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Directional detection of fission-spectrum neutrons

Peter E. Vanier, *Member, IEEE*, Leon Forman, Istvan Dioszegi, Cynthia Salwen, and Vinita J. Ghosh

[1]Brookhaven National Laboratory, Upton, NY 11973

[2]Ion Focus Technology, Miller Place, NY 11764

Nonproliferation and National Security Department
Detector Development and Testing Division

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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***Abstract*— Conventional neutron detectors consisting of ^{3}He tubes surrounded by a plastic moderator can be quite efficient in detecting fission spectrum neutrons, but do not indicate the direction of the incident radiation. We have developed a new directional detector based on double proton recoil in two separated planes of plastic scintillators. This method allows the spectrum of the neutrons to be measured by a combination of peak amplitude in the first plane and time of flight to the second plane. It also allows the determination of the angle of scattering in the first plane. If the planes are position-sensitive detectors, then the direction of the scattered neutron is known, and the direction of the incident neutron can be determined to lie on a cone of a fixed angle. The superposition of many such cones generates an image that indicates the presence of a localized source. Typical background neutron fluences from the interaction of cosmic rays with the atmosphere are low and fairly uniformly distributed in angle. Directional detection helps to locate a manmade source in the presence of natural background. Monte Carlo simulations are compared with experimental results.**

***Index Terms*— Directional detection, fast neutron, fission spectrum, proton recoil, special nuclear materials.**

I. INTRODUCTION

THERE is a growing need for large-area, high sensitivity radiation detectors to determine the presence and location of special nuclear materials and radiological dispersal devices at long stand-off distances. Such radioactive materials usually emit gamma rays, sometimes emit neutrons spontaneously, and can be stimulated to emit both types of radiation by active interrogation using beams of high-energy gammas or neutrons. Conventional large-area radiation monitors consist of plastic scintillators attached to photomultiplier tubes, and respond to either gamma rays or neutrons, but do not distinguish between them. Since the vast majority of natural background radiation consists of photons, the infrequent neutrons produced by cosmic rays are not normally identified using scintillators. Fast neutrons can be efficiently detected by pressurized ^{3}He tubes surrounded by plastic moderator, without interference by gamma background, but any information about the incident neutron direction is lost during the multiple-collision process of thermalization. This paper describes a practical method to use plastic scintillators for directional detection of fission-spectrum neutrons, so as to locate a point source at long distances despite the higher total count rate coming from the isotropic background.

The use of plastic scintillators as reasonably efficient detectors of fast neutrons has been known for a long time, and the calibration of the optical output from proton recoil in various organic scintillators was summarized [1] by Cecil et. al. in 1979. The principles of spectroscopy of fast neutrons by means of double-proton recoil were described as early as 1986 by Walker *et. al.* who used time-of-flight to measure the energy spectrum and the angular distribution of neutrons emitted by a thermonuclear plasma source [2]. In collaboration with Stony Brook University, our group used this method to show that one can distinguish between the energy spectrum of a spontaneous fission source [3] and the typical cosmic ray background neutron spectrum [4]. Neutron telescopes have been designed for spacecraft studying solar physics [5, 6] and for beam lines at accelerators [7] but those instruments have been designed for energy ranges much higher than those typical of fission neutrons. In 2005, we showed that a ^{252}Cf spontaneous fission source can be located within a wide field of view using an 8-element directional spectrometer based on double proton recoil in two planes of scintillators [8,9]. A similar experiment by Mascarenhas et. al. [10] was reported in 2006. At that time, we had started constructing a much larger detector [11] in order to acquire a statistically significant number of doubly scattered neutron events from a distant source in a reasonable time. In this paper, we describe some initial testing of the position-sensitive elements of the detector array, and an alternative (simpler) method of determining direction to the source.

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Peter Vanier, Istvan Dioszegi, Cynthia Salwen, and Vinita Ghosh are with Brookhaven National Laboratory, Upton, NY 11793 USA (phone: 631-344-3535; e-mail: vanier@bnl.gov).

Leon Forman is with Ion Focus Technology, Miller Place, NY 11764 USA and is a contractor to Brookhaven National Laboratory.

II. PRINCIPLES OF OPERATION

The principle of directional detection of fast neutrons by double proton recoil is depicted in Fig.1, which shows two layers of plastic scintillators. Any neutron that scatters in both layers within a chosen time window is recorded. If the spacing between the layers is great enough, the time of flight of the scattered neutron between the planes can be used to measure its energy and distinguish it from a Compton scattered gamma ray. Neutrons that are scattered more than once in the front layer do not provide directional information, but multiple scattering in the back layer is allowable.

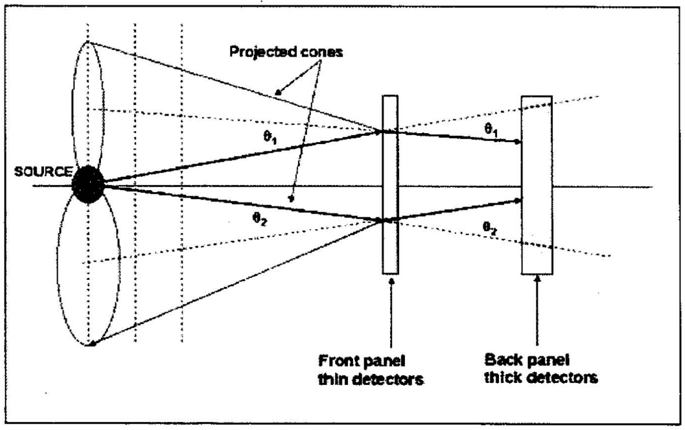


Fig. 1. Schematic of the neutron double-scatter spectrometer. Each event defines a cone of possible incident directions given by the scattering angle θ, and the overlap of the cones indicates a point source.

If the energy deposited by a recoiling proton in the front panel is E_p and the kinetic energy of the scattered neutron is E_{ns} as determined by time of flight, then the cone angle θ is given by

$$\tan\theta = \sqrt{\frac{E_p}{E_{ns}}} \quad \ldots(1)$$

Data from many events, either measured or simulated, can be combined to create an image in which the intensity is brightest at regions of overlap of the independent cones.

III. Monte Carlo Modeling

Using the MCNP code, the expected response of the new large-area double scatter detector was simulated. The arrangement of the detector components is shown in Fig. 2. The four scintillators paddles in the front layer have dimensions 2 cm x 10 cm x 100 cm, and the four paddles in the back layer have dimensions 5 cm x 10 cm x 100 cm. The geometry and the material were defined in the model, and a location was chosen for the neutron source. The information that can potentially be generated by these calculations includes:

a) Exact positions where energy was deposited in each layer;
b) Energy imparted to the protons E_p in front and back layers;
c) Energy of scattered neutron E_{ns};
d) Probability of a neutron scattering in both layers including multiple scatters;
e) Probability of a neutron scattering only once in the first layer and one or more times in the second layer.
f) Effects of scattering in the air for long ranges.

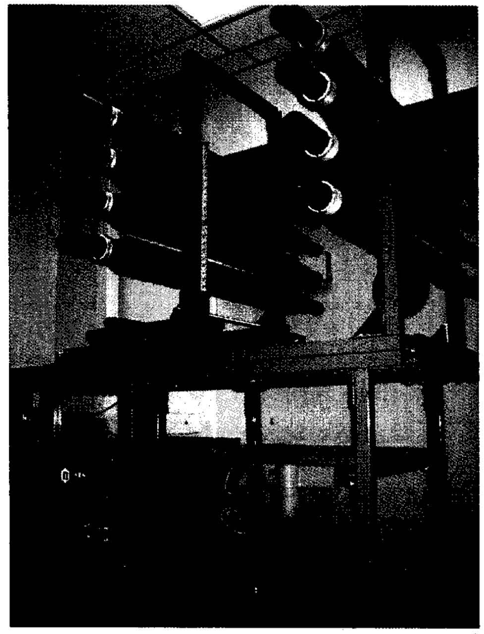


Fig. 2. Photograph of the large-area neutron double-scatter spectrometer during assembly. The spacing between the planes of scintillator paddles is adjustable, but is typically 50 cm.

For each simulated event, a cone was back-projected onto a plane at a chosen distance from the detector and the intensities of many events were accumulated. Intensity maps were generated for a series of projection planes at different distances. Typical contour maps for short ranges are shown in Figs. 3-5. The best contrast and spatial resolution is obtained when the projection plane coincides with the location of the source in the model, as in Fig. 4. The intensity of the brightest spot can be calculated for several projection planes at different distances from the detector front face, and plotted as shown in Fig. 6. A maximum is obtained at the actual source distance.

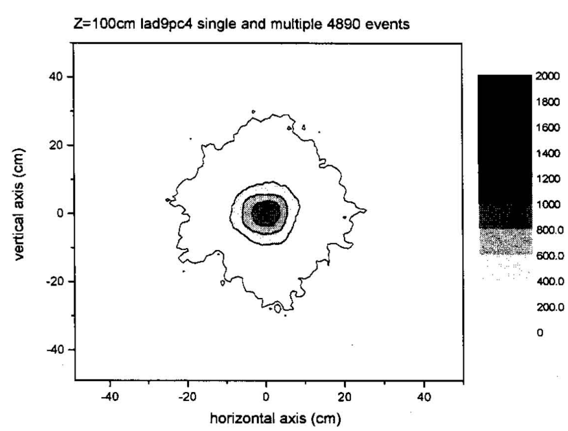


Fig. 3. Contour map obtained by back-projection of cones onto a plane at 100 cm for a model with the source at 200 cm range.

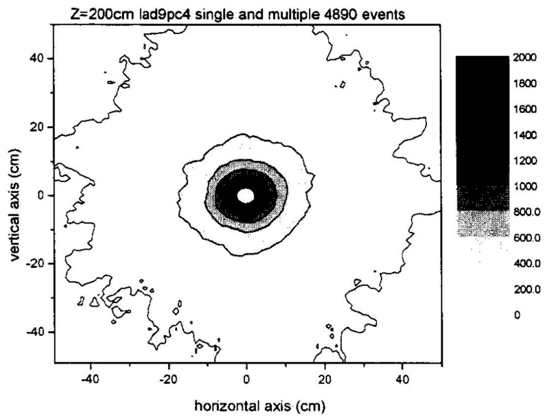


Fig. 4. Contour map obtained by back-projection of cones onto a plane at 200 cm for a model with the source at 200 cm range. The white spot at the center indicates more than 2000 coincidence events.

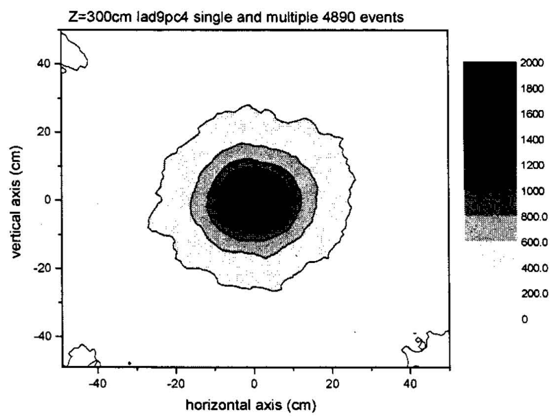


Fig. 5. Contour map obtained by back-projection of cones onto a plane at 300 cm for a model with the source at 200 cm range.

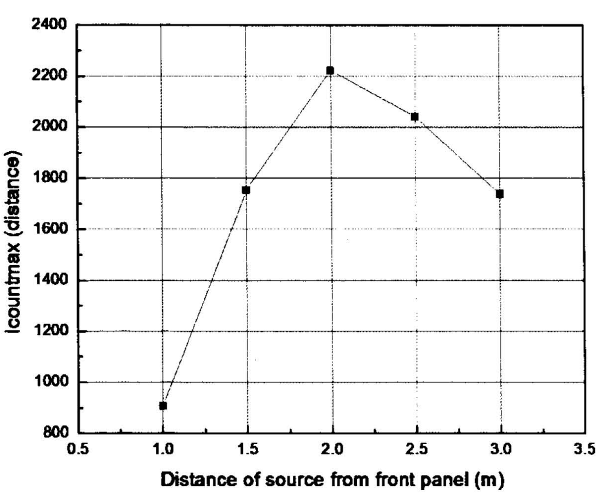


Fig. 6. Intensity of the brightest pixel as a function of distance to the projection plane, for a model with the source at 200 cm.

However, at ranges much greater than the dimensions of the detector elements, the maximum intensity does not vary strongly with the distance to the projection plane, and range information may not be precise, although the direction of the source should still be quite clear, as in Fig. 7.

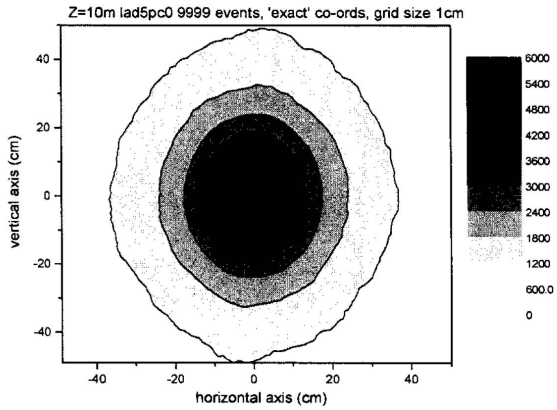
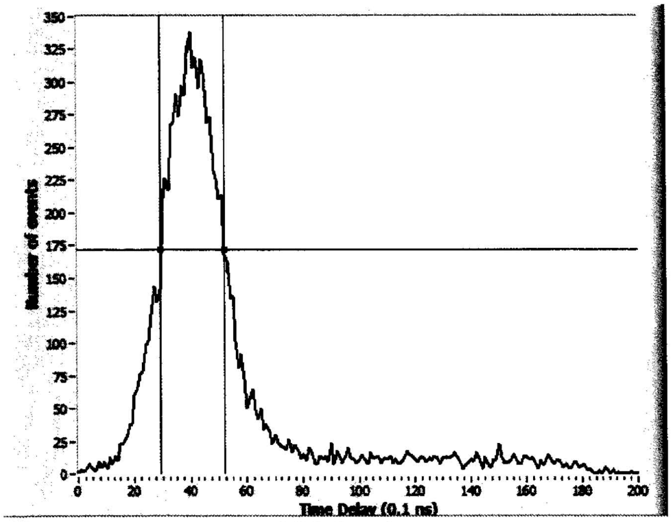


Fig. 7. Contour map obtained by back-projection of cones onto a plane at 10 m for a model with the source at 10 m range.

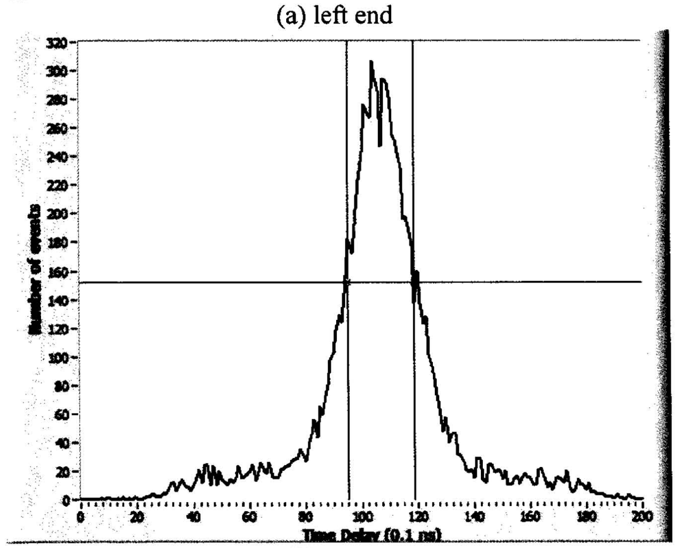
IV. System Calibration

The location of a proton recoil in the vertical direction is obtained by the index of the paddle in which the event is recorded, with a fixed pixel size given by the height of the paddle (10 cm). In the horizontal direction, the location of each event is determined by the time difference between the leading edges of the pulses detected by photomultipliers at the two ends of the paddle. We used a collimated ^{60}Co source to generate events at specific locations along one of the thick paddles to obtain an empirical calibration of distance as a function of delay time. The events were recorded using an Acqiris 1 GHz digitizer using a new program that displays the events in real time as they accumulate.

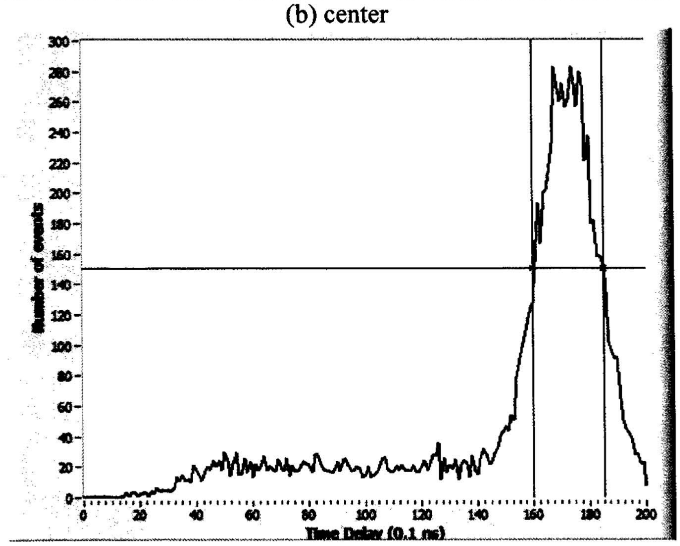
Typical histogram data are shown in Fig. 8 in which the number of events is plotted against the time delay in units of 0.1 ns, for three locations of the source (a) to (c) separated by 45 cm. We estimate the full-width at half-maximum (fwhm) of these distributions, as indicated by the cursors, to be 2.4 ns. When the source is moved 20 cm, the shift of the peak is about 3.0 ns, corresponding to an effective velocity of light in the plastic of 6.7 cm ns^{-1}. The shape of the histogram really represents two populations of events. The gamma background in the room is fairly uniformly distributed over the range of delay times corresponding to the full length of the paddle. The narrow peak is due to the localized source close to the scintillator. The horizontal spatial resolution is ~16 cm, which is comparable to that of the smaller detector array previously reported [8, 9] in which the pixel size was given by the 12.5 cm diameter of the disk-shaped scintillators. However, the continuous readout of the location of events along the new paddles should provide much smoother images and avoid aliasing. Also, the spacing between the front and back plane can be greater for a large area device without losing efficiency.



(a) left end



(b) center



(c) right end

Fig. 8. Data showing distribution of the number of events as a function of time delay (in units of 0.1 ns with a zero offset of ~10 ns) between signals from two ends of a paddle, when a source is placed in contact with the scintillator, at three locations about 45 cm apart. The shift of the peak corresponds to 13.2 ns for 90 cm and the fwhm of the peak is 2.4 ns.

The type of image of a point source produced by the BNL small detector array [11] shows an approximate 8-fold rotational symmetry as shown in Fig. 9, because the four front detectors were interleaved with the four back detectors. The present large area instrument, once fully integrated, will be expected to provide comparable data in a much shorter time, without the artifacts introduced by the small number of pixels.

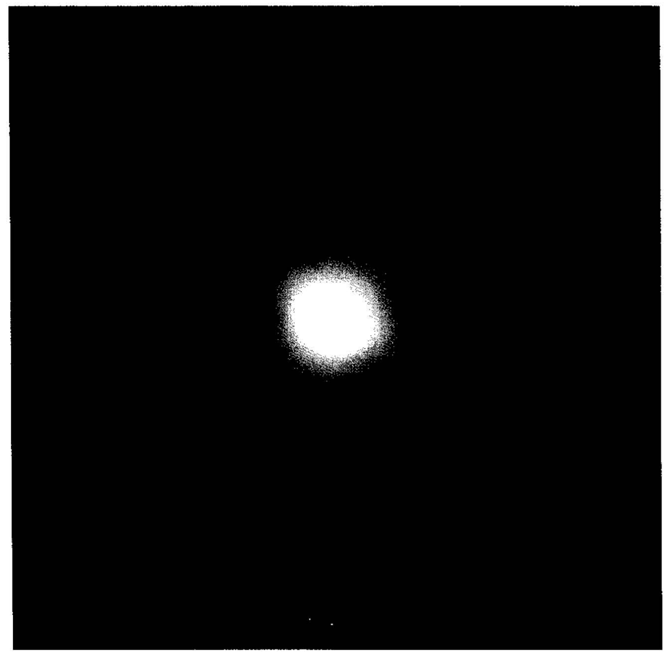


Fig. 9. Fast neutron data obtained with a source about 3 m from the small 8-element array described in a previous paper [11].

V. Conclusion

A new large-area fast-neutron directional detector is being developed for stand-off detection of Special Nuclear Materials. MCNP simulations show that if the locations of neutron interactions and the energies deposited are known precisely, the direction to the source can be extracted from the data, and some estimate of the range is possible. Preliminary experimental data indicate that the spatial resolution of the 100-cm paddles will be adequate for a practical direction-finding device.

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