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Digital discrimination of neutrons and γ-rays in liquid scintillators using pulse gradient analysis

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Abstract

A method for the digital discrimination of neutrons and γ-rays in mixed radiation fields is described. Pulses in the time domain, arising from the interaction of photons and neutrons in a liquid scintillator, have been produced using an accepted empirical model and from experimental measurements with an americium–beryllium source. Neutrons and γ-rays have been successfully discriminated in both of these data sets in the digital domain. The digital discrimination method described in this paper is simple and exploits samples early in the life of the pulse. It is thus compatible with current embedded system technologies, offers a degree of immunity to pulse pile-up and heralds a real-time means for neutron/γ discrimination that is fundamental to many potential industrial applications.

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1. Introduction

The disintegration of an atomic nucleus can result in a plurality of emitted radiations, often including neutrons and γ-ray photons. Whilst these components of mixed radiation fields interact with matter via fundamentally different mechanisms, their conversion to light and subsequently to electrical signals via scintillation detectors results in signals that are intrinsically similar and difficult to discriminate by any trivial means. The discrimination of neutrons and γ-ray photons is important because the difference in the mechanisms by which they interact with matter is manifest in a difference in the way their energy is deposited in matter. This distinction has important implications where such matter is living tissue, specifically with regard to the measured radiation dose. Moreover, for neutrons in the energy region 1 MeV and above, scintillation detection is a preferred means for neutron field measurement and characterization. Whilst it is common for γ-radiation to be present in the absence of neutron radiation, the converse is rarely possible due to secondary reaction mechanisms associated with neutron scattering in the environment and associated γ decay of the neutron-emitting radioactive isotopes and daughter products. Hence, the discrimination of neutrons and γ-rays in mixed fields can provide invaluable information about the nature of the radioactive substances responsible for such radiation. Most importantly, discrimination can provide insight into the dose associated with mixed fields.

The measurement of neutron dose has long been a requirement of radiation protection. More recently studies have been conducted into the use of neutrons for tomographical imaging [1] for which the measurement and timing of the neutron fluence is frequently a requirement. The use of fast neutrons for this purpose provides a basis for excluding contaminating thermalized neutron components but necessitates the use of organic scintillation detectors. Since organic scintillators are also sensitive to γ-ray photons, it is necessary to discriminate between events in order to select neutron events preferentially. As an added benefit, neutron–γ discrimination allows both the

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neutron and γ components of a field to be recorded simultaneously in a single detector and so avoids scattering from multiple detectors which would perturb the field. With knowledge of both the neutron and γ-ray components it is possible to assess the total dose rate encountered in an environment. The increase in the smuggling of radioactive material requires homeland security operatives to have equipment that can detect this material. The capability to simutaneously detect both the neutron and γ-ray components fulfills this requirement and may identify the smuggled material as fissile or non-fissile.

The efficacy of a given discrimination technique is important if the extent of confusion of events of one type with another is to be understood and thus minimized. However, due to the random nature of radiation it is common for a second event to occur before the output pulse from a previous event has finished. This situation, called pulse pile-up, can cause the energy information in the second pulse to be over-estimated. It may also mean that the discrimination technique cannot identify either pulse and so both pulses must be discarded. A fast discrimination technique (i.e. one that responds to features early in the lifetime of a pulse) is less prone to the effects of pulse pile-up.

The technique presented in this paper exploits the capabilities of fast digital electronics. The objective of this research was to develop a digital technique for the discrimination of neutron and γ-ray events in mixed radiation fields. This work presents a discrimination approach that is computationally simple, since it relies on the normalized amplitude of a single sample early in the decay of the pulse, termed *pulse gradient analysis* (PGA). This technique offers the potential for real-time, digital characterization of environments where neutrons and γ-rays co-exist.

2. Light production in organic scintillators

Plastic and liquid scintillators can be shaped to the size and design of the specific application concerned and therefore rank amongst the most popular detection modalities. The proprietary organic scintillator compounds used in such detectors are synthesized to yield a molecular structure in which unbound π-electrons are prone to excitation by incident radiation. Such excitation can result in the promotion of π-electrons from the ground state (S_0) to one of several excited singlet states (S_1, S_2, S_3, etc.). The eventual decay from such a state results in the emission of a photon which constitutes *fluorescence* and occurs a few nanoseconds after excitation. The intensity, I, of the fluorescence of an organic scintillator decays exponentially and is given by [2]

$$I = I_0 \exp(-t/\tau) \tag{1}$$

where I_0 is the intensity at $t = 0$, and τ is the fluorescence decay time.

An alternative decay path exists whereby an excited π-electron can undergo a spin reversal from the spin 0 singlet state to the spin 1 triplet state. This process is called *inter-system crossing* and involves a radiationless decay as the triplet state is always below the corresponding singlet state. The π-electron may undergo a T_1–S_0 decay with the emission of light with a longer wavelength than fluorescence. This light emission is called *phosphorescence* and has a decay time of 10^{-4} s or longer. The multiplicity selection rule causes the T_1–S_0 decay to be strongly forbidden and the associated phosphorescence is thus very weak compared to fluorescence [3]. Phosphorescence is more predominant in scintillators at low temperature [2].

A π-electron in a T_1 state may gain enough energy to return to this S_1 state. This energy may be thermal or it is possible for two π-electrons in the T_1 state to interact leaving one in the S_0 state and one in the S_1 state with the emission of phonons [3]. The subsequent decay of the S_1 electron emits light called *delayed fluorescence*. This has the same characteristics as the fluorescence described earlier except that the intensity does not decay exponentially. The proportion of delayed fluorescence in a pulse is then related to the triplet density in the wake of the incident particle as there is evidence that the bimolecular reaction rate is related to the square of the triplet density [4]. As the triplet density is determined by the rate of energy loss, $\mathrm{d}E/\mathrm{d}x$, of the incident particle, then the heavier the particle, the greater the energy loss rate and the more delayed fluorescence in the output. Consequently heavier particles will produce more delayed fluorescence and will therefore produce output pulses that decay more slowly then those from lighter particles. This difference between the pulse shapes arising from the interaction of heavy particles in scintillators, as opposed to those from the interaction of light particles and photons, has been exploited in pulse shape discrimination for many years and allows the radiation type to be determined.

The discovery that the decay rate of the light output of an organic scintillator depends on the radiation species causing it has resulted in several schemes for pulse-shape discrimination. The most popular of these are the charge comparison method [5] and the zero crossing method [6,7]. Both of these methods were originally implemented in analogue electronics, often in dedicated instrumentation modules. More recently, both of these methods have since been implemented in the digital domain [8–12] as digital electronic platforms have become available with the requisite speed and cost to make this possible. However, such translations of what are ostensibly analogue methods fail to exploit the intrinsic benefits of the digital domain and rarely result in programme flows that are optimized to ensure speed or efficient use of memory. Related high-density digital devices such as digital signal processors (DSP), field programmable gate arrays (FPGA) and other processors offer the potential for pulse shape discrimination algorithms that afford additional benefits in terms of speed, discrimination quality, and discrimination level