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Dual-particle imaging system based on simultaneous detection of photon and neutron collision events

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ABSTRACT

A dual-particle imaging (DPI) system capable of simultaneously detecting and imaging fast neutrons and photons has been designed and built. Imaging fast neutrons and photons simultaneously is particularly desirable for nuclear nonproliferation and/or safeguards applications because typical sources of interest (special nuclear material) emit both particle types. The DPI system consists of three detection planes: the first two planes consist of organic-liquid scintillators and the third plane consists of NaI(Tl) inorganic scintillators. Pulse shape discrimination technique(s) may be used for the liquid scintillators to differentiate neutron and photon pulses whereas the NaI(Tl) scintillators are highly insensitive to neutrons. A prototype DPI system was set up using a digital data acquisition system as a proof of concept. Initial measurements showed potential for use of the DPI system with special nuclear material. The DPI system has efficiencies of the order of 10^{-4} correlated counts per incident particles for both neutron and photon correlated counts, with simple-backprojection images displaying peaks within a few degrees of the source location. This uncertainty is expected to decrease with more extensive data interpretation.

1. Introduction

A rising concern in our society is ensuring adequate control of special nuclear material (SNM). To monitor the flow of materials of interest, such as undeclared activities involving SNM, extensive research has been conducted on various types of suitable detectors and detection systems. Among those detection systems, photon- and neutron-imaging systems have the advantage of being able to locate a radiation source in complex background environments [1]. Photon imaging has become a commonly used technique for standoff detection of radioactive sources with a particular focus on coded apertures [2]; however, photons can be relatively easily shielded with high-Z material and naturally occurring background radiation is composed primarily of photons. Therefore, neutron imaging has been more extensively researched as a technique to further improve detection of SNM, especially in a strong and/or strongly varying photon-background environment [3,4]. A combination of the photon and neutron imaging systems is particularly appealing as neutron imaging also has some disadvantages: materials usually yield significantly less neutrons than photons, and neutrons can be relatively easily shielded with low-Z material.

In this work, we investigate a transportable dual-particle imaging (DPI) system for imaging SNM and other radiation sources. A vehicle could be used to transport the system to areas of interest where it would then image/localize the source of radiation. The system is capable of imaging neutron and photon sources simultaneously; this capability is particularly appealing for imaging shielded SNM.

2. Imaging-system concept

The DPI system described here uses the concepts of a Compton camera (to image photons) and a neutron-scatter camera (to image fast neutrons) in a single instrument. Whereas other systems able to image photons and fast neutrons have been researched, they have focused only on the use of coded apertures [1].

A Compton camera is based on the Compton-scattering process [5–7]. Specifically, photons are scattered and subsequently absorbed in the position-sensitive detection system. The measured interaction positions and deposited energies are used to localize the origin of the photons: each correct succession of interactions allows creation of a cone of probable source locations. A back-projection image is then obtained by projecting those cones on a sphere surrounding the system. The cone angle is estimated from

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0168-9002/

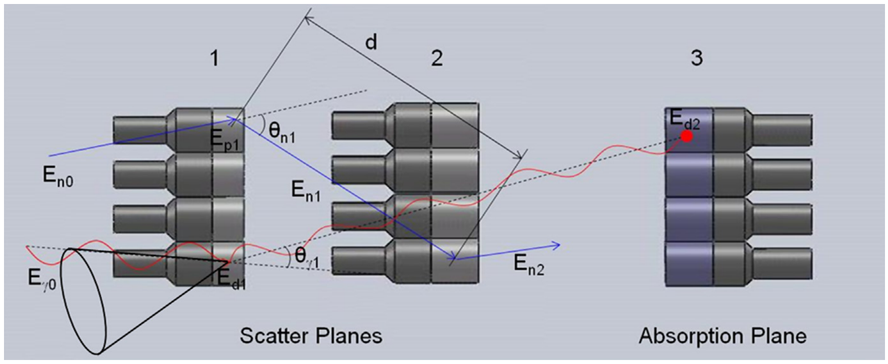

Fig. 1. Schematics of the DPI system, with a photon type 1–3 event and a neutron type 1–2 event depicted, along with the information used for image reconstruction. A backprojection cone is illustrated for the photon event.

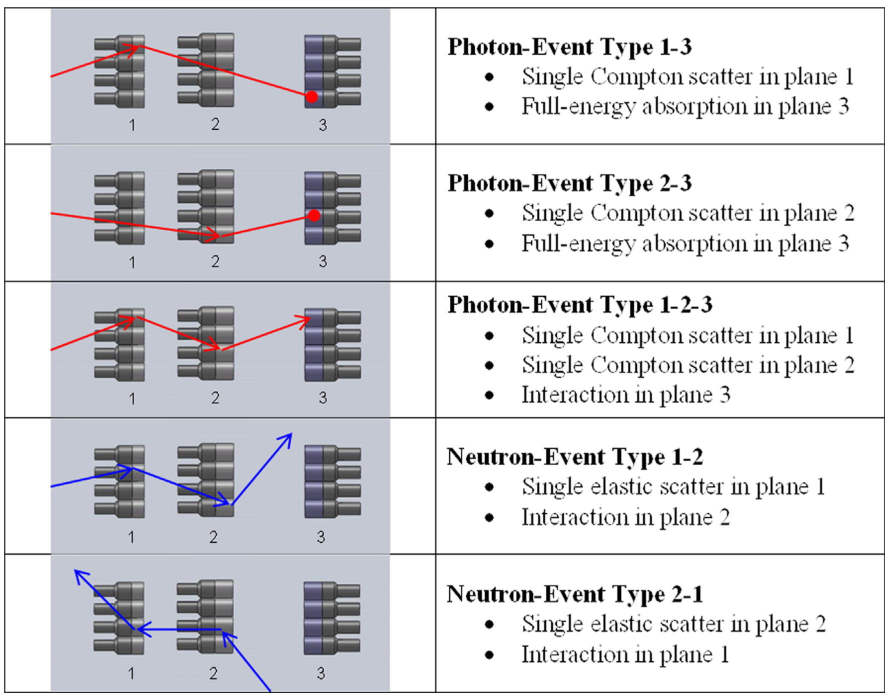

Fig. 2. List of all events measureable with the DPI system.

the energy measurements using the Klein–Nishina formula:

$$\cos\,\theta_{\gamma 1} = 1 - \frac{m_e c^2 E_{d1}}{E_{d2}(E_{d1}+E_{d2})} \tag{1}$$

where $m_e c^2 = 0.511$ MeV, $\theta_{\gamma 1}$ the scattering angle, E_{d1} the energy deposited in the scatter, and E_{d2} is the remaining photon energy after the scatter. The energies and angles are depicted in Fig. 1. The axis of the cone is determined from the interaction locations.

Various Compton-camera designs have been explored in the past, but they all utilize the same underlying physics. Our three-plane imaging system relates closely to two particular designs: two-plane and three-plane Compton cameras. In two-plane Compton cameras, source photons are scattered by the front (scatter) plane into the back (absorption) plane. As a consequence, it is preferred to use a low-Z material in the front-plane detectors, and a high-Z material in the back-plane detectors.

In three-plane Compton cameras, events require source photons to scatter once in each plane [8]. This method has the advantage of not needing absorptions of the particles to find their incoming energy; however, the two required scattering events coupled with another interaction (scatter or absorption) are less likely to be recorded (triple coincidence), especially for low-energy photons. The system efficiency is decreased when the number of coincident interactions is increased. The incoming energy can be calculated using iterations of Eq. (1).

Neutron imaging is based on neutron elastic-scattering physics on hydrogen (proton), which relates the angle of the scatter to the energy of the incoming neutron and the energy of the recoil proton [3]. The equation linking the angle to the energies of the particles is as follows:

$$\cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}} \tag{2}$$

where θ_1 is the scattering angle, E_{n0} is the incoming neutron energy, and E_{n1} is the remaining neutron energy after the scatter. The axis of the cone of probable source locations is given by the interaction positions, while the energy of the neutron after its first scatter is calculated using the time of arrival (time of flight (TOF)):

$$E_{n1} = \frac{m_n}{2} \times \frac{d^2}{\mathrm{TOF}^2} \tag{3}$$