

# Double beta decay searches by semiconductor detectors

Carla Maria Cattadori<sup>1</sup>

INFN-Milano Bicocca, Piazzale della Scienza 3, 20126 Milano

E-mail: [carla.cattadori@lngs.infn.it](mailto:carla.cattadori@lngs.infn.it)

**Abstract.** This paper is focused on forthcoming or planned experimental projects and R&D activities aiming to search for  $0\nu$  double beta decay ( $0\nu$ DBD) of  $^{76}\text{Ge}$ ,  $^{106}\text{Cd}$  and  $^{64}\text{Zn}$  by means of semiconductor detectors. Semiconductors detectors offer both exceptional intrinsic energy resolution, and extremely high intrinsic radiopurity. These features allow, once the external background is minimized, to reach high sensitivities on the half-life ( $T_{1/2}^{0\nu}$ ) of the  $0\nu$ DBD process i.e. on the effective Majorana neutrino mass  $|m_{ee}|$ . After a review of the pioneering and past experiments, the main experimental features, the attainable sensitivities on  $T_{1/2}^{0\nu}$  and  $|m_{ee}|$ , and the foreseen experimental schedule of GERDA, MAJORANA and COBRA will be reviewed.

## 1. Introduction and history of $^{76}\text{Ge}$ DBD searches

$^{76}\text{Ge}$  is the isotope that can claim the longest history in DBD direct searches as:

- it belongs to an isobar triplet whose energy levels are arranged as  $E_{A,Z+1}^0 > E_{A,Z}^0 > E_{A,Z+2}^0$  as shown in figure 1;
- germanium detectors are an established technology assuring a high ( $> 90\%$ ) efficiency for  $\beta$  events generated internally, and high energy resolution. They have been adopted since the '60s to search for DBD of  $^{76}\text{Ge}$ , acting as source and detector at same time. Ge(HP) is an intrinsically pure material ( $O(10^{10})$  impurities  $\text{cm}^{-3}$ ), and energy resolution of  $O(0.1\%)$  can be achieved with HPGe detectors, allowing full characterization of background sources.
- Ge density ( $5.3 \text{ g}\cdot\text{cm}^{-3}$ ) and low atomic mass allow compact and scalable setups with an high number of nuclei per unit mass (1 kg of  $^{76}\text{Ge}$  corresponds  $\sim 7 \cdot 10^{24}$  nuclei);
- the nuclear matrix element ( $M^{0\nu}$ ) for the zero neutrino transition is favorable (3.9 in the recentest RQRPA calculation [1]), and different computations differs of  $\sim 3$ , leading to an expected  $T_{1/2}^{0\nu} \sim 10^{27}$  for  $|m_{ee}| = 0.40 \text{ meV}$ ; the  $Q_{\beta\beta}$  value of 2039 keV provide favorable phase space and is above most of the  $\gamma$  lines of natural radioisotopes;
- germanium can be efficiently enriched (up to  $\sim 85\%$ ) in the 76 isotope, in form of  $\text{GeF}_4$  (a gaseous molecule) in isotopic centrifuge separation plants.

Finally it is worthwhile to mention that germanium detectors measure the energy of the ionizing events but not momentum and angular distributions of the particles; nevertheless in the last decade hardware and software techniques to distinguish between multi-ionization sites and single-site events, i.e.  $\gamma$  from  $\beta$  have been developed [2].

<sup>1</sup> On behalf of the GERDA collaboration

The existence of stable isobar triplets arranged as shown in fig. 1 was first hypothesized by Heisenberg in 1932 [3] to explain why only isobars of even difference in atomic number occur. Then in 1935 Wigner and Goeppert-Meyer [4], described and computed, as an extension of the  $\beta$ -decay Fermi theory, the  $2\nu$ DBD decay process  $(A,Z) \rightarrow (A,Z+2)$ ;  $2\nu$ DBD is a second order process of weak interactions with the emission of two electrons and two neutrinos. The  $0\nu$ DBD process was then proposed by Furry [5] in 1939, requiring lepton number violation, and that  $\nu_e$  is a Majorana particle ( $\nu_e = \bar{\nu}_e$ ) of finite mass  $|m_{ee}|$ ; the process can be also induced by the existence of right handed currents ( $W_R$ ) in weak interactions. The Feynmann diagramm of  $0\nu$ DBD is shown if figure 2. After the discovery of neutrino oscillations we know that ( $|m_{ee}| = |\sum_i U_{ei}^2 m_i|$ ), being  $U_{ei}$  the elements of the neutrino mixing matrix and  $m_i$  are the neutrino mass eigenstates. The half-live of  $0\nu$ DBD is related to the transition phase space ( $F^{0\nu}$ ), the nuclear matrix element ( $M^{0\nu}$ ) and the effective Majorana neutrino mass  $|m_{ee}|$ , in the following way:

$$(T_{1/2}^{0\nu})^{-1} = G_F \cdot F^{0\nu} |M^{0\nu}|^2 \frac{|m_{ee}|^2}{m_e}$$

Germanium spectrometry is an established technology adopted since the '60s to search for  $0\nu\beta\beta$  of  $^{76}\text{Ge}$ . The parameters determining the sensitivity of a DBD experiment are the mass of the sample  $M$ , the measurement time  $t$ , the background index  $b$ , the energy resolution  $R$ , the efficiency  $\epsilon$  and the fraction  $a$  of isotope enrichment. In case of non-zero background, the sensitivity on  $T_{1/2}^{0\nu}$ , i.e. the minimal number of detectable events above background at a given confidence level is  $\propto \epsilon a \frac{Mt}{bR}^{1/2}$ , while in absence of background is  $\propto \epsilon a Mt$

It is worthwhile to mention here that the first direct search of  $0\nu$ DBD of  $^{76}\text{Ge}$ , using a  $17 \text{ cm}^3$  Ge(Li) detector acting as source and detector at the same time, published in 1967 [6], gave the limit  $T_{1/2}^{0\nu} > 3.1 \cdot 10^{20}$  y (at 68% C.L.) for the  $0\nu$ DBD; this result was obtained from 712 hours of data taking with an energy resolution of 4.7 keV FWHM at  $^{60}\text{Co}$  1.332 MeV line, and a background rate at the  $Q_{\beta\beta}$  of  $1.1 \cdot 10^{-2}$  c/(keV·h) $^{-1}$ .

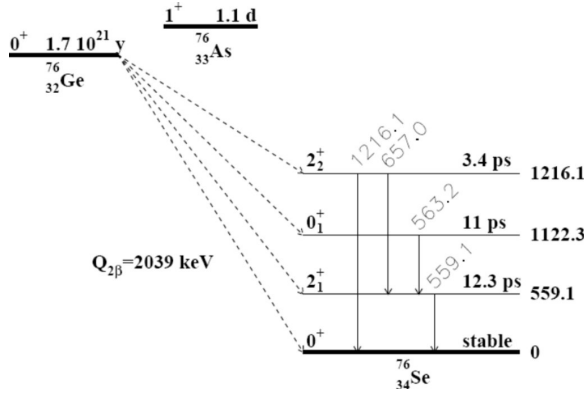
Then in the '70s and '80s other experiments performed with non-enriched germanium detectors came, and the experimental limits on the half-lives was further pushed in the  $10^{22} \div 10^{23}$  y range [7, 8]. The next step ahead in improving the sensitivity on  $T_{1/2}^{0\nu}$  came from adopting,  $^{76}\text{Ge}$  - enriched germanium detectors (up to 85%), and further improving the shielding and the radiopurity of the experimental apparatus.

The  $2\nu$ DBD of  $^{76}\text{Ge}$  has been observed and measured for the first time in 1990, i.e. only  $\sim 55$  years after it was suggested; the present highest statistic measurement of the  $2\nu$ DBD of  $^{76}\text{Ge}$  gives  $T_{1/2}^{0\nu} = 1.74 \cdot 10^{21}$  y [9].  $2\nu$ DBD has been observed also for several other isotopes as  $^{100}\text{Mo}$ ,  $^{136}\text{Xe}$ ,  $^{150}\text{Nd}$  etc. with different experimental techniques.

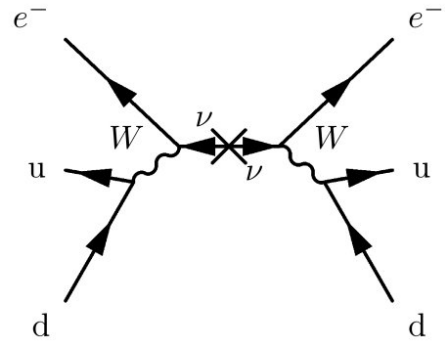
## 2. $0\nu\beta\beta$ decay of $^{76}\text{Ge}$ : present status

Evidence for  $^{76}\text{Ge}$  neutrinoless double beta decay [9] has been claimed at  $4.2 \sigma$  by a part of the Heidelberg-Moscow (HdM) collaboration; the experiment was performed at LNGS between 1996 and 2003. With a total exposure of 72 kg·y a background  $b=0.11$  cts/(kg·keV·y) (before pulse shape analysis) and energy resolution  $R=3.27$  keV, an evidence of  $0\nu$ DBD has been claimed with an half-life of  $1.2_{-0.5}^{+3.0} \cdot 10^{25}$  y ( $3\sigma$  errors), corresponding to  $0.1 < |m_{ee}| < 0.9$  depending on the adopted  $M^{0\nu}$ ; when the calculation by Klapdor-Kleingrothaus are used the claimed half-life corresponds to  $|m_{ee}| = 440$  meV.

No positive indication came from the IGEX experiment [2] performed at the Canfranc laboratory; with an exposure of 8.9 kg·y and  $b=0.2$  cts/(keV·kg·y) before pulse shape analysis (0.1 cts/(keV·kg·y) after pulse shape analysis), the obtained lower limit on the half-life was of



**Figure 1.** The  $A=76$  (Ge,As,Se) isobar triplet



**Figure 2.** The Feynmann diagram of  $0\nu$ DBD

$T_{1/2}^{0\nu} > 1.57 \cdot 10^{25}$  y corresponding to  $0.33 < |m_{ee}| < 1.3$  eV, depending on the assumed nuclear matrix element calculation.

To scrutinize the existing claim or improve the limit on  $T_{1/2}^{0\nu}$ , new generation experiments need to *i)* significantly reduce the background reaching at least the  $10^{-2}$  cts/(keV·kg·y) level, and *ii)* significantly improve the target mass, as the germanium detector energy resolution cannot be significantly further improved.

### 3. Forthcoming experiments: GERDA

The GERDA experiment was proposed in 2004 [10] and is in construction at LNGS. Figure 3 shows its conceptual design. The germanium detector array is placed at the center of concentric shields of increasing radiopurity and effective thickness;  $\sim 3$  m of ultrapure water to thermalize neutrons and veto cosmic rays, 5 to 7 cm of OFHC copper and finally  $\sim 2$  m of LAr. The detector array, formed by strings of 3 detectors each, is placed at the center of the shields. The experimental setup is conceived and built to have at the detector array location a background  $\leq 10^{-3}$  cts/(keV·kg·y). The GERDA main peculiarity is that detectors are operated naked in LAr acting as the same time as cooling medium and shielding material. The experimental technique was proposed in 1995 by G.Heusser [11]; setups based on this techniques have been described in the GEM [13], GENIUS [12] and GERDA [10] proposals. GERDA has chosen LAr as cooling and shielding medium for detectors, as it provides a better shielding ( $\rho_{LAr} = 1.4$  g/cm<sup>3</sup> vs  $\rho_{LN} = 0.8$  g/cm<sup>3</sup>) and the possibility to exploit the scintillation light produced by ionizing radiation to veto background events. Therefore the GERDA collaboration pursued a 3 year long original and extensive experimental activity to demonstrate the feasibility, the performances and the stability of naked detectors when operated in LAr, and to define the critical issues related to detector operation in GERDA environment, namely the detector mounting, manipulation and reprocessing (for Phase I detectors) technologies. The detector instabilities claimed in the GENIUS-TF experimental work [14] have been overcome (see f.i. poster n. 55 of this conference); in particular the stability of detector reverse current, gain and energy resolution has been proved.

GERDA is foreseen to proceed in two phases:

- (i) *Phase I:* eight reprocessed enriched ( $\sim 85\%$ ) (p-type semi-coaxial) HPGe detectors from the past HDM [15] and IGEX [16] experiments for a total mass of  $\sim 18$  kg and, eventually, five reprocessed natural (p-type semi-coaxial) HPGe detectors ( $\sim 15$  kg) from the Genius Test-Facility [17] will be deployed in strings. The expected background is  $\sim 10^{-2}$  cts/(keV·kg·y) in the  $Q_{\beta\beta}$  range, dominated by intrinsic detector background,

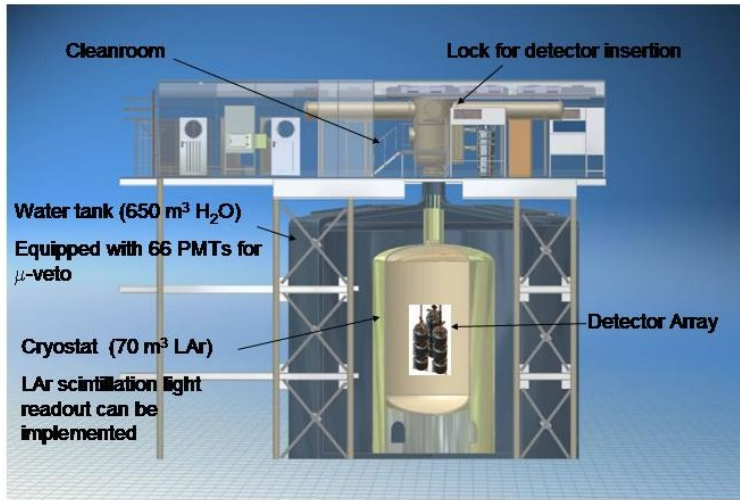


Figure 3. The GERDA conceptual design



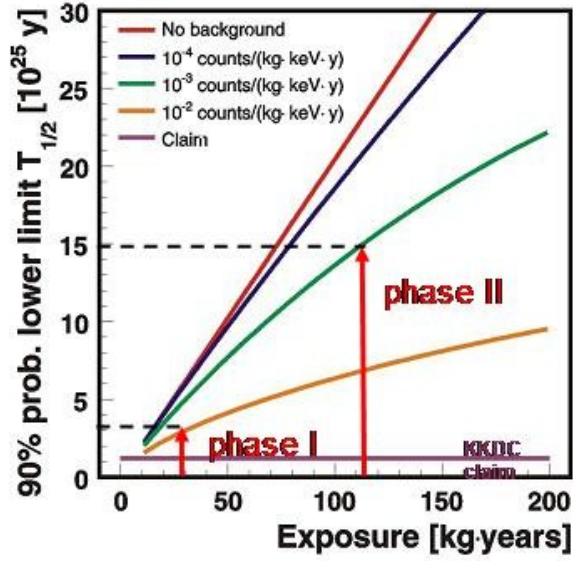
Figure 4. The construction of the GERDA water tank on May 2008

related to their history and fabrication procedures. Assuming an exposure of  $\sim 15$  kg·y and  $R \sim 3.6$  keV, if no event is observed, the limit on the half life will be  $T_{1/2}^{0\nu} > 3 \cdot 10^{25}$  y (90 % C.L.) resulting in an upper limit of  $|m_{ee}| < 270$  meV adopting  $M^{0\nu}$  from [1] (see figure 5 and 6)

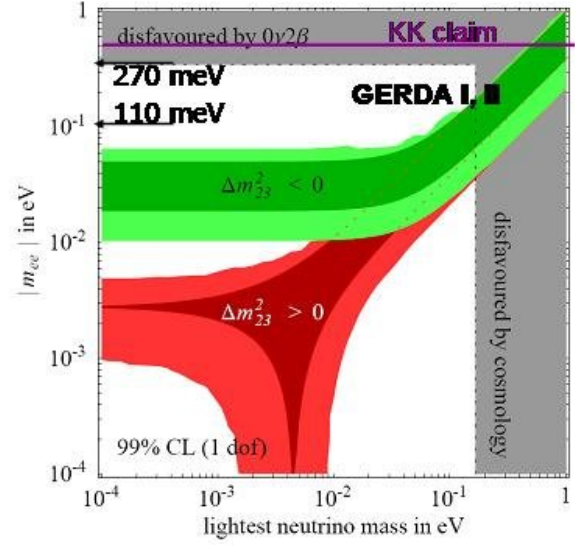
- (ii) *Phase II*: new diodes, with improved multi-site to single-site events discrimination capability, will be added to reach a total mass of  $^{76}\text{Ge}$  of  $\sim 40$  kg. Detectors fabrication procedures will guarantee to keep the intrinsic background well below  $10^{-3}$  cts/(keV·kg·y). Reducing the background index of an order of magnitude, will allow, with an exposure of about 120 kg·y, either to measure with improved accuracy the  $T_{1/2}^{0\nu}$  (assuming the claim) or, to set a limit on  $T_{1/2}^{0\nu} > 1.5 \cdot 10^{26}$  y (90% C.L.) corresponding to  $|m_{ee}| < 110$  meV adopting nuclear matrix elements from [1] .
- (iii) *Phase III*: Depending on results of Phase I and Phase II a ton-scale experiment on world wide collaboration is considered, to reach sensitivity on  $|m_{ee}|$  of 40 meV (see fig.6) and therefore be able to probe the inverted mass hierarchy region of the neutrino mass eigenstates: the experimental approach between the GERDA and MAJORANA ones that will prove to perform better will be taken. The collaborations are in strict contact developing working tools as MAGE, the joint simulation framework.

In case the HDM signal was  $0\nu\beta\beta$  decay, this would produce in about 1 year of GERDA Phase I data taking ( $\sim 15$  kg·y) 7 counts above background of 0.5 counts, and GERDA Phase II will be able to measure the  $T_{1/2}^{0\nu}$  but if no event is observed, the claim would be ruled out with 99.6 % C.L. [10].

The construction of the experimental setup started at LNGS on July 2007 and figure 4 shows the construction on-site of the water tank around the cryostat. The main achievements at September 2008 are listed in the following: the 70 m<sup>3</sup> cryostat entirely built of stainless steel  $\gamma$ -ray screened to have a  $^{228}\text{Th}$  content below few mBq/kg, has been delivered and tested on site (cryotests, Rn emanation) and the inner cryostat Cu lining has been installed; The 650 m<sup>3</sup> water tank has been fully constructed and partially tested, the technical building which surrounds and overwhelms the water tank is almost completed; the cryogenic infrastructures (cryogenic stocking container, pipings etc.) and ancillary plants have been fully designed and



**Figure 5.** The GERDA sensitivity on  $T_{1/2}^{0\nu}$  as a function of exposure and background rate.



**Figure 6.** The GERDA sensitivity on  $|m_{ee}|$ , derived from  $T_{1/2}^{0\nu}$ , superimposed to a  $|m_{ee}|$  vs mass of the lightest neutrino plot from [22]

will be installed in last trimester of 2008, and first trimester 2009. The lock (to insert detectors into the cryostat) is also in construction; The 66 PMTs to veto muon crossing the WT through readout of Cerenkov light have been procured, their encapsulation tested, and they will be mounted in the setup within 2008. The cryogenic front-end electronics to read-out the detectors has been originally designed to satisfy all the GERDA requirements and produced by AMS HV CMOS 0.8  $\mu\text{m}$  CZX technology [18]. It has an equivalent noise charge in the range of  $180 e^-$  r.m.s at cryogenic temperatures for  $C_{det} = 30$  pf and bandwidth of  $\sim 30$  MHz; the circuit has discrete input FET and feed-back components, and a fully integrated version is also under development. Coupling the semi-integrated circuit to an encapsulated and to a naked detectors an energy resolution (FWHM) of 2.3 keV and 3.2 keV respectively has been achieved. The latter figure can be further improved optimizing the detector-front-end and HV connections; The FADC signal readout system (14 bit, 100MHz, FADC through PCI bus), allowing to perform PSA analysis as well as spectrometry measurements is ready (hardware and software) and under test; The Phase I detectors have been completely reprocessed and their performances have been tested along summer 2008.

GERDA collaboration belongs 37.5 kg of  $^{76}\text{Ge}$  enriched (up to 86%) in form of  $\text{GeO}_2$ , which are presently stocked at the HADES underground facility. An extensive R&D activity has been started up to define procedure of germanium purification, minimizing the wastes, and to pull n-type crystals. The definition of detectors type for phase II is ongoing: beside the nominal option (18-fold segmentation,  $6\Phi \times 3z$ ) that allows a factor 10 reduction for internal contamination and a factor 3 reduction for external  $\gamma$ s [19], other options are at present under investigation, as Canberra BEGe detectors, with a modified electrode geometry, that recently proved to lead to similar multi-site event rejection capabilities.

The GERDA collaboration is finalizing the various activities to start the Phase I data taking within 2009.

#### 4. Future experiments: MAJORANA

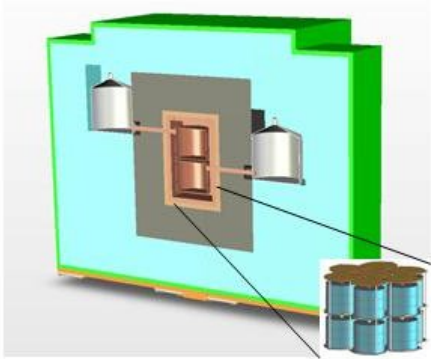
The original MAJORANA project foreseen eight modules with fifty-seven, 1.1 kg segmented Ge detectors each, for a total of  $\sim 500$  kg of Ge, enriched to 86% in  $^{76}\text{Ge}$ . The detectors within each module would be arranged in a hexagonal configuration of 19 towers, each three detectors high, inside of a copper cryostat. In order to reach the needed radiopurity for  $^{214}\text{Bi}$  and  $^{228}\text{Th}$  ( $0.3 \mu\text{Bq/kg}$ , and  $0.1 \mu\text{Bq/kg}$  respectively) the cryostats must be electroformed as in the case of the IGEX cryostats. An intense R&D project is underway to reach the following levels of radiopurity for the Cu.

At present the MAJORANA collaboration is working at the design and construction of one 30-kg Ge detector module to prove the background of the chosen experimental setup concept (Pb and Cu passive shields, Cu electroforming etc.). The science goal is to then build a 30-kg of  $^{76}\text{Ge}$  enriched detectors to scrutinize the recent  $0\nu\text{DBD}$  claim. This approach has been guided by NuSAG review (March '06), and a DOE NP  $0\nu\text{DBD}$  pre-conceptual design review panel (November '06). The demonstrator modules will be located at SUSEL/DUSEL laboratory and will contain p- and n-type, segmented and point-contact detectors. MAJORANA recentest technological progress are listed in the following:

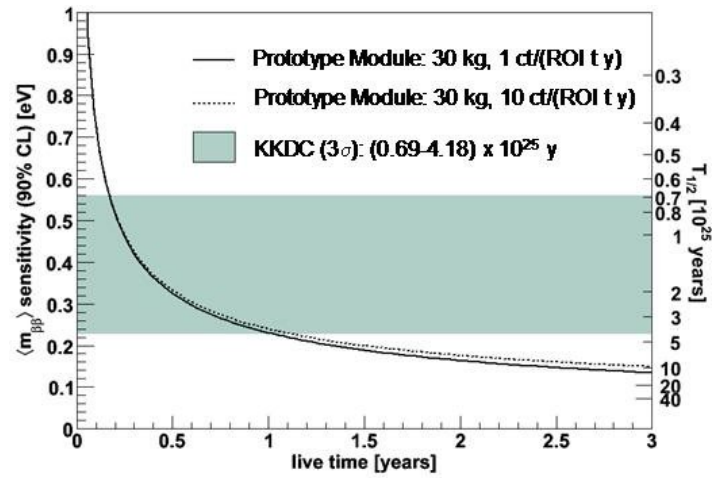
- *Materials & Assay* - Samples of low-activity plastics and cables have been obtained for radiometric counting and neutron activation analysis. Additional improvements have been gained in producing pure Cu through electroforming at PNNL and we have established an operating pilot program demonstrating electroforming underground at WIPP.
- *Ge Enrichment* - Options available for germanium oxide reduction, Ge refinement, and efficient material recycling are being considered, including developing this capability located near detector fabrication facilities.
- *Detectors* - Additional p-type point contact (PPC) detectors [20] have been ordered. Progress has been made in E-M modeling. A PPC detector has been successfully fabricated at the LBNL Instrument Support Laboratory. Efforts to deploy a prototype low-background N-type segmented contact (NSC) detector using the enriched SEGA crystal are underway. This will allow us to test low-mass deployment hardware and readout concepts while working in conjunction with a detector manufacturer.
- *Cryostat Modules* - A realistic prototype deployment system has been constructed at LANL. First measurements, with one string and a single P-type HPGe detector have been completed.
- *DAQ & Electronics* - Modeling of preamps to optimize noise are being compared to measurements. ORCA support for a TCP-IP based VME crate controller has been completed.
- *Facilities* - Designs for an underground electroforming facility and a detector laboratory located on the 4850 level in the Homestake Mine have been developed in conjunction with SUSEL engineers.
- *Simulations* - Developed a common framework (MAGE) in a joint effort with GERDA.

#### 5. Activities in R&D phase: COBRA

COBRA[23] is an R&D program developing CdZnTe (CZT) semiconductor crystal detectors for  $0\nu\text{DBD}$  searches. CZT detectors contain 9 DBD decaying isotopes: the isotopes  $^{116}\text{Cd}$ ,  $^{130}\text{Te}$ ,  $^{114}\text{Cd}$ ,  $^{70}\text{Zn}$ , and  $^{128}\text{Te}$  are  $\beta^-\beta^-$  emitters, whereas the isotopes  $^{64}\text{Zn}$ ,  $^{106}\text{Cd}$ ,  $^{108}\text{Cd}$ , and  $^{120}\text{Te}$  are  $\beta^+\beta^+$  emitters, or  $\beta^-$ -EC, or EC-EC. Among these  $^{116}\text{Cd}$  (isotopic abundance = 7.5%) has the highest  $Q_{\beta\beta} = 2.8$  MeV and therefore will offer the best sensitivity: enrichment will be mandatory for a competitive experiment. The proposal is to operate 64,000 1-cm<sup>3</sup> CZT detectors for a total mass of 418 kg. The detectors would be fabricated with Cd enriched to



**Figure 7.** The MAJORANA conceptual design

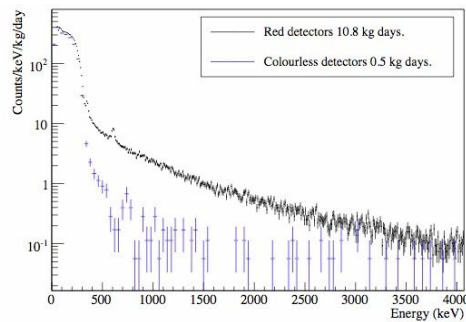


**Figure 8.** The MAJORANA sensitivity on  $T_{1/2}^{0\nu}$  (right scale) and  $|m_{ee}|$  (left scale).

90% in isotope 116, so about 44%, or 183 kg, of the detector mass is the isotope of interest. Current aim is to run an array of 64 detectors. Since 2006 the first 16, shown in figure 9, are running at LNGS and taking data. The best obtained energy resolution (FWHM) of the coplanar grid (CPG) detectors is better than 0.4% at 2.8 MeV. Analyzing the energy spectrum relative to 11.9 (kg·d) exposure the authors found that in the energy region around the  $^{116}\text{Cd}$  endpoint the background is at level of 1 c/(keV·kg·d) (see figure 10) and is dominated by Rn and radioactive impurities (mostly  $^{238}\text{U}$  and  $^{232}\text{Th}$ ) contained in the detector passivation varnish. When operating 4 detectors with different passivation the background is reduced of a factor  $\sim 10$ . With the level of background experienced in the  $\sim 12$  (kg·d) of exposure, the limit on the half-life of the  $0\nu\text{DBD}$  of  $^{116}\text{Cd}$  is  $6.05 \cdot 10^{19}$  y; the collaboration set also the limits of  $7.43 \cdot 10^{18}$  y on the  $0\nu 2EC$  (to g.s.) of  $^{64}\text{Zn}$  and of  $5.48 \cdot 10^{18}$  y on the  $0\nu 2EC$  (to g.s.) of  $^{106}\text{Cd}$ . The collaboration is planning to build pixelized detectors (pixel dimension 200  $\mu\text{m}$ ) to extensively reduce background by particle identification.



**Figure 9.** The COBRA 16-detector array



**Figure 10.** The background spectrum and the improvement obtained removing the passivation varnish

## 6. Conclusions

$0\nu$ DBD searches by germanium detectors have the longest history in the field. Solar neutrino and reactor experiments proved that neutrinos are massive particles. The mass of the electron neutrino could be measured by the KATRIN  ${}^3\text{H}$   $\beta$ -end-point spectral shape experiment, if the mass is  $\geq 0.2$  eV. If the mass is  $< 0.2$  eV, and neutrinos are Majorana particles,  $0\nu$ DBD searches are the only practicable method to determine the neutrino mass scale and nature. GERDA experiment is under construction and will be operative within 2009. MAJORANA is still in the funding and approval path; GERDA and MAJORANA are in strict contact to eventually proceed to a ton-scale experiment adopting the experimental technique that will prove to perform better. Other experimental techniques adopting CZT detectors are interesting but not yet competitive for the scientific goal.

## 7. References

- [1] V.A. Rodin et al., 2006 *Nucl. Phys.* **A766** 107.
- [2] C.E. Aalseth et al., 2002 *Phys. Rev.* **D65**, 092007.
- [3] W. Heisenberg, 1932 *Zeits. f. Physik* **78**, 156.
- [4] Goeppert-Mayer 1935 *Phys. Rev.* **48**, 512.
- [5] W.H. Furry, 1939 *Physical Review* **56**, 117.
- [6] E. Fiorini et al. 1967 *Phys. Lett.* **B25**, 602.
- [7] Caldwell, 1986, Proceedings of Neutrino 1986 - Sendai.
- [8] E. Bellotti et al., 1986, *Il Nuovo Cimento* **95A**, 1.
- [9] H.V.Klapdor-Kleingrothaus et al., 2004 *Phys. Lett.* **B586**, 198.
- [10] GERDA Collaboration 2004 *Proposal* <http://www.mpi-hd.mpg.de/GERDA/proposal.pdf>
- [11] G. Heusser, 1995 *Ann. Rev. Nucl. Part. Sci.* **45**, 543.
- [12] H.V. Klapdor-Kleingrothaus et al. *hep-ph/9910205* and L. Baudis et al., 1999 *NIMA***426** 425.
- [13] Yu.G. Zdesenko et al., 2001 *J. Phys.* **G27** 2129.
- [14] H.V.Klapdor-Kleingrothaus and I. Krivoshina, 2006 *Nucl. Instr. Methods* **A566**, 472.
- [15] C. Balysh et al. 1997 *Phys. Rev.* **D66** 54.
- [16] C.E. Aalseth et al., 2000 *Phys. of Atomic Nuclei* **63** 1225.
- [17] H.V. Klapdor-Kleingrothaus et al., 2002 *NIM* **A481** 149.
- [18] A. Pullia et al., 2006 *IEEE TRANS NUCL SCI* **53,3** 1744.
- [19] I. Abt et al., 2007 *NIM* **A577** 574.
- [20] P.S. Barbeau et al., 2007 *JCAP* **09** 009 and [*nucl-ex/0701012v1*].
- [21] Gaitskell et al., 2003 [*nucl-ex/0311013*]
- [22] F. Vissani and A. Strumia, 2006 *Nucl Phys.* **A766** 107, and [*hep-ph/0606054v2*].
- [23] K. Zuber, 2001, *Phys. Lett.* **B519**,001.