DIRECTIONAL DARK MATTER DETECTION

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The hypothesis of the existence of non-baryonic dark matter in our galactic halo is supported by all astrophysical observations performed from cosmological to local scales. The direct detection of an elastic collision with a target nucleus of a weakly interacting massive particle (WIMP), the most accepted candidate for such a matter, has to be discriminated from those produced by neutrons. The only non-ambiguous signature to be able to discriminate the WIMP events from background is to correlate those elastic collisions in the detector with the relative motion of our Solar system with respect to the galactic halo. It is the measurement of the direction in 3D of nuclear recoil tracks of a few tens of keV what is called directional detection. The directional detection opens a new field in cosmology bringing the possibility to build a map of nuclear recoils exploring the galactic halo and giving access to a particle characterization of dark matter. Many experiments all around the world try to demonstrate the ability to get this signature. This short and inevitably incomplete review will summarize the techniques and status of the most important experiments running in an underground site:, DRIFT, DMTPC, NEWAGE, Nuclear Emulsions and MIMAC .

1 Introduction

Cosmological and astrophysical observations converge to a standard cosmological model requiring a new kind of particle to explain a large amount of non-baryonic dark matter, being one of the most favorable candidates a stable weakly interacting massive particle (WIMP). In the context of direct detection of these new particles an alternative, complementary and in any case needed strategy is the development of detectors providing an unambiguous positive WIMP signal. Indeed, directional detection gives a new degree of freedom to reject neutrons, the particles that produce the same expected signal from the nuclear recoil energy. This can be achieved by searching for a correlation of the WIMP signal with the solar motion around the galactic center, observed as a direction dependence of the WIMP stream [1 2], coming from (l = 90^o, b = 0^o) in galactic coordinates, which happens to be roughly in the direction of the constellation Cygnus. The background events, coming from gamma rays and neutrons produced in the atmosphere or in the rock should follow the rotation of Earth isotropic in galactic coordinates and very different with respect to the Cygnus direction. A dedicated statistical study with simulated data analysis has shown that even a low-exposure, directional detector could allow a high significance discovery of galactic Dark Matter even with a sizeable background contamination [3] or to a robust and competitive exclusion curve [4], depending on the value of the unknown WIMP-nucleon cross section. In [5], a study has been performed on the capability of directional detectors to probe neutralino dark matter in the Minimal Supersymmetric Standard Model and the Next-to-Minimal Supersymmetric Standard Model with parameters defined at the weak scale. It shows that directional detectors at a scale of 50 m^3 will probe spin dependent dark matter scattering on nucleons that are beyond the reach of current most spin independent sensitive detectors being the scalar and axial cross section not correlated. The very weak correlation between the neutralino-nucleon scalar cross section and the axial one, as it was shown, in 2005 by E. Moulin et al. [6]and more recently by D. Albornoz et al.[5], makes this research, at the same time, complementary to the massive target experiments.

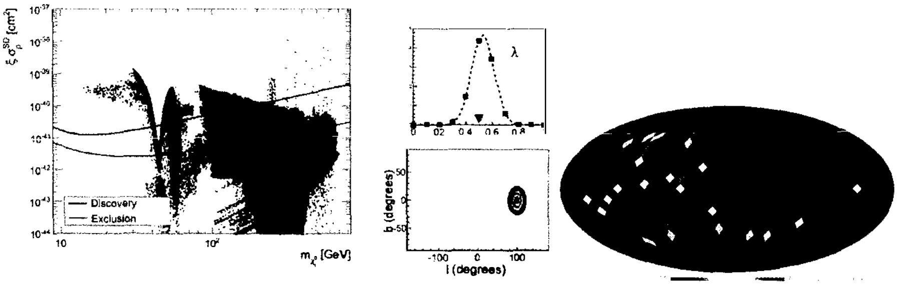

Figure 1: (Left) Proton-neutralino spin dependent elastic scattering cross section versus the neutralino mass with the exclusion and discovery projections for a 30 kg.year MIMAC detector. Points correspond to MSSM configuration allowed by collider and cosmological constraints. In blue safe points and in yellow points excluded by either XENON100 or Fermi-LAT. Figure from [19]. (Centre) The result of a maximum likelihood analysis of the map shown in (Right) giving the correct number of Wimp events (=S/(S+B) 0.5) and the directionality in galactic coordinates (l=90o,b=0o). (Right) The map made with 100 events assuming the neutron background at the same level than the signal (S/B=1) that means 50 Wimp events and 50 of background.

The main interest of the directional detection is based on the fact that the WIMP angular distribution is pointing towards the Cygnus constellation while the background one is isotropic. The right panel of figure 1 presents a typical recoil distribution observed by a directional detector : 100 WIMP-induced events and 100 background events generated isotropically. For an elastic axial cross-section on nucleon $\sigma_{\rm n} = 1.5 \times 10^{-3}$ pb and a 100 GeV.c^{-2} WIMP mass, this corresponds to an exposure of $\sim 1.6 \times 10^{3}$ kg.day in CF_4, as discussed in ref. [3]. Low resolution maps are used in this case ($N_{\rm pixels} = 768$) which is sufficient for the low angular resolution, $\sim 15^{\circ}$ (FWHM), expected for this type of detector. In this case, 3D read-out and sense recognition are considered, while background rejection is based on electron/recoil discrimination by track length and energy selection [7]. It is not straightforward to conclude from the recoil map of figure 1 (right) that it does contain a fraction of WIMP events pointing towards the direction of the solar motion. To extract information from this example of a measured map, a likelihood analysis has been developed. The likelihood value is estimated using a binned map of the overall sky with Poisson statistics, as shown in [3]. This is a four parameter likelihood analysis with m_χ, $\lambda = S/(B+S)$ the WIMP fraction (B is the background spatial distribution taken as isotropic and S is the WIMP-induced recoil distribution) and the coordinates (ℓ, b) referring to the maximum of the WIMP event angular distribution.

The result of this map-based likelihood method is that the main recoil direction is recovered and it is pointing towards ($\ell = 95^{\circ} \pm 10^{\circ}, b = -6^{\circ} \pm 10^{\circ}$) at 68 % CL, corresponding to a non-ambiguous detection of particles from the galactic halo. This is indeed the discovery proof of this detection strategy (centre panel of fig. 2) [3]. Furthermore, the method allows to constrain the WIMP fraction in the observed recoil map leading to a constraint in the (σ_n, m_χ) plane (left panel of fig. 2). As emphasized in ref. [3], a directional detector could allow for a high significance discovery of galactic Dark Matter even with a sizeable background contamination. For very low exposures, competitive exclusion limits may also be imposed [4]. We have recently shown by a Markov Chain Monte Carlo analysis [8] that the directionality opens the way to characterize also the dark matter particle mass describing at the same time our galactic halo, as shown in fig. 2.

A gas TPC can aim at achieving measurement of the direction of WIMP-induced nuclear

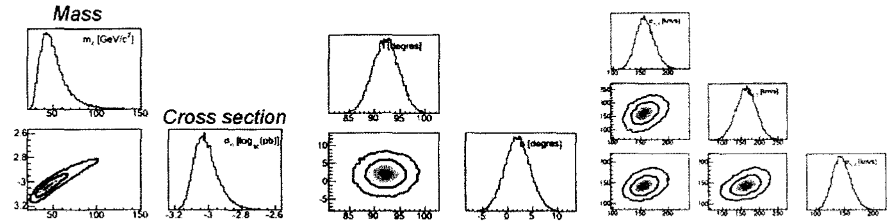

Figure 2: Marginalized distributions (diagonal) and 2D correlations (off-diagonal) plots of the 7 parameters from the analysis of simulated data in the case of an isothermal halo with a WIMP mass of 50 GeV.c-2 and a WIMP-nucleon cross section n = 103 pb, see [8] for more details

recoils. After a WIMP collision, the nuclei recoils with typical energies of 1-100 keV, travel distances of the order of few 100 amstrongs in solids, while in gases this distance can be up to the mm scale, depending on the type and pressure of the gas. Many projects over the world, DRIFT (USA, UK), DM-TPC (USA), Newage (Kyoto -Japan) , Nuclear Emulsions (Japan) and MIMAC (France), try to achieve the goals proposed for directional detection using different techniques. These efforts have been summarized at the status of 2009, in a collective work [9] and in June 2011, the third international workshop on directional dark matter detection CYGNUS 2011 was held at Aussois (France) and the proceedings were edited [10]. A brief and inevitably incomplete description of the most important projects will be done in the following sections.

2 DRIFT

The Directional Recoil Information From Tracks (DRIFT) dark matter collaboration at Boulby has, since 2001, pioneered construction and operation underground of low background directional TPCs at the 1 m^3 scale with Multi-wire Proportional Counter (MWPC) readout using negative ion (NITPC) CS_2 gas to suppress diffusion without magnetic fields.[11] The NITPC concept, as demonstrated first in DRIFT I, allows larger drift distances (> 50 cm) than is feasible with conventional gases like CF_4, thereby reducing the required readout area and hence cost [12]. Operation with 1 m^2 MWPC readout planes allows the study of realistic size detectors underground with near-conventional technology.

In DRIFT, the ionization generated from recoil events (mainly S recoils) goes to create tracks of CS_2 negative ions. Under the influence of an applied electric field, the negative ions drift to one of the two back-to-back MWPC planes for readout. The MWPCs include two orthogonal layers (x and y) of 512 20 micron wires with 2 mm spacing. Wires are grouped to reduce the number of readout channels. Reconstruction is feasible in 3D using timing information for the z direction (perpendicular to the x-y plane of wires). Additional R&D is underway to allow absolute z positioning, though some z positioning is feasible already through pulse shape analysis. Calibration is undertaken typically every 6 hours using internal ^{55}Fe sources (one for each MWPC) that are shielded by an automated shutter system when not in use.

The Boulby program, particularly with the second generation 1 m^3 scale DRIFT IIa-d experiments since 2006 (see Fig. 3 and [12]), has recently made progress on the practical understanding of all background types for directional TPCs operated underground, on scale-up issues such as safety and backgrounds, and on directional sensitivity, for instance demonstrating for the first time sensitivity to recoil direction sense (head-tail discrimination) at low energy (47 keV S recoil).[13]

Recently, very important improvements have been done on the radon progeny events reduction and on space fiducialization from minority charge carriers.

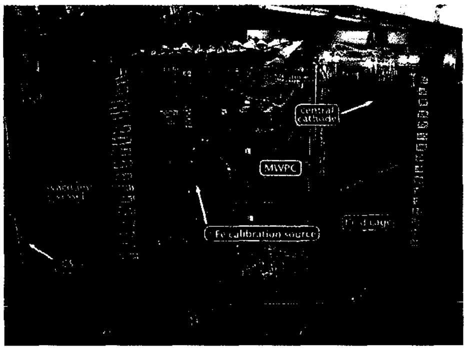

Figure 3: DRIFT IIb detector at Boulby mine. Two back-to-back TPCs each with a 50 cm drift distance, share a common vertical central cathode. Readout is done with two 3-layer MWPCs with 2 mm wire spacing. Operation is with negative ion CS_2 gas at 40 Torr (170 g target mass) [12]

3 DMTPC

The Dark Matter Time Projection Chamber (DMTPC) collaboration has developed and operated a 10-liter gas-based directional dark matter detector. The current instrument consists of a dual TPC, filled with CF_4 gas at $\sim$75 Torr. Proportional scintillation from the avalanches is read out with two CCD cameras. The charge on the TPC anode is also measured. With this instrument, DMTPC has demonstrated head-tail sensitivity for neutron-induced recoils above 100 keV, and an angular resolution for track reconstruction of 15° at 100 keV. A detector is running underground at the Waste Isolation Pilot Plant (WIPP) at a depth of 1600 meters water equivalent.

The 10-liter DMTPC detector is shown in Fig. 4. The dual-TPC is housed inside a stainless steel vacuum vessel. The drift region is defined by a woven mesh cathode, typically at a potential of -5 kV, separated from a wire mesh (28 μm wire, 256 μm pitch) ground grid 20 cm away. The vertical drift field is kept uniform to within 1% by stainless steel field-shaping rings spaced 1 cm apart. An amplification region is formed between the ground grid and a copper-clad G10 anode plane (at 720 V) which are separated from each other by 500 μm using resistive spacers (currently fishing line). A charge amplifier connected to the anode measures the ionization generated by a particle moving through the detector. A CCD camera images the proportional scintillation light generated in the amplification region. The CCD camera and readout electronics are located outside of the vacuum vessel. The mesh-based amplification region allows for two-dimensional images of charged particle tracks.

With a CF_4 pressure of 75 Torr, gas gains of approximately 10^5 are routinely achieved with minimal sparking. The energy resolution of the charge readout is 10% at 5.9 keV (measured with an ^{55}Fe source), and is 15% at 50 keV for the CCD readout (measured with an alpha source). Since the stopping dE/dx in the detector is much smaller for electrons than for nuclear recoils, the surface brightness of an electron track is dimmer, and electron tracks are easily distinguished from nuclear recoils. The gamma rejection of the detector was measured to be $> 10^6$ using an 8 μCi ^{137}Cs source[14]. For more details on background studies, see [15].

A program is underway to achieve full volume fiducialization by measuring the z-coordinate of an interaction in the TPC. This can be achieved through the detection of primary scintillation light or from an analysis of the charge pulse profile on the cathode. Techniques to reconstruct the third dimension of tracks (Δz) from the charge or PMT signal at the amplification region are also under development. In addition, a cubic meter detector design was done and its construction recently funded.

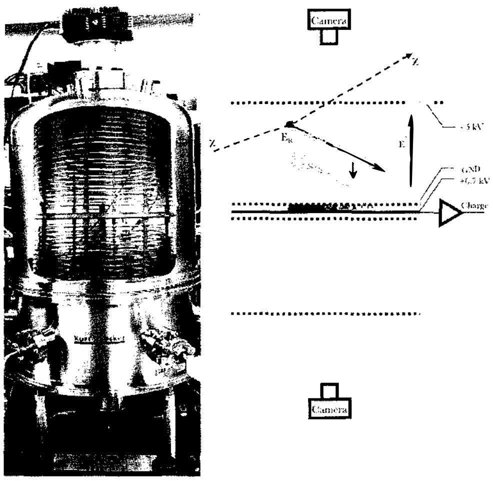

Figure 4: (left) Photograph of the 10-liter DMTPC detector with an image of the dual TPC overlaid to provide an artificial glimpse inside the vacuum vessel. The CCD cameras (top and bottom) each image an amplification region. The stack of stainless steel field shaping rings condition the drift fields. (right) A schematic representation of a WIMP-nucleus elastic scattering event in the detector.

4 NEWAGE

NEWAGE (NEw generation WIMP-search With an Advanced Gaseous tracking device Experiment) is a direction-sensitive dark matter search experiment with a gaseous micro-time-projection chamber (μ-TPC) that began detector R&D in 2003, and published the first direction-sensitive dark matter limits in 2007 (see [16].

The NEWAGE collaboration has been studying the detector background in the Kamioka Underground Observatory since 2007 [17] and important improvements on radon filtration and discrimination have been done.

The NEWAGE-0.3a detector, the first version of the $(0.3\text{m})^3$-class prototypes, is a gaseous μ-TPC filled with CF_4 gas at 152 Torr. The effective volume and the target mass are $20 \times 25 \times 31$ cm^3 and 0.0115 kg, respectively. For details of the detector system and performance studies, see [17]. A picture of the NEWAGE-0.3a detector is shown in Fig. 5. The NEWAGE-0.3a detector is read out by a 30.7×30.7 cm^2 μ-PIC. A μ-PIC is one of the several types of micro-patterned gaseous detectors. By orthogonally-formed readout strips with a pitch of 400 μm, the μ-PIC can generate two-dimensional images. A design of 1 m^3 detector is underway.

5 Nuclear Emulsions

Nuclear emulsions allow for both tracking resolution and large target mass, which has great potential for directional dark matter detection. Emulsions are photographic films composed of AgBr and gelatin that can be used as 3D tracking detectors with ~ 1 μm resolution. Nuclear emulsions may be useful in a directional dark matter search if they can detect the nuclear recoil tracks from WIMP interactions with sufficient accuracy.

The high density ($\sim$3 g/cm^3) of emulsions, and extremely high resolution are the strongest points. From SRIM simulations, the expected range of a WIMP-induced nuclear recoil track is of the order of 100 nm. However, it is difficult to detect nuclear recoil tracks in standard emulsions because the maximum resolution is about 1 μm. Therefore, it has developed a new

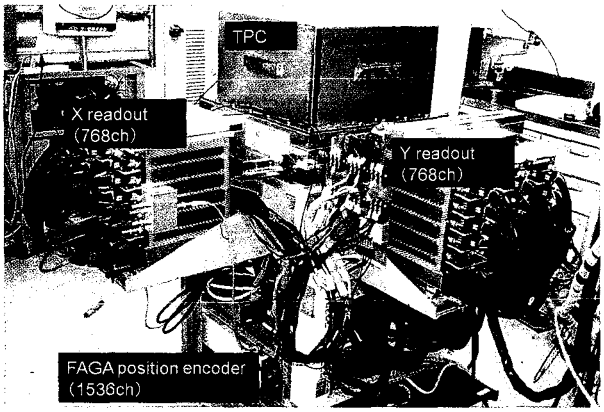

Figure 5: Picture of the NEWAGE-0.3a detector.

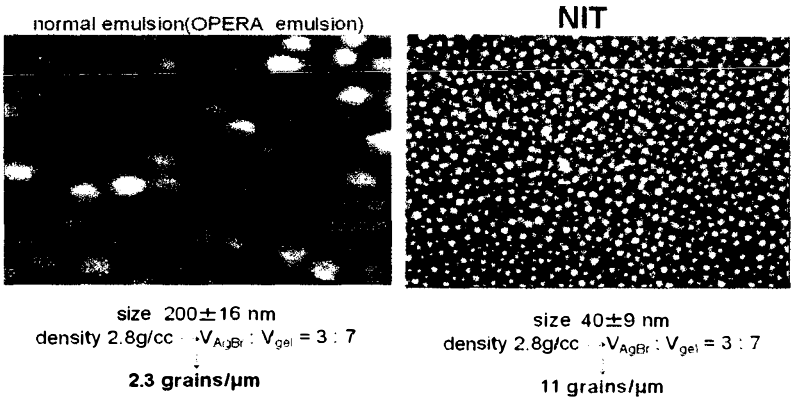

Figure 6: Electron microscope image of standard emulsion (left) and NIT emulsion (right)

high-resolution nuclear emulsion, called the "Nano Imaging Tracker" (NIT).[18] In the NIT, the AgBr crystal size is 40±9 nm and the density is 2.8 g/cm^3. The density of AgBr that an incoming particle can penetrate is 11 AgBr/μm (Fig. 6). When one considers a dark matter search, it is not realistic to use an electron microscope to scan a large volume of emulsions. Furthermore, nuclear recoil tracks which are less than 1 μm long (smaller than the optical resolution) cannot be identified as tracks by an optical microscope. To resolve this problem, a method was developed to expand the tracks.

Nuclear recoil tracks consist of grains spanning roughly 100 nm. If the emulsion is then expanded, the inter-grain spacing grows and the track length is expanded to several μm. With this technique, nuclear recoil tracks may be identified by an optical microscope. It has been used a pH-controlled chemical treatment to expand the emulsion. As a result, tracks from Kr ions with $E > 200$ keV attained lengths of several μm, and could be recognized as tracks by an optical microscope. Such tracks could be distinguished from random noise (fog) because the fog consists of single grain events. The angular resolution of the original state for NIT is about 12 degrees or better. However, the angular resolution is expected to be about 45 degrees with the expansion technique. In practice, if the expansion technique is used, two or more NIT emulsion detectors should be mounted in the directions horizontal and vertical to Cygnus on an equatorial telescope.

6 MIMAC

The MIMAC (MIcro-tpc MAtrix of Chambers) project [19], started in 2003, has recently built a bi-chamber prototype consisting of two chambers of (10 cm x 10 cm x 25 cm) with a common cathode, which is the elementary module of the future large matrix. The purpose of this prototype is to show the ionization and track measurement performances needed to achieve the directional detection strategy. The primary electron-ion pairs produced by a nuclear recoil in one chamber of the matrix are detected by driving the electrons to the grid of a bulk micromegas [24] and producing the avalanche in a very thin gap (256μm).

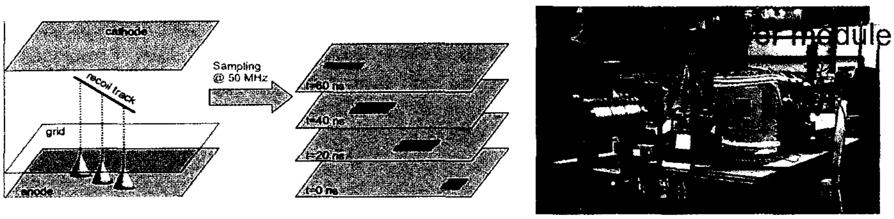

Figure 7: (Left): The anode is read every 20 ns and knowing the drift velocity of primary electrons the 3D track can be reconstructed from the consecutive number of images defining the event. (Right): A picture of the MIMAC bi-chamber detector installed at Modane in June 2012

As schematically shown on figure 7, the electrons are collected towards the grid in the drift space and are multiplied by avalanche to the pixellized anode thus allowing to get information on X and Y coordinates. To have access to the X and Y coordinates a bulk micromegas [24] with a 10 by 10 cm active area, segmented in pixels with a pitch of 424 μm was used as 2D readout [21]. In order to reconstruct the third coordinate Z of the points of the recoil track, the LPSC developed a self-triggered electronics able to perform the anode sampling at a frequency of 50 MHz. This includes a dedicated 64 channels ASIC [22] associated to a DAQ [23].

In order to get the total recoil energy we need to know the ionization quenching factor (IQF) of the nuclear recoil in the gas used. The MIMAC team has developed at the LPSC a dedicated experimental facility to measure such IQF. A precise assessment of the available ionization energy has been performed in ^{4}He + 5%C_4H_{10} mixture within the dark matter energy range (between 1 and 50 keV) by a measurement of the IQF [25 26]. For a given energy, an electron track in a low pressure micro-TPC is an order of magnitude longer and showing more straggling than a recoil one. It opens the possibility to discriminate electrons from nuclei recoils by using both energy and track information, as it was shown in [19] and [20].

In June 2012, wc have installed the bi-chamber module, at the Underground Laboratory of Modane (LSM). In order to characterize the total background of our detector at Modane, we worked without any shielding. Besides the very good stability of the calibration validating the gas circulation, one of the most interesting facts observed during this first run was the measurement for the first time of 3D tracks of nuclear recoils in the range of 30 keV in ionization. The 10 cm by 10 cm micromegas coupled to the MIMAC electronics running the 512 channels per chamber and working at high gain and without any problem during a long period of time (4 months in our first run at Modane), is in fact the validation of the feasibility of a large TPC for directional detection. As an illustration of the high quality of data obtained at Modane, we show on fig.8 a very interesting recoil event of 34 keV in ionization. For more details on the

MIMAC performances and preliminary results see Q. Riffard's presentation at this conference.

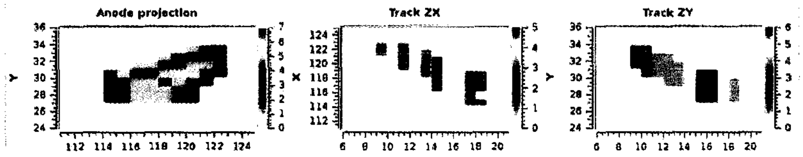

Figure 8: A 3D recoil track measured at 34 keV in ionization: On the left, the X-Y plane of the anode showing the intersections of the strips fired. On the centre, the X projection as a function of time, every 20 ns. On the right, the same but for the Y projection

7 Acknowledgements

I would like to thank J. Billard and the MIMAC collaboration for the work done in the last five years and J. Battat, D. Snowden-Ift for their slides used in my presentation. I apologize to have omitted projects and a lot of updates and very interesting points concerning background rejection of the mentioned ones but eight pages are not enough for such a wealth of detection techniques and many years of experimental efforts on this novel and needed detection strategy.

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