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Published in:
Physical Review D. Particles, Fields, Gravitation, and Cosmology

DOI:
10.1103/PhysRevD.96.122002

Link to publication

Citation for published version (APA):

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Download date: 12 Oct 2019
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(Received 8 September 2017; published 7 December 2017)

We present results of searches for vector and pseudoscalar bosonic super-weakly interacting massive particles (WIMPs), which are dark matter candidates with masses at the keV-scale, with the XENON100

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and cosmological observations constrain the mass of WDM streaming out from small-scale perturbations. Astrophysical retaining a larger velocity dispersion and more easily free-
early universe, WDM particles remain relativistic for longer,
time of their decoupling from the rest of the particles in the
(WDM). While CDM particles were nonrelativistic at the
cold dark matter (CDM), while sterile neutrinos with masses
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While the microscopic nature of dark matter is largely
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cold dark matter (CDM), while sterile neutrinos with masses
at the keV-scale are an example for warm dark matter
(WDM). While CDM particles were nonrelativistic at the
time of their decoupling from the rest of the particles in the
early universe, WDM particles remain relativistic for longer,
retaining a larger velocity dispersion and more easily free-
streaming out from small-scale perturbations. Astrophysical
and cosmological observations constrain the mass of WDM
to be larger than \( \sim 3 \text{ keV}/c^2 \) [7,8], with a more recent lower
limit from Lyman-\( \alpha \) forest data being 5.3 keV [9].

A large number of experiments aim to observe axions/
ALPs and WIMPs: directly, indirectly, or via production at the
LHC [10]. Direct detection experiments, which look for
low energy nuclear recoils produced in collisions of
WIMPs with atomic nuclei feature low energy thresholds,
large detector masses and ultralow backgrounds [11,12].
Such experiments can thus also observe other type of
particles, with nonvanishing couplings to electrons. Among
these, bosonic super-WIMPs [13] are an example for
WDM. These particles, with masses at the keV-scale, could
couple electromagnetically to standard model particles via
the axioelectric effect, which is an analogous process to the
photoelectric effect, and thus be detected in direct detection
experiments [13].

In this study we present a search for vector and pseudo-
scalar bosonic super-WIMPs with the XENON100 detector.
The super-WIMPs can be absorbed in liquid xenon (LXe)
and the expected signature is a monoenergetic peak at the
super-WIMP’s rest mass. We have presented first results
on pseudoscalar bosonic super-WIMPs, or axionlike par-
icles, in Ref. [14]. In this analysis we include two major
improvements: we extend the mass range up to 125 keV/c^2
and we improve the energy resolution by employing both
scintillation and ionization signals to determine the energy
scale and resolution of the XENON100 detector.

This paper is organized as follows. We describe the main
features of the XENON100 experiment in Sec. II, after
which we briefly review the expected signal and rates in a
dark matter detector in Sec. III. We detail the data analysis
methods in Sec. IV and present our main findings in Sec. V,
together with a discussion of their implications.

I. INTRODUCTION

There is overwhelming evidence for the presence of dark
matter in our universe. Its existence is inferred from a
variety of observations, including those of the temperature
fluctuations in the cosmic microwave background [1],
gravitational lensing [2], mass-to-light ratio in galaxy
clusters [3], and galactic rotation curves [4]. In addition,
simulations of large-scale structure and galaxy formation
require the presence of nonbaryonic matter to reproduce the
observed cosmic structures [5].

While the microscopic nature of dark matter is largely
unknown, the simplest assumption which can explain all
existing observations is that it is made of a new, as yet
undiscovered particle [6]. Leading examples are weakly
interacting massive particles (WIMPs), axions or axionlike-
particles (ALPs) and sterile neutrinos. WIMPs with masses
in the GeV range, as well as axions/ALPs are examples for
cold dark matter (CDM), while sterile neutrinos with masses
at the keV-scale are an example for warm dark matter
(WDM). While CDM particles were nonrelativistic at the
time of their decoupling from the rest of the particles in the
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II. THE XENON100 DETECTOR

Located at the Laboratori Nazionali del Gran Sasso
(LNGS), the XENON100 experiment operates a dual-phase
(liquid and gas) xenon time projection chamber (TPC). The
detector contains 161 kg of LXe in total, with 62 kg in the
active region of the TPC. A total of 178 1-inch square, low-
radioactivity, UV-sensitive photomultiplier tubes (PMTs)
arranged in two arrays, one in the liquid and one in the gas,
detect the prompt scintillation (S1) and the delayed,
proportional scintillation signal (S2) arising when a particle
interacts in the TPC. The ionisation electrons are drifted via
an electric field of 530 V/cm to the liquid-gas boundary
and extracted in the vapour phase via a ∼12 kV/cm field,
where proportional scintillation is produced. The three-
dimensional position of the original interaction site is
reconstructed via the time difference between the S1 and
S2 signal (z-position, with a 1σ resolution < 0.3 mm), and
by exploiting the S2 light pattern in the top PMT array
((x,y)-position, with a 1σ resolution < 3 mm). This
enables us to reject a large fraction of background events
via fiducial volume cuts and selection of single-scatters
[15]. A 4 cm thick, 99 kg LXe, layer surrounds the TPC and
is observed by 64 1-inch square PMTs, allowing us to
rejects events with energy depositions in this active LXe
region. Finally, nuclear recoils (NRs) induced by fast
neutrons and WIMP-nucleus scatters, and electronic recoils
(ERs), produced by β and γ-rays, as well as axions, can be
distinguished based on their (S2/S1)-ratio.

The XENON100 experiment is described in detail in
[15]. In this analysis, we use the Run II science data, with
224.6 live days of data taking and 34 kg of LXe in the fiducial region, to search for signatures from bosonic super-WIMPs in the mass range \((8-125)\) keV/c\(^2\) in the ER spectrum. A previous search in LXe was conducted by XMASS, constraining the mass range \((40-120)\) keV/c\(^2\) [16], and recent searches for axions/ALPs were conducted by LUX [17] and PandaX-II [18].

### III. EXPECTED SIGNAL

Viable models for super-WIMPs as dark matter candidates result in vector and pseudoscalar particles [13]. The expected interaction rates in a detector are obtained by convoluting the absorption cross section with the expected flux of these particles. The absorption cross section \(\sigma_{abs}\) for vector super-WIMPs can be written in terms of the cross section for photon absorption via the photoelectric effect \(\sigma_{pe}\), with the photon energy \(\omega\) replaced by the mass of the vector boson \(m_v\):

\[
\frac{\sigma_{abs}}{\sigma_{pe}(\omega = m_v)c} \approx \frac{\alpha'}{\alpha},
\]

where \(v\) is the incoming velocity of the vector boson, \(c\) is the velocity of light, \(\alpha\) and \(\alpha'\) are the fine structure constant, and its vector boson equivalent, respectively.

For pseudoscalar super-WIMPs, the relation between the two cross sections is as follows:

\[
\frac{\sigma_{abs}}{\sigma_{pe}(\omega = m_a)c} \approx \frac{3m_a^2}{4\pi\alpha f_a^2},
\]

where \(m_a\) is the mass of the pseudoscalar particle, and \(f_a\) is a dimensional coupling constant.

Assuming that super-WIMPs are nonrelativistic, and that their local density is 0.3 GeV/cm\(^3\) [19], the interaction rate in a direct detection experiment can be expressed as [13]:

\[
R = \frac{4 \times 10^{23}}{A} \frac{\alpha'}{\alpha} \left(\frac{\text{keV}}{m_v}\right) \left(\frac{\sigma_{pe}}{b}\right) \text{kg}^{-1} \text{d}^{-1},
\]

and

\[
R = \frac{1.29 \times 10^{19}}{A} g_{ae}^2 \left(\frac{m_e}{\text{keV}}\right) \left(\frac{\sigma_{pe}}{b}\right) \text{kg}^{-1} \text{d}^{-1},
\]

for vector and pseudoscalar super-WIMPs, respectively. \(g_{ae} = 2m_e f_a^{-1}\) is the axioelectric coupling, \(m_e\) is the mass of the electron, and \(A\) is the atomic number of the target atom.

With Eqs. (3) and (4), we can predict the interaction rate in XENON100, assuming a range of coupling constants, and an exposure of 34 kg \times 225 live days of data, as shown in Figs. 1 and 2 for vector and pseudoscalar super-WIMPs, respectively. The structures observed around 35 keV, as well as at lower energies are due to an increase in the cross section of the photoelectric effect in xenon at these energies, when new atomic energy levels are excited [20].

<FIG. 1. Predicted total number of events, assuming an infinite energy resolution, for vector super-WIMPs in XENON100 as a function of mass for a range of coupling constants. The assumed exposure is 34 kg \times 225 live days of data.>

<FIG. 2. Predicted total number of events, assuming an infinite energy resolution, for pseudoscalar super-WIMPs in XENON100 as a function of mass for a range of coupling constants. The assumed exposure is 34 kg \times 225 live days of data.>

### IV. DATA ANALYSIS

We perform this analysis using XENON100 Run II science data, with 224.6 live days of data and 34 kg of LXe in the fiducial region. Our data selection and treatment is similar to the one described in [14], with a few differences, to be detailed below. In particular, this is the first analysis of the XENON100 electronic recoil data that extends up to an energy of 140 keV. The overall background in the low-energy region is \(5.3 \times 10^{-3}\) events/(kg d keV) and it is flat in shape, because it is dominated by Compton scatters of high-energy gammas originating from the radio-activity of detector materials [21].
FIG. 3. Calculated acceptance \( \epsilon \) to electronic recoils (black dots) of all the event selection criteria as a function of energy, along with a fit (red curve) to the distribution. The energy threshold employed in this analysis (5 keV) is shown by the vertical dashed line.

A. Event selection and signal region

An interaction in the LXe-TPC gives rise to an S1 and a correlated S2 signal with a certain number of photoelectrons (PE) observed by the photosensors. To select valid events, we apply event selection criteria as described in [14]. These include basic data quality selection criteria, single-scatter and fiducial volume selection, and signal consistency checks. Furthermore, we use position-corrected S1 and S2 quantities as detailed in [15,22]. In contrast with [14], we determine the energy deposition of an interaction in LXe by using a linear combination of the prompt and delayed scintillation light signals, where we employ the S2 and \( Nb \) quantities as detailed in [15,22].

The combined acceptance of all applied event selection criteria, evaluated on calibration data acquired with \( ^{60}\text{Co} \) and \( ^{232}\text{Th} \) sources, is shown in Fig. 3. This acceptance, around 80%, is rather flat in energy above \( \sim 15 \) keV, below which it decreases to reach 53% at 5 keV.

The background events in the region of interest are predominantly due to interactions of \( \gamma \)-rays from decays of radioactive isotopes in the detector materials, yielding low-energy Compton-scatters, and from \( \beta \)-decays of the \( ^{222}\text{Rn} \) and \( ^{85}\text{Kr} \) isotopes distributed in the liquid xenon [21]. To model the expected shape of the background distribution in the region of interest, we employ calibration data acquired with \( ^{60}\text{Co} \) and \( ^{232}\text{Th} \) sources. The spectral shape is parameterised with a modified Fermi function, as shown in Fig. 4, together with the calibration data.

B. Statistical method

A profile likelihood analysis is employed to constrain the coupling constants \( g_{ae} \) and \( \alpha'/\alpha \), as described in [23,24]. The full likelihood function is given by

\[
\mathcal{L}(g_{ae}, \alpha'/\alpha, Nb) = \text{Poiss}(N|N_s + Nb) \prod_{i=1}^{N} N_s f_s(E_i) + Nb f_b(E_i), 
\]

where the parameters of interest are \( g_{ae} \) or \( \alpha'/\alpha \) and \( Nb \) and \( N_s \) are the expected number of background and signal events in the search region, respectively. \( N_s \) is considered as nuisance parameter, \( N_b \) is a function of the coupling constant, and the functions \( f_s \) and \( f_b \) are the background and signal probability distribution functions. \( N \) is the total number of observed events and \( E_i \) corresponds to the energy of the \( i \)th event. We model the expected event rate at a given energy with a Gaussian smeared with the energy resolution of the detector and multiplied by the total acceptance of the data selection criteria, shown in Fig. 3.

Our selected region of interest extends from 5 keV to 140 keV. The lower bound is chosen such as to have > 50% acceptance of the data selection criteria, as mentioned above. The upper bound is given by the width of the 164 keV line from \( ^{131}\text{Xe} \) decays, present in both calibration and physics data due to the activation of xenon during an AmBe neutron calibration. The relative resolution at this energy is 4.6%, and we consider the region up to 3-\( \sigma \) to the left of the peak.

For each considered mass \( m_a \) of the bosonic super-WIMP, the \( \pm 2-\sigma \)-region, as determined by the energy resolution at the given energy, is blinded. The number of events outside of this region is then used to scale the background model \( f_b \), shown in Fig. 4, and thus to predict the number of expected background events in the signal region. Since the \( \pm 2-\sigma \) window must not exceed the search region between (5–140) keV, the range of bosonic super-WIMP masses is restricted to (8–125) keV. We use the CL\(_s\) prescription [25] to protect against overly constrained parameters due to downward fluctuations in the background.

FIG. 4. Background model \( Nb \times f_b \) (red line) scaled to the correct exposure. The model is based on \( ^{60}\text{Co} \) and \( ^{232}\text{Th} \) calibration data (black dots) and used in Eq. (5). The energy threshold of 5 keV is shown by the vertical dashed line.
FIG. 5. Distribution of events (black dots with error bars) in the super-WIMP search region between (5–140) keV. The background model (red curve) along with the expected signal for various pseudoscalar super-WIMP masses (20, 40, 60, 80 and 100 keV) and a coupling of $g_{ae} = 1 \times 10^{-12}$ (blue dashed peaks) is also shown. The vertical dashed line indicated the energy threshold in this analysis.

FIG. 6. The XENON100 upper limits, at 90% C.L., on the coupling of pseudoscalar (top) and vector (bottom) super-WIMPs as a function of particle mass. The 1-$\sigma$ (2-$\sigma$) expected sensitivity is shown by the dark (light) blue bands. We compare our limits to the results obtained by the XMASS-I [16] (green), LUX [17] (magenta), PandaX-II [18] (orange) and Majorana Demonstrator [26] (red) experiments, as well as with astrophysical constraints from the gamma background, the dark matter abundance, red giant stars and horizontal branch stars (dashed and dash-dotted) [13] for the case of the vector super-WIMP.

V. RESULTS

Figure 5 shows the distribution of events in the region of interest, together with the expected signal for different pseudoscalar super-WIMP masses and an assumed coupling of $g_{ae} = 1 \times 10^{-12}$. We also assume that these particles constitute all the dark matter in our galaxy, with a local density of 0.3 GeV/cm$^3$. The widths of the monoenergetic signals are given by the energy resolution of the detector, in combined energy scale, at the given $S_1$ and $S_2$ signal size.

Our data are compatible with the background only hypothesis, and no excess above the predicted background is observed.

Figure 6 shows the 90% C.L. exclusion limit for pseudoscalar (top panel) and vector (bottom panel) super-WIMPs. Our 1-$\sigma$ (2-$\sigma$) expected sensitivity is shown by the dark (light) blue bands. The step in sensitivity around 35 keV/c$^2$ is due to an increase in the photoelectric cross section as new atomic energy levels are excited. We compare these results with those obtained by the XMASS-I [16], LUX [17] and the Majorana Demonstrator [26] experiments. While the XMASS-I constraints are more stringent in the mass range above 50 keV/c$^2$, our results improve upon these at lower masses, and in particular extend the excluded mass region down to 8 keV/c$^2$. Our results are comparable to those of the Majorana Demonstrator in the mass range $\sim$ (12–32) keV/c$^2$, but more stringent at higher masses. Finally, LUX presents the most constraining limit at masses of the pseudoscalar particle below 16 keV/c$^2$.

The observed fluctuations in our limit are caused by statistical fluctuations in the background (see Fig. 5). Due to the expected monoenergetic shape of the signal, the limit is very sensitive to such fluctuations. We have also studied the impact of systematic uncertainties on the analysis. In particular, we have considered the impact of varying the overall event selection acceptance, the energy resolution, as well as the energy scale. The combined effect of all systematic uncertainties changes the final result by around 10%, however this contribution is small compared to our statistical uncertainty that is accounted for in the profile likelihood analysis.

XENON100 thus sets new and stringent upper limits in the (8–125) keV/c$^2$ mass range. At 90% C.L. it excludes couplings to electrons $g_{ae} > 3 \times 10^{-13}$ for pseudoscalar super-WIMPs and $d/\alpha > 2 \times 10^{-28}$ for vector super-WIMPs. These limits are derived under the assumption that super-WIMPs constitute all of the galactic dark matter.
ACKNOWLEDGMENTS

We gratefully acknowledge support from the National Science Foundation, Swiss National Science Foundation, Deutsche Forschungsgemeinschaft, Max Planck Gesellschaft, German Ministry for Education and Research, Netherlands Organisation for Scientific Research, Weizmann Institute of Science, I-CORE, from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No. 674896, Fundacao para a Ciencia e a Tecnologia, Region des Pays de la Loire, Knut and Alice Wallenberg Foundation, Kavli Foundation, and Istituto Nazionale di Fisica Nucleare. J. C. is a Wallenberg Academy Fellow. We are grateful to Laboratori Nazionali del Gran Sasso for hosting and supporting the XENON project.