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Limits on Spin-Dependent WIMP-Nucleon Cross Sections from 225 Live Days of XENON100 Data

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XENON100 was built to search for hypothetical, weakly interacting massive particles (WIMPs), which could explain the nonbaryonic, cold dark matter in our Universe [1]. Independently of astrophysical and cosmological observations, WIMPs are a consequence of many extensions of the standard model of particle physics, as new, stable, or long-lived neutral particles. The WIMP dark matter hypothesis is testable by experiment, the most compelling avenue is to directly observe WIMPs scattering off atomic nuclei in ultralow background terrestrial detectors [2,3].

XENON100 is a double-phase xenon time projection chamber operated at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. A total of 178 low-radioactivity, UV-sensitive photomultiplier tubes detect the prompt (S1) and proportional (S2) light signals induced by particles interacting in the sensitive volume, containing 62 kg of ultrapure liquid xenon. The background level in the energy region of interest for dark matter searches (<50 keV_{nr}) is 5.3×10^{-3} events kg^{-1}d^{-1}keV^{-1}, before discrimination of electronic and nuclear recoils based on their S2/S1-ratio [4,5]. The instrument is described in [6], the analysis procedure is detailed in [7].

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WIMPs in the halo of our Galaxy are expected to be highly nonrelativistic and their interactions with nuclei can be characterized in terms of scalar (or spin-independent, SI) and axial-vector (or spin-dependent, SD) couplings [1,2]. In the case of SI interactions, the leading contribution of the scattering is coherent across the nucleus, and roughly scales with $A^2$, where $A$ is the number of nucleons. Our SI result was presented in [4] and excludes a WIMP-nucleon cross section above $2 \times 10^{-45}$ cm$^2$ at a WIMP mass of 55 GeV/c$^2$ at 90% confidence level. Here we use the same data set, with an exposure of 224.6 live days, a fiducial mass of 34 kg, identical event selection cuts, acceptances, relative scintillation efficiency, and background model to derive limits on spin-dependent interactions.

If the WIMP is a spin-1/2 or a spin-1 field, the contributions to the WIMP-nucleus scattering cross section arise from couplings of the WIMP field to the quark axial current. In the case of the lightest neutralino in supersymmetric models for instance, scattering occurs through the exchange of Z bosons or squarks [1]. To predict actual rates, these fundamental interactions are first translated into interactions with nucleons by evaluating the matrix element of the quark axial-vector current in a nucleon. Finally, the spin components of the nucleons must be added coherently using nuclear wave functions to yield the matrix element for the SD WIMP-nucleus cross section as a function of momentum transfer. The SD differential WIMP-nucleus cross section as a function of momentum transfer $q$ can be written as [8]:

$$\frac{d\sigma^\text{SD}(q)}{dq^2} = \frac{8G_F^2}{(2J+1)\nu^2} S_A(q),$$

where $G_F$ is the Fermi constant, $\nu$ is the WIMP speed relative to the target, $J$ is the total angular momentum of the nucleus and $S_A$ is the axial-vector structure function. In the limit of zero momentum transfer (at finite momentum transfer, or when WIMP couplings to two nucleons are included [9], the neutron-only coupling case implies also coupling to protons and vice versa) the structure function reduces to the form [10]:

$$S_A(0) = \frac{(2J+1)(J+1)}{\pi J} \left[a_p\langle S_p \rangle + a_n\langle S_n \rangle\right]^2,$$

where $\langle S_{p,n} \rangle = \langle J|\hat{S}_{p,n}|J\rangle$ are the expectation values of the total proton and neutron spin operators in the nucleus, and the effective WIMP couplings to protons and neutrons are defined in terms of the isoscalar $a_0 = a_p + a_n$ and isovector $a_1 = a_p - a_n$ couplings.

WIMPs will thus couple to the total angular momentum of a nucleus and only nuclei with an odd number of protons or/and neutrons will yield a significant sensitivity to this channel. Natural xenon contains two nonzero spin isotopes, $^{129}$Xe (spin-1/2) and $^{131}$Xe (spin-3/2), with an abundance of 26.4% and 21.2%, respectively. In XENON100, the isotopic abundances of $^{129}$Xe and $^{131}$Xe are changed to 26.2% and 21.8%, respectively, due to the addition of isotopically modified xenon to the available natural xenon.

To compare results from different target materials, a common practice is to report the cross section for the interaction with a single nucleon ($\sigma_{p, n}$) [11–13]. Assuming that WIMPs couple predominantly to protons ($a_0 = 0$) or neutrons ($a_p = 0$), the WIMP-nucleon cross section becomes

$$\sigma_{p,n}(q) = \frac{3}{4} \frac{\mu_p}{\mu_A^2} \frac{2J + 1}{\pi} \frac{\sigma_{\text{SD}}(q)}{S_A^{00} - (a_{p,n})^2},$$

where $\sigma_{\text{SD}}$ is the total WIMP-nucleus cross section, $\mu_A$ and $\mu_{p,n}$ are the WIMP-nucleus and WIMP-nucleon reduced masses, respectively.

Calculations of the structure functions $S_A(q)$ are traditionally based on the nuclear shell model, but differ in the effective nucleon-nucleon interactions and in the valence space and truncation used for the computation. For xenon as a WIMP target material, we consider three large-scale shell-model calculations: by Ressell and Dean [14] with the Bonn-A [15] two-nucleon potential, by Toivanen et al. [16], using the CD-Bonn potential [15], and the recent results by Menendez et al. [9], using state-of-the-art valence shell interactions [17,18] and less severe truncations of the valence space. Menendez et al. [9] also use for the first time chiral effective field theory (EFT) currents [19] to determine the couplings of WIMPs to nucleons. The currents for spin-dependent scattering are derived at the one-body level and the leading long-range two-nucleon currents are included, resulting in a reduction of the isovector part of the one-body axial-vector WIMP currents [9]. The resulting chiral EFT currents are then used to calculate the structure functions for the WIMP-xenon scattering. Theoretical errors due to nuclear uncertainties can be provided when chiral two-body currents are included [9]; we show their effect on our limits in this Letter. The shell-model calculations are based on the largest many-body spaces accessible with nuclear interactions, also used to calculate double-beta decay matrix elements for nuclei up to $^{136}$Xe and to study nuclear structures [17,18,20].

The new calculations by Menendez et al. [9] yield a far superior agreement between calculated and measured spectra of the $^{129}$Xe and $^{131}$Xe nuclei, both in energy and in the ordering of the nuclear levels, compared to older [16] results. The values for $\langle S_{p,n} \rangle$ are close to those of Ressell and Dean [14], but quite different from the results of Toivanen et al. [16], as summarized in Table I. We thus use the Menendez et al. [9] structure functions for our benchmark upper limits on WIMP-neutron and WIMP-proton cross sections. We also provide a comparison to the limits obtained when using the calculations by Ressell and Dean [14] and Toivanen et al. [16]. In all cases, $|\langle S_p \rangle| \gg |\langle S_n \rangle|$, as expected for the two xenon nuclei.
with an odd number of neutrons and an even number of protons.

Figure 1 shows the structure functions $S_A(q)$ obtained from the three calculations for pure neutron and pure proton couplings as a function of nuclear recoil energy. For the neutron coupling case, for which xenon has the best sensitivity, the functions are rather similar. For the proton coupling case, the structure function by Toivanen et al. [16] differs significantly from the other two results. We note that, for xenon, a significant effect in the proton channel had already been pointed out in [21], in a comparison between the results of Ressell and Dean with the Bonn-A potential, and Toivanen et al. using the Bonn-CD nucleon-nucleon potential.

Table I summarizes the expectation values of the total proton and neutron spin operators in the nucleus for $^{129}$Xe and $^{131}$Xe in the zero momentum transfer limit.

Constraints on the spin-dependent WIMP-nucleon cross sections are calculated using the Profile Likelihood

![Figure 1](color online). Structure functions for $^{129}$Xe (top) and $^{131}$Xe (bottom) for the case of neutron (plain) and proton (dashed) couplings, as a function of recoil energy using the calculations of Ressell and Dean [14], Toivanen et al. [16], and Menendez et al. [9]. The difference is most significant in the case of the proton coupling for the Toivanen et al. results.

![Figure 2](color online). XENON100 90% C.L. upper limits on the WIMP SD cross section on neutrons (top) and protons (bottom) using Menendez et al. [9]. The 1σ (2σ) uncertainty on the expected sensitivity of this run is shown as a green (yellow) band. Also shown are results from XENON10 [24] (using Ressell and Dean [14]), CDMS [25,26], ZEPLIN-III [21,27] (using Toivanen et al. [16] and Ressell and Dean [14] for the neutron and proton case, respectively), PICASSO [28], COUPP [29], SIMPLE [30], KIMS [31], IceCube [32] in the hard ($W^+W^−, \tau^+\tau^−$) for WIMP masses <80.4 GeV/c$^2$, and soft ($b\bar{b}$) annihilation channels.

**Table I.** Parameters of the xenon isotopes used in this analysis: nuclear total angular momentum and parity of the ground state, $J^P$, predicted expectation values of the total proton and neutron spin operators in the nucleus ($S_{n,p}$) by the Ressell and Dean (Bonn A potential) [14], Toivanen et al. (Bonn CD potential) [16], and Menendez et al. (state-of-the art valence shell interactions) [9] calculations.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$J^P$</th>
<th>$S_{n}$</th>
<th>$S_{p}$</th>
<th>$S_{n}$</th>
<th>$S_{p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{129}$Xe</td>
<td>(1/2)${}^+_x$</td>
<td>0.359</td>
<td>0.028</td>
<td>0.273</td>
<td>−0.0019</td>
</tr>
<tr>
<td>$^{131}$Xe</td>
<td>(3/2)${}^+_x$</td>
<td>−0.227</td>
<td>−0.009</td>
<td>−0.125</td>
<td>−0.00069</td>
</tr>
</tbody>
</table>
In conclusion, we have analyzed data from 224.6 live days × 34 kg exposure acquired by XENON100 during 13 months of operation in 2011/2012 for SD WIMP interactions. We saw no evidence for a dark matter signal and have obtained new experimental upper limits on the spin-dependent WIMP-nucleon cross section. For our limits, we use the new calculations by Menendez et al. [9], where the WIMP couplings to nucleons are derived using chiral EFT currents and which yield a good agreement between the calculated and measured energy spectra of the $^{129}$Xe and $^{131}$Xe nuclei. We note that the interpretation of the results in terms of SD pure-proton cross section strongly depends on the used nuclear model. However, regardless of the nuclear model, we obtain the most stringent limits to date on spin-dependent WIMP-neutron couplings for WIMP masses above 6 GeV/$c^2$ at 90% C.L.

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