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

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Abstract. We present an experimental method to determine the direction tag (“head-tail”) of dark matter wind using a low-pressure time-projection chamber. We demonstrate the method by tagging the direction of the elastic nuclear recoils created in the scattering of low-energy neutrons with CF₄ nuclei. The decreasing ionization rate along the recoil trajectory allows us to determine the direction of the incoming neutrons, and proves that the “head-tail” effect can be measured.

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 [1]. As the size of the experiments increases and the sensitivity to dark matter improves, some irreducible backgrounds will start to appear (e.g. [2]) rendering positive identification of dark matter signal difficult. 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, the dark matter particles appear to come from the Cygnus constellation. The direction tag of the of the incoming particle, often referred to as the “head-tail” effect, is very important since it increases the sensitivity of a directional detector by one order of magnitude [3].

In this paper we describe and demonstrate a technique to tag the direction of low-energy nuclear recoils created by dark matter particles by using a time-projection chamber with optical readout. The measurement relies on the fact that the stopping power (dE/dx) of recoiling nuclei depends on their residual energy, and therefore the direction of the recoil can be tagged from the light distribution along the track.

2. Observation of “head-tail” effect
The detector is in more details described in [4]. The chamber utilizes 10 × 10 cm² wire frames. The drift region between the cathode mesh and the ground wire plane is 2.6 cm with average electric field of 580 V/cm, while the amplification region between the ground and the anode wire plane (+3 kV) 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 scintillation light is recorded with a cooled CCD camera equipped with a photographic lens that images approximately 1 cm$^2$ of the anode plane. The spread of pixel yields due to ADC noise and dark current is 25 counts. Images are corrected for ADC bias and hot channels are identified and excluded from analysis.

Nuclear recoils are created in scattering with the 14.1 MeV neutron beam produced from deuteron-triton reactions. We estimate the total flux of 5000 neutrons per second into the solid angle of detector. The wires of the tracking chamber are aligned with the direction of the neutron beam. The recoil length projected to the wire axis is roughly 5 times longer in case of WIMP scattering, therefore, observation of “head-tail” effect in neutron scattering is expected to be harder. We take sequential 1-second exposures with the CCD camera. We expect a few percent of the exposures to contain the signature of an elastic fluorine recoil which has the cross section of 0.9 b [6]. The dominant background comes from the F(n,n+α)N process with the cross section estimated at 0.45 b. However, the α particles produced in this process are more energetic and have smaller energy loss than fluorine recoils, so they can be easily rejected. Empty images that make up around 70% of our data sample are rejected. We also reject images that have segments shorter than 0.36 mm, images with more than one segment per wire, and recoil tracks that fall close to the boundary of the CCD field of view. If a recoil is found to have scintillation light at two wires, we use the wire with the larger scintillation signal in the analysis. Approximately 5-7% of all events pass the selection criteria.

![Figure 1](image.png)

Figure 1. An image of recoil track showing CCD coordinates and pixel intensity. Neutrons are coming from the right. The noticeable asymmetry of the light yield along the wire indicates observation of the “head-tail” effect.

An image of a nuclear recoil in Figure 1 shows noticeable asymmetry of the light yield along the wire. In order to quantify this effect, we define the skewness $\gamma$ as the dimensionless ratio between the third and second moments of the light yield along the wire coordinate $(x)$:

$$\gamma = \frac{\langle (x - \langle x \rangle)^3 \rangle}{\langle (x - \langle x \rangle)^2 \rangle^{3/2}}.$$  \hspace{1cm} (1)

The skewness $\gamma$ provides a simple measure of the “head-tail” asymmetry. This quantity is zero for perfectly symmetric distributions, and non-zero for asymmetric distribution around the mean. The sign of the skewness indicates the slope of the light intensity along the track. Recoils that travel in the direction of the incoming neutrons have a decreasing light profile, and therefore a negative skewness. The skewness is defined to be dimensionless, and so it is not affected if the coordinate is multiplied by a constant factor, which in our case is the cosine of the recoil angle with respect to the wire. However, shorter segments can be affected by the finite detector resolution.
A plot of the measured skewness as a function of the segment length is shown in the top-left plot of Figure 2. The skewness is measured to be negative in (74 ± 4)% of events, as expected for the nuclear recoils from neutrons. The head-tail asymmetry is easier to observe for longer tracks that are better aligned with the anode wires and create more scintillation light. The top-left plot in Figure 2 shows the fraction of events with negative skewness as a function of the track length. The bottom plot of Figure 2 shows the mean values and the dispersion of the skewness in data and simulation. The agreement between data and simulation is satisfactory.

3. Discussion of Results
We exclude the possibility that the “head-tail” asymmetry is created by imperfections in the construction of the tracking chamber by taking a fraction of the data with anode wires rotated by 180 degrees with respect to the neutron beam. The measurement of the skewness is consistent in the two data-sets.

We collect data with the neutron beam perpendicular to the anode wires. In this configuration there are an equal number of recoils traveling in both directions, resulting in an equal number of events with positive and negative skewness. The number of events with negative skewness is measured to be (47.3 ± 2.5)%%, consistent with the expected symmetric distribution.

We also compute the skewness of hits created by α tracks traveling perpendicularly to the

Figure 2. Top-left: skewness as a function of the track length of the recoil segments. Open and closed circles refer to wire planes at 0º and 180º w.r.t. direction of neutrons. Top-right: fraction of events with negative skewness as a function of the track length. Bottom: comparison between data and simulation for the same distribution. The position of the dots (solid line) represents the mean value in each bin for data (MC). The error bars (shadowed region) measure the dispersion for data (MC) in each bin.
anodes. We measure the average skewness to be $\langle \gamma \rangle = 0.032 \pm 0.024$, consistent with having symmetrical scintillation transverse to the direction of the trajectory.

We consider the possibility that the scintillation signal is affected by recoil tracks leaving the drift region. We conclude that such segments would have abrupt endings, which is inconsistent with the slowly dimming signals that we observe in data.

Since the measured light yield is proportional to the energy of the recoil segment and the length is proportional to the track range projected to the wire, these two quantities should be correlated. Figure 3 shows clear correlation between the light yield versus length of the recoil segments measured in data.

![Figure 3. Correlation between the total light yield and the length of the recoil segments in data. Open (closed) circles refer to wire planes at 0° (180°) with respect to the direction of the incoming neutrons.](image)

As a final check, we collect data without sources and search for signatures that resemble nuclear recoils. In this analysis we count events with pixel yields at least five standard deviations above the background level. We measure the rejection rate to be approximately $10^{-3}$, which can be further improved by taking into account the range and direction of recoil candidates.

We assign a conservative error of 20% to the density of the CF$_4$ gas to account for problems with our pressure measurement. The error on the energy measurement from the light yield is dominated by systematic uncertainties on the non-uniformity in wire gain, the stability of the gain over time, and the pressure measurement. The statistical uncertainty on the energy measurements is about 10%. The error on the recoil range comes from the non-uniformity in the wire pitch (10%) and the analysis technique that overestimates the range for low-energy recoils with the range close to the diffusion width.

4. Conclusion

We have demonstrated a method for tagging the direction of low-momentum nuclear recoils generated in the elastic scattering of low-energy neutrons with CF$_4$ gas. The direction tag of the incoming particle is determined from the profile of the scintillation light along the track trajectory. This study has profound implications for the development of directional dark matter detectors, as it proves for the first time that “head-tail” discrimination is indeed feasible. Directional detectors will be essential to produce convincing evidence for dark matter particles in the presence of backgrounds.

5. References

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