high density polyethylene, 2 in. of lead, and 2 in. of Boroflex. The lead shielding reduces the background gamma rays that contaminate the beam, while allowing a large percentage of the thermal neutrons to pass through and into the detector. The high density polyethylene is a very ineffective gamma ray absorber, but a good thermal neutron scatterer. Hence gamma rays will pass through the high density polyethylene into the CdZnTe detector with little attenuation while neutrons will be efficiently scattered from the beam. The boron loaded Boroflex is also a very inefficient gamma ray absorber, but a very efficient thermal neutron absorber. Gamma rays pass through the Boroflex while thermal neutrons are removed from the beam through the $^{10}B(n, \alpha)^7Li$ reaction. Overall, background gamma rays are able to pass through the Boroflex and the high density polyethylene into the detector, while the lead attenuates the gamma rays significantly. Conversely, thermal neutrons will pass through the lead into the detector, while the Boroflex and the high density polyethylene will attenuate the thermal neutrons significantly.

A comparison of the absorber results are shown in Fig. 2. As can be seen, when only high density polyethylene or Boroflex are placed in the beam, the spectrum remains

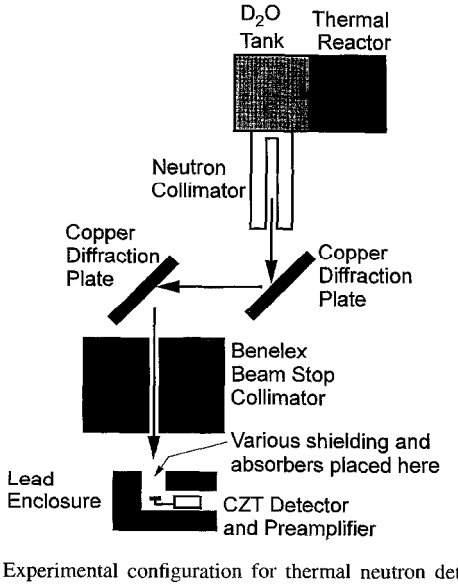

Fig. 1. Experimental configuration for thermal neutron detection with a CdZnTe detector. Different absorbers were placed in the working space directly in front of the CdZnTe detector in order to determine the source of the observed signals.

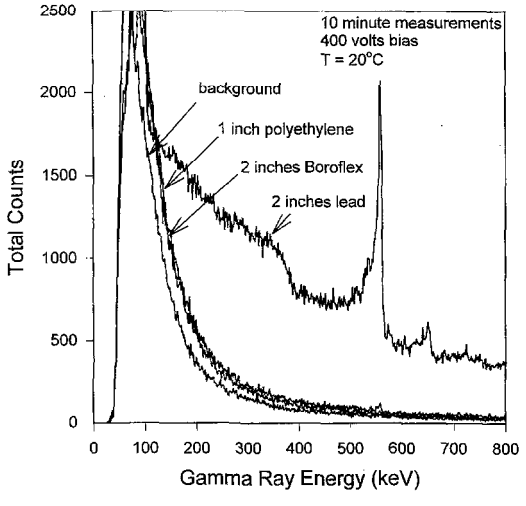

Fig. 2. Resulting pulse height spectra measured with a CdZnTe detector with different attenuators in the thermal neutron beam. All measurements were conducted for a 10 min live time duration. The spectra taken with neutron absorbers (polyethylene or Boroflex) in the beam were similar to the background spectrum. The spectrum taken with a gamma ray absorber (lead) in the beam (without neutron absorbers) demonstrated the appearance of distinctive gamma ray peaks at 558.6 and 651.3 keV.

similar to the background spectrum. These results indicate that gamma ray contamination from the beam is not a significant issue in the present case. However, a significantly different spectrum is observed when only 2 in. of lead are placed in the beam. Distinctive gamma ray features are observed at 558.6 and 651.3 keV, as expected for prompt gamma ray emissions from the $^{113}Cd(n, \gamma)^{114}Cd$ reaction [6–8].

An additional experiment was performed to ensure that the observed gamma rays were indeed from the cadmium in the CdZnTe detector. The experimental arrangement is shown in Fig. 3, in which a NaI(Tl) detector was moved away from the thermal neutron beam and well shielded from background gamma rays. The NaI(Tl) detector was pointed towards the thermal neutron beam working space. Different metals were placed in the thermal neutron beam such that gamma ray emissions from various neutron interactions could be observed with the NaI(Tl) detector, including Cu, Te, Zn, Pb, and Cd metal samples. A background measurement was performed without a sample in the beam, in which a 511 keV annihilation peak was very evident. The 511 keV peak was observed with all spectra taken, regardless of the sample composition. Additionally, the observed spectrum remained the same for all samples measured except for the Cd sample, in which case irradiation of the Cd sample demonstrated the appearance of 558.6 and 651.3 keV gamma rays (see Fig. 4). Hence, it is concluded that the 558.6 and 651.3 keV gamma rays are resulting from the $^{113}Cd(n, \gamma)^{114}Cd$ reaction, and that the CdZnTe detector is clearly sensing thermal neutrons.

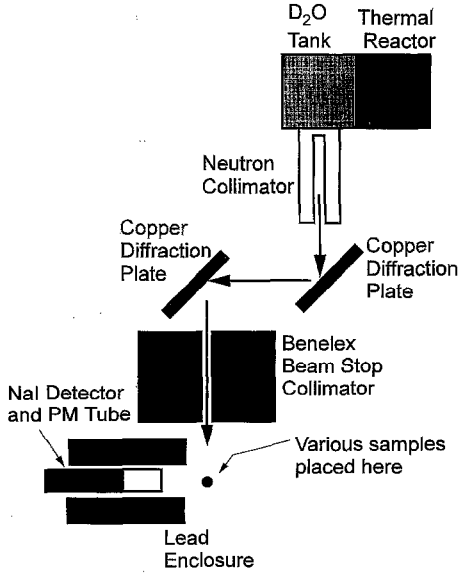

Fig. 3. Experimental configuration for detection of prompt gamma ray emissions from neutron induced reactions in different materials. The materials were placed directly in the beam such that the NaI(Tl) detector was directly facing the beam interaction location.

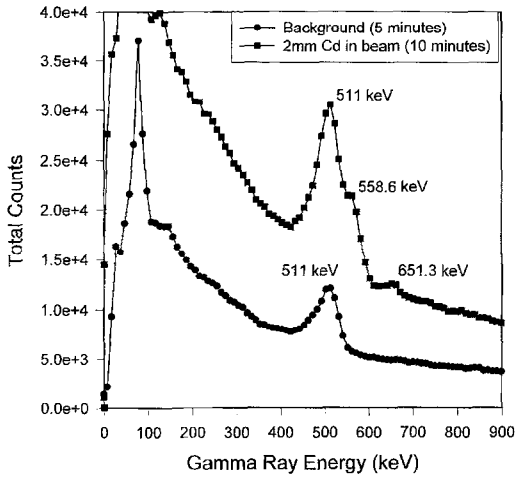

Fig. 4. Resulting pulse height spectrum measured with a NaI(Tl) detector of a Cd sample irradiated with thermal neutrons. The spectrum without any materials in the beam demonstrated the appearance of a 511 keV positron annihilation peak. The 511 keV gamma ray peak appeared in all spectra taken. Only when a 2 mm thick Cd sample was placed in the thermal neutron beam did additional gamma ray peaks appear in the pulse height spectrum, which were at 558.6 and 651.3 keV.

Two more measurements were conducted, in which the CdZnTe detector was placed in the thermal neutron beam as shown in Fig. 1 with no absorber in the beam. A 2 h measurement was obtained with the unshielded CdZnTe detector. The unshielded measurement was necessary in order to determine the thermal neutron detection efficiency. The net counts in the 558.6 keV peak measured approximately $1\,120\,000 \pm 5500$. The detector was removed and a 25 μm thick vapor deposited Gd screen coupled to Kodak SR film was used to image and calibrate the thermal neutron beam at the working space. The film image of the thermal neutron flux indicated a non-uniform distribution, thereby increasing the uncertainty regarding the flux that intersected the CdZnTe detector. From the film density measurements, the thermal neutron flux in which the CdZnTe detector was exposed measured to be $4.2 \times 10^3 \pm 2.1 \times 10^3$ n/cm^2 s. The resulting detector sensitivity to neutron induced prompt gamma ray emissions at 558.6 keV is $(3.7 \pm 1.9)\%$. Au foils are presently being activated in the thermal neutron beam to obtain a more accurate measurement of the flux.

Afterwards, 4 in. of lead were placed in the thermal neutron beam directly in front of the CdZnTe Detector, and a 9.5 h measurement was taken. As shown in Fig. 5, the long measurement allowed for the appearance of more detail in the prompt gamma ray emission spectrum. The identified prompt gamma rays result from the $^{113}Cd(n, \gamma)^{114}Cd$ reaction as documented in the literature [8].

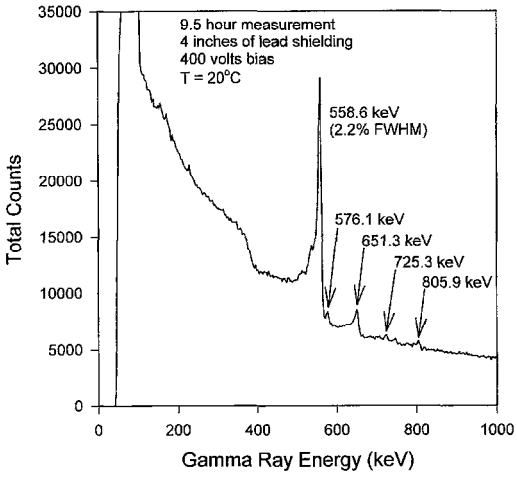

Fig. 5. A 9.5 h duration measurement of the $^{113}Cd(n, \gamma)^{114}Cd$ prompt gamma ray emission spectrum taken with a 3 mm × 10 mm × 10 mm $Cd_{0.8}Zn_{0.2}Te$ detector. Four inches of lead were placed directly in front of the detector during the measurement. The long measurement allowed for the appearance of detail in the prompt gamma ray emission spectrum.

3. Conclusions

A 3 mm × 10 mm × 10 mm CdZnTe detector has been demonstrated as a thermal neutron detection device with a measured sensitivity of (3.7±1.9)% at 558.6 keV. The device clearly demonstrated the appearance of the 558.6 and 651.3 keV prompt gamma ray emissions from the $^{113}Cd(n, \gamma)^{114}Cd$ reaction. The detector may be used as an alternative thermal neutron detector provided that the user is aware of its intrinsic problems. The device doubles as a gamma ray detector, hence a low thermal neutron flux may be easily masked in a high gamma ray environment, just as a small gamma ray source spectrum may be masked if a much larger gamma ray source is in the vicinity. Neutrons are efficiently absorbed in the CdZnTe detector, however the prompt gamma rays are subsequently emitted internally in the detector, of which a high percentage escape or deposit only a fraction of energy through Compton scattering. Hence, a CdZnTe detector is an efficient thermal neutron absorber, but not necessarily an efficient thermal neutron detector. The requirement for high efficiency to $^{113}Cd(n, \gamma)^{114}Cd$ prompt gamma ray emissions is large volume, which will also increase the overall sensitivity to background gamma ray interactions. It is therefore necessary for the size of a CdZnTe detector to be tailored to a specific use, in which the thermal neutron to background gamma ray sensitivity ratio is maximized in the case for thermal neutron detection.

Acknowledgements

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The CdZnTe detector investigated was acquired from eV Products. Similar devices are available from other commercial vendors.

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