Proposal for an R&D program for a double beta decay experiment sensitive to a 50 meV neutrino effective mass

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23 septembre 2005

Abstract

The neutrinoless double beta decay $\beta\beta0\nu$ is the most sensitive process for the search of leptonic number violation and its discovery would prove that the neutrino is a Majorana particle. This process may occur through several mechanisms. In particular the existence of the $\beta\beta(0\nu)$ decay by light neutrino exchange would allow to determine the mass scale of the neutrinos.

The NEMO 3 detector, searching for $\beta\beta0\nu$ decay with 7 kg of ^{100}Mo and 1 kg of ^{82}Se, has been running reliably since February 2003. The first NEMO 3 results have demonstrated that all the sources of backgrounds are well identified and understood and that the background reductions are at the expected levels for both internal and external backgrounds. The expected sensitivity of the NEMO 3 detector with 7 kg of ^{100}Mo is $T_{1/2}(\beta\beta0\nu) > 2\ 10^{24}$ years corresponding to a limit on the effective Majorana neutrino mass of $<m_\nu> < 0.3 – 1.3$ eV.

Since the NEMO technique can be extrapolated for a larger mass detector, the NEMO collaboration proposes a R&D program in order to design a detector (SuperNEMO) with 100 kg of ^{82}Se, coupling track reconstruction and calorimeter and sensitive to a $\beta\beta(0\nu)$ period of few 10^{26} years.

1. Introduction

The positive results obtained in the last few years in neutrino oscillation experiments [1-4] have demonstrated that neutrinos are massive particles and that lepton flavor is not conserved. In parallel, tritium β-decay experiments [5,6] have established a very low limit on the electron neutrino mass of $<m_\nu> < 2.2$ eV (95% CL). The discovery that neutrinos are massive particles is the first evidence for physics beyond the Standard Model. Among new models, Grand Unified Theories can provide a natural framework for neutrino masses and lepton number violation. In particular the see-saw model [7] which requires the existence of a Majorana neutrino, naturally explains the smallness of neutrino masses. The existence of Majorana neutrinos would also provide a natural framework for the leptogenesis mechanism [8] which could explain the observed baryon-antibaryon asymmetry in the universe. The observation of neutrinoless double beta decay ββ0ν would represent a major advance in our understanding of particle physics because it would prove that neutrinos are Majorana particles and that global lepton number is not conserved. It would also constrain the mass spectrum and the absolute mass of the neutrinos.

The experimental field of ββ0ν searches which is a very old subject has been renewed during the last two decades. The experimental approaches can be classified in two categories: a pure calorimeter or a combination of tracking device and a calorimeter.

The pure calorimetric measurements (as the enriched HPGe semi-conductor crystals or Te bolometer detectors) use the ββ source as the detector and measure only the total deposited energy of the two electrons. The advantage of such a technique is the very good energy resolution, a good detection efficiency and a relative compact detector. But the main disadvantage is that there is no direct signature of the two electrons. For example, if a signal is observed from ^{76}Ge with HPGe detector and not observed with ^{130}Te using bolometer, does it mean that the signal is a unknown γ-ray background or is it due to a unfavourable nuclear matrix element for ^{130}Te?

The combination of a tracking detector and a calorimeter (“tracko-calo” detector) is the unique method to directly identify the two emitted electrons with a tracking device. The detector is also independent from the source foil, which allows to measure different ββ isotopes. Howerver the efficiency and energy resolution are lower and the size of such a detector is larger than a pure calorimeter detector.

Up to now the best sensitivity on the ββ0ν half-life have been obtained with germanium diodes enriched in ^{76}Ge (around 10 kg of ^{76}Ge) by two ended experiments: Heidelberg-Moscow (Germany-Russia) [9] and IGEX (USA-Russia-Spain) [10]. Depending on the nuclear matrix element calculation, the corresponding limit for the effective Majorana neutrino mass is 0.35 - 1.05 eV. Part of the Heidelberg-Moscow collaboration published recently a positive result for a ββ(0ν) signal corresponding to an effective neutrino mass between 0.1 - 0.9 eV [11]. This result is extremely controversial (see for example [12,27]). At present two experiments are taking data and the results are expected for 2007: CUORICINO (bolometer experiment) should reach a mass sensitivity between 0.2 -1.2 eV with 11.1 kg of ^{130}Te and NEMO 3 (tracko-calo detector) for which the expected sensitivity is 0.3-1.3 eV with 6.9 kg of ^{100}Mo and 0.6 – 1.7 eV with 0.93 kg of ^{82}Se.

Several projects are proposed to go further in the near future to reach a sensitivity on the effective neutrino mass around 50 meV, for which at least 100 kg of isotopes are needed. Since the NEMO-3 technique can be extrapolated for a larger mass detector, the SuperNEMO collaboration have written in June 2004 an expression of interest for a « tracko-calo » detector which could accommodate 100 kg of isotope. Among all the existing future generation approaches it is the only one which offer to detect “bubble chamber” like images of the ββ0ν events with a practically zero background. We believe that any signal observed with a pure calorimetric detector should be confirmed with a NEMO-like approach. We also note that if the effective Majorana neutrino mass is sufficiently high, SuperNEMO will probably be in a unique position to investigate a particular mechanism of the 0νββ decay (for example the existence of right handed current) due to its capability to study the topology of the events like the angular distribution and the single electron energy spectrum.

In paragraph 2 of this paper are described topics of the neutrino physic associated to the search of neutrinoless double beta decay.

In paragraph 3 are presented the different experimental techniques, other than NEMO. For each methode the current status and the prospectives are presented.

In paragraph 4 the NEMO-3 detector and results are presented.

In paragraph 5 the SuperNEMO project and the R&D topics are presented

In paragraph 6 is presented the SuperNEMO collaboration.

In paragraph 7 is presented the preliminary tasks sharing for the R&D of SuperNEMO.

In paragraph 8 is presented the R&D program in LAL.

2. Neutrino physics and double beta decay

The observation of neutrinoless double beta decay (ββ0ν) would represent a major advance in our understanding of particle physics because it would prove that neutrinos are Majorana particles and that global lepton number is not conserved.

The ββ0ν decay would be a new natural radioactivity of some nuclei in which two neutrons turn into two protons and two electrons and nothing else:

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

This process may arise if β-transition towards intermediate daughter nucleus (Z+1) is forbidden or strongly suppressed. One can visualize it by assuming that the process involves the exchange of various virtual particles.

Experimental signature of the different ββ modes is the total energy sum of the two emitted electrons (see Figure 1). ββ0ν decay signal should produce accumulation of events at energy ($Q_{\beta\beta}$) at the end point of the allowed two-neutrino double beta decay ββ2ν:

$$(A,Z) \rightarrow (A,Z+2) +2\, e^- + 2\, \nu$$

The ββ2ν decay is a second order of weak interaction and presents a continuous spectrum with energies between 0 and $Q_{\beta\beta}$.

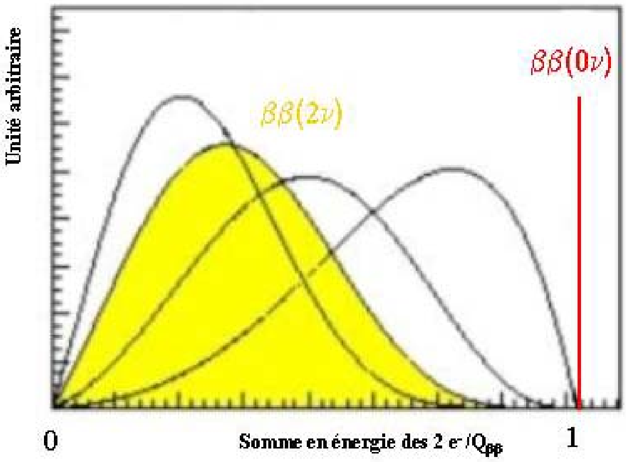


Figure 1 : Total energy sum of the two emitted electron normalized to the energy transition $Q_{\beta\beta}$. For ββ0ν decay in red the sum corresponds to Dirac peak with $Q_{\beta\beta}$ energy; In case of ββ2ν decay process,..there is a continuous spectrum. Black curves correspond to different hypothesis for Majoron emission

2.1. Exchange of light Majorana neutrino in neutrinoless double beta decay

Of primary interest is the process mediated by the exchange of light Majorana neutrinos (antineutrino emitted at first vertex is absorbed as neutrino at the second one) interacting through the left-handed V-A weak currents (see Figure 2). Note that change in helicity is possible only if exchanged Majorana neutrino is massive.

Half-life of ββ0ν decay process is connected to the effective neutrino mass by the relation:

$$T_{\frac{1}{2}}^{-1} = G_{0\nu}.\left|M_{0\nu}\right|^2.\langle m_\nu \rangle^2$$

with: $G_{0\nu}$ a phase space factor proportional to $Q_{\beta\beta}^5$ and also function of atomic number Z,
$M_{0\nu}$ the nuclear matrix element,
$<m_\nu>$ the effective neutrino mass, $\langle m_\nu \rangle = \sum_{i=1,3} U_{ei}^2 m_i$ where U_{ei} are the coefficients of the neutrino mixing matrix and m_i are the mass eigenvalues.

Effective neutrino mass is in turn related to the oscillation parameters by the relation [13] :

$$< m_\nu > = \left|\sum_i U_{ei} m_i\right| = \left|\cos^2\theta_{13}\left(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}\right) + m_3 e^{2i\beta}\sin^2\theta_{13}\right|$$

where :
θ_{ij} are the mixing angles between i and j eigenstates
α et β are Majorana phases

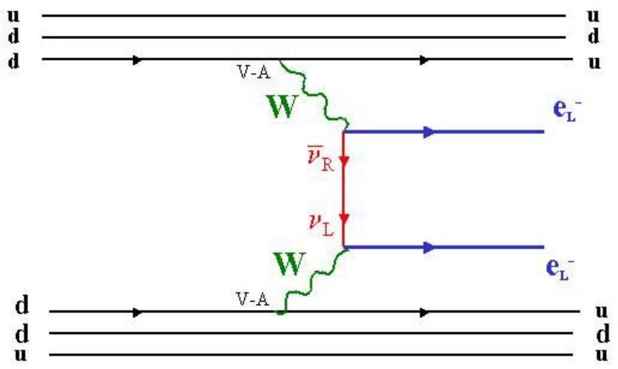


Figure 2 : Neutrinoless double beta decay scheme mediated by the exchange of light Majorana neutrino interacting through the left-handed V-A weak currents

Effective neutrino mass measurements should help to conclude on the scheme of neutrino mass scale, which is unknown due to its dependence on the still not yet measured value of the Δm_{23} sign. The figure 3 shows the effective neutrino mass as a function of the lightest neutrino mass, with the different patterns corresponding to the three different hierarchies:

- Quasi-degenerate masses: $m_1 \approx m_2 \approx m_3$, in this case $<m_\nu> > 50$ meV

- Inverse hierarchy: $m_3 << m_1 \approx m_2 \approx (\Delta m^2_{32})^{1/2}$ corresponding to
  10 meV $< <m_\nu> <$ 50 meV

- Normal hierarchy: $m_1 \le m_2 \approx \left(\Delta m_{12}^2\right)^{\frac{1}{2}} << m_3 \approx \left(\Delta m_{23}^2\right)^{\frac{1}{2}}$ corresponding to $<m_\nu> <$ 10 meV

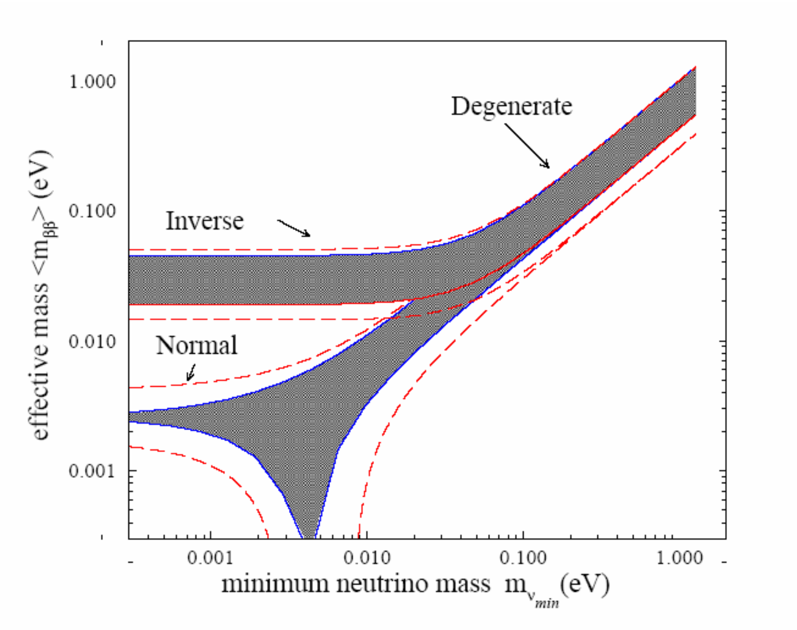


Figure 3 : Effective neutrino mass from ββ0ν decay measurements as a function of the lightest neutrino mass with indications on the different pattern mass. Depending on the <m_ν> value, it should be possible to determine the neutrino mass scale and the right spectrum, corresponding to quasi-degenerate, inverse or normal hierarchies.

2.2. Other processes in neutrinoless double beta decay

There are other possibilities for virtual particle exchange in neutrinoless double beta decay process:

- Right-handed V+A weak current interaction mediated by the W_R boson (see Figure 4):

The inverse of the period can be written as:

$$T_{0\nu}^{-1}(0^+ \to 0^+) = C_1 \frac{\langle m_\nu \rangle^2}{m_e^2} + C_2 \langle \lambda \rangle \frac{\langle m_\nu \rangle}{m_e} \cos\Psi_1 + C_3 \langle \eta \rangle \frac{\langle m_\nu \rangle}{m_e} \cos\Psi_2$$
$$+ C_4 \langle \lambda \rangle^2 + C_5 \langle \eta \rangle^2 + C_6 \langle \lambda \rangle \langle \eta \rangle \cos(\Psi_1 - \Psi_2)$$

$\lambda \sim \left(\frac{\mathrm{M_{WL}}}{\mathrm{M_{WR}}}\right)^2$: coupling term between left-handed leptons and right-handed quarks

η: coupling term between right-handed leptons and left-handed quarks depending on the mixing angle of $\mathrm{W_L}$ and $\mathrm{W_R}$

Ψ_1, Ψ_2: phases between m_ν and λ and m_ν and η

$\mathrm{C_i}$: coefficients consisting of products of nuclear matrix elements and phase-space factor

$\mathrm{m_e}$: electron mass

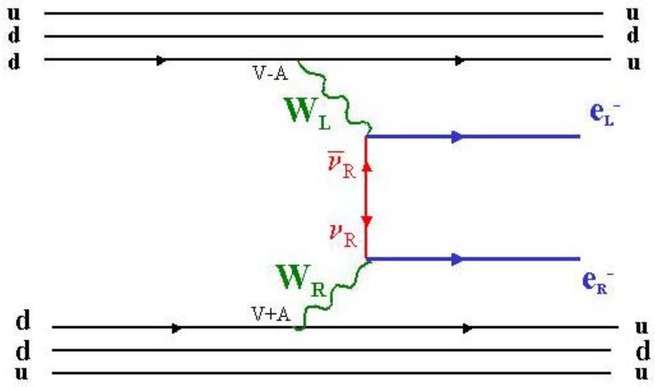


Figure 4 : Neutrinoless double beta decay process involving the exchange of right-handed V+A weak current interaction mediated by the W_R boson.

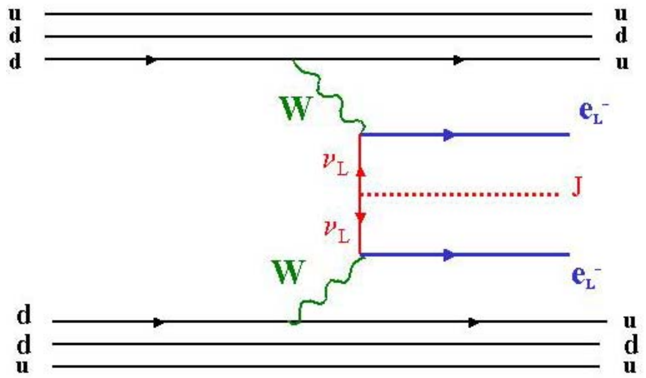


Figure 5 : Neutrinoless double beta decay process involving exchange of Majoron particle J.

- Right-handed weak current interaction between the fundamental states of father nucleus and daughter nucleus:

This process cannot be distinguished from the exchange of light neutrino except by the two-electron angular distributions. Note that neutrinoless transition from fundamental state towards 2^+ excited state of the daughter nucleus is possible only through right-handed current interaction at the second vertex.

Best limits obtained for <λ> and <η> parameters were published by HM experiment with ^{76}Ge isotope: $\langle\lambda\rangle < (0.8\text{-}2.1)\ 10^{-6}$ and $\langle\eta\rangle < (0.4\text{-}1.8)\ 10^{-8}$, these intervals corresponding to different nuclear matrix element values. These limits should be improved by NEMO 3 results.

- Majoron emission (see Figure 5):

Majoron is a Goldstone boson which appears in theory after B-L global symmetry breaking. Majoron interacts only with neutrino particles and has not been yet measured. Depending on theoretical models one or several Majorons can be emitted during double beta decay process. In case of only one Majoron emission inverse of the period can be written as:

$$T_{\frac{1}{2}}^{-1} = G_{0\nu M} \cdot \left|M_{0\nu M}\right|^2 \cdot \langle g_M \rangle^2$$

where $G_{0\nu M}$ is a phase space factor proportional to $Q_{\beta\beta}^5$ and also function of Z

$M_{0\nu M}$ is the nuclear matrix element
g_M is the coupling constant between neutrinos and Majoron

The present best limit is $\langle g_M \rangle < (5\text{-}8)\ 10^{-5}$ obtained with the NEMO 3 detector for ^{100}Mo.

- R-parity violation in supersymmetric models

R-parity is discrete symmetry associated to $R_p = (-1)^{3B+L+2S}$ quantum number where B, L and S are respectively baryon, lepton and spin numbers. In case of violation of lepton number L, neutrinoless double beta decay ββ(0ν) may occur by exchange of supersymmetric particles as gluinos or neutralinos. Double beta decay is sensitive to coupling constant λ'_{111}, for which present upper limit of $\sim 10^{-3}$ was obtained with double beta process.

3. Experimental status and prospect on double beta decay searches

3.1. Introduction

The experimental field of ββ0ν searches which is a very old subject has been renewed during the last two decades. Only the experimental results from direct searches, excess of counting at the end point of double beta decay ββ2ν, will be presented here.

The experimental approaches can be classified in three categories:

- pure calorimetric measurement as Ge semi-conductor diodes or bolometer detectors, for which ββ source is used as the detector and the measured quantity is the total deposited energy
- combination of a tracking detector and a calorimeter (“tracko-calo”) which not only measure the energy but also directly identify the two emitted electrons with a tracking device.
- calorimeter with the tagging of the daughter product.

The main advantages of pure calorimeter experiments are the very good energy resolution and a good detection efficiency. The disadvantage is that there is no direct signature of the two electrons and the origins of the background are more difficult to identify. In case of ββ0ν signal measurement it should be impossible to exclude the possibility that this signal comes from γ-ray backgrounds.

In contrary, “tracko-calo” experiments have less good energy resolution but are able to identify the two electron emissions and thus to reject backgrounds with greater efficiency than calorimeters do. These experiments also measure individual energy for each of the two electrons and their angular distribution, which allows distinguishing ββ0ν decay with light neutrino exchange or right current interaction. Another advantage is that the detector is independent from the source foil, which allows to measure different ββ isotopes.

3.2. Present status

The present experimental limits on the rate of ββ0ν decay are summarized in Table 1 for nine candidates. To extract the corresponding limits for the effective neutrino mass $\langle m_\nu \rangle$, we have made the choice to use only recent theoretical calculations of the nuclear matrix elements performed systematically on several experimentally interesting nuclei [14-19] in order to have comparable results. Even with these recent calculations, large uncertainties are remaining. Nevertheless, a conservative upper limit for the effective neutrino mass of ~ 1 eV (90 % C.L.) seems to be reasonable.

Here are some details for these differents measurements:

Nucleus	$T_{1/2}$ (90% CL) (year)	$<m_\nu>$ (eV)	Mass (kg.yr)	Reference	Experiment
^{48}Ca	$> 1.4\ 10^{22}$	$< 7 – 45$	0.005	[20]	CANDLE
^{76}Ge	$> 1.9\ 10^{25}$	$< 0.35 – 1.0$	35.5	[9]	HM
^{76}Ge	$> 1.57\ 10^{25}$	$< 0.4 – 1.1$	8.9	[10]	IGEX
^{82}Se	$> 1.0\ 10^{23}$	$< 1.7 – 4.9$	0.55	[21]	NEMO 3
^{96}Zr	$> 1.0\ 10^{21}$	$< 16 – 1476$	0.008	[22]	NEMO 2
^{100}Mo	$> 4.6\ 10^{23}$	$< 0.7 – 2.8$	4.10	[21]	NEMO 3
^{116}Cd	$> 0.7\ 10^{23}$	$< 2.2 – 6.3$	0.159	[23]	Solotvina
^{130}Te	$> 1.8\ 10^{24}$	$< 0.4 – 1.3$	3.16	[24]	CUORICINO
^{136}Xe	$> 4.4\ 10^{23}$	$< 0.8 – 4.9$	2.27	[25]	Gotthard
^{150}Nd	$> 1.2\ 10^{21}$	< 3	0.009	[26]	Irvine

Table 1: Present limits for different double beta decay isotopes. Limits on the effective neutrino mass $<m_\nu>$ have been obtained using only recent calculations of the nuclear matrix elements performed systematically on several experimentally interesting nuclei [14-19] (except for ^{48}Ca and ^{150}Nd where the value corresponds to the published one).

- ^{76}Ge: Heidelberg-Moscow and IGEX experiments

Up to now the best sensibilities have been obtained with enriched HPGe crystals(86% enrichment) by two ended experiments: Heidelberg-Moscow (Germany-Russia) [9] and IGEX (USA-Russia-Spain) [10]. With 36.53 kg.yr the Heidelberg-Moscow experiment obtained a limit on the $\beta\beta0\nu$ process of $T_{1/2}(\beta\beta0\nu) > 1.9\ 10^{25}$ years (90% C.L.) and gave a limit on the effective neutrino mass of $<m_\nu> < 0.35 - 1.05$ eV. Part of the Heidelberg-Moscow collaboration claimed recently a 4σ effect for a $\beta\beta0\nu$ signal corresponding to an effective neutrino mass between 0.1 - 0.9 eV [11]. This result is extremely controversial (see for example [27]).

- ^{130}Te: CUORICINO experiment

CUORICINO is based on the new technique of cryogenic detectors especially developed by the Milano group. When operated at low temperature ~10 mK the detectors have a heat capacity so low that even the small energy release by a single radioactive decay event can be measured by means of a suitable thermal sensor. The experiment CUORICINO is located in the Gran Sasso underground laboratory. It is an array of 44 crystal of natural TeO_2 5x5x5 cm^3 each and 18 crystals 3x3x6 cm^3 each. With such a mass of 40 kg CUORICINO is by far the most massive cryogenic set-up in operation. Due to the large isotopic abundance (33.8%) of the double beta decay candidate ^{130}Te no isotopic enrichment is performed but only two of the 3x3x6 cm crystals are enriched in ^{130}Te and two in ^{128}Te to investigate $\beta\beta2\nu$ decay. In only six months of operation CUORICINO obtained a limit on neutrinoless double beta decay of $T_{1/2}(\beta\beta0\nu) > 1.8\ 10^{24}$ years (90% C.L.) corresponding to a limit on the effective mass of $<m_\nu> < 0.4 – 1.3$ eV. This limit is in the same range than the best limit obtained from the searches of double beta decay period of ^{76}Ge with the enriched semi-conductor detectors.

- ^{136}Xe: Gotthard experiment

The Gotthard experiment was running with a high pressure TPC (Time Projection Chamber) which provides the energy deposited and some signature of the topology of the two contained electrons. It is a combination of a calorimeter and a tracking device.

- ^{48}Ca: CANDLE experiment

In principle the nucleus matrix element of this nucleus can be calculated accurately in the framework of the shell model but unfortunately the isotopic abondance of ^{48}Ca is only 0.2% and presently it is very difficult to enrich it. This is a calorimetric experiment based on light scintillation of CaF2 crystals.

- ^{150}Nd: Irvine experiment

The Irvine experiment was running with the TPC operating at normal pressure with a magnetic field which observed directly the two electrons and measured each momentum.

- ^{116}Cd: Solotvina experiment

This experiment is a pure calorimetric experiment based on the detection at light emission of $CdW0_4$ enriched crystals.

At present two experiments CUORICINO and NEMO-3 are taking data and the final results are expected for 2007.

- CUORICINO with ~ 40 kg of TeO_2 (10.4 kg of ^{130}Te) should reach a sensitivity of 4. 10^{24} years (90% C.L.) corresponding to a limit on the effective mass of $<m_\nu> < 0.25 - 0.85$ eV.
- NEMO-3: expected sensitivity of 2. 10^{24} years (90% C.L.) with 6.9 kg of ^{100}Mo and 8. 10^{23} years (90% C.L.) with 0.93 kg of ^{82}Se corresponding to a limit on the effective mass of $<m_\nu>$ $< 0.3 - 1.3$ eV for ^{100}Mo and 0.6 – 1.7 eV for ^{82}Se.

The expected sensitivity of these two experiments are similar to the limits obtained with the germanium detectors

3.3. Experimental prospects

There are many proposals to search for ββ0ν decay. Some of them have been funded for a research and development program and some for the experiment itself. Only these categories will be shortly described here. Expected sensitivities of each project are summarized in Table 2. To extract the corresponding limits for the effective neutrino mass $<m_\nu>$, we have made the choice to use only recent theoretical calculations of the nuclear matrix elements performed systematically on several experimentally interesting nuclei [14-19] in order to be able to compare the differents projects.

3.3.1. CUORE

CUORE is an extrapolation of the CUORICINO experiment which is currently running in the Gran Sasso underground Laboratory. It consists of an array at 19 towers of 13 modules of 4 natural TeO_2 crystals each 5x5 cm for a total of 988 crystals with a total mass of 741 kg of $Te0_2$ providing a source of 203 kg of ^{130}Te. The detector will be operated in a simple dilution refrigerator at ~10 mK. The present background of CUORICINO in the region of neutrinoless double beta decay is 0.18 ± 0.02 counts/keV.kg.y. The origin of the residual background is intensively studied. The background is mostly due to the surface contamination of copper and crystals. Recent test with 8 new crystals show a surface contamination reduced by a factor of 4. Taking into account that the structure of CUORE allows a suppression of background by requiring a local energy deposit in a single crystal a conservative value of background of 0.01 counts/keV.kg.y is expected corresponding to an expected sensitivity of $T_{1/2} > 2.10^{26}$ years.

An ultimate background of 1 count/ton.keV.y is the goal of the experiment which would give a sensitivity of $T_{1/2} > 6.10^{26}$ years. The device would be in operation in 2011. If the natural TeO_2

crystals are replaced by enriched TeO_2 crystals, CUORE could reach a sensitivity of 2.10^{27} years.

3.3.2. GERDA

The experimental concept of the GERDA experiment is to operate bare Ge crystals enclosed in a bath of high purity liquid nitrogen or liquid argon. In the liquid argon case an active anticoincidence with scintillation light for argon could be used. The advantage is that most others materials (support…) will be removed from the vicinity of the crystals, lowering the level of external background. The ultimate goal is to reach a background free regime. The GERDA collaboration has proposed three phases for the experiment.

In the first phase (Phase I), the crystals from the previous germanium experiments (Heidelberg-Moscow and IGEX) corresponding to a total mass of ~ 15 kg of ^{76}Ge will be installed in the final cryostat in liquid nitrogen. A pulse shape analysis to reject multi-site background will be used like in previous experiments. Anticoincidence rejection could be also used. The aim is to control the level of experimental background at a level of 0.01 count/kev.kg.y and to measure a period in the range of a few 10^{25} years. The $\beta\beta0\nu$ signal claimed by Klapdor could be confirmed or ruled out with the Phase I.

For the next step, phase II, the collaboration plan to reach an exposure time of 100 kg.y. The enrichment of 35 kg of ^{76}Ge with an ultra high purity of 99.99 % has started in February 2005 in Russia with a special attention to minimize the cosmogenic activity (crystals stored in underground facility, transported in a special shield). Segmentation of the crystals to discriminate the local energy deposition will be also investigated for this second phase. They plan to reach a background at a level at 0.001 count/keV.kg.y to be sensitive to a period of 2.10^{26} years.

The phase III would operate a 300 kg ^{76}Ge detector in the final configuration with a cosmic ray veto and an active shield. With an expected background similar to the Phase II of 1 count/keV.ton.y the sensitivity would be 3.10^{27} years. The experiment will be located in the Gran Sasso underground laboratory.

The phase I will start in 2007, the second phase is planed for 2010.

3.3.3. MAJORANA

The Majorana collaboration proposes to operate 500 kg of 86% enriched Ge detectors. By using segmented crystals and pulse shape analysis, multi-site events can be identified and removed from the data. Internal backgrounds from cosmogenic radioactivities will be greatly reduced. Remaining will be single-site events like that are due to $\beta\beta0\nu$. Several research and development activities are undertaken. A number of segmented crystals are studied to understand the impact of segmentation on background and signal. The MAJORANA design uses Ge detectors within a low-mass electroformed Cu cryostat. Electroformed Cu is special free from radioactive contaminants. The collaboration plan to form Cu underground. A module is an assembly of 3 units of 57 Ge detectors. It consists of 19 towers of 3 crystals each arranged in cylindrical geometry. The mass of a module is 60 kg of 86% enriched Ge. In phase I, 180 kg will be installed. In phase II, 3 modules, 540 kg total mass, would allow to reach a sensitivity of 4.10^{27} years with an ultimate expected background of 1 count/ton.keV.y. The experiment will be installed in the Sudburry Underground laboratory (Canada), the deepest underground laboratory in the world (6000 m.w.e) to minimize the cosmogenic activity which could be the residual background for the Ge experiments. The experiment would be in operation in 2012.

3.3.4. EXO

The EXO experiment proposed to search for the $\beta\beta0\nu$ decay of ^{136}Xe to ^{136}Ba in a time projection chamber. There is a research and development program to attempt to tag the daughter of the double beta decay ^{136}Ba^{++} ion after it is partially neutralized to ^{136}Ba^{+}. The final state ion tagging is possible by the observation of individual ions illuminated with an appropriate wavelength to produce atomic fluorescence. In EXO xenon will be used as an active double beta decay source in a TPC either in liquid or gas phase. In gas phase the laser beams illuminates the location where a candidate decay has occured. In the liquid phase case the ^{136}Ba^{+} ion candidate must be extracted and brought in a ion trap where the fluorescence would be observed.

Xenon is a scintillator in both gas and liquid phases. This feature will be used to provide a third spatial coordinate in the TPC. By observing the scintillation and ionisation the energy resolution in the liquid phase is 2% at 2.5 MeV (FWHM). The EXO collaboration is in the process of testing the extraction of the ^{136}Ba^{+} ion and determining its global efficiency. At the present time they have been funded to build a 200 kg isotopically enriched xenon prototype detector (EXO200) without the ^{136}Ba^{+} ion tagging and to install it in the WIPP underground laboratory in the U.S. The sensitivity of this prototype would be $T_{1/2} > 3.10^{25}$ years with a background in the range of 0.02 counts/keV.kg.y. The recent lower limit of the ββ2ν period is $T_{1/2}(\beta\beta2\nu) > 8.10^{21}$ years (90% C.L.). This very high value is encouraging for the remaining ββ2ν background in the ββ0ν region of interest.

3.3.3. MOON

MOON (Molybdenum Observatory of Neutrino) is a “hybrid" ββ and solar ν_e experiment with ^{100}Mo. A possible configuration of the MOON apparatus is a super-module of hybrid plate and fiber scintillators with ^{100}Mo film interleaved between X - Y fiber-planes and a plate of plastic scintillator. The fiber scintillators provide the position and the scintillator plates the energy. The energy resolution would be 5% at 3 MeV (FWHM). A resolution of 4.5 % (FWHM) have been obtained recently with a prototype of a scintillator plate read by a large number of PMTs.

A major background for the ββ0ν measurement is the ββ2ν decays for which the rate from ^{100}Mo is relatively high. However the technique can support other isotopes and if, if ^{82}Se is used instead of ^{100}Mo, the ββ2ν background will be substantially reduced at the expense of losing solar neutrino detection capability.

A prototype is in progress of installation in Otto Underground Laboratory in Japan with an expected mass of 0.8 kg of enriched ^{100}Mo. Future plans call for a 200 kg stage, with either ^{100}Mo or ^{82}Se. Assuming that the only component of background is the ββ2ν decays, the expected sensitivity after 3 years of data would be 7.0 10^{25} years with ^{100}Mo and 1.1 10^{26} years with ^{82}Se. However the other components of background mainly due to possible contaminations in ^{208}Tl and ^{214}Bi are omitted and could reduce the performance of the detector.

The present focus on R&D is on obtaining good energy resolution with scintillators plates and fibers in order to improve rejection of the ββ2ν background. The experience gained with this R&D could be useful for SuperNEMO.

Experiment	Nucleus	Mass (kg)	FWHM at $Q_{\beta\beta}$ (keV)	Background cts/FWHM.kg.y	Background cts/FWHM.y	$T_{1/2}(0\nu)$ limit (years)	$<m_\nu>$ limit (meV)
NEMO 3	^{100}Mo	7	350	~ 0.4	~ 3	2. 10^{24}	300 – 1300
	^{82}Se	1	350	~ 0.1	~ 0.1	8. 10^{23}	600 – 1700
CUORICINO	^{130}Te	10	7	~ 1.25	~ 50	4. 10^{24}	250 – 850
EXO-200	^{136}Xe	160	120	2.5	400	3. 10^{25}	90 – 550
GERDA Phase 1	^{76}Ge	15	4	0.04	0.6	3. 10^{25}	250 – 780
GERDA Phase 2	^{76}Ge	35	4	0.004	0.15	2. 10^{26}	100 – 290
GERDA Phase 3	^{76}Ge	300	4	0.004	1.2	3. 10^{27}	25 – 80
MAJORANA I	^{76}Ge	180	4	0.003	0.54	3. 10^{26}	90 – 250
MAJORANA II	^{76}Ge	540	4	0.003	1.6	4. 10^{27}	20 – 65
SuperNEMO	^{82}Se	100	210	0.01	1.	2. 10^{26}	35 – 105
CUORE	^{130}Te	203	5	0.05	35	2. 10^{26}	35 – 120
			5	0.005	3.5	6.6 10^{26}	20 – 65

Table 2: Features and expected sensitivities of the neutrinoless double beta decay running experiments (CUORICINO and NEMO 3) and projects for the next 10 years.

4. NEMO 3 : a multiple source « tracko-calo » detector

In this Section the NEMO 3 experimental techniques, the main physics results and what was learned about backgrounds are described.

4.1. The NEMO 3 detector

The NEMO-3 detector, installed in the Fréjus Underground Laboratory (LSM, France) and running since february 2003 is searching for ββ0ν decay with the direct detection of the two electrons by a combination of a tracking device and a calorimeter (Figure 6). The NEMO 3 detector [Aug05] is the result of 10 years of R&D from the NEMO collaboration (France, Czech Republic, Finland, Japan, Marocco, Russia, Ukraine, UK, USA). NEMO 3 is cylindrical in design and divided into 20 equal sectors. A full description of the detector and its performance can be found in reference [28].

- **The sources**

The nuclei present in the detector are ^{100}Mo (6914 g), ^{82}Se (932 g), ^{130}Te (454 g), ^{116}Cd (405 g),^{150}Nd (37 g),^{96}Zr (9 g) and ^{48}Ca(7 g). ^{100}Mo and ^{82}Se are devoted for ββ0ν search and other nuclei for ββ2ν measurement with high precision. The detector contains also 621 g of copper and 491 g of a very pure oxide of natural tellurium, both with a very high level of radiopurity in order to measure the external background in the experiment. The natural tellurium also provides an investigation of the ββ(2ν) because the natural abundance of isotope 130 for tellurium is 33.8%, which gives 166 g of ^{130}Te.

The source foils are in the form of very thin foils (~40-60 mg/cm^2), either metallic foils, or composite strips. The composite foils are a mixture of source powder and organic glue deposited on a Mylar sheet and then covered by another sheet forming a sandwich-like structure. The total surface of the foils is around 20 m^2.

- **Tracking device**

The source foils are fixed vertically between two concentric cylindrical tracking volumes composed of 6180 open octagonal drift cells, 270 cm long, operating in Geiger mode at 7 mbar above atmospheric pressure, in a mixture with helium gas, ethyl alcohol (4%), argon (1%) and water (1 ppm). The cells run vertically and three-dimensional tracking is accomplished with the arrival time of the signals on the anode wires and the plasma propagation times to the ends of the drift cells.

The vertex resolution in the two-electron channel has been measured using the simultaneous two electrons conversion of ^{207}Bi sources placed inside the detector. The resolution on the distance between the two reconstructed tracks is $\sigma_t = 0.6$ cm in the transverse plane and $\sigma_l = 1.3$ cm in the longitudinal plane.

- **Calorimeter**

Energy and time-of-flight measurements are acquired from plastic scintillators covering the two vertical surfaces of the active tracking volume. To further enhance the acceptance efficiency, the end-caps (the top and bottom of the detector) are also equipped with scintillators in the spaces between the drift cell layers. This calorimeter is made of 1940 large blocks of scintillators coupled to very low radioactivity Hamamatsu 3" or 5" PMTs. The 10 cm thick blocks of scintillator allow a good photon detection efficiency (~50% at 1 MeV).

The energy resolution (FWHM) of the calorimeter is 14% at 1 MeV for the scintillators equipped with a 5" PMTs on the external wall and 17% for the 3" PMTs on the internal wall.

The time resolutions measured in the two-electron analysis channel is around 250 ps at 1 MeV which is much smaller than the time-of-flight of a crossing electron (> 3 ns). Thus external crossing electrons are totally rejected.

Absolute energy calibrations are carried out every 40 days using ^{207}Bi sources. A daily laser survey controls the gain stability of each PMT.

The resolution of the summed energy of the two electrons in the $\beta\beta0\nu$ decay is mainly a convolution of the energy resolution of the calorimeter and the fluctuation in the electron energy loss in the foil source which gives a non-gaussian tail. The FWHM of the expected two-electron energy spectrum of the $\beta\beta0\nu$ decay is ~ 350 keV.

- **Magnetic field and shield**

A solenoid surrounding the detector produces a 25 Gauss magnetic field parallel to the foil axis, in order to identify the particle charge. Pairs e^+e^- are produced in the source foils in the 1 to 10 MeV energy region by high-energy γ-rays from neutron capture. The curvature measurements also permit an efficient rejection of incoming electrons.

Finally, an external shield, in the form of 20 cm of low radioactivity iron, covers the detector to reduce γ-rays and thermal neutrons. Outside of this iron there is a borated water shield to thermalize fast neutrons and capture thermal neutrons.

- **ββ event reconstruction**

The figures 7 and 7a present a typical two-electron event, candidate of a ββ(2ν) decay, selected from the NEMO-3 data with the reconstructed trajectory associated to the two electrons in both transverse and longitudinal views. A two-electron event is defined as follows:

- two tracks come from the same vertex on the source foil
- each track must be associated with a fired scintillator
- its curvature must correspond to a negative charge
- the time-of-flight must correspond to the two electrons being emitted from the same source

position

- any event with an extra isolated fired scintillator due to a gamma is rejected
- for each electron an energy threshold of 200 keV for ^{100}Mo and 300 keV for ^{82}Se is applied.

Such a two-electron event is detected every 2.5 minutes.

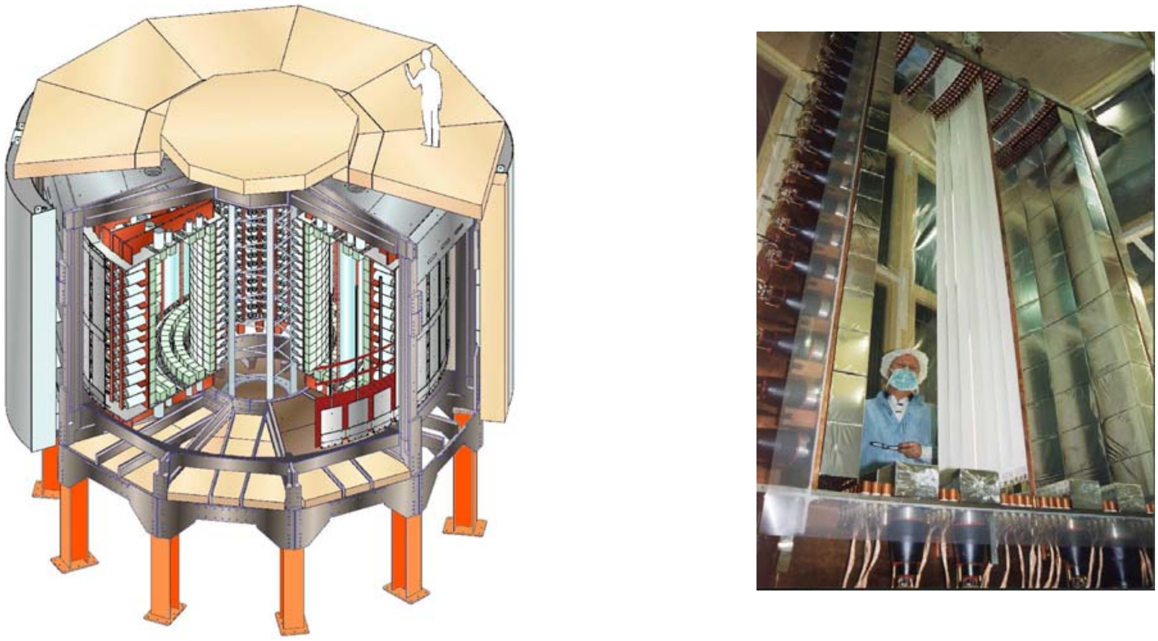


Figure 6 : *An exploded view of the NEMO 3 detector (note the coil, iron γ-ray shield, and the two different types of neutron shields, composed of water tanks and wood) and view of the third sector in the source mounting room just after the installation of the $\beta\beta$ tellurium source, with details on the source foil, copper cathode rings for Geiger cells on the top and bottom of the sector, scintillator blocks covered with aluminised Mylar and coupled to PMTs in their black light-tight sleeves.*

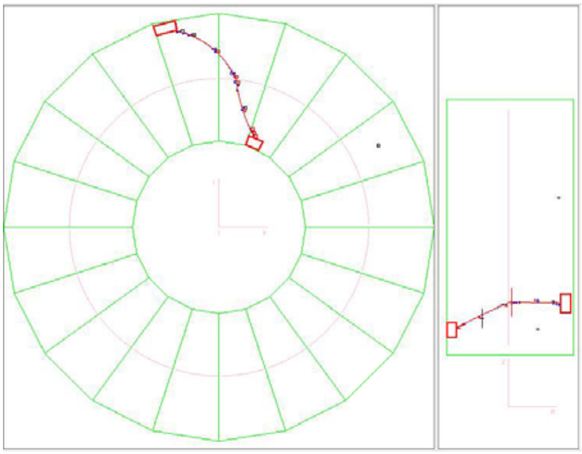


Figure 7: *Event with 2 electrons in transverse and longitudinal views.*

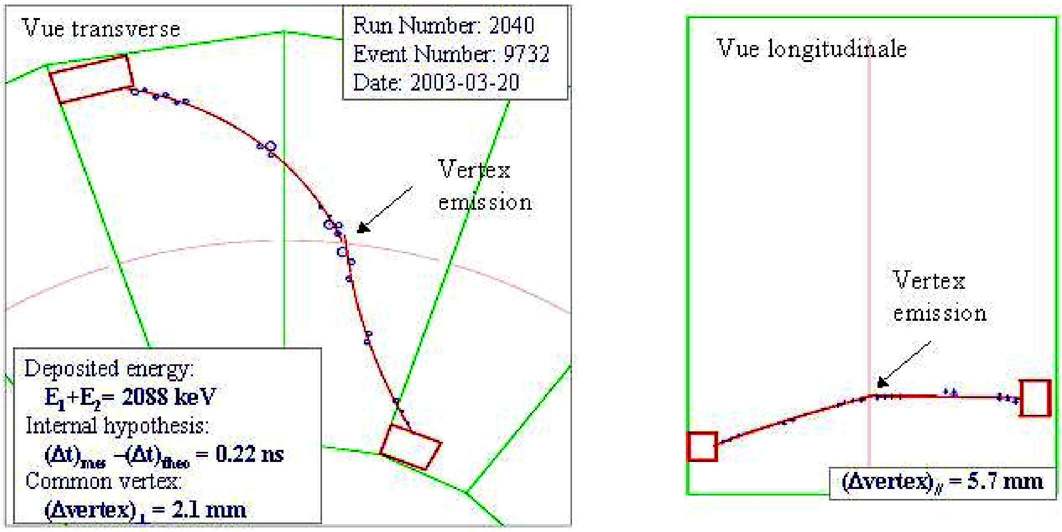


Figure 7a : Zoom on a typical two electron event produced in molybdenum source foil ($\beta\beta(2\nu)$ process in sector 04). The left portion of this figure shows the transverse top view of NEMO 3, while the right part presents the associated longitudinal view. The source foil is in pink and the red rectangles are scintillators where the electrons deposited their energy. The circles radii correspond to the transverse distance from the anode wire for each fired cell, they are not error bars. Time-of-flight measurement allows to ensure that the source foil is the emission point of the two electrons. The red curves are the tracks reconstructed using signals from Geiger cells. The curvature of the tracks due to the 25 Gauss magnetic field is clearly seen in the transverse view and allows the charge recognition. This event has a two electron energy sum of 2.088 MeV.

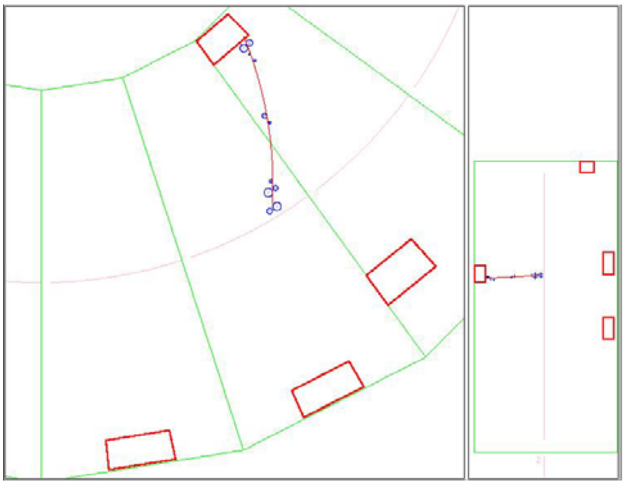


Figure 7b: : Electron and three gamma-rays event. The electron is identified by the fired cells (circles) with a scintillator associated to the red track. The other scintillators are fired by γ-rays.

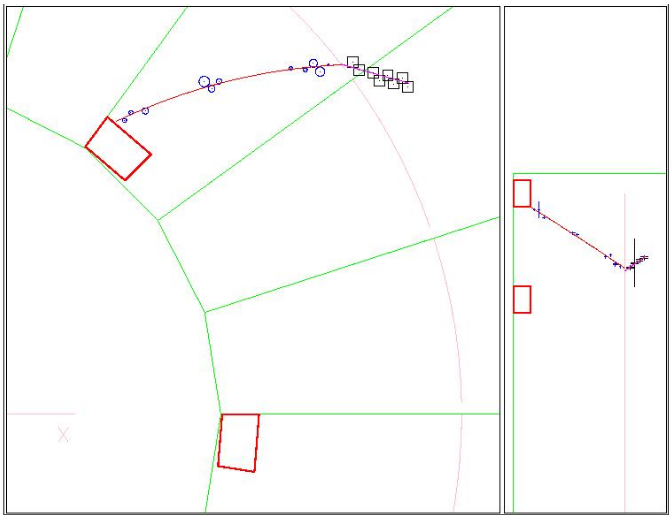


Figure 7c: Event with electron, alpha particle and gamma-ray. The electron is identified by the fired cells (circles) with a scintillator associated to the red track. The alpha particle corresponds to the delayed drift cells (squares).The trajectories of both particles have a common vertex on the source. The second scintillator is fired by a γ-ray.

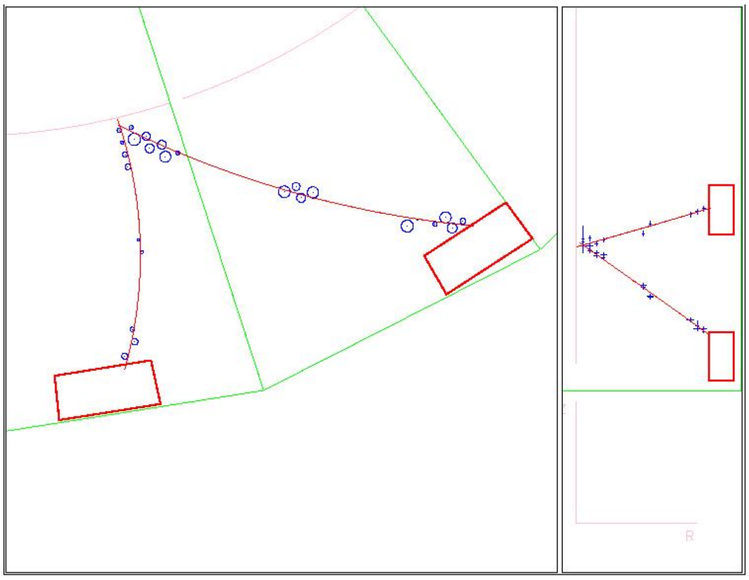


Figure 7d: Event corresponding to the creation of an e^+e^- pair in the source foil which is identify by the curvature of the tracks.

4.2. Comprehension of the backgrounds with NEMO 3

In the NEMO 3 detector, electrons, positrons, photons and delayed α-particles can be identified. Using different analysis channels as it will be described later, the detector is able to use the registered data to identify the different origins of background and measure the levels of each components (^{208}Tl, ^{214}Bi, radon, neutrons and external γ-rays). Results of the measurements are summarized in Table 3. We describe here the different origines of background and the analysis methodes for the measurements. It is convenient to distinguish the "internal" background coming from the ββ sources from the "external" background originating from outside the ββ source foils.

Background component	Mo	Se
$\beta\beta 2\nu$	0.3 cts/kg/y	0.02 cts/kg/y
External neutron and high energy γ	3.10^{-3} cts/kg/y	3.10^{-3} cts/kg/y
External ^{208}Tl and ^{214}Bi	$< 10^{-3}$ cts/kg/y	$< 10^{-3}$ cts/kg/y
Internal ^{208}Tl	0.1 cts/kg/y	0.3 cts/kg/y
Radon Phase I Phase II	1 ct/kg/y 0.1 ct/kg/y	1 ct/kg/y 0.1 ct/kg/y

Table 3 : level of background in the [2.8-3.2] MeV $\beta\beta 0\nu$ energy window, measured by different analysis channel using the NEMO 3 data.

4.2.1. Internal background

The internal background for the $\beta\beta(0\nu)$ signal in the 3 MeV region ($Q_{\beta\beta}$ of ^{100}Mo and ^{82}Se) has two origins.

- $\beta\beta 2\nu$ decay

The first is the tail of the $\beta\beta(2\nu)$ decay distribution of the source, which cannot be separated from the $\beta\beta(0\nu)$ signal and the level of overlap depends on the energy resolution of the detector. Thus, this ultimately defines the half-life limits to which $\beta\beta(0\nu)$ can be searched for.

The background due to the $\beta\beta(2\nu)$ decay which has been measured with the NEMO 3 detector is 2 events per year for 7 kg of molybdenum in the interval [2.8-3.2] MeV where the $\beta\beta(0\nu)$ signal is expected

- ^{214}Bi and ^{208}Tl impurities in the source foils

The second background comes from the β-decays of ^{214}Bi and ^{208}Tl, which are present in the source at some level. They can mimic $\beta\beta$ events by three mechanisms. These are β-decay accompanied by an electron conversion process, Möller scattering of β-decay electrons in the source foil and β-decay emission to an excited state followed by a Compton scattered γ-ray. The last mechanism can be detected as two electron events if the γ-ray is not detected. The initial constraints on the activity in ^{214}Bi and ^{208}Tl before the purification of ^{100}Mo was A(^{214}Bi) < 0.3 mBq/kg and A(^{208}Tl) < 0.02 mBq/kg. To reach these levels in the enriched Mo metal powder, the collaboration decided to use two different purification methods in parallel: a) a physical process developed by ITEP (Russia) transforming the powder into ultrapure monocrystals with a mass of around 1 kg each; b) a chemical process done in a class 100 clean room at INEEL (USA) used to separate the Mo from the impurity radioisotopes taking advantage of an equilibrium break in the ^{238}U and ^{232}Th decay chains.

The level of ^{208}Tl impurities inside the sources has been measured from the NEMO-3 data by searching for internal ($e^- \gamma\gamma$) and ($e^- \gamma\gamma\gamma$) events (see figure 7b). The measured activity is 80 ± 20 μBq/kg. This measurement is in good agreement with those obtained with HPGe detectors before the source foil mounting in NEMO 3. It corresponds to around 0.1 event/year/kg in the interval [2.8-3.2] MeV. Due to the radon contamination inside the detector, it was not possible up to now to precisely measure the internal background from ^{214}Bi inside the source foils but a preliminary analysis of ^{214}Bi contaminations show that its level is lower than 0.3 mBq/kg in agreement with HPGe detector measurement. The radon contamination is today suppressed and this measurement will be done soon. It can be noticed that the NEMO 3 sensitivity for the measurement of the ^{208}Tl contamination is ~10μBq/kg with one year of data.

4.2.2. External background

The external background is defined as events produced by γ-ray sources located outside the source foils and interacting with them. The interaction in the foils of γ-rays from natural decay chains can lead to two electron-like events by e+e- pair creation, double Compton scattering or Compton followed by Möller scattering. One of the main sources of this external radioactivity comes from radon, neutrons, cosmic muons and γ-rays from natural radioactivity.

In the LSM the flux of fast, epithermal and thermal neutrons is few 10^{-6} neutrons.cm^{-2}.s^{-1}. The external background contribution coming from neutrons is due to (α,n) reactions, spontaneous fission of uranium and the interaction of cosmic ray muons in the rocks. Capture of neutrons in the detector materials like iron or copper can create γ-rays with energies up to 10.2 MeV. Interaction of such photons with the $\beta\beta$ source foils can produce e^+e^- pairs (identified with the magnetic field) or two electrons by double Compton effect or by Compton effect followed by a Möller effect. The values of the magnetic field and the neutron shields (30 cm of water and 28 cm of wood) have been optimised to have no event due to neutron background above 2.8 MeV in 5 years of data taking.

The other external background contribution is the γ-ray flux produced in the LSM (4800 m.w.e.) by natural radioactivity and by the bremsstrahlung of muons (4 muons/m^2/day in LSM. From the natural decay chains of uranium ^{238}U and thorium ^{232}Th series, no γ-ray is emitted above 2.6 MeV, thus natural radioactivity is not a source of external background for $\beta\beta(0\nu)$ process in the case of ^{100}Mo or ^{82}Se, which have energy transitions greater than this value. Nevertheless it is essential to reduce this source of backgrounds to keep both a low trigger rate in the detector and the possibility to study $\beta\beta$ isotopes as ^{130}Te, which have a lower energy transition ($Q_{\beta\beta} = 2.5$ MeV). One of the main sources of this external radioactivity comes from the PMTs, even if a substantial effort has been made to reduce the contamination from ^{40}K, ^{214}Bi and ^{208}Tl. The Hamamatsu company was chosen to produce these low background PMTs, with very low contamination in all the components (glass, insulator, ceramics, etc) measured in γ-spectroscopy with HPGe detectors: the total activities in ^{40}K, ^{214}Bi and ^{208}Tl for the 600 kg of PMT glass are respectively 830 Bq, 300 Bq and 18 Bq, that means radiopurities being 100 to 1000 times better than for standard glass. All the other materials used in the detector construction (> 200 tons with iron shield) have been selected with the HPGe detectors for their radiopurity properties, which provide an activity in ^{214}Bi and ^{208}Tl less than few mBq/kg in ^{214}Bi and ^{208}Tl.

Bremsstrahlung of muons produces γ-rays of several tens of MeV. The flux and energy spectrum of these photons have been measured by the collaboration with a NaI detector surrounded by different shields and at the LSM depth. With the 20 cm of iron and the magnetic field to reject e^+e^- these photons do not contribute to the $\beta\beta(0\nu)$ background.

External backgrounds due to ^{214}Bi and ^{208}Tl contaminants outside the source foils (mostly in the PMTs) have been measured by searching for Compton electrons emitted from the source foils by external γ. For ^{208}Tl, a total activity of 40 Bq has been measured and is in agreement with the previous HPGe measurements of samples of the PMT glass. For ^{214}Bi, an activity of 300 Bq has been found, again in agreement with the HPGe measurements of PMTs and also the level of radon surrounding the detector inside the shield. The expected number of $\beta\beta0\nu$-like events due to this background is negligible, $< 10^{-3}$ counts/kg/y in the [2.8-3.2] MeV energy window where the $\beta\beta0\nu$ signal is expected

External neutrons and high energy γ backgrounds have been measured by searching for crossing electron events above 4 MeV. This corresponds to a negligible expected level of background of $\sim 3.10^{-3}$ counts/kg/y in the [2.8-3.2] MeV $\beta\beta0\nu$ energy window.

4.2.3. Radon

Radon (^{222}Rn), the decay product of ^{226}Ra, has a half-life of 3.8 days. It belongs to the group of inert gases. It is present in varying concentrations in all buildings as well as in free air. In the LSM, the radon level in air is 20 Bq/m^3. Radon decays to ^{218}Po, which has ^{214}Bi as a daughter, with a half-life of 30 minutes. The first data collections with NEMO 3 have shown a radon activity inside the detector at a level of ~ 20 mBq/m^3. It have been established that the radon penetrates in the detector by a tiny diffusion. This radon level in the detector lead to 1 event.kg^{-1}.yr^{-1} in the ββ0ν energy region for ^{100}Mo, which is higher than the allowed level of contamination.

In order to suppress this background, a radon-tight tent enclosing the detector has been installed in May 2004. A radon-trap facility delivering free-radon air inside the radon-tight tent is in operation since December 2004. With this system the level of radon surrounding the detector has been reduced to ~ 0.1 Bq/m^3 and the level of radon measured inside the NEMO 3 detector has been reduced to ~ 2 mBq/m^3, a factor 10 of reduction and corresponds to ~ 0.1 event.kg^{-1}.yr^{-1} in the ββ0ν energy region.

However we are still investigating the origin of the very low level of radon remaining in the NEMO 3 gas. The ultra high purity of the gas at the entrance have been controlled (<1 mBq/m^3). But we do not yet know if the remaining radon is still due to a diffusion of radon from outside the detector or due to a degassing of some materials. It is a very important issue for SuperNEMO since a level of radon inside the detector lower than 0.1 mBq/m^3 will be required.

4.3. First results of NEMO 3 and expected final sensitsivity

The first results for the Data Period I (February 2003 until September 2004) corresponding to 389 effective days of data collection have been accepted for publication in Phys. Rev. Lett. in August 2005 (hep-ex/0507083). We briefly present here the results.

The ββ2ν half-lives have been measured for ^{100}Mo and ^{82}Se with very high statistic (220.000 ββ2ν events collected) and higher accuracy compared to previous values. Two-electron energy sum spectrum, one-electron energy spectrum and angular correlation of the two electrons have been obtained with very high statistic and are in good agreement with expectation (see Figure 8). A strong signal of 219,000 ββ decay events have been collected for ^{100}Mo with a very low background corresponding to a ratio signal-to-background of 40.

All components of the background in the ββ0ν energy window have been measured directly using different analysis channels in the data.

After 389 effective days of data collection with NEMO-3, no evidence for ββ0ν decay was found (Figure 9). The corresponding limits at 90 % C.L. are $T_{1/2}(\beta\beta0\nu) > 4.5\ 10^{23}$ years for ^{100}Mo and 1.0 10^{23} years for ^{82}Se. Depending on the nuclear matrix element calculation, the limits for the effective Majorana neutrino mass are $<m_\nu> < 0.7$-2.8 eV for ^{100}Mo and $<m_\nu> < 1.7$-4.9 eV for ^{82}Se.

For this first running period (Phase~I) presented here, Radon was the dominant background at a level of about 3 times higher than the ββ2ν background for ^{100}Mo. It has now been significantly reduced by a factor ~10 by a radon-tight tent enclosing the detector and a radon-trap facility in operation since December 2004 which has started a second running period (Phase~II).

After five years of data collection, the expected sensitivity at 90\% C.L will be:

- for ^{100}Mo: $T_{1/2}(\beta\beta0\nu) > 2\ 10^{24}$ years corresponding to $<m_\nu> < 0.3 – 1.3$ eV
- for ^{82}Se: $T_{1/2}(\beta\beta0\nu) > 8\ 10^{23}$ years corresponding to $<m_\nu> < 0.6 – 1.7$ eV

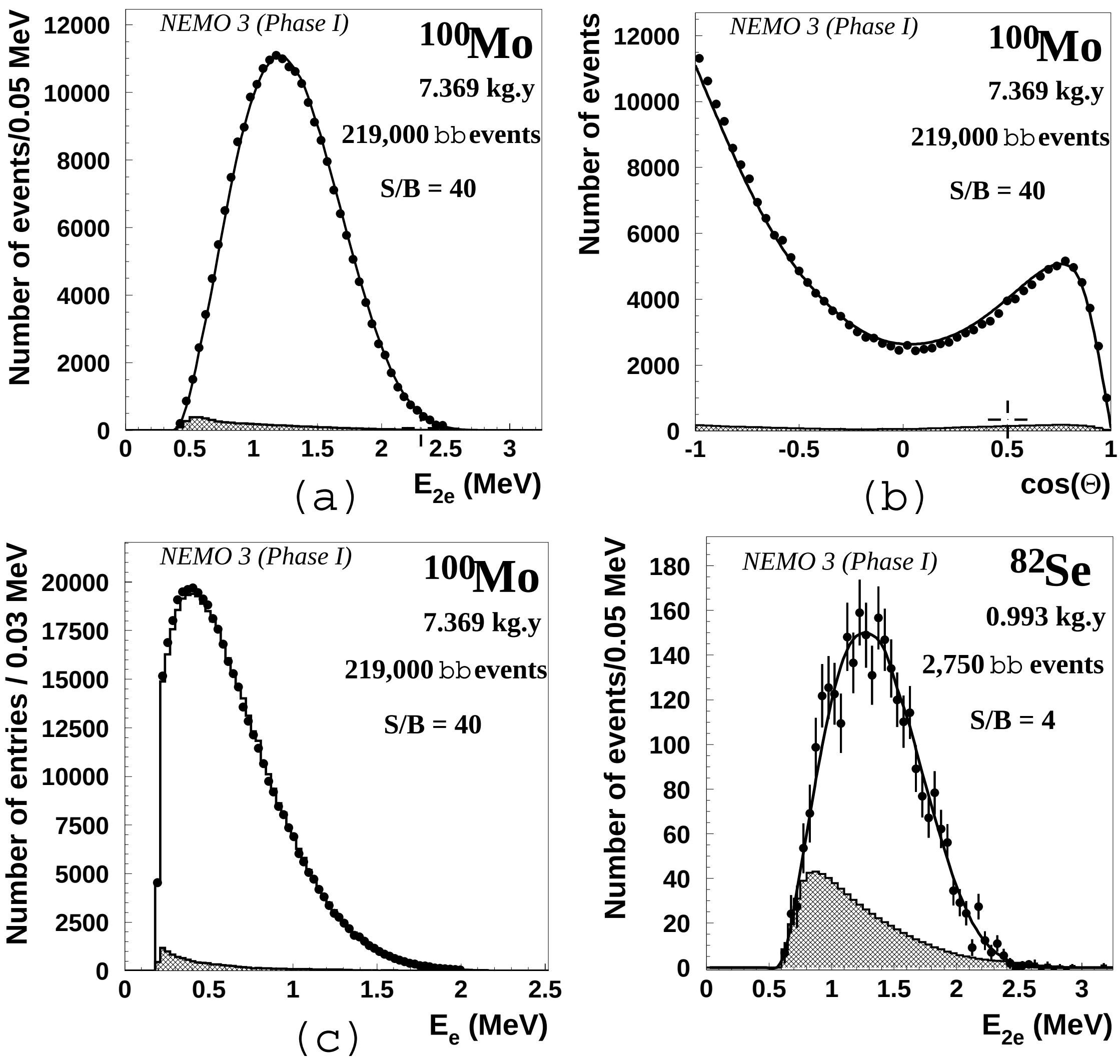
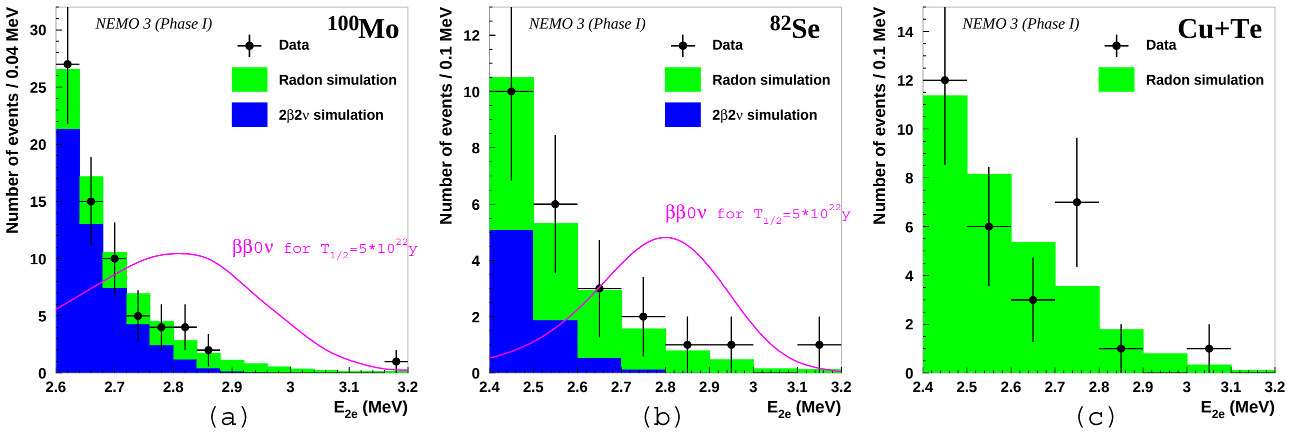


Figure 8: (a) Energy sum spectrum of the two electrons, (b) angular distribution of the two electrons and (c) single energy spectrum of the electrons, after background subtraction from ^{100}Mo with 7.369 kg.years exposure and (d) energy sum spectrum of the two electrons from ^{82}Se with 0.993 kg.years exposure. The solid line corresponds to the expected spectrum from ββ2ν simulations and the shaded histogram is the subtracted background computed by Monte-Carlo simulations. For ^{100}Mo the signal contains 219,000 ββ decay events and the signal-to-background ratio is 40.



(a) (b) (c)

Figure 9: Spectra of the energy sum of the two electrons in the ββ0ν energy window after 389 effective days of data collection from February 2003 until September 2004 (Phase I): (a) with 6.914 kg of ^{100}Mo; (b) with 0.932 kg of ^{82}Se; (c) with Copper and Tellurium foils. The shaded histograms are the expected backrounds computed by Monte-Carlo simulations: dark (blue) is the ββ2ν contribution and light (green) is the Radon contribution. The solid line corresponds to the expected ββ0ν signal if $T_{1/2}(\beta\beta0\nu) = 5.10^{22}$ years.

4.4. What was learnt from the NEMO 3 data collection ?

The NEMO 3 detector has been running reliably since February 2003 and the performance of the drift chamber and calorimeter are as expected. After two years of functioning, there is no sign of wire chamber or calorimeter aging.

The first NEMO 3 results have shown that the background reductions are at the expected levels, for both internal and external backgrounds.

The main result from this data collection is that all the sources of backgrounds are well identified and understood.

As a summary, the collaboration has shown with the NEMO 3 detector :

- its ability to identify all the sources of backgrounds associated with a tracko-calo detector,
- its ability to build a very low-background detector,
- the quality of the technical choices,
- its capability of using chemical methods to purify ββ isotopes removing ^{214}Bi and ^{208}Tl contaminants,
- its ability to remove radon from air,
- the detector's ability to measure internal contaminations of the source foils,
- its ability to control the external backgrounds (natural radioactivity, neutrons and muons),
- its expertise to develop ultra low background HPGe detectors as well as radon detectors which are sensitive to a 1 mBq/m^3 radon activity.

5. The SuperNEMO project

Since the NEMO technique can be extrapolated for a larger mass detector, the SuperNEMO collaboration have written in June 2004 an « expression of interest » for a « tracko-calo » experiment with a mass of at least 100 kg of enriched ββ isotope in order to reach a sensitivity of 50 meV on the effective neutrino mass. Such a detector could not only measure ββ(0ν) decay process but also search for Majoron, study right current interactions for neutrinos or exchange of supersymmetry particles.

The SuperNEMO detector would use the NEMO technical choices: a thin source between two tracking volumes surrounded by a calorimeter.

The main features of a SuperNEMO detector are compared to the ones of the NEMO-3 detector in Table 3. We remind here the expression of the sensitivity on $T_{1/2}(\beta\beta0\nu)$:

$$T_{1/2}(\beta\beta 0\nu) > \ln 2 \times N_{avo} \times \frac{M \times \varepsilon \times T_{obs}}{A \times \mathrm{N}_{excl}}$$

with: N_{excl} is the number of excluded ββ0ν events at 90% C.L.
M is the mass of enriched bb isotope (in g)
ε is the efficiency
T_{obs} is the time of observation
N_{avo} is the Avogadro number
A is the atomic mass

	NEMO-3	SuperNEMO
Mass of isotope	7 kg of ^{100}Mo $T_{1/2}(\beta\beta2\nu) = 7\ 10^{18}$ years	100 kg of ^{82}Se $T_{1/2}(\beta\beta2\nu) = 10^{20}$ years
sensitivity	$T_{1/2}(\beta\beta0\nu) > 2\ 10^{24}$ years	$T_{1/2}(\beta\beta0\nu) > 2\ 10^{26}$ years
Energy resolution - Calorimeter: FWHM at 1 MeV - Global: FWHM of the ββ0ν ray	 14 % 350 keV	 7 % 210 keV
Efficiency of ββ0ν	8 %	25 %
Internal contamination in the source foil	^{208}Tl ~ 80 μBq/kg ^{214}Bi < 300 μBq/kg	^{208}Tl < 2 μBq/kg ^{214}Bi < 10 μBq/kg
Expected background in the ββ0ν energy window	ββ2ν (^{100}Mo) ~ 0.3 cts/kg/y others ~ 0.2 cts/kg/y	ββ2ν (^{100}Mo) ~ 0.01 ct/kg/y others < 0.01 ct/kg/y

Table 3: Comparison of the main characteristics of NEMO 3 and SuperNEMO detectors.

Compare to the NEMO-3 detector, the main features which have to be improved by the R&D program are:

- the energy resolution,
- the $\beta\beta(0\nu)$ detection efficiency,
- the source radiopurity and its measurement.

All these points are studied in detailed below.

5.1. Choice of the isotope

Despite the recent progress in the calculation methods for the nuclear matrix elements, large uncertainties are remaining. Nuclear theory is not yet able to predict the best candidate, which means the isotope having the most favourable nuclear matrix element.

In order to reduce the background coming from the $\beta\beta(2\nu)$ decay, good criteria for the isotope selection are:

- a period $T_{1/2}(2\nu)$ greater than 10^{20} years
- a high $Q_{\beta\beta}$ energy transition in order to have a high phase space factor. In order to reduce the background, it is also recommended to choose an isotope with a $Q_{\beta\beta}$ greater than 2.615 MeV corresponding to the energy of the γ-ray produced by the decay of ^{208}Tl
- the enrichment process has to be done in a short time (typically a few years) with a reasonable cost.

With these criteria the best isotope is ^{82}Se, which has a $\beta\beta2\nu$ period measured by NEMO-3 of $T_{1/2}(\beta\beta2\nu) = 10^{20}$ years and an energy transition $Q_{\beta\beta} = 2.998$ MeV.

However it is very important to keep in mind that the SuperNEMO detector has to be designed, specially for the background issue, in order to be able to accommodate ^{76}Ge, ^{130}Te or ^{136}Xe in case of a positive signal by the other future experiments.

5.2. Design of the SuperNEMO detector

SuperNEMO detector would be composed of several identical modules (for example 20 modules with 5 kg of ^{82}Se each). Such modular design allows to begin the data collection before the end of the last module construction and mounting. Each module would consist of one source foil, one tracking volume and one calorimeter, these three parts being independent to make easier the construction, mounting and eventual changes.

The detector will be plane and not cylindrical as NEMO 3 was. The mass/volume ratio is not favoured but this solution is easier from a mechanical point of view, it will be easier to build and allow more flexibility on the mounting. Cabling and tightness seal against radon will also be easier.

A possible design of a module containing around 5 kg of ^{82}Se is shown in Figure 10. The size of the source plane would be 4 m long, 3 m high and 40 mg/cm^2 thick. Wire chambers and calorimeter walls would be 5 m x 4 m, with dimensions greater than the source size to increase detection efficiency. The width of the tracking detector would be 1 m. Using a solution with 20 x 20 cm^2 scintillator block size coupled with 8″ PMTs, 1200 PMTs should be necessary per module. Another possible design of the calorimeter would be scintillator bars instead of blocks, read at the two extremities by photomultipliers. Advantage of this design is the very small number of PMTs which would be reduced to 120 per module. A possible gamma calorimeter, consisting of 20 cm width plastic or liquid scintillators coupled to PMTs, would surround the detector to detect γ-rays and thus to allow background measurements and rejection.

With such a configuration, 20 modules should be necessary for a total isotope mass of 100 kg. Thus the total number of channels would be:

- 60 000 drift cells corresponding to 9000 electronics multiplexed channels,
- 2 400 PMTs for a design of calorimeter with scintillator bars
- 24 000 PMTs for a design of electron calorimeter similar to NEMO-3 with scintillators of 20x20 cm^2.

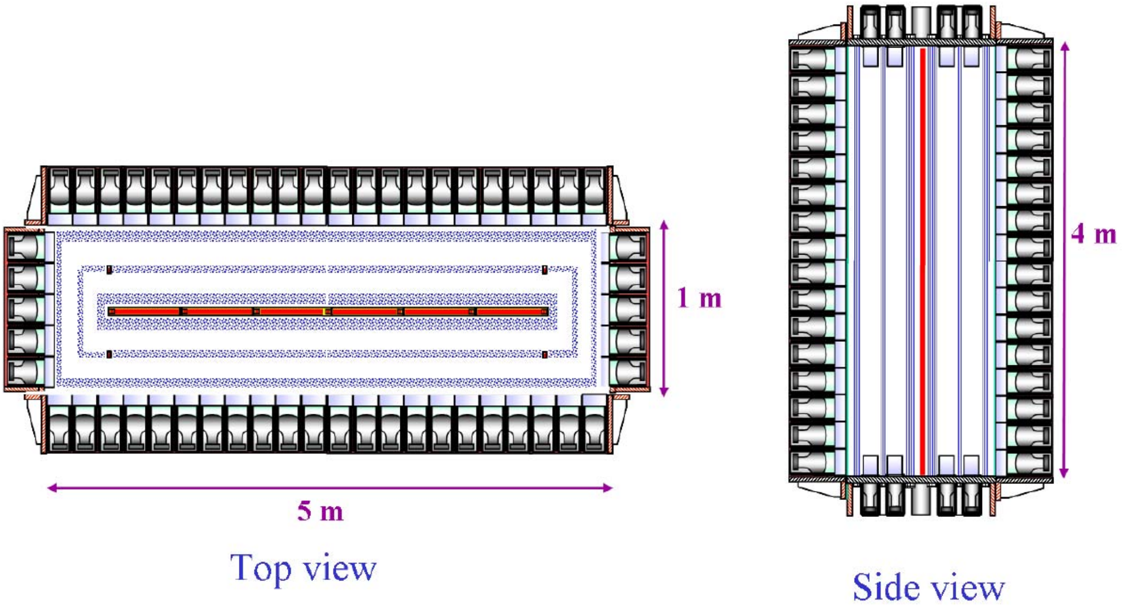


Figure 10 : View of a possible SuperNEMO module. The source is in the center. In blue is represented the electron calorimeter and in red an eventual calorimeter for the detection of γ-rays.

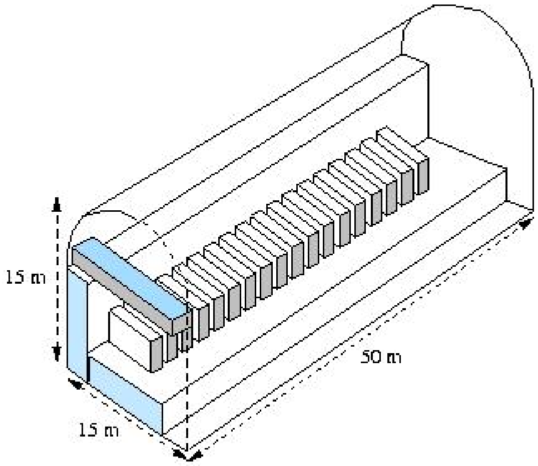


Figure 11 : Scheme of the 20 modules of SuperNEMO installed in a cavity and surrounded with a water shield to suppress the neutron background contribution.

5.3. ^{82}Se sources: enrichement, purification and production of the foils

- Enrichment of ^{82}Se

Using the actual enrichment factories in Russia, the production of 100 kg of ^{82}Se (> 95%) is feasible in 3 years for a reasonable cost. Preliminary cost is estimated to ~ 30 k€/kg.

A production of ~ 5 kg of enriched ^{82}Se have been funded by the ILIAS European program in 2005: the first kilogram will be delivered end of 2005 and the rest in 2006. The goal is to study the radiopurity of ^{82}Se at each production step (before and after enrichment) and to control the enrichment process in order to get the purest enriched ^{82}Se sample at the end of the process.

- Purification of enriched ^{82}Se

To reach a 10^{26} year sensitivity on the $\beta\beta(0\nu)$ period with 100 kg of ^{82}Se, ^{214}Bi and ^{208}Tl contamination levels of the source foils have to be lower than 10 μBq/kg and 2 μBq/kg respectively, that means a purity 10 times higher than the one required in the NEMO 3 specifications.

Chemical purification techniques used for ^{100}Mo sources [29] in INEL (Idaho Falls, USA) can be applied to ^{82}Se isotope. For ^{100}Mo, extraction factors obtained after chemical purification of the enriched powder for the heads of natural decay families were greater than 15 for uranium/radium series (^{214}Bi) and greater than 8 for thorium series (^{208}Tl). The extraction factors are constants whatever radium and thorium concentrations are. Thus it is possible to reach expected radiopurity levels after several cycles if ultra pure chemical reagents are used.

An R&D program began for chemical purification of selenium involving INEL, Mount Holyoke College, and CENBG for the gamma spectroscopy measurements. Already ~100 g of natural Se have been purified in INEL.

- Production of the foil

The composite foils in NEMO 3, produced by ITEP (Moscow, Russia) are a mixture (gel) of source powder and organic glue deposited on a Mylar sheet and then covered by another sheet forming a sandwich-like structure. The thickness of the foils are ~ 60 mg/cm^2 for ^{100}Mo and ~ 40 mg/cm^2 for ^{82}Se.

The same technique can be done with enriched ^{82}Se after chemical purification. However, for NEMO 3 the mylar had to be irradied by an ion beam in order to obtain large numebr of tiny holes to fix the mixture of source powder and glue. For a new production for SuperNEMO, irradied mylar would be replaced by capton in order to supress the irradiation process. An R&D study has to be done.

The collaboration studies the possibility to realize « active » sources in order to improve the rejection efficiency of internal background (^{208}Tl and ^{214}Bi). The figure 12 show an example of an active source which consists of two source planes of 20 mg/cm^2 each surrounding by two Geiger drift cell planes. With such a geometry a ββ event can be separated to a (β, Möller) or a (β, Compton) from a ^{208}Tl decay or a (ββ, delay–α) from a ^{214}Bi decay. Lower thickness will also increase the probability for α-particles to leave the source foils so increase the efficiency to tag the delay a from a ^{214}Bi decay.

In order to be able to produced 100 kg of foils of ultra pure enriched ^{82}Se in a short time, the best solution would be to purify the Se and produce the foils in the same geographic place.

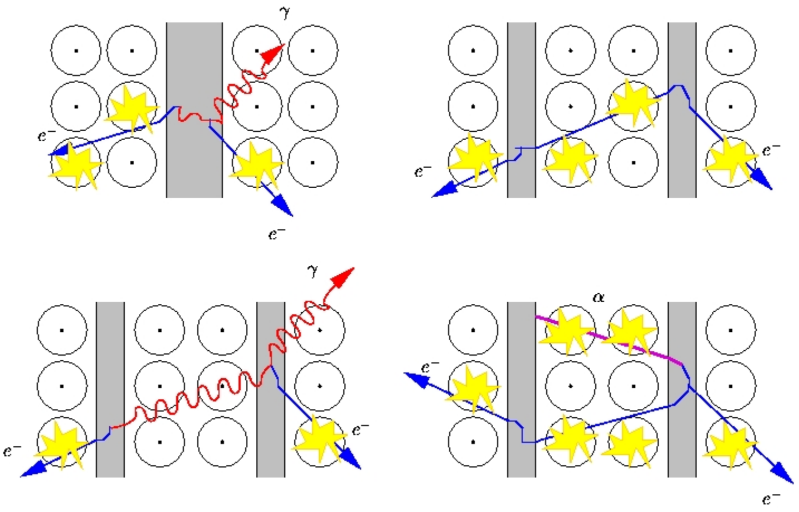


Figure 12 : Example of events which can be rejected using « active » sources. Left on the top, using 40 mg/cm^2 « classical », beta decay ^{214}Bi followed by gamma emission which produce a Compton effect in the source foil. If scattered γ-ray is not detected, this event topology is identical to those of ββ decay event. Right on the top, a ββ event detected using « active » source, which consists of 2 source planes of 20 mg/cm^2 each surrounding by 2 Geiger drift cell planes. Left on the bottom, identical event to the left on the top one but rejected due to the use of « active » source, because there is no fired cell between the source foils. And finally right on the bottom, an example of ^{214}Bi decay followed by the emission of two electrons and one α-particle (in pink). The detection of the α-particle in cells between the source foils allows this event's rejection.

5.4. Ultra Low Activity Measurement of ^{214}Bi and ^{208}Tl contamination in the source foils

- HPGe detectors

For NEMO 3, the measurement of ^{214}Bi and ^{208}Tl contamination in the source foils has been done with two 400 cm^3 HPGe detectors in Modane Underground Laboratory. The sensitivity was 60 μBq/kg for ^{208}Tl and 200 μBq/kg for ^{214}Bi, for one month measurement of one kilogram of enriched isotope. In order to be able to measure contamination levels as low as 10 μBq/kg for ^{214}Bi and 2 μBq/kg for ^{208}Tl as required for SuperNEMO, it is necessary to develop new HPGe detectors with 1000 cm^3 crystals and to improve their intrinsic backgrounds. An R&D program in the frame of ILIAS European program is starting in CENBG Bordeaux in order to develop such a detector.

An HPGe detector would be used to measure the enriched ^{82}Se in the form of powder during the production and purification phases. But because of limited size and geometry of the HPGe detectors, it seems to be impossible to measure in a short time (~1 month) several kg of final source before introduction inside the SuperNEMO detector.

- *BiPo*, a dedicated detector "à la NEMO" to measure ^{208}Tl and ^{214}Bi activity of the source foils

To check the ultra low radiopurity of the source in the form of foils before introduction inside the modules, it is necessary to have a dedicated planar detector "à la NEMO" of about 10 m^2 optimised for the source foil contamination measurement. The measurement time should not exceed one month for about 5 kg of sources with a sensitivity of 2 μBq/kg for ^{208}Tl and 10 μBq/kg for ^{214}Bi. The basic idea of such a detector is to measure the ^{212}Bi contamination (and thus the ^{208}Tl contamination) by the double detection of an electron emitted by the beta decay of ^{212}Bi followed by a delayed α of ^{212}Po decay with an half-life of 300 ns. The background for this dedicated detector could be dominated by possible surface contaminations on the entrance surface of the scintillators used to tag the delayed α. This background will be measured by a prototype. The development of this planar detector will be developed by LAL Orsay. Details are given in section 8 (R&D program in LAL).

5.5. Design of the calorimeter and energy resolution

The resolution of the summed energy of the two electrons in the ββ0ν decay is mainly a convolution of the energy resolution of the calorimeter and the fluctuation in the electron energy loss in the source foil which gives a non-gaussian tail. For NEMO 3, the FWHM of the expected two-electron energy spectrum of the ββ0ν decay (at 3 MeV) is ~ 12% (FWHM=350 keV) and is dominated by the energy resolution of the calorimeter.

For SuperNEMO, the goal is to have a resolution of the expected two-electron energy spectrum of the ββ0ν decay of FWHM ~ 7 % at 3 MeV (FWHM ~ 210 keV). With a source foil of 40 mg/cm^2, we must obtain a energy resolution of the calorimeter 4% (FWHM) at 3 MeV (or 7% at 1 MeV). In NEMO 3, the energy resolution of the calorimeter is 8% (FWHM) at 3 MeV (or 14% at 1 MeV).

The SuperNEMO calorimeter would use plastic or mineral scintillators coupled to PMTs. Use of silicon detectors is excluded because of the large backscattering of electrons.

An ideal scintillator must have a fast response for time-of-flight measurements, a very low atomic number Z to avoid electron back-scattering and it must also be ultra radiopure. No actual scintillator satisfies all the criteria. Plastic scintillators have a modest light yield (~8000 photons/MeV) and the mineral scintillators have relatively high Z values and they are generally no radiopure.

The collaboration began an R&D program to study different possibilities:

- keep the NEMO 3 techniques but improve plastic scintillator and PMT properties
- use mineral scintillators coupled to PMTs
- use liquid scintillators which have a better light yield
- use scintillator bars in order to reduce by a factor 10 the number of photodetectors
- replace PMTs by Avalanche PhotoDiodes (APD).

The NEMO 3 calorimeter resolution is related to the block geometry, to the use of a light guide between scintillator and PMT, to the need of a second PMMA interface to fit the curvature of 5’’ PMT photocathode, and finally to the PMT intrinsic resolution. All the scintillator blocks have a thickness of 10 cm which is a compromise to obtain a sufficient efficiency (50% at 500 keV) for γ-ray tagging with plastic scintillators without loss of transparency of the scintillation light for the electron energy resolution (electrons from double beta decay being detected only in the entrance face of the scintillator block).

There are two options for the thickness of the scintillator blocks in the SuperNEMO calorimeter, to use a small one (~2 cm) or a large one (10-20 cm). In the first case, the light collection should be better but only for electrons and the addition of a gamma calorimeter (in plastic or liquid scintillators) surrounding the detector should be necessary. Using the 10-20 cm option there is a risk to lose scintillation light. The R&D results will decide the final choice

In any case, to reach resolutions better than 4 % at 3 MeV, it is necessary to improve the scintillator light efficiency, the shape and the wrapping of the blocks to increase light collection efficiency, and the PMT efficiency.

Concerning plastic scintillators an R&D program began with collaboration between the Institute for Scintillation Materials from Kharkov, JINR in Dubna, LAL in Orsay and CENBG in Bordeaux (one PICS, which is an international CNRS program of scientific cooperation, was accepted between these four laboratories). NEMO 3 plastic scintillators were produced by ISM Kharkov and JINR Dubna laboratories, which both have already shown their expertise in production techniques and work at present to improve the properties of scintillators based on Polyvinyltoluene (PVT) or Polyvinylxylene (PVX). First results are very encouraging: with small volumes of scintillators coupled to Photonis XP5312B PMT resolutions of 7% (FWHM) at 1 MeV have been reached with PVT technology and better than 6% at 1 MeV with PVX technology.

Also the use of liquid scintillator is under studied. The main problem is to realize a system to envelop the liquid scintillator with a thin entrance window to minimize the electron energy loss. A second point is the safety problems related to the use of liquid scintillators in underground laboratories.

The optimisation of the scintillator shape and wrapping will be studied with simulations using special codes to follow γ-rays and next with prototype measurements.

Measurements of inorganic scintillator performances are realized at UCL London. The goal is to study YSO-type scintillators, which have good light efficiency and relatively low atomic number Z value compare to CSI or NaI inorganic scintillators. NEMO collaborators from Prague also study the possibility to use photodiodes instead of PMTs for the collection of scintillation light.

Low background PMTs, which are developing in collaboration with Photonis company, would have very good energy and time resolutions.

The PMT energy resolution can be written as:

$$R^2 = \frac{(2.35)^2}{N_{ph} \times Q.E \times c}\left(\frac{\delta}{\delta - 1}\right)$$

with N_{ph} : number of incident photons arriving on the photocathode,
Q.E : quantum efficiency (~ 34 % for the best PMTs),
c : collection efficiency of multiplication chain (0.7-0.9),
δ : coefficient of secondary emission for dynodes (δ~5).

Thus, improvements in PMT resolution are related to the increasing of the quantum efficiency and collection efficiency. The PMT response as a function of the entrance point on the photocathode must also presents a very good homogeneity.

An alternative and very attractive design is to use scintillator bars instead of block. It has the advantage to reduce the number of photodetectors. In case of classical scintillator blocks coupled to a PMT, the total number of PM with 20 modules would be 24,000 PMTs. With bars, the number of PMTs would be reduced to only 2,400 PMTs. Bars of 2 and 4 meters long have been developped in the Institute for Scintillation Materials in Kharkov and are now under measurements in UCL London. Bars of liquid scintillators are also studied.

Another solution, studied by the University of Texas, is to use also scintillator bars but the scintillation photons are collected by waveshifters optical fibers introduced inside the scintillator bars. Extremities of the optical fibers are coupled to an APD (Avalanch Photo Diode). Such a technique have been developped for Chashlyk detectors and recently improved by a new prototype for the KOPIO experiment [30]. Preliminary simulations of such a calorimeter for SuperNEMO are very promising. A prototype very similar to the one developed for KOPIO experiment is under construction in University of Texas and is going to be tested soon. This design has the advantage to supress PMTs and to allow to have the APD outside the shield. It would reduce strongly the external background. It is crucial if we plan to introduce ^{76}Ge source inside the detector in case of a positive signal observed by the germanium experiments (GERDA, Majorana). Indeed the external background dominated by the PMTs in NEMO-3 becomes a dominant background in the case of ^{76}Ge because of a low $Q_{\beta\beta}$ = 2.038 MeV.

5.6. Radiopurity of the other materials of the detector

- Radiopurity of the material

Knowing the allowed levels of backgrounds it would be necessary to impose strong constraints on the materials used in the detector's construction or surrounding the detector, to avoid any risk of pollution. In NEMO 3 all materials, except PMTs, have contamination activity in ^{208}Tl and ^{214}Bi lower than few mBq/kg.

- Radon in the gas

The level of radon inside the detector should be reduced down to 0.1 mBq/m^3 (compare to NEMO-3 ~ 1 mBq/m^3). This reduction will be based using the same Radon Trap Facility used in NEMO 3.

High-sensitivity radon detectors from Saga University which were built for the NEMO 3 experiment have a sensitivity of 1 mBq/m^3. The principle of radon detection in these detectors is the electrostatic collection of the positively charged daughter nuclei of ^{222}Rn (for example, 90% of ^{218}Po daughter atoms tend to become positively charged). Thus the radon detectors collect these daughter nuclei in the gas (70 l in volume) using an electrostatic field. Energy measurement of the alpha particle is carried out with a PIN photodiode. This technique can be extrapolated to gain a factor 10 with a detector of 1000 l. Such a detector is already under construction in Heidelberg for the Gran Sasso laboratory. The NEMO collaboration will have to develop a similar detector.

The NEMO-3 collaboration is still investigating the origin of radon remaining in the NEMO 3 gas. The ultra high purity of the gas at the entrance have been controlled (<1 mBq/m^3). But we do not yet know if the remaining radon is still due to a diffusion of radon from outside the detector or due to a degassing of some materials. It is a very important issue for SuperNEMO.

5.7. Tracking device

The tracking device would be similar to NEMO 3. It would consist of open drift cells operating in Geiger mode in helium gas with quenchers.

There are three R&D issue.

- The drift cells would be ~ 4 meters long which is longer than in NEMO3 with 2.7 meters.

The longitudinal propagation of the Geiger plasma has to be complete along 4 meters.
Prototypes of 4 m long geiger cells similar to the prototypes for NEMO-3 will be built in order to study the efficiency of the longitudinal propagation.

- The wire chamber has to be as transparent as possible. There are two possibilities to improve the transparency:
  - reduce the diameters of the wires: 50 μm in NEMO-3 to 30 μm.
  - for cathodic wires, replace metallic wires to carbon wires.

However, preliminary Monte-Carlo simulation show that decreasing the diameter and using carbon wires has a negligeable improvement on the sensitivity of the detector for $\beta\beta0\nu$ search. The transparency of the detector is not a crucial point for the efficiency of $\beta\beta0\nu$ search.

- Mecanical studies to develop an industrial process of the wiring for a large and fast production

The R&D program for the tracking device is shared by two laboratories: LAL and University of Manchester.

5.8. The laboratory

The detector must be installed in an underground laboratory to reduce muon and neutron fluxes. To protect the detector against the remaining neutron flux and to detect the muons going through the detector, a water shielding could be used. A thickness of 2 m of water, which is equivalent to 25 cm of iron, will also shield the detector against γ-rays.

SuperNEMO installation would need a cavity with dimensions around 100 x 15 x 15 m^3 (see Figure 11). At present there is only one laboratory in Europe where this detector can be placed, which is Gran Sasso laboratory (LNGS, Italy). Dimensions of the three cavities in this laboratory (100 x 20 x 18 m^3) are sufficient for SuperNEMO detector's mounting. Backgrounds constraints from neutrons and muons also impose to use underground laboratory with at least the Gran Sasso depth.

Other possibility should be to use an extension of LSM laboratory: this new cavity could be realized in the same time than the security gallery's driving. The main advantage of the LSM is its depth, which is 4800 m.w.e. to compare to 3800 m.w.e. for LNGS and allows a better protection against muons. The Canfranc (Spain) laboratory (2500 m.w.e.) could be another possible location and has to be studied. This "new" laboratory could be equipped directly with a 2 or 3 m width water shield to stop neutron flux; in the same time Cherenkov effect in water could be used to sign muons. Radon level could also be reduced using radon-free air facility as in NEMO 3 and covering rock walls with a special plastic layer against radon diffusion.

5.9. Expected sensitivity

Preliminary Monte-Carlo calculations based on the NEMO-3 Monte-Carlo program have been done with a very preliminary design presented in paragraph 5.1 and with the following assumption:

- a module of 5x4 meters
- source foils 4x3 meters 40 mg/cm^2
- 20 modules for a total mass of 100 kg of ^{82}Se
- internal contamination of the foils: ^{208}Tl = 2 μBq/kg and ^{214}Bi = 10 μBq/kg
- external background supposed to be negligeable
- Energy resolution of the calorimeter: 6% at 1 MeV
- Wire chamber like NEMO-3

The optimal sensitivity is obtained by searching the $\beta\beta0\nu$ signal in the energy window [2.75–3.0] MeV. In this energy window, the expected efficiency for $\beta\beta0\nu$ signal is

$\varepsilon(\beta\beta0\nu) = 22$ %

and the expected background is:

- $\beta\beta2\nu$: 1 event/year
- Internal ^{214}Bi: 0.5 events/years
- Internal ^{208}Tl: 0.5 events/years
- External background supposed to be negligeable

The expected sensitivity after 5 years of data is:

$$T_{1/2}(\beta\beta0\nu) > 1.0\ 10^{26} \text{ years (90 \% C.L.)}$$

With thicker scintillators (higher efficiency to tag γ) and 10 years of data, the expected sensitivity is:

$$T_{1/2}(\beta\beta0\nu) > 1.8\ 10^{26} \text{ years (90 \% C.L.)}$$

Depending on the nuclear matrix elements, it would correspond to a limit on the effective Majorana neutrino mass of:

$$\langle m_\nu \rangle < 40 - 115 \text{ meV (90 \% C.L.)}$$

Can SuperNEMO see the ββ0ν signal claimed by Klapdor ?

With 100 kg of ^{82}Se and a ββ0ν efficiency =20%, the number of detected ββ0ν events per year is:

$$N(\beta\beta0\nu) = 10^{26} / T_{1/2}(\beta\beta0\nu) \quad \text{(with } T_{1/2} \text{ in years)}$$

The ββ0ν signal claimed by Klapdor has a best value $T_{1/2}(\beta\beta0\nu) = 1.2\ 10^{25}$ y.
Using the recent nuclear matrix elements calculations for ^{76}Ge [14-19] we obtain a value

$$\langle m_\nu \rangle = 0.4 - 1.2 \text{ eV}$$

Using the same calculation of nuclear matrix elements but for ^{82}Se one get the number of detected bb0n events per year in Table 4

$\langle m_\nu \rangle$	$T_{1/2}(\beta\beta0\nu)$ for ^{82}Se in year	$N(\beta\beta0\nu)$ detected events/year
0.4 eV	$1.9\ 10^{24} - 1.5\ 10^{25}$	6 – 53
1.2 eV	$2.1\ 10^{23} - 1.7\ 10^{24}$	59 – 476
0.1 eV	$3.0\ 10^{25} - 2.4\ 10^{26}$	*0.4 – 3*

Table 4: Expected number of detected ββ0ν events in SuperNEMO corresponding to the signal claimed by Klapdor $\langle m_\nu \rangle = 0.4 - 1.2$ eV. The number is also given for $\langle m_\nu \rangle = 0.1$ eV for reference. For comparison, the expected level of background is < 2 events/year.

5.10. Planning

The planning for the SuperNEMO R&D could be the following:

2005-2007 : R&D calorimeter, to reach an energy resolution of 4 % at 3 MeV (FWHM)
R&D wire chamber, with 4 m long cells
R&D purification and foils production of ^{82}Se
Studies for the production of 100 kg of ^{82}Se
R&D « active » source
R&D development of HPGe detectors for ^{82}Se radiopurity measurements
R&D developpment of a dedicated planar detector to measure ^{208}Tl and ^{214}Bi activities in the foils
Monte-Carlo simulations for the design of the detector and the choice of the best shields
Mechanical studies

2008 : Construction of the 1st module
Studies with industrial companies for the production of the next modules
2009 : Start production and installation of the modules
Start data collection with the first module and addition of other modules
2012 : Data collection with the full detector

6. SuperNEMO Collaboration and funding

6.1. The SuperNEMO collaboration

Czech Republic :
- Charles University, Prague
- Czech Technical University, Prague

France :
- CENBG Bordeaux,
- IReS Strasbourg,
- LAL Orsay ,
- LSCE Gif/Yvette,
- LPC Caen

Japan :
- Saga University,
- Osaka University

Marocco:
- University of Fes

Russia :
- INR RAS Moscow,
- ITEP Moscow,
- JINR Dubna,
- RRC "Kurchatov Institute" Moscow

Ukrainio
- INR Kiev

USA :
- INEEL (Idaho),
- Mount Holyoke College (Massachusetts),
- University of Texas

UK:
- University College of London ,
- University of Manchester

6.2. Details of the french collaboration:

4 laboratories, 15 physicists and 3 PhD students:
- LAL: C. Augier, S. Jullian, D. Lalanne, X. Sarazin, L. Simard, G. Szklarz
  PhD student: M. Bongrand
- CENBG: P. Hubert, C. Marquet, F. Perrot, F. Piquemal, J. S. Ricol
  PhD students: G. Broudin
- IRES : R. Arnold
- LPC Caen: D. Durand, E. Liénard, F. Mauger
  PhD student: Y. Lemière

6.3. Support and Funding:

The R&D program for a design of a SuperNEMO detector has been accepted by the french IN2P3 Scientific Council in March 21st 2005. The french collaboration asked for 600 Keuros in 3 years.

The french collaboration have deposited in June 2005 a 600 Keuros funding plan for 3 years of R&D in the new french funding agency ANR.

The UK laboratories have deposited in March 2005 a 700 Keuros funding plan in their funding agency for SuperNEMO.

The US collaboration presented to the NuSAG comitee in June 1st 2005 a proposal for R&D in the US (Texas and INEL).

PICS between LAL, CENBG, Kharkov and JINR Dubna

7. Preliminary plan of the sharing tasks for the SuperNEMO R&D during the 2005-2007 period

- **Calorimeter** (task leader: CENBG)

Goal: to reach an energy resolution better than 4% at 3 MeV with scintillators coupled to photomultiplier tubes or other photodetectors.
Participants: CENBG, Kharkov, Dubna, UCL, Prague, Univ. Texas, Osaka,
Collaboration with Photonis company
Accepted program: PICS between LAL, Kharkov, CENBG and JINR Dubna laboratories

Scintillators

- Improvements of plastic scintillators based on Polyvinyltoluene technology (purity of products, polymerisation cycle, improvement of the production tools): *Dubna, Kharkov, CENBG, Osaka*
- Development of plastic scintillators based on Polyvinylxylene technology: *Kharkov , Dubna, CENBG*
- Tests of Dubna and Karkhov scintillators with an electron spectrometer: *CENBG*
- Tests of Bicron plastic scintillators and inorganic scintillators (YSO): *UCL*
- Tests of inorganic scintillators: *Prague*
- Simulations to optimize shape and wrapping: *CENBG, UCL, Prague, Texas University, Osaka*

Photomultipliers

- Collaboration *Photonis Company – CENBG* for very low background and large photomultipliers (greater than 8") with very good energy resolution and timing
- Tests of Hamamatsu and ETL photomultipliers: *UCL, U Texas*

Geometry with bars

- Development of bars with plastic scintillators based on Polyvinylxylene technology: *Kharkov*
- Measurement of bars: *CENBG, UCL*
- waveshifters optical fibers introduced inside the scintillator bars: *Univ. of Texas*

Electronics

- Study of integrated electronics with ASIC technology: LAL, CENBG

- **Drift chambers** (task leaders LAL and Manchester)

Goal: To obtain a full Geiger signal propagation on 4 m long wires.
To improve the transparency of the detector by decreasing diameter of wires
Participants : LAL, Manchester

Prototypes:

- Extrapolation from 2.7 m to 4 m: *LAL, Manchester*
- Decreasing of the wire diameter: *Manchester*

Electronics:

- Embedded electronics: *LAL*
- Conventional electronics : *Manchester*

- **ββ source foil** (task leader: LAL)

Goal : To be able to produce 100 kg of ^{82}Se with internal contaminations less than 2 μBq/kg in ^{208}Tl and 10 μBq/kg in ^{214}Bi

Participants: Kurchatov, ITEP, INEEL, MHC, Gif, Dubna, LAL, CENBG
Agreement: production and purification of 2 kg of ^{82}Se founded by ILIAS European program

- Production *Kurchatov, ITEP*
- Production survey and possibility to produce other isotopes: *LAL*
- Purification *INEEL, MHC, Gif, LAL*
- Radiopurity measurements: *CENBG*
- Production of thin foils: *Dubna, ITEP*

- **Low background measurements** (task leaders: CENBG and LAL)

Goal : To develop detectors able to measure the source contaminations with a sensitivity of 2 μBq/kg in ^{208}Tl and 10 μBq/kg in ^{214}Bi. Completion of HPGe detectors for the selection of SuperNEMO materials. Dedicated module for measurement à la NEMO Development of detectors sensitive to 0.1 mBq/m^3 of radon.
Participants : CENBG,LAL, IReS, Saga, Prague
Agreement : 3 years of CNRS Engineer contract at CENBG, half-time for low radioactivity technique development and half-time for applications in industry.

- Development of HPGe detector : *CENBG* (with Eurysis-Mesure company)
- Development of radon detector : CENBG, IReS, Saga
- Completion of HPGe detectors for materials selection: CENBG
- Development of the detector BiPo dedicated to measure purity of the foils before introduction in the detector.

- **Active Source** (task leader: LAL)

Goal: To improve the detection of α–particles emitted in coincidence with electrons to reject background events from ^{214}Bi and ^{208}Tl
Simulations: *LAL, LPC*

- **Electronics and slow control**

Participants: *LAL, LPC,IreS, CENBG, UCL, Manchester*

- Trigger: *LPC*
- Acquisition: *LPC, IreS, CENBG, UCL, Manchester*
- Slow control: *IReS, LPC, UCL, Manchester*

- **Calibration survey** (Task leader: UCL)

Goal: To develop a daily calibration check to follow the absolute calibration at a level better than 1% (currently 2% in NEMO 3)

Participants: *CENBG, UCL*

- Extrapolation of the NEMO 3 system based on laser light: *CENBG*
- System based on the use of LED light: *CENBG, UCL*

- **Simulations** (Task leaders: IReS and LPC Caen)

Goal: To design the detector, to determine precisely the required level of radiopurity and the ultimate sensitivity of SuperNEMO. Both GEANT 3 and GEANT 4 codes will be used for cross-checks.

Participants: *IReS, LAL, LPC, CENBG, Dubna, UCL, Manchester, U. of Texas*

- **Mechanics** (Task leader: LAL)

Goal: Design of the detector

Participants: *LAL, Manchester*

- **Nuclear matrix element theory** (Task leader: IReS)

Goal: To improve the nuclear matrix element calculations to predict the best ββ candidate.

Participants: IReS, Jyvaskula, Prague

- Calculations based on Shell Model: IReS
- Calculations based on QRPA: Jyvaskula, Prague

8. R&D Program in LAL Orsay

The R&D subjects in LAL Orsay are the following:

- tracking device
- enrichment of Se
- production of the double beta source foils
- mechanical design of the SuperNEMO detector
- simulation and software tools
- development of the detector BiPO: a dedicated planar detector "à la NEMO" to measure ^{208}Tl and ^{214}Bi contaminations in the source foils with a sensitivity of few μBq/kg in ^{208}Tl.

8.1. Tracking device

The R&D program for the tracking device is shared by two laboratories: LAL and University of Manchester. The program in Orsay is the following:

- **Study the longitudinal propagation efficiency of Geiger plasma for a a drift cell of 4 meters long** (extrapolation of NEMO3 with 2.7 meters).
  A construction of two prototypes 4 meters long of 9 Geiger cells are required. These prototypes will be similar to the 9 cells prototypes built for R&D of NEMO-3.
  The geometry of the cells, the mecanical design and the nature of the wires (material, diameter) will be similar to NEMO-3. Here we just want to study the longitudinal propagation efficiency.

  Physicists: Xavier Sarazin, Georges Szklarz
  2005 – 2006

- **Mecanical studies to develop an industrial and automatic process** of the wiring for a large and fast production.

  Ingenior: Jacques Forget
  2005 – 2006

- **Electronic study.** The goal is to develop an ASIC with both analogic and numeric parts, which could be mounted in a big contact board integrated to the detector in order to have all the ASICs multiplexed per plane of cells. This solution should decrease the cable numbers compare to NEMO 3, with only 3 cables per plane (HV, acquisition and trigger). The real difficulty of such electronic board is that all the electronic components must be ultra low radiactivity.

  Physicist: Corinne Augier
  2006 – 2007

8.2. Enrichement of ^{82}Se

A production of ~ 5 kg of enriched ^{82}Se have been funded by the ILIAS European program in 2005: the first kg will be delivered end of 2005 and the rest in 2006.

The R&D program is:

- To make possible in the actual enrichment factories in Russia the production of 100 kg of enriched ^{82}Se (> 95%) in 3 years for a reasonable cost (≤30 k€/kg).
- To study the radiopurity of ^{82}Se at each production step (before and after enrichment) and to control the enrichment process in order to get the purest enriched ^{82}Se sample at the end of the process.

  Physicist: Serge Jullian
  2006 – 2007

8.3.Production of the sources

In order to be able to produced 100 kg of foils of ultra pure enriched ^{82}Se in a short time, the best solution would be to purify the Se and produce the foils in the same geographic place.

Dominique Lalanne will be in charge for the next two years 2006 – 2007 to study the possibilities to have a unique lab in LAL to purify enriched ^{82}Se and produce the foils.

The facilities used in INEL (USA) to purify chemically the selenium are quite simple. A transfer of technology could be done with the help of the LSCE lab in Gif-sur-Yvette.

The productions of foils have be done in ITEP (Moscow) in collaboration with LAL. So again a transfert of technology could done here in LAL with russian visitors.

A large ultra clean room (classe 100) of ~ 5 x 6 m^2 would be necessary and could be mounted in hall IN2P3 on the west side.

Mechanical studies have to be done concerning the foils production, the foils strength and the possibility to introduce/remove easily the foils in a SuperNEMO module.

An ingenior is required for these studies.

Physicist: Dominique Lalanne
2006 – 2007

8.4. Mechanical design of the SuperNEMO detector.

LAL has the responsibility for the mechanical studies of the design of SuperNEMO.

Coordinator: Jacques Forget

8.5. Simulation and software tools.

Simulations are required for many topics to be studied:

- optimisation of the geometry of the detector: calorimeter, tracking chamber, sources etc…
- improvement of the $\beta\beta0\nu$ detection efficiency
- determine the required maximum levels of ^{208}Tl and ^{214}Bi contaminants in the source foil
- optimisation of the shielding and the magnetic field intensity
- contribution of the background induced by the remaining cosmic ray muons at the depth of the LSM, Gran Sasso or Canfranc laboratories must be investigated
- simulation of the dedicated BiPo planar detector to measure the ultra low activities of ^{208}Tl and ^{214}Bi in the source foils

In addition, in the hypothesis where a signal would be observed by GERDA (^{76}Ge) or CUORE (^{130}Te) experiments, sources of ^{76}Ge or ^{130}Te could be introduced inside the SuperNEMO detector. But these isotopes have quite low energy transition (2038 keV and 2528 keV, respectively). Thus to allow these two isotope measurement, the accepted levels of external background coming from the surrounding materials must be carefully studied by simulations and cross checked with the NEMO 3 data.

Since several groups or laboratories will study these topics, it is really important to have a common software simulation package. We need a tool that enables the change of many characteristics of the virtual setup in order to find optimal performance conditions. The simulation program should be done by many different people using the same versatile program. We also need a common analysis and visualisation framework.

Francois Mauger, physicist in LPC Caen is the Coordinator. In order to develop these software tools, an help from an expert and creative computing ingenior is required. It will be done in LAL Orsay by Guy Barrand and Jerôme Garnier.

Ingeniors: Guy Barrand, Laurent Garnier
Physicist: Francois Mauger (LPC Caen)
2006 – 2007

8.6. Study and development of the detector BiPo (Bismuth-Polonium), a dedicated detector “à la NEMO” to measure ^{208}Tl and ^{214}Bi contaminations in the source foils before introduction in the detector.

- **Goal**

To check the ultra low radiopurity of the sources in the form of foils before introduction inside the modules, it is necessary to have a dedicated planar detector “à la NEMO” of about 10 m^2 optimised for the source foil contamination measurements. The measurement time should not exceed one month for about 5 kg of sources with a sensitivity of 2 μBq/kg for ^{208}Tl and 10 μBq/kg for ^{214}Bi.

The basic idea of this detector is to use the so-called “Bi-Po” process to measure ^{208}Tl and ^{214}Bi contaminations in the source foils. The Bi-Po process is the emission of an electron from the ^{214}Bi β-decay which is followed by a delayed α from the ^{214}Po decay with an half-life of 164 μs.

$^{214}\mathrm{Bi} \rightarrow {}^{214}\mathrm{Po}$ β decay
$^{214}\mathrm{Po} \rightarrow {}^{210}\mathrm{Pb}$ α decay $T_{1/2} = 164\ \mu s$

This (e^-, delayed–α) analysis channel is used in NEMO-3 to measure the ^{214}Bi contamination thanks to a delayed electronic in the tracking device recording delayed tracks up to 700 μs.

^{208}Tl contamination can be measured by using a similar (e^-, delayed–α) signature ? The ^{212}Bi nuclei, parent of ^{208}Tl, decays with a branching ratio of 64% via a β-emission in ^{212}Po ($Q_\beta \cong 2.2$ MeV) which is again an α emitter with a short half-life of 300 ns.

$$\begin{tikzcd} {}^{212}\mathrm{Bi} \arrow[r, "64\%"] \arrow[d, "36\%"'] & {}^{212}\mathrm{Po} \\ {}^{208}\mathrm{Tl} & \end{tikzcd}$$

β decay
$^{212}\mathrm{Po} \rightarrow {}^{208}\mathrm{Pb}$ α decay $T_{1/2} = 300$ ns

So instead of measuring the direct β decay of ^{208}Tl, we can measure again the Bi-Po process of the ^{212}Bi, parent of ^{208}Tl. Unfortunatly the 300 ns half-life of the delayed α–decay from ^{212}Po is too short to be measured by a gaseous detector like in NEMO-3. To solve that problem, a solution is to measure the delayed α from ^{212}Po directly with a scintillator.

- **Preliminary design of the BiPo detector**

The BiPo detector (see figure 14) would consist of a horizontal planar detector. The foils to be measured would be installed directly on a wall of scintillator blocks (“lower wall”) coupled to ultra low radioactive PMTs. Above the foils is a wire chamber composed of few layers of drift cells operating in Geiger mode in helium gas. A second wall of scintillator blocks (“upper wall”) coupled to PMTs is installed on the top of the wire chamber.

The (e^-, delayed–α) signature of a ^{212}Bi decay is shown in figure 14. A track in the wire chamber due to the crossing emitted electron is associated with a fired scintillator block on the upper wall (energy $Q_\beta \cong 2.2$ MeV). It gives the timing reference T_0. A second scintillator block on the lower wall near the reconstructed vertex is fired by the delayed α emission of ^{212}Po with a delay time of $T_{1/2} =$ 300 ns and a high energy deposited ~ 1 MeV (1 MeV is deposited instead of the 8 MeV α energy because of quenching in the scintillator). Let’s note that the energy resolution of the scintillators is not an issue for this detector.

A 3 x 4 m^2 planar detector could accommodate ~ 5 kg of source foils (40 mg/cm^2 thickness) corresponding to a SuperNEMO module. An activity of 2 μBq/kg of ^{208}Tl would correspond to 46 (e^-, delayed−α) decays per month from ^{212}Bi.

- **Sensitivity of the BiPo detector**

A preliminary estimation of the efficiency of such a detector to detect a (e^-, delayed−α) decay gives an efficiency ~ 6% if there is a ^{208}Tl (so a ^{212}Bi) bulk contamination. Let's notice that the efficiency would be much higher in case of a surface contamination because the probability for the α to escape to the foil would be larger.

If no background is observed after 1 month of data collection, a (e^-, delayed−α) signal of 2.3 events is excluded at 90 % C.L. corresponding to a sensitivity of 2 μBq/kg of ^{208}Tl for bulk contamination. The sensitivity would be 4 μBq/kg if 4 background events are observed in 1 month.

- **Origin of the backgrounds**

A detector with a background lower than few counts per month is crucial for the BiPo detector.

One of possible backgrounds is due to random coincidence. In that case the time distribution of the delayed scintillator on the lower wall is flat (and not a exponential decrease corresponding to the α emission). The single counting rate of the 10x10x10 cm^3 scintillator blocks measured on NEMO 3 in Modane is ~ 0.1 Hz with a threshold energy of ~500 keV (which is lower than the energy deposited by the α of ~1 MeV). The trigger rate in NEMO 3 if one requires one short track and one PMT above 200 keV is ~ 5 Hz. So the frequency to have a random coincidence PMT in a 1 μs window with a fired scintillator associated to a track would be $5 \times 0.1 \times 10^{-6} = 5.\ 10^{-7}\ s^{-1}$. In one month of data collection it would correspond to ~ 1 background event. This background which will be measured in the first prototype (see below) can be strongly reduced by using thiner scintillator blocks (see Figure 16). Indeed the scintillator blocks in NEMO 3 are 10 cm thick. The thickness can be reduced to 2 cm to contain a 2.2 MeV electron.

Another origin of backgrounds is due to a thoron contamination in the gas between the source foils and the lower scintillator wall since the thoron gas decays to ^{212}Bi. Thoron above the foil is not a source of background because the α is absorbed by the source foils before reaching the lower scintillators wall. The thoron contamination in the gas inside the NEMO-3 wire chamber has been preliminary measured to a level of 2.0 ± 0.4 mBq/m^3. For example with a gap of 1 cm between the foil and the scintillator lower wall of a 3 x 3 m^2 planar detector, it would correspond to ~ 400 ^{212}Bi decays per month. With an efficiency of ~ 0.25 to detect it, it would correspond to ~ 100 collected background events per month. The simplest way to suppress this background is to remove any volume of gas between the source foils and the lower scintillator wall. Thus the source foil would be installed directly on the surface of the scintillators.

The main origin of background which can mimic (e^-, delayed−α) event is probably a ^{208}Tl (and thus ^{212}Bi) surface contamination on the entrance surface of the scintillator block on the lower wall (as shown in figure 15). A bulk contamination inside the block in the lower wall is not a source of background because the emitted electron will fire the lower scintillator block before escaping (so the fired scintillator block will be in time and not delayed with the fired block on the upper wall).

This background have been studied with the NEMO-3 data by searching for a crossing electron with the incoming scintillator block delayed in time. 1642 events have been observed in 240 days of data in NEMO-3. The time distribution is in agreement with an exponential decrease with $T_{1/2}$ = 300 ns. This background would come from a ^{212}Bi contamination inside the aluminized mylar wrapping the scintillator blocks. It would correspond to a ^{212}Bi activity in the mylar of ~ 2 mBq/kg.

The first conclusion of this analysis is that no wrapping has to be done on the surface entrance of the scintillators in the BiPo detector.

The second conclusion is that obviously some R&D must be done to measure and control the level of ^{212}Bi surface contamination on the entrance surface of the scintillator blocks.

We propose to do the following R&D program during the next year 2006.

- **two successive preliminary prototypes to qualify the level of background due to a possible ^{212}Bi surface contamination on the entrance surface of the scintillator blocks**

Step 1: First prototype (see Figure 17)

2005 – 2006

The first prototype consists of two face-to-face scintillator blocks coupled to ultra low radioactive PMTs (see Figure 17). The scintillators have no wrapping to avoid any contamination from the aluminized mylar. In order to isolate each scintillator of their scintillation light, an ultra thin and ultra high purity thin foil (copper for instance) separates the two entrance surface of the scintillators. This setup is surround by a shield and a radon-tight envelop. The prototype will be installed in Modane. We will use a small part of radon-free air produced by the radon-trap facility of NEMO 3.

With this simple setup, the acquisition can be done by a numeric oscilloscope to study the rate of delayed hit of one PM by triggering on the other one.

This first prototype will give us a first estimation of the ^{212}Bi surface contamination of the scintillators block.

If some delayed hits are observed with a decay half-life of $T_{1/2}$ = 300 ns due to a ^{212}Bi contamination this prototype would be a test facility to develop a process to clean the surface.

If no delayed hits are observed, we must increase the sensitivity by an extrapolation of this prototype.

Step 2: Second prototype (see Figure 18)

In 2006

The second prototype (see Figure 18) would be an extrapolation of the first prototype. The number of scintillators blocks is increased in order to increase the sensitivity to measure ^{212}Bi contamination on the entrance surface of the scintillators.

The goal of this second prototype is to qualify the purity of scintillators in order to have less than 1 count/month in the final BiPo detector. Such a sensitivity corresponds to a prototype of 1m x 1m. With 25 x 25 cm^2 scintillator blocks, it corresponds to ~ 16 blocks on each wall so a total of 32 scintillator blocks coupled to 32 low radioactive PMT.

A dedicated electronic board has to be developed with 32 TDC + ADC channels.

dynamic TDC: 1 μs.

dynamic ADC: ~ 3 MeV

The time and energy resolutions are not an issue.

Step 3: Construction of the BiPo detector

2007

If the test with the prototype 2 has been successful, we can start building the complete BiPo detector.

Simulation studies are required in order to study:

- the geometry
- the efficiency
- the sources of backgrounds
- the different geometries: size of the scintillator blocks, scintillator bars for the upper wall.

A possible size of the BiPo detector is 3 x 4 m^2 with a Geiger wire chamber with 4 layers of Geiger cells. The upper wall could would consist of 20 scintillator bars of 3 m long and 20 cm large, each bar would be coupled to two PMTs on each extremity. The lower wall would consist of 300 scintillator blocks of size 20 x 20 cm^2 coupled to 300 PMTs. The detector would be surrounded by a gamma shield and a neutron shield. As in NEMO-3, it must be enclose in a radon-tight tent with radon-free air.

The BiPo detector could be located in the new Canfranc underground laboratory in Spain or in Gran Sasso. It is probably difficult to find enough room in the Modane Underground Laboratory to accommodate this detector.

The total number of PMTs would be 340 PMTs corresponding to 340 electronic channels. It is around 10 times more than the prototype 2. Electronic would be similar to the one developed for the prototype 2. Relative important mechanic work must be done.

An ultra clean room (class ~ 100) of ~ 5 x 6 m^2 is necessary to built the BiPo detector and probably necessary for the 1 x 1 m2 prototype of step 2. This clean room could be coupled to the one required to produce the source foils and could be mounted in hall IN2P3 on the west side.

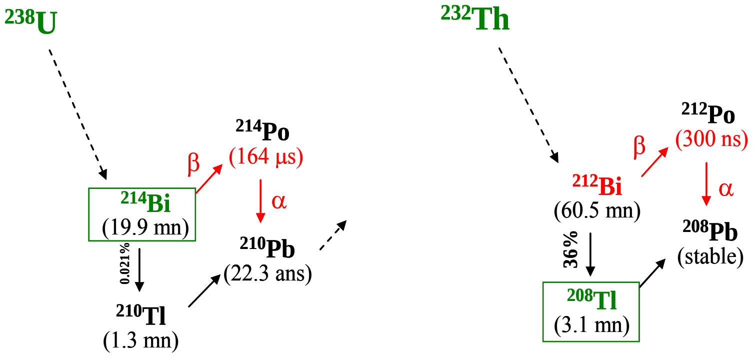


Figure 13

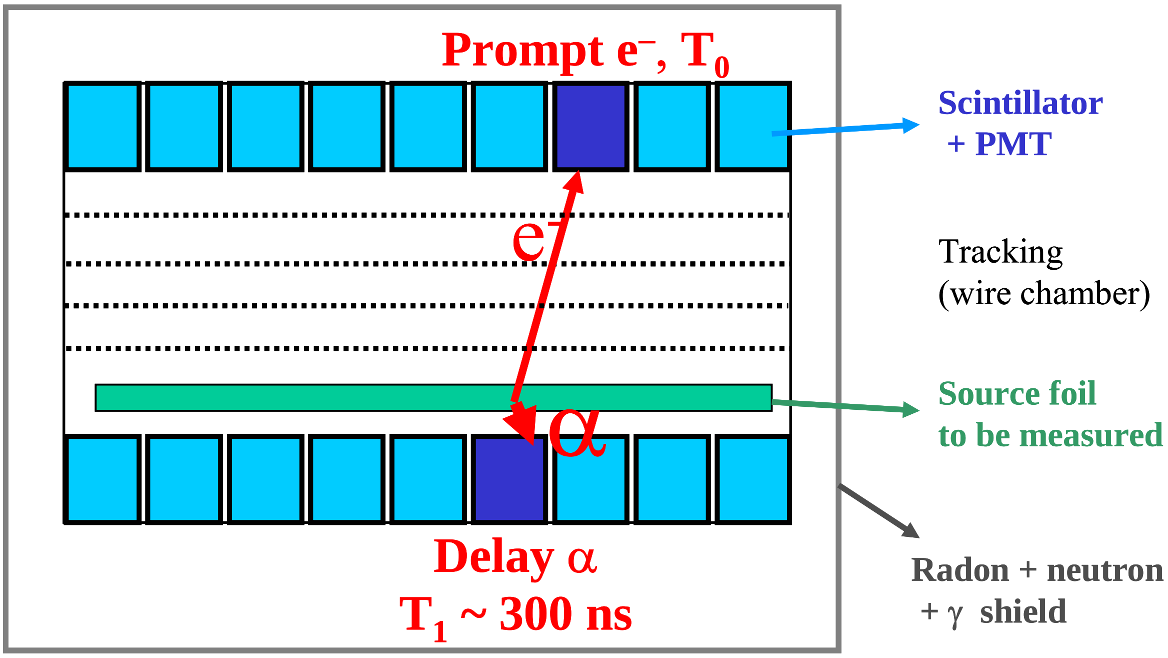


Figure 14: schema of the BiPo detector

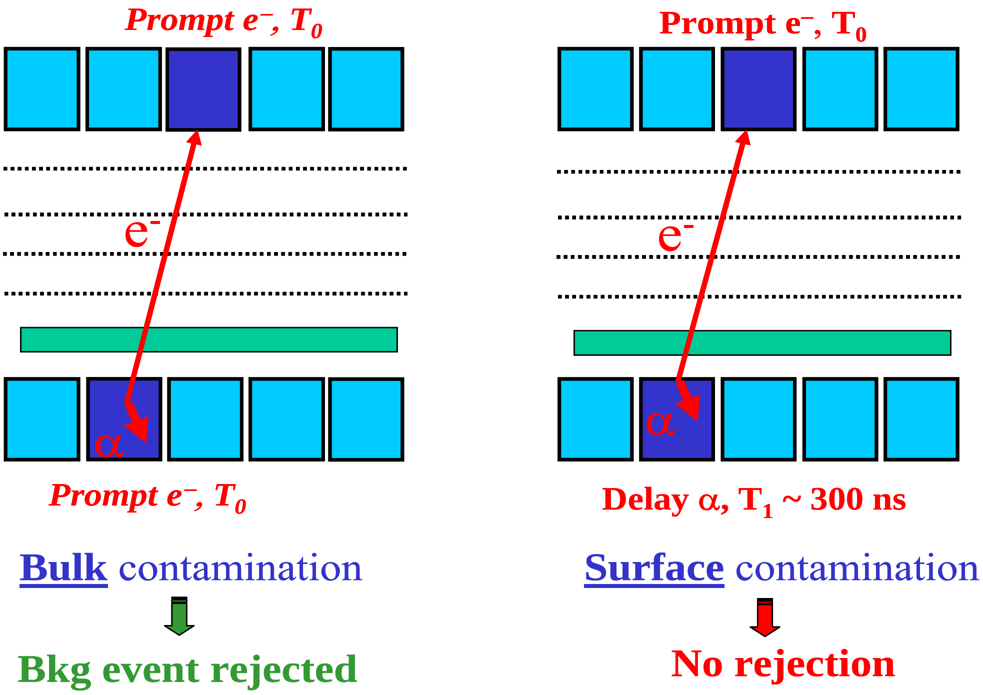


Figure 15: Backround due to a surface contamination of ^{212}Bi on the entrance surface of the scintillator block.

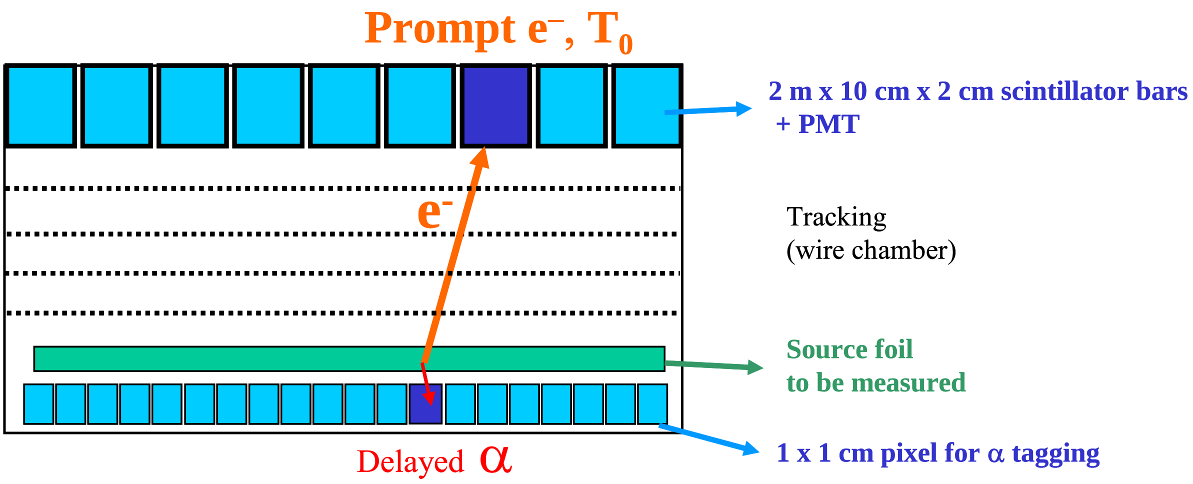


Figure 16: smaller scintillator block on the lower wall

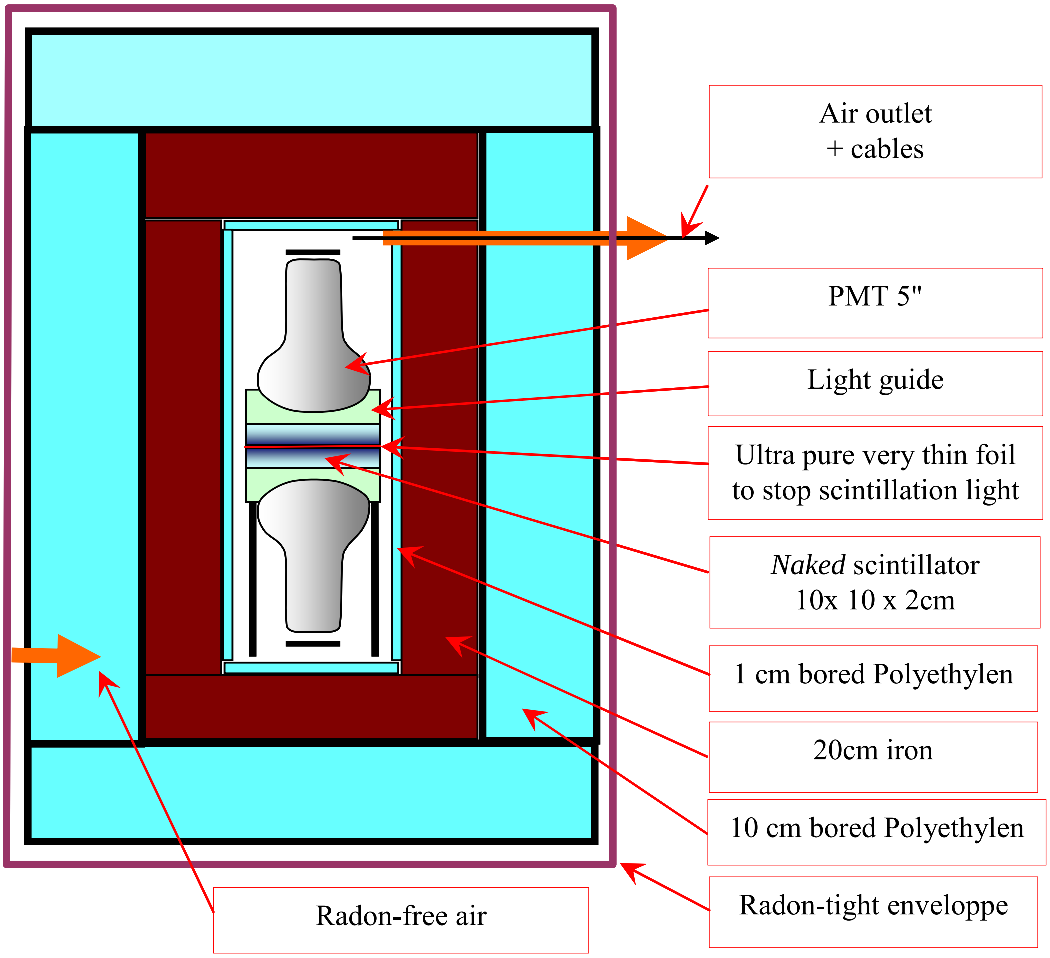


Figure 17: first prototype

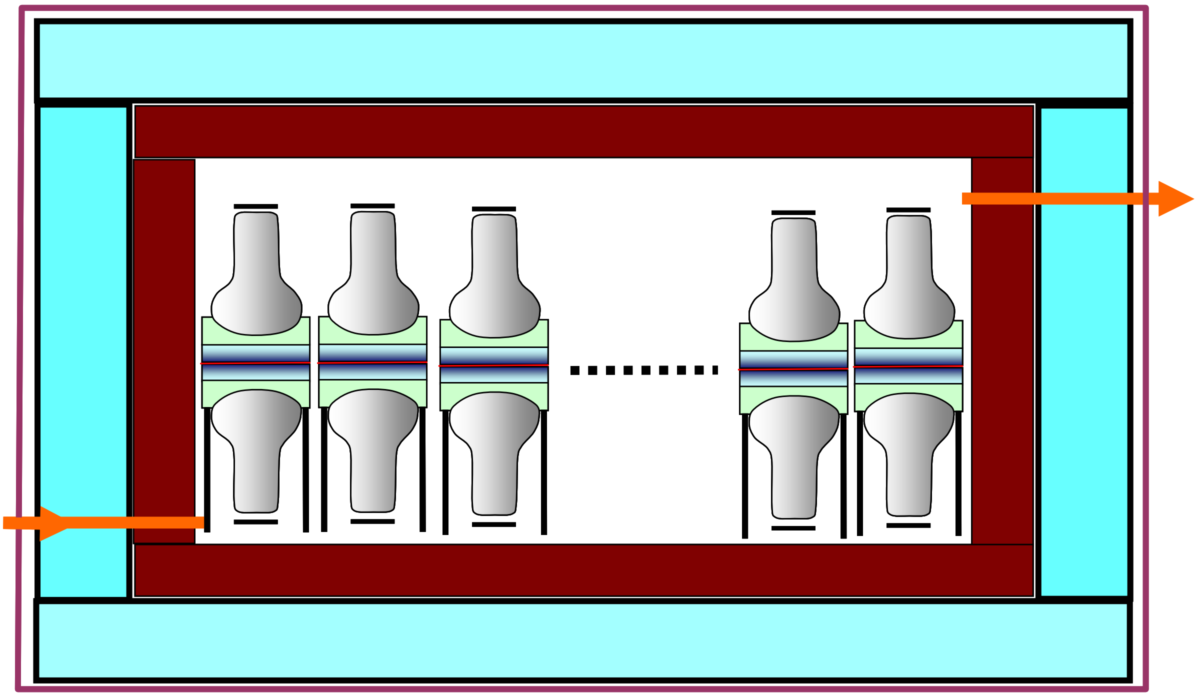


Figure 18: second prototype

9. Conclusion

Neutrinoless double beta decay is the most sensitive process to search for the lepton number violation. A $\beta\beta(0\nu)$ signal discovery should allow to determine the neutrino nature, Dirac or Majorana particle, and also to learn about the hierarchy of the neutrino mass states. Studies of the $\beta\beta(0\nu)$ process are also a way of search for right currents or Majoron and a mean of tests for some parameters of the supersymmetry theories.

The present experiments, NEMO 3 and CUORICINO, which use $\beta\beta$ sources with masses in the order of 10 kg, should allow to reach in 2007 a 0.2 to 0.4 eV sensitivity on the effective neutrino mass.

Since the NEMO-3 technique can be extrapolated for a larger mass detector, the NEMO collaboration plan to build a « tracko-calo » detector with a mass of 100 kg of enriched ^{82}Se able to reach in the next 10 years a sensitivity of 50 meV. It would require a cavity with dimensions at least 100 m x 15 m x 15 m. The SuperNEMO detector will be competitive compare to the other experimental projects (CUORE, Majorana, GERDA and EXO) which also plan to reach in the next 10 years a 50 meV sensitivity. The NEMO technique is the unique method to identify directly the two emitted electrons, which is not possible for pure calorimeters. Several experiments with different isotopes are needed due to the big uncertainties on the nuclear matrix elements. From this point of view, the ability of the SuperNEMO detector to accommodate several $\beta\beta$ isotopes and to change the source foils is an important advantage in the case of improvements in the nuclear matrix element theories, which could give the best $\beta\beta$ candidate. We believe also that any signal observed with a pure calorimetric detector should be confirmed with a NEMO-like approach. So the SuperNEMO detector has to be designed, especially for the background issue, in order to be able to accommodate ^{76}Ge, ^{130}Te or ^{136}Xe.

The SuperNEMO detector will use the same principles of detection than those used for NEMO 3. The NEMO collaboration proposes a R&D program in order to improve the characteristics of the detector. The main issues of the R&D program are:

- the improvement of the energy resolution,
- the enrichment, the purification and the production of ^{82}Se source foils with a level of contamination in ^{208}Tl of 2 μBq/kg and in ^{214}Bi of 10 μBq/kg,
- the development of new HPGe detectors with a high sensitivity to control the enrichment and purification of ^{82}Se in the form of powder,
- the development of a BiPo detector, a dedicated planar detector “à la NEMO” to measure ^{208}Tl and ^{214}Bi radiopurity of the double beta sources foils before introduction in the detector with a sensitivity of few μBq/kg in ^{208}Tl and few tens of μBq/kg in ^{210}Bi,
- the control of a radon-free gas in the tracking detector,
- the optimization and simplicity of the design (especially the calorimeter).

The R&D tasks in LAL concern mainly the enrichment, the purification and the production of ^{82}Se source foils and the development of the BiPo detector. It is a major contribution in the R&D program for the next two years 2006 and 2007.

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