Dark matter signal for the future ANDES laboratory

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Resumen / En este trabajo estudiamos la señal esperada de partículas de materia oscura en detectores terrestres. En particular, nos centramos en la técnica de detección directa, basada en el estudio de la dispersión de partículas de materia oscura con los núcleos del detector. Para el cálculo, hemos considerado un modelo de materia oscura, la ubicación geográfica del detector y el fondo de neutrinos del sitio. En este trabajo, hemos calculado la tasa de detección esperada y las modulaciones anuales y diurnas relativas a la detección de WIMPs. Realizamos predicciones para la señal esperada en experimentos ubicados en ANDES (Agua Negra DeepExperimental Site), que se construirá en San Juan, Argentina. También consideramos una función de respuesta y una eficiencia similar al detector Xenon1T para obtener una aproximación de la señal más realista. Hoy en día solo existen dos detectores directos de materia oscura planeados para instalarse en el hemisferio sur, por lo que resulta crucial comenzar a modelar las señales y los fondos esperados para el laboratorio ANDES.

Abstract / This work studies the expected signal of dark matter particles in terrestrial detectors. In particular, we focus on the direct detection technique, based on the study of the scattering of dark matter particles by a nucleus in a detector. In the calculation, we have considered the dark matter model, the geographical location of the detector, and the neutrino background for the site. In this work, we have computed the expected detection rate and annual and diurnal modulations concerning the detection of WIMPs. The signal predictions were carried out for experiments that may be performed in the planned new underground facility ANDES (Agua Negra DeepExperimental Site), to be built in San Juan, Argentina. We also consider a response function and an efficiency similar to the Xenon1T detector to get a more realistic signal approximation. There are only two direct dark matter detectors planned to settle in the Southern Hemisphere to this day. Therefore, it is crucial to start modeling the signals and backgrounds to define the characteristics that improve dark matter detection in the ANDES laboratory.

Keywords / astroparticle physics — dark matter

1. Introduction

One of the most important pursuits of modern cosmology is understanding the nature of dark matter (DM) in the Universe. A well-established paradigm is that most DM is cold and is made up of weakly interacting massive particles (WIMP), other promising alternatives are axions(Majumdar, 2014; Peccei & Quinn, 1977; Chadha-Day et al., 2021). The WIMPs as cold dark matter candidates arise naturally in various theories beyond the Standard Model, e.g., the lightest supersymmetric particle in supersymmetric theories (in many models, this is the neutralino χ). The expected mass is between $1 - 1000$ GeV (Gelmini, 2017).

A relevant strategy for searching WIMPs is the direct detection through the elastic scattering of DM particles with the nuclei in ultrasensitive low background experiments (Goodman et al., 1985; Wasserman, 1986). These experiments eventually reach a background (called neutrino floor) due to the coherent scattering of neutrinos produced from different sources (Sun, atmosphere, Earth, and reactors). One of the methods to distinguish a DM recoil signal from the background is to look for the annual and diurnal modulation of the signal due to the movement of the Earth with respect to the DM halo and the rotation around its axis (Freese et al., 2013). At the present, there are several experiments designed to measure this effect. The DAMA collaboration claims to have observed the annual modulation in the energy range between $1 - 6$ keV (Bernabei et al., 2018). Other collaborations, such as Xenon1T (Aprile et al., 2018), have reported null results.

The currently running detectors are located in the Northern Hemisphere. The ANDES Laboratory *(Civitarese, 2015), consists of the design and construction of an underground laboratory, in the Southern Hemisphere, adjacent to the Agua Negra Tunnel complex in San Juan, Argentina.

In line with previous studies focused on the ANDES laboratory (Machado et al., 2012; Civitarese et al., 2016), we present a complementary study on the expected dark matter signals, taking into account the neutrino floor for this specific site, as well as a detector with characteristics similar to Xenon1T.

*http://andeslab.org/index.php

Poster contribution

2. Dark matter model

We work in the framework of the MSSM (Minimal Supersymmetric Standard Model). The lightest neutralino state can be written as a linear combination of binos ($\tilde{B}$), winos ($\tilde{W}_3$) and higgsinos ($\tilde{H}_1, \tilde{H}_2$) (Engel et al., 1992)

$$\chi_1^0 = Z_{11}\tilde{B} + Z_{12}\tilde{W}_3 + Z_{13}\tilde{H}_1 + Z_{14}\tilde{H}_2 \,, \qquad (1)$$

where the parameters of the model are: the masses of the Bino, Wino and Higgsino (M', M and μ respectively) and the $\tan(\beta)$ (which is the ratio of vacuum expectation values of the two Higgs scalars). In the Grand-Unified-Theory (GUT), the parameters M and M' are related by $M' = \frac{5}{3}M\tan^2\theta_W$(Murakami et al., 2001; Ellis et al., 2000; Cerdeno et al., 2001).

We take μ as a free parameter of the model, and explore the parameter space, for μ and m_χ (Fushimi et al., 2020) considering the limits imposed on the cross-section mass plane given by the Xenon1T exclusion limit (Aprile et al., 2019) and by the neutrino floor (Schumann, 2019).

3. Direct detection technique

When the elastic collision occurs between the WIMP of mass m_χ and the nucleus of mass M, an energy E_{nr} is deposited. The experiments measure the number of events per day and per unit mass of the detector which can be written as (Civitarese et al., 2016):

$$\frac{dR}{dE_{\rm nr}} \simeq \Bigg\{ S_0 + S_{\rm m}(E_{\rm nr})\cos(w_{\rm rev}(t - t_{\rm a})) + S_{\rm d}(E_{\rm nr})\cos(w_{\rm rot}(t' - t'_{\rm d})) \Bigg\} \,, \qquad (2)$$

where $t_{\rm a} = t_{\rm eq} + \frac{\beta_{\rm m}}{w_{\rm rev}}$, $t'_{\rm d} = \frac{\beta_{\rm d}}{w_{\rm rot}} - t_0$, we define $w_{\rm rev}$ as the Earth revolution frequency, $t_{\rm eq}$ is the sidereal time corresponding to the March equinox (that is the sidereal day 80.22 referred to J2000.0), $\beta_{\rm m} = 1.260$ rad, $\beta_{\rm d} = 3.907$ rad, $w_{\rm rot} = 2\pi/(1 \text{ sidereal day})$, and t_0 is the time corresponding to the longitude of the laboratory λ_0. Furthermore, S_0 is the time-average of the rate, which does not present a modulation. $S_{\rm m}$ is the annual modulation amplitude and $S_{\rm d}$ is the diurnal modulation amplitude. The diurnal modulation term is proportional to $v_{ecu}\cos(\phi_0)$, where v_{ecu} is the rotational velocity in the Equator and ϕ_0 is the latitude of the laboratory.

To analyze the dependence of the signal with the characteristics and location of the future ANDES laboratory, we considered a xenon (Xe) detector with an efficiency and response function equal to that of the Xenon1T experiment to obtain a more realistic approach(Foot, 2020; Aprile et al., 2020) (see Table 1) .

To compare with the experimental data, we integrate the modulation amplitude over an energy range that is defined by the resolution of the detector. Since detectors do not measure nuclear recoil energy directly, it is necessary to consider a quenching factor Q, which relates the electron equivalent energy (E_{ee}) measured by the detector to the recoil energy ($E_{ee} = QE_{\rm nr}$). Therefore we can calculate them as (Freese et al., 2013):

$$\langle S_{\rm m}\rangle = \frac{1}{\Delta E}\int_{E_1}^{E_2} S_{\rm m}(E_{\rm nr})\varepsilon(E_{\rm nr}Q)\Phi(E_{\rm nr}Q, E_1, E_2)dE_{\rm nr} \,, \qquad (3)$$

$$\langle S_{\rm d}\rangle = \frac{1}{\Delta E}\int_{E_1}^{E_2} S_{\rm d}(E_{\rm nr})\varepsilon(E_{\rm nr}Q)\Phi(E_{\rm nr}Q, E_1, E_2)dE_{\rm nr} \,, \qquad (4)$$

where $\Delta E = E_2 - E_1$ is the bin length, $\varepsilon(E_{\rm nr}Q)$ is the efficiency of the experiment and $\Phi(E_{ee}, E_1, E_2)$ is a response function corresponding to the fraction of events given an expected observed energy (Savage & others, 2009).

Location	$30°30'S$ $69°53'W$
Target material	^{131}Xe (Z=54, N=77)
Q	1
$\varepsilon(E_{ee})$	$0.87\left(1 + e^{-\lambda(E_{ee}-E_{ee}^0)}\right)^{-1}$
$\sigma(E_{ee})$	$(0.31\text{keV})\sqrt{\text{E}_{\text{ee}}/\text{keV}} + 0.0037\text{E}_{\text{ee}}$

Table 1: Coordinates of the ANDES laboratory and test detector characterization. Where Q is the quenching factor, $\varepsilon(E_{ee})$ is the efficency, and σ is the dispersion entering in the response function Φ. The attenuation λ and the threshold energy E_{ee}^0 where taken from Foot (2020); Aprile et al. (2020).

4. Results and conclusions

We have computed the signal in the detector for different values of the neutralino mass. We fixed the parameter $\tan\beta = 10$ (Ellis et al., 2000; Cerdeno et al., 2001; Murakami et al., 2001), and varied the parameter μ. The value of the M parameter was determined as a function of μ and m_χ.

Different neutrino backgrounds could be measured in a direct dark matter detection experiment, such as geoneutrinos, reactor neutrinos, solar and atmospheric neutrinos. There are two contributions to the background that depends on the experiment's geographical location. These are the geoneutrinos (Monroe et al., 2007; Gelmini et al., 2019) and neutrinos produced in nearby reactors (Mueller et al., 2011; Gelmini et al., 2019). We consider the sum of all contributions for the analysis, generally called the neutrino floor. We have analyzed the dependence of the signal on the characteristics and location of an experiment located at the ANDES site (see Table 1).

In Fig. 1 we see that for the dark matter parameter space used in this work, we find that the signal for the WIMPs begins to exceed the neutrino floor of the ANDES laboratory for energies greater than 2.6 keV for $m_\chi > 10$ GeV (this energy could be 0.6 keV if m_χ=7 GeV is considered). Therefore, having a detector with a lower energy threshold is not essential unless we have a

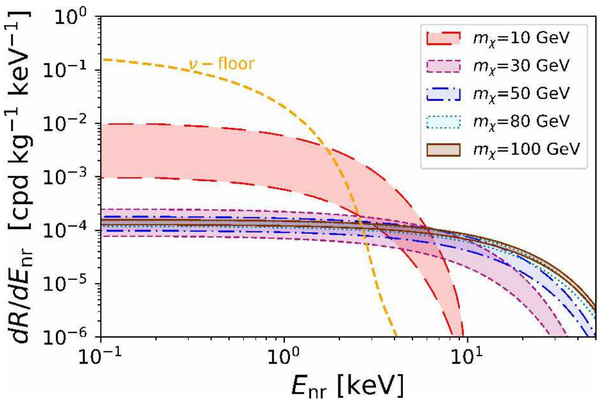

Figure 1: Differential recoil rates for different masses of WIMPs for the ^{131}Xe reference detector in the ANDES laboratory. The shaded regions correspond to different masses for the WIMPs and the widths represent the sweep of the parameter μ in the dark matter model. Dashed line: total neutrino background.

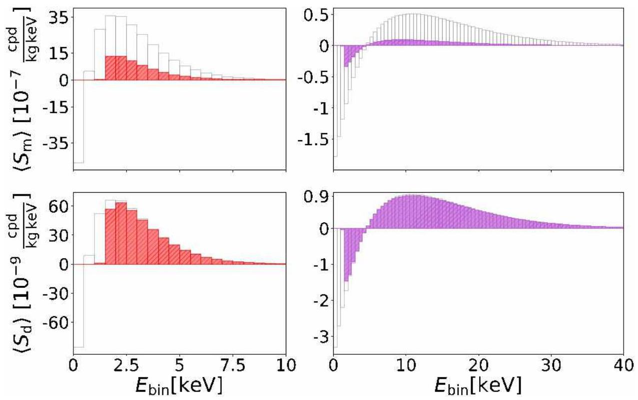

Figure 2: *Upper panel:* The average annual modulation amplitude as a function of the energy bin. (*Lower panel:*) The average diurnal modulation amplitude as a function of the energy bin. First column $m_\chi = 10$ GeV, second column $m_\chi = 30$ GeV. In all panels, the histograms show the results for an ideal detector and the hatched areas are those for a detector with the parameters given in Table 1, we consider the minimum value of the parameter μ.

mechanism to separate the dark matter signal from the neutrino background.

In Fig. 2 we see that both the annual and diurnal modulation are suppressed in the first energy bins when we consider a realistic detector. Furthermore, for a low WIMP mass (10 GeV), the sign change would not occur for a detector with characteristics similar to Xenon1T, while it could be observed for a high mass WIMP such as 30 GeV.

Moreover, the sign change in the modulation occurs for a specific recoil energy value located in the low energy bins. This energy depends on the mass of the WIMP but is independent of the value of the parameter μ. As the mass of the WIMP increases its value, the sign change occurs at higher recoil energies, and the modulation amplitude is smaller.

Although the diurnal modulation of dark matter signals is challenging to measure, if a detection is achieved, the difference between the data collected at the northern and southern locations could help refine the parameters used to characterize dark matter.

We hope that these studies will contribute to the planning and design of the future ANDES laboratory to maximize its ability to detect dark matter by direct methods.

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