Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T

XENON Collaboration; Aprile, E.; Aalbers, J.; Breur, P.A.; Brown, A.; Colijn, A.P.; Decowski, M.P.; Gaemers, P.

DOI
10.1103/PhysRevLett.123.241803

Publication date
2019

Document Version
Final published version

Published in
Physical Review Letters

License
CC BY

Citation for published version (APA):
XENON Collaboration, Aprile, E., Aalbers, J., Breur, P. A., Brown, A., Colijn, A. P., Decowski, M. P., & Gaemers, P. (2019). Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T. Physical Review Letters, 123(24), Article 241803. https://doi.org/10.1103/PhysRevLett.123.241803

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T

E. Aprile,1 J. Aalbers,2 F. Agostini,3 M. Alfonsi,4 L. Althueser,5 F.D. Amaro,6 V.C. Antochi,2 E. Angelino,7 F. Arneodo,8 D. Barge,2 L. Baudis,9 B. Bauermeister,2 L. Bellagamba,3 M.L. Benabderrahmane,8 T. Berger,10 P.A. Breur,11 A. Brown,9 E. Brown,10 S. Bruenner,12 G. Bruno,9 R. Budnik,13 C. Capelli,5 J. M.R. Cardoso,6 D. Cichon,12 D. Codreanu,14 A.P. Colijn,11,J. Conrad,2 J.P. Cussonneau,15 M.P. Decowski,11 P. de Perio,1 A. Depoian,16 P. Di Gangi,3 A. Di Giovanni,8 S. Diglio,15 J. A. M. Lopes,6,17 E. López Fune,22 C. Macolino,23 J. Mahlstedt,2 M. Manenti,8 A. Manfredini,9,13 F. Marignetti,20 T. Marrodán Undagoitia,12 J. Masbou,15 S. Mastroianni,20 M. Messina,18,8 K. Micheneau,15 K. Miller,19 A. Molinario,18,19 K. Morá,2 Y. Mosbacher,13 M. Murra,5 J. Naganoma,18,24 K. Ni,17 U. Oberlack,3 K. Odgers,10 J. Palacio,15 B. Pelssers,2 R. Peres,9 J. Pienaar,19 V. Pizzella,12 G. Plante,1 R. Podviiani,18 J. Qin,16 H. Qi,13 D. Ramirez García,14 S. Reichard,9 B. Riedel,19 A. Rocchetti,14 N. Rupp,12 J. M. F. dos Santos,6 G. Sartorelli,3 N. Šarčević,14 M. Scheibehlat,4 S. Schindler,4 J. Schreiner,12 D. Schulte,5 M. Schumann,14 L. Scotto Lavina,22 M. Selvi,3 P. Shagin,24 E. Shockley,19 M. Silva,6 H. Simgen,12 C. Therreau,15 D. Thers,15 F. Toschi,14 G. Trinchero,7 C. Tunnell,24 N. Uple,19 M. Vargas,5 G. Volta,9 O. Wack,12 H. Wang,25 Y. Wei,17 C. Weinheimer,5 D. Wenz,4 C. Wittweg,5 J. Wulf,9 J. Ye,17 Y. Zhang,1 T. Zhu,1 and J. P. Zopounidis22

(XENON Collaboration)

1Physics Department, Columbia University, New York, New York 10027, USA
2Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova, Stockholm SE-10691, Sweden
3Department of Physics and Astronomy, University of Bologna and INFN-Bologna, 40126 Bologna, Italy
4Institut für Physik und Exzellenzcluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany
5Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany
6LIBPhys, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal
7INAF-Astrophysical Observatory of Torino, Department of Physics, University of Torino and INFN-Torino, 10125 Torino, Italy
8New York University Abu Dhabi, P.O. Box 129188, Abu Dhabi, United Arab Emirates
9Physik-Institut, University of Zurich, 8057 Zurich, Switzerland
10Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York 12180, USA
11Nikhef and the University of Amsterdam, Science Park, 1098XG Amsterdam, Netherlands
12Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
13Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel
14Physikalisches Institut, Universität Freiburg, 79104 Freiburg, Germany
15SUBATECH, IMT Atlantique, CNRS-IN2P3, Université de Nantes, Nantes 44307, France
16Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA
17Department of Physics, University of California, San Diego, California 92093, USA
18INFN-Laboratori Nazionali del Gran Sasso and Gran Sasso Science Institute, 67100 L’Aquila, Italy
19Department of Physics and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois 60637, USA
20Department of Physics “Ettore Pancini,” University of Napoli and INFN-Napoli, 80126 Napoli, Italy
21Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
22LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris 75252, France
Direct dark matter detection experiments based on a liquid xenon target are leading the search for dark matter particles with masses above \(\sim 5 \text{ GeV}/c^2\), but have limited sensitivity to lighter masses because of the small momentum transfer in dark matter-nucleus elastic scattering. However, there is an irreducible contribution from inelastic processes accompanying the elastic scattering, which leads to the excitation and ionization of the recoiling atom (the Migdal effect) or the emission of a bremsstrahlung photon. In this Letter, we report on a probe of low-mass dark matter with masses down to about 85 MeV/c\(^2\) by looking for electronic recoils induced by the Migdal effect and bremsstrahlung using data from the XENON1T experiment. Besides the approach of detecting both scintillation and ionization signals, we exploit an approach that uses ionization signals only, which allows for a lower detection threshold. This analysis significantly enhances the sensitivity of XENON1T to light dark matter previously beyond its reach.

The XENON1T direct dark matter detection experiment [13] uses a dual-phase TPC containing 2 tonnes of ultrapure liquid xenon (LXe) as the active target material. It is located at the INFN Laboratori Nazionali del Gran Sasso (LNGS) in Italy, which has an average rock overburden of 3600 m water equivalent. The prompt primary scintillation (S1) and secondary electroluminescence of ionized electrons (S2) signals are detected by top and bottom arrays of 248 Hamamatsu R11410-21 3\(^{\prime}\) photomultiplier tubes (PMTs) [14,15]. They are used to reconstruct the deposited energy and the event interaction position in three dimensions, which allows for fiducialization of the active volume [16,17]. The XENON1T experiment has published WIMP search results by looking for NRs from WIMP-nucleus elastic scattering using data from a one-tonne-year exposure, achieving the lowest ER background in a DM search experiment [8]. The excellent sensitivity of LXe experiments to heavy WIMPs comes from the heavy xenon nucleus which gives a coherent enhancement of the interaction cross section and from the large NR energy. The sensitivity to sub-GeV/c\(^2\) LDM, on the other hand, decreases rapidly with lowering DM mass since detectable scintillation and ionization signals produced by these NRs become too small. The energy threshold (defined here as the energy at which the efficiency is 10\%) in a LXe TPC is \(\sim 25\) MeV/c\(^2\), but its nature remains unknown. The most promising DM candidate is the so-called weakly interacting massive particle (WIMP) [4], which explains the current abundance of dark matter as a thermal relic of the big bang [5]. In the past three decades, numerous terrestrial experiments have been built to detect the faint interactions between WIMPs and ordinary matter. Among them, experiments using dual-phase (liquid-gas) xenon time projection chambers (TPCs) [6–8] are leading the search for WIMPs with masses from a few GeV/c\(^2\) to TeV/c\(^2\). The mass of the WIMP is expected to be larger than about 2 GeV/c\(^2\) from the Lee-Weinberg limit [5] assuming a weak scale interaction. On the other hand, DM in the sub-GeV/c\(^2\) mass range has more recently been proposed in several models [9]. In this Letter, we report on a probe of light DM-nucleon elastic interactions by looking for electronic recoils (ERs) in XENON1T, induced by secondary radiation, bremsstrahlung (BREM) [10] and the Migdal effect [11,12], that can accompany a nuclear recoil (NR). ER signals induced by the Migdal effect and BREM can go well below 1 keV, where the detection efficiency for the scintillation signal is low. Therefore, in addition to the analysis utilizing both ionization and scintillation signals, we performed an analysis using the ionization signal only, which improves the detection efficiency for sub-keV ER events. We present results from a probe of light DM (LDM) with masses as low as 85 MeV/c\(^2\).
effect (MIGD) and BREM enables a significant boost of XENON1T’s sensitivity to LDMs, thanks to the lowered threshold.

When a particle elastically scatters off a xenon nucleus, the nucleus undergoes a sudden momentum change with respect to the orbital atomic electrons, resulting in the polarization of the recoiling atom and a kinematic boost of the electrons. The depolarization process can lead to a sudden momentum change with respect to the orbital atomic electrons, resulting in the polarization of the recoiling atom and a kinematic boost of the electrons. The depolarization process can lead to the depolarization of the recoiling atom and a kinematic boost of the electrons, the reduced mass of the xenon nucleus and DM, and the atomic electron shell that can result in ionization and/or excitation of the electron, since the typical timescale of the deexcitation process is \(10^{-13}\) fs. Atomic electrons can also undergo excitation instead of ionization, in which case an x ray or an Auger electron is emitted. Although only a very small fraction (about 3 × 10^\(-8\) and 8 × 10^\(-6\) for DM masses of 0.1 and 1.0 GeV/c^2, respectively) of NRs accompanies MIGD, the larger energy and ER nature make them easier to be detected than the pure NRs.

The data used in previous analyses [8] consist of two science runs with a live time of 32.1 days (SR0) and 246.7 days (SR1), respectively. The two runs were taken under slightly different detector conditions. To maximize the amount of data acquired under stable detector conditions, we decided to use SR1 only. The same event selection, fiducial mass, correction, and background models as described in Ref. [8] are used for the SR1 data, which we refer to as the S1-S2 data in later text. The exposure of the S1-S2 data is about 320 tonne-days. The interpretation of such S1-S2 analysis is based on the corrected S1 (cS1) signal and the corrected S2 signal from the PMTs at the bottom of the TPC (cS2b).

The region of interest in the S1-S2 data is from 3 to 70 photoelectrons (PEs) in cS1, which corresponds to median ER energies from 1.4 to 10.6 keV in the 1.3-tonne fiducial volume of XENON1T. The lower value is dictated by the requirement of the threefold PMT coincidence for defining a valid S1 signal [16]. A detailed signal response model [17] is used to derive the influence of various detector features, including the requirement of the threefold PMT coincidence, on the reconstructed signals. The effective exposure, which is defined as exposure times detection efficiency, and its uncertainty as a function of deposited ER energy for the S1-S2 data are shown in Fig. 2, with the signal spectra from MIGD and BREM induced by 0.1 and 1 GeV/c^2 DM masses overlaid. The (cS2b, cS1) distribution of S1-S2 data are shown in Fig. 3. The rise of the event rate at around 0.85 keV for DM mass of 1.0 GeV/c^2 is contributed by the ionization of M-shell electrons [10,12].

FIG. 1. Illustration of the ER signal production from BREM (green) and MIGD processes (pink) after elastic scattering between DM (χ) and a xenon nucleus. The electrons illustrated in pink represent those involved in ionization, deexcitation, and Auger electron emission during a MIGD process.
As detailed in Ref. [21], 30% of the data were used for choosing regions of interest (ROIs) in S2 and event selections. A different S2 ROI is chosen for each dark matter model and mass to maximize the signal-to-noise ratio, based on the training data. The event selections used for this work are the same as in Ref. [21], and mainly based on the width of each S2 waveform, reconstructed radius, and PMT hit pattern of the S2. Figure 4 shows the observed S2 spectra for the S2-only data, along with the expected DM signal distributions by MIGD with masses of 0.1, 0.5, and 1.0 GeV/c², respectively. The S2 ROIs for these three DM models shown in Fig. 4 are indicated by the colored arrows. Conserved estimates of the background from ²¹¹⁸⁷Pb-induced β decays, solar-neutrino-induced NRs, and surface backgrounds from the cathode electrode are used in the inference [21]. The background model is shown in Fig. 4 as a shaded gray region.
The unbinned profile likelihood is calculated using background models defined in cS2_h, cS1, and spatial coordinates. The uncertainties from the scintillation and ionization yields of ER backgrounds, along with the uncertainties in the estimated rates of each background component, are taken into account in the inference [17]. The inference procedure for the S2-only data is detailed in Ref. [21], which is based on simple Poisson statistics using the number of events in the S2 ROI. The event rates of spin-independent (SI) and -dependent (SD) DM-nucleon elastic scattering are calculated following the approaches described in Refs. [8,23] and Ref. [24], respectively.

The results are also interpreted in a scenario where LDM interacts with the nucleon through a scalar force mediator $\phi$ with equal effective couplings to the proton and neutron as in the SI DM-nucleon elastic scattering. In this scenario, the differential event rates are corrected by $m_\phi^2/(m_N^2 + q^2/c^2)$ [25,26], where $q = \sqrt{2m_N E_h}$ and $m_N$ are the momentum transfer and the nuclear mass, respectively. We take the light mediator (LM) regime where the momentum transfer is much larger than $m_\phi$ and thus the interaction cross section scales with $m_\phi^2$. In this regime, the contribution of NRs is largely suppressed compared with SI DM-nucleon elastic scattering due to the long-range nature of the interaction. Therefore, the results are interpreted for DM mass up to 5 GeV/c$^2$ for SI-LM DM-nucleon elastic scattering.

In addition, we also take into account the fact that a DM particle may be stopped or scatter multiple times when passing through Earth’s atmosphere, mantle, and core before reaching the detector (Earth-shielding effect) [27–29]. If the DM-matter interaction is sufficiently strong, the sensitivity for detecting such DM particles in terrestrial detectors, especially in an underground laboratory, can be reduced or even lost totally. Following Ref. [30], the VERNE code [31] is used to calculate the Earth-shielding effect for SI DM-nucleon interaction. A modification of the VERNE code based on the methodology in Ref. [32] is applied for the calculations of SD and SD-LM DM-nucleon interactions. To account for the Earth-shielding effect for SD DM-nucleon interaction, $^{14}$N in the atmosphere and $^{28}$Si in Earth’s mantle and core are considered, and their spin expectation values, $\langle S_n \rangle$ and $\langle S_p \rangle$, are taken from Ref. [33]. Both the lower and upper boundaries of excluded parameter space are reported in this work. The lower boundaries are conventionally referred to as upper limits in later context, and are the primary interest of this work. The upper boundaries are dominated by the overburden configuration of the Gran Sasso laboratory which hosts the detector.

No significant excess is observed above the background expectation in the search using the S1-S2 data. Figure 5 shows the 90% confidence level (C.L.) limits [34] on the SI and SD (proton-only and neutron-only cases) DM-nucleon interaction cross section using signal models from MIGD and BARE with masses from about 85 MeV/c$^2$ to 2 GeV/c$^2$, and Fig. 6 shows the 90% C.L. limits [34] on the SI-LM DM-nucleon interaction cross section with masses from about 100 MeV/c$^2$ to 5 GeV/c$^2$. The sensitivity contours for the results derived using S2-only data are not shown because of the conservativeness of the background model. The upper limits derived using the S1-S2
data deviate from the median sensitivity by about 1σ–2σ due to the underfluctuation of the ER background in the low energy region. As described in Ref. [21], the jumps in the S2-only limits are originating from the changes in the observed number of events due to the mass-dependent S2 ROIs. The results, by searching for ER signals induced by MIGD, give the best lower exclusion boundaries on SI, SD proton-only, SD neutron-only, and SI-LM DM-nucleon interaction cross section for mass below about 1.8, 2.0, and 4.0 GeV/c², respectively, as compared to previous experiments [30,35–42]. The upper limits derived from the S1–S2 data become comparable with those from the S2-only data at ∼GeV/c² since the efficiency of the S1–S2 data to DM signals with mass of ∼GeV/c² becomes sufficiently high. However, the upper limits derived from the S1–S2 data do not provide significantly better constraints than those from the S2-only data for DM masses larger than 1 GeV/c², because both data are dominated by the ER background, which is very similar to the expected DM signal.

In summary, we performed a search for LDM by probing ER signals induced by MIGD and BREM, using data from the XENON1T experiment. These new detection channels significantly enhance the sensitivity of LXe experiments to masses unreachable in the standard NR searches. We set the most stringent upper limits on the SI and SD DM-nucleon interaction cross sections for masses below 1.8 and 2 GeV/c², respectively. Together with the standard NR search [8], XENON1T results have reached unprecedented sensitivities to both low-mass (sub-GeV/c²) and high-mass (GeV/c²–TeV/c²) DM. With the upgrade to XENONnT, we expect to further improve the sensitivity to DM with masses ranging from about 85 MeV/c² to beyond a TeV/c².

The authors would like to thank Masahiro Ibe and Yutaro Shoji for helpful discussions on MIGD and for providing us with the code for calculating the rate of MIGD radiation in xenon. We would like to thank Bradley Kavanagh for helpful discussion on the Earth-shielding effect. We gratefully acknowledge support from the National Science Foundation, Swiss National Science Foundation, German Ministry for Education and Research, Max Planck Gesellschaft, Deutsche Forschungsgemeinschaft,
Netherlands Organisation for Scientific Research (NWO), Netherlands eScience Center (NLeSC) with the support of the SURF Cooperative, Weizmann Institute of Science, Israeli Centers Of Research Excellence (I-CORE), Pazy-Vatat, 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. This project has received funding or support from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreements No. 690575 and No. 674896, respectively. Data processing is performed using infrastructures from the Open Science Grid and European Grid Initiative. We are grateful to Laboratori Nazionali del Gran Sasso for hosting and supporting the XENON project.

Also at Institute for Subatomic Physics, Utrecht University, 3584 CC Utrecht, Netherlands. kazama@isee.nagoya-u.ac.jp
Also at Coimbra Polytechnic—ISEC, 3030-199 Coimbra, Portugal. xenon@lngs.infn.it

1 Also at Institute for Subatomic Physics, Utrecht University, 3584 CC Utrecht, Netherlands.
2 kazama@isee.nagoya-u.ac.jp
3 q12265@vip.163.com
4 Also at Coimbra Polytechnic—ISEC, 3030-199 Coimbra, Portugal.
5 xenon@lngs.infn.it

Correction: The second sentence of the caption to Figure 4 contained an error and has been fixed.