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Directional Detection of Fast Neutrons Using a Time Projection Chamber

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1 Introduction

Spontaneous fission in Special Nuclear Material (SNM) such as plutonium and highly enriched uranium (HEU) results in the emission of neutrons with energies in the MeV range (hereafter “fast neutrons”). These fast neutrons are largely unaffected by the few centimeters of intervening high-Z material that would suffice for attenuating most emitted gamma rays, while tens of centimeters of hydrogenous materials are required to achieve substantial attenuation of neutron fluxes from SNM. Neutron detectors are therefore an important complement to gamma-ray detectors in SNM search and monitoring applications.

The rate at which SNM emits fast neutrons varies from about 2 per kilogram per second for typical HEU to some 60,000 per kilogram per second for metallic weapons grade plutonium. These rates can be compared with typical sea-level (cosmogenic) neutron backgrounds of roughly 5 per second per square meter per steradian in the relevant energy range [1]. The fact that the backgrounds are largely isotropic makes directional neutron detection especially attractive for SNM detection. The ability to detect, localize, and ultimately identify fast neutron sources at standoff will ultimately be limited by this background rate.

Fast neutrons are particularly well suited to standoff detection and localization of SNM or other fast neutrons sources. Fast neutrons have attenuation lengths of about 60 meters in air, and retain considerable information about their source direction even after one or two scatters. Knowledge of the incoming direction of a fast neutron, from SNM or otherwise, has the potential to significantly improve signal to background in a variety of applications, since the background arriving from any one direction is a small fraction of the total background. Imaging or directional information therefore allows for source detection at a larger standoff distance or with shorter dwell times compared to non-directional detectors, provided high detection efficiency can be maintained.

Directional detection of neutrons has been previously considered for applications such as controlled fusion neutron imaging [2], nuclear fuel safety research [3], imaging of solar neutrons and SNM [4], and in nuclear science [5]. The use of scintillating crystals and fibers has been proposed for directional neutron detection [6]. Recently, a neutron scatter camera has been designed, constructed, and tested for imaging of fast neutrons, characteristic for SNM material fission [7]. The neutron scatter camera relies on the measurement of the proton recoil angle and proton energy by time of flight between two segmented solid-state detectors. A single-measurement result from the neutron scatter camera is a ring containing the possible incident neutron direction.

Here we describe the development and commissioning of a directional neutron detection system based on a time projection chamber (TPC) detector. The TPC, which has been widely used in particle and nuclear physics research for several decades, provides a convenient means of measuring the full 3D trajectory, specific ionization (i.e particle type) and energy of charged particles. For this application, we observe recoil protons produced by fast neutron scatters on protons in hydrogen or methane gas. Gas pressures of a few ATM provide reasonable neutron interaction/scattering rates.

2 Time Projection Chambers

TPCs comprise a gas filled interaction region, a two dimensional charge collection surface and some form of electron gain located just in front of the charge collection surface to improve the signal to noise. For this application, a hydrogen bearing gas is chosen – when an incoming neutron scatter produces a recoil proton, the ionization produced as the proton slows is drifted to the readout surface. The combination of the two dimension charge collection information with the charge arrival time yields the 3D ionization profile of the recoiling particle (Figure 1). This is a particular advantage of TPCs for SNM imaging – the ability to record particle specific ionization. This means that efficient particle identification is available, allowing strong rejection of gamma-ray backgrounds.

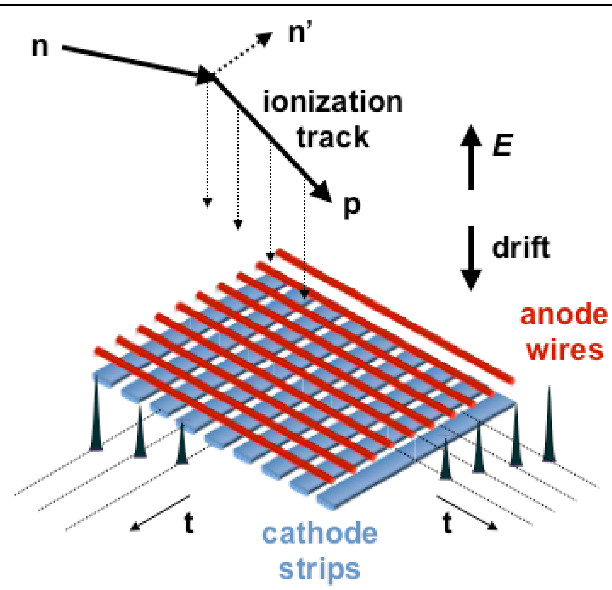

Figure 1
Representation of TPC operation using, in this example, a crossed wire/strip readout.

So long as the particle track is contained within the active region of the detector, the interaction can occur anywhere within the device. For this application an incident particle need only interact once with the detector for directional information to be obtained. The directional information is obtained directly from the measurement of the charged particle trajectory. Furthermore, a TPC can in principle achieve a full 4π field of view. Therefore, TPCs promise high directional detection efficiency – only a single interaction is required, near 4π field of view is provided, and a large fraction of the volume occupied by the device is active.

3 Detector Description

The laboratory prototype neutron TPC (nTPC) consists of a 44 cm-diameter, 66-cm long pressure vessel, which contains the detector gas, drift field cage, amplification region, and the 2D readout plane consisting of 128 anode wires and 64 cathode strips (Figure 2). Low event multiplicity allows the use of a cost-effective readout system employing independent readouts for cathode and anode planes, resulting in a total of 192 channels. The outer pressure vessel is made from standard stainless steel components and allows a maximum operational pressure of 10 bar(a). The entire assembly weighs approximately 0.5 ton, although for this lab prototype no effort was expended to design the vessel to a fieldable weight.

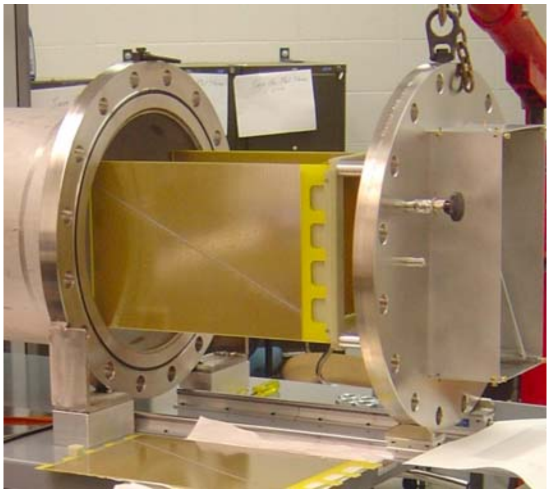

Figure 2
Detector vessel and field cage assembly

4 Data Analysis

We have developed reconstruction software that consists of a data parser, hit finder, tracking algorithm, and an ionization profiler. Due to the use of two orthogonal detector readout planes, we use the time correlation between those two planes to identify 3-dimensional hit locations. This use of time coincidence also represents a powerful method for electronic noise rejection. The list of 3-dimensional hits is subsequently projected back into two planes, allowing the use of two independent tracking algorithms.

The tracking algorithm is based on a combination of a standard Hough transform algorithm [8] with a least squares linear fit. The Hough transform algorithm is used initially to obtain the directions of the projections of the particle track in two detector planes, since this transform is a robust means of finding a track in datasets which might contain events that lie off of a track. Hits that lie on the track found by the Hough transform are identified, and the track angle is then found with greater precision by employing a least squares fit (Figure 3a). The amplitude of the hits found along the reconstructed track are used to form an ionization profile that is then used for particle identification purposes. An example ionization profile is shown in Figure 3b; one can clearly see the expected features of the ionization profile, e.g. the Bragg peak at the end of the particle track.

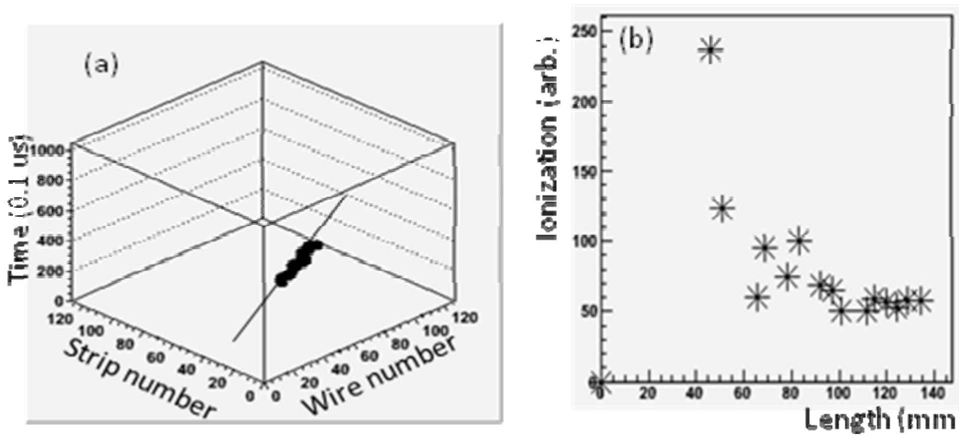

Figure 3
An example of a 3D particle track (a) , and the ionization along that track (b).

5 Results

Using the this device, and the reconstruction algorithm described above we are clearly able to observe events due to proton recoils caused by incident fast neutrons, alpha particles due to natural radioactivity in the field cage walls, and gamma rays. We note the response to gamma rays is highly suppressed due to the low specific ionization of electrons created by Compton scattering (Figure 4).

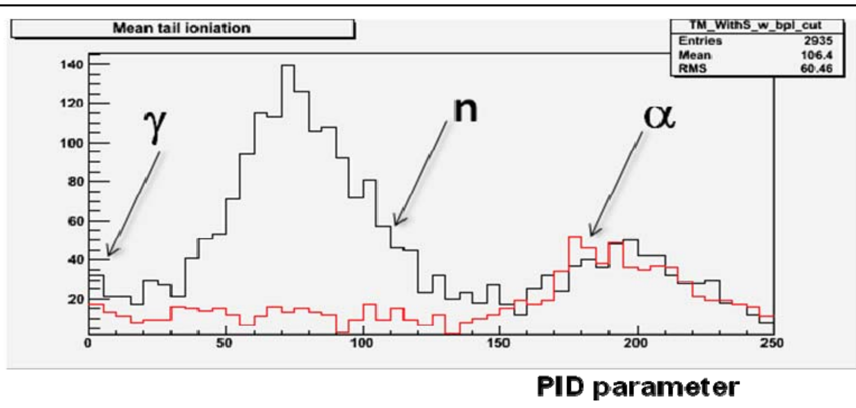

Figure 4
Particle identification in the current nTPC, using the mean ionization of the particle track tail. The background response of the nTPC is shown in red, the response to a neutron source in black. Electrons produced by gamma ray Compton scatters are strongly rejected, as they produce relatively little ionization density. The peak due to neutron scatters on protons is at about 1/3 the value of that for alpha particles, as expected.

By selecting events due to proton recoils we can study the angular response of this device. To date, sensitivity to fast neutrons from a ^{252}Cf fission source (strength equivalent to 6kg of WGPu) has been demonstrated out to 20m. The angular response achieved using 2 bar(a) of H_2 gas with the fission neutron source at 10m is shown in Figure 5. In this example, ~300,000 fast neutrons per second are emitted by the source, ~18 per second fall upon the active nTPC volume, ~0.3 neutrons per second scatter in the active volume, and 0.1 neutrons per second are recorded in the nTPC after analysis. That is, the neutron detection efficiency using H_2 at this pressure is approximately 0.5%.

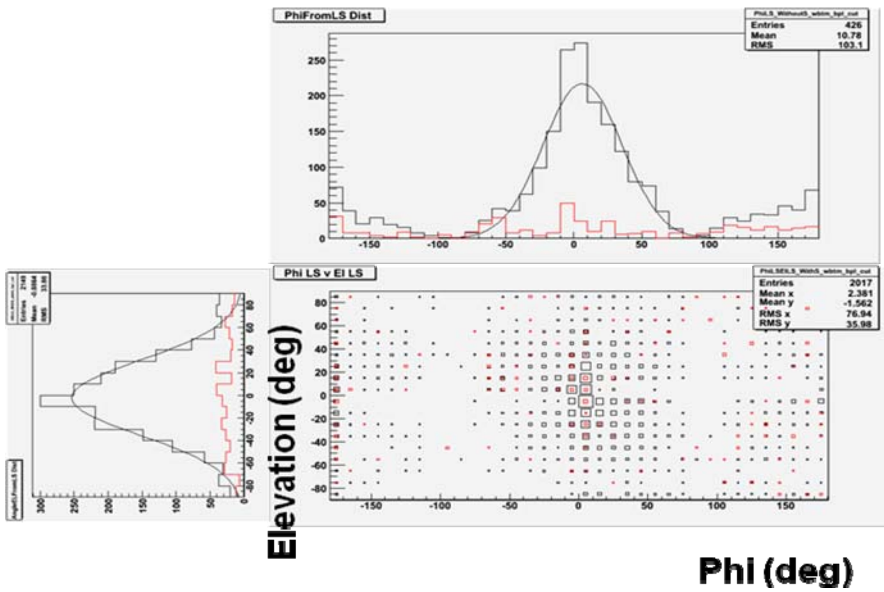

Figure 5
The response of the nTPC to fast neutron source at 10 meter standoff. The background response of the nTPC is shown in red, the response to a neutron source in black. Phi is the angle of the reconstructed recoil proton track in horizontal plane of the nTPC and the elevation is the angle of the track above or below that plane.

6 Conclusion

We have demonstrated a directional neutron detector based on proton recoils using a neutron TPC. This detector is particularly suitable for detection of fast neutrons produced by the SNM in the presence of background due to its ability to directly measure the direction and amplitude of the ionization profile of charged particles traversing the gas filled region. The detector strongly rejects gamma-ray events, since the specific ionization produced by Compton scattered electrons is very low compared to that for proton recoils.

We are currently using the laboratory prototype nTPC to understand the ultimate detection efficiency and pointing resolution that such a device can achieve. As part of this study we are also experimenting with other hydrogen bearing gases that have higher hydrogen density (e.g. CH_4), various gas pressures, and are studying the tradeoffs between neutron detection efficiency and pointing resolution that result. We are also developing a fieldable nTPC design using a lightweight and portable carbon fiber pressure vessel.

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