BNL-76974-2006-CP

Analogies between neutron and gamma-ray imaging

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ABSTRACT

Although the physics describing the interactions of neutrons with matter is quite different from that appropriate for hard x-rays and gamma rays, there are a number of similarities that allow analogous instruments to be developed for both types of ionizing radiation. A pinhole camera, for example, requires that the radiation obeys some form of geometrical optics, that a material can be found to absorb some of the radiation, and that a suitable position-sensitive detector can be built to record the spatial distribution of the incident radiation. Such conditions are met for photons and neutrons, even though the materials used are quite different. Neutron analogues of the coded-aperture gamma camera and the Compton camera have been demonstrated. Even though the Compton effect applies only to photons, neutrons undergo proton-recoil scattering that can provide similar directional information. There is also an analogy in the existence of an energy spectrum for the radiation used to produce the images, and which may allow different types of sources to be distinguished from each other and from background.

Keywords: Neutron, gamma, image, camera, coded aperture, Compton, proton-recoil, double-scatter

1. INTRODUCTION

Neutrons are detected only when they interact with nuclei and excite ionized particles, for example by elastic collisions with protons or by nuclear reactions that generate alpha particles. Gamma rays, being energetic photons, interact primarily with the electrons in a material, by the photoelectric effect, Compton scattering or electron-positron pair production. Neutrons interact most effectively with materials of low atomic number, Z, while photons interact more strongly with high Z materials. Although the underlying mechanisms of these interactions are quite different for neutrons and photons, both types of penetrating radiation can be used to form images that can help to locate a lost source and to distinguish a localized bright spot from a uniform background. The designs of practical instruments for forming such images depend on the properties of very different materials, but can have basic geometrical features that are common to both neutrons and gammas, simply because the radiation travels in straight lines until it is absorbed or scattered. The analogy can be extended to describe two classes of imaging devices – cameras that rely on near-total absorption of the radiation by a material forming an aperture, and those that rely on two or more scattering events that are kinematically related to the incident direction of the radiation. Absorption is more effective for low energies, while scattering is more applicable at high energies. Energetic photon imaging devices can have several different applications, including astrophysics, medicine, industrial radiography, nuclear nonproliferation and counterterrorism. Neutron imaging can also be applied to many of the same problems, providing complementary information. This paper focuses on the problem of finding radiation sources in unknown locations, using passive stand-off detection, where the most important parameters are absolute sensitivity to weak sources and rejection of background. Spatial and angular resolution are not as crucial for our purposes as they are for medical imaging. Scalability to large areas is important for achieving maximum sensitivity. We will not discuss the obvious parallel between x-ray and neutron transmission radiographies, in which a collimated source is used to irradiate an object that casts its shadow onto a detector screen.

2. THE PINHOLE CAMERA AND THE CODED APERTURE

The essential components of a simple pinhole camera are an enclosure that excludes the radiation of interest and a 2-dimensional position-sensitive detector. A small aperture in the enclosure then admits a fraction of the incident radiation and projects an inverted image of the scene on the detection plane. This geometry can be used successfully for optical photons, x rays, gamma rays and neutrons. The main drawback is that the absolute sensitivity is limited by the

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area of the aperture, and the spatial resolution becomes worse as the aperture is increased. So a single pinhole is mainly useful in high flux environments. Another limitation is imposed by the transmission of high energy radiation through the enclosure and the material surrounding the aperture. Thus the pinhole camera and the coded aperture camera derived from it for low fluxes are best used for low energy gammas and neutrons.

Coded apertures[1-6] have been used with non-focusable photons over the last 25 years for numerous applications including astronomy, plasma diagnostics, and medical imaging and were proposed more recently for nuclear warhead verification and countering nuclear terrorism. A coded aperture is a mask with an array of apertures that provide greater sensitivity with the same resolution as a single aperture. The mask pattern is chosen so that an image can be reconstructed unambiguously from its shadow, and can be as much as 50% transmitting over the sensitive area of the detector. Typically, the shield and mask material for a gamma camera are constructed from material having a high atomic number, such as tungsten. A thickness of 5-10 mm provides enough attenuation to give reasonable contrast for gamma energies up to 1 MeV. For higher energy gammas, a thicker mask would be necessary to provide useful contrast, but the separation between adjacent apertures should be not less than the mask thickness to avoid transmission and scattering from one aperture to the next. Therefore, an instrument designed to have good contrast at gamma energies greater than 1 MeV is likely to have low angular resolution and to be very massive. Figure 1 shows a drawing of a coded-aperture gamma camera being developed at BNL using detector modules consisting of an array of Zr-Gd_2SiO_5(Ce) scintillator elements coupled to avalanche photodiodes[6] (see Fig. 2). The readout of the large number of individual pixels is performed by custom-designed Application Specific Integrated Circuits (ASICs) that amplify the detected pulses and impose upper and lower discriminator levels. Later versions of this design could provide more detailed spectroscopy from each pixel. However, with the current design it should be possible to acquire successive images of a given scene in which desired bands of the gamma spectrum are selected. Such a procedure would allow the user to distinguish objects in the scene that emit or scatter gammas in selected parts of the spectrum. The advantages of this design over existing commercial and laboratory-prototype cameras are that it operates at room temperature, is potentially capable of spectroscopy, can be scaled up to large areas with good angular resolution.

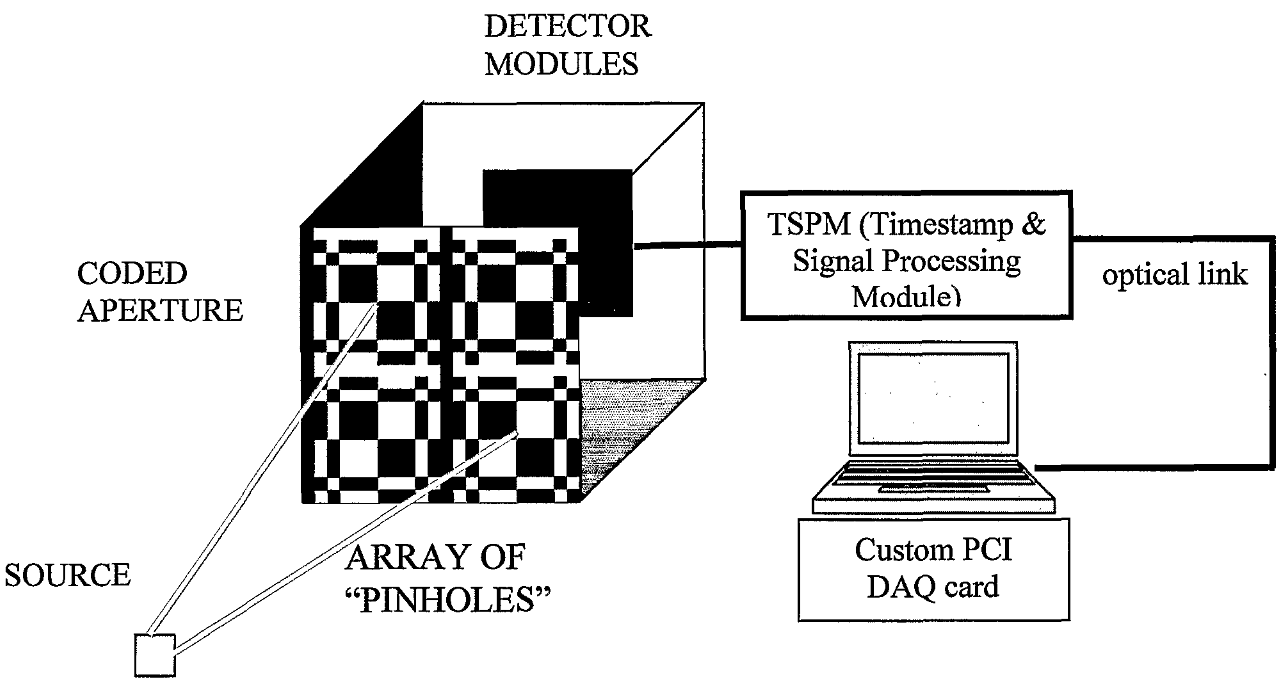
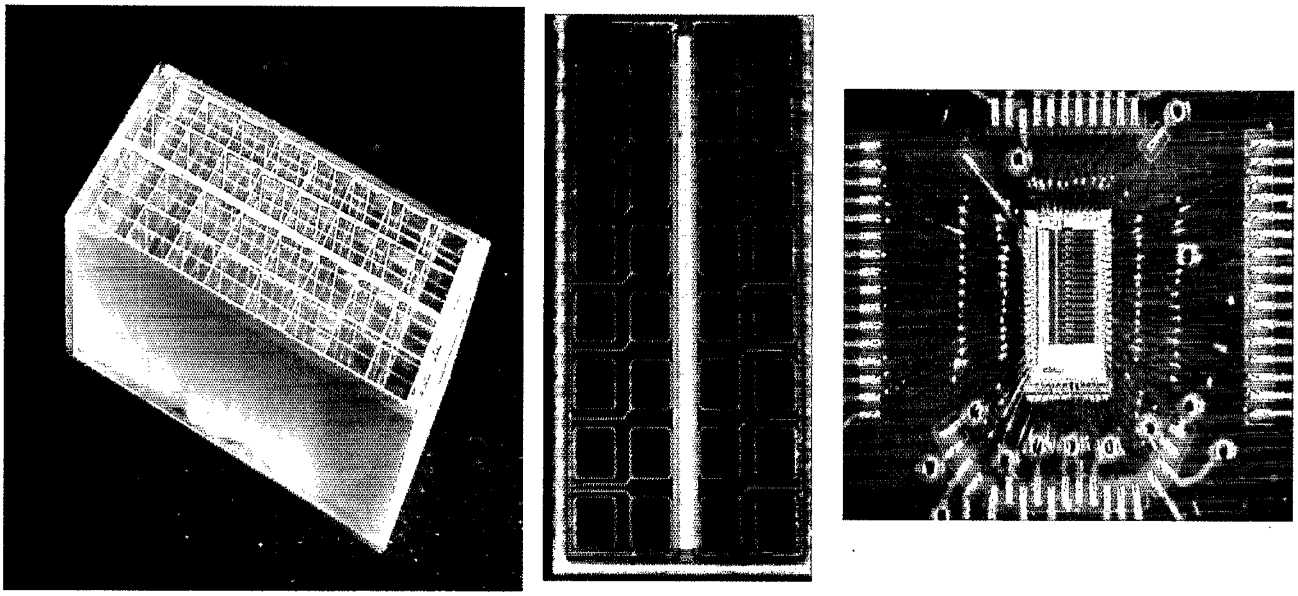


Figure 1: Coded aperture camera concept is viable for either gammas or neutrons.



(a) (b) (c)

Figure 2: Components of detector array designed for gammas: (a) scintillator crystals, (b) avalanche photodiodes, (c) ASIC readout

An analogous situation exists for low energy neutrons. Thermal neutrons are effectively shielded using thin (0.5 mm) cadmium or gadolinium sheet, which have very high absorption cross-sections for neutrons with energies below 1 eV. Neutrons are liberated by numerous mechanisms at energies above 1 MeV, but can be slowed down to thermal energies by hydrogenous materials through multiple elastic scattering on protons. If a source of fast neutrons is surrounded by hydrogenous material, it appears to be a thermal neutron source, which can be detected at considerable stand-off distances. The mean free path in air for thermal neutrons is about 20 m. A coded aperture camera that works with thermal neutrons has been successfully demonstrated[7,8] at ranges up to 60 m. Figure 3 shows one such existing system[9].

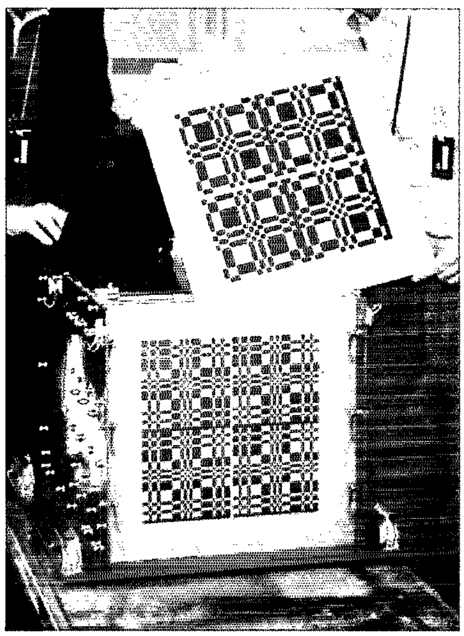
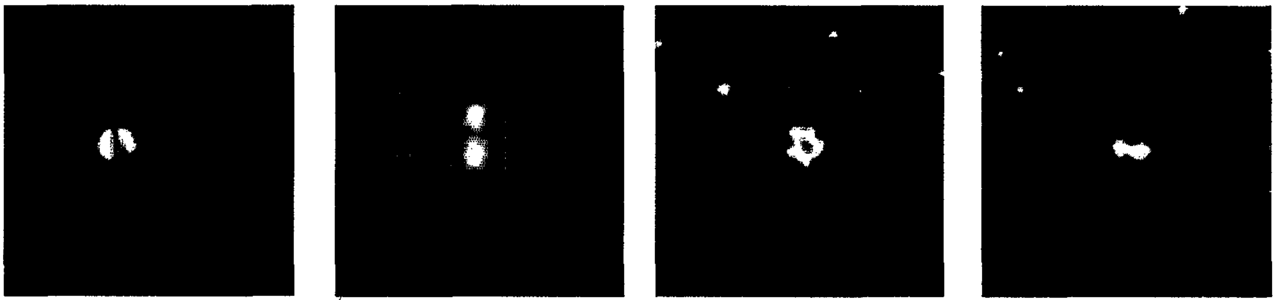


Figure 3: A thermal-neutron coded-aperture camera that uses thin cadmium masks and a pressurized ^{3}He wire chamber

Examples of images acquired with the thermal neutron camera are shown in Figure 4. These consist of combinations of spontaneous fission sources and thermalizing materials in various configurations: (a) a triangular wedge of wood scatters and absorbs thermal neutrons emitted by the end of a 30-cm thick polyethylene cylinder thermalizer behind it, using an embedded Am-Be source; (b) two ^{252}Cf sources are embedded in 10-cm cubes of polyethylene, separated by a third cube; (c) a can of Pu oxide is surrounded by a 10-cm thick jacket of water; (d) side view of configuration c.



(a) (b) (c) (d)

Figure 4: Thermal neutron images acquired passively

However, if the coded aperture principle were to be extended to fast neutrons, there would be a difficulty analogous to the case of high energy gammas. The mask material would need to be at least 5 cm thick (e.g. of boron-loaded polyethylene) with a pixel size of comparable dimensions. For a mask pattern consisting of 19 x 19 pixels, the detector area would need to be about 1 m x 1 m. While these dimensions are not out of the question, they represent a massive instrument, an order of magnitude larger than is currently in use for thermal neutron imaging. In addition, an efficient position-sensitive fast-neutron detector would be required to replace the ^{3}He wire chamber presently used for thermal neutron imaging. Such a device is also needed for scatter cameras, as discussed in the next section.

3. SCATTER CAMERAS

At energies in the range of 1 MeV to 3 MeV, gamma rays are most likely to interact with a detector by Compton scattering, in which the fraction of energy deposited is related to the angle between the incident photon direction and the scattered photon direction. If the locations and energies deposited by two consecutive scattering events can be determined with position-sensitive detectors, the scattering angle can be calculated, and a cone of possible locations can be projected backwards towards the source as depicted in Fig. 4. The overlap of several cones determines the most probable direction to the source. The two events can be detected by separate layers of two-dimensional detectors or by a single three-dimensional detector. The Compton camera concept[10-15] has been developed over many years for a variety of applications, including astrophysics, medical imaging and -- more recently -- national security. The scattering angle ϕ is related to the incident gamma energy E_0 and the scattered gamma energy E_2 by equation 1.

$$\cos \phi = 1 + m_0 c^2 \left(\frac{1}{E_0} - \frac{1}{E_2} \right) \qquad \ldots(1)$$

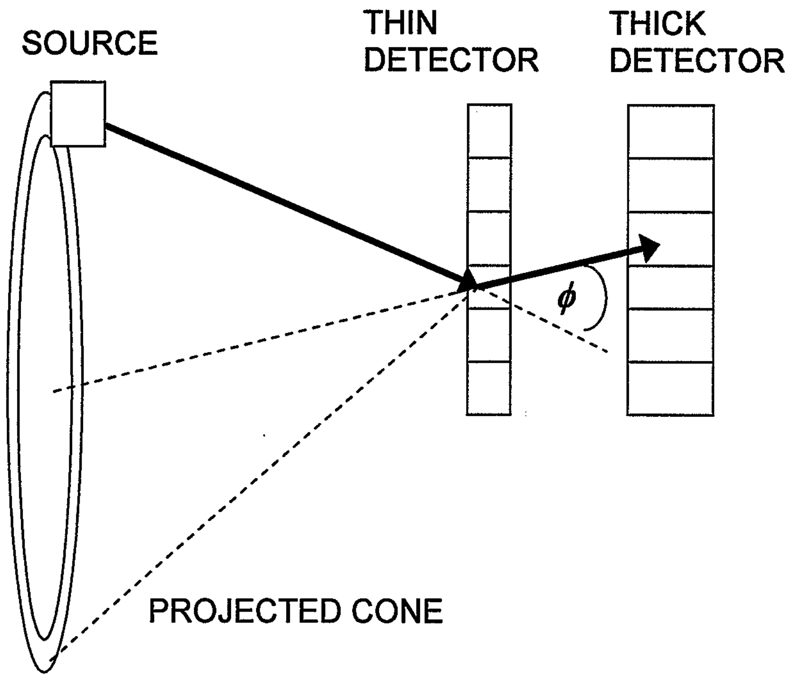


Figure 5: The basic geometry of a scatter camera relies on Compton scattering for gammas and on proton recoil for fast neutrons

In an analogous fashion, fast neutrons can be tracked through consecutive scattering events and their initial directions can be back-projected. Even though the physical scattering mechanism is completely different, and the expression for the scattering angle is different, the principle of back-projecting a sequence of overlapping cones is quite analogous. In the case of neutrons, the scattering angle ϕ is calculated by kinematics from the energy E_p deposited in the thin detector by the recoil proton and the remaining scattered neutron energy, E_{ns} that can be measured by the time of flight to the thick detector (Equation 2).

$$\tan^2\phi = E_p / E_{ns} \qquad ...(2)$$

Organic scintillators with fast photomultiplier tubes can be used in such devices, allowing the proton recoil energy to be evaluated from the pulse amplitude and the scattered neutron energy to be measured by means of time of flight between the segmented (or position-sensitive) front and the back detector planes. Since the scintillators are sensitive to muon and gamma ray background as well as to neutrons, it is important to discriminate between the different types of radiation by means of the time of flight.

A double-scatter fast neutron detector with a long flight path was used as early as 1986 to measure the energy spectrum of neutrons and the angular extent of a thermonuclear plasma source[20]. In 2003 a short flight path 2-detector device was used by Forman et al to detect a fission source at a distance with limited energy resolution and angular dependence[21]. The technique was shown to be capable of distinguishing a fission source spectrum from cosmic rays[22]. The directional capability of an 8-element double-scatter neutron spectrometer was demonstrated in 2005 by Vanier and Forman using overlapping conic projections[23] (see Figs. 6 and 7). This approach was designed to have good efficiency for fission neutrons in the range 0.5-3 MeV, with modest angular resolution, limited by the size and separation of the 12.7 cm-diameter scintillators. In contrast, a fiber-optic space-based imaging neutron detector was designed by Miller et al.[24] for much higher energy (20-250 MeV) neutrons emitted by solar flares. Another astrophysical space telescope design for 2-20 MeV neutrons is the FNIT[25] which represents a high degree of complexity, using a large number of wavelength-shifting fibers to deliver optical pulses to position-sensitive photomultipliers.

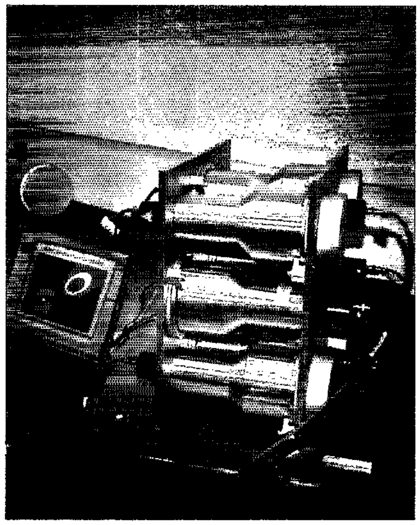


Figure 6: An eight-element double-scatter fast-neutron directional detector and spectrometer

Figure 7: Data obtained with eight-element detector showing directional capability with a ^{252}Cf source moved through 4 positions.

Figure 8 shows a relatively simple design of a large-area double-scatter fast-neutron imager being developed at BNL for long-range stand-off detection of spontaneous fission sources. It relies on 1-meter long plastic scintillator paddles in which the approximate location of a proton recoil event can be determined by means of timing or amplitude differences between the optical signals detected at both ends of the paddles in photomultiplier tubes. The front layer is 2 cm thick which gives a 25% probability of scattering a 1 MeV neutron, and the back layer is 5 cm thick, giving a 60% probability of a second scatter. Since back-scatter is not allowed by the kinematics of neutrons on protons, and the most probable scattering angle is 45 degrees, the losses due to the scattered neutron missing the second detector are not more than about 50%, provided the plane spacing is less than the x and y dimensions. This can be calculated by a convolution of the detector geometry with the scattering distribution of the neutrons, or by Monte Carlo simulations. Thus the absolute efficiency of the combined fast neutron detector is expected to be about 7 %, which is better than many non-directional detectors that depend on moderation of the fast neutrons followed by detection of the thermal neutrons in ^{3}He.

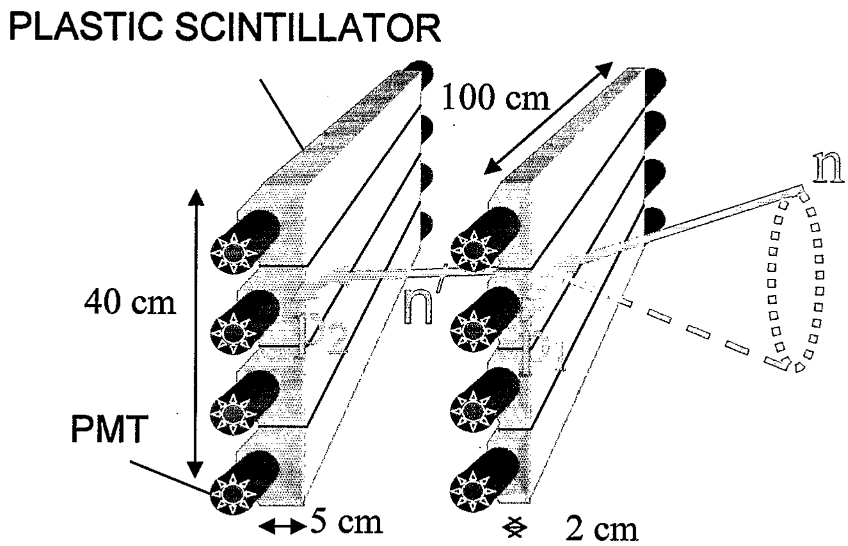


Figure 8: Large area double-scatter detector directional detector under construction at BNL

4. CONCLUSIONS

Methods of generating images with x rays and gamma rays have existed for a long time and instruments have been built by many groups. Apart from transmission radiography, imaging systems for neutrons are relatively recent and few in number. Nevertheless, geometrical principles apply to neutrons, both at low energies and high energies, and instruments analogous to the coded aperture imager and the Compton scatter camera have been demonstrated to work just as well for neutrons as for photons. Examples of images generated by these instruments are presented. The primary challenge for neutron detection is the low count rate obtained with isotopic sources rather than a nuclear reactor or accelerator. Therefore, there is a motivation for constructing large-area devices for long range stand-off detectors.

5. ACKNOWLEDGEMENTS

I am grateful for the advice and guidance received from my colleague Leon Forman during all the years leading up to this paper. Much of the work would not have been possible without the support of Graham Smith, Neil Schaknowski and Joe Mead of the BNL Instrumentation Division. I would also like to acknowledge the collaboration of Cynthia Salwen, Istvan Dioszegi, Paul Vaska of BNL, Klaus Ziock of ORNL and Tim Brown of SRL.

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