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A capture-gated neutron spectrometer for characterization of neutron sources and their shields

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ABSTRACT

A portable capture-gated neutron spectrometer was designed and built. The spectrometer consists of a boron-loaded scintillator. Data acquisition is performed in list-mode. ^{252}Cf and AmBe sources and various neutron and gamma shields were used to characterize the response of the device. It is shown that both the unfolded capture-gated neutron spectrum and the singles spectrum up to 5 MeV should be utilized. Source identification is then possible and important information is revealed regarding the surroundings of the source. The detector's discrimination of neutrons from photons is relatively good; specifically, one out of 10^5 photons is misclassified as a neutron and, more importantly, this misclassification rate can be calculated precisely for different measurement environments and can be taken into account in setting alarm limits for neutron detection. The source and source shield identification capabilities of the detector make it an interesting asset for security applications.

1. Introduction

Neutron detection is an important part of radiation detection in border control and other in-field security-related operations. Characterizing the neutron source and the source shield facilitates correct countermeasures. For instance, identifying the presence of a neutron shield facilitates source activity estimation. Information on the energy of neutrons can be used for source identification, since neutron sources emit fast neutrons with relatively distinct energy spectra. One method for fast neutron detection is to detect recoil protons in a hydrogen-containing scintillator. Neutrons incident on the scintillator transfer part of their energy to the medium (zero to full energy) primarily via elastic scatterings with hydrogen. The scintillation pulses caused by the recoil protons can be discriminated from gamma pulses with pulse shape discrimination [1,2] or by using a neutron capture reaction producing a distinct pulse as a trigger (or gating) event [3]. The former requires fast signal processing. The latter can be performed, for example, with boron-loaded or boron-coated scintillators.

In this work, a portable capture-gated neutron spectrometer was assembled and studied. The sensitive volume is a boron loaded plastic scintillator. The research objectives were to examine the detector's response with different neutron sources and source shields. Recoil proton spectrometry has certain challenges caused by the nonlinear light output and the stochastic nature of the neutron scattering reactions, producing protons of different energies (as well as heavier ions) [4]. In [2] it was demonstrated that neutron source identification is possible by direct analysis of the neutron pulse height spectrum, i.e. without unfolding the spectrum. A rather similar approach concerning the neutron pulse height spectrum was taken in the present study. However, the present study uses the high-energy (>3.5 MeV) singles spectrum, capture-gated spectrum and neutron capture peak separately and together to extract more information from the data. High-energy (>3.5 MeV) photons in the singles spectrum provide important supplementary information to detect a neutron source and to characterize its properties [5]. To the authors' knowledge, combining these signals to obtain quantitative indicators for source and source shield characterization is a novel approach.

In the present work, ^{252}Cf and AmBe sources were measured to demonstrate discrimination between fission and Be-based neutron sources. Both source types are used in industrial applications and illicit use of them is thus possible. Because of its use in nuclear weapons, plutonium is often considered the most important neutron emitter in security applications. Both the neutron spectra and high-energy (>3.5 MeV) gamma spectra of ^{239}Pu and ^{252}Cf are very similar (see [6] for gamma spectra and [7] for distribution parameters of neutron spectra). ^{252}Cf was thus considered a good substitute for ^{239}Pu in the present measurements. Neutron and gamma shields were applied between the source and detector to

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demonstrate that source identification is possible and that the source's shielding, if any, can be characterized as well.

2. Experimental procedure

The assembled measurement system consists of a cylindrical 7.6 cm × 7.6 cm borated plastic scintillator (EJ254 with 5% natural boron by weight, Eljen Technology) coupled to a photomultiplier (Scionix ETL 9305) and a Canberra Osprey digital MCA. The device is shown in Fig. 1. The neutron capture reaction ^{10}B (n,αγ) ^{7}Li has a Q value of 2.79 MeV. The alpha and lithium particles obtain on average 2.34 MeV, which according to the manufacturer produces a capture pulse with an energy of 76 keVee (keV electron equivalent). The photon has an energy of 478 keV (yield 94%) and often escapes the detector without interaction (the mean free path of a 478 keV photon is ca 7.2 cm in EJ-254). List-mode data acquisition was performed with software developed at STUK. The 2048 channel Osprey MCA provides a timestamp resolution of 100 ns and has an ADC sampling rate of 20 MHz. Using minimal pulse shaping parameters (rise time 200 ns and flat top time 100 ns), a dead time of approximately 500 ns was observed after a detected pulse. This is shorter than the average lifetime (ca 1.6 μs) of a thermal neutron in the detector. The gain was set to its minimum value, 1, to obtain a wide energy range (up to 5.2 MeV with 660 V bias). Coincidence analysis was performed after measurements with in-house interactive software known as Liisteri.

The neutron sources used are characterized in Table 1. Nominal neutron fluxes were used in the detector performance calculations. Neutron scattering from the laboratory walls and deviations from the nominal fluxes (because of Cf isotopic composition [8], for instance) were not taken into account.

Gamma and neutron shields were placed around the sources and detector to test their impact on the measurement system. The shields are described in Table 2. The source–detector distance (SDD) was defined as the horizontal distance from the center of the source to the front surface of the detector. All measurements were performed with an SDD of 1 m. With unshielded sources, the height h of the source and detector above floor level was 1 m; however, the source shields were not lifted from floor level,

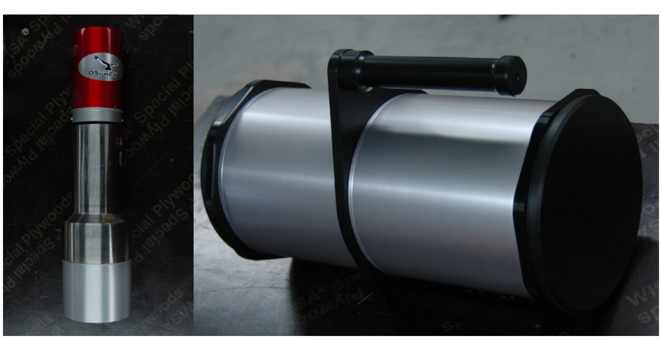

Fig. 1. Borated plastic scintillator (76 mm × 76 mm) coupled to a photomultiplier and a digital MCA (left). Detector in the final lead shield package (right). The lead shield covers the scintillator and is 23 mm thick on the side, 10 mm thick in the front, and extends 5.4 cm behind the scintillator.

Table 1
Neutron sources and emission rates *F*.

Source (Activity)	*F* [10^6 neutrons/s]
Cf (20 MBq)	2.3
AmBe (11 GBq)	0.8
AmBe (175 GBq)	14

Table 2
Detector shields (DS) and source shields (SS) used.

Shield	Description
DS1	1 mm thick Pb covering only the scintillator sides and the front
DS2	12 mm thick Pb on the front side; 26 mm Pb covering the side, extending 6 cm behind the scintillator
SS1	Wall thickness 23 cm PE (rectangular cross-section)
SS2	Wall thickness 50 cm borated PE (cylindrical)
SS3	Wall thickness 3.8 mm Pb (cylindrical)
SS4	Wall thickness 10 cm Pb (cylindrical)

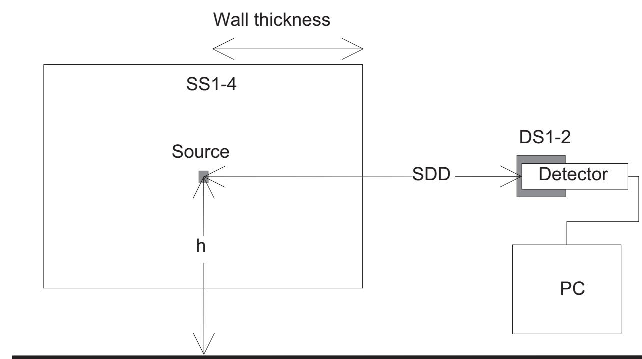

Fig. 2. Measurement geometry.

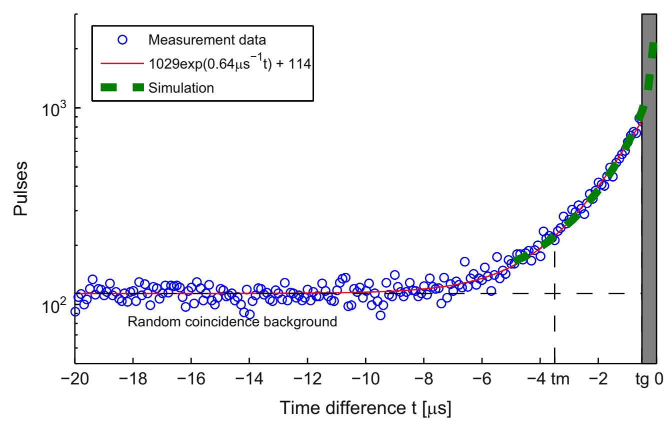

Fig. 3. Scattering and capture pulse time difference distribution measured with the ^{252}Cf source at SDD of 1 m. The measurement was performed without detector or source shields. The dashed straight lines illustrate the time trigger window limit t_m and random coincidence background. The gray box represents the dead time of the detector (500 ns). The MCNPX simulation result was shifted by adding the constant background level to the simulation to illustrate the almost equal slope of the simulation and measurement.

i.e., they were nearer the floor (SS1: $h \approx 57$ cm, SS2: $h \approx 44$ cm, and SS4: $h \approx 21$ cm). The measurement geometry is shown in Fig. 2.

3. Results

3.1. Time difference distribution

Fig. 3 shows the histogram of the time difference between the capture and scattering pulses measured with an unshielded ^{252}Cf source at SDD = 1 m. No detector shield was used. The measurements were compared to simulations performed with MCNPX version 2.6f [9] with a monodirectional plane source of 1 MeV neutrons covering the front side of a 7.6 cm × 7.6 cm EJ-254 scintillator. Both the simulated and measured time difference