Study of the Response Functions of a Cs_2LiYCl_6 Scintillator to Neutron and Gamma Radiation

N. Khan, R. Machrafi
University of Ontario Institute of Technology, Ontario, Canada

A PhD Level Submission

Summary

A new scintillator, Cs_2LiYCl_6 (CLYC), has been investigated for its response to neutron and gamma radiation. The current sensor technology that is used to detect fast neutrons has many challenges and drawbacks such as detection efficiency and energy dependence. CLYC can overcome these challenges. The neutron absorption reaction of ^{35}Cl for high energy neutrons makes this sensor promising by using a distinct proton peak that is proportional to the energy of the incident neutron. The calculated response functions of this detector to neutron and gamma radiation have been obtained and analyzed using Monte Carlo N-Particle eXtended code (MCNPX).

1. Introduction

Neutron spectrometry is a fundamental part of the dose calculation of individuals working in nuclear facilities. This is due to its dependence on the incident neutron energy. The detection of neutrons is typically divided into two parts, thermal and fast neutrons. Traditionally, thermal neutrons have been detected using sensors based on either ^{3}He, ^{6}Li, and ^{10}B based detectors which have a high neutron absorption cross section at thermal energies. Currently, there are two main methods that are used to detect fast neutrons. The first is by using the neutron scattering process on ^{1}H; and the second is by slowing them down using a moderator and consequently capturing them at thermal energies. The drawback with the first method is that the neutron energy transferred to the proton highly depends on the scattered angle. As a result, a distribution of energies from the proton is observed and complicated unfolding techniques are required to determine the incident neutron energy. While the drawback with the second method is that, after the neutron is thermalized, its spectral information is lost. In addition, due to the current shortage of ^{3}He, there is a need to sought out other sensors.

Recently, there has been a newly developed sensor, Cs_2LiYCl_6:Ce, which has been tested mainly for thermal neutron detection based on the $^{6}Li(n,\alpha)^{3}H$ reaction [1-6]. Another useful reaction that can be utilized for fast neutrons is $^{35}Cl(n,p)^{35}S$. In this reaction, the energy from the emitted proton can be observed as a distinct peak in the detector response function. The value at this peak is equal to the incident neutron energy plus the *Q*-value of the reaction.

This paper presents the response of a CLYC scintillator to neutron and gamma radiation. Simulated detector response functions were obtained using Monte-Carlo N-Particle eXtended code (MCNPX).

2. Methodology

Neutrons may undergo a few reactions in this crystal, depending on the neutron energy and isotope the interaction occurs with. At thermal energies, a neutron is detected by the capture reaction:

$$ {}^{1}_{0}n + {}^{6}_{3}Li \rightarrow {}^{3}_{1}H + {}^{4}_{2}He \quad (1) $$

where the neutron absorption cross section is 940 barns. The *Q*-value of this reaction is 4.78 MeV where the alpha particle takes 2.05 MeV and the triton takes 2.73 MeV.

Fast neutron detection can be achieved by using the capture reaction:

$$ {}^{1}_{0}n + {}^{35}_{17}Cl \rightarrow {}^{35}_{16}S + {}^{1}_{1}p \quad (2) $$

The *Q*-value of this reaction is 0.615 MeV. The proton produced has energy equal to the *Q*-value of this reaction plus the incident neutron energy; therefore the incident neutron energy can be deduced using this full energy peak. The absorption cross-section values for ^{35}Cl and ^{6}Li, are given in Table 1 for energies up to 2 MeV.

Table 1: Neutron Cross Section Data for the Reactions

Neutron Energy (keV)	**σ (b)**	
	$^{35}Cl(n,p)$	**$^{6}Li(n,\alpha)$**
100	1.51×10^{-4}	0.654
500	0.021	0.379
1000	0.047	0.229
1500	0.109	0.212
2000	0.146	0.216

2.1 Cs_2LiYCl_6 Scintillator

CLYC is a cylindrical inorganic crystal with 95% ^{6}Li-enriched. All of the other elements that constitute the crystal are in their natural abundances, for example chlorine, which is 75% ^{35}Cl and 25% ^{37}Cl. It has a density of 3.31 g/cm^3. It has three light decay times; 1, 50, or 1000 nanoseconds. It has a very high light output of 73,000 ph/neutron and its maximum wavelength of emission is 370 nanometers. A 1 inch x 1 inch CLYC scintillator was modeled in MCNPX and can be seen in Fig. 1 using Visual Editor.

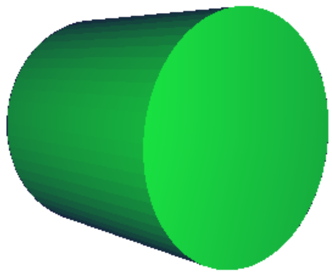

Figure 1: MCNPX Model of CLYC Scintillator using VisEd

3. Results and Discussion

3.1 Gamma Radiation

The detector was irradiated with ^{137}Cs at a distance of 10 cm from the detector. Ideal resolution was taken.

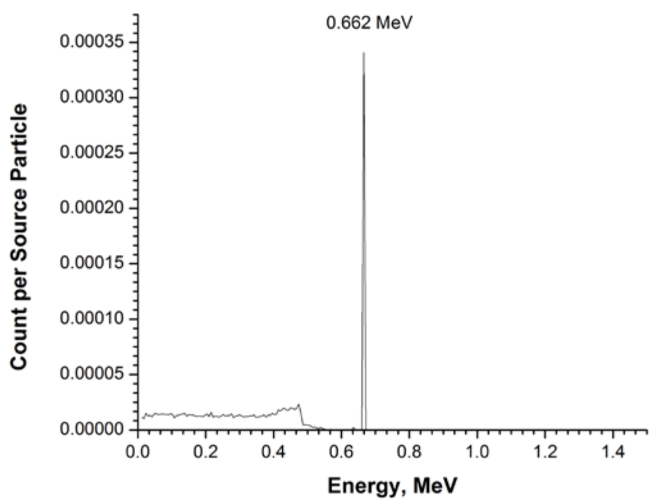

Figure 2: Detector Response Function to ^{137}Cs

From Fig. 2, the x-axis represents the scintillation light from the energy deposited by the electrons in the scintillator. Two methods of gamma interaction are prevalent with this scintillator; the photoelectric effect and Compton scattering. The photoelectric peak can be seen at 0.662 MeV and Compton edge at 0.478 MeV. The photoelectric effect is slightly more dominant due to more high Z constituents in the crystal.

3.2 Neutron Radiation

The detector was irradiated with neutrons of varying energies from 0.1 MeV to 2 MeV. These energies were chosen based on their weight in the neutron fluence-to-dose conversion factor. A hypothetical energy resolution of 3% was applied to the spectrum in order to validate the simulation. Figure 3 shows the response function to 0.1 MeV neutrons.

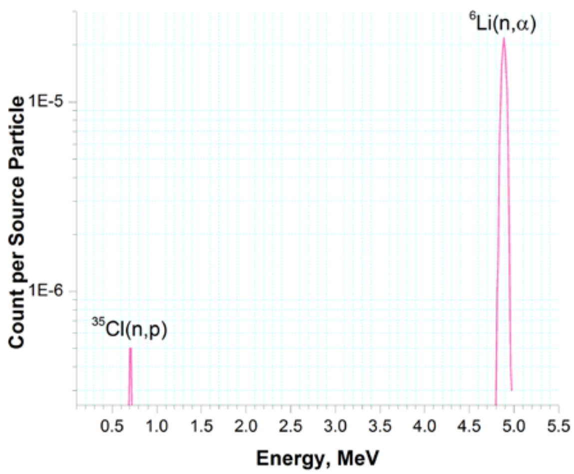

Figure 3: Detector Response Function to 0.1 MeV Neutrons

From Fig. 3, the x-axis represents the scintillation light from the energy deposited by protons from the ^{35}Cl(n,p) reaction and alpha particles and tritons from the ^{6}Li(n,α) reaction. There are two peaks seen at 0.72 MeV and 4.88 MeV, which should theoretically be the kinetic energy of the incoming neutron added to the Q reactions. At lower energies, like 0.1 MeV, neutrons are mainly captured by the ^{6}Li isotope since the capture cross section for ^{35}Cl is very small. However, even though it is almost negligible in comparison, there are still events from this reaction.

The main purpose of using this detector is for fast neutron detection. Due to the large gap of *Q*-value for both reactions, this scintillator can tolerate detecting fairly high energy neutrons without any peak interfering for a wide range of energies. This means that this sensor can detect up to around 4 MeV neutrons without any overlapping of the peaks. This is very useful for fast neutron spectrometry. Particularly, for use in nuclear power plants, where the energy range of neutrons is from thermal to a few MeV. Figure 4 shows the response function for neutrons at 0.1, 0.5, 1, and 1.5 MeV.

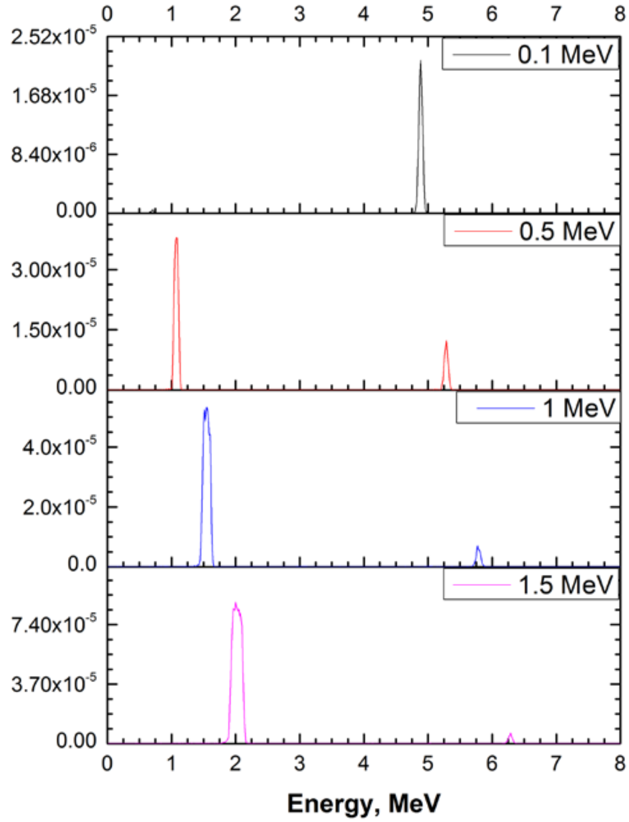

Figure 4: Detector Response Functions to 0.1 MeV, 0.5 MeV, 1 MeV, and 1.5 MeV Neutrons

Both reactions have distinct peaks on the spectra, corresponding to the *Q*-value of the reaction plus the incident neutron energy. Therefore, as energy increases, the peaks of the emitted proton shift proportionally. Even though at some energies, the $^{6}Li(n,\alpha)$ reaction has a higher cross section, due to the greater abundance of ^{35}Cl in the crystal, the $^{35}Cl(n,p)$ reaction rate increases.

4. Conclusion

A Cs_2LiYCl_6 scintillator has been simulated for its use in neutron spectrometry. A Monte Carlo model was developed and irradiated with different energies of neutrons and gamma-rays. Simulated response functions were generated using MCNPX. The response showed that this scintillator has the capability to detect neutrons of low and high energies as well as gamma-rays. Lower energy neutrons are dominated by the reaction of $^{6}Li(n,\alpha)$ and higher energy neutrons are dominated by the reaction of $^{35}Cl(n,p)$. With good resolution, the neutron energy spectrum can be derived.

5. References

[1] C.M. Combes, P. Dorenbos, C. W. E. Van Eijk, K. W. Kramer, and H. U. Gudel, "Optical and scintillation properties of pure and Ce^{3+}-doped Cs_2LiYCl_6 and Li_3YCl_6: Ce^{3+} crystals", Journal of Luminescence, Vol. 82, 1999, pp. 299-305.

[2] Bessiere, P. Dorenbos, C. W. E. Van Eijk, K. W. Kramer, and H. U. Gudel, "New thermal neutron scintillators: Cs_2LiYCl_6: Ce^{3+} and Cs_2LiYBr_6: Ce^{3+}", IEEE Transactions on Nuclear Science, Vol. 51, Iss. 5, 2004, pp. 2970-2972.

[3] Bessiere, P. Dorenbos, C. W. E. Van Eijk, K. W. Kramer, and H. U. Gudel, "Luminescence and scintillation properties of Cs_2LiYCl_6: Ce^{3+} for γ and neutron detection", Nuclear Instruments & Methods in Physics Research A, Vol. 537, 2005, pp. 242-246.

[4] J. Glodo, W. M. Higgins, E. V. D. Van Loef, and K. S. Shah, "Scintillation properties of 1 inch Cs_2LiYCl_6: Ce crystals", IEEE Transactions on Nuclear Science, Vol. 55, Iss.3, 2008, pp. 1206-1209.

[5] W. M. Higgins, J. Glodo, U. Shirwadkar, A. Churilov, E. Van Loef, R. Hawrami, G. Ciampi, C. Hines, and K.S. Shah, "Bridgman growth of Cs_2LiYCl_6: Ce and ^{6}Li-enriched $Cs_2{}^6LiYCl_6$:Ce crystals for high resolution gamma ray and neutron spectrometers", Journal of Crystal Growth, Vol. 312, 2010, pp. 1216-1220.

[6] J. Glodo, E. Van Loef, R. Hawrami, W. M. Higgins, A. Churilov, U. Shirwadkar, and K. S. Shah, "Selected properties of Cs_2LiYCl_6, $Cs_2LiLaCl_6$, and $Cs_2LiLaBr_6$ scintillators", IEEE Transactions on Nuclear Science, Vol. 58, Iss.1, 2011, pp. 333-338.