A directional Dark Matter argon detector at LNGS

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A directional Dark Matter argon detector at LNGS

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Abstract. The potentialities of an argon Dark Matter detector with real-time directional information located at Laboratori Nazionali del Gran Sasso are discussed. Columnar recombination combined with a dual-phase Liquid Argon Time Projection Chamber provides a concrete approach for a directional detector. Even in the case of a minimal angular resolution, a very clear signature of WIMP scattering on target nuclei is shown to be expected. Indeed, the ratio of horizontal to vertical events changes by a factor of four during the day and has a characteristic sidereal-day periodicity.

1. Introduction

At present, a plausible explanation of the nature of Dark Matter (DM) is that it is constituted by yet undetected Weakly Interacting Massive Particles (WIMPs). Nowadays, it is believed that every visible galaxy is surrounded by a roughly spherical halo of DM, extending far beyond the visible disk. The standard non-directional direct detection, which exploits the elastic scattering of WIMPs on nuclear targets in the detector, is experimentally very challenging in particular in what concerns background rejection. An important additional information that could strengthen the DM signature hypothesis is a possible annual modulation of the interaction rate due to the motion of the Earth around the Sun. Indeed, the solar system orbits around the center of the Galaxy, with a velocity $V_{SG} \simeq 220$ km/s. Earth moves around the Sun with a velocity $V_{ES} \simeq 30$ km/s in an orbit inclined about 60° relative to the disk of the Galaxy. The combination of these motions results in a cosine dependence of the count rate with time. Unfortunately, this modulation is quite small and it is very hard to disentangle from other effects, leaving doubts on the authenticity of the few DM observation claims [1]. In addition, numerous radioactive backgrounds are known to exhibit a modulation over the course of the year.

If detectors were able to distinguish the recoil direction of the scattered nucleus after a WIMP interaction, then the signal would have a large and characteristic angular dependence within a sidereal day[1]. Indeed, due to the Earth's rotation around its axis, the detector would face a change in the direction of the WIMP wind and accordingly the angular distribution of the recoil nuclei will vary with time. This modulation in arrival direction produces a much more sizeable and unambiguous signature with respect to a non-directional annual modulation. In principle, assuming the most advantageous experimental conditions, the effect of this modulation can be as large as 100%. The most attractive feature of this kind of modulation is that no known background is correlated with the sidereal period. Actually, a sidereal rate modulation goes out

[1] The sidereal day is about four minutes shorter than the solar day. It correspond to $23^{\mathrm{h}}\ 56^{\mathrm{m}}\ 04^{\mathrm{s}}.090$.

of phase with the solar time, avoiding possible accidental day/night effects which could take place in the laboratory.

Nowadays, a detector capable of measuring the direction of the scattered nucleus has not yet been developed. There are few prototypes [2] of detectors capable of reconstructing the tracks of the recoil nucleus but, since they exploit the usage of rarefied gases, this technology clashes with the necessity of building multi-tonne detectors. For this reason the most promising approach is to explore a detector based on the so-called Columnar Recombination (CR) effect on a Noble Liquid [3], that despite a far from perfect angular resolution can reach large target masses.

2. A directional LAr TPC

By filling a gap in the literature, the sensitivity of an argon detector to the galactic WIMP directional signal has been studied. In particular, a dual phase Liquid Argon Time Projection Chamber (LAr TPC) has been considered, where recoiling nuclei cause argon excitation and ionization. Each event is then detected in two ways: the prompt scintillation light, S1, from argon de-excitation, and the signal from free ionization electrons. The latter drift towards the top of the TPC, thanks to an electric field, and extracted into the argon gas phase, confined in the so-called "gas pocket", close to the top array of photosensors. Accelerated electrons produce a secondary light pulse, S2. A fraction of free electrons, however, recombine with ions in the ion-electron cloud produced by the ionizing track itself.

CR models suggest that the magnitude of the recombination effect should vary with the angle between the field and the track direction. Namely, when the ionizing track is parallel to the electric field the electrons have to drift in a "column" of ion-electron pairs produced by the ionizing track, maximizing the recombination probability. When it is perpendicular, the "column" needs to be crossed and the recombination probability is minimized. The net effect of the electron-ion recombination is the reduction of the ionization signal (S2), and the consequent enhancing of the primary scintillation pulse (S1). An accurate measurement of these two signals and their combination (the sum S1+S2 and the ratio S1/S2) may provide informations on the nuclear track direction and thus on the WIMP directionality. The results shown below were obtained considering an Earth-bound detector, located at Laboratori Nazionali del Gran Sasso (LNGS), with a 100 tonne target mass of argon.

3. Distribution of observables

In a given reference frame, $\mathbf{v_i}$ is the the velocity of the incoming WIMP of mass m_W, $\mathbf{u}$ the velocity of the recoiling nucleus of mass M_N, $\mathbf{q} = M_N\mathbf{u}$ and $E_r = q^2/(2M_N)$ the corresponding momentum and energy, respectively. The azimuthal and zenith angles of the recoiling nucleus are ϕ_r and θ_r, while $\cos\vartheta = \hat{\mathbf{v}}_i \cdot \hat{\mathbf{q}}$ is the cosine of the angle between the incoming WIMP direction and the recoiling nucleus.

For a spin-independent interaction with equal couplings for neutrons and protons the WIMP-nucleus cross section, σ_{W-N}, can be expressed in terms of WIMP-nucleon cross section, σ_n as $\sigma_{W-N}/\mu_N^2 = A^2\sigma_n/\mu_n^2$, where A is the atomic mass and μ_N and μ_n are the WIMP-nucleus and the WIMP-nucleon reduced masses, respectively. The finite size of the nucleus is taken into account thanks to the standard Helm form-factor, $F(q)$.

In the frame where the target nucleus is at rest, the double differential cross section becomes dependent on $\cos\vartheta$; the azimuthal symmetry of the scattering around the WIMP arrival direction gives $d\Omega = 2\pi\, d\cos\vartheta$, thus

$$\frac{d^2\sigma(q, \hat{\mathbf{v}}_i \cdot \hat{\mathbf{q}})}{dq^2 d\Omega} = \frac{d^2\sigma(q, \cos\vartheta)}{2M_N dE_r 2\pi d\cos\vartheta} = \frac{\sigma_{W-N}}{8\pi\mu_N^2 v_i}\, F^2(q)\, \delta\left(\mathbf{v}_i \cdot \hat{\mathbf{q}} - \frac{q}{2\mu_N}\right) . \tag{1}$$

Given a normalized velocity distribution for the incoming WIMP, $f(\mathbf{v}_i)$, and a WIMP mass density, ρ, the double differential recoil rate per unit mass as a function of the nuclear recoil energy, E_r, and of the recoil direction $\hat{\mathbf{q}}$ is

$$\frac{d^2R(E_r,\hat{\mathbf{q}})}{dE_r d\Omega_r} = \frac{\rho}{m_W}\frac{\sigma_{W-N}F^2(q)}{4\pi\mu_N^2}\hat{f}\,(v_{min},\hat{\mathbf{q}})\ , \tag{2}$$

where $v_{min} = q/(2\mu_N) = \sqrt{2M_N E_r}/(2\mu_N)$ is the minimal WIMP velocity that can give momentum q or energy E_r to the recoiling nucleus and $\hat{f}\,(v_{min},\hat{\mathbf{q}})$ is the 3-dimensional Radon transform of the velocity distribution $f(\mathbf{v})$.

In this work, the Standard Halo Model, i.e. an Isotropic Maxwell-Boltzmann (IMB) WIMP velocity distribution of width σ_v in a inertial reference frame at rest with respect to the Galactic center, is assumed. The corresponding Radon transform [4] is

$$\hat{f}\,(v_{min},\hat{\mathbf{q}}) = \frac{1}{\sqrt{2\pi\sigma_v^2}}\exp\left[-\frac{1}{2}\left(\frac{v_{min}+\hat{\mathbf{q}}\cdot\mathbf{V}}{\sigma_v}\right)^2\right]\ . \tag{3}$$

Therefore, if recoils are measured in a Galactic rest frame, $\mathbf{V}=0$ and the rate is isotropic. On the other hand, when measured in a frame at rest with respect to the Sun, $\mathbf{V}$ is the Sun velocity relative to the galactic center, $\mathbf{V}_{SG}$, which points towards the galactic coordinates (ℓ_c=90°, b_c=0°), roughly in the direction of the Cygnus constellation. It has magnitude $V_{SG} \approx v_0$, where v_0 is the Galactic orbital speed at the Sun position. For an Earth-bound laboratory the velocity $\mathbf{V}$ can be decomposed as $\mathbf{V} = \mathbf{V}_{SG} + \mathbf{V}_{ES}$, where $\mathbf{V}_{ES}$ is the Earth velocity relative to the Sun.

Given E_{th} and E_{max} the threshold and maximum detector energy, respectively, such that the detector energy range is $E_{th} < E_r < E_{max}$, the direction dependent recoil rate per unit mass is obtained by substituting the Radon transform introduced in Eq. (3) inside Eq. (2) and integrating over the energy range

$$\frac{dR(E_{th},E_{max},\hat{\mathbf{q}})}{d\Omega_r} = \int_{E_{th}}^{E_{max}} dE_r \frac{d^2R(E_r,\hat{\mathbf{q}})}{dE_r d\Omega_r}\ . \tag{4}$$

In general, a CR directional detector should be able to discriminate only between tracks with different inclination relative to the vertical (electric field) direction. For this reason, the only measurable angle is the polar angle θ_r, and the azimuthal angle should be integrated out. The relevant recoil rate is

$$\frac{dR(E_{th},E_{max},\cos\theta_r)}{d\cos\theta_r} = \int_0^{2\pi} d\phi_r \int_{E_{th}}^{E_{max}} dE_r\ \frac{d^2R(E_r,\hat{\mathbf{q}})}{dE_r d\Omega_r}\ . \tag{5}$$

In addition, since a detector based on CR cannot distinguish signals from recoil tracks differing by 180°, i.e. events that differ by 180° are summed together, the relevant rate is the so-called "folded" angular recoil rate

$$\frac{dR_F}{d\cos\theta}(|\cos\theta_r|) \equiv \frac{dR}{d\cos\theta_r}(\cos\theta_r) + \frac{dR}{d\cos\theta_r}(-\cos\theta_r)\ , \tag{6}$$

which depends only on $|\cos\theta_r|$. In this work the results are shown using the reference values $m_W = 200$ GeV, $M_N = 0.923\,A$, where $A = 39.9$ is the argon atomic mass, $\rho = 0.3$ GeV cm^{-3}, and the IMB $\sigma_v = v_0/\sqrt{2}$. Rates are shown for a reference cross section $\sigma_n = 10^{-46}$ cm^2, which is one order of magnitude smaller than the most stringent limit set by the LUX collaboration [5], and for a recoil energies range from $E_{th} = 50$ keV to $E_{max} = 200$ keV.

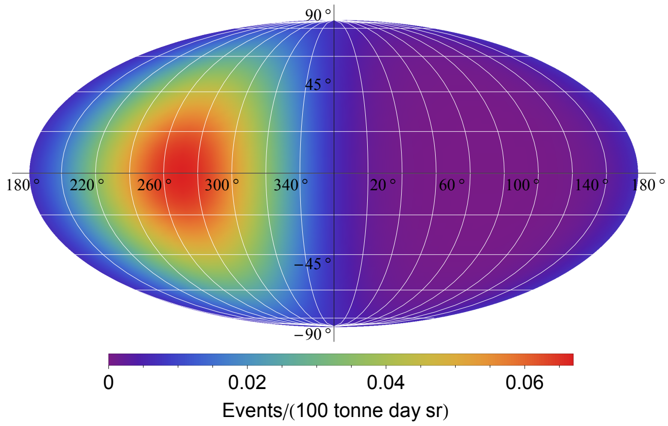

Figure 1. Directional differential recoil rate in argon integrated over the energy range 50÷200 keV, plotted in Mollweide equal area projection map of the celestial sphere in Galactic coordinates (ℓ, b). A WIMP mass of 200 GeV and a WIMP-nucleon cross section of 10^{-46} cm^2 is considered.

Note that the anisotropy of all rates in Eqs. (4), (5), and (6) depends only on the velocity $\mathbf{V}$. In a given frame, which fixes $\mathbf{V}$, one can choose different coordinate systems, yielding different components for $\mathbf{V}$. The coordinates can be also time dependent. In a frame at rest with respect to the Earth and using Galactic coordinates, $\mathbf{V}_{SG}$ is constant and only $\mathbf{V}_{ES}$ rotates with the annual periodicity of the Earth revolution. Since $\mathbf{V}_{ES}$ is an order of magnitude smaller than $\mathbf{V}_{SG}$, the recoil rate points back to a direction that rotates with an opening angle about one tenth of a radiant and annual periodicity around the $\mathbf{V}_{SG}$ direction. In this frame the peaked angular distribution is the main signature of the WIMP signal and allows background reduction. In a coordinate system fixed with a laboratory, the coordinates and, therefore, the apparent direction of $\mathbf{V}$ makes an additional rotation with the periodicity of a sidereal day and an amplitude that depends on the latitude. This specific periodicity is a characteristic signature and provides more background suppression.

Most of our results will be shown for a detector located at the latitude of LNGS in the local coordinate system where the polar axis points in the vertical direction. A reference frame at rest with respect to the Sun is used only to introduce the potentialities of a directional detector, as it has been extensively done in literature [6].

4. Recoil spectrum in galactic coordinates

The general potentialities of a directional detector and, more specifically, the signature in the angular recoil rate of the detector motion through the WIMP wind are best illustrated in Galactic coordinates. In this coordinate system $\hat{x}$ points from the Sun towards the Galactic center, $\hat{y}$ in the direction of the Solar motion and $\hat{z}$ towards the Galactic north pole; therefore, $\mathbf{V} = v_0\hat{y}$. In Fig. 1 it is shown the angular recoil rate of Eq. (4) on a Mollweide equal area projection map in Galactic coordinates. The horizontal axis is the Galactic longitude, $0°< \ell < 360°$, and the vertical axis the Galactic latitude, $-90°< b < 90°$. The recoil rate is clearly anisotropic and points towards coordinates (ℓ=270°, b=0°), opposite to the direction of the Sun motion throughout the Galaxy.

5. Recoil directional signals at LNGS

In this section, the expected rates of WIMP scattering, Eqs. (4-6), is illustrated as a function of $\cos\theta_r$ for different times of an arbitrary chosen day, corresponding to the Summer Solstice

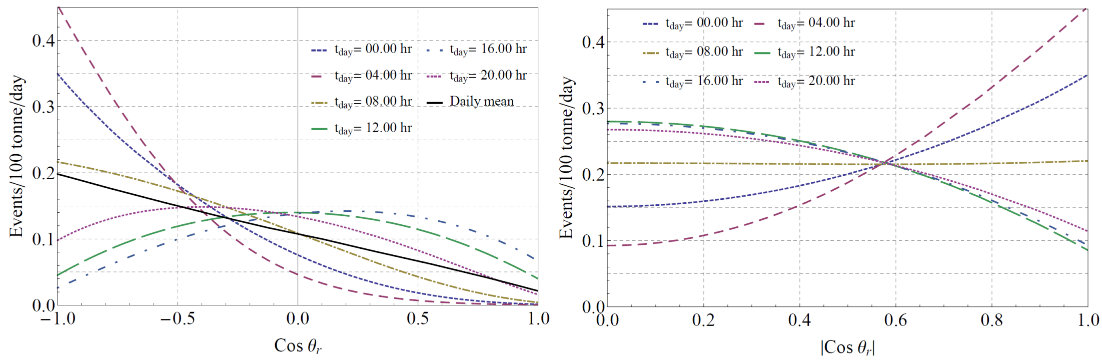

Figure 2. Differential (left) and folded differential (right) recoil rate as a function of the polar angle $\cos\theta_r$ at the latitude of LNGS. The y axis represents events per day in a 100 tonne Argon detector with a 50 keV energy threshold for a cross section $\sigma_n = 10^{-46}$ cm^2. The solid curve is the daily average, while the other six curves show the rate at times of the day four-hour apart.

(SS). Obviously, there is a strict correlation between the expected signal and the position of the Cygnus in the sky as seen at the LNGS latitude since it corresponds to the main direction of the WIMP wind. During most of the day, the Cygnus constellation is over the horizon, reaching the zenith at ∼4:00 a.m. and setting around 12 hours later, remaining near the horizon just for few hours. Fig. 2 shows on the left the recoil rate, Eq. (5), as a function of $\cos\theta_r$ for different times of the day and the daily average. There is a strong dependence on the time of the day, since the asymmetry is larger when the Cygnus is high in the sky (00:00 $\leq t_{day}$[hr] $\leq$ 08:00), smaller when it is close to the horizon (12:00 $\leq t_{day}$[hr] $\leq$ 20:00). This implies that it is possible to discriminate the WIMP nature of the events against possible backgrounds. Indeed, even the average rate varies considerably since it changes from ∼0.2 events/(100 tonne day) for $\cos\theta_r = -1$, to ∼0.02 events/(100 tonne day) for $\cos\theta_r = 1$. In the right panel of Fig. 2 it is shown the "folded" differential recoil rate introduced in Eq. (6), which should be the rate relevant for a CR detector. The angular and time dependences of the rate remain quite strong even without the information on where the track is pointing. At times when the Cygnus is close to the zenith (horizon) the rate is peaked at $|\cos\theta_r| \sim 1$ ($|\cos\theta_r| \sim 0$).

5.1. A realistic CR detector

A realistic CR detector have a finite angular resolution. Here, it is studied how much the angular signature of the signal is reduced assuming to have only a minimal amount of angular information. Events are divided in only two classes. Horizontal events (HOR), defined by $|\cos\theta_r| < 0.5$ or 60°$< \theta_r <$120°, and vertical events (VER=UP+DOWN), defined by $|\cos\theta_r| > 0.5$, as shown schematically in the left panel of Fig. 3. From an experimental point of view, ratios of event rates are useful quantities in order to keep the systematic uncertainties budget under control. Thus, the ratio, R, of HOR and VER events is defined, which should be constant and equal to one for an isotropic signal. On the right panel of Fig. 3 the time dependence of this ratio and of the single components is shown. The dashed lines represent the daily variation of the HOR and VER event rates, and their ratio, R, for four equidistant sidereal days. Use of the sidereal day (s.d.) as a unit is convenient because after a s.d. the Cygnus constellation returns exactly in the same position in the sky and the angle between the WIMP wind and the detector axis has the same value. Apart from a small variation in the velocity of the WIMP wind caused by the Earth revolution around the Sun, a similar behaviour of the HOR and VER components during different sidereal days is expected. Therefore it is possible to make the annual averages of the daily rates in order to accumulate statistics. The

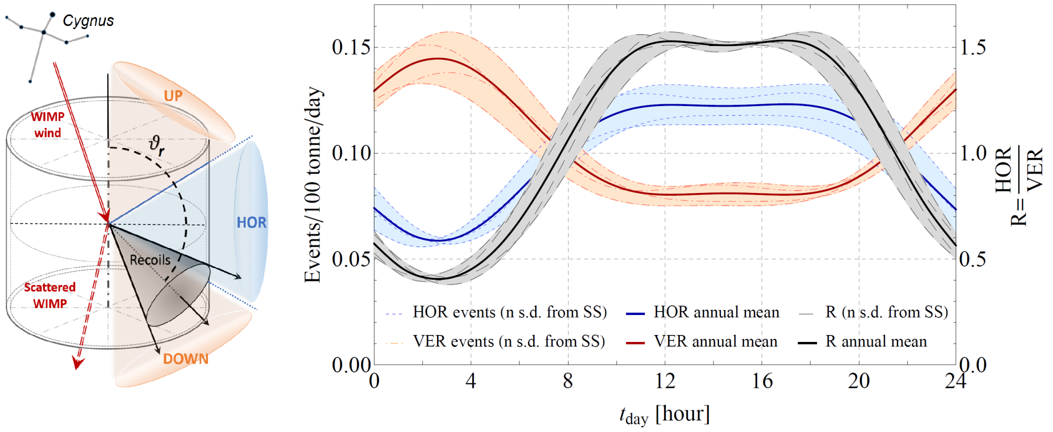

Figure 3. Left: Schematic representation of the recoils distribution between horizontal (HOR $\equiv |\cos\theta_r| < 0.5$) and vertical (VER=UP+DOWN $\equiv |\cos\theta_r| > 0.5$) events in a cylindrical LAr TPC for a particular positions of the Cygnus constellation in the sky. Right: Daily variation of HOR (VER) event rate in blue dashed (orange dotted) lines for different sidereal days of the year. The solid blue (orange) line represents the annual mean of the HOR (VER) events. They refer to the left scale. Ratio of HOR and VER events for different sidereal days (dashed black lines) and the corresponding annual mean (solid black line) refer to the right scale.

results are shown in the right panel of Fig. 3 in which the blue (orange) band represents the overall variation registered in the HOR (VER) component among different sidereal days of the year, while the solid curves represent the averages over different sidereal days. Considering the annual mean, the variation of the single component is of the order of 35% (29%), with respect to the average daily value. For comparison, the seasonal modulation of the events that can be observed under the same assumptions, for the case of a non-directional WIMP detection is only about 8%. Compared to it, the effect of the daily variation in a directional detector, even for this minimal angular resolution, confirms that adding the directional information increases significantly the discovery potential of a WIMP signature. Moreover, the annual mean ratio, R, shows a remarkable deviation from one since it varies during the day by a factor $f \approx 4$.

6. Conclusions

In these proceedings, it is discussed how a directional detector located at LNGS could provide a very clear signature for WIMP signal. This signature remains sizeable even for a minimal angular resolution which should be easily obtained by a detector based on columnar recombination. In particular, the daily modulation shown in Fig. 3 is an order of magnitude larger than the annual modulation obtained ignoring the angular information. Thus, a realistic detector able to use the angular information to reject the background would provide a strong and unambiguous evidence of DM, the latter due to the fact that no known background is correlated with the sidereal period of the DM modulation.

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