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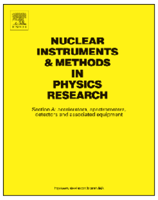

A first comparison of the responses of a ^{4}He-based fast-neutron detector and a NE-213 liquid-scintillator reference detector

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ABSTRACT

A first comparison has been made between the pulse-shape discrimination characteristics of a novel ^{4}He-based pressurized scintillation detector and a NE-213 liquid-scintillator reference detector using an Am/Be mixed-field neutron and gamma-ray source and a high-resolution scintillation-pulse digitizer. In particular, the capabilities of the two fast neutron detectors to discriminate between neutrons and gamma-rays were investigated. The NE-213 liquid-scintillator reference cell produced a wide range of scintillation-light yields in response to the gamma-ray field of the source. In stark contrast, due to the size and pressure of the ^{4}He gas volume, the ^{4}He-based detector registered a maximum scintillation-light yield of 750 keV$_{ee}$ to the same gamma-ray field. Pulse-shape discrimination for particles with scintillation-light yields of more than 750 keV$_{ee}$ was excellent in the case of the ^{4}He-based detector. Above 750 keV$_{ee}$ its signal was unambiguously neutron, enabling particle identification based entirely upon the amount of scintillation light produced.

1. Introduction

Fast neutrons are important both as probes of matter and as diagnostic tools [1–14]. In the case that information about the energy and emission time of a neutron is available, conclusions about its origin can be drawn. The timing precision required to obtain this information may only be provided by neutron detectors that are fast, providing signals with short risetimes. Today, organic liquid scintillators are the detectors-of-choice for fast neutrons. Drawbacks associated with these scintillators are their toxicity, reactive nature, and sensitivity to a broad range of gamma-ray energies.

Scintillators are substances which emit light when subjected to ionizing radiation. The characteristic time constant associated with the light emitted is a function of the properties of the scintillator in question. Certain scintillators respond to different types of ionizing radiation differently; that is, the time constant of the emitted light is different depending upon the density of ionization produced by the incident radiation. Normally, there are several components with different time constants. The relative intensity of these components affects the effective integrated time constant. By carefully analyzing the behavior of the scintillation light as a function of time, one can determine the incident particle type. This procedure is called pulse-shape discrimination (PSD). PSD is often used to distinguish between different types of uncharged particles, namely gamma-rays and neutrons. In scintillators with good PSD properties, incident gamma-rays interact primarily with the atomic electrons of the scintillator, producing close to minimum-ionizing electrons which give a fast (decay times of some 10 s of ns) flash of light. On the other hand, incident neutrons interact primarily with the hydrogen in liquid scintillators and ^{4}He nuclei in noble-gas scintillators via scattering, transferring some of their energy. For hydrogen, this energy transfer can be 100%, while for ^{4}He, the energy transfer is at best 64%. The resulting flashes of light arising from the much denser ionization produced by the relatively large energy loss of the recoiling protons and alpha particles have longer decay times (100–1000 s of ns). PSD

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and thus incident particle identification may be performed by recording the time dependence of the scintillation pulse form and comparing the fast and slow components.

2. ^{4}He as a scintillation medium for fast neutron detection

The development of both liquid and gaseous ^{4}He based scintillators for fast-neutron detection has been reported [6,8,12,14,15]. ^{4}He, like most noble gases, is a good scintillator. It has an ultra-violet light yield comparable to the intrinsic non-Tl doped light yield of NaI crystals [16–19]. Neutron interactions lead to ^{4}He recoils, where energy is deposited very locally within the gas. Gamma-ray interactions lead to recoiling electrons, which deposit only tens of keV per centimeter of trajectory. This difference in deposition density and therefore ionization density is believed to ultimately enable the PSD capability. PSD properties may be degraded significantly if the geometry and size of the detector results in a smearing of the transit times of scintillation photons comparable to the scintillation decay times. Good PSD also requires good scintillation efficiency; that is, a sufficient number of scintillation photons to define the time dependence of the pulse accurately, and low noise in the pulse-processing electronics.

With only two electrons per atom, ^{4}He has a very low charge density, thereby significantly limiting its sensitivity to gamma-rays. This is useful for fast-neutron detection, where insufficient gamma-ray rejection is often the factor which constrains the desired performance. The following physical effects contribute positively to the gamma-ray rejection performance of pressurized ^{4}He gas:

1. *Low gamma-ray interaction probability.* Due to the low electron density of ^{4}He, gamma-ray interaction probabilities are two orders of magnitude lower than neutron interaction probabilities.
2. *Low energy deposition.* Depending on the chosen geometry (i.e. a tube with radius of a few cm), the amount of energy the gamma-rays can deposit in the detector volume is limited. This is because the corresponding Compton or pair electrons cannot transfer much energy to the gas before striking a detector wall.
3. *Similar scintillation-light yield for gamma-rays and neutrons.* The scintillation light production in organic liquid scintillators is highly velocity dependent. Thus, for the same amount of deposited energy, gamma-ray interactions produce more scintillation light than neutron interactions. In contrast, the scintillation-light yield for gamma-rays and neutrons is similar in noble-gas scintillators [17] such as ^{4}He. ^{4}He is commonly called a linear scintillator.
4. *PSD.* 1–3 above together with the fast and slow components of the ^{4}He scintillation signals lead to excellent PSD and thus excellent separation of neutrons and gamma-rays.

The purpose of this project was to compare the neutron/gamma discrimination obtained using the Arktis ^{4}He-based neutron-diagnostic tool (NDT) to that obtained using a reference liquid-scintillator cell filled with the organic liquid scintillator NE-213 [20].

3. Apparatus

3.1. Am/Be source

The detector characterizations reported on in this paper were carried out using a nominal 18.5 GBq ^{241}Am/^{9}Be (Am/Be) source [21] which emitted $(1.106 \pm 0.015) \times 10^6$ neutrons per second nearly isotropically [22]. The source is a mixture of americium oxide and beryllium metal contained in an X.3 capsule, which is a stainless-steel cylinder 31 mm (height) × 22.4 mm (diameter) [23]. ^{241}Am has a half-life of 432.2 years and decays via alpha emission (5 discrete energies with an average value of about 5.5 MeV) to ^{237}Np. The dominant energy of the gamma-rays associated with the decay of the intermediate excited states in ^{237}Np is ~60 keV. A 3 mm thick Pb sheet was used to complement the stainless steel X.3 capsule to attenuate these 60 keV gamma-rays. The half-value layer for Pb for 60 keV gamma-rays is 0.12 mm, while for 1 MeV gamma-rays, it is 8 mm. Neutrons are produced when the emitted alpha particles undergo a nuclear reaction with ^{9}Be resulting in ^{12}C and a free neutron. The resulting neutron distribution has a maximum energy of about 11 MeV [24], while approximately 25% of the neutrons have an energy of less than 1 MeV [25]. The de-excitation of the ^{12}C results in a 4.44 MeV gamma-ray about 55% of the time [25–27]. This gamma-ray is too energetic to be absorbed by the stainless steel of the X.3 capsule. Thus the radiation field from the Am/Be is a combination of high-energy gamma-rays and fast neutrons. Both the gamma-ray and fast-neutron dose rates at a distance of 1 m from the source in the unshielded X.3 capsule were measured using a Thermo Scientific Corporation FHT 752 dosimetric neutron detector [28]. They were both determined to be 11 μSv/h for a total unshielded dose rate of 22 μSv/h, in exact agreement with the data sheet from the supplier.

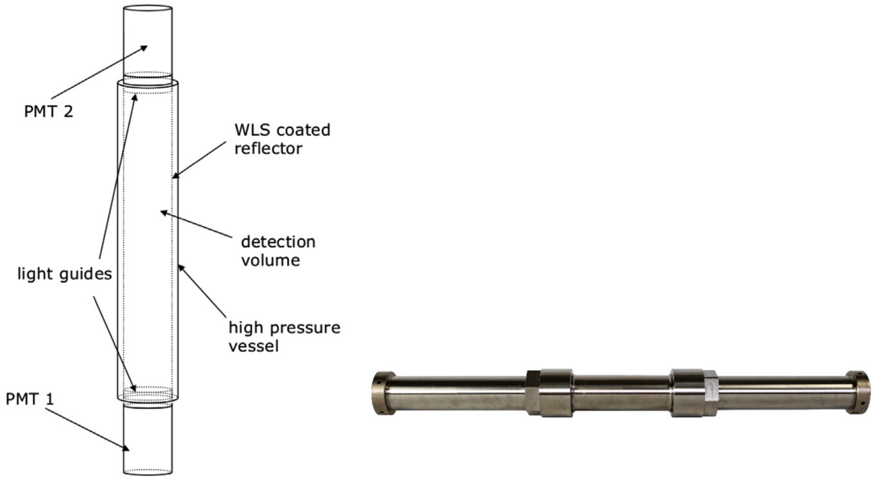

Fig. 1. Schematic (left) and photograph (right) of the pressurized ^{4}He gas fast-neutron detector. The outer diameter was 5.08 cm (2 in.) and the active length was 19.5 cm.