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Directional detection of a neutron source

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Abstract

Advantages afforded by the development of new directional neutron detectors and imagers are discussed. Thermal neutrons have mean free paths in air of about 20 meters, and can be effectively imaged using coded apertures. Fission spectrum neutrons have ranges greater than 100 meters, and carry enough energy to scatter at least twice in multilayer detectors which can yield both directional and spectral information. Such strategies allow better discrimination between a localized spontaneous fission source and the low, but fluctuating, level of background neutrons generated by cosmic rays. A coded aperture thermal neutron imager will be discussed as well as a proton-recoil double-scatter fast-neutron directional detector with time-of-flight energy discrimination.

KEYWORDS: Neutron, coded aperture, time-of-flight, proton recoil, directional, fission, cosmic ray, counterterrorism

1. Introduction

Neutrons emitted by a localized source, such as special nuclear material undergoing spontaneous fission, tend to radiate outwards from the origin, thereby carrying information about the location of the material. Background neutrons also exist at low densities in the environment as a result of interactions of cosmic-ray ions with the atmosphere and the ground. In order to determine a spatial gradient in the neutron flux, a simple neutron detector that measures only a scalar count rate must be moved between several measurement locations. Such a strategy for finding a source can be further complicated by the fact that the cosmic-ray background fluctuates with time far more than can be attributed to simple neutron counting statistics. Directional neutron detectors and imagers offer distinct advantages over traditional methods because they make use of the three vector components of the neutron velocity. They can help to distinguish between a "point" source and a more or less uniformly distributed background. Imagers acquire data from a wide field of view simultaneously and they will average any background fluctuations over the total acquisition time. This feature distinguishes true imagers from scanned collimated detectors, which may confuse temporal background fluctuations with spatial features. Thus these new technologies not only offer better background rejection but they rapidly indicate the location of an accidentally lost source or a potential terrorist threat.

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2. Thermal Neutrons

2.1 Coded Aperture Imaging

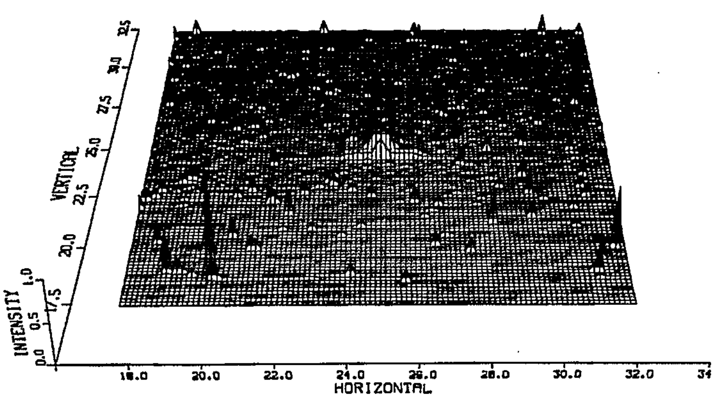
Astronomers and others interested in imaging with the non-focusable higher energy regions of the electromagnetic spectrum have been using coded aperture imagers for many years. These devices act like multiple pinhole cameras working in parallel, using a common position sensitive focal plane detector. The mask patterns and algorithms to decode the images from the associated shadow patterns have been described extensively in the literature [1-4]. We have demonstrated that the same principles can be applied to thermal neutrons, using the same mask patterns and algorithms [5,6]. Our position-sensitive neutron detector is a crossed wire chamber containing compressed ^3He [7].

One criticism of the coded aperture approach is that the mask blocks at least 50% of the incident radiation, and therefore discards useful information. In situations where the measurement is limited by counting statistics, which is usually the case, it is sometimes argued that one would be better off to use the entire area of the detector. Then the number of counts required to trigger an alarm (or exceed a preset rate) would be obtained in half the time. The counter argument relies in the fact that for each neutron detected, there are two pieces of information recorded: the x and y coordinates on the position-sensitive detector. A scalar detector records only one bit of information per neutron and thus also suffers from discarding half the data. Furthermore, the imager measures both the signal in the brightest pixel and the background in all the other pixels at the same time. Not only does this approach give the location of the source, but also it gives the level of confidence by which the brightest pixel is distinguished from the population of all the other pixels representing statistical fluctuations.

2.2 Passive Stand-off Detection

Around 1993, we began to construct thermal neutron imaging devices at Brookhaven National Laboratory. Monte Carlo simulations performed for us by a colleague, Eldon Schmidt, convinced us that the concept had merit. Fig. 1 shows the results of a simulation of a thermal neutron source embedded in a steel ship at sea [8].

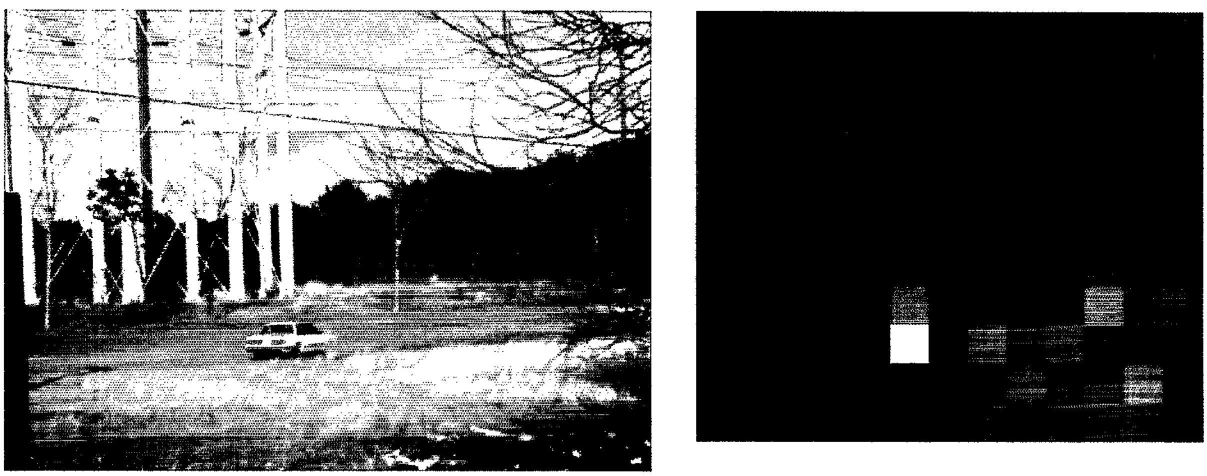
Figure 1: Monte Carlo simulation of directions of thermal neutrons arriving at a detector focal plane from a scene consisting of a steel ship carrying a moderated neutron source (center).



The calculation illustrates that although the number of neutrons traveling unscattered from the thermalizer surface to the imager may be smaller than the number of neutrons scattered into the detector by the atmosphere, the source region stands out from the background. This is because the scattered neutrons are distributed all over the image, while those associated with the source are grouped together in a spatially correlated region.

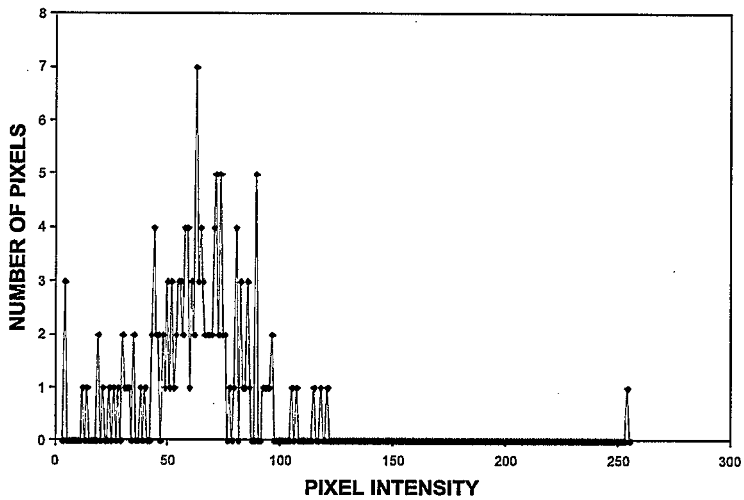
Early experiments demonstrated that thin Cd sheet was suitable for constructing coded aperture masks for thermal neutrons, and that a ^{3}He position-sensitive wire chamber provided the ideal high-efficiency, high-resolution detector. Experiments were performed in which a thermalized source was detected and located at distances up to 60 m (see Fig. 2). The source was a ^{252}Cf spontaneous fission source embedded in a 15-cm diameter polyethylene cylinder and a low-resolution (11x13) Uniformly Redundant Array mask was used such that all the direct neutrons were encoded into one pixel.

Figure 2: Image of a thermalized neutron source placed in the trunk of a car (photo on left), measured at a range of 20 m. The white pixel locates the source (neutron data on right).



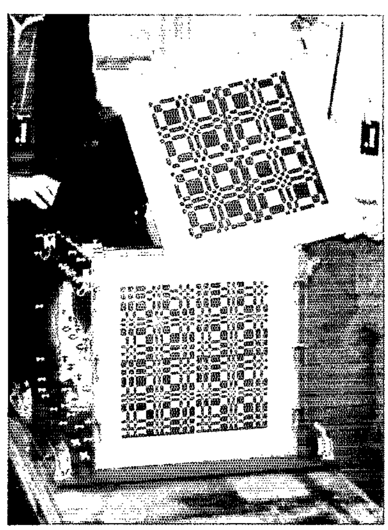
The significance of the brightest pixel is illustrated in the histogram in Fig. 3, where it is clearly seen to be far outside of the random distribution. After normalization by the imaging software, the brightest pixel has a value of 255, and the standard deviation of the distribution is 27. This type of statistical analysis provides a method of deciding whether there is a source within the field of view and calculating a confidence level.

Figure 3: Histogram of pixel intensities for data in Fig. 2. The white pixel has a value of 255, or about 7 σ relative to the mean background.



The current version of the BNL coded aperture imager is shown in Fig. 4. It utilizes a set of antisymmetric Modified Uniformly Redundant Array masks which can be rotated by 90 degrees to become their own "antimasks". Subtraction of antimask images from mask images has been shown to improve image quality by canceling out systematic effects due to non-uniformity of response of the detector [4].

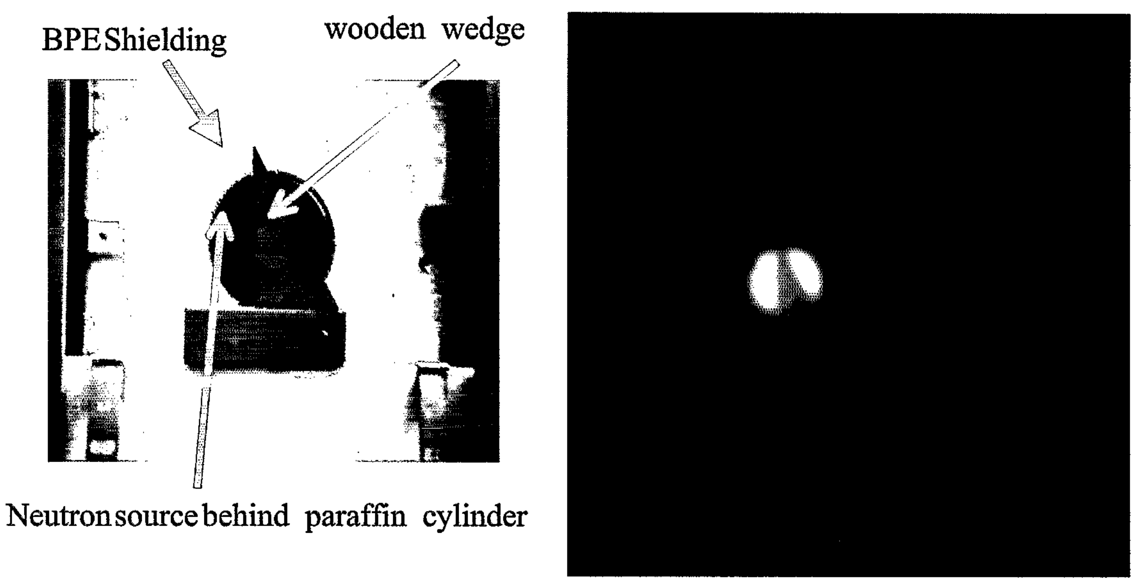
Figure 4: Coded aperture thermal neutron imager based on ^3He proportional wire chamber and MURA masks made from Cd sheet.



2.3 Passive Shape Determination

When the imager is close enough to the source to collect significant numbers of neutrons in more than one pixel it is possible to show the shapes of objects with details limited by the resolution of the mask. The resulting image is essentially a linear superposition of images of several bright pixels. The thermal neutron imager has been demonstrated to collect images of as many as 6 separated point sources, as well as geometrical shapes. For example, Fig. 5 shows an image acquired using an ^{241}Am-Be source embedded in a 30 cm long, 15 cm diameter cylinder of polyethylene, in front of which was placed a triangular piece of wood. A photo of the source assembly is shown at the left, where the cylindrical source (in shadow) is surrounded by a white borated polyethylene shield. The resulting neutron image is shown on the right, showing a dark triangle where the wood has scattered the thermal neutrons out of the picture, but the remaining sector of the cylinder show up as bright areas. These images show that the technique has potential for revealing the source configuration provided that the source is in contact with some hydrogenous material.

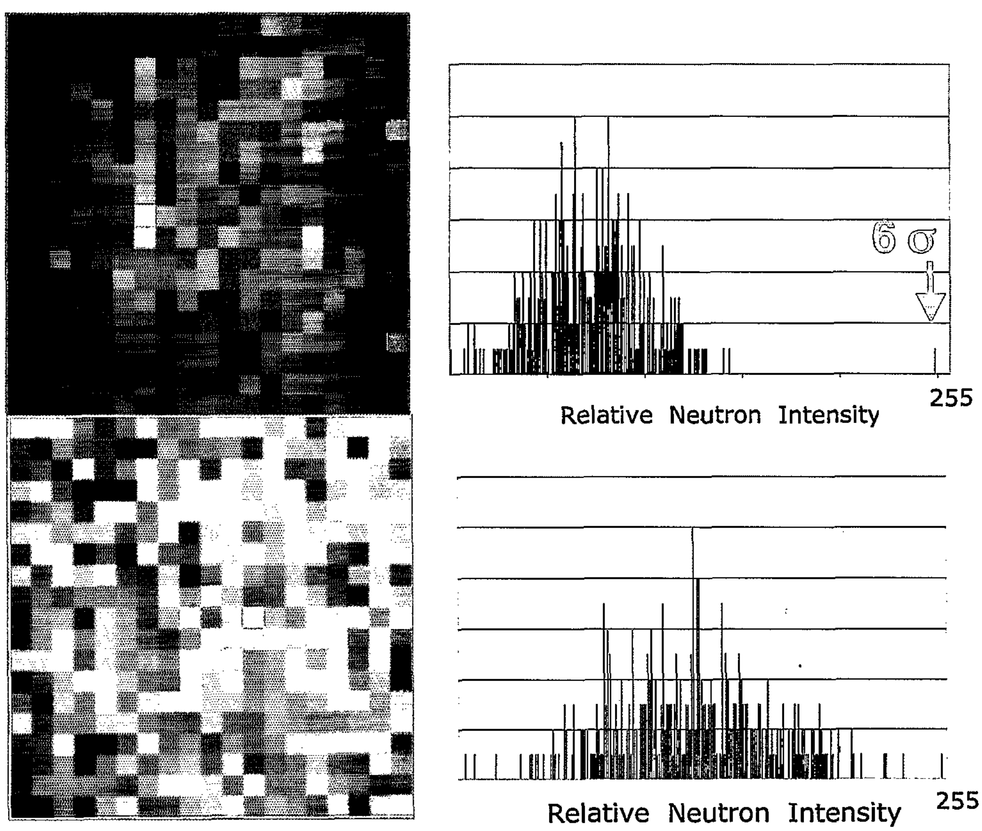
Figure 5: Shape determination using thermal neutron imager.



2.4 Active Interrogation

In collaboration with D.R. Norman, J.L. Jones and K.J. Haskell of Idaho National Laboratory, we have performed preliminary experiments [9] with the neutron imager in the environment of a 9 MeV pulsed photon source, which can create excited states in uranium nuclei and cause the emission of both prompt and delayed neutrons, the latter being an indicator of photofission. The standard method for performing such measurements relies on detection of fast neutrons that are moderated at the detector. The standard detectors do not provide imaging capability. Our detector is mainly sensitive to thermal neutrons, and can be gated so as to count neutrons during a chosen time interval after the excitation photon pulse. Our detector was saturated by the intense radiation field during each pulse, but recovered after about 1.5 ms. During the first 2-4 ms, the remnants of the prompt neutrons were still dying away, and could be used to create an image of targets containing non-fissionable heavy metals like Pb, W and Bi, if they were next to some hydrogenous material. Using longer delay times of 6-20 ms, delayed neutrons from photofission were used to create images of ^{238}U samples. Thus imaging capability can be added to an active interrogation system and it will provide information on the shape and location of thermalizing materials in contact with Special Nuclear Materials. In Fig. 6, two experimental results are compared using fissionable and non-fissionable targets. The upper image and histogram was measured with a 6.5-17.5 ms acquisition delayed gate using a ^{238}U target clad with polyethylene. The brightest pixel shows a 6s significance. The lower image and histogram were acquired with a tungsten target clad with polyethylene using the same delayed gate. In this case, the pixel intensities are close to Poisson statistics with no significant outliers.

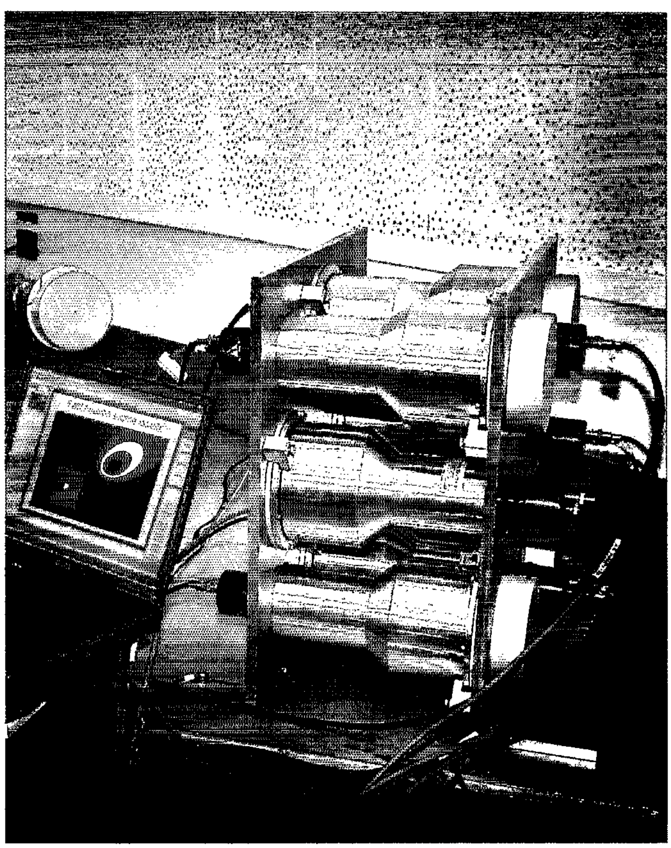
Figure 6: Neutron imaging combined with an active interrogation system.



3. Fast Neutrons from Spontaneous Fission

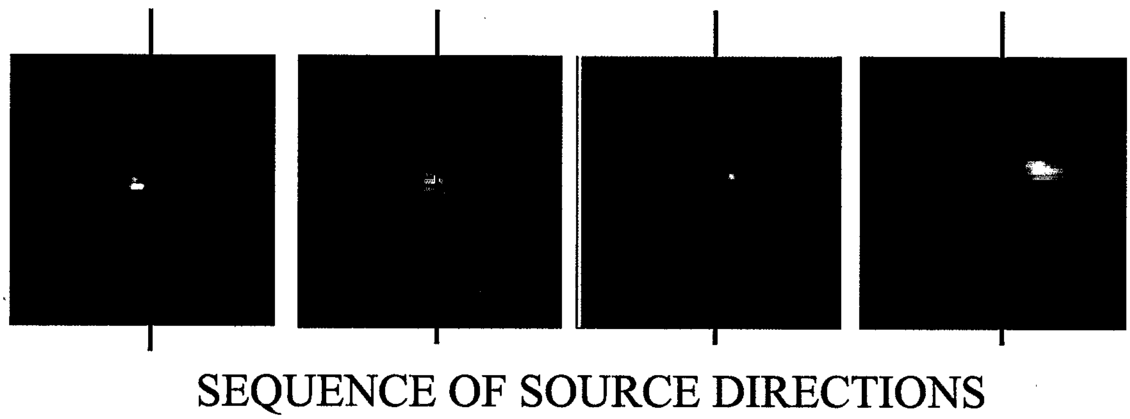
Some sources of neutrons may not be found with hydrogenous materials packed around them, or at least the shielding may not be sufficient to prevent the escape of fission neutrons in the range of 1-2 MeV. In those cases, it is still possible to detect the predominant direction of travel of the neutrons by measuring scattering angles in proton-recoil scattering. We have demonstrated a proof-of-principle proton-recoil double-scatter neutron spectrometer that provides both directional detection of fast neutrons and their energy spectrum [10]. Fig. 7 shows the equipment, which consists of two planes of liquid organic scintillators with photomultipliers. The 2-cm thickness of the front plane is chosen to give about a 25% probability of scattering a 1 MeV neutron by proton recoil. The second plane is 5 cm thick, to give a 66% probability of a second scattering event. The amplitude of the pulse recorded in the first plane can be calibrated on a nonlinear scale to estimate the energy deposited. The scattered energy is measured by time of flight between the planes using sub-nanosecond timing electronics. The ratio of these two energies can be used to calculate the scattering angle, and each neutron event can be back-projected as the surface of a cone. The intersection of many cones indicates the origin of the radiating neutrons.

Figure 7: Fast neutron directional detector based on double proton recoil events in organic scintillators.



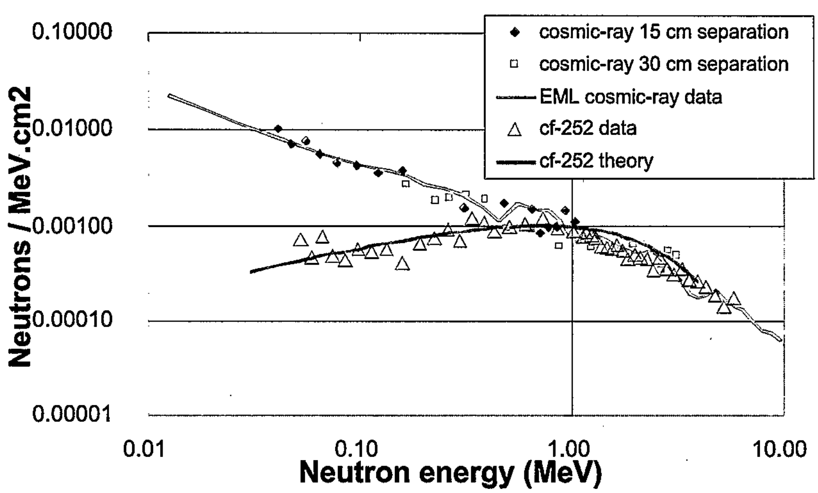
The directional capability of the fast neutron detector is shown in Fig. 8, where a sequence of acquisitions was used to track the movement of a source within the field of view. The images have been thresholded to reduce the confusion of the overlapping ellipses.

Figure 8: Directional measurements made with fast neutron double-scatter spectrometer.



The sum of the two measured energies can be used to accumulate a spectrum, which allows one to distinguish between spontaneous fission and background due to cosmic rays. These spectra are markedly different at energies below 1 MeV, as shown in Fig. 9. By noting the slope of the spectrum between 0.1 and 2 MeV, it should be evident whether the neutrons have been generated in the atmosphere by energetic cosmic ions [11,12].

Figure 9: Comparison of spectra for fission and cosmic ray neutrons.



4. Conclusion

In searching for a source of neutrons, a directional detector provides additional information beyond the total number of events. Imaging can enhance the signal to background ratio by highlighting a point source in a relatively smooth background. Fast neutrons from fission have a different energy spectrum from cosmic ray neutrons, and this can be measured by a proton recoil double scatter spectrometer.

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