# Table-top neutron source for characterization and calibration of dark matter detectors

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A table-top plasma focus device is shown to be an ideal neutron source for the calibration and characterization of dark matter detectors and has been optimized to produce a maximum yield of $2.0 \times 10^7$ neutrons per shot. The interaction of energetic neutrons is similar to that expected from weakly interacting massive particles (WIMPs)—a favored candidate for the dominant component of dark matter in the universe. The weak interaction of a neutron with liquid xenon gas was measured in a prototype xenon two-phase detector. We have developed a detector system in which both the primary scintillation and ionization from the initial interaction can be detected. Both measurements are critical for identifying WIMP's. © *2002 American Institute of Physics.*
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Over the past several years there has been a significant amount of research with regard to the applications of plasma focus discharge devices. While they have been shown to be inexpensive and compact sources of intense x-rays,[1–3] neutrons,[4] and electron and ion beams,[5] the use of these devices for technological applications has not become widespread. X-ray and particle emission from the plasma focus have been demonstrated to be useful in applications such as lithography,[1,6] contact microscopy,[2] x-ray backlighting,[7] and materials research.[8] In addition, there have been extensive studies of neutron emission via deuterium fusion reactions in plasma focus devices.[9–12]

In this letter, we report the use of a plasma focus neutron source for dark matter research. The principal advantage of the plasma focus source compared with other sources is that it is inexpensive and extremely compact. In addition, it produces a large number of neutrons in a short pulse ($10^5$ neutrons with 100 J driver and $10^9$ neutrons with 10 kJ)[13] with a well defined energy (2.45 MeV), peaked in the forward direction (due to acceleration of ions in the axial direction). These properties make it much easier to calibrate and characterize proposed dark matter detector designs both in the laboratory and in underground experimental sites. This demonstration indicates that weakly interacting massive particles (WIMP) may be measurable using such detectors.

Experiments were performed on an innovative two-phase xenon prototype dark-matter detector which was designed to observe weakly interacting massive particles.[14] This detector contains both liquid and gaseous xenon and an incident particle produces scintillation and ionization in the liquid phase. An electric field is applied to drift the charge into the gas phase producing secondary scintillation. Analysis of the resulting scintillation signal can consequently allow discrimination of different particle types. It is believed

that a WIMP–xenon interaction would be very similar to a neutron–xenon interaction.[15] Therefore, a compact pulsed high flux source of energetic neutrons is necessary to test and calibrate these detectors.

A schematic of the prototype dark matter detector is shown in Fig. 1. It contains a photomultiplier and high voltage electrodes. The lower grid is used to shield the photomultiplier from the high voltage. The basic principle of the detector is as follows: A WIMP or neutron enters the detector and collides with a xenon nucleus in the liquid phase. The nucleus then recoils and produces scintillation and ioniza-
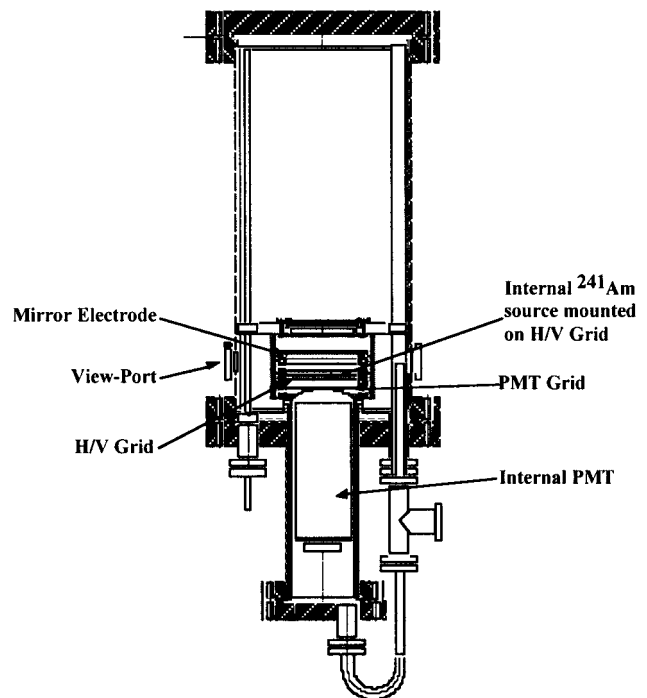


FIG. 1. Schematic of the two-phase prototype dark matter detector.

tion. The photons are detected immediately by the photomultiplier and the electrons drift due to the applied electric field upward through the liquid phase and escape into the gas phase. While drifting through the gas, the electrons produce secondary scintillation via electroluminescence in direct proportion to the amount of charge. The electroluminescence lasts during the full transit of the gas phase until the electrons reach the upper electrode. This then allows a measurement of both the scintillation and ionization from the original interaction by photometric means. The ratio of the two signals gives a direct measure of the ratio of scintillation to ionization in the interaction. This is highly dependent upon the density of the ionization [partial ionization and plasma type local shielding effects occur suppressing the level of ionization for densely ionizing (nuclei) objects] species of the interesting particle. Therefore, the measurement of the ratio of primary to secondary (ionization) scintillation allows clear discrimination between different interacting species. With the rather low interaction rate expected for WIMPs, it is important for a dark matter detector to be able to discriminate between signal and background events (primarily gamma rays). For example, the expected WIMP event rate in any target is between 0.1 and 0.01 events/kg/day with a background event rate of order of $10^6$ events/kg/day at a deep site 1.1 km underground.

The calibration of the two-phase prototype detector with electrons, $\alpha$-particles, etc. has been reported. Electron lifetime in excess of 100 $\mu$s was measured by sensing the charge on the top mirror electrode using a high gain charge sensitive amplifier.[14] The value of over 100 $\mu$s was obtained by reducing the electric field to less than 10 V/cm. Normal operation of the chamber is at a field of 5 kV/cm, where the drift time is reduced to less than 10 $\mu$s. The long free time is crucial for two reasons: First, the full-scale dark-matter detector, ZEPLIN III, will operate with three times the liquid depth. This will result in drift times in excess of 30 $\mu$s. In order for the detector to operate at full efficiency and sense single free electron produced from the WIMP-induced nuclear recoil, a lifetime in excess of this value is required. Secondly, a dark-matter detector will be required to run for long periods of time ($\sim$1 year) without any repurification or change. The electron lifetime is indicative of the level of impurities. Maintenance of a long lifetime will be a measure of low impurity level (ingressing from internal materials) and minimal degradation with time.

A compact table-top plasma focus in deuterium gas was used for the calibration. The plasma focus was a conventional Mather type. The details of the device can be found in Ref. 7. The electrode structure consists of a 50 mm long, 20 mm diameter copper tube anode, and an outer cathode of eight, 10 mm diameter copper rods uniformly spaced on a diameter of 45 mm. The anode and cathode were separated by a pyrex glass tube enclosing a 20 mm length of the anode. A triggered spark gap switch connected the anode to a 2.6 $\mu$F capacitor, charged to 38 kV, generating a peak current of 175 kA in 800 ns. A silver activation counter placed 28 cm in the side-on direction was used to record the integrated neutron signal. Photomultipliers each fitted with NE 102A scintillators were used as time of flight detectors. Photomultipliers were placed to detect the neutron emission in the end-on
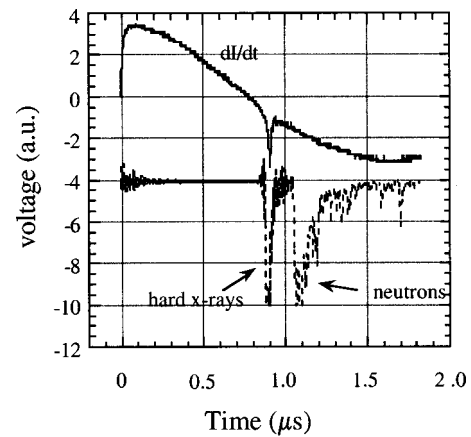


FIG. 2. $dI/dt$ trace with neutron signal recorded with a side-on photomultiplier.

and side-on directions. In addition, a number of *p-i-n* diodes fitted with hard and soft filters monitored the x-ray emission.

A typical $dI/dt$ trace is shown in Fig. 2. The dip in $dI/dt$ trace is associated with the formation of a pinched plasma column on the axis. A time-of-flight signal is also shown in Fig. 2. The first peak is caused by prompt hard *x* rays at the time of pinching and the second is the signal from $D(d,n)^3$He fusion reactions. From the time-of-flight signals, the neutron energy is $\sim$2.7$\pm$0.4 MeV in the end-on direction and 2.4$\pm$0.5 MeV in the side-on direction. The neutron yield was larger in the end-on direction. The difference of energy and anisotropy of neutron emission is due to the generation of a directed beam of deuterons in the axial direction.

The neutron yield measured by activation counter is shown as a function of deuterium gas fill pressure in Fig. 3. Each point is the mean of ten shots and the error bars are the standard deviations. The yield is maximum of 2.0$\pm$0.5 $\times 10^7$ at 3.5 mbar. This yield agrees well with established scaling laws[13] $- Y = 10^7 E^2$ and $Y = I^{3.3}$ ($E$ in kJ and $I$ in kA).

In order to simplify calibration and analysis, the dark matter detector was completely filled with liquid xenon and no electric field was applied, so that there is no secondary scintillation in the gas. The pulses were similar to that observed with side-on and end-on photomultipliers placed around the plasma focus as shown in Fig. 2.

Once the interaction of neutrons with liquid xenon was established, both liquid and gaseous phases of xenon were introduced into the detector and an electric field was applied. Figure 4 shows the photomultiplier trace when an electric field of 5 kV/cm in liquid xenon and 10 kV/cm in gas xenon was applied. In order to avoid complications due to multiple
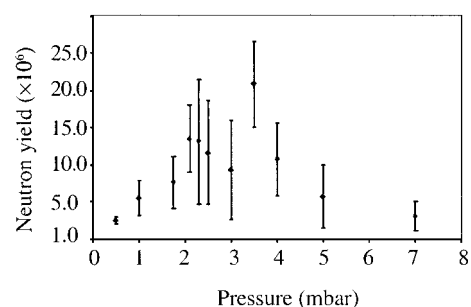


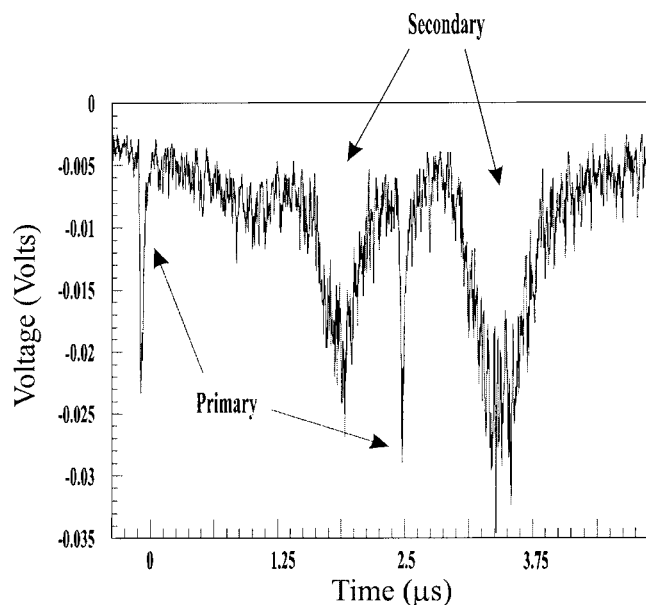FIG. 3. Total neutron yield versus deuterium filling pressure.

FIG. 4. Photomultiplier signal with both liquid and gas xenon with electric field switched on in both phases.

neutron interaction in liquid xenon and the subsequent scattering (elastic and inelastic), the signals were observed at very late times—100's of microseconds after the prompt hard x-ray signal. The first peak is that due to the scintillation by photons produced by the neutron–xenon interaction in the liquid, which results in the recoil of the nucleus. The electron produced in the process drifts upwards through the liquid phase and into the gas, where ionization is produced through electroluminescence and is responsible for the second peak. The lifetime of the electron signal was estimated to be greater than 100 $\mu$s as measured previously[14] and as explained herein is of crucial importance for dark matter detection.

In conclusion, we have reported the measurements of the interaction of neutrons with liquid xenon in a prototype dark-matter detector. This indicates that such detectors may be able to measure the existence of WIMPs in larger scale experiments. Interpretation of the data is complicated by multiple interactions causing both elastic and inelastic scattering within the experimental room, which produces signals up to 1 ms after the initial pulse. This is coupled with the relatively long event length in the detectors (several $\mu$s) due to the electrons drifting into the gas phase. Future experiments will be performed with increased collimation between the neutron source and the detector to allow more accurate temporal identification and reduce the event rate such that elastic and inelastic interactions can be distinguished.

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