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 CF₄ gas, with both optical

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(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.

Keywords: Dark matter, WIMP, direct detection, directional detection, DMTPC, CCD, TPC, dark matter wind

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

20 that the predicted recoil energy spectrum is a featureless falling exponential,
21 which is degenerate with the neutron background-induced energy spectrum.
22 Furthermore, the other main signature, the annual modulation in the event
23 rate, is a few percent effect at realizable thresholds and may be similar to
24 backgrounds that modulate annually [6, 7].

25 The current status of direct WIMP detection is challenging to inter-
26 pret. At low WIMP mass (~ 10 GeV/c²), the DAMA/LIBRA and Co-
27 GeNT experiments report excesses of events that they attribute to dark
28 matter [8, 9]. Additionally, the three nuclear recoil candidates found by
29 the CDMS silicon search favor a 8.6 GeV/c² WIMP over a background-only
30 model [10]. Meanwhile, published results from several direct detection ex-
31 periments [11, 12, 13, 14] exclude some or all of the parameter space of these
32 candidate signals.

33 Over 25 years ago, nuclear recoil direction was proposed as a more defini-
34 tive signature for dark matter interactions [15]. The motion of the Earth
35 through the galactic WIMP halo should produce a head-wind of WIMP dark
36 matter and therefore an anisotropy in the direction of nuclear recoils in the
37 galactic frame. This corresponds to a daily directional oscillation of the
38 mean recoil direction in the detector frame. Known backgrounds, on the
39 other hand, are generally isotropic in the galactic frame, so directional de-
40 tectors can test for anisotropies in the angular recoil spectrum with only a
41 few WIMP events, even in the presence of backgrounds [16, 17, 18, 19, 20].
42 Because tracking detectors can measure both recoil track length and energy
43 deposition, they can use the charge-to-mass ratio dependency of the stop-
44 ping power to discriminate signal from backgrounds on an event-by-event

45 basis (except in the case of background nuclear recoils, which can be differ-
 46 entiated from signal statistically through the use of directional information).
 47 Furthermore, directional detectors could eventually be used for dark matter
 48 astrophysics to distinguish between dark matter halo models [21]. For an
 49 overview of directional detection see Ref. [22].

50 The challenge of directional detection is to build a detector with many kg
 51 of target mass while maintaining recoil direction sensitivity. There is a long
 52 history of work toward that goal, including gas-based [23] and solid crystal
 53 scintillator based detectors [24, 25, 26]. At present, there are six active direc-
 54 tional dark matter detection experiments underway worldwide. One group
 55 uses nuclear emulsions read out by high-resolution microscopy [27]. The other
 56 five make use of diffuse-gas targets in which low-energy nuclear recoil tracks
 57 extend $\mathcal{O}(1\text{ mm})$ and can therefore be reconstructed. These experiments are
 58 the Dark Matter Time Projection Chamber (DMTPC) [28], D³ [29], DRIFT
 59 [30], MIMAC [31], and NEWAGE [32]. Of these groups, DMTPC and the
 60 latter three have detectors operating underground, and three have set dark
 61 matter limits [28, 33, 34]. In addition to these six experiments, there is ex-
 62 ploratory work on other technologies including columnar recombination in
 63 high pressure (10 bar) xenon gas [35], a biological tracking chamber using
 64 strands of DNA anchored to thin gold foils [36], roton anisotropy in liquid
 65 helium [37], and continued work on anisotropic photon emission in crystal
 66 scintillators [38]. In this work, we describe the DMTPC 4Shooter prototype
 67 directional dark matter detector and present basic detector performance mea-
 68 surements.

69 2. 4Shooter overview

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

78 Prior to the 4Shooter, DMTPC demonstrated successful track reconstruc-
79 tion, including vector recoil direction determination (head/tail) with CCDs
80 [39, 40]. Additionally, a surface run with a 10-liter prototype DMTPC detec-
81 tor (called the 10L) produced a limit on the WIMP-proton spin-dependent
82 interaction that was the strongest limit from a directional detector at the
83 time [28]. The 4Shooter is a factor of two larger in active volume than
84 the 10L and was designed as a platform to test the technologies needed for
85 the next-generation DMTPC detector, a cubic-meter volume detector called
86 DMTPCino [41]. In particular, the 4Shooter design focused on material
87 selection and made use of rigorous cleaning procedures for all detector com-
88 ponents. Also, the 4Shooter uses four CCD cameras to make a mosaic image
89 of the full active region of the TPC, as will be done in DMTPCino (in the 10L
90 detector, each CCD imaged a subset of the active region of a single TPC).
91 Based on background studies carried out with the 10L detector, the 4Shooter
92 employs a current-sensitive amplifier for electron recoil rejection [42], and a
93 current monitor on the amplification region power supply for independent

94 tagging of spark events in the detector. Finally, the 4Shooter incorporates
95 PMT readout, which along with the charge readout channels can be used to
96 investigate the potential for full 3D tracking and for triggered readout of the
97 CCD cameras.

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

105 **3. Choice of detector gas**

106 An advantage of diffuse-gas TPC detectors is the ability to alter the tar-
107 get gas with little to no modification of the detector hardware. In the past,
108 DMTPC and other groups have experimented with a broad range of detector
109 gases and gas mixtures for dark matter and related applications. For exam-
110 ple, the DMTPC group has measured ionization tracks in Xe+CF₄ mixtures
111 [45]. Other directional detection groups use fluorine-rich gases such as CHF₃,
112 and the negative-ion drift mixture of CS₂ and CF₄ [31, 33]. TPCs with opti-
113 cal readout have also been used with a He-CF₄ mixture to monitor neutron
114 backgrounds at the Double Chooz neutrino experiment [46] and neutrons
115 from fissile material for homeland security applications [47].

116 The current DMTPC scientific program focuses on the WIMP-proton
117 spin-dependent interaction [48], for which fluorine is a sensitive target [49].

118 The 4Shooter detector uses CF_4 gas because of its high fluorine content, and
119 because it has good detector properties, namely high scintillation yield with
120 emission spectrum well-matched to CCD readout [50, 51], and low electron
121 diffusion for a proportional gas [52].

122 The operating CF_4 pressure is typically in the range of 60 to 100 Torr and
123 represents a trade-off between track length and particle stopping power, as
124 well as target mass and stability of detector operation. At higher gas pres-
125 sure, the larger stopping power enhances the signal-to-noise in a CCD pixel,
126 however the shorter tracks at higher pressure make head-tail reconstruction
127 more challenging. The majority of the commissioning data for the 4Shooter
128 was taken at 60 Torr. Studies have shown [53, 54] that for directional detec-
129 tion of 100 GeV/c² WIMPs, the optimum CF_4 operating pressure is 10–30
130 Torr (depending on the details of the readout). It would be advantageous to
131 operate the 4Shooter detector at a lower gas pressure, but we are currently
132 limited by the stability of the amplification region (see Section 8.2).

133 4. Vacuum chamber and gas system

134 4.1. Vacuum system

135 The active region of the DMTPC 4Shooter detector is housed inside a
136 vacuum chamber (manufactured by Sharon Vacuum in Massachusetts, USA)
137 to contain the CF_4 gas and maintain its purity (see Figure 1). This is crucial,
138 as electronegative contaminants such as oxygen capture ionization electrons
139 in the gas and degrade the system gain of the detector. The vacuum chamber
140 interior was electropolished, and metal seals were used where possible to
141 minimize outgassing and permeation into the target gas.

142 The vacuum chamber consists of a cylindrical bell jar that mates via a
143 wire seal to a round bottom flange (see Fig. 2). This main seal can be made
144 with either a single-use copper or a reusable elastomer gasket. In the work
145 described here, the elastomer seal was used. The inner diameter of the bell
146 jar is 39.8 cm, and there is 46.4 cm vertical clearance between the vacuum
147 side of the bell jar lid and the vacuum side of the bottom flange. The main
148 chamber volume is therefore 60 L. The flat top of the bell jar has five ConFlat
149 (CF) optical viewports (four 6" CF for CCD cameras and one 2-3/4" CF for
150 three PMTs, see Section 6). The bottom flange has a 6" CF pump-out port
151 that connects via a 6" to 4-1/2" CF reducer to a pneumatically driven 4-1/2"
152 CF VAT UHV gate valve and then to a Varian V81-M turbo pump with a
153 4-1/2" CF flange. The turbo is backed by an Edwards XDS-5 dry scroll
154 pump. The chamber pressure is monitored by two pressure gauges attached
155 to the bottom flange. The first gauge is a capacitance manometer, which
156 provides an accurate pressure reading (0.2%) independent of gas composition,
157 but only above 0.5 Torr. The second is a combination Bayard-Alpert Pirani
158 gauge, which operates from atmosphere to 10^{-10} Torr, but is gas-composition
159 dependent.

160 4.2. Gas system

161 During standard operation, the chamber is evacuated, typically below
162 10^{-5} Torr, and then back-filled with CF_4 gas through a gas-input port on
163 the bottom flange of the chamber. Prior to back-filling, the observed rate of
164 pressure rise is a few millitorr per hour. An MKS 1479A Mass Flow Con-
165 troller (MFC) regulates the flow rate of the supply gas. Gas fills are done by
166 computer control and can be initiated and monitored through the detector's

Figure 1: Left: CAD model of the 4Shooter detector, showing two of the four CCD ports on the top of the vessel, as well as the field cage structure inside the vacuum vessel. A single PMT port containing three PMTs is surrounded by the four CCD ports. Right: A composite image of the 4Shooter detector showing the vessel exterior with an overlaid, semi-transparent image of the copper field cage structure contained inside the vessel.

Figure 2: Schematic of the 4Shooter gas and vacuum system.

web interface (see Section 7). When the fill is complete, the electromagneti-
cally actuated valve seals the chamber. An evacuate-and-refill cycle generally
lasts 10 min. At present, a gas circulation and purification system is not used,
but on a larger detector, such a system may be desirable.

5. Time Projection Chamber

The cylindrical TPC is housed inside the vacuum vessel and consists of
a drift region and an amplification region (see Figure 3). Ionizing radia-
tion traversing the drift region loses energy through interactions with the
surrounding gas. The resulting ionization electrons are driven toward the

176 amplification region by a drift field. Once in the amplification region, the
 177 electrons experience a large electric field resulting in exponential amplifica-
 178 tion of the ionization charge, as well as the production of scintillation light
 179 from molecular deexcitation. The CCD cameras image the scintillation light
 180 through the mesh cathode and ground electrodes. This section describes the
 181 drift and amplification regions of the 4Shooter.

182 5.1. Drift region

183 The drift region defines the active volume of the detector (see Figure 4).
 184 High transparency meshes are used for the drift end-cap electrodes to en-
 185 sure high optical throughput from the amplification region to the CCDs and
 186 PMTs. The top electrode (the cathode) is a woven stainless steel mesh (50 lpi,
 187 30 μm wire diameter, 89% transparency¹) biased at a large negative voltage
 188 (generally -5 kV to minimize electron transverse diffusion in the pressure
 189 range 60 – 100 Torr). The lower electrode is also a woven stainless steel
 190 mesh (100 lpi, 30 μm wire diameter, 78% transparency), grounded through a
 191 20 Ω resistor. Copper field-shaping rings supported by four vertical 1/4"-20
 192 threaded Delrin rods are connected by 1 M Ω resistors to establish a uniform
 193 electric field defining the drift direction $\hat{z}$. Near the rings, the drift field
 194 is non-uniform, and some ionization electrons are therefore captured on the
 195 rings (rather than reaching the amplification region). This leads to strong
 196 suppression of scintillation light from tracks in the outer 1 cm of the veto re-
 197 gion (see Section 5.2). Each ring is 3 mm thick with a 30.7 cm inner diameter

¹Transparency, T , refers to the geometric open area, and is given by $T = [1 - d_w * (\text{lpi} - 1)]^2$, where d_w is the wire diameter in inches.

Figure 3: Electrical schematic of the 4Shooter detector including a side-view of the TPC showing several of the field-shaping rings and resistor chain elements. The three electrodes on the top of the anode plate are shown, along with their connections to the three charge readout channels: Mesh Amp, Veto CIA and Anode CIA (CIA stands for Charge Integrating Amplifier). The CCD and PMT readouts are shown atop the vacuum vessel (only two of the four CCDs are shown). Drawing is not to scale.

and a 33.8 cm outer diameter and is machined from ultra-high purity copper provided by the Aurubis Group. The lowest field-shaping ring is electrically connected to the grounded vacuum chamber via a 1 MΩ resistor. The cathode mesh is secured under tension to a copper ring using a low-outgassing epoxy (3M DP-460 EG) and then covered by a second ring, both with the same characteristics as the field-shaping rings. In total, there are 28 rings: 26 field-shaping rings and two cathode rings and a total field cage resistance of 27 MΩ. The total drift distance measured 26.7 ± 0.1 cm.

The field rings are mechanically and electrically separated from each other

Figure 4: Mechanical drawing of the 4Shooter field cage. The active region of the TPC is indicated by the shaded gray rectangle.

207 by spacers composed of a stack of three copper washers (1.65 ± 0.38 mm thick)
 208 sandwiched between two thin (0.76 ± 0.25 mm) Delrin washers. These spacers
 209 are primarily composed of copper for material purity. The target size for the
 210 spacers is 0.635 cm, and the measured spacer thicknesses range from 0.635
 211 to 0.686 cm. The resistor chain is made of through-hole resistors whose leads
 212 tuck under the spacers to make electrical contact with the rings (Fig. 3). The
 213 resistors are placed on alternating field cage posts to avoid a tilt in the field
 214 cage. Kapton-insulated high-voltage wire connects the cathode to a 30 kV
 215 ConFlat high-voltage vacuum feedthrough on the bottom flange of the vessel,
 216 which, in turn, is fed by a Bertan 380N NIM high-voltage supply, typically
 217 set to -5 kV.

218 *5.2. Amplification stage*

219 The amplification region (see Figure 5) is a custom, monolithic device.
220 It consists of a stainless steel woven mesh epoxied under tension onto a 1/4"
221 thick copper-clad (on both sides) G-10 plate (the same mesh that serves as
222 the ground electrode for the drift region described above). The mesh-plate
223 gap is defined by 13 non-conductive fused silica capillary tubes (“spacers”)
224 of $435 \pm 10 \mu\text{m}$ diameter oriented approximately parallel to each other² on a
225 1 inch pitch.

226 The wire pitch of the ground mesh is $257 \mu\text{m}$. The choice of mesh pitch
227 balances spatial resolution (finer mesh), optical transparency (larger gaps),
228 and maximum achievable mesh tension (wire diameter) and therefore the
229 number of required spacers.

230 Machined channels divide the copper-clad G-10 plate into three electri-
231 cally isolated regions – the outer, veto and anode electrodes. The mesh is
232 epoxied to the outermost annular region of inner diameter 30.7 cm and outer
233 diameter flush with the edge of the 34.8 cm diameter G-10 plate. A second,
234 concentric, annular region (the “veto”) of outer diameter 30.7 cm and inner
235 diameter 29.2 cm serves as a veto to identify ionization events near the outer
236 radius of the active region (i.e. the electrical signal from this electrode is
237 used for (x, y) fiducialization). Finally, the central 29.2 cm diameter circular
238 region (the “anode”) defines the fiducial region of the detector. A Bertan
239 375P NIM high-voltage supply biases both the veto and anode electrodes
240 (typically at 670 V) to provide Townsend amplification in the narrow gap

²The ends of the spacers are fixed at precise intervals on the anode plate, but the central portion of the spacers can move.

Figure 5: Photograph and schematic drawing of the amplification region. The schematic shows the three distinct electrodes – the central circular anode, surrounded by the annular veto, surrounded by the ground electrode. In addition to these three electrodes, the photograph shows the quartz spacers (parallel lines running from top left to bottom right in the image), and the ground mesh, which is epoxied to the ground electrode.

241 (435 μm) between the mesh and the anode and veto electrodes.

242 5.3. Active volume and target mass

243 The active region of the 4Shooter is defined by the height of the drift
244 region (26.7 ± 0.1 cm) and the outer diameter of the central anode region
245 (29.2 cm), and it has a total volume of 19.8 L. The system gain of the de-
246 tector near the amplification region spacers is degraded by 20–30%, and in
247 practice additional cuts are made to ignore tracks within 1.3 mm of spac-
248 ers. The resulting total fiducial volume is 13.9 L, corresponding to fiducial
249 target masses of fluorine and CF_4 at 298 K and 60 Torr of 3.5 g and 4.1 g,
250 respectively.

251 6. Readout channels

252 An ionization event produces two main observable signatures: scintilla-
253 tion light and electron/ion pairs. CCDs image the scintillation light, and
254 PMTs measure the temporal profile of the photon emission. In addition, the
255 integral and temporal profile of the charge signal are measured by charge
256 amplifiers.

257 6.1. CCDs

258 The entire active region of the amplification region is imaged by four
259 CCD cameras, which measure the 2D projection of the ionization tracks.
260 Each CCD is an Apogee Alta U6 containing a Kodak KAF-1001E front-
261 illuminated CCD. The CCD chips consist of 1024×1024 pixels, each with
262 $24 \times 24 \mu\text{m}^2$ area. Each CCD views the TPC through a multi-element Canon
263 85 mm $f/1.2$ SLR lens, and images a $16.4 \times 16.4 \text{ cm}^2$ region of the anode.

264 Prior to digitization, the CCD pixels are binned 4×4 on-chip to enhance
 265 the signal-to-noise in each digitized bin, and reduce dead-time by shortening
 266 readout. In the images shown here, each recorded bin from the CCD images
 267 a square region of the anode 0.6416 mm on a side. The cameras are arranged
 268 such that adjacent cameras' fields of view overlap by approximately 1 cm.
 269 The CCDs also image the inactive region outside of the field cage. Figure 6
 270 shows the 4-camera mosaic image of an alpha track that traverses the field
 271 cage.

272 The details of the scintillation spectrum of CF_4 [50] depend on the gas
 273 pressure [55], but in general the spectrum contains two broad emission peaks.
 274 One is centered near 300 nm. The other is centered near 625 nm, and is well-
 275 matched to the response of CCD cameras. For example, the Alta U6 cameras
 276 have a peak quantum efficiency (QE) of 70% at 550 nm. The negligible QE of
 277 the CCDs below 350 nm mean that the CCDs are not sensitive to the short-
 278 wavelength scintillation photons (200–350 nm), and so standard Kodial glass
 279 viewports are used to couple the cameras to the vacuum chamber.

280 The choice of CCD balances signal to noise and cost for a given field of
 281 view. In particular, assuming isotropic photon emission in the amplification
 282 region and by making use of the lens-maker's formula, it is possible to express
 283 the fraction of scintillation photons η that reach the CCD chip as:

$$\eta = \frac{1}{16} \left(\frac{1}{f/\#} \right)^2 \left(\frac{1}{1+m} \right)^2 \quad (1)$$

284 where $f/\#$ is the f -number of the lens (the ratio of the focal length to
 285 the diameter of an equivalent single lens), and m is the demagnification
 286 of the optical system (the ratio of the object size to the image size). This
 287 expression shows that a fast lens (low f -number) and large CCD chip (low m)

Figure 6: Mosaic CCD image showing an alpha particle traversing the field cage and passing through the fields of view of three CCD cameras. The overlaid circles show the anode-veto boundary (inner circle) and the outer diameter of the veto (outer circle). This alpha likely originated from the decay of an atom near the surface of the copper field-cage ring and terminated on a field cage ring. Regions of suppressed signal along the track are created by the spacers that define the amplification gap.

288 are advantageous. It also makes clear the need for a large gas amplification
 289 to compensate for the small value of η (for the 4Shooter, $f/\# = 1.2$ and
 290 $m = 6.67$, so $\eta = 7 \times 10^{-4}$). This expression is purely geometric and does
 291 not account for the reflective copper anode, which can boost the photon
 292 throughput. Nor does it account for photon losses due to mesh or window or
 293 lens transparency or the quantum efficiency of the CCD. The CCD energy
 294 calibration, described in Section 8.6, includes all of these factors. The signal-
 295 to-noise ratio in a CCD pixel could be improved by using back-illuminated
 296 CCDs ($\sim 95\%$ QE) with lower read noise ($3 e^-$ RMS are readily available
 297 now).

298 Figure 7 shows a nuclear recoil candidate in the 4Shooter detector from
 299 an AmBe neutron source exposure. From this data, the following informa-
 300 tion about the track can be obtained: total ionization energy, total projected
 301 track length, stopping (dE/dx) vs. position, track orientation in 2D, track
 302 diffusion, and the absolute (x, y) location of tracks, useful for detector fidu-
 303 cialization.

304 A typical run of the detector consists of 100 dark frames followed by 1000
 305 event exposures. A dark frame is a CCD exposure of the same duration
 306 as the event exposures but with the CCD shutter closed. This pattern is
 307 repeated for 24 hours. Then the detector is refilled with fresh CF_4 gas to
 308 ensure gas gain stability (see Section 8.2). At present, no event trigger is
 309 implemented, so all images are saved for off-line analysis (witness mode). In
 310 typical operation (4 cameras, 4×4 binning, 1-second exposures), the total
 311 uncompressed CCD data rate is 0.5 MB/s. We are actively investigating
 312 triggered readout using PMT and charge readout information.

Figure 7: Enlarged view of a high energy (175 keV_{ee}) nuclear recoil candidate from an AmBe neutron exposure, imaged by a single CCD. The intensity variation along the track, represented by the color scale, is proportional to dE/dx , and indicates that the track travels from bottom left to top right.

313 6.2. Photomultiplier Tubes

314 The PMTs provide a complementary measurement of the scintillation
315 light from events in the detector. Like the CCDs, the PMTs sit outside of the
316 active volume and do not contact the detector gas. In the 4Shooter, three
317 face-on 8 mm diameter PMTs (Hamamatsu R7400U-20 with Hamamatsu
318 E5780 bases) are mounted together in the central port of the top flange of
319 the vacuum vessel and couple optically to the chamber through a single 2-
320 3/4" CF quartz viewport. The PMTs are biased at -925 V with Bertan
321 NIM HV supplies, and the output signal is digitized by Alazar ATS860 PCI
322 boards (12-bit, 250 MS/s, 100 MHz analog bandwidth for DC-coupled 50 Ω
323 termination). In addition to providing an independent measurement of the
324 energy of an event, the temporal profile of the PMT signal can be used to
325 extract information about the third dimension of the track – tracks with large
326 Δz will produce wider pulses in the PMT. This effect was demonstrated with
327 the 4Shooter for high-energy tracks by using an ^{241}Am source and in a similar
328 detector with fixed-length decay products of thermal neutron capture on ^3He
329 ($n + ^3\text{He} \rightarrow p + ^3\text{H}$) [45]. The bandwidth of the digitizers is not well-
330 matched to the fast PMT pulses, however, and many PMT waveforms show
331 distortions such as wrong polarity pulses and excess noise. This prevents
332 the full utilization of the PMT channels at low energies, and as a result, the
333 PMT readout is not yet integrated into the data analysis.

334 6.3. Charge readout

335 The ionization signal in the amplification region is measured in two differ-
336 ent ways using three charge amplifiers. All three amplifiers are kept outside

337 of the vacuum vessel. The Alazar ATS860 digitizes the charge signals. Fig-
338 ure 8 shows waveforms from the same nuclear recoil candidate event shown
339 in Figure 7.

340 A current-sensitive amplifier (Route2Electronics HS-AMP-CF) attached
341 to the ground mesh measures the temporal evolution of ionization pulses in
342 the amplification region. DMTPC has previously shown that a pulse-shape
343 analysis of this signal can effectively discriminate between electronic and
344 nuclear recoils [42]. A nuclear recoil event will exhibit a dual-peak structure
345 in the mesh amplifier signal (see Figure 8). The first peak arises from the
346 fast-moving electrons in the amplification region, while the second, broader,
347 peak comes from the slower-moving ions. That work also demonstrated a
348 correlation between Δz , the vertical extent of a track, and the pulse rise-
349 time. Ongoing work explores the possibility of using the amplifier rise-time
350 to measure Δz for dark matter induced nuclear recoils.

351 In addition, two measurements of the total integrated charge after gas
352 amplification are made. First, a Cremat CR-113 charge-sensitive amplifier
353 (nominal gain 1.3 mV/pC) mounted on a Cremat CR-150 board integrates
354 the induced charge on the central anode. Second, a Cremat CR-112 charge-
355 sensitive amplifier (nominal gain 13 mV/pC), also mounted on a CR-150
356 board, integrates the charge on the veto channel. Both amplifiers have a
357 300 Ω resistor in series with their inputs to protect against spark discharges
358 in the amplification region.

359

Figure 8: Nuclear recoil candidate waveforms. Top: current-sensitive mesh amplifier. Bottom: central circular anode (upper, black) and annular veto (lower, gray). The top figure shows the separate fast (electron) and slow (ion) peaks in the mesh amplifier signal.

360 7. Hardware control and data acquisition

361 The 4Shooter detector was designed to be operated remotely under-
362 ground. This section briefly describes the Slow Control and DAQ software
363 framework.

364 7.1. Control

365 The detector control and monitoring scripts (the Slow Control) are a
366 collection of Python, Perl, and C/C++ code that track and log detector
367 operation parameters to a MySQL database. This code runs on a Linux
368 computer that doubles as a server for a web interface to control and monitor
369 the detector. The TPC voltages and CCD operational parameters (exposure
370 time, number of exposures, binning) can be set and monitored, as can data
371 acquisition parameters such as the waveform digitizer card trigger conditions.
372 The vacuum system can be controlled (valves can be opened and closed), and
373 autonomous detector gas refills to a user-defined pressure can be initiated and
374 monitored. General environmental parameters such as external temperature
375 are also monitored. The measured parameters are recorded at a rate of 1 Hz
376 and are obtained either by USB or RS-232 connections, or through analog-to-
377 digital conversion using a National Instruments NI-6229 multifunction DAQ
378 PCI card.

379 7.2. Acquisition

380 Data acquisition is handled on a dedicated Linux machine by a suite of
381 C++ code that makes use of the ROOT data analysis framework [56]. Data
382 from the 4Shooter detector is stored in ROOT data files for later off-line

analysis. The off-line analysis of CCD images and charge and PMT wave-
forms follows from [57, 43, 44], and will be described in detail in subsequent
publications. A Monte Carlo detector simulation of the CCD images has
been implemented, with simulated data stored in the same format as the real
data, allowing common analyses and intercomparisons of the two.

During acquisition, summary statistics of the incoming data are measured
and logged to the database for real-time viewing. For example, dark frames
for each run are displayed, as are the mean pixel intensity of the CCD images,
as a function of time.

8. Detector performance

In this section, we discuss the calibration of the CCD (recoil track length,
energy and noise measurements), and charge channels (recoil energy measure-
ment). We also present measurements of the gas gain as a function of gas
pressure, anode voltage, and time, as well as the transverse electron diffusion,
measured *in situ*.

8.1. Length calibration and image mosaic technique

The calibration of the recoil length scale of the CCD is done *in situ* when
the hardware configuration is altered. This calibration determines how much
area of the anode is imaged by each pixel of the CCD, and therefore the
conversion from track length in pixels to mm. This calibration is generally
done with the CCDs at full readout resolution (unbinned) to provide the
highest possible spatial resolution. The length calibration for the 4Shooter is
 0.1604 ± 0.0004 mm/pixel. In standard operations, the CCD is binned 4×4

406 and so each digitized channel of the CCD images a $0.642 \times 0.642 \text{ mm}^2$ area
407 of the anode.

408 The calibration proceeds by illuminating the detector interior with an
409 LED and then identifying in the CCD images the pixel coordinates of the
410 two machined channels that belong to the annular veto region. The LED is
411 located in one of the camera mounts adjacent to the Canon SLR lens and
412 points down toward the vacuum viewport. The LED can be turned on and
413 off remotely, without disturbing the mechanical configuration of the detector.

414 This dataset is also used to determine the image transformation parame-
415 ters required to form a single mosaic image of the amplification region from
416 the four CCD images. Each image is translated and rotated. The rotation
417 is chosen so the spacers in the amplification region are parallel to the x -axis
418 of the mosaic image, and the translation is chosen such that fitted circles to
419 the quadrants of the machined veto channels share a common center. Images
420 from the LED-off data (where no TPC features are visible) are then stitched
421 together using these transformations in order to form mosaic images as in
422 Figure 6.

423 8.2. Gas gain

424 An ^{55}Fe x-ray source is used to measure the gas gain as a function of
425 anode bias voltage and gas pressure, and also to calibrate the energy scale
426 of the charge readout electronics. The source ($30 \mu\text{Ci}$) is placed on the cath-
427 ode mesh, and the energy spectrum of the resulting photoelectric absorption
428 events is recorded. For these low-energy events, a CR-112 charge-integrating
429 amplifier with higher gain is used on the anode readout channel in place of
430 the CR-113 amplifier.

Figure 9: (Top): Sample waveform from an ^{55}Fe calibration exposure with 60 Torr CF_4 and an anode voltage of 670 V. (Bottom): Pulse height spectrum from the same calibration along with a fitted Crystal Ball function. For this spectrum $\sigma/\mu = 8.5\%$, where σ is the standard deviation of the Gaussian portion of the fitted Crystal Ball function, and μ is the mean.

431 A sample charge readout ^{55}Fe ionization event and the accumulated spec-
 432 trum is shown in Figure 9. A Crystal Ball function [58] is fit to the spectrum,
 433 and the gas gain G at that particular gas pressure and anode bias voltage is
 434 calculated from:

$$G = \frac{W_{CF_4}}{\Delta E} \frac{V_{peak}}{eA} = 2.75 \times 10^3 V_{peak}[\text{mV}], \quad (2)$$

435 where $W_{CF_4} = 34.3$ eV [59] is the W-value of CF_4 (but see comments below),
 436 ΔE is the ionization energy deposited in the detector (the energy of the ^{55}Fe
 437 x-ray), V_{peak} is the voltage of the peak of the measured energy spectrum, $e =$
 438 1.60×10^{-7} pC is the elementary charge, and $A = 13$ mV/pC is the conversion
 439 gain of the CR-112 charge-integrating amplifier. The measured gas gain as
 440 a function of anode bias voltage for three different gas pressures (45, 60 and
 441 75 Torr) is shown in Figure 10. In all cases, the gas gain exceeds 10^4 , with a
 442 maximum gas gain of 10^5 at 75 Torr. At a given anode voltage, the field in
 443 the amplification region is uniform, and the Townsend amplification factor
 444 is $\exp(\alpha d)$, where α is the Townsend coefficient, and d is the amplification
 445 gap size (here $435 \mu\text{m}$). In CF_4 , α grows linearly with electric field above
 446 $E/N = 100 \times 10^{-17}$ V cm 2 [52], and so the expected gas gain increases
 447 exponentially with anode voltage: $\exp(V_{anode} d)$. Figure 10 shows that the
 448 fits of the exponential function $\exp(a + b \cdot V_{anode})$ match the data at each gas
 449 pressure (the constants a and b are free parameters for each data set).

450 We measure the stability of the gas gain as a function of time using a
 451 series of ^{55}Fe pulse height spectra over a 24-hour period (see Figure 10), and
 452 find that the gas gain degrades by less than 3% over 24 h, with an exponential
 453 decay time constant of 10.1 h. Based on this measurement, we have chosen
 454 to evacuate and refill the 4Shooter with fresh CF_4 gas once per day during

Figure 10: (Top) Gas gain versus voltage for three operating pressures (45, 60 and 75 Torr), along with fits of the exponential function $\exp(a + b \cdot V_{\text{anode}})$. (Bottom) Gas gain as a function of time (normalized to the gain at $t = 0$), along with an exponential plus constant offset fit: $\text{Gain} = a + \exp(b + c \cdot t[\text{hr}])$ showing a gain degradation of 3% over one day. Data taken at a gas pressure of 75 Torr and an anode voltage of 720 V.

455 standard running operation. From ^{55}Fe data we also find that the gas gain
456 is stable to 2% from gas fill to gas fill.

457 In this gas gain analysis, we have assumed a W -value for CF_4 of 34.3 eV.
458 There are discrepant values published in the literature, including 34.3 eV [59]
459 and 54 eV [60, 61]. To help resolve this discrepancy, our group has carried
460 out an independent measurement of W_{CF_4} and found $W_{\text{CF}_4} = 33.8 \pm 0.4$ eV
461 [62].

462 We find that the measured gas gain decreases with x-ray flux, most likely
463 due to the well-documented effect of space charge in the amplification gap
464 [63]. At full source intensity, the measured gain was 30% lower than at
465 lower intensities. When making the gas gain measurements, we attenuated
466 the source with layers of aluminum until the measured gas gain plateaued
467 at a stable value. The data reported here used $150\text{ }\mu\text{m}$ of aluminum. The
468 ^{55}Fe produces x-rays at three main energies 5.888, 5.899 and 6.49 keV with
469 relative intensities of 0.506, 1.0 and 0.176, respectively [64]. Because the x-ray
470 cross-sections in aluminum decrease with energy in this regime, we use the
471 tabulated photon cross-sections in aluminum [65] to estimate the weighted
472 average energy of the ^{55}Fe source after attenuation as $\Delta E = 6.00\text{ keV}_{\text{ee}}$. To
473 explore the effect of source location on measured gas gain (and charge energy
474 calibration), an additional study was done in which the (x, y) location of the
475 ^{55}Fe source was varied on the cathode mesh. The measured gas gain varied
476 by less than 1% level with source location.

477 As the anode voltage is increased, the probability of spontaneous dis-
478 charge in the amplification region (sparks) increases sharply, thereby limit-
479 ing the achievable gas gain. At 60 Torr and 670 V on the anode (standard

operating point), the discharge frequency is 5 mHz. These discharges produce intense scintillation light that can saturate pixels in the CCD camera and lead to spurious clusters of bright pixels in subsequent exposures [28]. Furthermore, each discharge initiates an interval of suppressed gas gain while the amplification region recharges with a measured recovery time constant of 3 seconds (set by the bandwidth of the anode high-voltage noise filter outside of the chamber). Events occurring during the recovery time are ignored. Further, at very high gas gains, tracks with large ionization density (e.g. nuclear recoils) can trigger sparks when Raether’s limit is exceeded [66]. This sets a maximum stable operational gain for each combination of gas pressure and drift field.

8.3. Charge energy calibration

Using the energy calibration of the CR-112 amplifier, determined from the ^{55}Fe spectrum peak at 6 keV, the measured energies of x-ray quanta from ^{241}Am (specifically, the neptunium L-shell line emission at 13.9, 17.5 and 21.1 keV [67]) agree with expectations at the 1% level. This calibration is transferred to the anode charge integrating amplifier (CR-113) by an independent measurement of the conversion gain ratio between the CR-113 and the CR-112 of A_{113}/A_{112} . The gain ratio was determined by matching the features of the source-free (background) spectra measured by each amplifier in the energy range 40 – 150 keV, under the same operating conditions (gas pressure and anode and cathode voltages). The background spectrum is a broken power law with a knee near 70 keV (see Fig. 11). At an anode voltage of 670 V and a CF_4 pressure of 60 Torr, a gain ratio of $A_{113}/A_{112} = 0.112$ matches the features in the spectrum, and the total rates measured by the

Figure 11: Background energy spectrum measured with the CR-112 charge integrating amplifier attached to the anode. The peak between 5 and 15 keV_{ee} is consistent with minimum-ionizing particles traversing the full vertical length of the detector. At energies higher than the peak, the spectrum is a power law ($E^{-2.15}$), followed by a “knee” from 60 to 100 keV_{ee}, and a steepened spectrum ($E^{-6.6}$). The knee arises because electrons with energies higher than ≈ 60 keV_{ee} are typically not fully contained in the detector. The ^{55}Fe energy calibration of the CR-112 preamplifier is transferred to the CR-113 preamplifier by matching the observed background energy spectra in the vicinity of the knee.

two amplifiers agree at the 1% level. Changing the gain ratio by 5% leads to significant differences between the measured spectra, and so we assign a 2.5% uncertainty to the gain ratio.

The conversion factor g_{113} from mV to keV_{ee} for the standard 4Shooter configuration (CR-113 connected to the central anode) is then

$$g_{113} [\text{keV}_{\text{ee}}/\text{mV}] = \left(\frac{6.0 \text{ keV}_{\text{ee}}}{V_{112}} \right) \left(\frac{A_{112}}{A_{113}} \right), \quad (3)$$

where V_{112} is the mean voltage of the ^{55}Fe spectrum measured with the CR-112 amplifier (in mV). At 60 Torr CF₄ and an anode voltage of 670 V, we find $g_{113} = 2.2 \text{ keV}_{\text{ee}}/\text{mV}$ with a total systematic uncertainty of approximately 4% and minimal statistical uncertainty [44].

8.4. CCD noise measurements

The two main noise sources intrinsic to CCDs are read noise and dark noise. The pixel values of a difference image of two same-duration dark exposures are distributed normally. The width σ of that Gaussian distribution is equal to $\sqrt{2} \sigma_N$, where σ_N is the total per-pixel noise in the CCD (nominally dominated by read and dark noise). When the 4Shooter CCDs are run in their native resolution (unbinned), we measure σ_N in the range of 5 to 8 ADU (the arbitrary digital units recorded by the camera – see Section 8.6 for the calibration from ADU to deposited energy in the detector), depending on the camera. Given the nominal CCD conversion gain of 1.3 to 1.65 e^-/ADU (again, depending on the camera), this corresponds to 7 to 13 e^- total noise.

To increase the signal to noise in a single image, we bin the CCDs 4×4 prior to digitization. We discovered, however, that σ_N increases linearly with the CCD binning in the parallel direction, likely due to the so-called spurious

Figure 12: Total per-pixel noise for 4×4 binning in a single 4Shooter CCD as a function of exposure time. Filled black circles are data, and the gray curve is a fit of $\sqrt{\sigma_R^2 + R_D t}$ to the data. The dark noise contributes significantly to the total noise for exposure times above 10 seconds. These measurements were made by constructing difference images from pairs of dark exposures to remove fixed-pattern noise in the CCD.

charge effect, as described in Ref. [68]. CCD vendors generally quote the noise for unbinned operation, and so we measure the noise vs. binning. At 4×4 binning, the CCD noise σ_N ranges from 7 to 11 ADU, depending on the camera.

Figure 12 shows the dependence of σ_N on exposure time t for one CCD when binned 4×4 . The leading contributions to the total noise are the read noise σ_R and the dark noise $\sqrt{R_D t}$, where R_D is the per-bin dark rate (ADU/sec), such that $\sigma_N = \sqrt{\sigma_R^2 + R_D t}$. For short exposure times, the noise is read-noise dominated and therefore independent of exposure time. At the transition point $t \approx 10$ s, the dark noise is comparable to the read noise. A fit finds $\sigma_R = 11.5 \pm 0.1$ ADU and $R_D = 1.05 \pm 0.03$ ADU bin $^{-1}$ sec $^{-1}$. These CCDs are operated at -20° C using thermoelectric coolers but no cryogenics. During standard operation, we restrict the CCD exposure times to be less than 10 seconds where $\sigma_N \approx \sigma_R$.

8.5. *Spatial variations in the CCD response*

The number of photons detected by the CCD, per keV of ionization energy, varies spatially across the amplification region. There are many different causes for this non-uniformity, including variations in the amplification region gap and suppressed light production in the vicinity of the insulating spacers. Even if the amplification region provided uniform light production, the measured image would still show spatial variations in brightness due to the throughput of the optical system.

To take this effect into account during event reconstruction, we generate a gain map to measure the CCD energy calibration correction factor as a function of (x, y) position. To obtain a gain map, one would ideally like to

553 deposit a uniform distribution of ionization charge in the (x, y) plane of the
 554 detector and image the resulting photons. As an approximation, we use a
 555 ^{57}Co source of 122 keV γ -rays, whose interaction length in the low-pressure
 556 CF_4 gas is orders of magnitude greater than the dimensions of the TPC.
 557 For example, at 60 Torr, the interaction length is 240 m. This produces
 558 an approximately uniform distribution of ionization across the amplification
 559 region. In any single CCD exposure, the detectable photon signal is very
 560 weak. However, by averaging together thousands of these exposures, we
 561 obtain an image showing the main features described above (Fig. 13). In
 562 practice, careful image and pixel selection criteria are applied to deal with
 563 sparks and background tracks in the detector, as well as hot pixels in the
 564 CCD. The resulting gain map is smoothed using a Gaussian bilateral filter
 565 [69] with a domain width of 12 pixels and a range width of 3 ADU. These
 566 filter parameter values were chosen heuristically, and validated through the
 567 resulting gain map's performance on data, as described quantitatively at the
 568 end of this section. The choice of the filter range width was driven by the
 569 desire to limit the leakage of anomalously high or low ADU-valued pixels
 570 into neighboring pixels in the filtered map, while the choice of the filter
 571 domain width was driven by the need to remove the pixel-to-pixel variations
 572 in the unfiltered map due to finite statistics. The filtered gain map was then
 573 normalized to the smoothed average pixel value for pixels at least 10 pixels
 574 within the boundary of the central anode, and further than 20 pixels away
 575 from a spacer.

576 The dominant spatial structure in the gain map arises from two main
 577 contributions: (1) suppressed system gain near the insulating spacers in the

Figure 13: 4Shooter detector gain map from a long-duration ^{57}Co source exposure used to calibrate the spatial variations in CCD gain. Larger values in the gain map correspond to regions of higher gain. The amplification stage spacers are clearly visible as locations of reduced gain, and for each camera, a radial fall-off in gain from vignetting is observed. The faint glow visible about the periphery of the circular amplification region arises from the reflections of photons off of the drift stage field shaping rings.

578 amplification region (see the 11 horizontal stripes in Fig. 13), and (2) vi-
 579 gnetting in the optical system.

580 The suppressed response in the mosaic gain map image along the lines $x =$
 581 0 and $y = 0$ arises from vignetting by the optical system. The characteristic
 582 signature of vignetting is a radial fall-off in the measured brightness in the
 583 field of view of each CCD camera. In Figure 13, these radial gradients are
 584 present in each individual CCD image in the mosaic. Detailed explanations

585 of vignetting, along with fits of vignetting models to CCD data, are provided
586 in Ref. [70].

587 The calibration of the CCD energy scale (see Section 8.6) relies on CCD
588 measurements of long alpha tracks in the detector, and therefore uses the
589 gain map described here. Before gain map correction, the energy of tracks
590 determined from the CCD alone is more than 20% less than the energy
591 determined from charge alone on the periphery of images, where the effects
592 of vignetting are most pronounced. After gain map correction, the CCD-
593 derived energy is consistent with the charge-derived energy independent of
594 the radius at which tracks are reconstructed relative to the center of each
595 CCD's image to within 3%.

596 *8.6. CCD energy calibration*

597 The energy scale of the CCD cameras is determined by fitting the stopping
598 versus range for collimated alpha tracks from an ^{241}Am source in Monte Carlo
599 to data. For these alpha particles (which deposit ≈ 4.5 MeV in the detector),
600 SRIM simulations [71] show that more than 99% of the alpha energy goes
601 into the ionization of the CF_4 gas, and so this measurement determines the
602 conversion factor from ADU to keV_{ee} . In order to further calibrate the energy
603 scale for low-energy nuclear recoils, a measurement of the quenching factor
604 is needed. The gas quenching quantifies what fraction of the recoil energy
605 goes into ionization (as opposed to other forms of energy loss such as nuclear
606 excitation). For a description of quenching in CF_4 gas, see e.g. Refs. [61]
607 and [72].

608 For the $\text{ADU}/\text{keV}_{\text{ee}}$ calibration, one collimated ^{241}Am source is placed in
609 the field of view of each camera (see Figure 14). The source orientations

Figure 14: Left: four ^{241}Am alpha tracks emitted by sources in each of the four cameras during a typical alpha energy calibration. The exposures from each 4Shooter camera have been stitched together to form a composite mosaic image, based on their known relative orientations. The dashed white circle shows the boundary of the central anode electrode of the amplification stage. Right: the average longitudinal projection of alpha tracks in a typical calibration dataset for one of the 4Shooter CCDs (black) compared with the tuned Monte Carlo prediction (gray), for data taken in 60 Torr CF_4 . The normalization of the Monte Carlo curve has been fit to the data to extract the total CCD gain in $\text{ADU}/\text{keV}_{\text{ee}}$ within the bounds indicated.

610 ensure that the emitted alpha particles travel horizontally (parallel to and
611 above the amplification region), and are fully contained in a single camera's
612 field of view. The collimators are further aligned such that the alpha tracks
613 do not cross the fused silica spacers in the amplification region. A 1-second
614 CCD exposure time was chosen such that the majority of images contained
615 either zero or one alpha track in a single camera's field of view. A software cut
616 on the reconstructed alpha track energies is used to remove images containing
617 multiple, overlapping alpha tracks.

618 A series of data selection cuts are applied to the detected tracks to elimi-
619 nate outliers in total range, energy, track angle, and straightness (relative to
620 the collimator boresight). The reconstructed directions of alpha tracks in the
621 data and Monte Carlo are required to be within 2° of the nominal collimator
622 boresight because multiple scattering is not presently modeled in our Monte
623 Carlo. Reconstructed alpha tracks were discarded if their position and ori-
624 entation was inconsistent with the known placement of the ^{241}Am sources.
625 Additional data quality cuts were applied to ensure that no amplification
626 region discharges (sparks) occurred in the 15 seconds prior to the relevant
627 exposure. This 15 second waiting period was chosen to be $5\times$ the measured
628 time constant for gain recovery after discharge in ^{55}Fe x-ray measurements
629 of the instantaneous gas gain. The input parameters to the Monte Carlo
630 are then iteratively adjusted (see below) until the average longitudinal and
631 transverse intensity profiles of the alpha tracks match the data.

632 The five input parameters that control the detector response are the trans-
633 verse electron diffusion during drift, the CCD gain in ADU/ keV_{ee} (this is the
634 parameter under study), the gas quenching factor, the CCD length scale, and

the CCD noise. The latter two parameters are constrained through independent measurements (see Sections 8.1 and 8.4), and are therefore fixed for all simulations. Although the effect of quenching is negligible for 5 MeV alpha particles, for completeness, we model the amount of ionization deposited in the detector as [40]:

$$LET_{el}(E_r) = S_e(E_r) + 0.3 S_n(E_r), \quad (4)$$

where LET_{el} is the electronic energy deposited in the detector per unit length, and E_r is the total energy of the alpha particle. S_e and S_n are the electronic and nuclear stopping, respectively, as predicted by SRIM-2006 [71]. The factor of 0.3 is chosen to be consistent with predictions by Hitachi [61] over a range of ion energies.

The total electron diffusion in the Monte Carlo is adjusted until the mean transverse width of the alpha tracks in data that pass all cuts is consistent with the mean transverse width of the simulated alpha tracks that pass all cuts. See Section 8.7 for further discussion of diffusion.

The mean and RMS energies of the alpha source in the Monte Carlo are initially fixed to the values measured for each source in vacuum with an ion-implanted silicon surface barrier detector. Only ≈ 4.5 MeV of the initial alpha track energy remains after the alphas have straggled out of the thin foil covering the ^{241}Am in each source and through the approximately 1" long gas-filled collimator bore hole. The alpha source location in the Monte Carlo is defined relative to the active region of the TPC by the boresight line of the collimator and the starting position of alphas along that line. Only pixels within the active central anode region (see Section 5.2) are populated with Monte Carlo tracks. The collimator boresight line is defined from the

659 orientation (angle and absolute position) of the data alpha tracks that pass
 660 all selection cuts. To account for the fact that the alpha sources are housed
 661 in collimators whose exit apertures do not lie exactly at the boundary of the
 662 active region of the detector, the initial energies of the alpha tracks in the
 663 Monte Carlo are adjusted until the mean longitudinal position of the alpha
 664 tracks' Bragg peaks agree with data. Adjusting the alpha track energies in
 665 the Monte Carlo implicitly assumes that a shift in the alpha track energies is
 666 equivalent to a shift in the alpha sources' positions, which is true in the limit
 667 that the alpha track energy variance is not dominated by straggling over the
 668 short inactive portion of the detector that the alphas must traverse between
 669 the ends of their collimators and the active region of the detector.

670 Once the source energy in the Monte Carlo has been tuned, the longitu-
 671 dinal projection of the tracks are computed in ≈ 5 -mm-wide bins (see right
 672 plot in Figure 14). To account for spatial variations in the gain, the data are
 673 normalized by the gain map (Section 8.5). The projections are averaged and
 674 compared between data and Monte Carlo. The system gain in $\text{ADU}/\text{keV}_{ee}$
 675 in the Monte Carlo is iteratively tuned to achieve agreement with data in
 676 the region ≈ 24 mm after the start of the track and ≈ 24 mm before the
 677 Bragg peak. This interval was chosen for the fit such that the Bragg curves
 678 are approximately linear, in order to reduce systematic errors from improper
 679 alignment of the data and Monte Carlo longitudinal projections. According
 680 to SRIM, the alpha stopping in this region is approximately 30% lower than
 681 the ionization per unit length produced by a 100 keVr fluorine nucleus. Ta-
 682 ble 1 lists the measured CCD energy calibration for each of the four CCD
 683 cameras for 60 Torr and 670 V anode bias. The resulting data and Monte

CCD #	Gain (ADU/keV _{ee})
1	10.3 ± 0.2
2	18.4 ± 0.2
3	18.6 ± 0.2
4	16.6 ± 0.2

Table 1: The CCD energy scales in ADU/keV_{ee} for the four 4Shooter cameras measured with ²⁴¹Am tracks in 60 Torr CF₄ with a 670 V anode bias. The gain measurement for each CCD has been averaged over data taken at a range of different heights z and positions (x, y) in the 4Shooter TPC. The error is the fit error on a constant fit to the data as a function of z . The RMS spread of the individual gain measurements at different positions and heights is observed to be less than 2%.

684 Carlo comparison, after the gain is tuned, is shown in Figure 14 (right).

685 The differences between the camera gain values are partially due to differ-
686 ences in the intrinsic CCD conversion gains (e^-/ADU) between the cameras,
687 and partially due to differences in optical throughput. Tests performed sub-
688 sequent to the majority of the results presented in this paper determined that
689 the conversion gain of the CCD with the lowest ADU/keV_{ee} gain, CCD #1,
690 was both anomalously large, and dependent on the intensity of illumination.
691 This out of specification behavior largely accounts for its systematically lower
692 ADU/keV_{ee} gain, relative to the other three cameras. Due to its abnormal
693 performance, CCD #1 has since been replaced.

694 By repeating this measurement with the alpha sources at a range of
695 heights z we verified that, as desired, the CCD gain calibration is insensitive
696 to the electron drift distance z at the 2% level. This sets an upper-limit on
697 the electron loss during drift (from e.g. fringe fields in the TPC or attachment

on to gas impurities), and also on the accuracy of the track energy reconstruction for diffuse tracks (long drift distance). The measured gain was also found to be spatially uniform in (x, y) at the 1 – 2% level (after correcting for the gain map) from measurements performed with the alpha sources at eight distinct positions (x, y) over the anode, although these studies did not sample the full field of view. This same set of data was used to measure the transverse electron diffusion, as described in the following section.

8.7. *Transverse electron diffusion*

The diffusion of the drifting electrons in the TPC sets a limit on the total viable length L of the drift region of the TPC before the transverse diffusion exceeds the track length, and therefore compromises the directional sensitivity of the instrument. For example, fluorine recoils of energy 40 keV_r travel 1 mm in 60 Torr CF₄, which sets the scale for allowable diffusion. Previous measurements of electron diffusion in CF₄ gas [52, 73] show that at 60 Torr and the drift field that minimizes transverse diffusion (225 V/cm) the RMS track width reaches 1 mm after 25 cm of drift. We define the RMS track width as the square root of the transverse moment of the track, and the transverse moment as the second central moment of the track. To calculate the second central moment of the track, we first determine the track axis, and then calculate the intensity-weighted sum of the squares of the distances of each pixel in the track from the track axis.

In this work, measurements of D_T/μ , the ratio of the electron transverse diffusion constant to the electron mobility in CF₄ gas, have been made in-situ, as a function of the ratio of the drift electric field to the number density of gas molecules E/N . These measurements were carried out using the same

723 collimated alpha sources and track selection criteria from the energy cali-
 724 bration measurements described in Section 8.6. This time the sources were
 725 inserted into the detector at a range of heights z . As described in [73], the
 726 measured transverse moment σ_T^2 of these alpha tracks grows linearly with z
 727 because of electron diffusion:

$$\sigma_T^2(z) = \sigma_{T,0}^2 + 2 \left(\frac{D_T}{\mu} \right) \left(\frac{zL}{V} \right), \quad (5)$$

728 where $\sigma_{T,0}^2$ is the transverse moment for zero drift length, and V is the applied
 729 drift field voltage (the cathode voltage).

730 To simulate the effect of transverse diffusion from drift, the primary ion-
 731 ization tracks in the Monte Carlo are spatially convolved with a Gaussian
 732 kernel of width σ_T^{MC} prior to the simulated CCD digitization. This spatial
 733 smearing accounts primarily for diffusion, but also for the imperfect focus of
 734 the CCD cameras and the intrinsic widths of the track-induced avalanches
 735 in the amplification stage of the detector. Measurements of D_T/μ are ob-
 736 tained by adjusting the gaussian width σ_T^{MC} applied to collimated alpha
 737 tracks in Monte Carlo until the mean transverse moment σ_T^2 of the recon-
 738 structed Monte Carlo alpha tracks matches the mean transverse moment of
 739 the reconstructed alpha tracks in data for a range of drift distances z (at
 740 constant gas pressure and anode and drift bias voltages).

741 Data was taken at a gas pressure of 60 Torr and an anode bias voltage
 742 of 635 V. The transverse moment used in Monte Carlo $(\sigma_T^{MC})^2$ required to
 743 obtain agreement for σ_T^2 between data and Monte Carlo is shown in Figure 15
 744 versus drift height z , along with the fit of Equation 5. Unlike in Ref. [73],
 745 fitting Equation 5 to $(\sigma_T^{MC})^2$ instead of to the observed transverse moment
 746 $(\sigma_T)^2$ decouples the diffusion measurement from possible bias introduced by

747 the digitization and readout. The values of D_T/μ (see Table 2) can be cal-
 748 culated from the slope of the fitted lines, and agree with the published value
 749 of $D_T/\mu = 0.051$ V for $E/N = 9.5$ Td [52]. The errors have been computed
 750 as the difference in values obtained for D_T/μ and $\sigma_{T,0}^{MC}$ between the results
 751 of this analysis applied to Monte Carlo data and the known input values.
 752 The y -intercept of the fitted lines represents the inferred intrinsic, height-
 753 independent transverse width of the alpha tracks, prior to CCD digitization
 754 and readout. The zero-drift-length transverse widths listed in Table 2 are
 755 comparable across each of the four CCDs, with variations arising because
 756 these parameters depend not only on the width of the alpha tracks in ab-
 757 sence of diffusion, but also on a number of effects presently not incorporated
 758 in the Monte Carlo simulation including the secondary electron avalanche
 759 width, the amplification stage grid spacing ($254\ \mu\text{m}$), the imperfect focus of
 760 each CCD, and lateral straggling of the alphas themselves, with the latter
 761 expected to be dominant. None of these effects, however, are expected to
 762 vary with source height. This assumption is validated by the similar slopes
 763 of transverse moment vs. alpha source height for all four CCD cameras (see
 764 Figure 15).

765 9. Conclusions

766 The 4Shooter detector has been built and commissioned in a surface lab-
 767 oratory at MIT. The detector performance, including the CCD and charge
 768 readout energy calibrations, gas gain measurements and transverse electron
 769 diffusion, has been described. Additional studies are underway, including a
 770 neutron calibration run to measure the track angle reconstruction resolution

Figure 15: The spatial gaussian smearing before digitization and readout required in the Monte Carlo to match the mean reconstructed transverse moment of alpha tracks in the data. For this study, alpha sources were placed at varying heights z above the amplification stage in the 4Shooter in 60 Torr CF_4 with a 635 V anode bias and a 187 V/cm drift field. The lines represent fits of Equation 5 to the data for each CCD separately.

CCD #	D_T/μ [V]	$\sigma_{T,0}^{MC}$ [mm]
1	0.052 ± 0.005	0.79 ± 0.05
2	0.054 ± 0.005	0.69 ± 0.04
3	0.052 ± 0.005	0.66 ± 0.07
4	0.053 ± 0.005	0.72 ± 0.05

Table 2: The electron transverse diffusion constant D_T/μ and the inferred transverse width of the alpha tracks at zero drift length prior to CCD readout and digitization $\sigma_{T,0}^{MC}$, based on a fit to Equation 5, as described in the text. Data was taken in 60 Torr CF₄ with a 635 V anode bias and a 187 V/cm drift field. The errors have been estimated from comparing the results of the calibration procedure on purely Monte Carlo datasets to the known input diffusion. This result agrees with the published value of $D_T/\mu = 0.051$ V for our operating point of $E/N = 9.5$ Td [52].

771 and head-tail reconstruction efficiency at low recoil energies.

772 The 4Shooter detector was designed as a prototype for the cubic-meter
773 scale detector (DMTPCino), not to set competitive limits on WIMP-proton
774 spin-dependent interactions. That said, we have shown [43] that the 4Shooter
775 nuclear recoil detection efficiency is 50% at 50 keV_r, which gives a spin-
776 dependent WIMP-proton cross-section reach of 5×10^{-37} cm² at a WIMP
777 mass of 100 GeV/c² if run background-free for one live-year. Under the same
778 conditions, the DMTPCino detector sensitivity would be a factor of 50 better
779 (1×10^{-38} cm²), and comparable to the current leading limits from COUPP
780 [74] and SIMPLE [75].

781 Acknowledgements

782 PF acknowledges support from the US Department of Energy (contract
783 number DE-FG02-05ER41360). SV and IJ acknowledge support from the
784 U.S. Department of Homeland Security under Award Number 2011-DN-077-
785 ARI050-03 and the U.S. Department of Energy under Award Number DE-
786 SC0007852. JM, RE, and GS acknowledge support from the Science and
787 Technology Facilities Council under Award Number ST/K502261/1, and
788 Royal Holloway University of London. We also acknowledge the support
789 of the the Pappalardo Fellowship program at MIT, the MIT Kavli Insti-
790 tute for Astrophysics and Space Research, and the Physics Department at
791 the Massachusetts Institute of Technology. We would like to thank Ulrich
792 Becker (MIT) for useful discussions and generosity with hardware. We also
793 acknowledge the valuable technical assistance of Mike Grossman and Mark
794 Belanger (MIT), and Ernie Ihloff, Jim Kelsey, Chris Vidal and Peter Binns
795 at the MIT Bates Research and Engineering Center for support with the
796 vacuum system. Additionally, we acknowledge electrical engineering support
797 from Jim MacArthur at the Harvard Instrument Design Laboratory. Finally,
798 we thank the anonymous reviewer for detailed comments on this work.

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