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The Dark Matter Time Projection Chamber 4Shooter directional dark matter detector: Calibration in a surface laboratory

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ABSTRACT

The 4Shooter is a prototype dark matter detector built by the Dark Matter Time Projection Chamber (DMTPC) collaboration. The aim of the collaboration is to observe dark matter with directional sensitivity by measuring the recoil directions of nuclei struck by dark matter particles. The 4Shooter is a single time projection chamber containing CF_4 gas, with both optical (CCD and photomultiplier tube) and charge readout. This paper describes the 4Shooter and presents results from the commissioning of the detector in a surface laboratory.

1. Introduction

By now, astrophysical observations provide compelling evidence that over 80% of the matter content of the universe is non-baryonic [1,2]. Although astrophysical observations constrain the gross anatomy of dark matter, direct detection experiments have not yet produced a definitive detection of dark matter. There are many viable theoretical dark matter candidates [3]. A popular and well-motivated dark matter candidate is the Weakly Interacting Massive Particle (WIMP), and a global effort is underway to detect and characterize the particle properties of WIMPs. This paper presents results from the calibration of the 4Shooter detector, a prototype directional dark matter detector built by the Dark Matter Time Projection Chamber (DMTPC) collaboration.

The field of direct WIMP detection aims to identify the interaction of a dark matter particle with a baryonic target in a detector by measuring WIMP-induced nuclear recoils [4,5]. Most of these detectors measure the recoil energy through one or more of ionization, scintillation or thermal energy deposition. A common observable for these detectors is the nuclear recoil energy spectrum (or integrated spectrum in the case of threshold detectors), and the nuclear recoil rate versus time. A challenge in direct detection is that the predicted recoil energy spectrum is a featureless falling exponential, which is degenerate with the neutron background-induced energy spectrum. Furthermore, the other main signature, the annual modulation in the event rate, is a few percent effect at realizable thresholds and may be similar to backgrounds that modulate annually [6,7].

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The current status of direct WIMP detection is challenging to interpret. At low WIMP mass (~10 GeV/c^2), the DAMA/LIBRA and CoGeNT experiments report excesses of events that they attribute to dark matter [8,9]. Additionally, the three nuclear recoil candidates found by the CDMS silicon search favor a 8.6 GeV/c^2 WIMP over a background-only model [10]. Meanwhile, published results from several direct detection experiments [11–14] exclude some or all of the parameter space of these candidate signals.

Over 25 years ago, nuclear recoil direction was proposed as a more definitive signature for dark matter interactions [15]. The motion of the Earth through the galactic WIMP halo should produce a head-wind of WIMP dark matter and therefore an anisotropy in the direction of nuclear recoils in the galactic frame. This corresponds to a daily directional oscillation of the mean recoil direction in the detector frame. Known backgrounds, on the other hand, are generally isotropic in the galactic frame, so directional detectors can test for anisotropies in the angular recoil spectrum with only a few WIMP events, even in the presence of backgrounds [16–20]. Because tracking detectors can measure both recoil track length and energy deposition, they can use the charge-to-mass ratio dependency of the stopping power to discriminate the signal from backgrounds on an event-by-event basis (except in the case of background nuclear recoils, which can be differentiated from the signal statistically through the use of directional information). Furthermore, directional detectors could eventually be used for dark matter astrophysics to distinguish between dark matter halo models [21]. For an overview of directional detection see Ref. [22].

The challenge of directional detection is to build a detector with many kg of target mass while maintaining recoil direction sensitivity. There is a long history of work toward that goal, including gas-based [23] and solid crystal scintillator based detectors [24–26]. At present, there are six active directional dark matter detection experiments underway worldwide. One group uses nuclear emulsions read out by high-resolution microscopy [27]. The other five make use of diffuse-gas targets in which low-energy nuclear recoil tracks extend $\mathcal{O}(1\ \mathrm{mm})$ and can therefore be reconstructed. These experiments are the Dark Matter Time Projection Chamber (DMTPC) [28], D^3 [29], DRIFT [30], MIMAC [31], and NEWAGE [32]. Of these groups, DMTPC and the latter three have detectors operating underground, and three have set dark matter limits [28,33,34]. In addition to these six experiments, there is exploratory work on other technologies including columnar recombination in high pressure (10 bar) xenon gas [35], a biological tracking chamber using strands of DNA anchored to thin gold foils [36], roton anisotropy in liquid helium [37], and continued work on anisotropic photon emission in crystal scintillators [38]. In this work, we describe the DMTPC 4Shooter prototype directional dark matter detector and present basic detector performance measurements.

2. 4Shooter overview

The 4Shooter is a Time Projection Chamber (TPC) with both optical (CCD and photomultiplier tube) and charge readout. The CCDs image the TPC amplification plane, and therefore provide a 2D projection of recoil tracks. CCDs provide high spatial resolution with a simple interface (USB cable to a PC) at a low cost per channel. Furthermore, the CCDs couple optically to the detector volume through vacuum viewports and are therefore not in contact with the target gas, reducing sources of outgassing and suppressing alpha backgrounds.

Prior to the 4Shooter, DMTPC demonstrated successful track reconstruction, including vector recoil direction determination (head/tail) with CCDs [39,40]. Additionally, a surface run with a 10-liter prototype DMTPC detector (called the 10L) produced a limit on the WIMP–proton spin-dependent interaction that was the strongest limit from a directional detector at the time [28]. The 4Shooter is a factor of two larger in active volume than the 10L and was designed as a platform to test the technologies needed for the next-generation DMTPC detector, a cubic-meter volume detector called DMTPCino [41]. In particular, the 4Shooter design focused on material selection and made use of rigorous cleaning procedures for all detector components. Also, the 4Shooter uses four CCD cameras to make a mosaic image of the full active region of the TPC, as will be done in DMTPCino (in the 10L detector, each CCD imaged a subset of the active region of a single TPC). Based on background studies carried out with the 10L detector, the 4Shooter employs a current-sensitive amplifier for electron recoil rejection [42], and a current monitor on the amplification region power supply for independent tagging of spark events in the detector. Finally, the 4Shooter incorporates PMT readout, which along with the charge readout channels can be used to investigate the potential for full 3D tracking and for triggered readout of the CCD cameras.

In this paper, we describe the 4Shooter detector and readout channels. We also present the results of the surface commissioning of the detector, including the calibration of the CCD and charge readout channels, and measurements of the gas gain and electron diffusion. Forthcoming publications will detail the head-tail reconstruction capability of the 4Shooter, as well as the algorithms used to identify and reconstruct properties of tracks in the CCD images. Additional detail is provided in Refs. [43,44].

3. Choice of detector gas

An advantage of diffuse-gas TPC detectors is the ability to alter the target gas with little to no modification of the detector hardware. In the past, DMTPC and other groups have experimented with a broad range of detector gases and gas mixtures for dark matter and related applications. For example, the DMTPC group has measured ionization tracks in Xe+CF_4 mixtures [45]. Other directional detection groups use fluorine-rich gases such as CHF_3, and the negative-ion drift mixture of CS_2 and CF_4 [31,33]. TPCs with optical readout have also been used with a He–CF_4 mixture to monitor neutron backgrounds at the Double Chooz neutrino experiment [46] and neutrons from fissile material for homeland security applications [47].

The current DMTPC scientific program focuses on the WIMP–proton spin-dependent interaction [48], for which fluorine is a sensitive target [49]. The 4Shooter detector uses CF_4 gas because of its high fluorine content, and because it has good detector properties, namely high scintillation yield with emission spectrum well-matched to CCD readout [50,51], and low electron diffusion for a proportional gas [52].

The operating CF_4 pressure is typically in the range of 60–100 Torr and represents a trade-off between track length and particle stopping power, as well as target mass and stability of detector operation. At higher gas pressure, the larger stopping power enhances the *signal-to-noise* in a CCD pixel, however the shorter tracks at higher pressure make head–tail reconstruction more challenging. The majority of the commissioning data for the 4Shooter was taken at 60 Torr. Studies have shown [53,54] that for directional detection of 100 GeV/c^2 WIMPs, the optimum CF_4 operating pressure is 10–30 Torr (depending on the details of the readout). It would be advantageous to operate the 4Shooter detector at a lower gas pressure, but we are currently limited by the stability of the amplification region (see Section 8.2).