GERDA commissioning results and summary of double beta decay projects

F. Cossavella for the GERDA collaboration
Max-Planck-Institut für Physik, Föhringer Ring 6,
80805 München, Germany

The Germanium Detector Array (GERDA) experiment searches for neutrinoless double beta decay of ^{76}Ge to test if neutrinos are Majorana particles, identical to their own antiparticles, or Dirac particles with distinct antiparticles. Neutrinoless double beta decay experiments can also place a limit on the effective neutrino mass and probe the neutrino mass hierarchy. Acting as both source and detector, germanium crystals enriched in ^{76}Ge will be submerged in an ultrapure cryogenic liquid that serves as a cooling medium and a shield against radiation. Together with a careful selection of radiopure construction materials and backround recognition techniques, GERDA can suppress background signals up to two orders of magnitude better than earlier experiments. This contribution presents the status of the GERDA experiment, installed in the underground laboratory of LNGS (INFN, Italy). The expected performance is compared to other neutrinoless double beta decay searches that start commissioning in the near future.

1 Neutrino properties

Several experiments have observed the oscillation of neutrino species, which requires nonzero neutrino masses, and measured their squared-mass differences.[1] However, there are still unknowns: the neutrino absolute mass scale, the mass hierarchy, and whether the neutrinos are their own antiparticles, that is whether the neutrino is a Majorana particle or the neutrino and the antineutrino are distinc Dirac particles.

The best known method to directly test the Majorana nature of the neutrino is the observation of neutrinoless double beta ($0\nu\beta\beta$) decay. Neutrino-accompanied double beta ($2\nu\beta\beta$) decay has been observed in several even-even nuclei,[2] for which the single beta decay is energetically forbidden. In these cases the final state consists of the residual nucleus, the two $\overline{\nu}_e$ and two electrons; and so the spectrum of the combined electron energies is continuous. Since the neutrino is massive, if it is its own antiparticle, then the $0\nu\beta\beta$ decay is allowed.[3] Since all the energy released by the nuclear decay is carried by detectable particles, the characteristic signature is a sharp peak in the combined-electron-energy spectrum at the Q value of the decay, known experimentally to within a fraction of a keV.

The $0\nu\beta\beta$ decay half life $T_{1/2}$ is inversely proportional to the square of the effective Majorana neutrino mass ($\langle m_{ee}\rangle$) according to the following relation:

$$\frac{1}{T_{1/2}} = F(Q,Z) \cdot |M_{\mathrm{nucl}}|^2 \cdot \langle m_{ee}\rangle^2 \tag{1}$$

$$\langle m_{ee}\rangle = \left|\sum_{i=1}^{3} |U_{e_i}|^2\, e^{i\beta_i}\, m_i\right|, \tag{2}$$

Table 1: Selective list of past $0\nu\beta\beta$ decay experiments and their 90%-C.L. half life lower limits.

Experiment	Underground lab	Isotope	Technology	$T_{1/2}[10^{24}\,\mathrm{y}]$	Ref.
Heidelberg-Moscow	LNGS (Italy)	^{76}Ge	HPGe	>19	5
claim:				$22.3^{+4.4}_{-3.1}$	6
IGEX	LSC (Spain)	^{76}Ge	HPGe	>16	7
NEMO-III	LSM (France)	^{82}Se	Foils btw.	>0.36	2
		^{100}Mo	tracker	>1.1	2
$CdWO_4$	Solotvina (Ukrain)	^{116}Cd	Scintillator	>0.17	8
CUORICINO	LNGS (Italy)	^{130}Te	Bolometry	>2.8	9

where the U_{e_i} are the electron-neutrino elements from the mixing matrix, $e^{i\beta_i}$ are their phase factors, m_i are the neutrino mass eigenvalues, $F(Q, Z)$ is the phase-space factor of the decay of a nucleus with atomic number Z and Q values Q, and $|M_{\mathrm{nucl}}|^2$ is the decay nuclear matrix element. Measurement of the $0\nu\beta\beta$ decay half life also gives information on the absolute mass scale of the neutrino, assuming the neutrino exchange is the dominant mechanism of the process. The overall uncertainty in the derived effective Majorana neutrino mass will be dominated by the uncertainties in the nuclear matrix element calculations.[4]

2 Results from former experiments

There are approximately thirty isotopes for which double beta decay is the primary decay channel. The sensitivity on the half-life $T_{1/2}$ for an experiment with nonvanishing background rate can be expressed as

$$\text{sensitivity on } T_{1/2} \propto \epsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}, \tag{3}$$

where ϵ is the detection efficiency, A is the double beta decay active mass fraction, M the target mass, T the measuring time, b the background rate, and ΔE is the energy resolution of the detector.

Increasing the exposure $M \cdot T$ is not sufficient to improve the sensitivity, if it is not accompanied by a reduction of the background level. Additionally, the sensitivity can be increased by an improvement of the energy resolution and by using source isotopes with a high natural abundance. We reduce the background rates by carefully selecting radiopure construction materials for any apparati in close proximity to the detectors and by shielding against external radiation. Employing high-resolution spectroscopy, we define a small energy window around the Q value in which to search for the $0\nu\beta\beta$ decay peak. By using a detector that is constructed from the source material, we obtain a detection efficiency of $\approx$100%.

Table 1 shows the results of some of the experiments performed so far. A variety of technologies and isotopes have been used in these experiments. They have measured lower limits on the half life of the decay. The best limits are set by the Heidelberg-Moscow (HdM)[5] and IGEX[7] collaborations, together with the most recent results of CUORICINO.[9] The corresponding upper limits on $\langle m_{ee} \rangle$, which are affected by the uncertainties in the calculation of the nuclear matrix elements, are in the sub-eV range. A subgroup of the Heidelberg-Moscow experiment claims evidence[6] for neutrinoless double beta decay with a half life of $22.3^{+4.4}_{-3.1} \cdot 10^{24}$ y, which gives[9] an effective Majorana neutrino mass of 0.18 eV–0.70 eV.

3 The GERDA experiment

The Germanium Detector Array (GERDA) experiment,[10] located at the Laboratori Nazionali del Gran Sasso of the INFN, Italy, uses germanium detectors enriched in the isotope ^{76}Ge to search for neutrinoless double beta decay. Although the ^{76}Ge natural abundance is only of 7.6%, it is possible to enrich germanium material to an abundance of more than 85%. This material can be used to produce high-purity germanium detectors that have good energy resolutions ($\Delta E = 3\,\mathrm{keV}$ at 2039 keV). Due to the uncertainties on the nuclear matrix elements, the claim[6] reported by part of the Heidelberg-Moscow collaboration can only be directly checked using the same isotope (^{76}Ge). GERDA is currently the only experiment able to do this.

The experiment is foreseen to proceed in two phases. In the first phase, enriched-Ge detectors which were previously operated by the Heidelberg-Moscow and IGEX collaborations will be redeployed, for a total mass of approximately 18 kg. With a background rate of 10^{-2} cts/(keV kg y), GERDA will be able to check the HdM claim within one year.[11] In the second phase, about 20 kg of new high-purity ^{76}Ge detectors will be produced with the goal of reaching an exposure of about 100 kg·y. GERDA Phase II aims at probing $0\nu\beta\beta$ decay of ^{76}Ge with a sensitivity of $T^{0\nu}_{1/2} > 1.5 \cdot 10^{26}$ y, corresponding to an upper limit on the effective Majorana neutrino mass in the range from 90 meV to 150 meV.[4] To reach this goal the background rate has to be further reduced to 10^{-3} cts/(keV kg y). For this purpose, GERDA will use Broad Energy Germanium (BEGe) detectors with a special electrode configuration, allowing for event-topology reconstruction by pulse-shape analysis and thus identification of background-like events.[12] A performance test of segmented germanium detectors[13,14] is also under discussion.

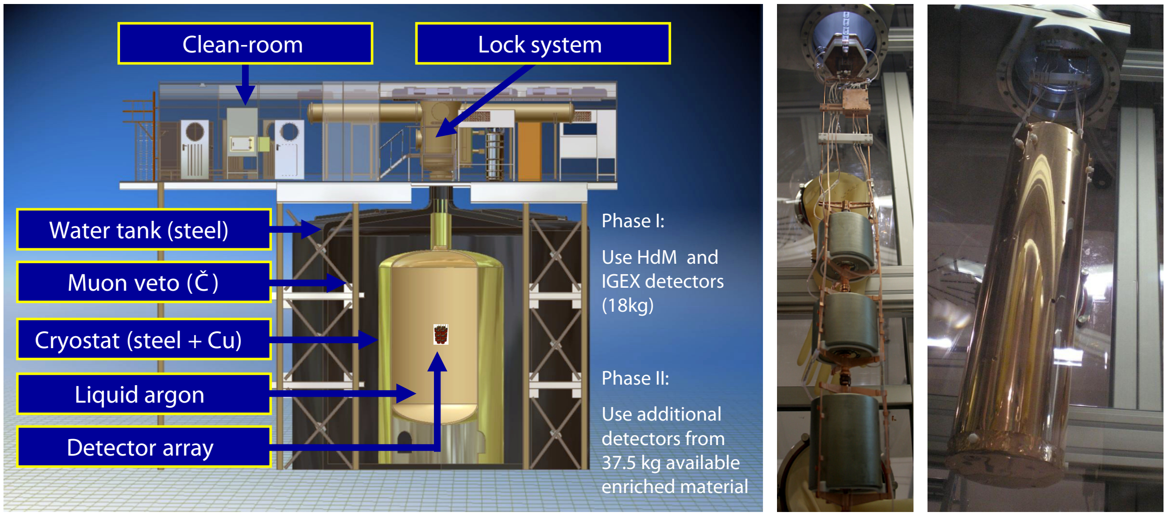
The detector array has to be shielded against external radiation. To reduce material in the proximity of the detectors, they are operated with minimal support and cabling in liquid argon, which acts as both a cooling medium and a shield. The cryostat is constructed from radiopure stainless steel with a low-background copper inset. It has a diameter of 4 m and a height of 8.9 m, and it is surrounded by a 10-m-diameter tank (8.5 m in height) containing ultrapure water that serves as a neutron moderator. This tank is equipped with photomultiplier tubes to detect the Čerenkhov light emitted by charged particles crossing the water medium; this allows it to also function as an active muon veto. A clean room with a lock system is placed on top of the cryostat. It allows for the clean access to the detectors and their submersion into the cooling medium. The setup is schematically depicted in Figure 1a.

3.1 Commissioning results

In June 2010 GERDA deployed the first string of natural Ge detector in the cryostat. A resolution of approximately 4 keV at 2.6 MeV was achieved in all three of the detectors on the string.

Since then, GERDA has been measuring the background spectrum and has seen a prominent line at 1524.7 keV from the decay of ^{42}K, a daughter of ^{42}Ar, expected to be a rare contaminant in atmospheric argon from a measured upper limit[15] and from numerical estimations.[16] ^{42}Ar is a β^- emitter with $T_{1/2} = 32.9$ y and a Q value of 599 keV.[17] The daughter of this reaction, ^{42}K, is also a β^- emitter ($T_{1/2} = 12.36$ h), which decays to the ground state of the stable isotope ^{42}Ca with a branching ratio of 82% and $Q_\beta = 3525.3$ keV. With 18% probability it decays to an excited level of ^{42}Ca that decays to the ground state by emission of a 1524.7 keV γ-ray, as has been observed in the background spectrum of GERDA. Since the endpoint energy of the ^{42}K decay is higher than that of ^{76}Ge, it can contribute to the GERDA background in the region of the ^{76}Ge Q value.

The decay of ^{42}Ar produces positively-charged ions that in the presence of an electrical field may drift long distances in liquid argon. Since the detectors have voltage-biased surfaces,



(a) (b) (c)

Figure 1: (a) Sketch of the GERDA experiment. The diameter of the cryostat is of 4 [m] for a height of 8.9 m and it is inserted into a water tank with a diameter of 10 m and height of 8.5 m)(b) First string deployed in June 2010 (c) Mini-shroud surrounding the string of detectors.

potassium ions drift to the detector surface before they neutralize, where they can contribute to the observed background above 1600 keV.

To close the electrical field lines from the germanium detectors and prevent the drifting of the ions onto the detector surface, the detector string has been surrounded by a thin copper layer (mini-shroud, Figure 1c). The mini-shroud was used for data taking runs 10 and 11; we compare the results to those from run 1–3, in which the mini-shroud was not present. Figure 2a shows that the count rate under the 1524.7 keV peak drops approximately by a factor of four when the mini-shroud is used. The integral count rate above this peak (between 1550 keV and 3000 keV) is also considerably reduced. In runs 1–3 a count rate of 0.17 cts/(keV kg y) was measured, with a 68% credibility interval from 0.16 cts/(keV kg y) to 0.19 cts/(keV kg y). In runs 10 and 11, with the introduction of the mini-shroud, the count rate in the same energy interval has been reduced to 0.074 cts/(keV kg y), with a 68% credibility interval of 0.066 cts/(keV kg y)–0.084 cts/(keV kg y) (see Figure. 2b).

From June 2010 to March 2011 a total of twelve runs with different detectors, electric field configurations and read out schemes were performed. To evaluate the background rate we take into account the total count rate in the region of interest, an energy window 400 keV-wide centered at $Q_{\beta\beta}$. The calculation is performed according to a Bayesian analysis, under the assumption that the spectrum in the energy window is flat. Using the framework Bayesian Analysis Toolkit (BAT),[18] the lowest measured background rate is 0.055 cts/(keV kg y) with a 68% credibility interval ranging from 0.041 cts/(keV kg y) to 0.072 cts/(keV kg y) (see fig. 3).

The measured background rate is a factor of two better than the past experiments,[5,7] although still a factor of five higher than the goal of GERDA Phase I. It has to be noticed that no pulse-shape analysis to discriminate background-like from signal-like events has been applied so far and that the measurement was performed with ^{nat}Ge detectors, whose cosmogenic-activation history is not as well known as that of the enriched Ge detectors. The origin of the background counts observed at $Q_{\beta\beta}$ is currently under investigation, in particular the contribution of the Compton continuum from natural chains (^{226}Ra, ^{228}Th) and from ^{42}K decays.

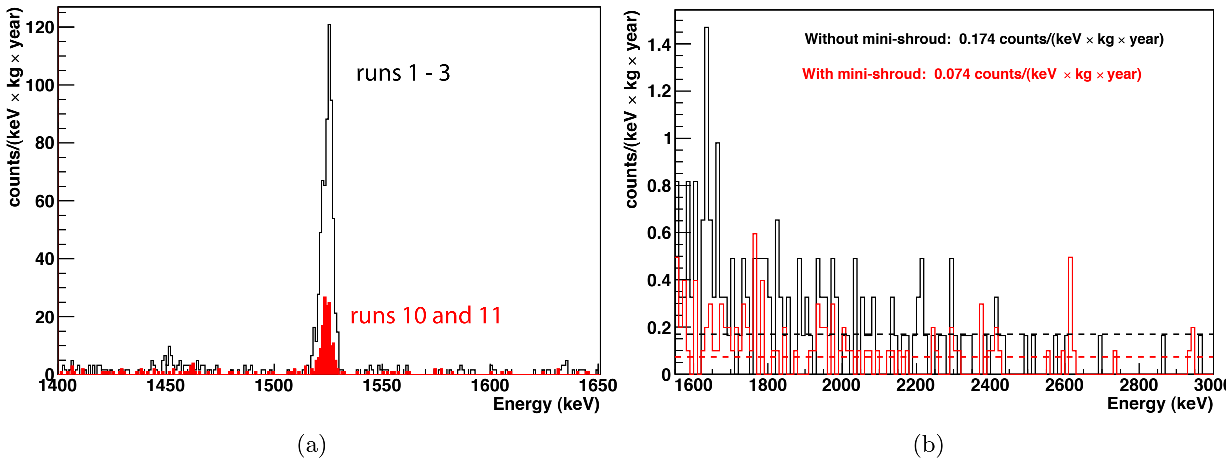


Figure 2: (a) Measured spectrum in an energy range centered at 1524.7 keV. In black are events from runs 1–3, without the mini-shroud; and in red are data collected in runs 10 and 11, with the mini-shroud. (b) Measured spectrum above 1550 keV for runs 1–3 (black) and runs 10 and 11 (red).

4 Status of other $0\nu\beta\beta$ decay experiments

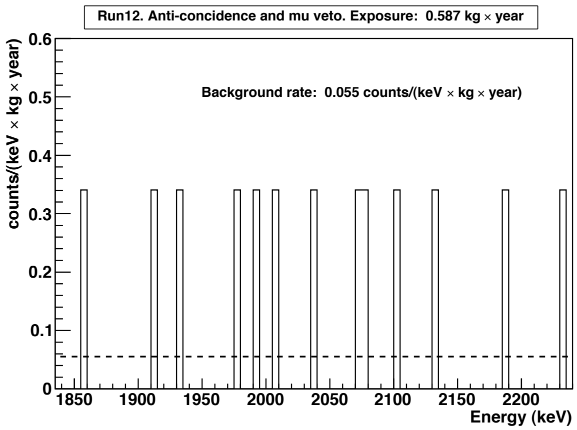
In the coming years, a few other experiments will be able to test the Heidelberg-Moscow results. Some of them are summarized in Table 2 and discussed in this contribution.

4.1 Majorana demonstrator

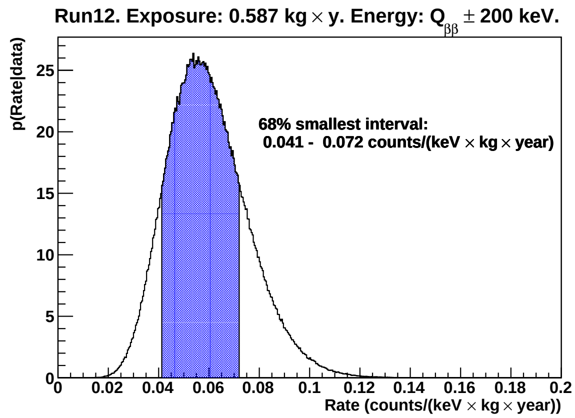
The Majorana demonstrator[19] is located at the Sanford laboratories, USA. The design uses high-purity ^{76}Ge-enriched BEGe detectors, which will be operated inside conventional low-background copper cryostats electro-formed underground. Like in GERDA Phase II, BEGe detectors with their very good pulse-shape analysis capabilities will allow for a better recognition of the background events. Majorana is currently in the construction phase. Commissioning of a prototype cryostat is foreseen in 2012. The first run with three strings of ^{enr}Ge detectors and four strings of ^{nat}Ge detector, with a total mass of about 20 kg, is planned for 2013. In 2014, an additional module with 20 kg detectors enriched in ^{76}Ge will be included, increasing the total target mass to 40 kg. The aim is to reach a background rate of 0.001 cts/(keV kg y) and a sensitivity on the neutrino Majorana mass better than 140 meV within three years of measurements.[20]

4.2 CUORE

The CUORE experiment[21] is currently being built at the Laboratori Nazionali del Gran Sasso. CUORE will use the ^{130}Te isotope in the form of TeO_2 crystals. The crystals, cooled down to mK temperatures, will be operated as bolometers, the energy deposits being measured by the induced temperature increase in the crystal. ^{130}Te has a natural isotopic abundance of 33.8%, so no enrichment is required. CUORE will also run in two phases. CUORE-0 will deploy into the cryostat of the CUORICINO experiment a detector tower with 52 crystals with improved radiopurity, for a total ^{130}Te mass of 11 kg. The background in this first phase is limited by an irreducible contribution from the CUORICINO cryostat to approximately 0.06 cts/(keV y) per kg of TeO_2. Together with the measured surface background contributions, the total background rate in the region of interest is estimated[22] to be approximately 0.12 cts/(keV y) per kg of TeO_2, which scales to approximately 0.4 cts/(keV y) per kg of ^{130}Te. With this assumption a sensitivity



(a)



(b)

Figure 3: (a) Measured spectrum in a 400-keV-wide window around $Q_{\beta\beta} = 2039\,\text{keV}$ for run 12. (b) posterior pdf for the background rate given the observed counts in the window. The smallest 68% interval is highlighted.

Table 2: Selective list of $0\nu\beta\beta$ decay experiments that are commissioned now or in the near future and will be able to test the HdM claim. Measured or estimated background rates and sensitivities on the effective Majorana neutrino mass are quoted (references in the text). The latter depend on the nuclear matrix element calculations used.

Experiment	Isotope	mass [kg]	FWHM %	BI [cts/(keV kg y)]	Sens. on $\langle m_{ee}\rangle$[meV]	Planned
GERDA I GERDA II	^{76}Ge	18 40	0.2	0.05 (0.01) 0.001	230-390 90-150	2011 2013
Majorana demonstrator	^{76}Ge	~ 20 40	0.2	0.001	<140	2013 2014
CUORE-0 CUORE	^{130}Te	~ 10 200	0.25	~ 0.4 <0.04	~ 300 35-82	2011 2014
EXO-200	^{136}Xe	200	3.7	~ 0.002	109-135	2011

to a half life of $8 \cdot 10^{24}$ y could be reached within two years of measurement, corresponding to a limit on $\langle m_{ee}\rangle$ of the order of 300 meV. Commissioning of the complete CUORE experiment is foreseen for 2014. In its final configuration CUORE will operate 988 TeO_2 crystals, with a total active mass of ^{130}Te of 200 kg. Most of the effort is directed to the reduction of the background rate to less than 0.04 cts/(keV kg y).[23,24] Given a resolution of 0.25% FWHM and the expected background rate, CUORE will be sensitive[22] to masses in the 35 meV[a] to 82 meV[b] range.

4.3 EXO-200

EXO[28] is a multiphase program to search for neutrinoless double beta decay of ^{136}Xe, the ultimate aim being a ton-scale experiment with a sensitivity to the Majorana neutrino mass of about 10 meV.

EXO-200 is a 200-kg prototype experiment using a time projection chamber (TPC), filled

[a]Nuclear matrix element from the RQRPA model[25]
[b]Nuclear matrix elements from the ISM model[26]

with liquid xenon enriched to 80% in ^{136}Xe. The experiment will detect scintillation light of liquid Xenon using avalanche photodiodes, and ionization electrons with grid wires. This technique is easy to scale to big masses, however a resolution of only 3.7% FWHM has been reported so far. Currently a TPC containing 200 kg of cryogenic liquid is being commissioned. In fall 2010 the TPC was filled with 200 kg ^{nat}Xe and results from engineering runs are being analyzed. For 2011 a refill of the system followed by low-background measurements is scheduled. With a nominal background rate of 0.002 cts/(keV kg y), EXO-200[29] will probe the Majorana neutrino mass down to 109 meV[c] – 135 meV[d].

5 Conclusions

The observation of $0\nu\beta\beta$ decay is the only practical way to test the charge-conjugation nature of the neutrino. Past experiments set upper limits on the effective Majorana neutrino mass in the sub-eV range. A claim of evidence has been reported by a subgroup of the Heidelberg-Moscow experiment and it must be tested by a new generation of experiments based not only on ^{76}Ge, but also on different isotopes.

The GERDA infrastructure has been completed in 2010, and the first background measurements have been performed, resulting in a background rate of approximately 0.05 cts/(keV kg y). The first detectors from enriched Ge will be deployed in summer 2011. Majorana, CUORE, and EXO-200, the latter two based on different isotopes, are also commissioning and expected to start taking data in the next few years.

References

1. S.N. Ahmed et al. SNO Collaboration, *Phys. Rev. Lett.* **92**, 181301 (2004)
2. A.S. Barabash, *Phys. Atom. Nucl.* **74**, 603-613 (2011)
3. J. Schechter and J. W. F. Valle, *Phys. Rev.* D **25**, 295 (1982)
4. A. Smolnikov, P. Grabmayr, *Phys. Rev.* C **81**, 028502 (2010) and references therein
5. H.V. Klapdor-Kleingrothaus et al., *Eur. Phys. J.* A **12**, 147-154 (2001)
6. H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, *Mod. Phys. Lett.* A **21**, 1547-1566 (2006)
7. C.E. AAlseth et al., *Phys. Rev.* D **65**, 092007 (2002)
8. F.A. Danevich et al., *Phys. Rev.* C **68**, 035501 (2003)
9. E. Andreotti et al., *Astropart. Phys.* **34**, 822-831 (2011) and references therein
10. S. Schönert et al., *Nucl. Phys. Proc. Suppl.* **145**, 242 (2005)
11. A. Caldwell, K. Kröninger, *Phys. Rev.* D **74**, 092003 (2006)
12. M. Barnabe-Heider et al., *JINST* **5**, P10007 (2010)
13. I. Abt et al., *Nucl. Instrum. Methods* A **577**, 574 (2007)
14. I. Abt et al., *J. Instrum.* **4**, p11008 (2009)
15. V.D. Ashitkov et al., [arXiv:nucl-ex/0309001]
16. P. Cennini et al., *Nucl. Instrum. Methods* A **356**, 526-529 (1995)
17. R.B. Firestone, Table of Isotopes, Eight Edition, John Wiley and Sons, Incorp., N.Y. (1998)
18. A. Caldwell, D. Kollar, K. Kröninger, *Computer Physics Communications* **180**, 2197-2209 (2009)
19. The Majorana Collaboration, arXiv:nucl-ex/0311013
20. G.K. Giovanetti, talk at International Student Workshop on Neutrinoless Double Beta Decay, November 11-13 2010, LNGS
21. CUORE proposal, R. Ardito et al., arXiv:hep-ex/0501010

[c] nuclear matrix element from RQRPA model[27]
[d] nuclear matrix element from NSM model[26]

22. E. Previtali, talk at WIN'11 (Cape Town, South Africa, January 31- February 5, 2011), proceeding to be published by World Scientific
23. J.J. Gómez-Cadena et al., arXiv:1010.5112v4
24. A. Giuliani, talk at International Student Workshop on Neutrinoless Double Beta Decay, November 11-13 2010, LNGS
25. F. Šimkovic et al., *Phys. Rev.* C **77**, 045503 (2008)
26. F. Menéndez et al., *Nucl. Phys.* A **818**, 139-151 (2009)
27. F. Šimkovic et al., *Phys. Rev.* C **79**, 055501 (2009)
28. M. Dabilov et al., *Phys. Lett.* B **480**, 12 (2000)
29. M. Dolinski, talk at Neutrino 2010 (Athens, Greece, June 14-19, 2010), proceeding to be published in *Nucl. Phys. B. Proceedings Supplements*