Dark matter directional detection with MIMAC

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The MIMAC project aims at the directional detection of dark matter using a gaseous Time Projection Chamber (TPC) which enables the measurement of the energy and the track of low energy nuclear recoils. A 5-liter prototype has been developed and operated during several months. In this paper, after a description of the detector and the calibration procedure, we report the first results of the background studies.

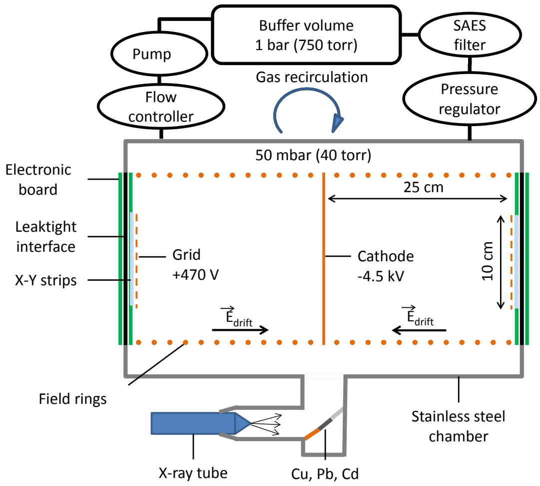
1 Introduction

The dark matter directional detection firstly proposed by Spergel [1] consists in measuring the direction of the nuclear recoil induced by the WIMP-nucleus elastic scattering. Given the earth motion in the galaxy, the WIMPs of the galactic halo are expected to originate from a preferred direction, which corrresponds roughly to the Cygnus constellation. Since the background is supposed to be isotropic in galactic restframe, an anisotropy in the nuclear recoil direction distribution would provide a non-ambiguous signature of WIMP interactions [2]. Phenomenological studies have shown that a $50\,\mathrm{m}^3$ detector filled with 10 kg of CF_4 at 50 mbar and operating during 3 years could reach a better sensitivity than the current limits in the spin-dependent interaction parameter space [3]. In case of a positive signal, the measurement of the nuclear recoil direction would also allow to constrain the galactic dark matter properties [4]. The MIMAC project [5] is one of the current R&D projects investigating the feasibility of the directional detection [6]. The proposed detector would be a matrix of TPC allowing the measurement of the 3D tracks and the energy of nuclear recoils down to 20 keV. A first 5-liter prototype has been developped and operated during several months to study the detector performance. In this paper, we first describe the current prototype. Then, we detail the calibration procedure. Finally, we report preliminary results of the background studies.

2 The MIMAC detector

The current MIMAC prototype (see fig. 1) is composed of two TPCs sharing one common cathode. Each TPC is 25 cm long and equipped with a pixelized micromegas detector ($10 \times 10\,\mathrm{cm}^2$). Anode pixels are interconnected to constitute 512 X-Y strips with a pitch of $424\,\mu$m. Ionization electrons created by nuclear recoils drift toward the micromegas under an electric field of

$\sim 200\,\text{V/cm}$. The electron avalanche in the micromegas thin gap ($256\,\mu$m) induces a current on the strips. Every 20 ns, the fired X-Y strips (*i.e.* with a signal higher than a given threshold) are stored, providing two 2D images (X(t) and Y(t)). 3D tracks are obtained by combining these two images. In addition, the current collected on the micromegas grid is also sampled at 50 MHz. The total energy deposited in the detector can be measured by integrating this signal.



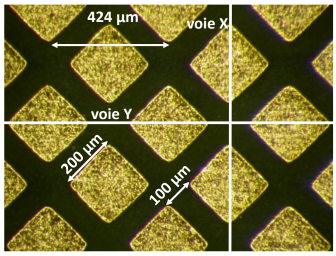


Figure 1: (left) Design of the 5-liter prototype which is composed of two TPC sharing one common cathode. (right) Picture of a portion of the pixelized anode.

The MIMAC detector is filled with a mixture of CF_4 (70 %), CHF_3 (28 %) and C_4H_{10} (2 %). To measure the nuclear recoil directions at very low energy (few tens of keV), the pressure inside the detector has to be as low as 50 mbar. CF_4 has been chosen for its qualities as a detection medium and because fluorine is an excellent target for the WIMP-nucleus spin-dependent interaction. CHF_3 is added to slow down the drift of ionization electrons, which allows for a better track sampling. Finally, C_4H_{10} is used as a quencher to improve the avalanche process in the micromegas gap. To ensure a good charge collection, the gas is permanently recirculated through a SAES filter which removes impurities, mainly H_2O and O_2 molecules.

3 Detector calibration

The detector is calibrated using electronic recoils induced by X-rays. A X-ray tube operated at 20 kV generates X-rays, with a continuous energy spectrum, towards copper, lead and cadmium foils. Secondary X-rays are emitted by fluorescence at several known energies and can interact inside the detector. The orientation of the X-ray tube is chosen in such a way that primary X-rays cannot enter the detector volume. An example of a measured spectrum is shown in figure 2. The spectrum is fitted very well with a sum of six Gaussian functions corresponding to the main expected X-rays, including the ones emitted by the cobalt and iron atoms of the stainless steel chamber. The detector resolution inferred from the Gaussian widths is about 8 % (σ) at 8 keV. The right plot demonstrates the excellent linearity between 3 and 12 keV. The relative size of lead peaks reveals that the detector becomes transparent above 10 keV due to the low pressure. Consequently, it is not possible to use this method at higher energy.

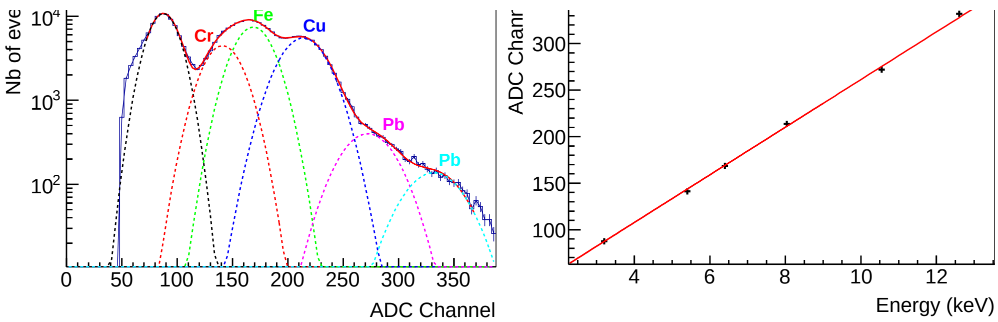


Figure 2: (left) Energy spectrum measured with the X-ray tube and fitted with a sum of 6 Gaussians corresponding to X-ray emitted by fluorescence. (right) Linearity of the detector.

To calibrate the detector at higher energy and in nuclear recoil energy, a new device is under development. This device, which includes an ECR source, is able to generate electrons and ions between 5 keV and 50 keV. These particles are injected inside the detector via a micro hole. This device will be also very useful to characterize all the aspects related to the energy and track measurements (efficiencies, angular resolution, drift dependences, etc.).

4 Background studies

To reach a competitive sensitivity on the WIMP-nucleus spin dependent interaction, a very low background is needed. In summer 2012, the detector has been installed at the Laboratoire Souterrain de Modane (LSM) to identify the main background sources. Thanks to the gas recirculation system, the detector could be operated remotely during several months. A weekly calibration showed that the detector gain was very stable.

The background studies are based on event discrimination using the track and the grid signal. There are several kinds of events. First, electronic recoils due to gamma interactions or beta decays are the dominant background. Most of them can be rejected because they do not have any track or only few-pixel tracks due to their low ionization density. Second, alpha events are easily identified with their very long straight track and their large energy. Remaining events are nuclear recoils. The length of their short tracks is correlated with energy. Nuclear recoils below 100 keV are the most problematic background since they correspond to the WIMP interaction signature. In this paper, only basic and preliminar cuts are used together with a conservative threshold of 20 keV while the trigger threshold is at the keV scale.

The rates of alpha events and nuclear recoil events are presented in figure 3. In normal operation with gas recirculation, the rates are stable: about 200 alphas and 10 nuclear recoils per hour are observed. When the recirculation is switched off, the rates decrease exponentially with a time constant compatible with 3.8 days, the [^{222}Rn] half-life. This demonstrates that the background is dominated by radon decay, and its progeny, coming from outside (probably due to a small leak in the pump). The corresponding contamination of the gas has been estimated to be few 10 mBq/g. Nuclear recoils that are detected correspond to the recoil of daughter nuclei when the alpha decay happens on the edge of the TPC (anode or cathode) and when the alpha is emitted outward from the detector. Daughter nuclei being positively charged, they are expected to drift and to stick on the cathode. The two peaks of the nuclear recoil energy spectrum (see fig. 3) would therefore correspond to the recoils of ^{210}Pb and ^{214}Pb after the alpha decays of ^{214}Po and ^{218}Po. Given the theoretical recoil energies (112 keV and 146 keV), the mean energies of the peaks (32 keVee and 45 keVee) result in a quenching factor of $\sim 30\,\%$, which is a reasonable value for heavy nuclei. The constant background at higher energies could be explained with alpha events that escape from the detector leaving only a small part of their energy in the detector. The different components of the spectrum can be better separated using more sophisticated cuts, on the track shapes in particular. More details will be given in an upcoming paper.

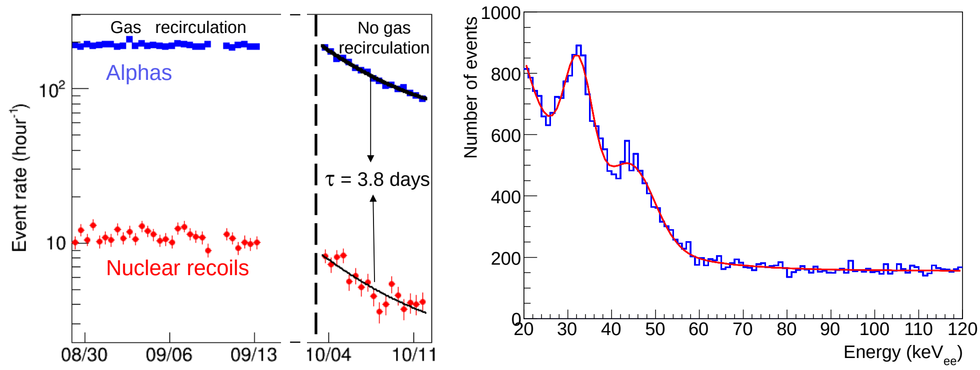


Figure 3: (left) Rate evolution of the alpha and nuclear recoil events. (right) Energy spectrum of the nuclear recoil background.

To reduce the nuclear recoil background, a new recirculation pump with a better leakage rate has been installed. The cathode has been also replaced with a thinner one (12 μm). Together with a time synchronization of both TPC, it will help to reject nuclear recoils emitted from the cathode since alphas should be detected in coincidence. New underground data taking is ongoing to validate these upgrades.

5 Conclusion and Outlook

The 5-liter bi-chamber prototype, which has been developed to investigate the feasibility of a dark matter directional detector, allows to measure the energy and the track of low energy nuclear recoils. The detector calibration using X-ray fluorescence has demonstrated the excellent linearity of the energy scale. The resolution is about 8 % at 8 keV. The first underground data taking in summer 2012 have shown that the dominant source of background is radon and its progeny. Several upgrades have been performed and they are currently tested underground. If the new level of background is low enough, the next step will be to build a detector at the cubic meter scale.

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