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Observation of the "head-tail" effect in nuclear recoils of low-energy neutrons

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Abstract

Directional detection of dark matter can provide unambiguous observation of dark matter interactions even in the presence of background. This article presents an experimental method to measure the direction tag ("head-tail") of the dark matter wind by detecting the scintillation light created by the elastic nuclear recoils in the scattering of dark matter particles with the detector material. The technique is demonstrated by tagging the direction of the nuclear recoils created in the scattering of low-energy neutrons with CF_4 in a low-pressure time-projection chamber that is developed by the DMTPC collaboration. The measurement of the decreasing ionization rate along the recoil trajectory provides the direction tag of the incoming neutrons, and proves that the "head-tail" effect can be observed.

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1. Introduction

Searches for non-baryonic dark matter in the form of weakly interacting massive particles (WIMPs) rely on detection of nuclear recoils created by the elastic scattering between a WIMP and the detector material. The current generation of experiments [1] attempt to suppress all backgrounds to negligible levels so that any remaining events would be attributed to the WIMP signal. However, as the size of the apparatuses increases and the sensitivity to dark matter improves, some irreducible backgrounds will start to appear, rendering a positive observation of a dark matter signal suspect. Examples of such backgrounds are nuclear recoils due to neutrons generated by cosmic rays in the rock surrounding the detector, or neutrinos from the sun [2]. The measurement of an annual modulation of the interaction rate of dark matter has been suggested [3], but this effect is expected to be small (a few percent).

An unambiguous observation of dark matter in presence of background is possible by detecting the direction of the incoming dark matter particles. As the Earth moves in the galactic halo with a velocity of approximately 220 km/s, the dark matter particles appear to come from the Cygnus constellation. By measuring the direction of the WIMPs and correlating such measurement with the position of Cygnus in the sky, an experiment can gain orders of magnitude in sensitivity to dark matter [4]. The determination of the vector direction of the incoming particle, often referred to as the "direction tag" or the "head-tail", is very important since it further increases the sensitivity of a directional detector by approximately an order of magnitude [5].

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The DRIFT experiment [6] pioneered the study of directional detection of dark matter and demonstrated the ability to reconstruct the direction of the incoming particles by detecting the direction of recoiling nuclei in a gaseous detector. However, the capability of detecting the direction tag of the incoming particles has not been demonstrated by any experiment to date.

This paper demonstrates a technique to determine the direction tag ("head-tail") of low-energy nuclear recoils created by dark matter particles by using a time-projection chamber (TPC) with optical readout developed by the DMTPC collaboration. The projection of nuclear recoils along the anode wires of the TPC is recorded by a charge-coupled device (CCD) camera imaging the scintillation photons produced during the avalanche process. The measurement of the direction tag relies on the fact that the stopping power (dE/dx) of recoiling nuclei depends on their residual energy, and therefore the recoil direction can be tagged from the light distribution along the track. The energy of the nuclear recoils created by the scattering of low energy neutrons or dark matter particles is of the order of a few keV per nucleon, well below the Bragg peak. Therefore a decreasing light yield along the track is expected.

2. Experimental setup

A schematic of the detector is shown in Fig. 1. The chamber utilizes $10 \times 10\,\text{cm}^2$ wire frames. The drift region between the cathode mesh and the ground wire plane is 2.6 cm, while the amplification region between the ground and the anode wire planes is about 3 mm. The pitch of the wires for the ground (anode) plane is 2 mm (5 mm) and the wire diameter is 50 μm (100 μm). The chamber is filled with CF_4 at 150−380 Torr. The pressure is monitored with a capacitance gauge (Inficon PCG400) in the calibration runs with alpha particles, and a thermocouple gauge (LVG-200TC) in the nuclear scattering runs.

The scintillation light is recorded with a CCD camera manufactured by Finger Lake Instrumentation equipped with a 768×512 CCD chip (Kodak KAF-0401E). The camera has a built-in cooler that maintains the temperature in the range [−20, −18] C to minimize electronic noise. The pixel size is $9 \times 9\,\mu\text{m}^2$. The photographic lens has the aperture ratio, $f/\#$ of 1.4 and the focal length of 55 mm. The peak value for the quantum efficiency of the CCD chip is approximately 80%. The gain of the camera is measured to be 1.6 e^-/ADC count. The RMS spread of pixel yields due to ADC noise and dark current is measured to be seven counts when all pixels are read out, and 25 counts when 8×8 pixels are combined during the CCD readout. Pixels that have intensity greater than five standard deviations from the mean dark field at least 10% of the time are flagged as 'hot channels' and excluded in the data analysis. ADC bias is corrected for by subtracting from each image the average of 100 images taken with the shutter closed.

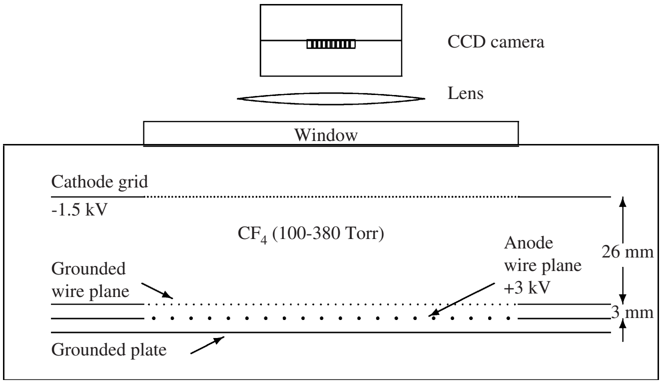

Fig. 1. A schematics of the detector.

Neutrons used in this work are produced isotropically with 14.1 MeV energy from deuteron–triton reactions in a neutron generator (Thermo MF Physics A-325). The deuterium plasma is generated by a 3 kV voltage pulse and accelerated through a 70 kV region toward a triton target. The pulses are 100 μs wide and issued at a frequency of 1 kHz. Using the manufacturer's specifications, the total isotropic flux of neutrons is estimated to be 5×10^7 neutrons/s.

3. Calibration with α source

The detector response is evaluated using 5.5 MeV α particles from a collimated ^{241}Am source. The chamber is filled with CF_4 at various pressures in the range 100−380 Torr. The drift field is set to 580 V/cm, while the amplification voltage is varied between 2.1 and 4.1 kV. Images are taken sequentially with 1 s exposure time.

Fig. 2 shows the accumulation of 12 images of α tracks from a source placed in the upper-left corner of the CCD field of view with its collimator pointing toward the lower-right corner. The anode wires are oriented parallel to the α source. As the particle travels in the medium, the intensity of the scintillation light increases until it reaches a maximum corresponding to the Bragg peak, and then decreases toward the end of the track. The longitudinal scintillation profile is shown in the lower plot of Fig. 2. This profile can be described with the energy loss due to ionization and excitation of gas molecules. This assumption is verified by fitting the distribution with the stopping power curve obtained with the SRIM simulation. The result of such a fit is shown in the same plot.

The range of α particles in CF_4 is obtained by varying the end-point of the track in the fit. Images at pressures ranging from 280 to 380 Torr are taken in 20 Torr increments. The range measured in data (R_{data}) is compared with values predicted by the simulation (R_{SRIM}). The agreement between data and simulation is found to be within the experimental errors, $R_{\text{data}}/R_{\text{SRIM}} = 0.85 \pm 0.11(\text{stat}) \pm 0.10(\text{syst})$.

The gain of the detector is determined by measuring the intensity of the scintillation light recorded by the CCD camera as a function of the energy deposited in the detector

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