Novel neutrino-floor and dark matter searches with deformed shell model calculations

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Event detection rates for WIMP-nucleus interactions are calculated for 71Ga, 73Ge, 75As and 127I (direct dark matter detectors). The nuclear structure form factors, that are rather independent of the underlying beyond the Standard Model particle physics scenario assumed, are evaluated within the context of the deformed nuclear shell model (DSM) based on Hartree-Fock nuclear states. Along with the previously published DSM results for 73Ge, the neutrino-floor due to coherent elastic neutrino-nucleus scattering (CEνNS), an important source of background to dark matter searches, is extensively calculated. The impact of new contributions to CEνNS due to neutrino magnetic moments and Z′ mediators at direct dark matter detection experiments is also examined and discussed. The results show that the neutrino-floor constitutes a crucial source of background events for multi-ton scale detectors with sub-keV capabilities.

I. INTRODUCTION

In the last few decades, the measurements of the cosmic microwave background (CMB) radiation offered a remarkably powerful way of modelling the origin of cosmic-ray anisotropies and constraining the geometry, the evolution and the matter content of our universe. Such observations have in general indicated the consistency of the standard cosmological model [1] and the fact that our universe hardly contains ∼ 5% luminous matter, whereas the remainder consists of non-luminous dark matter (∼ 23%) and dark energy (∼ 72%) [2]. After the discovery of the CMB fluctuations by the Cosmic Background Explorer (COBE) satellite [3], the extremely high precision of the WMAP satellite and especially of the Planck third-generation space mission, have helped us to produce maps for the CMB anisotropies and other cosmological parameters (see Ref. [4] for details). We also mention that, high-resolution ground-based CMB data, like those of the Atacama Cosmology Telescope (ACT) [5] and the South Pole Telescope (SPT) [6] have recovered the underlying CMB spectra observed by the space missions.

Focusing on the topic we address in this work, it is worth noting that the CMB data, the Supernova Cosmology project [7], etc., suggest that most of the dark matter of the universe is cold. Furthermore, the baryonic cold dark matter (CDM) component can be considered to consist of either massive compact halo objects (MACHOs) like neutron stars, white dwarfs, jupiters, etc., or Weakly Interacting Massive Particles (WIMPs) that constantly bombard Earth’s atmosphere. Several results of experimental searches suggest that the MACHO fraction should not exceed a portion of about 20% [1]. On the theoretical side, within the framework of new physics beyond the Standard Model (SM), supersymmetric (SUSY) theories provide promising non-baryonic candidates for dark matter [8] (for a review see Ref. [9]). In the simple picture, the dark matter in the galactic halo is assumed to be Weakly Interacting Massive Particles (WIMPs). The most appealing WIMP candidate for non-baryonic CDM is the lightest supersymmetric particle (LSP) which is expected to be a neutral Majorana fermion traveling with non-relativistic velocities [10].

In recent years, there have been considerable theoretical and experimental efforts towards WIMP detection through several nuclear probes [11–13]. Popular target nuclei include among others the 71Ga, 73Ge, 75As, 127I, 134Xe and 208Pb isotopes [14–15]. Towards the first ever dark matter detection, a great number of experimental efforts take place aiming at measuring the energy deposited after the galactic halo WIMPs scatter off the nuclear isotopes of the detection material. Because of the low count rates, due to the fact that the WIMP-nucleus interaction is remarkably weak, the choice of the detector plays very important role and for this reason spin-dependent interactions require the use of targets with non-zero spin. The Cryogenic Dark Matter Search (CDMS) experimental facility [16] has been designed to directly detect the dark matter by employing a 73Ge as the target nucleus, setting the most sensitive limits on the interaction of WIMP with terrestrial materials to date. The development of upgrades is under way and will be located at SNOLAB. Another prominent dark matter experiment is the EDELWEISS facility in France [17] which uses high purity germanium cryogenic bolometers at millikelvin temperatures. There are also other experimental attempts using detectors like 127I, 129,131Xe, 133Cs, etc. (see Refs. [13–20]).

I. INTRODUCTION

Inevitably, direct detection experiments are exposed to various neutrino emissions, such as those originating from astrophysical sources (e.g. Solar [21], Atmospheric [22,23] and diffuse Supernova [24] neutrinos),

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Earth neutrinos (Geoneutrinos [25]), and in other cases even from artificial terrestrial neutrinos (e.g. neutrinos from nearby reactors [26]). The subsequent neutrino interactions with the material of dark matter detectors, namely the neutrino-floor, may perfectly mimic possible WIMP signals [27]. Thus, the impact of the neutrino-floor on the relevant experiments looking for CDM as well as on the detector responses to neutrino interactions need be comprehensively investigated. Since Geoneutrino fluxes are relatively low, astrophysical neutrinos are recognised as the most significant background source that remains practically irreducible [28]. The recent advances of direct detection dark matter experiments, mainly due to the development of low threshold technology and high detection efficiency, are expected to reach the sensitivity frontiers in which astrophysical neutrino-induced backgrounds are expected to limit the observation potential of the WIMP signal [29].

In this work, we explore the impact of the most important neutrino background source on the relevant direct dark matter detection experiments by concentrating on the dominant neutrino-matter interaction channel, e.g. the dominant elastic neutrino-nucleus scattering (CEνNS) [30]. It is worthwhile to mention that, events of this process were recently measured for the first time by the COHERENT experiment at the Spallation Neutrino Source [31], completing the SM picture of electroweak interactions at low energies. Such a profound discovery motivated our present work and we will make an effort to shed light on the nuclear physics aspects. Neutrino non-standard interactions (NSIs) [32] may constitute an important neutrino background source on the relevant detector responses to neutrino interactions with the material of dark matter detectors, e.g. the coherent elastic neutrino-nucleus scattering (νeA) is a very promising channel to search for dark matter. The direct detection experiments are currently entering a precision era, and nuclear structure effects are expected to become rather important and should be incorporated in astroparticle physics applications [33]. For this reason, our nuclear model is at first tested in its capability to adequately describe the nuclear properties before being applied to problems like dark matter detection. This work considers the deformed shell model (DSM), on the basis of Hartree-Fock deformed intrinsic states with angular momentum projection and band mixing [34] all with a realistic effective interaction and a set of single particle states and single particle energies, which is established to be rather successful in describing the properties of nuclei in the mass range $A=60–90$ (see Ref. [35] for details regarding DSM and its applications). In particular, the DSM is employed for calculating the required nuclear structure factors entering the dark matter and neutrino-floor expected event rates by focusing on four interesting nuclei regarding dark matter investigations such as $^{71}$Ga, $^{73}$Ge, $^{75}$As and $^{127}$I. Let us add that details of nuclear structure and dark matter event rates for $^{73}$Ge obtained using DSM have been reported recently [36].

The paper has been organised as follows: Section II gives the main ingredients of WIMP-nucleus scattering, while Sect. III provides the formulation for neutrino-nucleus scattering (neutrino-floor) within and beyond the SM. Then in Sect. IV we describe briefly the methodology of the DSM, and the main results of the present work are presented and discussed in Sect. V. Finally, the concluding remarks are drawn in Sect. VI.

## II. SEARCHING WIMP DARK MATTER

The Earth is exposed to a huge number of WIMPs originating from the galactic halo. Their direct detection through nuclear recoil measurements after scattering off the target nuclei at the relevant dark matter experiments is of fundamental interest in modern physics and is expected to have a direct impact to astroparticle physics and cosmology. In this section we discuss the mathematical formulation of WIMP-nucleus scattering. The formalism introduces an appropriate separation of the SUSY and nuclear parts entering the event rates of WIMP-nucleus interactions in our effort to emphasise the important role played by the nuclear physics aspects. In particular we perform reliable nuclear structure calculations within the context of DSM based on Hartree-Fock states.

### A. WIMP-nucleus scattering

For direct detection dark matter experiments, the differential event rate of a WIMP with mass $m_{\chi}$ scattering off a nucleus $(A, Z)$ with respect to the momentum transfer $q$, can be cast in the form [1]

$$\frac{dR(u, v)}{dq^2} = N_t \phi \frac{d\sigma}{dq^2} f(v) d^3v,$$

(1)

where, $N_t = 1/(Am_p)$ denotes the number of target nuclei per unit mass, $A$ stands for the mass number of the target nucleus and $m_p$ is the proton mass. In the above expression the WIMP flux is $\phi = \rho_0 v/m_s$, with $\rho_0$ being the local WIMP density. The distribution of WIMP velocity relative to the detector (or Earth) and also the motion of the Sun and Earth, $f(v)$, is taken into account and assumed to resemble a Maxwell-Boltzmann distribution to ensure consistency with the LSP velocity distribution. Note that, by neglecting the rotation of Earth in its own axis, then $v = |v|$ accounts for the relative velocity
of WIMP with respect to the detector. For later convenience a dimensionless variable \( u = q^2 b^2 / 2 \) is introduced with \( b \) denoting the oscillator length parameter, and the corresponding WIMP-nucleus differential cross section in the laboratory frame reads \([10] [15] [35] [47]\)

\[
\frac{d\sigma(u, v)}{du} = \frac{1}{2}\sigma_0 \left( \frac{1}{m_P b} \right)^2 \frac{c^2}{v^2} \frac{d\sigma_A(u)}{du},
\]

with

\[
\frac{d\sigma_A}{du} = \left[ f_A^0 \Omega_0(0) \right]^2 F_{00}(u) + 2f_A^0 f_A^1 \Omega_0(0)\Omega_1(0) F_{01}(u) + \left[ f_A^1 \Omega_1(0) \right]^2 F_{11}(u) + \mathcal{M}^2(u).
\]

The first three terms account for the spin contribution due to the axial current, while the fourth term accounts for the coherent contribution arising from the scalar interaction. The coherent contribution is expressed in terms of the nuclear form factors given as

\[
\mathcal{M}^2(u) = \left[ f_S^0 \left[ Z F_Z(u) + N F_N(u) \right] \right]^2 + f_S^1 \left[ Z F_Z(u) - N F_N(u) \right]^2.
\]

The coherent part in the approximation of nearly equal proton and neutron nuclear form factors \( F_Z(u) \approx F_N(u) \), is given as

\[
\mathcal{M}^2(u) = A^2 \left( f_S^0 - f_S^1 \frac{A - 2Z}{A} \right)^2 |F(u)|^2.
\]

The respective values of the nucleonic-current parameters \( f_V^0, f_V^1 \) for the isoscalar and isovector parts of the vector current (not shown here), \( f_A^0, f_A^1 \) for the isoscalar and isovector parts of the axial-vector current, and \( f_B^0, f_B^1 \) for the isoscalar and isovector parts of the scalar current, depend on the specific SUSY model employed \([38]\). The spin structure functions \( F_{\rho\rho'}(u) \) with \( \rho, \rho' = 0, 1 \) for the isoscalar and isovector contributions respectively, take the form

\[
F_{\rho\rho'}(u) = \sum_{\lambda, \kappa} \frac{\Omega_{\rho\kappa}^{(\lambda, \kappa)}(u)}{\Omega_{\rho}(0)\Omega_{\rho'}(0)} \Omega_{\rho\kappa}^{(\lambda, \kappa)}(u),
\]

with

\[
\Omega_{\rho}^{(\lambda, \kappa)}(u) = \frac{4\pi}{2J_\lambda + 1} \times \langle J_f \mid \sum_{j=1}^A \left| Y_{\lambda}(\Omega_j) \otimes \sigma(j) \right|_{\kappa} j_\lambda(\sqrt{u} r_j) \omega_\rho(j) \mid J_i \rangle.
\]

III. NEUTRINO-NUCLEUS SCATTERING

The neutrino-floor stands out as an important source of irreducible background to WIMP searches at a direct detection experiment. In this work we explore the neutrino-floor due to neutrino-nucleus scattering since the corresponding floor coming from neutrino-electron scattering is relatively low \([49]\). Considering various astrophysical neutrino sources, our calculations involve the various conventional and beyond the SM interactions channels discussed below.

A. Differential event rate at dark matter detectors

For a given interaction channel \( x = SM, EM, Z' \), the differential event rate of CEνNS processes at a dark matter detector is obtained through the convolution of the neutrino energy distribution \( \lambda_{\nu, \nu}(E_\nu) \) of the background neutrino source in question (i.e. Solar, Atmospheric and Diffuse Supernova Neutrinos, see below) with the CEνNS cross section, as follows \([50]\)

\[
\left( \frac{dR_{\nu}}{dT_N} \right)_x = K\int_{E_{\nu\min}}^{E_{\nu\max}} \lambda_{\nu, \nu}(E_\nu) \frac{d\sigma_x}{dT_N}(E_\nu, T_N) dE_\nu,
\]

where \( K \) is a constant depending on the detector response and the specific interaction channel. Inserting the different cross sections \( \frac{d\sigma_x}{dT_N} \) and the respective energy distribution functions \( \lambda_{\nu, \nu}(E_\nu) \) for the various neutrino sources, one can compute the corresponding WIMP-nucleus event rate per unit mass of the detector is conveniently written as

\[
\langle R \rangle = (f_A^0)^2 D_1 + 2f_A^0 f_A^1 D_2 + (f_A^1)^2 D_3 + A^2 \left( f_S^0 - f_S^1 \frac{A - 2Z}{A} \right)^2 |F(u)|^2 D_4.
\]

The functions \( D_i \) enter the definition of the WIMP-nucleus event rate through the three-dimensional integrals, given by

\[
D_i = \int_{-1}^{1} d\kappa \int_{\psi_{\min}}^{\psi_{\max}} \frac{d\psi}{2\pi} \int_{\xi_{\min}}^{\xi_{\max}} G(\psi, \xi) X_i du,
\]

with

\[
X_1 = |\Omega_0(0)|^2 F_{00}(u),
X_2 = |\Omega_0(0)|^2 F_{01}(u),
X_3 = |\Omega_0(0)|^2 F_{11}(u),
X_4 = |F(u)|^2.
\]
where $E_{\text{min}}^\text{m} = \sqrt{MT_N/2}$ is the minimum neutrino energy that is required to yield a nuclear recoil with energy $T_N$. In the latter expression $K = t_{\text{run}} N_{\text{arg}} \Phi_\nu$ with $t_{\text{run}}$ being the exposure time, $N_{\text{arg}}$ is the number of target nuclei and $\Phi_\nu$ is the assumed neutrino flux.

1. Standard Model interactions

Assuming SM interactions only, at low and intermediate neutrino energies $E_\nu \ll M_W$, the weak neutral-current CEνNS process is adequately described by the four-fermion effective interaction Lagrangian \[32, 35\]

$$L_{\text{SM}} = -2\sqrt{2} G_F \sum_{f = u,d} \sum_{\alpha = e,\mu,\tau} g_{\alpha f} \bar{\nu}_{\alpha} [\bar{\nu}_f \gamma^\mu \nu_f] [f \gamma^\rho P f], \quad (12)$$

where $P = \{L, R\}$ denote the chiral projectors, $\alpha = \{e, \mu, \tau\}$ represents the neutrino flavour and $f = \{u, d\}$ is a first generation quark. By including the radiative corrections of Ref. \[51\], the $P$-handed couplings of the $f$ quarks to the $Z$-boson, are expressed as

$$g_{\alpha f}^u = \rho_{eN}^{NC} \left( \frac{1}{2} - \frac{2}{3} \kappa_{\nu N} s_Z^2 \right) + \lambda_{\nu L}^u,$$

$$g_{\alpha f}^d = \rho_{eN}^{NC} \left( -\frac{1}{2} + \frac{1}{3} \kappa_{\nu N} s_Z^2 \right) + \lambda_{\nu L}^d,$$

$$g_{\alpha f}^u = \rho_{eN}^{NC} \left( -\frac{2}{3} \kappa_{\nu N} s_Z^2 \right) + \lambda_{\nu R}^u,$$

$$g_{\alpha f}^d = \rho_{eN}^{NC} \left( \frac{1}{3} \kappa_{\nu N} s_Z^2 \right) + \lambda_{\nu R}^d,$$

with $s_Z^2 = \sin^2 \theta_W = 0.2312$, $\rho_{eN}^{NC} = 1.0086$, $\kappa_{\nu N} = 0.9978$, $\lambda_{\nu L}^u = -0.0031$, $\lambda_{\nu L}^d = -0.0025$ and $\lambda_{\nu R}^u = 2 \lambda_{\nu R}^d = 7.5 \times 10^{-5}$.

Focusing on the dominant CEνNS channel, the relevant SM differential cross section with respect to the nuclear recoil energy $T_N$, takes the form \[10\]

$$\frac{d\sigma_{\text{SM}}}{dT_N}(E_\nu, T_N) = \frac{G_F^2 M}{\pi} \left[ (Q_W^V)^2 \left( 1 - \frac{M T_N}{2 E_\nu^2} \right) + (Q_A^A)^2 \left( 1 + \frac{M T_N}{2 E_\nu^2} \right) \right], \quad (14)$$

with $E_\nu$ denoting the neutrino energy and $M$ the mass of the target nucleus. The relevant vector $(Q_W^V)$ and axial-vector $(Q_A^A)$ weak charges entering the CEνNS cross section, are given by the relations \[15\]

$$Q_W^V(Q^2) = [g_N^V Z F_W^V (Q^2) + g_N^V N F^V (Q^2)],$$

$$Q_A^A(Q^2) = [g_N^A (Z_+ - Z_-) + g_N^A (N_+ - N_-)]. \quad (15)$$

Here, $Z_\pm (N_\pm)$ stands for the number of protons (neutrons) with spin up (+) and spin down (−), respectively, while $g_N^V (g_N^A)$ represent for the axial-vector couplings of protons (neutrons) to the $Z^0$ boson. At the nuclear level, the relevant vector (axial-vector) couplings of protons $g_{\nu}^V (g_{\nu}^A)$ and neutrons $g_{\nu}^V (g_{\nu}^A)$ take the form

$$g_{\nu}^V = 2(g_{\alpha}^{u,R} + g_{\alpha}^{d,R}) + (g_{\alpha}^{d,L} + g_{\alpha}^{d,R}),$$

$$g_{\nu}^V = 2(g_{\alpha}^{u,L} + g_{\alpha}^{d,R}) + 2(g_{\alpha}^{d,L} + g_{\alpha}^{d,R}),$$

$$g_{\nu}^A = 2(g_{\alpha}^{u,L} - g_{\alpha}^{u,R}) + (g_{\alpha}^{d,L} - g_{\alpha}^{d,R}),$$

$$g_{\nu}^A = (g_{\alpha}^{u,L} - g_{\alpha}^{d,R}) + 2(g_{\alpha}^{d,L} - g_{\alpha}^{d,R}). \quad (16)$$

We note that for spin-zero nuclei the axial-vector contribution vanishes, while for the odd-$A$ nuclei considered in the present study $Q_A^A$ it is negligible and of the order of $Q_A^A/Q_W^V \sim 1/A$. At this point, we stress that the weak charges in Eq. \[15\] encode crucial information regarding the finite nuclear size through the proton $F_W^V(Q^2)$ and neutron $F_N^V(Q^2)$ nuclear form factors, which in our work are obtained within the context of the DSM (see below), as functions of the momentum transfer $-q^2\mu_\nu = Q^2 = 2M T_N$. Contrary to similar studies considering the conventional Helm-type form factors, the present work also takes into account the nuclear effects due to the non-spherical symmetric nuclei employed in dark matter searches.

2. Electromagnetic neutrino contributions

Turning our attention to new physics phenomena we now address potential contributions to CEνNS in the framework of non-trivial neutrino EM interactions, that may lead to a new neutrino-floor at low detector thresholds. In this framework, the presence of an effective neutrino magnetic moment $\mu_\nu$, leads an EM contribution of the differential cross section, that has been written as \[10\]

$$\frac{d\sigma_{\text{EM}}}{dT_N}(E_\nu, T_N) = \frac{d\sigma_{\text{SM}}}{dT_N}. \quad (17)$$

Neglecting axial effects, the EM contribution to CEνNS at a direct detection dark matter is encoded in the factor

$$\mathcal{G}_{\text{EM}} = 1 + \frac{1}{G_F^2 M Q_W^V} \left( \frac{Q_E^V}{Q_W^V} \right)^2 \frac{1 - T_N/E_{\nu}}{T_N^2 / 2 E_{\nu}^2}, \quad (18)$$

where the relevant EM charge $Q_E$ is written in terms of the electron mass $m_e$, the fine-structure constant $\alpha$ and the effective neutrino magnetic moment $\mu_\nu$.

$$Q_E = \frac{\pi a_{\text{EM}} \mu_\nu}{m_e} Z. \quad (19)$$

In contrast to the $N^2$ dependence of the SM case, Eqs. \[15\] and \[19\] imply the existence of a $Z^0$ coherence along with a characteristic $1/T_N$ enhancement of the total cross section. This implies a potential distortion of the expected recoil spectrum at very low recoil energies that may be detectable at future direct dark matter detection with sub-keV operation thresholds.
3. Novel mediator contribution

We now explore novel mediator fields that could be accommodated in the context of simplified $U(1)'$ scenarios \[43, 54\] predicting the existence of a new $Z'$ vector mediator with mass $M_{Z'}$. \[55\] Such beyond the SM interactions may constitute a new neutrino-floor at direct detection dark matter experiments \[55\]. The presence of a $Z'$ mediator gives rise to sub-leading contributions to the SM CEνNS rate, described by the Lagrangian \[57\]

$$L_{\text{vec}} = Z'_\mu \left( g^\nu_{Z'} q \bar{q} \gamma^\mu q + g^\nu_{Z'} \bar{\nu}_L \gamma^\mu \nu_L \right) + \frac{1}{2} M_{Z'_\mu}^2 Z'_\mu Z'^\mu, \tag{20}$$

where only left-handed neutrinos are assumed (right-handed neutrinos in the theory would lead to vector-axial-vector cancellations). The resulting cross section reads \[10\]

$$\left( \frac{d\sigma}{dT_N} \right)_{SM+Z'} = G_{Z'}^2(T_N) \frac{d\sigma_{SM}}{dT_N}, \tag{21}$$

with the factor $G_{Z'}$ being written in terms of the neutrino-vector coupling $g^\nu_{Z'}$, as

$$G_{Z'}^2 = 1 - \frac{1}{2\sqrt{2}G_F} \frac{Q_{Z'}}{2MT_N + M_{Z'}^2}. \tag{22}$$

The relevant charge in this case is expressed through the vector quark couplings $g^\nu_{Z'}$ to the $Z'$ boson, as \[55\]

$$Q_{Z'} = (2g^\nu_{Z'} + g_{Z'}^\nu) Z + \left( g^\nu_{Z'} + 2g_{Z'}^\nu \right) N. \tag{23}$$

Let us mention that emerging degeneracies can be either reduced through multi-detector measurements \[55\] and broken in the framework of NSIs \[55\].

### B. Neutrino sources

#### 1. Solar Neutrinos

In terrestrial searches for dark matter candidates at low energies, the Solar neutrinos emanating from the interior of the Sun generated through various fusion reactions produce a dominant background for direct CDM detection experiments. Assuming WIMP masses less than 10 GeV, an estimated total Solar neutrino flux of about $6.5 \times 10^{11}$ cm$^{-2}$s$^{-1}$ \[54\] hitting the Earth is expected to appreciable limit the sensitivity of such experiments \[27\]. On the other hand, the theoretical uncertainties of Solar neutrinos are presently quite large and depend strongly on the assumed Solar neutrino model. To maintain consistency with existing Solar data, in this work we consider the high metallicity Standard Solar Model (SSM) \[21\]. We note however that, the dominant Solar neutrino component coming from the primary proton-proton channel ($pp$ neutrinos) that accounts for about 86% the Solar neutrinos flux, has been recently measured by the Borexino experiment with an uncertainty of 1% \[64\]. Through CEνNS, the direct detection dark matter experiments are mainly sensitive to two sources of Solar neutrinos, namely the $^8B$ and the $\text{hep}$ neutrinos which cover the highest energy range of the Solar neutrino spectrum. Since, $^8B$ neutrinos are generated from the decay $^8B \rightarrow ^7Be^* + e^+ + \nu_e$ while $\text{hep}$ neutrinos from $^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e$, both sources occur in the aftermath of the $pp$ chain. Following previous similar studies \[28\], in this work, we explore the neutrino-floor extending our analysis to the lowest neutrino energies, by considering the $\text{pep}$ neutrino line which belongs to the $pp$ chain and the $e^-\text{capture}$ reaction on $^7\text{Be}$ that leads to two monochromatic beams at 384.3 and 861.3 keV as well as the well known CNO cycle. The latter neutrinos appear as three continuous spectra ($^{13}\text{N}$, $^{15}\text{O}$, $^{17}\text{F}$) with end point energies close to the $\text{pep}$.
neutrinos.

2. Atmospheric Neutrinos

Atmospheric neutrinos are decay products of the particles (mostly pions and kaons) produced as a result of cosmic ray scattering in the Earth’s atmosphere. The generated secondary particles decay to $\nu_e$, $\nu_\mu$, and $\nu_\tau$ constituting a significant background to dark matter searches especially for WIMP masses above 100 GeV. In particular, the effect is crucial on the discovery potential of WIMPs with spin-independent cross section of the order of $10^{-48}$ cm$^2$. The direct detection dark matter experiments, due to the lack of directional sensitivity, are in principle sensitive to the lowest energy (less than $\sim 100$ MeV) Atmospheric neutrinos. For this reason, in our present work Atmospheric neutrinos are considered by employing the low-energy flux coming out of the FLUKA code simulations [22].

3. Diffuse Supernova Neutrinos

The weak glow of MeV neutrinos emitted from the total number of core-collapse supernovae, known as the Diffuse Supernova Neutrino Background (DSNB), creates an important source of neutrino background specifically for the WIMPs mass range 10–30 GeV [23]. Despite the appreciably lower flux compared to Solar neutrinos, DSNB neutrino energies are higher than those of the Solar neutrino spectrum. In our simulations, the adopted DSNB distributions (usually of Fermi-Dirac or power-law type) correspond to temperatures 3 MeV for $\nu_e$, 5 MeV for $\bar{\nu}_e$ and 8 MeV for the other neutrino flavours denoted as $\nu_x$ or $\bar{\nu}_x$, $x = \mu, \tau$.

Figure 1 shows the Solar neutrino spectra of the dominant neutrino sources assuming the high metallicity Standard Solar Model (SSM) as defined in Ref. [21]. Also shown is the low-energy Atmospheric neutrino flux as obtained from the FLUKA simulation [22] as well as the DSNB spectrum [61]. The corresponding neutrino types, maximum energies and fluxes are listed in Table I.

![FIG. 2. HF single-particle spectra for $^{71}$Ga corresponding to the lowest prolate configuration. In the figure, circles represent protons and crosses represent neutrons. The HF energy $E$ in MeV, the mass quadrupole moment $Q$ in units of the square of the oscillator length parameter and the total azimuthal quantum number $K$ are given in the figure.](image)

IV. DEFORMED SHELL MODEL

In the formalism of the WIMP-nucleus or neutrino-nucleus event rates of Sects. II and III both for the case of elastic or inelastic interaction channels, the nuclear physics and particle physics (SUSY model) parts appear almost completely separated. In the present work our main focus drops on the nuclear physics aspects which are contained in the nuclear structure factors discussed in Sect. II. Special attention is paid on the factors $D_i$ of Eq. (9) that depend on the spin structure functions and the nuclear form factors. These quantities have been calculated using the DSM method [15] (for a comprehensive discussion of DSM see Ref. [14]) given the kinematics and the assumptions describing the WIMP particles.

The construction of the many-body wave functions for the initial $|f_j^*\rangle$ and final $|f_j^f\rangle$ nuclear states in the framework of DSM involves performance of the following steps. (i) At first, one chooses a model space consisting of a given set of spherical single-particle (sp) orbits, sp energies and the appropriate two-body effective interaction matrix elements. For $^{71}$Ga and $^{75}$As, the spherical sp orbits are $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$ with energies 0.0, 2.20, 2.28 and 5.40 MeV and 0.0, 0.78, 1.08 and 3.20 MeV respectively, while the assumed effective interaction is the modified Kuo interaction [62]. Similarly for $^{127}$I, the sp orbits, their energies and the effective interaction are taken from a recent paper [63]. (ii) Assuming axial symmetry and solving the HF single particle equations self-consistently, the lowest-energy prolate (or oblate) intrinsic state for the nucleus in question is obtained. An example is shown in Fig. 2 for $^{71}$Ga. (iii) The various excited intrinsic states then are obtained by making particle-hole $(p-h)$ excitations over the lowest-energy intrinsic state (lowest configuration). (iv) Then, because
the HF intrinsic nuclear states $|\chi_K(\eta)\rangle$ ($K$ is azimuthal quantum number and $\eta$ distinguishes states with same $K$) do not have definite angular momentum, angular momentum projected states $|\phi^J_{MK}(\mu)\rangle$ are constructed as,

$$|\phi^J_{MK}(\eta)\rangle = \frac{2J+1}{8\pi^2\sqrt{N_{JK}}} \int d\Omega D_{MK}^\ast(\Omega)R(\Omega)|\chi_K(\eta)\rangle.$$  \hspace{1cm} (24)

Here, $\Omega = (\alpha, \beta, \gamma)$ represents the Euler angles and $R(\Omega)$ denotes the known general rotation operator. Here, $N_{JK}$ is the normalisation constant which by assuming axial symmetry is defined as

$$N_{JK} = \frac{2J+1}{2} \int_0^\pi d\beta \sin\beta \ d^J_K(\beta)\langle\chi_K(\eta)|e^{-i\beta J_y}|\chi_K(\eta)\rangle.$$  \hspace{1cm} (25)

The functions $d^J_K(\beta)$ are the diagonal elements of the matrix $d^J_{MK}(\beta) = \langle J M | e^{-i\beta J_y} | JK \rangle$. Finally, the good angular momentum states $\Phi_J$ are orthonormalized by band mixing calculations and then, in terms of the index $\eta$, it is possible to distinguish between different states having the same angular momentum $J$,

$$|\Phi^J_M(\eta)\rangle = \sum_{K,\alpha} S^J_{MK}(\alpha)|\phi^J_{MK}(\alpha)\rangle.$$  \hspace{1cm} (26)

Within the DSM method, for the evaluation of the reduced nuclear matrix element entering Eqs. (6) and (7), we first calculate the single particle matrix elements of the relevant operators $\hat{t}^{(l,s)J}$, as

$$\langle n_i l_i j_i | \hat{t}^{(l,s)J} | n_k l_k j_k \rangle = \sqrt{(2j_k + 1)(2j_i + 1)(2J + 1)(s + 1)(s + 2)} \times \left\{ l_i \quad 1/2 \quad j_i \right\} \left\{ l_k \quad 1/2 \quad j_k \right\}_I \langle i_l || \sqrt{4\pi} Y_l^s || k_l \rangle \langle n_i l_i || j_i (kr) || n_k l_k \rangle,$$  \hspace{1cm} (27)

where $\left\{ \ldots \right\}$ is the 9-j symbol. For more details, the reader is referred to Refs. [64-66]. It should be noted that in the DSM method one considers an adequate number of intrinsic states in the band mixing calculations.

V. RESULTS AND DISCUSSION

A. Nuclear physics aspects

To maximise the significance of our WIMP-nucleus and neutrino-floor calculations, the reliability of the obtained nuclear wave functions is tested by comparing the extracted energy level spectrum and magnetic moments with available experimental data. The consistency of this method obtained for $^{73}$Ge has been already presented in Ref. [49]. Furthermore, in the DSM calculations for $^{71}$Ga and $^{75}$As, we restrict ourselves to prolate solutions only, since the oblate solution does not reproduce the energy spectra and electromagnetic properties of these nuclei.

It also does not mix with the prolate solution. Hence we neglect the oblate solutions in the calculations. For each of these nuclei, we consider only four intrinsic prolate states which should be sufficient to explain the systematics of the ground state and close lying excited state. Due to size restrictions, in Fig. 3 we illustrate only the calculated spectrum for $^{71}$Ga.

For $^{75}$As, the ground state is $3/2^-$ and there are also two $1/2^-$ and $3/2^-$ levels around 0.12 MeV. In addition there is a collective band consisting of $5/2^-$, $9/2^-$, $13/2^-$, $17/2^-$ levels at 0.279, 1.095, 2.150 and 3.091 MeV, respectively. All these levels are well reproduced by the DSM method. Turning to the $^{127}$I spectrum, there are four observed collective bands with band heads $5/2^+$, $(7/2^+)_{1,2}$ and $9/2^+$. There are evidences suggesting that low-lying states in $^{127}$I have oblate deformation [68]. Hence for this nucleus, we consider only oblate configurations and take the six lowest oblate intrinsic states in the band mixing calculation. These intrinsic states are found to provide adequate description of the energy spectrum and electromagnetic properties for this nucleus. The calculations for this nucleus utilise a new effective interaction developed by an Italian group very recently [63]. The new effective interaction is seen to reproduce well the $^{127}$I spectrum; details will be presented elsewhere.

We thus conclude that concerning the evaluation of
TABLE II. List of potential Dark Matter detectors considered in the present study. The calculated magnetic moments for the ground states of $^{71}$Ga, $^{73}$Ge, $^{75}$As and $^{127}$I, are shown. The results involve the bare gyromagnetic ratios and experimental data are from [67]. The ground state $J^\pi$ and the harmonic oscillator size $b$ are also shown.

| Nucleus | $A$ | $Z$ | $J^\pi$ | <$l_p$> | <$S_p$> | <$l_n$> | <$S_n$> | $\mu$ (nm) | Exp | $b$ [fm$^{-1}$] |
|---------|-----|-----|---------|--------|--------|--------|--------|----------|-----|------------|
| Ga      | 71  | 31  | 3/2$^-$ | 0.863  | 0.257  | 0.369  | 0.011  | 2.259    | 2.562| 1.90       |
| Ge      | 73  | 32  | 9/2$^+$ | 0.581  | -0.001 | 3.558  | 0.362  | -0.811   | -0.879| 1.91       |
| As      | 75  | 33  | (3/2$^+$) | 0.667  | 0.164  | 0.626  | 0.042  | 1.422    | 1.439| 1.92       |
| I       | 127 | 53  | 5/2$^+$ | 2.395  | -0.211 | 0.313  | 2.343  | 1.207    | 2.813| 2.09       |

FIG. 4. Comparison of the DSM nuclear form factors obtained in the present work with the effective Helm form factors.

the WIMP-nucleus and CE$\nu$NS event rates we are interested in this work, the required ground state wave functions obtained through the DSM method are reliable and the intrinsic states used in the subsequent analysis are considered sufficient. From the perspective of nuclear physics, spin contributions constitute significant ingredients in the evaluation of WIMP-nucleus event rates. For this reason, the first stage of our work involves the calculation of the magnetic moment, which is decomposed into an orbital and spin part. The relevant results for the proton and neutron contributions to the orbital and spin parts concerning the ground states of the four nuclear isotopes studied in this paper are given in Table II. A comparison between the obtained magnetic moments and the respective experimental data is also provided. Despite the fact that, these calculations adopt bare values of $g$-factors neglecting quenching effects, the obtained DSM result of the ground state magnetic moments are consistent with the experimental values.

Having successfully reproduced the energy spectrum and the magnetic moments within the context of the DSM wave functions, we evaluate important nuclear physics inputs entering the WIMP-nucleus and CE$\nu$NS cross sections. Figure 4 presents a comparison between the DSM nuclear form factors and the effective Helm-type ones employed in various similar studies, where as can be seen, the DSM results differ from the Helm-type ones. The behaviour of the proton form factor for $^{71}$Ga is found to be different from those of the other nuclei and this may be due to the nearby proton shell closure and the neutron sub-shell closure. Calculations with several different effective interactions are under way to rule out the possibility of any deficiency of the effective two-body interaction used. We furthermore, illustrate the spin structure functions of WIMP-$^{71}$Ga elastic scattering calculated using Eqs. (6) and (7). The variation of $F_{00}$, $F_{01}$ and $F_{11}$ with respect to the parameter $u$ is shown in Fig. 5, while similar results are obtained for $^{75}$As and $^{127}$I (for the $^{73}$Ge case see Ref. [65]).

B. WIMP-nucleus rates and the neutrino-floor

The WIMP-nucleus event rates and the neutrino-floor due to neutrino-nucleus scattering are calculated for a set of interesting nuclear targets such as $^{71}$Ga, $^{73}$Ge, $^{75}$As and $^{127}$I (see Table II). In evaluating the neutrino-induced backgrounds, we consider only the dominant CE$\nu$NS channel, since neutrino-electron events are ex-
pected to produce less events by about one order of magnitude \cite{27}. For the case of a $^{71}$Ga target, in Fig. 6 we provide the coefficients $D_i$ associated to the spin dependent and coherent interactions given in Eq. (9) as functions of the WIMP mass $m_{\chi}$ by assuming three typical values of the detector threshold energy $T_N=0, 5, 10$ keV. For the special case of $T_N=0$, all plots peak at $m_{\chi} \sim 35$ GeV, while for higher threshold energies $D_i$ are shifted towards higher values of the WIMP mass. The calculations take also into account the annual modulation which is represented by the curve thickness. As can be seen from the figure, the modulation signal varies with respect to the WIMP mass, being larger for $m_{\chi} \leq 50$ GeV while its magnitude is slightly different for the spin dependent and coherent channels.

Proceeding further, in Fig. 7 we evaluate the expected event rates for the four target nuclei assuming elastic WIMP scattering for WIMP candidates with mass $m_{\chi} = 110$ GeV, by adopting the nucleonic current parameters $\rho_A^3 = 3.55 \times 10^{-2}$, $f_A^3 = 5.31 \times 10^{-2}$, $\rho_B^3 = 8.02 \times 10^{-4}$ and $f_B^3 = -0.15 \times f_B^3$. As in the previous discussion, the thickness of the graph accounts for the annual modulation. We find that there is a strong dependence of the event rate on the studied nuclear isotope. Again the modulation is found to decrease for heavier mass. Among the four studied nuclei, we come out with a larger event rate for the case of a $^{71}$Ga nuclear detector, since $D_1, D_2, D_3$ are all positive and have similar values. For $^{73}$Ge, $D_2$ is negative and its magnitude is comparable to $D_1$ and $D_3$, while for $^{75}$As, $D_3$ is positive but small, and finally for $^{127}$I, $D_2$ and $D_3$ are relatively smaller and $D_1$ is large. The coherent contribution $D_2$ has more or less similar values for all nuclei considered.

For each component of the Solar, Atmospheric and DSNB neutrino distributions we calculate the expected neutrino-floor due to CE\textsubscript{NS}, by considering the target nuclei presented in Table II. In our calculations, we neglect possible recoil events arising from Geoneutrinos as
they are expected to be at least one order of magnitude less that the aforementioned neutrino sources (see e.g. Refs. [25, 26]). The differential event rate due to CEνNS, for the various dark matter detectors considered in the present study, is presented in Fig. 8. It can be noticed that, the neutrino-background is dominated by Solar neutrinos at very low recoil energies. We stress that, for the typical keV-recoil thresholds of the current direct detection dark matter experiments only the hep and 8B sources constitute a possibly detectable background. From our results we conclude that, for recoil energies above about 10 keV, Atmospheric neutrinos dominate the neutrino background event rates, having a tiny contribution coming from the DSNB spectrum.

The number of expected background events due to CEνNS for each component of the Solar, Atmospheric and DSNB neutrino fluxes is illustrated in Fig. 9. Similarly to the differential event case, at low energies the neutrino background is dominated by the Solar neutrino spectrum with, the dominant components being the hep and 8B neutrino sources. The results imply that future multi-ton scale detectors with sub-keV sensitivities may be also sensitive to 3Be and pp neutrinos. We comment however that, such sensitivities will be further limited due to the quenching effect of the nuclear recoil spectrum which is not taken into account here. Moreover, it is worth mentioning that neutrino-induced and WIMP-nucleus scattering processes provide similar recoil spectra, e.g. the recoil spectrum of 8B neutrinos may mimic that of a WIMP with mass 6 GeV (100 MeV) [28].

At this point, we consider additional interactions in the context of new physics beyond the SM that may enhance the CEνNS rate at a direct detection dark matter experiment. Specifically we study the impact of neutrino EM properties as well as the impact of new interactions due to a novel Z’ mediator, on the neutrino floor. We assume the existence of a neutrino magnetic moment μν = 4.3 × 10⁻⁹ μB, being the current limit extracted in Ref. [40] as well as typical values regarding the Z’ interaction such as MZ’ = 1 TeV, gZ’ = 10⁻⁶. We note that, by assuming universal couplings, our calculations involve the product of neutrino and quark Z’ couplings defined as

$$g_{Z'}^2 = \frac{g_{Z'}^{\nu V} Q_{Z'}}{3A}.\quad (28)$$

The corresponding results are presented in Fig. 10 indicating that such new physics phenomena may constitute a crucial source of background even for multi-ton scale detectors with sub-keV capabilities.

VI. CONCLUSIONS

In this work, we studied comprehensively the expected event rates in WIMP-nucleus and neutrino-floor processes by performing reliable calculations for a set of prominent nuclear materials of direct dark matter detection experiments. The detailed calculations involve crucial nuclear physics inputs in the framework of the deformed shell model based on Hartree-Fock nuclear states. This way, the nuclear deformation as well as the spin structure effects of odd-A isotopes, that play significant role in searching for dark matter candidates, are incorporated. The chosen nuclear detectors involve popular nuclear isotopes in dark matter investigations such as the 71Ga, 73Ge, 75As and 127I isotopes. The DSM results
indicate that $^{71}$Ga needs further investigation by employing another effective two-body interaction than the one used in the chosen set of nuclear isotopes.

More importantly, by exploiting the expected neutrino-floor due to Solar, Atmospheric and DSNB neutrinos, which constitute an important source of background to dark matter searches, the impact of new physics CE$
u$NS contributions based on novel electromagnetic neutrino properties and $Z'$ mediator bosons have been estimated and discussed. Our results also indicate that the addressed novel contributions may lead to a distortion of the expected recoil spectrum that could limit the sensitivity of upcoming WIMP searches. Such aspects could also provide key information concerning existing anomalies in $B$-meson decays at the LHCb experiment [69], and offer new insights to the LMA-Dark solution [70, 71].

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.
