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Aprile, E.; et al., [Unknown]; Colijn, A.P.; Decowski, M.P.

DOI
10.1103/PhysRevLett.111.021301

Publication date
2013

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):
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We present new experimental constraints on the elastic, spin-dependent WIMP-nucleon cross section using recent data from the XENON100 experiment, operated in the Laboratori Nazionali del Gran Sasso in Italy. An analysis of 224.6 live days of XENON100 data reveals no excess signal due to axial-vector WIMP interactions with 129Xe and 131Xe nuclei. This leads to the most stringent upper limits on WIMP-neutron cross sections for WIMP masses above 6 GeV, with a minimum cross section of 3.5 × 10^{-40} cm^2 at a WIMP mass of 45 GeV/c^2, at 90% confidence level.

DOI: 10.1103/PhysRevLett.111.021301

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].
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 that result was presented in [4] and excludes a WIMP-nucleon cross section above 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 supersymmetry 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]:

\[
\frac{d\sigma_{SD}(q)}{dq^2} = \frac{8G_F^2}{(2J+1)\nu^2} S_{A}(q),
\]

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]:

\[
S_{A}(0) = \frac{(2J+1)(J+1)}{\pi J} [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2,
\]

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, \(^{129}\text{Xe} \) (spin-1/2) and \(^{131}\text{Xe} \) (spin-3/2), with an abundance of 26.4% and 21.2%, respectively. In XENON100, the isotopic abundances of \(^{129}\text{Xe} \) and \(^{131}\text{Xe} \) 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 \( (\sigma_p, \sigma_n) \) [11–13]. Assuming that WIMPs couple predominantly to protons \( (\sigma_p \approx 0) \) or neutrons \( (\sigma_n \approx 0) \), the WIMP-nucleon cross section becomes

\[
\sigma_{p,n}(q) = \frac{3 \mu_{A}}{4} \frac{2J + 1}{\pi} \frac{\sigma_{SD}(q)}{S_{A}} S_{p,n}(q),
\]

where \( \sigma_{SD} \) 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 \(^{136}\text{Xe} \) 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 \(^{129}\text{Xe} \) and \(^{131}\text{Xe} \) 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, \( |\langle S_{n} \rangle| \gg |\langle S_{p} \rangle| \), as expected for the two xenon nuclei

\[
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\]
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](image1.png)

**FIG. 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](image2.png)

**FIG. 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 $1\sigma$ ($2\sigma$) uncertainty on the expected sensitivity of this run is show as a green (yellow) band. Also shown are results from XENON10 [24] (using Ressel 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.
approach described in [22]. Systematic uncertainties in the energy scale and in the background expectation are taken into account when constructing the Profile Likelihood model and are reflected in the actual limit. It is given at 90% C.L. after taking into account statistical downward fluctuations in the background. We assume that the dark matter is distributed in an isothermal halo with a truncated Maxwellian velocity distribution with a local circular speed of \( v_c = 220 \text{ km/s} \), galactic escape velocity \( v_{esc} = 544 \text{ km/s} \) and a local density of \( \rho = 0.3 \text{ GeV cm}^{-3} \) [23].

The resulting upper limits from XENON100, along with results from other experiments, are shown in Fig. 2 for neutron couplings (top panel) and proton couplings (lower panel). The 1\( \sigma \) (2\( \sigma \)) uncertainty on the sensitivity of this run, namely the expected limit in absence of a signal above the background, is shown as a green (yellow) band in Fig. 2. The impact on these limits when using the Toivanen et al. and the Ressell and Dean calculations are shown in Fig. 3. XENON100 provides the most stringent limits for pure neutron couplings for WIMP masses above 6 GeV/\( c^2 \), excluding previously unexplored regions in the allowed parameter space. The minimum WIMP-neutron cross section is \( 3.5 \times 10^{-40} \text{ cm}^2 \) at a WIMP mass of 45 GeV/\( c^2 \), using Menendez et al. [9]. It changes to \( 2.5 \times 10^{-40} \text{ cm}^2 \) and \( 4.5 \times 10^{-40} \text{ cm}^2 \) when using Ressell and Dean and Toivanen et al., respectively. The sensitivity to proton couplings (Fig. 2, bottom panel) is much weaker because, as detailed above, both \(^{129}\text{Xe} \) and \(^{131}\text{Xe} \) have a unpaired neutron but an even number of protons, thus \( |\langle S_p \rangle| \ll |\langle S_n \rangle| \) (see Table I). Upper limits from other direct and indirect detection experiments are shown for comparison.

In conclusion, we have analyzed data from 224.6 live days \( \times 34 \) 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 \(^{129}\text{Xe} \) and \(^{131}\text{Xe} \) 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.

We gratefully acknowledge support from NSF, DOE, SNF, UZH, FCT, INFN, Région des Pays de la Loire, STCSM, NSFC, DFG, Stichting voor Fundamenteel Onderzoek der Materie (FOM), the Max Planck Society, the Weizmann Institute of Science, and the EMG research center. We thank Achim Schwenk and Javier Menendez for many helpful discussions and for providing their structure functions in numerical form. We thank Jounti Suhonen for providing us the numerical data for Fig. 3 and Michael Pitt (WIS) for his contribution. We are grateful to LNGS for hosting and supporting XENON100.

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