An 8-element fast-neutron double-scatter directional detector

Peter E. Vanier¹, Leon Forman²

¹Brookhaven National Laboratory, Bldg 197C, Upton, NY 11973; USA;
²Ion Focus Technology, 52 Pardom-Knoll, Miller Place, NY 11764, USA

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An 8-element fast-neutron double-scatter directional detector

Peter E. Vanier* a, Leon Forman b
a Brookhaven National Laboratory, Bldg 197C, Upton, NY 11973, USA;
b Ion Focus Technology, 52 Pardom Knoll, Miller Place, NY 11764, USA

ABSTRACT

We have constructed a fast-neutron double-scatter spectrometer that efficiently measures the neutron spectrum and direction of a spontaneous fission source. The device consists of two planes of organic scintillators, each having an area of 125 cm², efficiently coupled to photomultipliers. The four scintillators in the front plane are 2 cm thick, giving almost 25% probability of detecting an incident fission-spectrum neutron at 2 MeV by proton recoil and subsequent ionization. The back plane contains four 5-cm-thick scintillators which give a 40% probability of detecting a scattered fast neutron. A recordable double-scatter event occurs when a neutron is detected in both a front plane detector and a back plane detector within an interval of 500 nanoseconds. Each double-scatter event is analyzed to determine the energy deposited in the front plane, the time of flight between detectors, and the energy deposited in the back plane. The scattering angle of each incident neutron is calculated from the ratio of the energy deposited in the first detector to the kinetic energy of the scattered neutron.

Keywords: fast neutron, directional neutron detector, fission spectrum, plutonium, counterterrorism

1. INTRODUCTION

Traditional neutron detectors consist of high-pressure ³He ionization tubes surrounded by polyethylene moderator, and can be quite efficient (up to ~10%) for counting incident fission-spectrum neutrons. However, multiple scattering of a neutron passing through the moderator results in the loss of useful information about its initial direction and energy. Thus, a single traditional fast-neutron detector in a fixed position does not indicate the source location or its energy spectrum. In this paper we describe a neutron detection system designed to record the energy lost by the neutron in its first scattering event (by pulse amplitude) and its subsequent kinetic energy after the initial scattering (by time of flight). From these quantities, it is possible to estimate the total energy of each neutron, and a limited cone of angles that might point back to the source location ². By combining energy data from many events, it is possible to generate an energy spectrum of the source ³, which distinguishes an isotopic source from background neutrons produced by cosmic rays ⁴. A combination of the directional information from multiple events indicates the most probable direction to a point source. The system is a laboratory demonstration that will provide empirical design parameters to be used in constructing larger, more efficient arrays of scattering elements.

2. SYSTEM COMPONENTS

The concept requires two planes of liquid organic scintillators, supplied by Alpha Spectra Corp., equipped with fast photomultiplier tubes (PMTs), as shown in Fig. 1. The front plane consists of four 2-cm-thick scintillators with a diameter of 12.6 cm arranged at the midpoints of the sides of a 30-cm square. In this thickness of scintillator, a neutron with an energy of 2 MeV has a probability of interaction by proton recoil of 25%. The back plane consists of four 5.1-cm-thick scintillators of the same diameter positioned at the vertices of a 30-cm square. The thicker scintillators have an interaction efficiency of 40% at 2 MeV. The perpendicular distance between the planes is adjustable, but for the initial testing was set to 20 cm. The tubes in the back plane are mounted facing in the reverse direction from those in the front plane so that both sets of tubes can be supported by two aluminum plates bored to fit both ends of the tubes. The eight PMTs are biased independently with an 8-channel high-voltage power supply so that the gain of each tube can be adjusted and calibrated separately. The anode signals are connected to an 8-channel Aquiris digitizer, which samples...
each signal at 1-ns intervals. The digitizer is triggered only when pulses above a threshold are detected in both the front and the back planes within a time window of 500 ns. This triggering signal is generated using threshold discriminators to generate NIM logic gates. The front signals are combined together using OR gates, and the back signals are similarly combined. Then a coincidence between front and back signals is generated by an AND gate. The coincidence output is used to trigger the Aquiris, which stores the 8 traces from its continuously-updated volatile memory on a common time scale, starting near the beginning of the coincidence window. The precision of time-of-flight measurements is determined by the synchronization of the Aquiris channels, but not by the jitter in the NIM discriminators and logic modules. A typical 8-channel trace of a coincidence event is shown in Fig. 2.

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**Figure 1:** The directional double-scatter neutron spectrometer consisting of 4 organic scintillators in each detection plane, with the Aquiris 8-channel high-bandwidth data recording system.

**Figure 2:** Raw data acquired by the double-scatter neutron spectrometer showing signals from 8 PMTs. The traces have been displaced vertically for clarity. The top four traces are from the front set of PMTs and the bottom four are from the back PMTs. Two traces show pulses with a time of flight of about 90 ns.

The system acquires and stores a sequence of events in list mode using the standard Aquiris software package, and the data files are later processed using customized programs constructed using the LabView development system from National Instruments. The Aquiris data files are consolidated into a single file for each run, and the traces are analyzed to obtain pulse amplitudes and delay time between pulses, as well as the indices of the detectors involved. The time to reach the half-maximum point of the leading edge on each pulse defines the arrival time of the neutron, and is located to a precision of 0.1 ns by interpolation. The time of flight is then the difference between the leading edges of the front pulse and the back pulse. The amplitude of each pulse is obtained by summing the data for a fixed region of interest centered on the maximum reading in the pulse. The essential parameters are accumulated in a summary file containing...
all events in a run. Tests are then applied to select gamma-gamma events or neutron double scatters, based on the time of flight. By imposing limits on the time of flight, a range of neutron energies can be selected to include a fission spectrum (0.5-2 MeV) while excluding higher-energy cosmic-ray events and longer-delayed room scatter.

3. DATA

3.1 Calibration

The scintillators are sensitive to both gammas and neutrons, both of which are emitted by a fission source. Calibration of the pulse amplitudes was performed using a Co-57 and a Cs-137 source, for each PMT operated independently without the coincidence gate. The histogram of pulse amplitudes was plotted for each source, and the upper limit to the response curve was equated to the Compton edge for the particular gamma line. (Organic scintillators do not generate spectra with full-energy peaks or photopeaks, because the primary mode of interaction is Compton scattering that deposits energy in a continuum up to the maximum allowed by momentum conservation). The PMT bias voltages were adjusted so that each tube gave approximately equivalent response to a given calibration source, and the Compton edge measured by each tube was recorded in a calibration table. The energy of a neutron that deposits an ionization pulse equivalent to the calibrated photon energy was calculated using a semi-empirical expression recommended by Alpha Spectra Corp., as described in the literature.

3.2 Distinguishing gamma and neutron responses

With the logic gates all switched to the OR mode, the eight scintillators provide a large-area gamma detector with relatively high sensitivity. The total area of the organic scintillators is about 1000 cm² which is comparable to the sensitive area of commercial portal monitors based on plastic scintillators. Without a nearby isotopic source, a count rate of about 450 cps is observed just from the background radiation in the laboratory. Very few of these are neutrons. When a ²⁵²Cf source emitting 37,000 n/s (and a corresponding rate of gammas) is placed at 50 cm distance from the array, the total count rate is 900 cps, so the net signal is approximately equal to the background. When the source is moved to a distance of 220 cm, the net signal drops to 40 cps, or about 9% of the background.

With the coincidence AND gate switched on to require a pulse in the front plane of detectors and another pulse in the back plane, the trigger rate drops by orders of magnitude. The coincidence events can be characterized by the delay time between the two events.

1. If two pulses occur within about 5 ns of each other, they are probably both produced by gamma rays in events such as:
   (a) a spontaneous fission event that produces multiple gammas, two of which are detected by front and back scintillators respectively;
   (b) a single gamma emitted from the source undergoes Compton scattering in the first scintillator, and the scattered photon is detected in the second plane.

2. If the two pulses are separated in time by 5-200 ns, they are probably caused by neutron events such as:
   (a) one neutron scatters and produces ionization by proton recoil in the front plane and then continues at reduced energy to interact in the second plane;
   (b) two neutrons emitted simultaneously from the source are detected independently by two tubes within the time window.

3. If the second pulse is delayed more than 200 ns, it probably represents an event in which the first detector responds to a gamma ray from the fission event, and the second detector responds to a neutron (emitted by the same fission event) that traveled a long distance, possibly scattering a few times on the way. This type of event should be very unlikely at long stand-off distances because the time of flight of the neutron would exceed the acquisition window.

The neutron double-scatter events of interest in this paper are of type 2(a) and can be selected by means of time of flight. Their frequency should vary as the inverse square of the distance to the source, whereas events such as 2(b) and 3 should vary as the inverse fourth power of the distance. When only neutron-double-scatter events are counted, the background rate in the absence of a fission source is extremely low (1.4 cpm). Thus, the count rate from the same ²⁵²Cf source at a range of 220 cm is 8.4 cpm, which gives a net signal that is 5 times background. This signal-to-background ratio should be maintained if the system is scaled up to larger areas and higher total count rates.
3.3 Directionality

Another feature of the multi-element detector that enhances signals of interest over background arises from the fact that background radiation is fairly uniform in all directions, while a manmade source is likely to be localized. The directional information from the neutron scattering process can be used to highlight a point source within a wide field of view. The scattering angle $\phi$ is defined as the change in direction of the incoming neutron when it scatters in the front plane, as shown in Fig. 3. A neutron originating from a source, with energy $E_n$(MeV), scatters off a proton in the front detector imparting a kinetic energy of $E_p$ to the proton. The scattered neutron, with energy $E_{ns}$, may then be detected in the second detector after having traveled a distance $L/\cos\theta$, where $L$ is the distance in cm between detectors associated with the associated time-of-flight (TOF) in nanoseconds, and $\theta$ is the scatter angle relative to the central axis. The kinematic equations describing the neutron scattering are:

$$E_n = E_{ns} + E_p$$  

$$E_{ns} = \left( \frac{0.723L}{TOF \cos \theta} \right)^2$$  

$$\tan^2 \phi = \frac{E_p}{E_{ns}}$$

Figure 3: Scattering angles in a plane of three detectors. For an off-axis source, there are two values of $\phi$ for the two back detectors, whereas if the source were on the central axis, $\phi$ would be equal to $\theta$ for both of them.

4. RESULTS

Figure 4 shows histograms of the measured scattering angles using a $^{252}$Cf source and only three detectors lying in a plane for simplicity. The deflection angle $\phi$ was estimated from the relative amplitudes of the pulses recorded by front and back detectors. When the source is centered on the axis, the angles of deflection are equal for each of the back detectors, and there is one peak in the distribution at about 32 degrees (a). When the source is moved to 30 cm off-center at a range of 56 cm, the distribution is split into two peaks (b). These results indicate that directional information can be obtained with a relatively small number of detected coincidences.
Software has been created to analyze the 3-dimensional vector geometry and plot the locus of possible source directions for each double-scatter event. Each event selects a pair of PMTs defining a scattered neutron axis. The experimentally estimated scattering angle is then “projected” as a cone until it intersects a plane passing through the source perpendicular to the detector axis. The locus of intersection points of the cone with the plane plots an ellipse for each event. These ellipses are summed to form the image of the source plane. A Lorentzian point spread function is used to defocus the ellipses in order to take account of the finite size of the PMTs.

The same raw data used to generate Fig. 4 can be displayed as a series of elliptical traces representing the probability of finding the source in a given x,y pixel of the field of view (Fig. 5). In Fig. 5(a), the ellipses are symmetrical, with an overlap at the center; although there are more events recorded by the right side detector (perhaps due to differences in trigger-logic thresholds). In Fig. 5(b), the ellipses are not symmetric, and the overlap has shifted to the left.
By combining similar data for all the possible combinations of front and back detectors, it is possible to display high-contrast images that help to locate point sources. For best results, the 8 detectors must be well-calibrated and triggered appropriately to produce equal probabilities of detection of double-scatter events. This process of calibration is still being optimized. Fig. 6 shows thresholded images in which the brightest areas match the locations of the Cf-252 target on axis and at x = -30 cm at a range of 56 cm from the front detector.

Figure 6: Overlap of ellipses from 8 detectors with source (a) on axis and (b) 30 cm off-center, thresholded.

5. CONCLUSIONS

The double-scatter technique has been demonstrated to improve the signal-to-noise by spectroscopy and directionality. The fast neutrons can be measured with relatively high efficiency. If the front and back planes of scintillators were fully tiled, the efficiency could reach ~ 8%. The 8-channel system was demonstrated to have a high rejection rate of photons (> 10,000/1). Neutron time of flight can be used to select events that correspond in energy to a fission source spectrum rather than the cosmic-ray background. The neutron-double-scatter response is directional, and its angular resolution capability depends on the size and separation of the detector pairs. The angular distribution not only gives the direction of the source, but also improves discrimination of the localized signal from the diffuse angular distribution of cosmic-ray background.

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