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Using the Doppler broadened γ line of the $^{10}B(n,\alpha\gamma)^{7}Li$ reaction for thermal neutron detection

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ABSTRACT

When a thermal neutron is absorbed by ^{10}B in the $^{10}B(n,\alpha)^{7}Li$ reaction, there is a chance of 94% that a 478 keV photon be emitted by an excited ^{7}Li nucleus. This reaction is exothermic with a Q-value of 2.31 MeV and the nuclei are emitted with kinetic energies of $E(\alpha)=1.47$ MeV and $E(^{7}Li^{*})=0.84$ MeV. This implies that the 478 keV γ line is emitted by a moving ^{7}Li nucleus and hence is expected to be Doppler broadened. In the present work we suggest to use this broadening of the γ line as a fingerprint for the detection of thermal neutrons using a high resolution gamma spectrometer. We thus developed a Monte Carlo program using a MATLAB code based on a High Purity Germanium (HPGe) detector coupled with a Boron Carbide (B_4C) sheet to calculate the γ line broadening. Our simulation shows that the FWHM width of the resulting γ line is 12.6 keV, in good agreement with our measurement. Hence the broadened γ line emitted by the $^{10}B(n,\alpha\gamma)^{7}Li$ reaction and detected by a HPGe detector shows that this method is an effective tool for neutron detection while maintaining good gamma discrimination.

1. Introduction

High Purity Germanium (HPGe) detectors are considered the gold standard technology for high resolution gamma spectrometry. This is because the average energy required for creating an electron–hole pair is only 2.7 eV, and the resolution is directly related to the number of charge carriers, as expressed by $FWHM \propto N^{-0.5}$ [1], where FWHM is Full width at half maximum and N is the number of counts. As a comparison, the energy required to generate ion pair in air gas filled detectors is about 30 eV, while in scintillator based detectors, the energy to produce a photo-electron is around several hundred eVs [2]. Therefore, the HPGe detector produces a much larger number of charge carriers which results in a detector with higher resolution compared to other technologies [1,3]. Consequently, the excellent energy resolution of FWHM $<1\%$ at 662 keV is highly suitable for identification of gamma emitting isotopes and the quantification of their activity. Despite this advantage for gamma measurement, there is also a requirement for identification and measurements of neutron emitters in several applications, such as waste measurements and decommissioning of nuclear facilities. For neutron measurements, a converting material is required and ^{10}B is considered among the best candidates for thermal neutron detectors and was demonstrated as an efficient converter for coated straw [4], and coated semiconductors [5,6] detectors. In this approach, the incident neutron is absorbed in a converter (e.g. B_4C) and the emitted γ line from the $^{10}B(n,\alpha\gamma)^{7}Li$ reaction is monitored using a HPGE detector. In 94% of n-absorption in ^{10}B, an alpha particle and an excited ^{7}Li nucleus are emitted with kinetic energies of 1.47 MeV and 0.84 MeV respectively. While recoiling with such a kinetic energy, the excited ^{7}Li emits a gamma line at 478 keV which is expected to be Doppler broadened (DB) [7] as compared with other gamma lines of nearby energies and of different origin. This special feature is being used in the present work as a as a tool for thermal neutron detection in conjunction with a HPGe detector. In this suggested method, high intrinsic efficiency is maintained while improving gamma discrimination. This is accomplished by an evaluation of FWHM of the measured spectra and discrimination of un-broadened γ lines. A Previous work, mentions the identification of the broadened 478 keV for analysis of boron amounts in various compounds [8]; yet, in this study we suggest the use of the same phenomenon for neutron emitting isotopes identification. Note that the stopping power for each particle in B_4C is relatively high; hence, their penetration through the coating is limited to only a few microns [9]. This limitation of the coating thickness, drastically reduces the efficiency of the detector. In our pervious study [10], we overcome the coating thickness limitation by suggesting to detect the

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478 keV γ line while using a natural Boron neutron converter coupled with a scintillation detector, thus improving the intrinsic efficiency for neutron detection. However, an additional gamma compensation detector for gamma discrimination was required.

2. Modeling and experimental methods

In order to examine the validity of the suggested neutron detection method, a mathematical Monte Carlo (MC) model based on the properties of a High Purity Germanium (HPGe) detector coupled with a Boron Carbide (B_4C) as a neutron-gamma converter was developed. We simulated the Doppler broadening effect and the response of the detector. The measured results were found to be in good agreement with that of the present simulation.

2.1. Monte-Carlo code for DB

In order to evaluate the response of the detector to an incoming γ line of well-defined energy, a MATLAB code was developed. This model takes into account the parameters of the specific detector used in our study. We assume that the response of the Multi-Channel Analyzer (MCA), coupled to a HPGe detector, to an un-broadened γ line, is a Gaussian of the form.

$$f(E) = Ce^{-\left(\frac{E-E_0}{A}\right)^2} \quad (1)$$

where C and A are constants related to the normalization and width respectively of the Gaussian function, and E_0 is the peak energy of the incident γ line. The factors C and A were calculated as described in ref. [11].

Each $^{10}B(n,\alpha\gamma)^7Li$ interaction in the model produces the emitted gamma energy with a slight shift from the expected 478 keV and with different probability. This shift depends on several random parameters which were taken into account in the MC model. The random numbers which affect the stochastic nature of the DB are described below.

The energy shift $\Delta E[n]$ is calculated as follows:

$$\Delta E[n] = \frac{E_{\gamma 0} \cdot v_o \cdot u[n] \cdot e^{-D \cdot t[n]}}{c} \quad (2)$$

where, n is the index of the MC histories run (number of photons), $E_{\gamma 0}$ is a constant (un-shifted γ energy) with a value of 478 keV, c is the speed of light, $u[n]$ is a uniformly distributed random number in the range of -1 and to 1, and v_0 is the initial velocity of the Li nucleus derived from its mass (6.94 amu) and initial energy (0.84 MeV), as given in Eq. (3):

$$v_o = \sqrt{\frac{2E_{Li}}{m_{Li}}} \approx 4.83 \cdot 10^6 \frac{m}{s} \quad (3)$$

$D = 2.147 \pm 0.016\ \text{ps}^{-1}$ is the degradation constant as given in ref. [12] and $t[n]$ is the decay time of the Li^* nucleus. The decay time is calculated as an exponentially distributed random number with a mean of 0.105 ps as discussed in ref. [12]. The product of $v_0 \cdot u[n]$ in Eq. (2) simulates the uniform distribution of the initial velocity (and direction) according to [13]. In the MC code, we considered $D = 2.147\ \text{ps}^{-1}$ as a constant parameter. Therefore, the shifted gamma energy $E_0[n]$ is the sum of the initial energy $E_{\gamma 0}$ with the energy shift ΔE[n] as follows:

$$E_0[n] = E_{\gamma 0} + \Delta E[n] \quad (4)$$

According to Eq. (4), the range of E_0 [n] values is between 470.4 keV and 485.6 keV, when $(\Delta E_{max} = \pm 7.6 keV)$. Finally, in order to simulate the γ line shape in every MC run, a single energy line response to a shifted photon is simulated according to Eq. (1). However, the function which will illustrate the line shape after N photons is the sum of all generated Gaussians (neglecting pile-up), as presented in Eq. (5).

$$f(E, N) = \sum_{n=1}^{N} Ce^{-\left(\frac{E-E_0[n]}{A}\right)^2} \quad (5)$$

2.2. FWHM of the broadened line

As mentioned above, in our model, the neutron identification relies on the ability to distinguish the broadened photo-peak at 478 keV from other photo-peaks of nearby energies. The expected FWHM for the un-broadened 478 keV line is 1.3 keV, however, the FWHM of broadened peak in the detector is evolved as follow: the first photon generates a single un-broadened peak, the second photon has a different energy and therefore broadens it, followed by the third and fourth photons which further broaden the peak, etc. The FWHM of the broadened peak at the end of the MC run was found to be 12.6 keV. This calculation leads to: (a) the maximum expected FWHM value of the broadened peak; (b) an estimate of the total number of photons necessary to build up the broadening (see Section 3.1 below).

2.3. Experimental setup

The experimental setup includes the following components: a coaxial HPGe detector with dimensions of 56 mm diameter and 44.8 mm high, a ^{252}Cf neutron source and a natural B_4C sputtering target (5.08 mm diameter and 0.32 mm thick) of 99.5% purity, supplied by RHP Technology GmbH. For neutron moderation, we used a polypropylene (PP) platform 6 cm thick, placed between the HPGe detector and the ^{252}Cf source. Energy calibration and detector resolution was measured using ^{137}Cs and ^{133}Ba sources. The results are given in Table 1.

The energy calibration data of Table 1 was fit by the following polynomial:

$$E[keV] = -3.144 \cdot 10^{-8} \cdot CH^2 + 4.8115 \cdot 10^{-1} \cdot CH + 2.3349 \quad (6)$$

Assuming that the FWHM peak behavior is the same as in Ref. [14], namely:

$$FWHM[keV] = a + b\sqrt{E + cE^2} \quad (7)$$

and using the data of Table 1 and Eq. (7), the FWHM calibration curve may be written as:

$$FWHM[keV] = -0.8751 + 0.1262\sqrt{E + -6.9514 \cdot 10^{-4} E^2} \quad (8)$$

Eq. (8), shows that the expected FWHM for a 478 keV γ line is 1.38 keV. Similar FWHM values are expected for γ lines at 470.4 keV and 485.6 keV. In order to study the contribution of the B_4C converter we measured two spectra: In the first we used a neutron source and a moderator placed in front of the HPGe detector and in the second, the B_4C neutron converter was added. Each experiment was run for 4 h, under the same conditions and same background.

Table 1
Meaured FWHM and energy calibration of the HPGe detector.

Peak Number	Channel	E [keV]	FWHM [keV]
1	735	356	1.19
2	791	383	1.24
3	163	81	1.07
4	1371	662	1.51