

## Limits on Spin-Dependent WIMP-Nucleon Cross Sections from the XENON10 Experiment

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XENON10 is an experiment to directly detect weakly interacting massive particles (WIMPs), which may comprise the bulk of the nonbaryonic dark matter in our Universe. We report new results for spin-dependent WIMP-nucleon interactions with <sup>129</sup>Xe and <sup>131</sup>Xe from 58.6 live days of operation at the Laboratori Nazionali del Gran Sasso. Based on the nonobservation of a WIMP signal in 5.4 kg of fiducial liquid xenon mass, we exclude previously unexplored regions in the theoretically allowed parameter space for neutralinos. We also exclude a heavy Majorana neutrino with a mass in the range of  $\sim 10 \text{ GeV}/c^2$ – $2 \text{ TeV}/c^2$  as a dark matter candidate under standard assumptions for its density and distribution in the galactic halo.

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Evidence for a significant cold dark matter component in our Universe is stronger than ever [1–3], a well-motivated particle candidate being the lightest neutralino from supersymmetric extensions to the standard model [4]. Such a particle is neutral, nonrelativistic, stable, and more generally classified as a weakly interacting massive particle (WIMP). The open question of the nature of WIMPs is being addressed by numerous direct and indirect detection experiments [5–7].

Among these, the XENON10 experiment aims to directly detect galactic WIMPs scattering elastically from Xe atoms. Moving with velocities around  $10^{-3}c$ , WIMPs can couple to nucleons via both spin-independent and spin-dependent (axial-vector) interactions. Spin-independent WIMP-nucleon couplings are in general smaller than axial-vector couplings [4]. However, for low momentum transfer, they benefit from coherence across the nucleus, and therefore the overall event rate for WIMP interactions is expected to be dominated by the spin-independent coupling for target nuclei with  $A \geq 30$ . The sensitivity of XENON10 to spin-independent interactions is published in [8].

We report here on a spin-dependent analysis of 58.6 live days of WIMP-search data, taken in low-background conditions at the Laboratori Nazionali del Gran Sasso (LNGS), which provides  $\sim 3100 \text{ m}$  water equivalent rock overburden. XENON10 is a dual phase (liquid and gas) xenon time projection chamber, discriminating between the predominantly electron-recoil background and the expected nuclear-recoil WIMP signal via the distinct ratio of ionization to scintillation for each type of interaction [8]. A nuclear-recoil energy threshold of 4.5 keV was achieved, and 10 candidate events were recorded for an exposure of about 136 kg days after analysis cuts (the fiducial mass was 5.4 kg). Although all observed events are consistent with expected background from electron recoils (see [8] for details on the analysis and the candidate events), no background subtraction is employed for calculating the WIMP upper limits. In the following analysis, we use identical data quality, fiducial volume, and physics cuts as reported in [8].

For axial WIMP-nuclei interactions, the WIMPs couple to the spins of the nucleons. Although the interaction with the nucleus is coherent (as it is in the spin-independent

case) in the sense that scattering amplitudes are summed over nucleons, the strength of the interaction vanishes for paired nucleons in the same energy state. Thus only nuclei with an odd number of nucleons will yield a significant sensitivity to axial WIMP-nuclei interactions [9]. Almost half of naturally occurring xenon has nonzero nuclear spin:  $^{129}\text{Xe}$  (spin-1/2) makes up 26.4%, and  $^{131}\text{Xe}$  (spin-3/2) another 21.2%. The differential WIMP-nucleus cross section for the spin-dependent interaction can be written as [4]

$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{C_{\text{spin}}}{v^2} G_F^2 \frac{S(|\mathbf{q}|)}{S(0)}, \quad (1)$$

where  $G_F$  is the Fermi constant,  $v$  is the WIMP velocity relative to the target,  $S(|\mathbf{q}|)$  is the spin structure function for momentum transfer  $q > 0$ , and  $S(0)$  represents the zero-momentum transfer limit. The so-called enhancement factor,  $C_{\text{spin}}$ , is given by

$$C_{\text{spin}} = \frac{8}{\pi} [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2 \frac{J+1}{J}, \quad (2)$$

where  $J$  is the total nuclear spin,  $a_p$  and  $a_n$  are the effective WIMP-nucleon couplings (these depend on the quark spin distribution within the nucleons and on the WIMP type), and  $\langle S_{p,n} \rangle = \langle N | S_{p,n} | N \rangle$  are the expectation values of the spin content of the proton and neutron groups within the nucleus.

Detailed nuclear shell-model calculations for  $\langle S_{p,n} \rangle$  for two different Hamiltonians describing the nuclei exist in the literature [10]. The Hamiltonians are based on realistic nucleon-nucleon potentials, Bonn A [11] and Nijmegen II

[12]. The accuracy of these calculations is typically assessed by comparing their predictions of the magnetic moment  $\mu$  with experimental values, due to the similarity between the magnetic moment operator and the matrix element for WIMP-nucleon coupling.

For  $^{129}\text{Xe}$  the magnetic moment agrees to within 25% and 11% for the Bonn A and Nijmegen II potentials, respectively, using the standard free-particle  $g$  factor (and to within 19% and 52% for using effective  $g$  factors). We calculate our main WIMP-nucleon exclusion limits using the Bonn A potential (Fig. 1, solid curves), with  $\langle S_p \rangle = 0.028$  and  $\langle S_n \rangle = 0.359$ . In order to indicate the level of systematic uncertainty associated with the different models we also calculate limits using the alternate Nijmegen II potential (Fig. 1, dashed curves), with  $\langle S_p \rangle = 0.0128$  and  $\langle S_n \rangle = 0.300$ . For  $^{131}\text{Xe}$ , the same Bonn A and Nijmegen II models predict the magnetic moment to within 8% and 50% of the measured value, respectively. However, for this isotope there are calculations by Engel using the quasiparticle Tamm-Dancoff approximation (QTDA) [13], which yield a magnetic moment within 1% of the experimental value. We follow [10,14] and use the calculation by Engel, choosing  $\langle S_p \rangle = -0.041$  and  $\langle S_n \rangle = -0.236$ , the effect of the 3 different models for  $^{131}\text{Xe}$  on the variation in the exclusion limits being quite small. We also note that recent calculations by Kortelainen *et al.* [15] yield values for the magnetic moments within about 20% and 10% for  $^{129}\text{Xe}$  and  $^{131}\text{Xe}$ , respectively, without using effective  $g$  factors. For the sake of brevity and comparison with other experimental results (which follow [10]), we use the  $\langle S_{p,n} \rangle$  values detailed above.

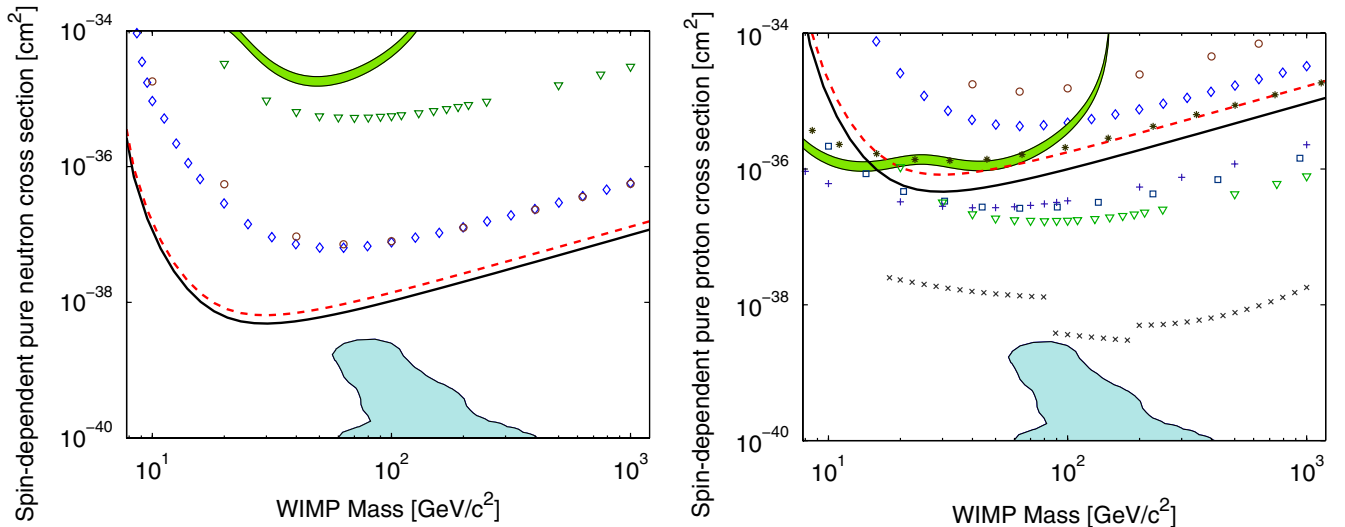


FIG. 1 (color online). XENON10 combined 90% C.L. exclusion limits for  $^{129}\text{Xe}$  and  $^{131}\text{Xe}$  for pure-neutron (left) and pure-proton (right) couplings (solid curves). The dashed curves show the combined Xe limits using the alternate form factor. Also shown are the results from the CDMS experiment [20] (diamonds), ZEPLIN-II [21] (circles), KIMS [22] (triangles), NAIAD [23] (squares), PICASSO [24] (stars), COUPP [25] (pluses), SuperK [26] (crosses), as well as the DAMA evidence region under the assumption of standard WIMP nuclear recoils and dark halo parameters (narrow green filled region) [18]. The theoretical regions (blue filled regions below the limit curves) for the neutralino (in the constrained minimal supersymmetric model) are taken from [27].

In the limit of zero-momentum transfer the WIMP essentially interacts with the entire nucleus. Once the momentum transfer  $q$  reaches a magnitude such that  $\hbar/q$  is no longer large compared to the nucleus, the spatial distribution of the nuclear spin must be considered. This is described by the spin structure function

$$S(q) = a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q), \quad (3)$$

here written by using the isospin convention in terms of the isoscalar ( $a_0 = a_p + a_n$ ) and isovector ( $a_1 = a_p - a_n$ ) coupling constants. The independent form factors, namely, the pure isoscalar term  $S_{00}$ , the pure isovector term  $S_{11}$ , and the interference term  $S_{01}$ , can be obtained from detailed nuclear shell-model calculations. Ressel and Dean [10] parametrize the structure function in terms of  $y = (qb/2\hbar)^2$ , where  $b$  parametrizes the nuclear size with  $b = \sqrt[3]{A}$  fm  $\simeq 2.3$  fm for heavy nuclei. For a WIMP mass of  $100 \text{ GeV}/c^2$  with velocity  $10^{-3}c$ , typical Xe nuclear-recoil energies are below  $\sim 25$  keV. We have restricted our search to below 26.9 keV, resulting in a maximum momentum transfer of  $q \simeq 81 \text{ MeV}/c$ , i.e.,  $\hbar/q \geq 2.4$  fm and  $y < 0.25$ . For our analysis, we use the structure function calculated with the Bonn A and Nijmegen II potentials [10] and with the QTDA method [13] for  $^{129}\text{Xe}$  and  $^{131}\text{Xe}$ , respectively.

In order to set limits on spin-dependent WIMP-nucleon couplings, we follow the procedure described in [16–18],

avoiding model-dependent assumptions on the (Majorana) WIMP composition. We first present exclusion limits for the cases of pure-proton ( $a_n = 0$ ) and pure-neutron ( $a_p = 0$ ) couplings, by assuming that the total cross section is dominated by the proton and neutron contributions only. We calculate the 90% C.L. exclusion limits as a function of WIMP mass with Yellin’s maximal gap method [19]. The exclusion limits presented here assume a flat 19%  $\mathcal{L}_{\text{eff}}$  for the xenon scintillation efficiency of nuclear recoils relative to electron recoils. The motivation for this choice is explained in Ref. [8], in which we also show that the uncertainty in  $\mathcal{L}_{\text{eff}}$  could raise the limits by about 15% (18%) for a WIMP mass of  $30 \text{ GeV}/c^2$  ( $100 \text{ GeV}/c^2$ ).

In Fig. 1 we show the combined upper limit curves in the WIMP-nucleon cross section versus WIMP mass plane, for the simple case of pure-neutron (left) and pure-proton (right) couplings for the  $^{129}\text{Xe}$  and  $^{131}\text{Xe}$  isotopes. We also include limits from CDMS [20], ZEPLIN-II [21], KIMS [22], the NAIAD experiment by UKDMC [23], PICASSO [24], COUPP [25], as well as the indirect detection limits from Super-Kamiokande [26] for the case of pure-proton couplings. Given that  $^{129}\text{Xe}$  and  $^{131}\text{Xe}$  both contain an unpaired neutron, XENON10 is mostly sensitive to WIMP-neutron spin-dependent couplings and excludes previously unexplored regions of parameter space. The minimum WIMP-nucleon cross section of  $\sim 6 \times 10^{-39} \text{ cm}^2$  is achieved at a WIMP mass of around  $30 \text{ GeV}/c^2$ . The sensitivity to pure-proton couplings is less strong; however, XENON10 improves upon the pa-

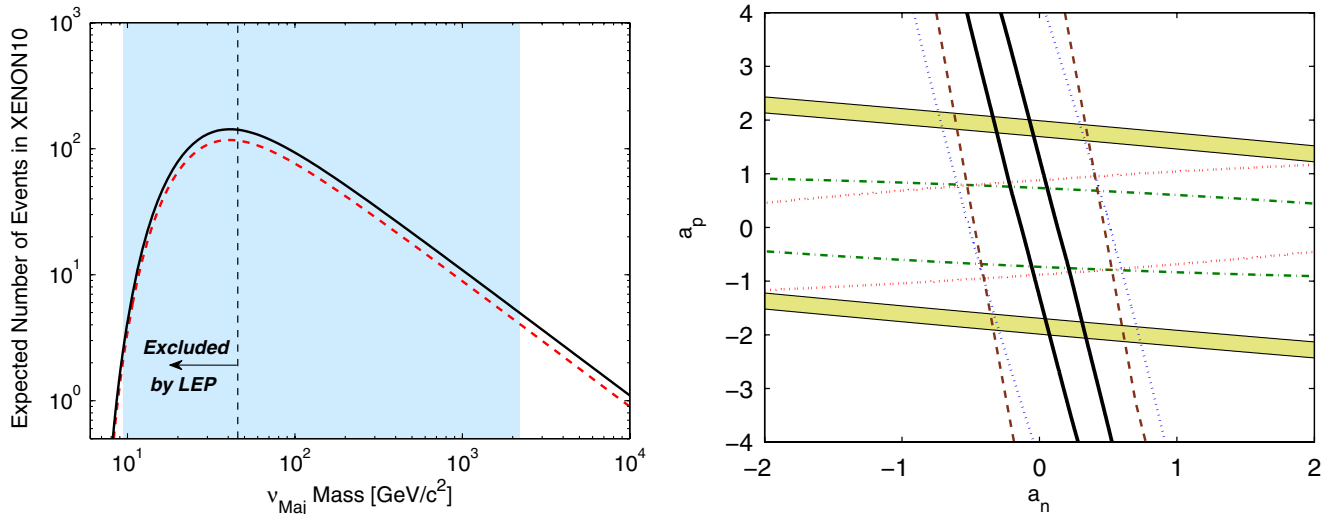


FIG. 2 (color online). Left: Predicted number of events in XENON10 for a heavy Majorana neutrino with standard weak interaction as a function of the neutrino mass, using the main (solid curve) and alternate (dashed curve) form factors. The light shaded area shows the excluded mass region at 90% C.L., calculated with Yellin’s maximal gap method [19] for the main form factors. Right: Regions allowed at the 90% C.L. in  $a_n - a_p$  parameter space for a WIMP mass of  $50 \text{ GeV}/c^2$ . The combined limit from  $^{129}\text{Xe}$  and  $^{131}\text{Xe}$  is shown as a dark solid curve (using the main form factor, see text), The exteriors of the corresponding ellipses are excluded, the common space inside the ellipses being allowed by the data. We also show the results obtained by KIMS [22] (dot-dashed line), COUPP [25] (dotted line) (“horizontal” ellipses), and CDMS [20] (dotted line), ZEPLIN-II [21] (dashed line), and the DAMA evidence region [18] (light filled region) (“vertical” ellipses).

parameter space constrained by the ZEPLIN-II [21] and the CDMS [20] experiments and approaches the sensitivity of other direct detection experiments such as NAIAD [23], PICASSO [24], KIMS [22], and COUPP [25], all containing nuclei with unpaired protons. We also show the DAMA evidence region for standard WIMP interactions and halo parameters [18], as well as predictions of neutralino-nucleon cross sections in the constrained minimal supersymmetric model [27]. Although the expected cross sections are still below the current experimental spin-dependent sensitivity, direct WIMP detection experiments are now for the first time approaching the theoretically predicted parameter space for neutralinos.

As a further benchmark, we consider heavy Majorana neutrinos with standard weak interactions. Such neutrinos, with masses in the region 100–500 GeV/ $c^2$ , have recently been proposed as dark matter candidates in minimal technicolor theories in cosmologies with a dynamical dark energy term [28,29]. The expected cross section on protons and neutrons can be written as [30]

$$\sigma_{\nu N} = \frac{8G_F^2}{\pi\hbar^4} \mu^2 C_{\text{spin},\nu} \quad (4)$$

where  $\mu$  is the neutrino-nucleon reduced mass, and the spin enhancement factor in this case is

$$C_{\text{spin},\nu} = [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2 \frac{J+1}{J}, \quad (5)$$

with the values for the WIMP-nucleon spin factors  $a_p = 0.46$  and  $a_n = 0.34$  taking into account the strange quark contribution to the nucleon spin, as measured by the EMC Collaboration and given in [31] for coupling to protons and neutrons, respectively.

In Fig. 2 (left) we show the predicted number of events in XENON10 as a function of the heavy Majorana neutrino mass, the light shaded area showing the excluded mass region at 90% C.L. for using the main form factors. Our result excludes a heavy Majorana neutrino as a dark matter candidate with a mass between 9.4 GeV/ $c^2$ –2.2 TeV/ $c^2$  (9.6 GeV/ $c^2$ –1.8 TeV/ $c^2$  for the alternate form factor). We note that a heavy Majorana neutrino with a mass below half the Z-boson mass has already been excluded at LEP [32].

We now present the results in terms of the more general phase space for  $a_n$  and  $a_p$  for a fixed WIMP mass. We follow [18] and express the expected number of recoil events  $N_{\text{xenon}}$  as a function of  $a_n$  and  $a_p$ :

$$N_{\text{xenon}} = Aa_p^2 + Ba_p a_n + Ca_n^2, \quad (6)$$

with  $A$ ,  $B$ ,  $C$  being constants of integration of the differential event rate  $dR/dE$  over the relevant energy region, in our case 4.5–27 keV nuclear-recoil energy.

Figure 2 (right) shows the allowed regions at 90% C.L. in the  $a_p - a_n$  parameter space for a WIMP mass of 50 GeV/ $c^2$ . We include the published CDMS [20],

ZEPLIN-II [21], KIMS [22], and the DAMA allowed region [18] for comparison. The advantage of using different isotopes with spin as dark matter targets is evident: the presence of both odd-neutron and odd-proton number isotopes breaks the degeneracy and only the common space inside the ellipses is allowed by the data.

In conclusion, we have obtained new limits on the spin-dependent WIMP-nucleon cross section by operating a liquid-gas xenon time projection chamber at LNGS, in WIMP-search mode for 58.6 live days with a fiducial mass of 5.4 kg. The results for pure-neutron couplings are the world's most stringent to date, reaching a minimum cross section of  $5 \times 10^{-39}$  cm<sup>2</sup> at a WIMP mass of 30 GeV/ $c^2$ . We exclude new regions in the  $a_p - a_n$  parameter space, and, for the first time, we directly probe a heavy Majorana neutrino as a dark matter candidate. Our observations exclude a heavy Majorana neutrino with a mass between  $\sim 10$  GeV/ $c^2$ –2 TeV/ $c^2$  for using a local WIMP density of 0.3 GeV/cm<sup>3</sup> and a Maxwell-Boltzmann velocity distribution. We note that our sensitivity to axial-vector couplings could be strongly improved by using a larger mass of enriched <sup>129</sup>Xe as the dark matter target.

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