CALIBRATION TECHNIQUE FOR STILBENE-BASED NEUTRON DETECTOR

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Abstract – Fast neutron detection requires application of the detector material that is rich in hydrogen with a sufficient level of detection efficiency and the capability to discriminate neutron signals in the presence of undesirable gamma-ray background. In this work, we evaluated the performance of neutron modules with the measurement of gamma-sources. In particular, the light yield of the detectors was calibrated with a set of standard ^{22}Na, ^{137}Cs and ^{241}Am sources by the use of Compton Edge technique. In the meanwhile, the time resolution was estimated by measuring gamma-gamma coincidences with ^{60}Co source.

INTRODUCTION

Most detectors used in experimental nuclear physics are based on the detection of charged particles through ionization when they interact with the detector material. Neutrons do not produce direct ionization and can be registered through the ionization of secondary charged particles - products of the interaction of neutrons with the detector material. With relatively high efficiency, registration of neutrons in the energy range from $0.1 < E_n < 10$ MeV occurs through their scattering in hydrogen-containing materials with subsequent registration of recoil protons. For this reason, solid or liquid hydrogen-containing scintillators are widely used as the basis for neutron detectors. At the ACCULINNA-2 separator [1] in the Flerov Laboratory of Nuclear Reactions, the organic scintillator stilbene was chosen as the basis, which has a number of advantages and meets the requirements, such as: fast timing response, high light yield, excellent pulse shape discrimination ability for separation of neutrons from gamma-rays, acceptable registration efficiency and flexibility of the array consisting of individual modules.

This work is devoted to the development and study of the characteristics of the neutron detector array modules in terms of amplitude and time resolution. Measurements were performed with gamma sources (^{22}Na, ^{137}Cs, ^{241}Am and ^{60}Co). The processes of neutron interaction with stilbene were simulated using the GEANT4 toolkit.

A NEUTRON DETECTOR BASED ON STILBENE CRYSTALS

Currently, the neutron detector array consists of 48 modules [2]. Each module consists of a single crystal of stilbene ($C_{14}H_{12}$) read by a photomultiplier tube encapsulated in a steel housing. The scintillator is shaped as a cylinder with a diameter of 80 mm and a thickness of 50 mm and is packaged in an aluminum shell with an end glass window for optical readout. To improve light collection, the free faces of the crystal are coated with magnesium oxide (MgO) - an absolute reflector with a reflectivity equal to unity in a wide spectral band. The signals are read out by a fast 3-inch photomultiplier tube with a specially designed voltage divider. The components of a single stilbene module are shown in Fig. 1a. The ET-Enterprise 9822B photomultiplier tube was chosen because it has a good single-electron response, high pulsed linearity and fast rise time (~2.1 ns). Figure 1b shows the experiment configuration of the three stilbene detectors for the measurement of time resolution with ^{60}Co source.

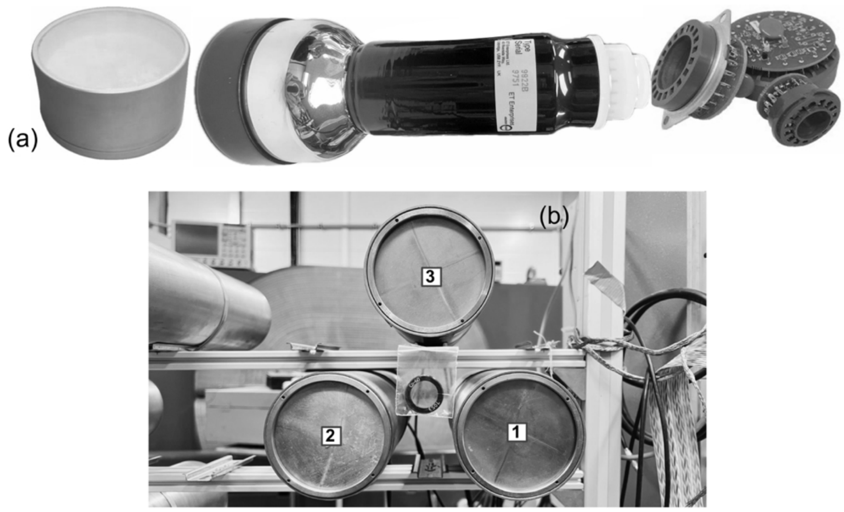

Fig. 1. a) A single detector module comprises a stilbene crystal, ET-Enterprise 9822B PMT and voltage divider. b) The configuration of the three detectors for time measurement with ^{60}Co source.

AMPLITUDE CALIBRATION

We used a set of standard gamma-radiation sources, such as ^{22}Na, ^{137}Cs, ^{241}Am and ^{60}Co for the purpose of amplitude calibration. Due to the low atomic number of organic scintillators, the probability of photopeak effect is significantly less than Compton scattering process at the energy of gamma-quanta more than 100 keV. The observed spectrum is formed owing to ionization by recoil electrons from Compton scattering, hence this spectrum is characterized by the sharp cut-off at maximal energy (so called Compton Edge, CE). Numerous studies have noted a linear dependence of the light output on electron energy for wide-ranging scintillators, thus we utilized these spectra for our detector amplitude calibration.

Apparently, the finite amplitude resolution causes problems for positional accuracy of CE, relying on measured spectra analysis, and there are several applicable methods proposed for different CE positions at 66% [3], 70% [4] or 85% [5] from the maximum count in the spectrum. In the present work, we leveraged the first derivative method [6] combined with Monte Carlo (MC) simulation in the GEANT4 toolkit for precise CE determination. Figure 2a depicts the measured spectrum from a ^{22}Na source at a distance of 10 cm, where the calculated first derivative is shown by a solid gray line, and its minimum value was credited as a CE position with a dashed line.

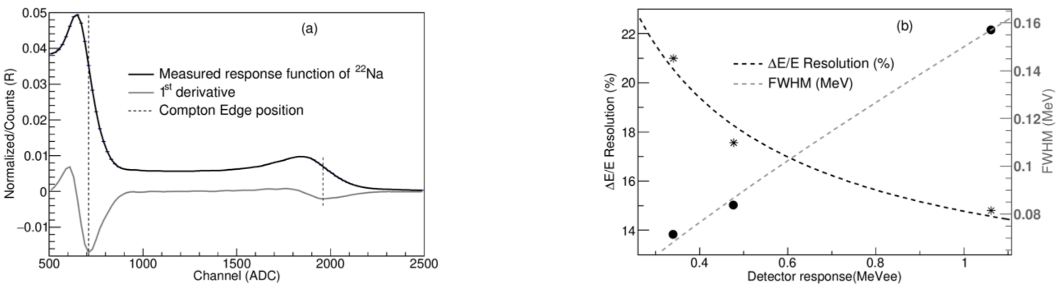

Fig. 2. a) The measured response functions of stilbene from the ^{22}Na source and its calculated first derivative. b) The amplitude dependent resolution (FWHM) in the detector.

Defining the CE position is not only to calibrate the detector response but also to specify its resolution at that given energy. Obviously, the most responsive area of instrumental energy resolution is the slope of CE to the right in the gamma-spectra. The detector response as a function of energy resolution is shown in Fig. 2b.

Evidently, one can notice a slight difference in the CE positions between GEANT4 calculations and first derivative methods, as shown in Fig. 3. The amplitude calibration procedure based on GEANT4 simulation always produces the correct CE positions (the sharp cut-off at maximal energy). Whereas the first derivative method is preferably applicable with a large number of detectors since it is easy and time-effective. All measured spectra demonstrate an agreement with GEANT4 simulations in the CE region with a very small different between the two methods.

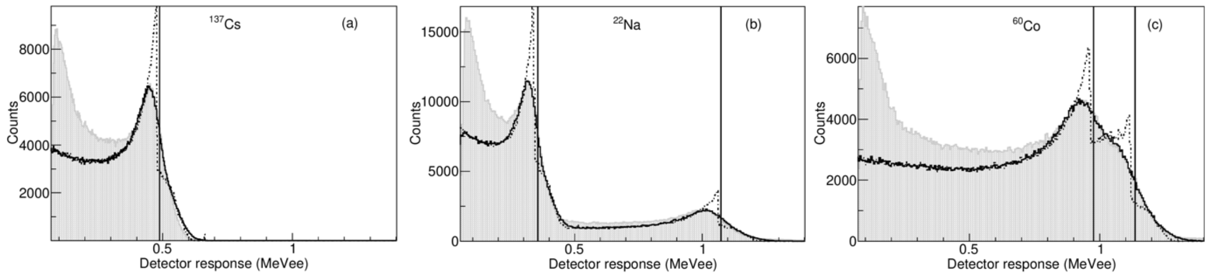

Fig. 3. The simulated and measured response functions of ^{137}Cs, ^{22}Na and ^{60}Co γ-sources in the stilbene detector. The measured data is presented in hatch-filled histograms, while the GEANT4 calculation of energy deposited are shown with dash-lines and black lines shows the same but with instrumental energy resolution is taken into account. The vertical line represents the Compton edge positions defined with the first derivative method.

However, there is a noticeable difference in the lower energy being attributed by multiple scattering and strongly reliant on surrounding materials that was not included in the simulations. Our main interest is to localize precisely the CE position for amplitude calibration, thus the low energy region is not taken into account for data analysis in this work.

TIME RESOLUTION

The ^{60}Co source was used to measure time resolution of the neutron detector array in the gamma-gamma coincidence setup. Due to the large spin of the ground state of ^{60}Co, the main branch of β-decay leads to the population of the excited state of ^{60}Ni with subsequent emission of a cascade of two gamma quanta. The measurements employed three detection modules, where the data acquisition system was triggered with either a signal from any module or a coincidence signal from any two modules. A short run was performed with trigger multiplicity that equals 1 to calibrate the amplitude signals as described in the previous section. A long run was conducted with a multiplicity of more than 1 to collect sufficient statistics for event coincidence analysis. The amplitude of all modules along with the time difference of coincidence signals were recorded event-by-event. To generate time signals, the constant fraction mode of the MCFD-16 discriminator was utilized.

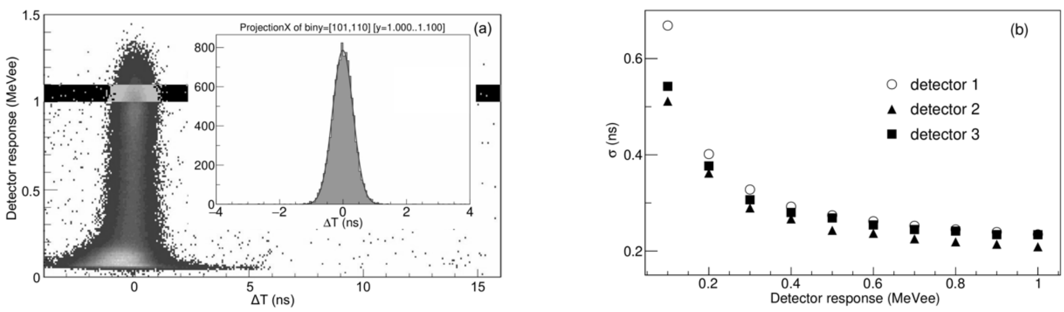

Fig. 4. a) The two-dimensional spectrum of time difference in both modules (detector 1 and 2) at the amplitude signal in detector 1 exceeds 1 MeVee. b) The dependence of time resolution on pulse amplitude for each detector in the energy range 0.1 - 1.0 MeVee.

Figure 4a shows a two-dimensional spectrum of the time difference between signals in both modules (detector 1 and 2) depending on the amplitude signal in detector 2, provided that the amplitude signal in detector 1 exceeds 1 MeVee. In particular, the inset in Fig. 4a displays the projection of time difference for the amplitude signals for the one module in the range of 0.95 - 1.05 MeVee fitted by Gaussian distribution. Apparently, the width of time difference relies on the amplitude signals in both modules and can be defined as

$$(\sigma_{jk}^{exp})^2 = \sigma_j^2 + \sigma_k^2,$$

where σ_{jk}^{exp} is the width of the observed time distribution at given amplitudes in two detectors; and σ_j, σ_k are the time resolution of detectors j, k, respectively.

The distribution width slightly depends on the amplitude in the energy range greater than 1.0 MeVee. Since we have three detectors, i.e. three combinations of double coincidences, we can estimate the resolution of each module by solving a set of linear equations. As a result, for amplitudes exceeding 1 MeVee we obtained a time resolution σ = 225, 205, 227 picoseconds for detector 1, 2, 3, respectively. Figure 4b reveals the dependence of walk time on pulse amplitude of each individual module and one can use this correlation to study the amplitude-dependent resolution. These results are consistent with previous study [2] where the amplitude and timing properties of two different stilbene modules were assumed to be equal and independent.

CONCLUSIONS

The parameters of the neutron detector modules of the ACCULINNA-2 setup were measured in this work. Amplitude calibration and time resolution measurements of the neutron detectors were carried out by analyzing the amplitude spectra using the first derivative and GEANT4 simulation results. We demonstrated that by applying the first derivative method one could accurately determine the CE position, which is crucial for calibration purposes. To determine the time resolution and walk depending as a function of pulse amplitude, the measurements were carried out using three detection modules. The time resolution was σ = 225, 205, 227 picoseconds at the amplitude of 1.0 MeVee for each detector, respectively. With such timing characteristics, our stilbene scintillators are fast enough for neutron energy measurements by using time of flight technique and become advantageous for our study of resonance states of various neutron-rich nuclei like $^{5-7}$H, ^{7,9}He, ^{10}Li, etc. The latest results of the ^{7}He population [7] have demonstrated that neutron detection significantly improved the overall experimental resolution.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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