Angular resolution of a MIMAC Dark Matter directional detector prototype

Y. Tao, a, 1 C. Beaufort, b I. Moric, a, d C. Tao, c, a D. Santos, b N. Sauzet, b C. Couturier, b O. Guillaudin, b J.F. Muraz, b F. Naraghi, b N. Zhou d, a and J. Busto c

a Tsinghua Center for Astrophysics, Department of Physics, Tsinghua University, Beijing 100084, China
b Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes(UGA), CNRS/IN2P3, Institut Polytechnique de Grenoble, 53, rue des Martyrs, Grenoble, France
c Centre de Physique des Particules de Marseille, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
d INPAC and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai Laboratory for Particle Physics and Cosmology, Shanghai 200240, China

E-mail: taoy15@mails.tsinghua.edu.cn

Abstract. In the coming decade, the mainstream direct detection Dark Matter experiments will propose candidates or will reach the neutrino floor. Directional Dark Matter Detection (DDMD) in the form of Weakly Massive Interacting Particles (WIMPs) will open a new signature. The unique directional signature providing a way to overcome background [1] correlating the Galactic Dark Matter halo with the nuclear recoil tracks detected. In order to measure the track direction, the Dark Matter detectors should be sensitive to low energy recoils in the keV range and have an angular resolution better than 20° [2]. A low pressure TPC-Micromegas detector developed by the MIMAC collaboration, measures the energy and reconstructs three-dimensional track of nuclear recoils. We have performed experiments using low energy (6-26 keV) ion beam facilities to measure the angular distribution of nuclear recoil tracks in a MIMAC detector prototype. In this paper, we study angular spreads with respect to a known incoming reference direction of 19 F nuclei tracks in this low energy range. The estimated angular resolution is better than 13° at 10 keV kinetic energy and agrees with the simulations within 20%. These results are showing that the directional signature from the Galactic halo origin of a Dark Matter WIMP signal is experimentally achievable.

1 Corresponding author.
1 Introduction

Weakly Interactive Massive Particles (WIMPs) are one of the best motivated Dark Matter candidates. Goodman and Witten [3] suggested that they would interact with detector nuclei and Spergel [1] has pointed out that measuring the angular distribution would be a needed signature of the Galactic origin of a Dark Matter signal.

Taking the example of a 10 kg CF$_4$ 50 m$^3$ MIMAC detector with a recoil energy range of (5, 50) keV, angular resolution of 10$^\circ$ and after 3 years of operation, Billard et al. [4] conclude from simulations that even in the presence of a significant background, the detector could set constraints for spin-dependent interactions comparable or better than existing detectors, (PICO 2019 [5]).

Billard et al. [2] show that with a 100% sense recognition, an angular resolution of 20$^\circ$ and with no background contamination, this type of detector could reach a 3$\sigma$ sensitivity at 90% C.L. down to 10$^{-5}$ pb for a WIMP-proton spin dependent cross section.

Several projects of Directional Dark Matter Detection (DDMD) are being developed [6–11]. This paper presents a MIMAC detector prototype performance in terms of its angular resolution at low nuclear recoil kinetic energies (6 to 26 keV). These kinetic energy nuclear recoils will release in ionization just a few keV (1-10 keV) (see Ref. [12]). The experimental setup, presented in Section 2, consists of a MIMAC chamber prototype coupled to an ion beam facility. In Section 3 we explain how we define and reconstruct the nuclear recoil track direction and discuss the method used to measure the angular resolution. As pointed out in the companion work [13], the MIMAC readouts on the pixelated anode need to be corrected for, and we include this in our analysis of the angular resolution. We present the final reconstructed angular resolution and show that it is below 13$^\circ$ at an energy as low as 9.32 keV. In Section 4 we compare the results of our measurements with simulations, including a dedicated study of several systematic effects. We show that the detection efficiency may have an impact on the angular resolution.
2 Experimental Setup and Principle of Operation

The MIMAC detector consists of a matrix of micro-Time Projection Chamber (TPC) ([14–16]) developed in a collaboration between LPSC (Grenoble) and IRFU (Saclay). Each chamber module contains a pixelated bulk Micromegas coupled to fast self-trigger electronics. In this work, we are using a $10.8 \times 10.8 \times 5 \text{ cm}^3$ prototype detector [13].

The main target for spin dependent Dark Matter detection, $^{19}\text{F}$, is a light odd nucleus, for which the momentum transfer from low mass WIMP elastic scattering is enhanced. The optimized working gas is chosen to be a special mixture (called MIMAC gas): 70% CF$_4$ + 28% CHF$_3$ + 2% C$_4$H$_{10}$, operating at a pressure of 50 mbar.

We used the LHI (Ligne expérimentale à Haute Intensité) ion beam line [13] to generate $^{19}\text{F}^+$ ions with given kinetic energy. The required species were filtered out, thanks to a high resolution 0.33 T magnetic spectrometer. The prototype was coupled to the beam line via a $1\mu\text{m}$ hole and the ions are thus injected in the direction of the beam line parallel to the drift field in the chamber.

The high voltages on the grid (or micromesh) and the cathode were set to $-570\text{ V}$ and $-1320\text{ V}$ respectively, building up a drift field of 150 V/cm, while the anode was grounded. Due to the negative voltage applied on the cathode, an extra component of the kinetic energy (1.32 keV) must be added to the original one from ECR ion source.

Part of the kinetic energy of the incident $^{19}\text{F}^+$ ion was finally released in the detector active volume by ionization. Primary electron clouds along the physical track generated from ionization started drifting under the drift field. The avalanches took place in the amplification gap of the Micromegas, producing secondary electrons which triggered strips of pixels in the $X$ and $Y$ directions (pitch of 424.3$\mu\text{m}$) [17], and are read out by a self-triggered electronics system developed at LPSC [18, 19]. The $Z$ coordinate of each primary electron is obtained by multiplying the primary electron drift velocity with the relative timing sampling.

The total ionization energy was measured by a charge pre-amplifier coupled to the grid by a flash-ADC. Both the anode signal and grid charge collection were sampled at 50 MHz (20 ns), and events were recorded as coincidence entries one by one.

The gain of the detector coupled to the preamplifier during the experiment is estimated to $O(10^4)$ from the 5.9 keV peak of the energy calibration source $^{55}\text{Fe}$ [13].

3 3D Reconstruction of Ion Track and Its Direction

The X-Y 2D positional information is provided by the secondary electrons created by the MIMAC Micromegas avalanche field (see Figure 2 in [13]). The sampling of the anode every 20 ns allows the reconstruction of a 3D cloud of primary electrons for each detected event. In our experiment, we applied a 150 V/cm electric field, and thus the drift velocity of primary electrons was $V_{\text{drift}} = 22.9\mu\text{m/ns}$, computed by the MAGBOLTZ code [20]. After applying a correction on the effective drift velocity, as discussed in the companion paper [13], due to space charge effects in the 512$\mu\text{m}$ gap of the Micromegas detector, we obtain the 3D primary electron cloud for each ion event.

3.1 Definition of angular resolution

The direction of a recoil track or an incident ion track is modified in the first collision between the injected ion and nuclei in the gas. The important information for DDMD is the
initial ion direction defined by the beam. However, this ideal information will be washed out by secondary interactions in the drift and avalanche regions.

In order to overcome this challenge, the strategy for reconstructing a track direction is to perform a 3D linear regression fit on the pixelated electron cloud. Then we derive the direction of the fitted track with respect to the drift direction ($Z$-axis).

The 3D linear fit on pixelated primary electron clouds was performed by a least squares minimizing algorithm using the coordinate distances of the barycenters of each time slice. An example of a 3D fit for a 26.32 keV (25 keV from the voltage acceleration in ion source plus 1.32 keV from the cathode voltage with respect to the ground) $^{19}$F$^+$ ion event (and a 2D representation of the same track) is shown in Figure 3. The combination of the straggling and the detector spatial resolution gives the direction of the recoil coming from $\hat{r}(\Omega)$ being interpreted as $\hat{r}'(\Omega')$, where $\Omega \equiv \Omega(\theta, \varphi)$ is the solid angle (Figure 1).

A polar angle $\theta$ was derived for each track, with $0^\circ$ being the direction of the $^{19}$F$^+$ beam ($Z$-axis and primary electron drift direction). $\theta$ is actually the angular deviation from $0^\circ$ from all effects combined, after the ion enters the chamber at $0^\circ$, hence its distribution can be used to define an angular resolution as discussed below.

However, the distribution of the reconstructed angle $\theta$ between the track and the low energy beam is not a Gaussian variable by definition. In contrast, $\theta_x$ and $\theta_y$ defined in Figure 1, appear as Gaussian variables in our experiments as shown in Figure 2. All directional information are embedded in $\theta_x$ and $\theta_y$ via

$$\tan \theta_x = \tan \theta \cos \varphi, \quad \tan \theta_y = \tan \theta \sin \varphi$$

The spread of angular distribution can be written as

$$\sigma_\theta(\theta_x, \theta_y) \bigg|_{\theta_x=\mu_{\theta_x}, \theta_y=\mu_{\theta_y}} = \sqrt{f^2(\theta_x)\sigma_{\theta_x}^2 + f^2(\theta_y)\sigma_{\theta_y}^2}$$

in terms of $\theta_x$ and $\theta_y$, where $f(\theta) = (\tan^2 \theta + 1) \tan \theta$.

Both the angular distribution of the incident ions and the dispersion of the primary electron distribution contribute to the final angular resolution:

- Distribution of the incident ions: The reconstructed direction deviates from the initial direction. This is due to several physical effects: (1) primary electrons diffusion, (2) initial ion beam not exactly at zero degree: the hole through which the ions enter the chamber has a 1 $\mu$m diameter and 13 $\mu$m length (maximum angle of 4.4$^\circ$) and (3) eventual bias from the reconstruction algorithm.

- Statistical dispersion: Spread of the distribution, usually defined as the standard deviation of a Gaussian Probability Distribution Function (PDF). The main contribution to the statistical dispersion should be the straggling of ions, which is a convolution of multiple small angle scattering with the nuclei of the gas. Other factors deteriorating angular resolution are the interactions of the primary electrons inside the gas chamber, straggling caused by electron collisions and re-combinations with the gas atoms [15], and diffusion [21].

The measured mean angle of the incident ions distribution is small (< 1.6$^\circ$) and the dispersion has an effect about 10 times larger than the shift of the central value (more than 4 times for 26.3 keV), as shown in Table 1. Thus we simply take the spread of the angular distribution (3.2) as the definition of angular resolution.
### 3.2 Analysis results on angular resolution

The analysis was performed for $^{19}$F$^+$ ions with 9 kinetic energies in the range of [6.3, 26.3] keV, and a statistics of over $1.8 \times 10^4$ events per each energy, after the background rejection. Figure 3 and Figure 4 show examples of track trajectories in $ZX$, $ZY$ projections for ions with kinetic energies of 26.3 keV and 9.3 keV respectively, with the best fit line in 3D.

The final angular resolution as a function of the ion kinetic energy is shown in Figure 5 (red). Its dispersion is better than the required $20^\circ$ [2] down to kinetic energy of 9.3 keV. We also plot the mean angle between the incident and reconstructed direction (denoted as $\delta(\theta)$) for each ion kinetic energy (blue).

The derived uncertainty (denoted as $\Delta\theta$) on angular resolution is based on the determination of the spatial coordinates of the reconstructed primary electron cloud and the error of the 3D linear fit:

\[
\Delta\theta(x, y, z)\Big|_{\theta=\bar{\theta}} = \sqrt{\left(\frac{\partial\theta}{\partial x}\right)^2 \Delta^2(x) + \left(\frac{\partial\theta}{\partial y}\right)^2 \Delta^2(y) + \left(\frac{\partial\theta}{\partial z}\right)^2 \Delta^2(z) + \Delta^2_{\text{fit}}} \approx \cos^2\theta \frac{\Delta^2_X + \tan^2\theta \cdot \Delta^2_Z}{z} \tag{3.3}
\]

where $\Delta(z) = \Delta(V_{\text{drift}} \cdot t)$ mainly depends on sampling time, $\Delta_X = \Delta(x) = \Delta(y)$ is the intrinsic systematic uncertainty due to alignment and finite size of anode strips. The fit error $\Delta_{\text{fit}}$ is negligible, so we can only take the first term into consideration. For $\theta \approx 0^\circ$ case, the uncertainty can be further approximated and simplified to be only dependent on the pitch of the anode strips and the reconstructed track length:

\[
\Delta\theta(x, y, z)\Big|_{\theta=\bar{\theta}=0^\circ} = \frac{\Delta_X}{L}, \tag{3.4}
\]

where $\Delta_X$ is the same as in (3.3) and $L$ describes the primary electron cloud dimensions (the reconstructed ion track length after the empirical correction [13]). For the accuracy of our estimation, the error bars presented in Figure 5 are derived from (3.3). The error we obtained is $\pm 1.57^\circ$ for the lowest ion kinetic energy and $\pm 0.67^\circ$ for the highest.

We have applied various algorithms in order to find the best way to reconstruct the initial angle. The differences among these algorithms are mainly whether to use the entire electron cloud or only part of it, and how to set weight on each pixel. Modifying the algorithms to use only the first part of the track (with a $\chi^2$ test to select the optimum number of points) does not yield an improvement on the angular resolution. In addition, initial and final time slices of the track usually have a larger than average deviation from the track direction. This is because the anode samples the endpoints of the transversely diffused primary electron cloud. Removing the first and last time slice does not produce better results either.
We finally chose to use the barycenter weighted method with the information from all 3D pixels, which average reconstructed angle is closest to the initial \(0^\circ\) angle, and has the lowest dispersion.

4 Comparison of simulations with measurements

The angular resolution measurements have been compared to Garfield++ [22] simulations. Garfield++ is a toolkit for particle tracking simulations, which proposes an interface to SRIM [23] to generate ion tracks, and whose electron transport algorithm solves the second-order equations of motion based on the MAGBOLTZ [20] gas tables.

The simulations reproduce the LHI experiment conditions. For each kinetic energy, we have sent 200 fluorine ions at \((X,Y,Z) = (5.4 \text{ cm}, 5.4 \text{ cm}, 5 \text{ cm})\) along the \(Z\)−direction. Each primary electron is transported up to the grid and suffers the transverse and longitudinal diffusion on the way.

We have observed a continuous reduction of the drift velocity depending on the detector gain and the charge density. A possible explanation for such a phenomenon lies on the slow ion backflow in the Micromegas which builds a space-charge up and locally distorts the electric field. The asymmetry of the flash-ADC signal gives a direct observation of this velocity reduction, which enables to determine an asymmetric factor that quantifies the magnitude of the elongation. We have experimentally validated the ability of this factor to describe the phenomenon as a first approximation [13]. This high-gain systematic effect has been included in the simulations: the drift velocity is linearly reduced according to the value of the asymmetric factor.

The simulations sample the arriving of charges MIMAC-wise: a 50 MHz (20 ns) readout and a pixelization in the \(X-Y\) plane with strips at 424.3 \(\mu\text{m}\) pitch. For this reason we can apply the same analysis algorithms on the measurements and the simulations, allowing for the results to be compared.

4.1 Angular resolution

The simulation results of the projected angles \(\theta_x\) and \(\theta_y\) are presented in Figure 6. The angle dependence on the kinetic energy follows the same evolution shown in the measurements. At 6.32 keV, the spread of the simulated distribution is twice narrower than the measured one; this difference decreases with the energy and remains below 20\% for energies above 13.82 keV. This difference at low energies propagates to the angular resolution, as shown in Figure 5. An explanation of the differences observed will be given below.

4.2 Study of systematic effects

Along its way to the anode, the primary electron cloud suffers several distortions modifying its shape. The question is: will the physical information of the initial direction be washed out by these shape distortions? We identified four main effects: (1) the diffusion, (2) the high-gain systematic in the amplification region, (3) the avalanche, (4) the anode strips lack of efficiency. We propose to study how the angular resolution is affected by each one of these effects.

The angular resolution depends not only on the conservation of the primary cloud shape, but also on the experimental access to this information.
According to SRIM and without the distortions, a $^{19}$F$^+$ ion track of kinetic energy below 20 keV would be seen as a few pixels cloud but only one or at most two time slices of 20 ns) in a MIMAC detector chamber and no clear direction would be measured.

We show in the companion paper that the diffusion in 5 cm drift enlarges the primary cloud of about one order of magnitude in each direction. In this case, the diffusion appears as a helping process for 3D detection of low energy nuclear recoils. If the diffusion was fully symmetric, the directional information would be conserved during the cloud enlargement. However, according to MAGBOLTZ, the longitudinal diffusion dominates the transverse one by a factor $\frac{293.9}{283.1} = 1.16$.

In addition, the high-gain systematic effect in the avalanche reduces the primary charge collection drift velocity given a reduced total effective drift velocity, and thus giving more time slices describing the primary electron cloud along the $Z$-direction.

We have mentioned previously, cf. companion paper [13] and its Figure 5, reproduced in Figure 7 of this paper, that this effect can be described by an asymmetric factor between the flash-ADC rising and falling times. This multiplicative factor comes from the reduction of the drift velocity under space charge effects, and has a value in the range [0.66, 0.71] in the conditions of our LHI experiment.

The Garfield++ simulations give the possibility to include or not this drift velocity reduction in order to study the high-gain systematic effect. Figure 8 shows the simulation of $\theta_x$ and $\theta_y$ angles computed from 1000 $^{19}$F$^+$ ions of 9.32 keV kinetic energy, with and without the drift velocity reduction. The charges are collected in 9 time slices for the simulated clouds with the reduction; in 6 time slices otherwise. Even if the final clouds are more affected, the distortion increases the number of points to be fitted and leads to a better angular resolution: 8.00° compared to 11.2°.

In the companion paper [13], we have shown that the avalanche contribution to the depth was negligible, see Figure 7, being symmetric in $X$ and $Y$ directions. For this reason, the barycenter weighted method used for the 3D linear fit is not affected by the avalanche enlargement.

Finally, after the avalanche, the positions in the $X$-$Y$ plane are measured by the anode strips. Each strip has its intrinsic noise threshold and can only be triggered if the number of charges within one time slice exceeds this threshold. This eventual lack of efficiency results in some non-detected charges, especially at low energies. We have studied the angular resolution dependence on the strip threshold with Garfield++. Since we do not simulate the avalanche, the threshold value is applied on the number of primary electrons needed. The results are presented on Figure 5, where the same threshold value is applied on $X$ and $Y$ strips.

As one can see on Figure 5, the anode lack of efficiency represents a significant systematic effect, especially at low energies. The tendency of the LHI angular resolution suggests that the measurements suffer from such an effect showing at the same time the expected results having one primary electron efficiency.

The Garfield++ simulations have allowed to isolate each systematic effect in order to study its influence on the angular resolution. At low energy, the number of readouts acts as a critical parameter for the 3D linear regression accuracy. For this reason, even if they distort the primary electron cloud, this distortion is well fitted by our simulations showing that diffusion and the high-gain systematic effect give experimental access to angular resolution measurements by the MIMAC detector.
5 Conclusion and Outlook

The angular resolution represents a decisive aspect for Dark Matter identification, especially beyond the neutrino floor. In this paper, we report experiments performed with a MIMAC prototype and the LHI facility are at zero angle to the beam line. For $^{19}$F$^+$ ion kinetic energies between 6.3 keV and 26.3 keV, the angular resolution ranges between 25° and 3°, respectively. We find that down to 10 keV kinetic energy, the angular resolution ($< 13°$) of our MIMAC prototype detector is better than the required 20° from Ref. [2].

Diffusion, phenomena in the amplification gap, and anode pixelization contribute to the angular resolution that we measure. Dedicated Garfield++ simulations have shown that these effects allow an experimental access to the angular resolution measurements. The simulations agree with the measurements within 20% for energies above 13.82 keV.

The directional detection also plays a key role for neutron spectroscopy from neutron-induced nuclear recoils. Several experiments performed with MIMAC detectors with 18 cm and 25 cm drift chambers have demonstrated the ability of the MIMAC strategy to perform neutron spectroscopy in the range [27 keV, 15 MeV] [24, 25]. We are currently analysing data of 565 keV mono-enegetic neutrons produced by the AMANDE facility [26] giving nuclear recoils at different angles with respect to the drift direction with a 25 cm drift chamber.

The MIMAC collaboration is developing a 1 m$^3$ detector built from bi-chamber modules with 25 cm drift each, to be installed in Modane Underground Laboratory (LSM). If a candidate Dark Matter signal is observed in the range of few GeV, the angular resolution that we observe can provide a clear signature for the Galactic origin of such Dark Matter candidate signal.

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Figure 1. Schematic diagram for direction-related geometrical observables in 3D space. The incoming beam direction is along the $Z$-axis, which is the same as the direction of the drift electric field. An example of reconstructed track direction $\Omega(\theta, \phi)$ is shown as a red arrow with polar angle $\theta$ and azimuthal angle $\phi$ indications. The orange arrows represent the 2D projections of this 3D directional vector, defining $\theta_x$ and $\theta_y$.

Figure 2. Normalized distributions of $\theta_x$ and $\theta_y$ for $^{19}$F$^+$ ions of kinetic energy ranging from 6.3 keV to 26.3 keV.
Figure 3. Example of an ion track in ZX and ZY projection using barycenter representation (left) and 3D (right) for an ion of kinetic energy of 26.3 keV. To derive the direction of the track, a 3D linear fit is performed on the 3D cloud of primary electrons.

Figure 4. Example of an ion track in ZX and ZY projection using barycenter representation (left) and 3D (right) for an ion of kinetic energy of 9.3 keV. To derive the direction of the track, a 3D linear fit is performed on the 3D cloud of primary electrons.
Figure 5. The measurement (red) and simulation (green and magenta, with different threshold) of angular resolution of MIMAC detector as a function of $^{19}$F$^+$ ion kinetic energy. At lower energies, the ion tracks are shorter and have more straggling resulting in worse angular resolution and bigger error bars. The measured angular resolution is better than $13^\circ$ down to a kinetic energy of 9.3 keV. Error bars are derived from the pixel strips pitch and reconstructed track length as described in the text. We also show the measured mean angle $\delta(\theta)$ between the incident and reconstructed direction for each ion kinetic energy (blue).

Figure 6. Normalized distributions of the projected angles from Garfield++ simulations with 200 $^{19}$F$^+$ ions per energy.
Figure 7. Main results of the companion work [13] showing comparison of ion depths ($\Delta Z$) at different energies between experiment (red stars) and Monte Carlo simulation (blue circles) combining SRIM and diffusion. The orange box is for SRIM only, the green diamond when diffusion and other effects are included using Garfield++. The magenta triangles are experimental measurements with an asymmetric factor correction.

Figure 8. High-gain systematic influence on the projected angles from Garfield++ simulations with 1000 $^{19}$F$^+$ ions of 9.32 keV. Measurement results of LHI experiment are also presented for comparison.