Limits on the Spin-Dependent WIMP-Nucleon Cross Sections from the First Science Run of the ZEPLIN-III Experiment

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We present new experimental constraints on the WIMP-nucleon spin-dependent elastic cross sections using data from the first science run of ZEPLIN-III, a two-phase xenon experiment searching for galactic dark matter weakly interacting massive particles based at the Boulby mine. Analysis of $\sim$450 kg $\cdot$ days fiducial exposure allow us to place a 90%-confidence upper limit on the pure WIMP-neutron cross section of $\sigma_n = 1.9 \times 10^{-2}$ pb at 55 GeV/c^2 WIMP mass. Recent calculations of the nuclear spin structure based on the Bonn charge-dependent nucleon-nucleon potential were used for the odd-neutron isotopes ^{129}Xe and ^{131}Xe. These indicate that the sensitivity of xenon targets to the spin-dependent WIMP-proton interaction could be much lower than implied by previous calculations, whereas the WIMP-neutron sensitivity is impaired only by a factor of $\sim$2.

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ZEPLIN-III completed its first run at the Boulby Underground Laboratory (UK) in search of weakly interacting massive particles (WIMPs), proposed to explain the nonbaryonic cold dark matter in the Universe. In several supersymmetry (SUSY) extensions to the standard model of particle physics, the lightest supersymmetric particle (LSP) is stable and its relic abundance could account for the matter content observed today [1]. In some scenarios this particle is the neutralino, $\tilde{\chi}$—a linear combination of the SUSY partners of the electroweak gauge bosons (gauginos) and Higgs bosons (Higgsinos). Neutralinos are expected to scatter elastically from ordinary matter, producing low-energy nuclear recoils, predominantly through scalar (or spin-independent, SI) interactions. This is especially so for heavier elements ($A \gtrsim 30$, with A the number of nucleons), for which the scattering involves the entire nucleus rather than individual nucleons. This coherence enhancement of the scalar term in the interaction cross section is proportional to A^2. Our SI result excludes a WIMP-nucleon cross section above 8.1×10^{-8} pb for 60 GeV/c^2 mass with 90% confidence [2].

Nonetheless, axial-vector (or spin-dependent, SD) interactions could dominate in some SUSY scenarios in regions where the SI term is suppressed [3,4]. In addition, interpretation of the DAMA annual modulation [5,6] in terms of nuclear recoils caused by a dominant SD interaction [7] has remained viable for WIMP masses below $\sim$15 GeV until recently. It is therefore important to continue pursuing the search in the SD channel. Xenon targets have good sensitivity to the WIMP-neutron interaction since approximately half of natural abundance consists of the odd-neutron isotopes ^{129}Xe and ^{131}Xe (the proton interaction is highly suppressed for these isotopes, and neither is likely in the even-even nuclei).

It is also possible that a SD inelastic interaction with these nuclei could be significant for relatively heavy WIMPs [8,9]. Deexcitation of low-lying nuclear states in ^{129}Xe and ^{131}Xe (emitting 39.6 keV and 80.2 keV γ rays, respectively) provides a detection mechanism with low effective energy threshold, since the γ rays can be efficiently detected. Although neutrons also scatter inelastically producing the same signatures, differences in spatial distribution between signal and background might be exploited in very large detectors—assuming that the dominant γ-ray backgrounds could be suitably mitigated. Most direct search experiments are still focused on detecting nuclear recoils down to $\sim$keV energies; this is so in the case described in this Letter.

WIMP search experiments propose to measure the total WIMP-nucleus elastic cross section, σ_A. Assuming dominance of either the SI or the SD term, one can write:

$$\sigma_A = 4G_F^2 \mu_A^2 C_A, \tag{1}$$

where G_F is the Fermi weak-coupling constant, μ_A is the reduced mass of the WIMP-nucleus system, and C_A is an enhancement factor which depends on the type of interaction and, possibly, the WIMP composition. For the SI case, $C_A \propto A^2$ (i.e., C_A is model independent for Majorana WIMPs). For a dominant SD case, C_A involves the total nuclear spin J instead:

$$C_A = \frac{8}{\pi}(a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2 \frac{J+1}{J}, \tag{2}$$

where $\langle S_{p,n} \rangle$ are the expectation values for the proton or neutron spins averaged over the nucleus and $a_{p,n}$ are the effective WIMP-nucleon coupling constants. The latter depend on the WIMP particle content (e.g., more Higgsino- or gauginolike) as well as the quark spin distributions inside the nucleons.

Two spin distribution calculations were adopted, both based on the nuclear shell model but using different nucleon-nucleon (NN) potentials (see, e.g., reviews [10,11]). Their ability to reproduce experimental measurements of the magnetic moment is the standard benchmark, as this observable is reasonably similar to the WIMP-nucleus scattering matrix element. For comparison with other Xe experiments we use spin structures with the Bonn A potential for both isotopes [12]. Agreement of the magnetic moment (using effective g factors) is quite reasonable: within 19% and 8% for ^{129}Xe and ^{131}Xe, respectively. In addition, new calculations based on the Bonn-CD G matrix have become available which improve on these figures significantly (to 1% and 2%) for both isotopes [9]. The spin expectation values $\langle S_{p,n} \rangle$ are given in Table I for both cases.

In order to compare (1) with an experimental result a nuclear form factor, $F^2(q)$, must be assumed at momentum transfer $q > 0$ to account for finite nuclear size. Although cross sections are conventionally given in the limit of zero momentum transfer (the "standard" cross section), $F^2(q)$ must be factored into (1) to describe the interaction with a particular nucleus. The definition of C_A in (2) justifies the use of a normalized form factor $F^2(q) = S(q)/S(0)$, where $S(q)$ folds the spin structure functions $S_{jj'}(q)$ with an arbitrary neutralino composition in the isospin convention. The related functions $F_{\rho\rho'}(u)$ derived with Bonn CD [9] were converted into the same $S_{jj'}(q)$ normalization used with Bonn A [12] by employing Eq. (18) in Ref. [13] and then parametrized with a 6th-order polynomial for low q. As noted in Ref. [9], the new calculation gives smaller spin structures than those found for simpler models: by a factor of $\sim$2 for Xe^{129} and $\sim$4 for Xe^{131} at low q. More significantly, the spin factors are also smaller, in particular $\langle S_p \rangle$.

Calculating the cross section per nucleon allows comparison of different target materials and with theoretical model predictions, which are usually computed for free protons and neutrons. This conversion is not straightforward for the SD case since the cross section has contributions from both proton and neutron terms, as indicated explicitly in (2). In addition, $F^2(q)$ is similarly contaminated by both couplings. A simple approach exists that allows a straightforward calculation in a model-independent way by assuming that WIMPs couple predominantly to protons *or* neutrons [14]. By setting, in turn, $a_n = 0$ and $a_p = 0$, no assumption is required as to the neutralino composition, either explicitly in the standard cross section or in the form factor. In this instance one may write, in the limit of zero momentum transfer:

$$\frac{\sigma_{p,n}}{\sigma_A} = \frac{3}{4} \frac{\mu_{p,n}^2}{\mu_A^2} \frac{1}{\langle S_{p,n} \rangle^2} \frac{J}{J+1}, \tag{3}$$

where $\mu_{p,n}$ is the WIMP-nucleon reduced mass. Once σ_A is obtained from experimental limits on the allowed nuclear recoil spectrum, (3) is used to calculate the corresponding SD cross section for each isotope, $\sigma_{p,n}^{129}$ and $\sigma_{p,n}^{131}$. These are combined to obtain the total cross sections: $(\sigma_{p,n})^{-1} = (\sigma_{p,n}^{129})^{-1} + (\sigma_{p,n}^{131})^{-1}$.

ZEPLIN-III is a two-phase xenon time projection chamber operating 1100 m underground at Boulby (2850 m.w.e.). It discriminates nuclear recoil signals from the more prevalent electron-recoil background by measuring both the scintillation light ($S1$) and the ionization charge ($S2$) produced in a 12 kg liquid xenon target. Three-dimensional reconstruction of the interaction vertex, a strong electric field (3.9 kV/cm in the liquid) and a geometry which avoids surfaces near a central fiducial region allow powerful discrimination down to low energies. Data analysis procedures are detailed with our SI result [2] and only briefly summarized here. The instrument itself is fully described in Refs. [15,16].

A WIMP acceptance region was defined in the range [10.7,30.2] keV recoil energy and $[\mu - 2\sigma, \mu]$ in the $\log_{10}(S2/S1)$ discrimination parameter, where μ and σ describe the means and standard deviations of log-normal distributions fitted to the nuclear recoil population pro-

TABLE I. Xe isotope parameters: nuclear spin J, isotopic fraction (nat. abundance), effective exposure and spin factors $\langle S_{n,p} \rangle$ with Bonn A [12] and Bonn CD [9] NN potentials.

					Bonn A		Bonn CD	
	J	%	(n.a.)	kg · days	$\langle S_n \rangle$	$\langle S_p \rangle$	$\langle S_n \rangle$	$\langle S_p \rangle$
^{129}Xe	1/2	29.5	(26.4)	37.7	0.359	0.028	0.273	−0.0019
^{131}Xe	3/2	23.7	(21.2)	33.7	−0.227	−0.009	−0.125	−0.00069

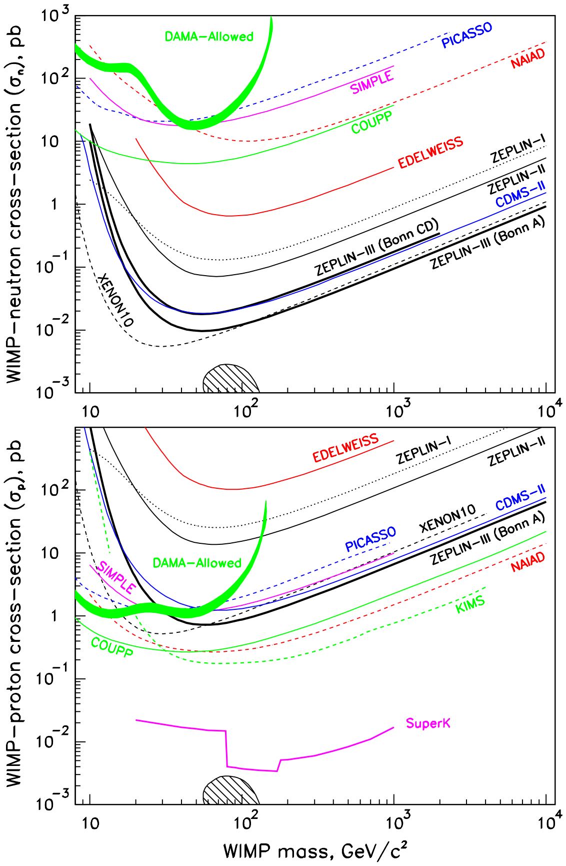

FIG. 1 (color online). Upper limits on pure WIMP-neutron and WIMP-proton SD cross sections. In addition to ZEPLIN-III with both NN potentials, we show other xenon experiments in black: ZEPLIN-I [23], ZEPLIN-II [24] and XENON10 (Bonn A) [18,19]. Additional curves are CDMS-II [25], COUPP [26], EDELWEISS [27], KIMS [28], NAIAD [29], PICASSO [30] and SIMPLE [31]. The pure-proton indirect limit from Super-Kamiokande is also shown [32]. The DAMA evidence region interpreted as a nuclear recoil signal in a standard halo [7] is indicated in green. The hatched area is the tip of the 95% probability region for neutralinos in the constrained minimal supersymmetric standard model (CMSSM) [22].

duced by elastic neutron scattering. An effective exposure of 127.8 kg · days was accumulated during the 83-day science run (27th Feb to 20th May 2008). This exposure is derived from a fiducial mass of 6.5 kg, defining a "geometrical" exposure of 454 kg · days, and a factor subsuming all energy-independent hardware and software inefficiencies (and the restricted acceptance). An energy-dependent detection efficiency, which reaches unity near 14 keV recoil energy, is applied separately. Conversion of visible to nuclear recoil energy utilizes the varying quenching factor discussed in Ref. [2]. The exposure of the odd-neutron isotopes reflects their relative abundance. Our xenon was depleted from high-mass isotopes, especially ^{136}Xe used in $0\nu\beta\beta$-decay experiments. This enhances slightly the composition in ^{129}Xe and ^{131}Xe relative to natural abundance (see Table I), as confirmed by residual gas analysis using mass spectroscopy.

Seven events were observed in the acceptance region, all near the upper boundary of the discrimination parameter where an electron-recoil background is expected. Since an accurate prediction of such background within the box is affected by systematic uncertainty, we adopted a simple and conservative approach which relies very little on such prediction. As described in Ref. [2], the search region is partitioned such that the up-most 20% of signal acceptance contains all 7 events, while the remaining 80% are empty. Observing that there are zero WIMP events in the lower region and up to seven in the upper region, we derived a two-sided 90%-confidence upper limit of 3.05 events in the whole box using simple Poisson probabilities. The experimental limit on the WIMP-nucleus cross section, σ_A, was calculated as described in Ref. [17]. We assumed an isothermal halo with truncated Maxwellian velocity distribution with characteristic velocity $v_0 = 220$ km/s, escape velocity $v_{esc} = 600$ km/s, Earth velocity $v_E = 230$ km/s and local dark matter density $\rho_0 = 0.3$ GeV/cm^3. The differential spectrum was corrected by the nuclear form factor and detector parameters such as energy resolution and detection efficiency.

The SD cross section limits, with no assumption on the coupling strength to neutrons and protons, are shown in Fig. 1 for the two spin structures. Values at 55 GeV/c^2 WIMP mass, the minimum of the curves, are given in Table II. Our Bonn A result surpasses that from XENON10 [18] above 100 GeV (taking into account new quenching factor measurements for xenon [19]). Together these experiments place the world's most stringent limit on σ_n, when this NN potential is assumed. However, Bonn CD affects these limits unfavorably: σ_n is just under twice higher, but σ_p increases by orders of magnitude, virtually eliminating the sensitivity to WIMP-proton scattering (this curve is not shown in the figure as it would fit poorly within the range plotted). Naturally, these corrections apply to all xenon detectors. We note that comparison with other experiments is not always straightforward: (i) different spin structures may be used for the same isotopes, as new calculations are still emerging; (ii) the model-independent approach of Ref. [14] is not used universally (e.g., a combined SI and SD limit is extracted in Heidelberg Dark Matter Search (HDMS), where a novel background

TABLE II. Spin-dependent cross section limits (pb) at $M_W = 55$ GeV for ^{129}Xe and ^{131}Xe, and the combined ZEPLIN-III result.

	σ_n^{129}	σ_p^{129}	σ_n^{131}	σ_p^{131}	σ_n	σ_p
Bonn A	1.2×10^{-2}	8.6×10^{-1}	6.1×10^{-2}	$6.1 \times 10^{+0}$	1.0×10^{-2}	7.6×10^{-1}
Bonn CD	2.2×10^{-2}	$5.1 \times 10^{+2}$	1.6×10^{-1}	$2.1 \times 10^{+3}$	1.9×10^{-2}	$4.1 \times 10^{+2}$

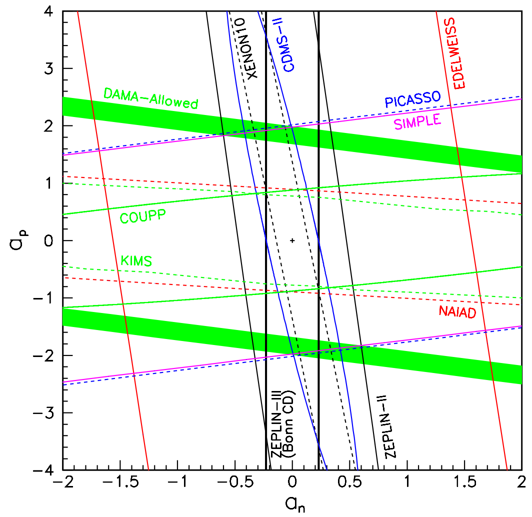

FIG. 2 (color online). Allowed regions in the $a_n - a_p$ parameter space for 50 GeV WIMP mass.

subtraction technique is also employed [20]) and (iii) statistical significance may vary, as with the XENON10 result, for which a C.L. $< 90\%$ is acknowledged for the upper limit (c.f. note [26] in [21]).

The allowed region of $a_n - a_p$ parameter space can be derived from the experimental cross section limits [14]:

$$\sum_i \left(\frac{a_p}{\sqrt{\sigma_p^i}} \pm \frac{a_n}{\sqrt{\sigma_n^i}} \right)^2 \leq \frac{\pi}{24 G_F^2 \mu_p^2} \tag{4}$$

where i labels the two Xe isotopes, and the sign in parenthesis is that of $\langle S_p \rangle / \langle S_p \rangle$. For xenon and other multi-isotope targets, (4) defines an ellipse—albeit an elongated one—which reduces to two parallel lines for single-isotope experiments. The region allowed by each experiment lies within the corresponding ellipse. Figure 2 shows our Bonn CD result (nearly vertical lines, reflecting the poor constraint on a_p) for a reference WIMP mass of 50 GeV$/c^2$ (the cross sections coincide with those in Table II within the precision shown). The Bonn A result (not shown) is very similar to that from XENON10.

In conclusion, new experimental limits on the SD WIMP-nucleon cross section are placed by the first science run of ZEPLIN-III operating at Boulby. A fiducial exposure of $\sim$450 kg · days revealed a most likely signal of zero events, which allow 90% C.L. exclusion of the pure WIMP-neutron cross section above $\sigma_n = 1.9 \times 10^{-2}$ pb for 55 GeV$/c^2$ WIMP mass. New spin structure calculations based on the Bonn CD *NN* potential were used for ^{129}Xe and ^{131}Xe. These increase the cross section limits relative to previous calculations—quite dramatically in the case of the proton. Xenon targets are still the very sensitive to the WIMP-neutron interaction. Our result adds weight to the exclusion of the DAMA evidence region for a 50 GeV$/c^2$ WIMP causing nuclear recoils. Theoretical predictions in the CMSSM [22] point to $\tilde{\chi}$-nucleon cross sections below $\sim 3 \times 10^{-3}$ pb near 100 GeV mass at 95% C.L.. ZEPLIN-III, XENON10, and CDMS-II provide the leading constraint on SD $\tilde{\chi}$-neutron scattering at that mass, nearly missing that probability boundary. Experimental efforts are still far from probing the favored parameter space for the $\tilde{\chi}$-proton interaction (the CMSSM best-fit regions suggest $\sim 1 \times 10^{-4}$ pb for both nucleons).

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