Title

First Limit on the Direct Detection of Lightly Ionizing Particles for Electric Charge as Low as e/1000 with the Majorana Demonstrator

Journal
Physical Review Letters, 120(21)

ISSN
0031-9007

Authors
Alvis, SI
Arnquist, IJ
Avignone, FT
et al.

Publication Date
2018-05-25

DOI
10.1103/physrevlett.120.211804

Peer reviewed

First Limit on the Direct Detection of Lightly Ionizing Particles for Electric Charge as Low as $e/1000$ with the Majorana Demonstrator

S.I. Alvis,[1] I.J. Arnquist,[2] F.T. Avignone III,[3,4] A.S. Barabash,[5] C.J. Barton,[6] F.E. Bertrand,[4] V. Brudanin,[8] M. Busch,[9,10] M. Buuck,[1] T.S. Caldwell,[11,10] Y-D. Chan,[12] C.D. Christofferson,[13] P.-H. Chu,[14] C. Cuesta,[1,*] J.A. Detwiler,[1] C. Dunagan,[13] Yu. Efremenko,[15,4] H. Ejiri,[16] S.R. Elliott,[14] T. Gilliss,[11,10] G.K. Giovanetti,[17] M.P. Green,[18,10,4] J. Gruszko,[19] I.S. Guinn,[1] V.E. Guiseppe,[3] C.R. Haufe,[11,10] L. Hehn,[12] R. Henning,[11,10] E.W. Hoppe,[2] M.A. Howe,[11,10] S.I. Konovalov,[5] R.T. Kouzes,[2] A.M. Lopez,[15] R.D. Martin,[20] R. Massarczyk,[14,†] S.J. Meijer,[11,10] S. Mertens,[7,21] J. Myslik,[12] C. O'Shaughnessy,[11,10,‡] G. Othman,[11,10] W. Pettus,[1] A.W.P. Poon,[12] D.C. Radford,[4] J. Rager,[11,10] A.L. Reine,[11,10] K. Rielage,[14] R.G.H. Robertson,[1] N.W. Ruof,[1] B. Shanks,[4] M. Shirchenko,[8] A.M. Suriano,[13] D. Tedeschi,[3] R.L. Varner,[4] S. Vasilyev,[8] K. Vorren,[11,10] B.R. White,[14] J.F. Wilkerson,[11,10,4] C. Wiseman,[3] W. Xu,[6] E. Yakushev,[8] C.-H. Yu,[4] V. Yumatov,[5] I. Zhitnikov,[8] and B.X. Zhu[14]

(Majorana Collaboration)

[1]*Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA, USA*
[2]*Pacific Northwest National Laboratory, Richland, WA, USA*
[3]*Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA*
[4]*Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[5]*National Research Center "Kurchatov Institute" Institute for Theoretical and Experimental Physics, Moscow, Russia*
[6]*Department of Physics, University of South Dakota, Vermillion, SD, USA*
[7]*Max-Planck-Institut für Physik, München, Germany*
[8]*Joint Institute for Nuclear Research, Dubna, Russia*
[9]*Department of Physics, Duke University, Durham, NC, USA*
[10]*Triangle Universities Nuclear Laboratory, Durham, NC, USA*
[11]*Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC, USA*
[12]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[13]*South Dakota School of Mines and Technology, Rapid City, SD, USA*
[14]*Los Alamos National Laboratory, Los Alamos, NM, USA*
[15]*Department of Physics and Astronomy, University of Tennessee, Knoxville, TN, USA*
[16]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, Japan*
[17]*Department of Physics, Princeton University, Princeton, NJ, USA*
[18]*Department of Physics, North Carolina State University, Raleigh, NC, USA*
[19]*Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA*
[20]*Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston, ON, Canada*
[21]*Physik Department, Technische Universität, München, Germany*

(Dated: February 5, 2018)

The Majorana Demonstrator is an ultra low-background experiment searching for neutrinoless double-beta decay in ^{76}Ge. The heavily shielded array of germanium detectors, placed nearly a mile underground at the Sanford Underground Research Facility in Lead, South Dakota, also allows searches for new exotic physics. Free, relativistic, lightly-ionizing particles with electrical charges less than e are forbidden by the standard model but predicted by some of its extensions. If such particles exist, they might be detected in the Majorana Demonstrator by searching for multiple-detector events with individual-detector energy depositions down to 1 keV. This search is background free and no candidate events have been found in 285 days of data taking. New direct-detection limits are set for the flux of lightly ionizing particles for charges as low as $e/1000$.

PACS numbers: 95.30.Cq, 14.80.-j

Lightly ionizing particles (LIPs) are hypothetical particles for which the electromagnetic interaction is suppressed compared to particles like charged hadrons and leptons. A particle with a charge $q = e/f$ that has a fraction f of the electron charge, e, is expected to have weaker electromagnetic interactions compared to standard single charged particles. The standard model (SM) of particle physics does not include free fractionally charged particles [1] since the quarks are bound within hadrons and do not exist as free particles. However, the SM cannot explain the nature of dark matter or dark energy in the cosmos, hence extensions or alternatives must exist. Much of the literature refers to milli/mini-charged particles (mCP) as opposed to LIPs. The LIP designation describes the energy loss phenomenology related to a class of detection techniques. Therefore, the term LIP includes mCPs since their signature would be a diminished ionization, but it does not preclude other possible particles. Unbound quarks, non-integer-charged bound states of quarks, or new leptons with fractional charge are a few possible candidates with LIP character. There are a variety of theories that permit an mCP including, as examples, a fermion singlet [2, 3], an additional mirror U(1) paraphoton that can mix with the photon [4], neutrinos with electromagnetic couplings [5], vector particles [6], dark constituents bound to atoms [7], charge quantization [8–11], or composite mCPs [12]. The phenomenology of these models and their variants is very broad and therefore a variety of search techniques is justified. The experimental literature is very rich as a result.

Although the masses of these particles can exceed energies obtained with current accelerators, experimental constraints on the masses and charges of mCPs have been derived from fixed target accelerators [13–20], colliders [21–28], stellar models [3, 29–31], the cosmic microwave background [29, 30, 32–37], big-bang nucleosynthesis [30], Supernova 1987A [30, 38], neutron stars [39], pulsars and gamma ray bursts [40], galaxy clusters [41, 42], the Lamb shift [29, 43, 44], positronium decay [45], reactor neutrinos [46, 47], and μ magnetic moment [29]. An early levitation experiment [48] found an indication for the existence for fractional charges that was not confirmed by following efforts [49, 50]. Millikan's method is a long-standing technique to search for fractional charges [51], combining the advantage of large probe sizes and high counting statistics. Brownian motion, however, limits sensitivity [52]. Direct searches for LIPs, including MACRO [53, 54], Kamiokande-II [55], and LSD [56] placed stringent limits on the LIP flux for $0.4 < f < 6$. The Cryogenic Dark Matter Search experiment (CDMS) [57, 58] placed limits for a direct search for exotic particles for $f < 200$. The review [59] summarizes the experimental state of the field prior to the results of CDMS in 2010, while Refs. [3] and [60] provide a broad list of references and give recent overview on the results over the last decade while discussing the mass-charge parameter space. Here we describe an improved direct search for such particles.

The Majorana Demonstrator [61, 62] is located at a depth of 4850 ft at the Sanford Underground Research Facility in Lead, South Dakota [63]. In addition to its primary goal of searching for neutrinoless double-beta decay, its ultra low-background configuration permits additional physics studies including the searches for dark matter [64], axions, and exotic physics. Two modules contain 44.1 kg of high-purity germanium detectors of which 29.7 kg have a 88% ^{76}Ge enrichment. Fifty-eight detector units are installed in strings of three, four, or five detectors. The setup has similarities to that of CDMS, which also has towers of detectors. The detector masses, diameters, and heights range from 0.5-1 kg, 6-8 cm, and 3-4 cm, respectively. Compared to CDMS, Majorana Demonstrator detectors are 3 to 5 times thicker providing with comparable thresholds a higher sensitivity to lower energy deposits per crossing and hence higher values of f. The low energy thresholds, excellent energy resolution, reduced electronic noise, and pulse shape characteristics of the P-type point contact detectors [65–68] allow a competitive LIP search based on the taken Demonstrator data.

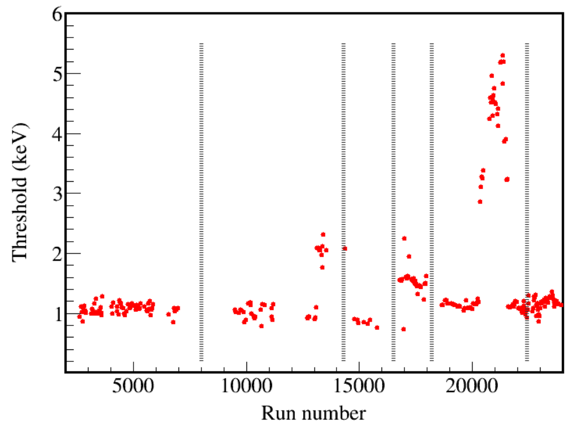

FIG. 1. The threshold value associated with a 99.7% trigger efficiency for an example detector plotted versus data run in various data sets. The boundaries of each data set are represented by the vertical lines. The gaps in between the runs are due to calibration runs or runs where blind data was taken.

The analysis presented here includes data taken from June 2015 until March 2017. Excluding calibration, commissioning and blind data, the analyzed data includes 285 days of live time, of which 121 days were taken with both modules operating in the final Demonstrator configuration [62]. Physics runs are typically one hour long. Since the set of operable detectors and their respective threshold changed over the course of data taking, our simulation mirrored the changing conditions on a run-by-run basis. For several runs the threshold was increased to avoid noise introduced by external work during the construction phase.

The flux ($\Phi(f)$) of LIPs through the detector array is given as:

$$\Phi(f) = \frac{n}{\sum_i \sum_m A_{i,m}\epsilon_{i,m}t_i\Omega_{i,m}}, \tag{1}$$

where n is the number of detected interactions. For zero candidates an upper bound on Φ can be set using the method of Feldman and Cousins in Ref. [69]. The sum index i is over data runs and index m is over the multiplicity values considered for LIP candidates. The multiplicity is defined as the number of coincident detector signals within the 4-μs-long waveform digitization window. We consider events with m = 4, 5, and 6. The length of a run is given by its dead-time corrected live time (t_i). The detection efficiency (ϵ) depends on each detector's threshold and the geometry of the active detectors, both of which vary run-by-run. Figure 1 shows the trend of the threshold over time. For this analysis the threshold for each detector was chosen to have a 99.7% probability to trigger a detector. The surface area ($A_{i,m}$) for an incident LIP is taken as the endcap area of the smallest detector crossed. For the DEMONSTRATOR detectors, A = 30-37 cm^2 ($\pm$1 cm^2). The MAGE [70, 71] framework, based on GEANT4 [72] was used to estimate $A_{i,m}$ and and the solid angle (Ω) for each run. Non-interacting particles were shot as a proxy for LIPs through the individual detectors as a function of the angle of incidence. Since the path length through detectors depends on the LIP trajectory angle through the array, Ω is a function of the efficiency and depends on the impinging flux distribution. CDMS assumed an isotropic distribution from above [58]. We present results for that same distribution for comparison as well as numbers for a $\cos^2\theta$ distribution. The latter function is a proxy for particles created in the upper atmosphere [59]. For $m = 4$ events, the average solid angle is $\sim$2.4 sr (1.5 sr) for a uniform flux from above ($\cos^2\theta$ distribution with θ as polar angle). The exact number varies for each run. Larger m's have a smaller number of possible detector combinations and hence smaller Ω. For m =5 and 6, the average solid angles are 1 sr (0.6 sr) and 0.06 sr (0.02 sr), respectively.

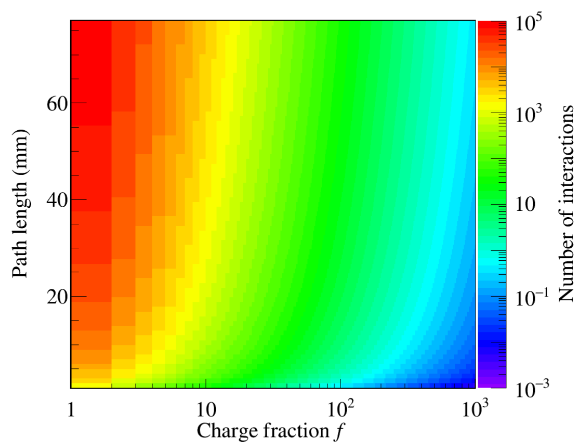

FIG. 2. The average number of interactions for a LIP in germanium as a function of path length and charge of the particle.

For large f, LIPs interact potentially only once in a detector, cf. Fig. 2, leading to large energy-deposit fluctuations. Similarly to CDMS [58, 73], we calculate the expected LIP energy-loss distribution based on the single-interaction energy loss. The photo absorption ionization (PAI) Model [74] was used to calculate the interaction cross section. This probability distribution function (PDF) for the single-interaction energy loss is convolved with itself N times to derive the PDF for N such interactions [75]. The number of interactions per unit path length through a detector was calculated using the approach of Ref. [76]. The result is a function of f as shown in Fig. 2. The expected energy deposited as a function of track length and f is shown in Fig. 3. The probability that a LIP with f deposits enough energy to exceed the detector threshold is calculated for simulated events. The total efficiency is the product of these individual detector probabilities.

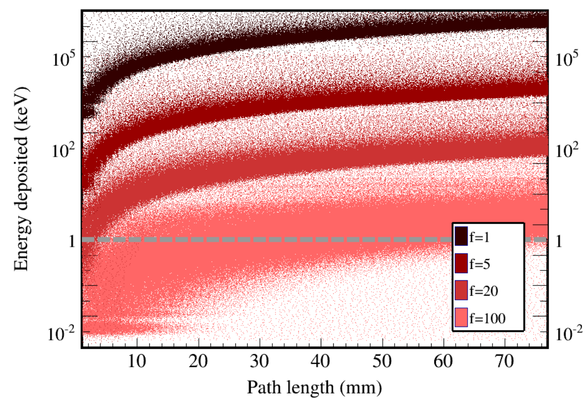

FIG. 3. Distribution of energy depositions for a path length in germanium for four different values of f. The grey dashed line indicates a 1-keV threshold.

For each run and detector, the data acquisition threshold is applied in combination with the simulation, resulting in a run-dependent detection efficiency for LIPs with a given m and trajectory. The simulated efficiency distributions also take into account inoperable channels and exclude them from the analysis. Two factors mainly contribute to the uncertainty of the efficiency ϵ. (See Fig. 4.) One uncertainty is the traversed-detector path length that determines the number of interactions. This results from uncertainty in the thickness of the dead layer surrounding each detector. Furthermore, the detectors have a finite energy resolution. Both effects contribute to the uncertainty in the probability that a LIP energy deposit will be above threshold, especially for large f and small energy depositions. In order to estimate systematic uncertainties, we analyzed the simulated efficiency 100 times for each individual run varying the track length inside one detector ($\pm$1 mm), the number of interactions, and the energy resolution of the DEMONSTRATOR ($\sim$0.2 keV FWHM at 10 keV [64]). Finally all efficiencies of one data set are combined in one histogram. In Fig. 4, the distribution of efficiencies for $m = 4$-events is drawn. The width of the distribution for each slice on f is used as systematic uncertainty. This conservative approach allows us to show that our sensitivity is not very dependent on short variations in detector settings.

Relative to CDMS, we can greatly increase Ω, and therefore sensitivity, by searching for LIPs that traverse multiple strings. In each detector within the DEMONSTRATOR, a fair number of low energy events contribute as background. These events include noise, microphonics

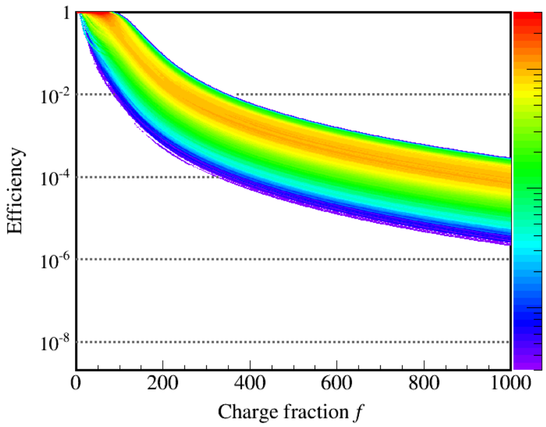

FIG. 4. Detection efficiency for $m = 4$ events for one data set as a function of f. For each individual f the probability of the detection efficiecnies are given by the z-scale.

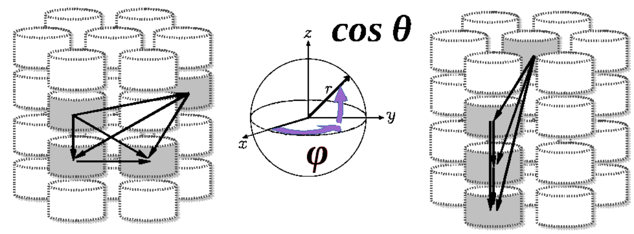

FIG. 5. (left) The figure shows the vectors connecting the detector centers for noise or background events, that do not point to a common location. The grey detector indicate four detectors that triggered. (middle) The definition of the angles on an outer sphere. (right) For a simulated LIP, the variation of directions ($\Delta\cos\,\theta$ and $\Delta\,\phi$) is much smaller.

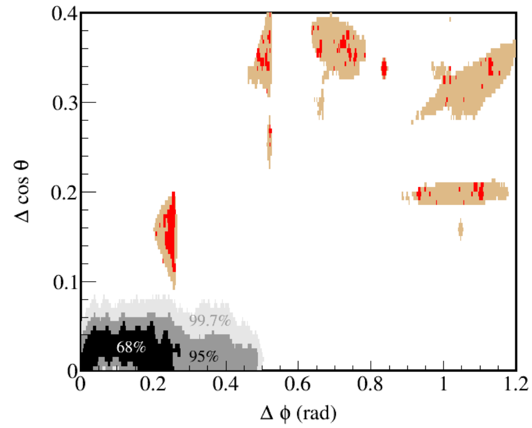

FIG. 6. Event-by-event variation in the two spherical angles for Demonstrator data (brown). Events within a one-second coincidence with the muon veto [77] are shown in red. For simulated LIPs from an isotropic source, the region that include 68 % (black), 95 % (dark grey), and 99.7 % (light grey) of all events are shown.

during nitrogen fills, and pulser cross talk. A multiplicity requirement of $4 \leq m \leq 6$ eliminates the majority (≈97%) of these low-energy triggers without significant additional analysis. It is not possible due to the different individual detector sizes to include a CDMS-like energy consistency requirement because the path lengths are not necessarily comparable. Hence to reduce the remaining background within the high-m sample, a tracking algorithm was applied. Each candidate event is compared to the simulated signature of a LIP. A LIP will traverse the array in a straight line and vectors connecting pairs of triggered detectors (see Fig. 5) should all point roughly to the same direction on an imaginary sphere surrounding the array. The direction of these vectors can be described with two angles when using spherical coordinates, cf Fig. 5. Due to the lack of knowledge of where exactly the particles interacted within the detector, the center of the detectors is used as start and end point of each vector. The m=4, 5, or 6 events in the Demonstrator data have larger variations in θ and ϕ than simulated LIP signatures. This arises because these events are due to instrumental effects, internal background or muons and not LIPs. As shown in Fig. 6, events in coincidence with the muon veto can be somewhat LIPs-like. However, the particle shower accompanying the muon tends to trigger more than 6 detectors, or additional out-of-line detectors. A minimally ionizing LIP with high f will not deposit enough energy to trigger the veto, which is made of 2-inch thick scintillator panels and has a trigger threshold of 1 MeV. Furthermore, simulations show that LIPS for $f > 6$ do not significantly shower, unlike muons. The efficiency for retaining a LIP candidate for cuts in θ and ϕ is effectively unity with an uncertainty of less then 0.3 % which is negligible compared to the other uncertainties.

We find no LIPs candidates in the recorded data. Applying the Feldman and Cousins procedure [69], a value of 2.44 (90% C.L.) is used as the upper limit for n in Eq. 1. Figure 7 displays the results as a function of f. For charges between $e/2$ and $e/30$, a limit of $2{\times}10^{-9}$ particles per $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ is found. A deviation from the minimally ionizing character of the particle would result in a higher detection efficiency, would result in a higher detection efficiency, hence, the limits presented are conservative upper limits. Using the assumption that LIPs are impinging with a $\cos^2\theta$ distribution would result in a slightly smaller detection efficiency and therefore in a limit which is about 38% above the one for the isotropic model.

This work presents the first limits on massive relativistic particles with a fractional charge using the unique features of the Majorana Demonstrator. The large path length due to thick detectors in combination with the low thresholds allows for sensitivity down to $1/1000^{th}$ of an elementary charge. These are the first results for a non-accelerator based experiment on the

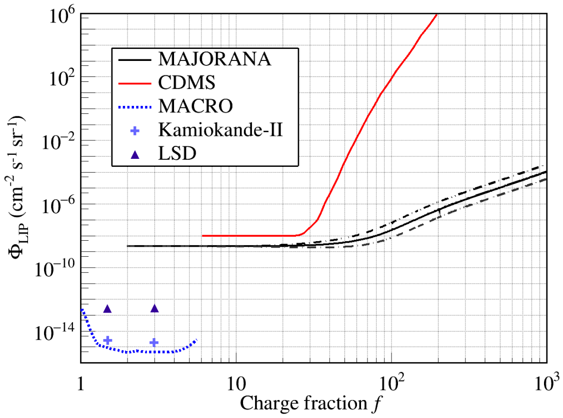

FIG. 7. LIP flux limit from above on the MAJORANA DEMONSTRATOR using a 90% confidence level (black line) and its 1-σ uncertainty bands (dashed black lines). Results from MACRO [54], Kamiokande-II [55], LSD [56], and CDMS [58] are shown as well. All limits assume an isotropic flux. As indicated in the text, a $\cos^2\theta$ distribution of LIPs would result in an 38% less restrictive curve.

natural flux of lightly ionizing particles with charges less then $e/200$ and an improvement of the existing limits for charges between $e/6$ and $e/200$. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Numbers DE-AC02-05CH11231, DE-AC05-00OR22725, DE-AC05-76RL0130, DE-AC52-06NA25396, DE-FG02-97ER41020, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-SC0010254, DE-SC0012612, DE-SC0014445, and DE-SC0018060. We acknowledge support from the Particle Astrophysics Program and Nuclear Physics Program of the National Science Foundation through grant numbers MRI-0923142, PHY-1003399, PHY-1102292, PHY-1206314, and PHY-1614611. We gratefully acknowledge the support of the U.S. Department of Energy through the LANL/LDRD Program and through the PNNL/LDRD Program for this work. We acknowledge support from the Russian Foundation for Basic Research, grant No. 15-02-02919. We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada, funding reference number SAPIN-2017-00023, and from the Canada Foundation from Innovation John R. Evans Leaders Fund. We thank the Yamaha Science Foundation Japan for their support. This research used resources provided by the Oak Ridge Leadership Computing Facility at Oak Ridge National Laboratory and by the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility. We thank our hosts and colleagues at the Sanford Underground Research Facility for their support.

* Present address: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, CIEMAT 28040, Madrid, Spain

† Corresponding author : massarczyk@lanl.gov

‡ Present address: Los Alamos National Laboratory, Los Alamos, NM, USA

[1] P. Langacker and S.-Y. Pi, Phys. Rev. Lett. **45**, 1 (1980).
[2] L. Okun, M. Voloshin, and V. Zakharov, Physics Letters B **138**, 115 (1984).
[3] N. Vinyoles and H. Vogel, Journal of Cosmology and Astroparticle Physics **2016**, 002 (2016).
[4] B. Holdom, Phys. Lett. **166B**, 196 (1986).
[5] R. Foot, G. Joshi, H. Lew, and R. Volkas, Mod. Phys. Lett. A **5**, 95 (1990).
[6] E. Gabrielli, L. Marzola, M. Raidal, and H. Veermäe, Journal of High Energy Physics **2015**, 150 (2015).
[7] J. M. Cline, Z. Liu, and W. Xue, Phys. Rev. D **85**, 101302 (2012).
[8] A. Y. Ignatiev, V. A. Kuzmin, and M. E. Shaposhnikov, Phys. Lett., B **84**, 315 (1979).
[9] X.-G. Wen and E. Witten, Nuclear Physics B **261**, 651 (1985).
[10] A. Schellekens, Physics Letters B **237**, 363 (1990).
[11] K. S. Babu and R. N. Mohapatra, Phys. Rev. D **41**, 271 (1990).
[12] C. Kouvaris, Phys. Rev. D **88**, 015001 (2013).
[13] J. Aubert *et al.*, Phys. Lett. B **133**, 461 (1983).
[14] F. Bergsma *et al.*, Z. Phys. C **24**, 217 (1984).
[15] E. Golowich and R. W. Robinett, Phys. Rev. D **35**, 391 (1987).
[16] Y. He and P. B. Price, Phys. Rev. C **44**, 1672 (1991).
[17] G. Hüntrup, D. Weidmann, S. E. Hirzebruch, E. Winkel, and W. Heinrich, Phys. Rev. C **53**, 358 (1996).
[18] D. Ghosh *et al.*, Fizika B **5**, 135 (1996).
[19] A. A. Prinz, R. Baggs, J. Ballam, S. Ecklund, C. Fertig, J. A. Jaros, K. Kase, A. Kulikov, W. G. J. Langeveld, R. Leonard, T. Marvin, T. Nakashima, W. R. Nelson, A. Odian, M. Pertsova, G. Putallaz, and A. Weinstein, Phys. Rev. Lett. **81**, 1175 (1998).
[20] D. E. Soper, M. Spannowsky, C. J. Wallace, and T. M. P. Tait, Phys. Rev. **D90**, 115005 (2014), arXiv:1407.2623 [hep-ph].
[21] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **46**, R1889 (1992).
[22] D. Buskulic *et al.*, Phys. Lett. B **303**, 198 (1993).
[23] R. Akers *et al.*, Z. Phys. C **67**, 203 (1995).
[24] P. Abreu *et al.*, Phys. Lett. B **396**, 315 (1997).
[25] D. Acosta *et al.*, Phys. Rev. Lett. **90**, 131801 (2003).
[26] G. Abbiendi *et al.*, Phys. Lett. B **572**, 8 (2003).
[27] J. Jaeckel, M. Jankowiak, and M. Spannowsky, Phys. Dark Univ. **2**, 111 (2013), arXiv:1212.3620 [hep-ph].
[28] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. D **87**, 092008 (2013).
[29] M. I. Dobroliubov and A. Y. Ignatiev, Phys. Rev. Lett. **65**, 679 (1990).
[30] S. Davidson, S. Hannestad, and G. Raffelt, JHEP **05**, 003 (2000), arXiv:hep-ph/0001179 [hep-ph].
[31] J. L. Feng, J. Smolinsky, and P. Tanedo, Phys. Rev. D **93**, 115036 (2016).
[32] M. Ahlers, Phys. Rev. D **80**, 023513 (2009).
[33] C. Burrage *et al.*, Journal of Cosmology and Astroparti-

cle Physics **2009**, 002 (2009).
[34] S. L. Dubovsky, D. S. Gorbunov, and G. I. Rubtsov, JETP Lett. **79**, 1 (2004), [Pisma Zh. Eksp. Teor. Fiz.79,3(2004)], arXiv:hep-ph/0311189 [hep-ph].
[35] Z. Berezhiani and A. Lepidi, Physics Letters B **681**, 276 (2009).
[36] H. Vogel and J. Redondo, JCAP **1402**, 029 (2014), arXiv:1311.2600 [hep-ph].
[37] A. D. Dolgov and A. S. Rudenko, Journal of Experimental and Theoretical Physics **124**, 564 (2017).
[38] R. N. Mohapatra and I. Z. Rothstein, Phys. Lett. **B247**, 593 (1990).
[39] X. Huang, X.-P. Zheng, W.-H. Wang, and S.-Z. Li, Phys. Rev. D **91**, 123513 (2015).
[40] A. K. Kvam and D. C. Latimer, (2014), arXiv:1412.0708.
[41] M. Korwar and A. M. Thalapilli, (2017), arXiv:1709.07888.
[42] K. Kadota, T. Sekiguchia, and H. Tashirob, (2016), arXiv:1602.04009.
[43] S. Davidson, B. Campbell, and D. C. Bailey, Phys. Rev. **D43**, 2314 (1991).
[44] M. Glück, S. Rakshit, and E. Reya, Phys. Rev. D **76**, 091701 (2007).
[45] A. Badertscher, P. Crivelli, W. Fetscher, U. Gendotti, S. N. Gninenko, V. Postoev, A. Rubbia, V. Samoylenko, and D. Sillou, Phys. Rev. **D75**, 032004 (2007), arXiv:hep-ex/0609059 [hep-ex].
[46] S. N. Gninenko, N. V. Krasnikov, and A. Rubbia, Phys. Rev. **D75**, 075014 (2007), arXiv:hep-ph/0612203 [hep-ph].
[47] J.-W. Chen, H.-C. Chi, H.-B. Li, C.-P. Liu, L. Singh, H. T. Wong, C.-L. Wu, and C.-P. Wu, Phys. Rev. D **90**, 011301 (2014).
[48] G. S. LaRue, J. D. Phillips, and W. M. Fairbank, Phys. Rev. Lett. **46**, 967 (1981).
[49] P. Smith *et al.*, Physics Letters B **153**, 188 (1985).
[50] D. C. Moore, A. D. Rider, and G. Gratta, Phys. Rev. Lett. **113**, 251801 (2014).
[51] P. C. Kim, E. R. Lee, I. T. Lee, M. L. Perl, V. Halyo, and D. Loomba, Phys. Rev. Lett. **99**, 161804 (2007).
[52] V. Halyo, P. Kim, E. R. Lee, I. T. Lee, D. Loomba, and M. L. Perl, Phys. Rev. Lett. **84**, 2576 (2000).
[53] M. Ambrosio *et al.*, Phys. Rev. D **62**, 052003 (2000).
[54] M. Ambrosio *et al.*, (2004), arXiv:hep-ex/0402006.
[55] M. Mori, Y. Oyama, A. Suzuki, K. Takahashi, M. Yamada, K. Miyano, H. Miyata, H. Takei, K. S. Hirata, T. Kajita, K. Kihara, M. Nakahata, K. Nakamura, S. Ohara, N. Sato, Y. Suzuki, Y. Totsuka, Y. Yaginuma, M. Koshiba, T. Suda, T. Tajima, Y. Fukuda, Y. Nagashima, M. Takita, K. Kaneyuki, T. Tanimori, E. W. Beier, E. D. Frank, W. Frati, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van Berg, and W. Zhang, Phys. Rev. D **43**, 2843 (1991).
[56] M. Aglietta *et al.*, Astropart. Phys. **2**, 29 (1994).
[57] Z. Ahmed *et al.* (CDMS II Collaboration), Science **327**, 1619 (2010).
[58] R. Agnese *et al.* (CDMS Collaboration), Phys. Rev. Lett. **114**, 111302 (2015).
[59] M. L. Perl, E. R. Lee, and D. Loomba, Annu. Rev. Nucl. Part. Sci. **59**, 47 (2009).
[60] A. Haas *et al.*, Phys. Lett. B **746**, 117 (2015).
[61] N. Abgrall *et al.*, Advances in High Energy Physics **2014**, 1 (2014).
[62] C. Aalseth *et al.*, (2017), https://arxiv.org/abs/1710.11608.
[63] J. Heise, Journal of Physics: Conference Series **606**, 012015 (2015).
[64] N. Abgrall *et al.* (MAJORANA Collaboration), Phys. Rev. Lett. **118**, 161801 (2017).
[65] P. N. Luke, F. S. Goulding, N. W. Madden, and R. H. Pehl, IEEE Trans. Nucl. Sci. **36**, 926 (1989).
[66] P. S. Barbeau, J. I. Collar, and O. Tench, JCAP **09**, 009 (2007).
[67] E. Aguayo *et al.*, (2011), sLAC eConf C110809, arXiv:1109.6913.
[68] R. Cooper *et al.*, NIM A **629**, 303 (2011).
[69] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).
[70] M. Bauer *et al.*, Journal of Physics: Conference Series **39**, 362 (2006).
[71] M. Boswell *et al.*, IEEE Trans. Nucl. Sci. **58**, 1212 (2011).
[72] S. Agostinelli *et al.*, NIM A **506**, 250 (2003).
[73] K. B. Prasad, PhD thesis, Texas A&M University (2013).
[74] W. Allison and J. Cobb, Ann. Rev. Nucl. Part. Sci. **30**, 253 (1980).
[75] H. Bichsel, Nucl. Instrum. Meth. A **562**, 154 (2006).
[76] H. Bichsel, Rev. Mod. Phys. **60**, 663 (1988).
[77] N. Abgrall *et al.*, Astroparticle Physics **93**, 70 (2017).