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Status of the Majorana Demonstrator (MJD)

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The MAJORANA Collaboration is constructing the MAJORANA DEMONSTRATOR, an ultra-low background, 40-kg modular high purity Ge (HPGe) detector array to search for neutrinoless double-beta decay ($0\nu\beta\beta$-decay) in ^{76}Ge and to demonstrate a background rate at or below 3 counts/(ROI-t-y) in the 4 keV region of interest (ROI) around the 2039 keV Q-value for ^{76}Ge $0\nu\beta\beta$-decay. In this paper, the status of the MJD, including its design and measurements of properties of the HPGe crystals is presented.

1   Introduction

Neutrinoless double-beta decay is the most general, model independent method to search for lepton number violation and correspondingly to determine the Dirac-Majorana nature of the neutrino [1, 2]. Furthermore, the Majorana nature of the neutrino would allow for the see-saw mechanism [3, 4] to explain the, seemingly finely-tuned, small neutrino masses. Finally, the rate of $0\nu\beta\beta$-decay could be used to determine the neutrino mass scale [5]. The $0\nu\beta\beta$-decay rate may be written as:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta} \rangle}{m_e}\right)^2 \tag{1}$$

where $G^{0\nu}$ is a phase space factor including the couplings, $M_{0\nu}$ is a nuclear matrix element, m_e is the electron mass, and $m_{\beta\beta}$ is the effective Majorana neutrino mass. The latter is given by

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=0}^{3} U_{ei}^2 m_i \right| \tag{2}$$

where U_{ei}^2 specifies the admixture of neutrino mass eigenstate i in the electron neutrino. Then, assuming that $0\nu\beta\beta$-decay is mainly driven by the exchange of light Majorana neutrinos, it is possible to establish an absolute scale for the neutrino mass, provided that nuclear matrix elements are known.

Experimentally, $0\nu\beta\beta$-decay can be detected by searching the spectrum of the summed energy of the emitted electrons for a monoenergetic line at the Q-value of the decay ($Q_{\beta\beta}$). In previous-generation searches, the most sensitive limits on $0\nu\beta\beta$-decay came from the Heidelberg-Moscow experiment [6], and the IGEX experiment [7], both using ^{76}Ge. A direct observation of $0\nu\beta\beta$-decay was claimed by subgroup of the Heidelberg-Moscow collaboration [8]. Recent sensitive searches for $0\nu\beta\beta$ have been carried out in ^{76}Ge (GERDA

[9]) and ^{136}Xe (KamLAND-Zen [10] and EXO-200 [11]), setting sensitive limits that do not support such a claim.

The sensitivity of a $0\nu\beta\beta$ search increases with the exposure of the experiment, but ultimately depends on the achieved background level. This relationship is illustrated in Fig. 1, where the Feldman-Cousins [12] definition of sensitivity was used in order to transition smoothly between the background-free and background-dominated scenarios.
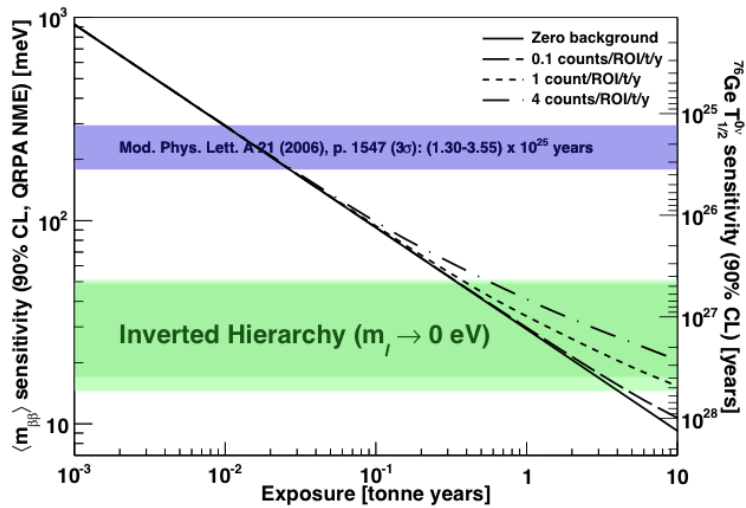

Figure 1: 90% C.L. sensitivity as a function of exposure for $0\nu\beta\beta$-decay searches in ^{76}Ge under different background scenarios. The matrix element from Ref. [13] was used to convert half-life to neutrino mass. The upper shaded band shows the region where a signal would be detected should Klapdor-Kleingrothaus claim [8] be correct. m_l in the lower shaded band refers to the lightest neutrino mass.

In order to reach the neutrino mass scale associated with the inverted mass hierarchy, 15-50 meV, a half-life sensitivity greater than 10^{27}y is required. This corresponds to a signal of a few counts or less per tonne-year in the $0\nu\beta\beta$ peak. Observation of such a small signal will require tonne-scale detectors with background contributions at or below a rate of 1 count/(ROI-t-y).

2 The MAJORANA DEMONSTRATOR

2.1 Overview

The MAJORANA DEMONSTRATOR [14] is an array of enriched and natural germanium detectors that will search for the $0\nu\beta\beta$-decay of ^{76}Ge. The specific goals of the MJD are:

- Demonstrate a path forward to achieving a background rate at or below 1 count/(ROI-t-y) in the 4 keV region of interest around the 2039 keV $Q_{\beta\beta}$ of the ^{76}Ge $0\nu\beta\beta$-decay.

- Show technical and engineering scalability toward a tonne-scale instrument.

- Field an array that provides sufficient to test the Klapdor-Kleingrothaus claim to be comparable with alternate approaches.

- Perform searches for other physics beyond the standard model, such as dark matter and axions.

To this end, the collaboration is building the DEMONSTRATOR, a modular instrument composed of two cryostats built from ultra-pure electroformed copper, each of which can house over 20 kg of HPGe detectors contained in an ultra-low background structure that maximizes the concentration of crystals while minimizing the amounts of structural materials. Cryostats are mounted on moveable transporters allowing independent assembly and testing before installation into the shield. The array will contain about 30 kg of detectors fabricated from 87% enriched ^{76}Ge and 10 kg of detectors from natural Ge (7.8% ^{76}Ge).

Starting from the innermost cavity, the cryostats will be surrounded by an inner layer of electroformed copper (5 cm), an outer layer of Oxygen-Free High thermal Conductivity (OFHC) copper (5 cm), high-purity lead (45 cm), an active muon veto (nearly 4π), borated polyethylene (5 cm), polyethylene (25 cm) (see Fig. 2). The cryostats, copper, and lead shielding will all be enclosed in a radon exclusion box. The Rn enclosure is a gas barrier whose internal volume will be continuously purged with liquid nitrogen boil-off gas to reduce Rn levels near the cryostats. The entire experiment will be located in a clean room at the 1478 m level of the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA.
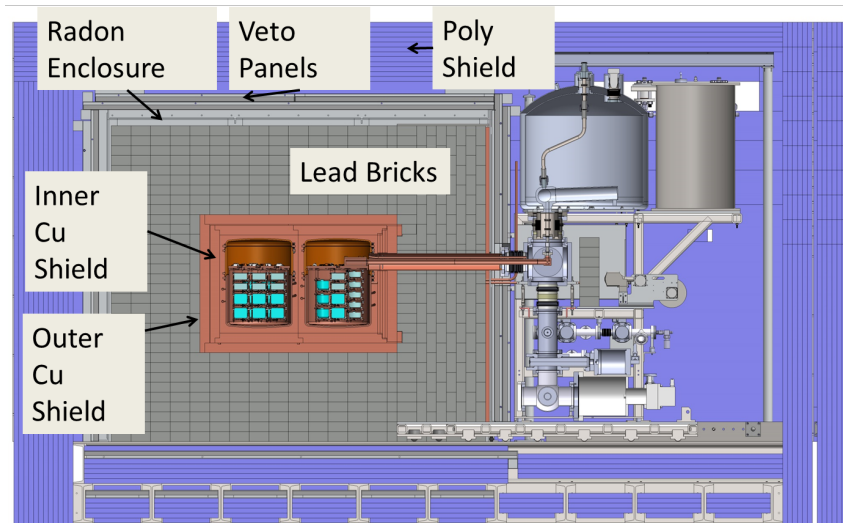
Figure 2: Cross-sectional view of the MAJORANA DEMONSTRATOR.

An essential aspect of the DEMONSTRATOR is the production and use of ultra-clean Cu. In typical materials uranium (U) and thorium (Th) decay-chain contaminants are found at levels of μg/g to ng/g, which will produce unacceptable background in the DEMONSTRATOR. Electroforming copper in a carefully-controlled and clean environment allows one to produce copper with U and Th below the level of 10^{-12} g/g [15]. The copper being produced by MAJORANA has about ten times lower U and Th impurities than commercial electroformed copper, with a projected activity of 0.3 μBq/kg for Th or lower. To avoid cosmogenic activation of the most sensitive parts, the copper is being produced at an underground (UG) production facility at SURF and at a shallow facility at Pacific Northwest National Laboratory, and is being machined UG in an ultra-clean machine shop installed and operated by the collaboration. Copper has mechanical, thermal, and electrical properties that are suitable for the DEMONSTRATOR's cryostats, detector mounts, and inner shield.

2.2 P-type Point-contact HPGe detectors

The DEMONSTRATOR uses p-type point-contact (PPC) HPGe detectors [16, 17] that have masses in the range of 0.6-1.1 kg. PPC style detectors were chosen after extensive R&D by the collaboration for their advantages: simple fabrication, excellent pulse shape discrimination between $0\nu\beta\beta$ events and backgrounds, and very low capacitance, providing a low-energy threshold that allows the reduction of background from cosmogenic ^{68}Ge.

These detectors have all the benefits of coaxial HPGe detectors traditionally used for $\beta\beta(0\nu)$, but also possess superb pulse shape analysis (PSA) discrimination between single-site interactions (such as $\beta\beta(0\nu)$-decay events) and multi-site interaction events (such as Compton scattering of γ-ray backgrounds), making them highly suitable for $\beta\beta(0\nu)$ searches. Measured signals from a PPC detector are shown in Fig. 3.
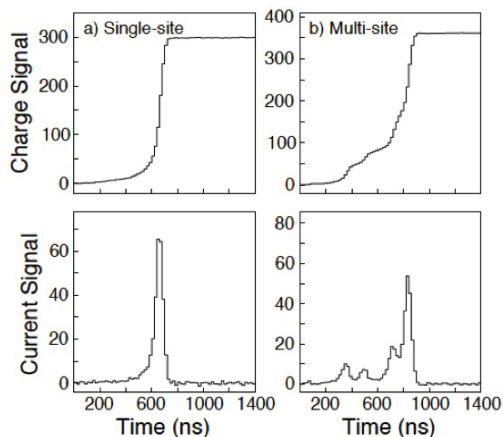

Figure 3: Charge and current pulse response of a PPC detector to single- and multi-site γ-ray events.

Both charge and current pulses are shown, for both a single-site (a) and a multi-site (b) γ-ray events. The difference in signal shape is readily apparent, with four distinct interactions evident in (b). The MAJORANA Collaboration uses two different types of PSA algorithm to discriminate between these two classes of events. The first of these, developed by the GERDA collaboration [18], compares the maximum height of the current pulse (A) to the total energy of the event (E) as determined from the height of the charge pulse.

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Multiple interactions result in multiple charge pulses separated in time, and therefore in a reduced value of A/E.
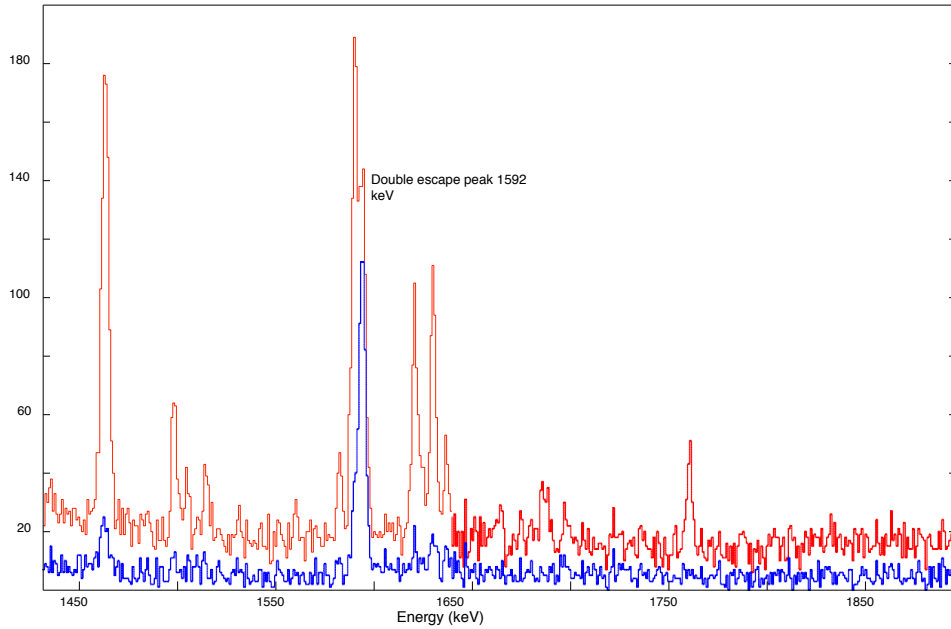

Figure 4: Pulse-shape analysis results for PPC data. The high spectrum is for all events within the energy range, while the low spectrum is for events that pass the PSA cut.

An alternative approach [19] uses a library of unique, measured single-site signals to perform event-by-event χ^2 fitting of experimental pulse shapes. A method for building this library from a large number of measured signals has been developed and tested with simulation and experimental studies. Results of this optimized PSA algorithms on PPC data are shown in Fig. 4, where the high spectrum is all events from a ^{232}Th source, and the low spectrum is for events that pass the PSA cut. The peak at 1592 keV is the double-escape peak from the pair production interaction of the 2615 keV gamma-ray in

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^{208}Tl, the final daughter in the chain. The double-escape peak has a similar two-β event topology and serves as a proxy for the $0\nu\beta\beta$-decay signal. The algorithm retains at least 95% of these events, while rejecting up to 99% of the single-escape, multi-site events. One should compare this to the A/E results of Ref. [18] where the double-escape peak events are accepted at 89% and the single-escape peaks are rejected at 93%. The conclusion from these measurements is that pulse shape analysis is a very effective background reduction technique with point-contact Ge detectors.

3 Status of the Majorana Demonstrator

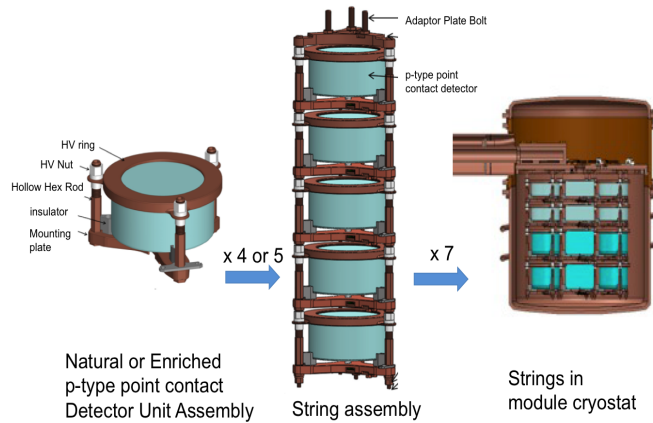Figure 5: The modular approach of Majorana Demonstrator.

The Majorana Collaboration choose to use a modular approach to construct the experimental apparatus. Four or five individual HPGe detectors and their associated low-mass low-radioactivity mounting structures and electronics are stacked together into one string assembly, and seven string assemblies are installed into one cryostat, as shown in Fig. 5.
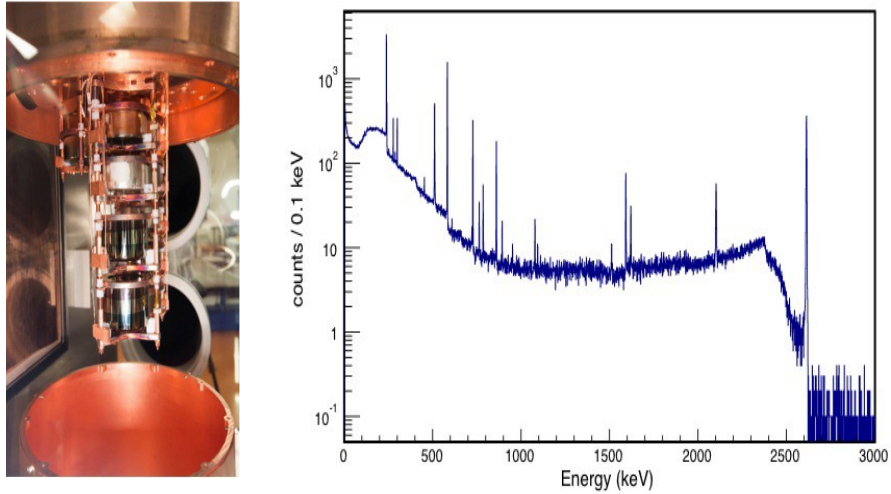
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Figure 6: Left: a photograph inside the prototype cryostat which is opened up to allow the mounting of three strings of HPGe detectors. Right: a spectrum taken by one of the HPGe detectors in the prototype cryostat during in a calibration run with a ^{228}Th source.

The construction of the DEMONSTRATOR is organized in three phases. In the first phase, a prototype cryostat made of commercial OFHC copper with three strings of natural HPGe detectors was constructed in 2013 and has been in commissioning. The goal of this prototype is to demonstrate the integration of the various components (detectors, vacuum, cooling, shielding, data acquisition). Most of the natural Ge detectors are the Broad Energy Ge detectors (BEGe) manufactured by Canberra [20], and all of the enriched Ge detectors and two natural Ge detectors are manufactured by AMETEK/ORTEC [21].

Ten natural HPGe detectors of both BEGe and ORTEC types are arranged into three strings and mounted onto the cold plate inside the prototype module cryostat. DAQ systems based on the Object-Oriented Real-time Control and Acquisition (ORCA) platform [22] have been instrumented to control both commercial and collaboration-manufactured electronics, and background data and calibration data are being taken. The HPGe detectors in the prototype cryostat have shown good energy resolution similar to that in commercial cryostats. As an example, a spectrum taken by one of the HPGe detectors during in a calibration run with a ^{228}Th source is shown in Fig. 6. The Full Width at Half Maximum (FWHM) at 2615 keV is 3.2 keV.

In the second phase, the first module made from electroformed copper will be populated with a mix of natural and enriched HPGe detectors and run inside the completed shield alongside the prototype cryostat. This second phase is anticipated to begin commissioning in September of 2014. Finally, in the third phase, a second cryostat made of electroformed copper and containing only enriched detectors will replace the prototype cryostat in the shield. At the time of this presentation, 25.2 kg of enriched germanium detectors are underground and MAJORANA is aiming for additional ≈ 4 kg of detectors from the recovery of scrap material. All enriched detectors are extensively tested and characterized in their vendor cryostat both at ORTEC$^{\textcircled{R}}$ and at SURF. The tests include measurements of the mass, impurity concentration, depletion and operating voltages, leakage current, energy resolution, electronic noise, dead layer, relative efficiency compared to a 3x3-inch NaI(Tl) detector, and pulse-shape discrimination performance.

Flood measurements are performed with various sources placed 25 cm above the top surface of the cryostat. Data taken with ^{60}Co are used to determine the detector energy resolution at 1332.5 keV and the detection efficiency relative to a 3x3-inch NaI(Tl) detector. The FWHM of all detectors are better than the experimental specification of 2.3 keV, which is shown as the dotted horizontal line (see Fig. 7).

Prior to the final installation of the strings in the module cryostats, they are again tested in the a so-called String Test Cryostat (STC). The goal of these tests is on the one hand to check the integrity of the detector, front-end electronics and HV connection after the re-installation of the detector in the MAJORANA mount, and on the other hand, this configuration allows the measurement of the crystal axis orientation of each detector in the string and the homogeneity of the dead layer along the side of each detector. The crystal axis orientation is of particular interest in view of a possible axion search with MAJORANA.
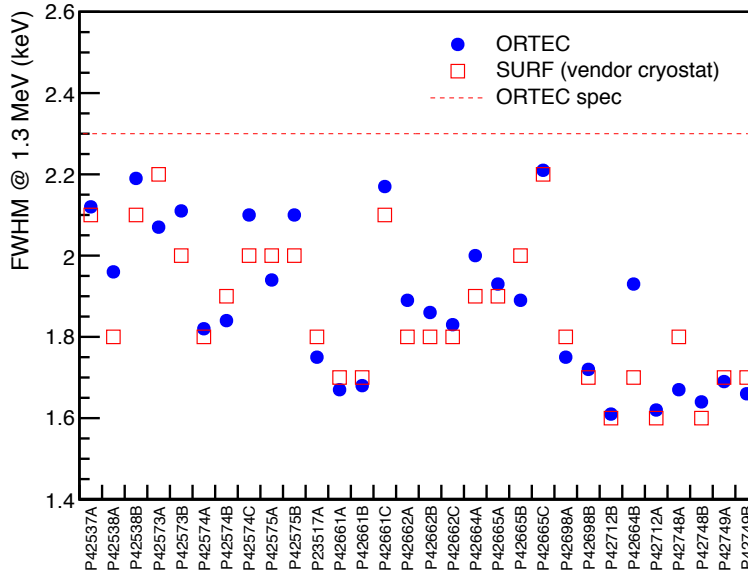
Figure 7: Energy resolution at 1332.5 keV of the 30 enriched detectors measured by ORTEC (dots) and by MJD collaboration at SURF (open squares), plotted against detector serial number.

4 Conclusion

Developed ultra sensitive ICP-MS assays show that the Cu being electroformed underground is clean and the background budget projects to < 3.1 counts/(ROI-t-y). Prototype module with three strings of ^{nat}Ge detectors was constructed in 2013 and has been in commissioning. All enriched detectors met requirements during characterization in the vendor cryostat at ORTEC$^{®}$ and SURF. At the time of this presentation MAJORANA is in the process of installing the detectors in specially designed low-background mounts and strings. First measurements in the string test cryostats show

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positive results with respects to integrity and performance of the detectors in the MAJORANA mounts.

Acknowledgment

References

[1] *L. Camilleri, E. Lisi, and J. F. Wilkerson* Neutrino Masses and Mixings: Status and Prospects// Ann. Rev. Nucl. Part. Sci. 58, 343 (2008)

[2] *F. T. III. Avignone, S. R. Elliott, and J. Engel* Double beta decay, Majorana neutrinos, and neutrino mass// Rev. Mod. Phys. 80, 481 (2008)

[3] *M. Gell-Mann, P. Ramond, and R. Slansky* Supergravity // North-Holland, Amsterdam, 1979, p. 315

[4] *R. N. Mohapatra, and G. Senjanovic*// Phys. Rev. Lett. 44, 912-915 (1980)

[5] *J. Vergados, H. Ejiri, and F. Simkovic*// Rept. Prog. Phys. 75, 106301 (2012), 1205.0649

[6] *L. Baudis et al.* Limits on the Majorana Neutrino Mass in the 0.1 eV Range// Phys. Rev. Lett., 83:41,1999

[7] *C.E. Aalseth et al.* IGEX ^{76}Ge neutrinoless double-beta decay experiment:Prospects for next generation experimentts// Phys. Rev. D, 65:092007, 2002

[8] *H.V. Klapdor-Kleingrothaus and I.V. Krivosheina* The evidence for the observation of 0nu beta beta decay: The identification of 0nu beta beta events from the full spectra// Mod. Phys. Lett. A, 21:1547, 2006

[9] *M. Agostini et al.* Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment// Phys. Rev. Lett., 111:122503, 2013

[10] *A. Gando et al.* Limit on Neutrinoless $\beta\beta$ Decay of ^{136}Xe from the First Phase of KamLAND-Zen and Comparison with the Positive Claim in ^{76}Ge// Phys. Rev. Lett., 110:062502, 2013

[11] *J.B. Albert et al.* Improved measurement of the 2 half-life of ^{136}Xe with the EXO-200 detector// Phys. Rev. C, 89:015502, 2014

[12] *G.J. Feldman, and R.D. Cousins*// Phys. Rev. D 57, 3873-3889 (1998)

[13] *F. Simkovic, A. Faessler, H. Muther, V. Rodin, and M. Stauf*// Phys. Rev. C 79, 055501 (2009)

[14] *N. Abgrall et al.* The Majorana Demonstrator Neutrinoless Double-Beta Decay Experiment// Adv. High En. Phys. 2014: 365432, 2014

[15] *E.W. Hoppe et al.*// J. Radioanal. Nucl. Chem. 282, 315 (2009)

[16] *P.N. Luke, F.S. Goulding, N.W. Madden, and R.H. Pehl* Low capacitance large volume shaped-field germanium detector// IEEE Transactions on Nuclear Science 36, 926 (1989)

[17] *P.S. Barbeau, J.I. Collar, and O. Tench* Large-mass ultralow noise germanium detectors: performance and applications in neutrino and astroparticle physics// JCAP, 2007, 9 (2007)

[18] *D. Budjas, M.B. Heider, O. Chkvorets, N. Khanbekov, and S. Schonert*// 2009 JINST 4 P10007

[19] *R. Cooper et al.*// Nucl. Instr. and Meth. A 629, 303 (2011)

[20] *Canberra Industries, Meriden, Conn, USA, 2009*

[21] *ORTEC, Oak Ridge, Tenn, USA, 2009*

[22] *M.A. Howe et al.*// 2004 IEEE Transactions on Nuclear Science 51 878