Progetto. *Experimenting on a hyper-pure Ge crystal to unveil the nature of neutrinos*

Response to the comments by the referees

1. Previous and present experience with "naked" Ge diodes in cryogenic liquids

The GENIUS project was proposed to the LNGS in 1997 for dark matter and double beta decay searches, operating High-Purity Germanium detectors directly in liquid nitrogen [GENIUS-Proposal, 20 November 1997; H.V. Klapdor-Kleingrothaus, Int. J. Mod. Phys. **A 13** (1998) 3953]. Monte Carlo calculations showed that this technique should be able to reduce the background by three or four orders of magnitude with respect to the same detectors operated in the usual way.

The Laboratory however, before considering the project for approval, requested the realisation of a test experiment aiming to clarifying the basic assumptions of GENIUS. This became known as GENIUS-Test-Facility. GENIUS-TF operated, discontinuously, over three years at LNGS with finally six naked Ge detectors (15 kg). The results were published in 2006 [H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Nuclear Instr. and Meth. **A 566** (2006) 472–476]. Three data taking periods, called I, II and III, were performed, interrupted by opening of the apparatus for deploying new detectors and maintenance operations. An increase of the leakage current was observed when measurements restarted after having completed the cooling cycle at the beginning of run II (see Table 1 of the quoted paper). The phenomenon, however, does not appear to have been further investigated.

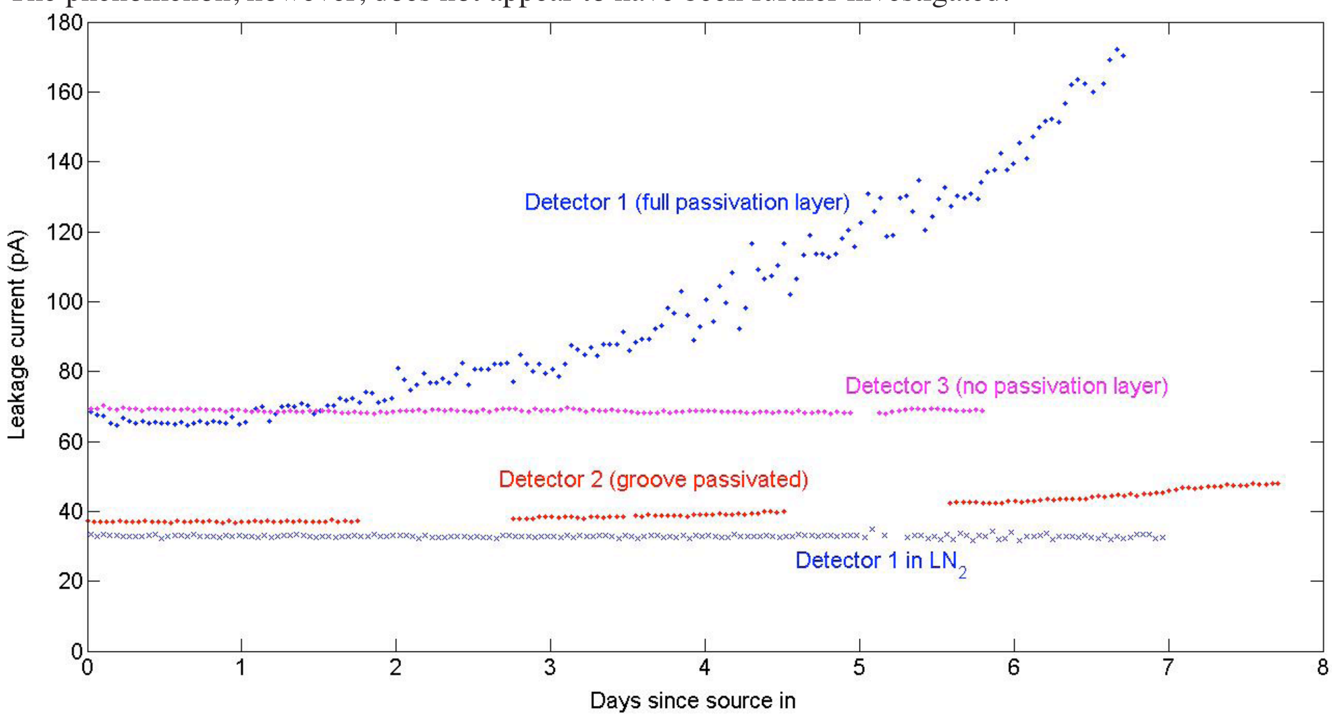

Figure 1: Comparison of leakage current changes under gamma irradiation for three detectors with different passivation layer configurations operated in liquid argon. Reducing the size of the passivation layer to the groove area (detector 2/GTF-42) strongly reduces the increase of LC under gamma radiation. No LC increase is observed for the detector without passivation layer in LAr (detector 3/GTF-44) and similar, for detector 1 in liquid nitrogen. All leakage current increases were found to be fully reversible. From [LNGS-EXP 33/05 add. 6/08].

A similar step-wise increase of the leakage current was observed by the GERDA collaboration in summer 2006 during the test phases of the diodes. The cause was found to be an improper detector handling and was cured by refurbishment of the detector [GERDA Progress Report to LNGS Scientific Committee. LNGS-EXP 33/05 add. 4/07]. Indeed, the naked Ge detectors must be handled with extreme care. The correct procedures were then understood by GERDA by performing a series of several worming-cooling cycles on Ge counters.

The GERDA collaboration performed a series of systematic studies of the behaviour of naked Ge detectors in liquid Argon, in the especially built Underground Detector Laboratory (Gdl) at LNGS. The results have been periodically reported to the LNGS Scientific Committee. A new phenomenon, different from the previously mentioned one was observed, namely the increase of the leakage current under gamma irradiation of the detector assembly, including its bath liquid. The phenomenon was systematically investigated with long-term (several months long) runs of different detectors. Procedures to control the leakage current increase and to bring it back to the original value were developed. The understanding of the underlying physics enabled GERDA to a novel design of the passivation layer allowing to bring the effect within fully acceptable limits, as shown in Fig. 1.

In order to give some more details, we notice that Fig. 1 shows the increase of leakage current under identical gamma radiation and bias voltage conditions for the different detector configurations. A 44 kBq ^{60}Co is located at approximately 20 cm distance irradiating mainly the signal contact side. The experimental observation that the reduction in area of the passivation layer reduces the leakage current increase under gamma radiation, corroborates our hypothesis that charge collection on the surface of the insulating passivation layer is the origin of the (reversible) leakage current increase. Moreover, no radiation induced leakage current increase has been observed when operating GS935 in liquid nitrogen. The measurements with GTF-42 and GTF-44 in LAr are ongoing and the leakage current values are stable at 10 pA and 5 pA respectively. A periodic 10 minutes irradiation of GTF-42 with a ^{60}Co gamma source is carried out once per week in order to simulate the energy calibration in GERDA, while monitoring the leakage current stability with high accuracy

2. Overview of the experiments and proposals on double beta decay

If neutrinos are Majorana particles, the $0\nu2\beta$ process $N(A,Z) \rightarrow N\left(A,Z+2\right)+2e^{-}$ can happen on certain nuclides. The observation of this process would prove the Majorana nature of the electron neutrino. The decay probability is proportional to the square of the so-called “Majorana mass” $M_{ee} = \left|\sum_{i=1}^{3} U_{ei}{}^{2} m_i\right|$. Fig. 2 shows M_{ee} as a function of the smallest neutrino mass, for the two possible hierarchies (where $\Delta m^2 = m_3^2 - \left(m_2^2 - m_1^2\right)/2$), calculated by Feruglio, Strumia and Vissani [Nucl. Phys. **B 637** (2002) 345].

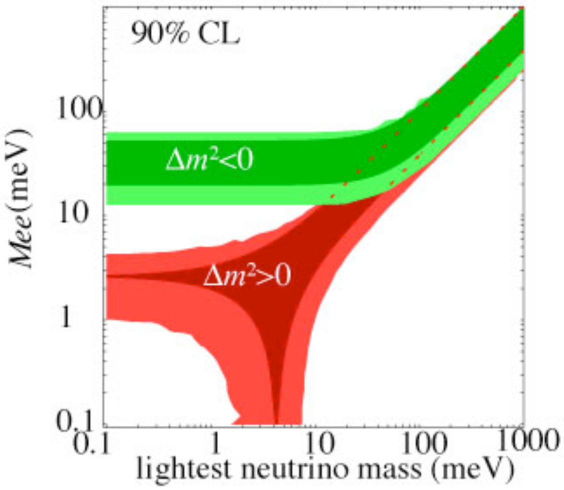

FIGURE 3. "Majorana mass" as a function of the lightest neutrino mass.

The experiments measure (or limit) the decay probabilities, which are proportional to M_{ee}^2 and to the absolute square of the relevant nuclear matrix element. The latter are very difficult to evaluate and have been uncertain by large factors. The situation is improving and recent calculations quote uncertainties around 30%[Rodin et al. Nucl. Phys. **A 766** (2006) 107; erratum arXiv:0706.4304].

Experimentally, by far the largest issue is the background. In presence of background the sensitivity to M_{ee} scales with the fourth root of the exposure. Consequently, background free conditions must be achieved in the region of the signal, which is known with high precision, in a range determined by the energy resolution ΔE.

There are two basic experimental approaches.

In the "calorimetric" approach, the source coincides with the detector; the energy deposited by the two electrons is accurately (a few ‰ FWHM) measured. Its distribution is a continuous spectrum from $2\nu 2\beta$, which is certainly present, and a line after its end-point if $0\nu 2\beta$ exists. To this the backgrounds add both continuous and consisting in monochromatic lines.

In the "tracking" approach source and detector are separated. The tracks of the two electrons are detected, providing more detailed information and an added means for background discrimination. However, the energy resolution is worse than in the calorimetric approach typically by an order of magnitude. Moreover, the tracking system increases considerably the total detector volume for a given source mass.

The Heidelberg-Moscow experiment at Gran Sasso, the most sensitive so far, used enriched Ge diodes. It took data for 13 years with 11 kg sensitive mass and the lowest background index ever reached, b=0.11/(keV kg yr). A subset of the collaboration reported a positive evidence at 4.2σ level in 2004 in the range 100 meV<M_{ee}<900 meV, depending on the assumed nuclear matrix element

Due to the uncertainty of the nuclear matrix elements, the confirmation or rejection of this claim must necessarily be done on Germanium and is the aim of the first phase of GERDA. No other experiment can do that in the next several years.

The search for $0\nu 2\beta$ is presently one of the most active field in neutrino physics. It has been recently reviewed by F. T. Avignone, S. R. Eliott and J. Engel [Rev. Mod. Phys. **80** (2008) 481-516]. We reproduce here the TABLE IV from this article, in which the authors summarise the experiments, proposals, ideas at the time of writing. (The NEXT proposal, similar to HPXe is later). The search with several double-beta active isotopes is mandatory, given the uncertainty of the nuclear matrix elements.

TABLE IV. A summary list of the $\beta\beta(0\nu)$ proposals and experiments.

Experiment	Isotope	Mass	Technique	Present status	Reference
CANDLES	^{48}Ca	few tons	CaF_2 scint. crystals	Prototype	Umehara *et al.* (2006)
CARVEL	^{48}Ca	1 ton	$CaWO_4$ scint. crystals	Development	Zdesenko *et al.* (2005)
COBRA	^{116}Cd	418 kg	CZT semicond. det.	Prototype	Zuber (2001)
CUORICINO	^{130}Te	40.7 kg	TeO_2 bolometers	Running	Arnaboldi *et al.* (2005)
CUORE	^{130}Te	741 kg	TeO_2 bolometers	Proposal	Ardito *et al.* (2005)
DCBA	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Ishihara *et al.* (2000)
EXO-200	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Construction	Piepke (2007)
EXO	^{136}Xe	1–10 ton	Liq. ^{enr}Xe TPC/scint.	Proposal	Danilov *et al.* (2000)
GEM	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive	Zdesenko *et al.* (2001)
GENIUS	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive	Klapdor-Kleingrothaus *et al.* (2001a)
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Construction	Schönert *et al.* (2005)
GSO	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	Danevich *et al.* (2000); Wang *et al.* (2002)
MAJORANA	^{76}Ge	120 kg	^{enr}Ge semicond. det.	Proposal	Gaitskell *et al.* (2003)
MOON	^{100}Mo	1 ton	^{enr}Mo foils/scint.	Proposal	Nakamura *et al.* (2007)
SNO++	^{150}Nd	10 ton	Nd loaded liq. scint.	Proposal	Chen (2005)
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Barabash (2004)
Xe	^{136}Xe	1.56 ton	^{enr}Xe in liq. scint.	Development	Caccianiga and Giammarchi (2001)
XMASS	^{136}Xe	10 ton	Liquid Xe	Prototype	Takeuchi (2008)
HPXe	^{136}Xe	tons	High pressure Xe gas	Development	Nygren (2007)

Notice that the entries of the TABLE range from experiments under construction, projects in their R&D phase, ideas in very preliminary stage of development and proposals that have not been accepted (called "Inactive"). Notice also that the numbers in the third column are not always the masses of the double-beta active isotope.

The three experiments under construction aim to a sensitivity in M_{ee} of about 100 meV in round numbers. To fix the ideas this requires exposures of the order of 100 kg yr with a background index of the order of 10^{-3}/(keV kg yr), which is two orders of magnitude better than the past generation experiments. Longer term projects aim to source masses of the order of 1 t and background index values of the order of 10^{-4}/(keV kg yr). While it is clear that such detectors will be needed to reach the few tens of meV scale, nobody knows today how to do that. The R&D effort will presumably take more than 20 years.

Coming to the TABLE, there is only one running experiment **CUORICINO**, at LNGS. The basic detector elements are TeO_2 bolometers. The natural abundance of the double beta active isotope, ^{130}Te, is 34%, large enough to make enrichment not necessary. It is sensitive to M_{ee} values of a few hundreds meV. **CUORE** is the next step, already under construction at LNGS. It will be made of closely packed CUORICINO like towers for a total ^{130}Te mass of 203 kg. To reach a sensitivity in M_{ee} below 100 meV, the background should be reduced below 10^{-2}/(keV kg yr).

GERDA is the second experiment under construction at LNGS. In Phase-I, existing detectors (from HM and IGEX), about 15 kg mass, will be used with an expected background index of about 10^{-2} c/(kg keV yr). This will be enough to confirm or refute the Klapdor et al. evidence on ^{76}Ge in an exposure of one year. In phase-II, about 20 kg of new, segmented, detectors will be added aiming at a global background index $b=10^{-3}$/(keV kg yr). A sensitivity in M_{ee} of about 140 meV will be reached with a 100 kg yr exposure.

MAJORANA was originally proposed as an array of enriched Ge diodes for a total of about 500 kG. To exploit such a large mass the background index must be reduced to about $b=10^{-4}$/(keV kg yr). Differently from GERDA, MAJORANA effort is to reduce the background using more traditional techniques. The project is presently in its feasibility studies.

EXO-200 is the third, and last experiment under construction searching for $0\nu2\beta$ in ^{130}Xe in a liquid (enriched) Xe Time Projection Chamber, which will provide tracking and a limited energy resolution.

If the experiment will be able to suppress and discriminate all the other background sources, it will be limited by the tail of the $2\nu 2\beta$ spectrum. The contribution of the latter will depend both on the presently unknown lifetime and on the achieved energy resolution. If successful, EXO-200 may approach a 100 meV sensitivity. On the longer run, the EXO proposal aims to reach the 1-ton source mass by identifying the daughter ^{136}Ba ion by LASER spectroscopy. The technique is under development.

COBRA is an R&D programme at LNGS developing CdZnTe semiconductor crystal detector. The first prototypes are presently under test. If successful, much more research and development will be needed to reach the competitive phase.

MOON is presently in its prototype-testing phase. MOON-I is made of three 48 cm × 48 cm enriched ^{100}Mo foils, 47 g each, sandwiched between six plastic scintillators measuring separately the energy of each electron (and tagging its direction). The control of the backgrounds, especially those associated with the large surfaces, and a substantial improvement of the energy resolution are crucial issues to establish the feasibility of the project.

SuperNEMO is a proposal being developed as the next step after NEMO-3, which is presently running in the LSM. These experiments use thin foils of square metre size areas made of the enriched isotope under study. The structure is modular. Each module is made of one source foil between two tracking gas detectors and calorimetric elements on each side. In order to reach the 100-200 kg source necessary to be sensitive to M_{ee} in the 100 meV range, the background must be reduced by two orders of magnitude and the energy resolution improved by almost an order of magnitude over NEMO-3. This work is currently being done. Another issue is the very big size of the detector, which will require a big underground hall.

HPXe and **NEXT** are proposals to use high-pressure enriched Xe gas Time Projection Chambers. In principle, these devices can provide rather good energy resolution (1% FWHM) and tracking of the two electrons, a potentially powerful background discrimination handle. However, several years of R&D are needed before establishing the feasibility of the technique.

The **BOREXINO** experiment at LNGS has shown that extremely low background levels can be reached with hyper-pure liquid scintillators. Consequently, proposals to dissolve, after the solar phase of the experiment, double beta active isotopes, like ^{116}Cd and ^{136}Xe, have been studied. The **SNO++** project is presently under development in Canada, based on similar ideas.

3. Details on the requested budget. **Total: 355 kEuro**

No	Item	Sub -item cost (KEuro)	Partial cost (kEuro)	Total Item cost (kEuro)
1	**Consumables**			**80**
	● Front–end electronics		20	
	● ● ASIC prototype preamplifier	2		
	● ● Preamplifiers mass production (20 p)	18		
	● Ge crystal pulling		40	
	● Various consumables		20	
2	**Investments**			**65**
	● Electronics modules		65	
	● ● 6 x 4 channels digitizer boards with FADC	40		
	● ● Standard NIM electronic modules for the external trigger system	14		
	● ● High voltage power supply with low current readout	5		
	● ● NIM bin for the digitizer boards	6		
3	**Personnel**			**40**
	● One PhD position 3 years		40	
4	**Personal computers**			**6**
	● Two workstation PC		6	
	● ● One for the DAQ control and monitoring	3		
	● ● One for offline data analysis and data storage	3		
5	**External services**			**100**
	● Mechanical design and realization		20	
	● ● Cryostat	15		
	● ● Crystal mounting and handling mechanism	5		
	● Crystal segmentation		80	
6	**Travel**			**32**
	● Conference presentations		8	
	● Contacts with companies		8	
	● Contacts with Munich group		16	
7	**Overhead**			**32**