Performance characteristics of a thermal neutron detector based on $Li_6Y(BO_3)_3$:Ce single crystals

A.K. Singh[1], M. Tyagi[1], S.G. Singh[1], S. Sen[1], S.S. Desai[2], S.S. Ghodke[3] and S.C. Gadkari[1,*]

[1]*Technical Physics Division,* [2]*Solid State Physics Division,* [3] *Radiological Physics & Advisory Division*
Bhabha Atomic Research Centre, Mumbai- 400085, India
* email: gadkari@barc.gov.in

Introduction

Neutron detectors find several applications in research, defence, security and nuclear industries. The conventional neutron detectors are based on ^{3}He and BF_3. While BF_3 is corrosive and toxic, the shortage of ^{3}He has made it prohibitively expensive. Due to the dwindling supply of ^{3}He, there is an urgent need to explore other solid state detectors that can replace these gas based detectors. Inorganic scintillators are promising candidates to be used as neutron detectors in many applications. Single crystals of $Li_6Y(BO_3)_3$ (LYBO) doped with cerium, have been proven as a promising neutron scintillator [1]. This material contains ^{6}Li (natural abundance 7.4%, σ_{abs} = 940 barns) and ^{10}B (natural abundance 20%, σ_{abs} = 3835 barns) that have large cross sections for thermal neutrons and produce charged particles (α and ^{3}H) after interaction [1]. The alpha particles generated in ^{10}B (n, α) ^{7}Li and ^{6}Li (n, α) ^{3}H reactions excite the Ce^{3+} ions resulting in a fast (27 ns) and efficient emission at 420 nm. This matches well with the efficiency response of Bialkali photomultiplier tubes (PMT) and therefore can be easily read out using standard electronics. A lower effective Z of the LYBO compared to other neutron scintillators also helps impart insensitivity to gamma that prevails in mixed field radiations [2].

Experiment

Crystal Growth

Single crystals of 0.1% and 0.2% cerium doped LYBO were grown using the Czochralski technique. Typical photograph of an as-grown crystal is shown in Fig.1. Initial material was prepared from 4N pure (99.99%) constituent oxides (Li_2CO_3, Y_2O_3, CeO_2, H_3BO_3) using the high temperature solid state reaction at 700ºC with intermediate mixing. The synthesized material in the form of pellets was filled in a platinum crucible. Since the material has a supercooling of more than 250ºC, a higher melt level (more than 80% of the crucible height) was used in the absence of any after-heater for the growth of single crystals. The temperature was kept at about 50ºC more than the melting point (865ºC) of LYBO to homogenise the melt. A pull rate of 0.5 mm/h and rotation rate of 10 rpm were used. The grown crystals were then cooled down to room temperature at 30ºC/h to avoid cracking due to thermal stress.

Fig. 1 As-grown single crystal of LYBO:Ce.

Characterization

Cylindrical samples of 2 mm thickness and 20 mm diameter were cut and polished to optically finish. The processed scintillator was then mounted on a 1 inch PMT (Hamamatsu E2979-500) with the help of optical grease. Teflon reflectors were used to collect the light through one end of the scintillator coupled to the PMT. Pulse height spectra (PHS) were recorded using a pulse processing chain consisting of PMT, pre-

Amp, shaping amp and MCA. The measurements were carried out at different neutron sources including, Am-Be, Pu-Be, ^{252}Cf lab neutron sources and a neutron beam line at Dhruva reactor. These sources have different thermal neutron flux in the range from 100 n.cm^{-2}.s^{-1} to 2 x 10^{5} n.cm^{-2}.s^{-1}.

Results and discussion

Interaction of neutrons with LYBO crystals takes place via following reactions:

With ^{10}B

$^{10}B_5$ + n →$^{7}Li_3$ + α (Q value = 2.792 MeV, ground state)

$^{10}B_5$ + n → Li_3 (excited) +α + γ (0.48 MeV) (Q value = 2.310 MeV)

With ^{6}Li

$^{6}Li_3$ + $_0n^1$ → $^{4}He_2$ (2.05 MeV) + $^{3}T_1$ (2.75 MeV

The charged particles generated deposit energy with an average Q value of 2.5 MeV in the case of reaction with ^{10}B; while energy of 4.8 MeV is deposited in case of ^{6}Li. However in the latter case both the generated charged particles are lighter and therefore cause a higher ionization which effectively results in a larger equivalent electron energy deposition [1]. Therefore the photon yield from ^{6}Li (n, α) ^{3}H is about five times higher than that obtained from the ^{10}B (n, α) ^{7}Li interaction. Fig.2 shows the response of the scintillator to thermal neutrons measured at a beam line of Dhruva reactor.

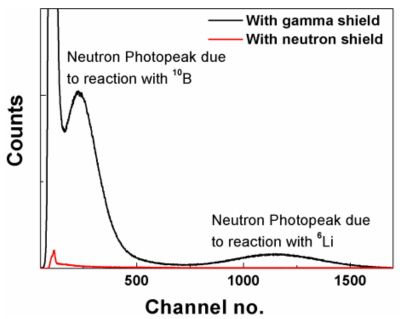

Fig. 2 Pulse height spectra of LYBO:Ce for thermal neutrons at a beam line of Dhruva reactor.

It clearly shows the photo-peaks corresponding to ^{10}B reaction at channel No. ~ 240 while that due to ^{6}Li at channel No. of 1200. These peaks were not observed when a neutron shield (borated rubber) was used to block them from reaching the detector. The difference in the relative intensities of the two peaks in both the spectra can be attributed to the lager neutron capture cross section for ^{10}B and its higher isotopic presence in the natural sample.

In order to determine the minimum detection efficiency of the scintillator, they were exposed to standard neutron sources with lower neutron fluxes of 150 and 250 neutrons cm^{-2} s^{-1}. Fig.3 shows the relative ratio of the pulse height spectra measured at these two neutron fluxes. The calculated ratio of integrated counts from the measurement was found in the good agreement with the actual value. The thermal neutron detection efficiency for 1mm thick crystals grown from naturally abundant Li and B compounds was calculated to be about 80%. It can be further increased to ~ 100% for 1 mm thick crystals enriched in ^{6}Li and ^{10}B.

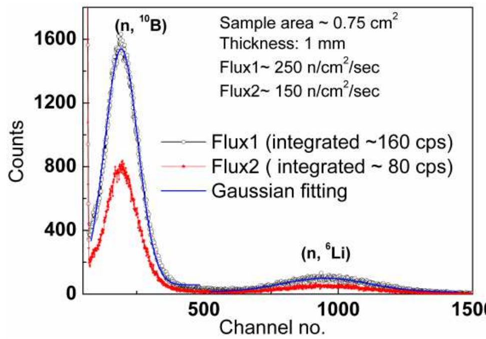

Fig. 3 Response of LYBO crystals to two different neutron fluxes.

Conclusion

Single crystals of LYBO:Ce exhibited a promising detection performance to thermal neutrons. The efficiency and gamma insensitivity can be further improved by using Li enriched in ^{6}Li.

References

[1] J.B. Czirr et al., Nucl. Inst. And Meth. A **424** (2011) 15.
[2] A. K. Singh et al., J Lumin. **137** (2013) 208.