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Dark Matter Directional Detection with MIMAC

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Abstract. The MIMAC (MIcro-tpc MAtrix of Chambers) experiment is a micro-TPC matrix for directional dark matter search. Directional detection is a strategy based on the measurement of the WIMP flux anisotropy due to the solar system motion with respect to the dark matter halo. The main purpose of MIMAC project is the measurement of nuclear recoils energy and their 3D track direction from the WIMP elastic scattering on target nuclei. The first ionization energy and 3D track observations of nuclear recoils produced by the radon progeny recently reported being shown. This measurement shows the capability of the MIMAC detector and opens the possibility to explore the low energy recoil directionality signature. The measurement of the drift velocity from an implementation of the cathode signal is also mentioned.

1. Introduction

A wide variety of astrophysical observations at different scales converge to the hypothesis of the existence of an important dark matter component in our Universe. According to cosmological precision measurement, dark matter represents roughly 85% of the matter in the Universe [1]. At the galaxy scale, the dark matter particles would form cold and static halos around the disks of galaxies. This dark halo would be composed by particles called WIMP (Weakly Interacting Massive Particle), a stable particle interacting only by weak and gravitational interactions with a mass ranging from 1 GeV to 1 TeV scale. The motion of the solar system with respect to the dark halo should generate a detectable WIMP flux through the WIMP-nucleus interaction on an underground detector. The dark matter directional detection opens a new field in cosmology bringing the possibility to build a map of nuclear recoils that would be able to explore the galactic dark matter halo giving access to a particle characterization of such matter and the shape of the halo [10]. The directional signature would be the only way to go further the ultimate neutrino background [11]. MIMAC is a dark matter directional detection project based on a matrix of micro-TPC chambers at low pressure having a high spatial resolution in 3D [2, 4]. As the other directional detection experiments [3], the aim of the MIMAC project is the measurement of the WIMP-induced nuclear recoil energy and angular distributions in order to constrain the WIMP dark matter properties. In this context, the MIMAC collaboration developed an original detector and readout strategy allowing the measurement of nuclear recoil tracks in 3D. Since June 2012, a bi-chamber prototype was installed at the Modane underground laboratory (Laboratoire Souterrain de Modane[1]) for preliminary tests. This first data analysis showed the most important source of background for dark matter search came from the radon progeny recoils. The first 3D tracks measurement of the daughter nuclear recoils from radon progeny α-decay were detected and recently published [13].

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[1] LSM

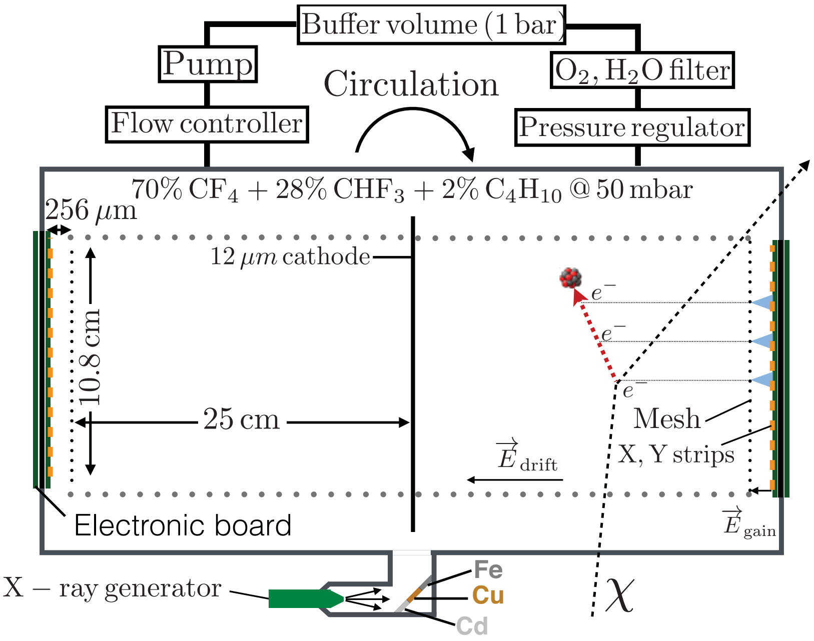

Figure 1. Scheme of the bi-chamber prototype configuration and the ionization electron collection from a nuclear recoil produced by a WIMP elastic scattering.

2. The MIMAC experiment at Modane Underground Laboratory (LSM)

The bi-chamber prototype is filled with a low pressure (50 mbar) $CF_4 + 28\%CHF_3 + 2\%C_4H_{10}$ gas mixture. As schematically shown in figure 1, this prototype is composed of two mirroring chambers sharing a thin 6 μm aluminized mylar cathode at 25 cm from the anode. The anode consists of a pixelated micromegas [5, 6] of 10.8 cm side linking the 200 μm pixels by strips with a 424 μm pitch coupled to a fast self-triggered electronic system specially developed for MIMAC [7, 8].

3. Radon Progeny spectra and their 3D tracks

The intrinsic pollution of ^{238}U and ^{232}Th of the detector materials is the source of ^{222}Rn and ^{220}Rn emanations. After successive alpha decays, radon isotopes can migrate from the materials bulk to their surfaces. The events associated with α and β decays of the radon chain radio-nuclei constitute a background for WIMP dark matter search and they should be discriminated in dark matter detectors. Radon Progeny Recoils (RPR) denote nuclear recoils produced by α-decays of radioactive elements of ^{222}Rn and ^{220}Rn decay chains, it includes α-particles and daughter nuclei recoils. In the MIMAC detector, in the dark matter search configuration, it is not possible to measure α-particle energies or their track lengths because at 50 mbar their tracks are not fully contained in the active volume of one chamber. Instead, we can observe the daughter nuclear recoils produced by the α-particle emission measuring their 3D tracks with their total ionization energy showing the ability of the detector to get a clear signature of low energy nuclear recoil tracks.

The ratios of the two peak amplitudes are 2.6 ± 0.3 for the chamber 1 and 2.4 ± 0.3 for the chamber 2. In addition, RPR events occur at different positions inside the detector which impact their tracks and energies and in consequence their discrimination. In figure 3 a RPR event of 41.1 keV is shown at the cathode level and another of 36.4 keV on a grid level. The difference between them is the 25 cm diffusion in their charge collection.

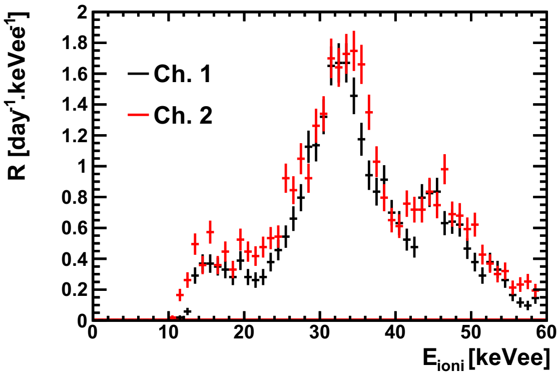

Figure 2. Energy spectra measured by the chamber 1 (black line) and the chamber 2 (red line). It should be pointed out that each event represented on these spectra has its own 3D track associated. These distributions were obtained applying the low energy electron/recoil discrimination.

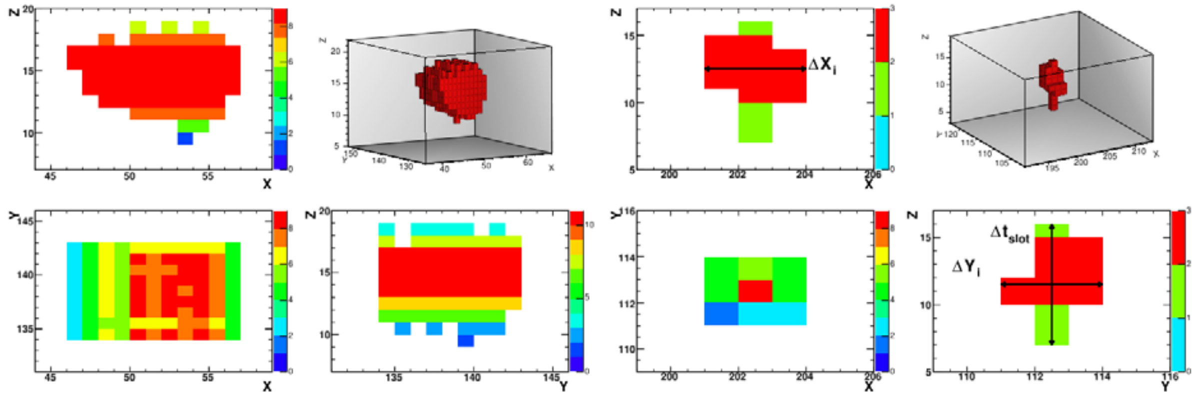

Figure 3. Projections of a 41.1 (left panels) and a 36.4 keVee (right panels) measured nuclear recoil tracks in the (X,Z), (Y,Z) and (X,Y) planes and 3D reconstructions. The Z axis is in units of time-slice (20 ns) and the X and Y axis in strip number. The color scale corresponds to the number of strips fired on the time-slice. The horizontal arrows represent one time-slice width X/Y along the X/Y axis. The vertical arrow represents the slot duration Δt_{slot}.

4. Electron-nuclear recoil discrimination

In order to reject the electron recoil background from dark matter searches data, we have developed an original electron/recoil discrimination method described in [15]. We placed a MIMAC mono-chamber detector on a monochromatic neutron field allowing us to acquire two specific data sets: electron and nuclear recoil and electron recoil only. We applied a Boosted Decision Tree (BDT) algorithm on these two data sets. It gives a 10^5 electron recoil rejection power. The application of the BDT analysis on the Monte Carlo shows a $86.49 \pm 0.17\%$ nuclear recoil efficiency considering the full energy range and $94.67 \pm 0.19\%$ considering a 5 keV energy threshold with a 10^5 electron recoil rejection power.

This method was applied on the 2013 data run (103 days) and figure 2 presents the resulting nuclear recoil energy spectra. After the application of this analysis, we can consider the electron recoil event contamination on our data as negligible. These energy spectra show two peaks at 33 and 46 keVee, in both chambers (black line chamber 1 and red line chamber 2) [13].

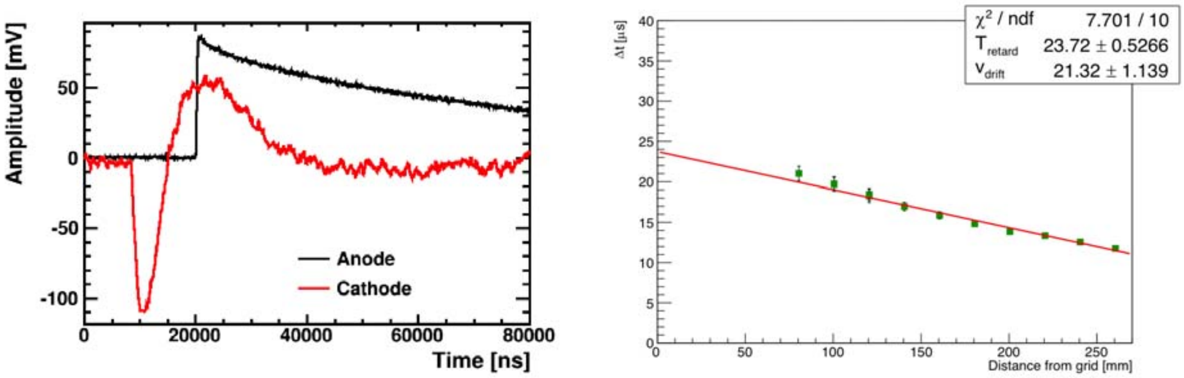

Figure 4. Left: amplitudes of the signals from the cathode preamplifier and from the grid preamplifier as shown on the oscilloscope. Note that here, the cathode signal is not delayed, and is detected before the grid signal. Right: Measure of the time differences (ΔTAC) between the grid signal and the delayed cathode signal as a function of the distance of the α source from the anode (green points) ; only the statistical errors are displayed. A linear fit of these points is superimposed in red and provides the values of the drift velocity and the imposed delay on the cathode signal.

5. The cathode signal

In order to place the 3D track in the active volume with respect to the position of the cathode, we have implemented an electronic device to take the induced current on the cathode signal produced by the movement of the primary ionization electrons during their transport to the grid by the drift electric field. In figure 4 we show the cathode signal generated by an alpha particle parallel to the cathode placed at 14 cm from it. The validation of this signal as a new observable has been done performing the measurement of the drift velocity in our MIMAC mixed gas chamber, see figure 4 and [14] for more details. The final value of the drift velocity obtained was:

$$v_{\text{drift}} = (21.2 \pm 1.2(\text{stat}) \pm 0.04(\text{sys}))\mu\text{m/ns}.$$

It differs slightly from the value obtained using the MAGBOLTZ software [16]:

$$v_{\text{drift}} = (24.1 \pm 0.02)\mu\text{m/ns}.$$

The difference can be explained by the experimental conditions, in general, not the same as those introduced as input in the simulation: the pressure of the mixed gas varying with the temperature of the room ($\sim$1 mbar), the gas containing some impurities not at all evaluated, and the electric field in the drift volume can contain some amount of inhomogeneity. The same difference has been reported by an alternative experimental method in 2013 [9]. The measurement of the drift velocity performed with the method described here corresponds to a setup with real experimental conditions, which are not fully taken into account when performing the MAGBOLTZ simulation.

6. Conclusions

In this proceeding, we have summarized some of the main results of MIMAC collaboration in the last years. We have shown, for the first time, the observation of low energy nuclear recoil 3D tracks from daughter nuclei of the ^{222}Rn decay chain. This measurement shows the capability of the MIMAC detector and opens the possibility to explore the low energy recoil directionality signature. The radon gas emanation monitoring and its reduction is a major topic for rare event experiments such as dark matter or double-β decay search experiments. The new degrees of freedom, offered by the observation of 3D low energy nuclear recoil tracks describing these events shed a new light on them improving their localization and discrimination. The implementation of the cathode signal in a TPC is an interesting result opening the possibility to place the 3D tracks in the active volume.

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