Available online at www.sciencedirect.com

C. R. Physique 6 (2005) 778–788

COMPTES RENDUS PHYSIQUE

http://france.elsevier.com/direct/COMREN/

Neutrino Physics/Physique des neutrinos

Experimental status on neutrinoless double beta decay searches

Serge Jullian

Laboratoire de l'accélérateur linéaire, université Paris-sud, B.P. 34, 91898 Orsay cedex, France

Abstract

We describe the present neutrinoless double beta decay $0\nu\beta\beta$ experiments and the sensitivity to an exchange of a light Majorana neutrino. We then discuss the proposed next generation $0\nu\beta\beta$ decay experiments. The sensitivity should be beyond a half life of a few 10^{26} years corresponding to a few tens of meV Majorana neutrino mass. ***To cite this article: S. Jullian, C. R. Physique 6 (2005).***

Résumé

État des recherches sur la double désintégration beta sans émission de neutrino. Nous décrivons l'état actuel des expériences de double désintégration beta sans émission de neutrino $0\nu\beta\beta$ et leur sensibilité à un échange de neutrino de Majorana léger. Nous discutons ensuite les expériences de la prochaine génération dont la sensibilité sera au-delà d'une demi vie de quelques 10^{26} années ce qui correspond à une masse de neutrino de Majorana de quelques dizaines de meV. ***Pour citer cet article : S. Jullian, C. R. Physique 6 (2005).***
© 2005 Académie des sciences. Published by Elsevier SAS. All rights reserved.

Keywords: Double beta decay; Neutrino mass; Majorana neutrino

Mots-clés : Double désintégration beta ; Masse du neutrino ; Neutrino de Majorana

1. Introduction

The standard model of electroweak interactions developed in the late 1960s incorporated neutrinos as left-handed massless partners of the charged leptons. Later efforts to unify the strong and electroweak interactions led to the development of Grand Unified Theories (GUT). The non observation of the proton instability at a level of a few 10^{33} years by the Super Kamiokande experiment [1] leads us to consider only GUTs which provide for most of them a framework for Majorana neutrino masses.

During the last three decades, several neutrino experiments discovered the neutrino oscillations from different neutrino sources (Sun, nuclear power plants and atmospheric neutrinos) in the energy region from MeV to a few GeV. These discoveries constituted the first manifestation for new physics beyond the standard model and established that neutrinos have mass.

Despite the recent important experimental discoveries in neutrino physics, several questions remain to be answered. Establishing whether neutrinos are Dirac fermions (different from their antiparticle) or Majorana fermions (i.e., spin 1/2 particles identical to their antiparticles) is of fundamental importance for understanding the underlying symmetries of particle interactions and the origin of ν masses. The searches of neutrinoless double beta decay and the end-point anomaly in single beta decay are unique to answering two questions:

E-mail address: jullian@lal.in2p3.fr (S. Jullian).

1631-0705/$ – see front matter
doi:10.1016/j.crhy.2005.07.008

- are neutrinos their own antiparticle (i.e., Majorana-type) unlike all the other constituents of matter?
- what are the absolute masses of neutrinos and their pattern?

2. Double beta decay-neutrino oscillation and Majorana effective neutrino mass

The neutrinoless double beta decay $0\nu\beta\beta$ would be a new natural radioactivity of some nucleus in which two neutrons turn into two protons and two electrons and nothing else.

$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^-$$

The electron sum energy of the $0\nu\beta\beta$ is simply a peak at $T_{e_1} + T_{e_2}$ = Q smeared only by the detector resolution located at the end point of the allowed double beta decay $2\nu\beta\beta$ (Fig. 1)

$$(Z, A) \rightarrow (Z, +2, A) + e_1^- + e_2^- + \nu_1 + \nu_2$$

The observation of the $0\nu\beta\beta$ decay would prove that the total lepton number is not conserved and would establish a non vanishing neutrino mass of Majorana nature [2]. The process can be mediated by an exchange of a light Majorana neutrino interaction (mass mechanism) through the left-handed V-A, or by an exchange of other particles. Here only the mass mechanism (Fig. 2) will be discussed. The observable $0\nu\beta\beta$ rate is proportional to the square of the effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle$. The rate is:

$$\left[T_{1/2}^{0\nu}\left(O^+ \rightarrow 0^+\right)\right]^{-1} = G^{0\nu}.\left|M^{0\nu}\right|^2.\langle m_{\beta\beta}\rangle^2$$

where $G^{0\nu}$ is the accurately calculable phase space, and $M^{0\nu}$ is the nuclear matrix element of the process. The computation of $M^{0\nu}$ is subject to considerable uncertainty. The problem associated with the evaluation of the nuclear matrix elements will be briefly discussed in Section 3.

If the $0\nu\beta\beta$ is observed, and the nuclear matrix elements are known, one can deduce from the rate the corresponding $\langle m_{\beta\beta}\rangle$ value, which in turn is related to the oscillation parameters. The effective Majorana neutrino mass in given by:

$$\left|\langle m_{\beta\beta}\rangle\right| = \left||U_{e_1}|^2 m_1 + |U_{e_2}|^2 m_2 \mathrm{e}^{\mathrm{i}\phi_2} + |U_{e_3}|^2 m_3 \mathrm{e}^{\mathrm{i}\phi_3}\right|$$

m_1, m_2, m_3 are the neutrino mass eigenstates, U_{e1}, U_{e2}, U_{e3} are the coefficients of the neutrino mixing matrix, and where ϕ_1 and ϕ_2 are the Majorana CP phases (± 1 if CP is conserved). $\langle m_{\beta\beta}\rangle$ can be expressed in terms of three unknown quantities: the mass scale (the lightest neutrino $m_{\nu\,\mathrm{min}}$) and the two Majorana phases. The measured values of δm_s^2 (solar) and δm_{AT}^2 (atmospheric) motivate the pattern of masses in three hierarchy schemes. There are three mass patterns: normal hierarchy (NH) where $m_1 < m_2 \ll m_3$ ($m_1 = m_{\nu\,\mathrm{min}}$); inverted hierarchy (IH) where $m_3 \ll m_1 < m_2$ ($m_3 = m_{\nu\,\mathrm{min}}$); and the quasi degenerate (QD) spectrum where $< m_1 \simeq m_2 \simeq m_3$ and $m_{\nu\,\mathrm{min}} > \sqrt{|\Delta m_{32}^2|}$ as well as $m_{\nu\,\mathrm{min}} \gg \sqrt{|\Delta m_{21}^2|}$. A detailed discussion of the relation between the $\langle m_{\beta\beta}\rangle$ and the absolute mass scale can be found in [3]. Fig. 3 shows the effective neutrino mass as a function of the lightest neutrino mass with the three different hierarchies. The predicted ranges for $\langle m\beta\beta\rangle$ are: $\langle m_{\beta\beta}\rangle > 50$ meV for the QD pattern; $\langle m_{\beta\beta}\rangle$ between 10 meV and 50 meV for IH; $\langle m_{\beta\beta}\rangle < 5$ meV for the normal hierarchy NH.

At present, the neutrinoless double beta decay experiments are sensitive only to the quasi-degenerate pattern for 'reasonable' values of nuclear matrix element computations. Many projects are proposed to go further in the near future to establish the pattern of the three neutrino masses and the absolute neutrino mass scale.

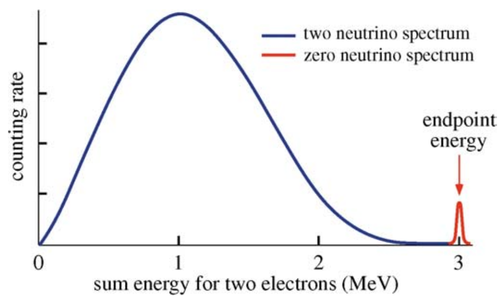

Fig. 1. Energy spectrum for the two electrons.

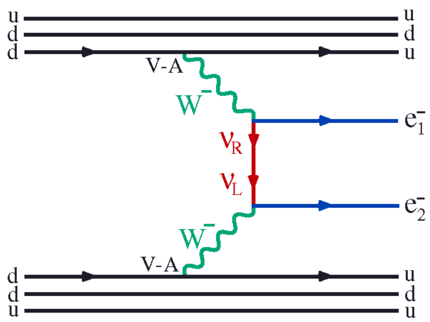

Fig. 2. Neutrinoless double beta decay scheme mediated by the exchange of a light Majorana neutrino interacting through the left-handed V-A weak currents.

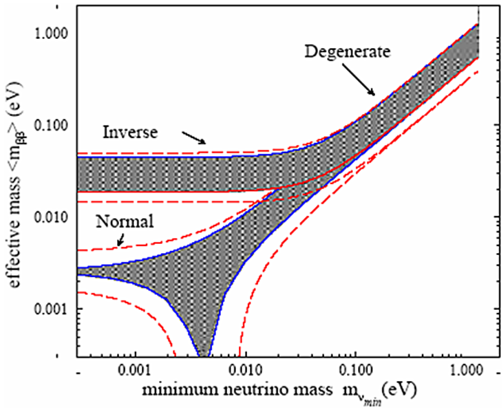

Fig. 3. Effective neutrino mass as a function of the lightest neutrino mass for the three pattern neutrino masses. The shaded region corresponds to the central values of the neutrino oscillation parameters and $\theta_{13} = 0$. The dashed lines corresponds to a 1σ error for the parameters.

3. Experimental status of double beta decays, $0\nu\beta\beta$ and $2\nu\beta\beta$ searches

The experimental field of $0\nu\beta\beta$ searches 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 $2\nu\beta\beta$, will be presented here. Table 1 summarizes the experimental status for nine nuclei sensitive to the double beta decay. The experimental approaches can be classified in three categories: pure calorimetric measurement; a combination of a tracking and calorimetry; and calorimetry with the tagging of the daughter product. From an experimental point of view this field of research is very attractive as it covers a wide range of the techniques of detection available in particle and nuclear physics with strong constraints on the radiopurities of the devices.

3.1. The different decays

- ^{48}Ca: in principle the nucleus matrix element of this nucleus can be calculated accurately in the framework of the shell model [4], but, unfortunately, the isotopic abundance of ^{48}Ca is only 0.2% and it is presently very difficult to enrich it. This is a calorimetric experiment based on light scintillation of CaF_2 crystals [5].
- ^{76}Ge: the two Germanium experiments obtained the best sensitivity in terms of rate. Both experiments are based on enriched HPGe crystals (85% enrichment). One of the experiments, Heidelberg [6] claimed a 4σ effect in the energy region of interest, which is not confirmed by the IGEX Collaboration [7] with practically the same criteria of analysis. These experiments are calorimetric experiments with Ge diodes.
- ^{130}Te: the Milano group has developed for 20 years a new technique with cryogenic detectors working at low temperature $\simeq$ 10 mK at a large mass $\simeq$ 40 kg. Cuoricino (Fig. 4) is an array of $Te0_2$ crystals which is running and reliable. In this phase of the experiment no enrichment is needed because the isotopic abundance of ^{130}Te is 34%. This is a calorimetric experiment using a new technique [8].

Table 1
Present experimental limits on the rate of neutrinoless double beta decay for nine candidates and the corresponding limits for the effective neutrino mass

Isotope $\beta\beta$	$T^{0\nu}_{1/2}$ (90% C.L.) (years)	$\langle m_\nu \rangle$ (eV)	kg. year	Ref.	Experiment
^{48}Ca	$> 1.4 \times 10^{22}$	< 7.2–44.7	0.005	[5]	CANDLES
^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35–1.05	35.5	[6]	HM
	$> 1.57 \times 10^{25}$	< 0.35–1.30	8.9	[7]	IGEX
^{82}Se	$> 1.0 \times 10^{23}$	< 1.70–4.80	1.01	[13]	NEMO3
^{96}Zr	$> 1.0 \times 10^{21}$	< 23	0.008	[12]	NEMO2
^{100}Mo	$> 4.6 \times 10^{23}$	< 0.7–2.8	7.47	[13]	NEMO3
^{116}Cd	$> 0.7 \times 10^{23}$	< 1.7	0.16	[11]	Solotvina
^{130}Te	$> 1.8 \times 10^{24}$	< 0.2–1.1	3.16	[8]	Cuoricino
^{130}Xe	$> 4.4 \times 10^{23}$	< 1.8–5.2	2.27	[9]	Gotthard
^{150}Nd	$> 1.2 \times 10^{21}$	< 3	0.009	[10]	Irvine

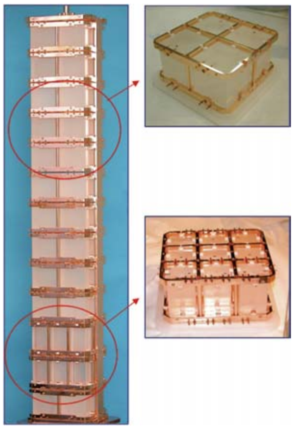

Fig. 4. Photograph of the Cuoricino tower.

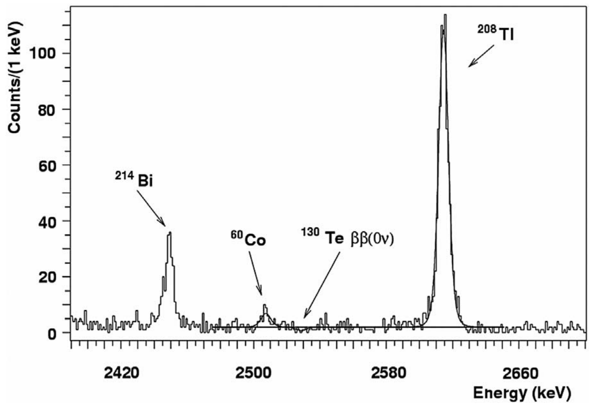

Fig. 5. Cuoricino experimental spectrum summed over all the 5 cm cube detector. Clearly visible are the two well-known gamma ray lines from ^{238}U and ^{232}Th chains and the energy region of the expected $0\nu\beta\beta$ decay.

- ^{136}Xe: this 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 [9].
- ^{150}Nd: this experiment was running with the TPC operating at normal pressure with a magnetic field which observed directly the two electrons and measured each momentum [10].
- ^{116}Cd: this experiment is a pure calorimetric experiment based on the detection at light emission of $CdW0_4$ enriched crystals [11].

The results on ^{100}Mo, ^{82}Se and ^{96}Zr [12,13] obtained with the NEMO2 and NEMO3 devices, which are a combination of a tracking and a calorimeter detectors, are presented below.

The experimental rates (Table 1) are quoted in column 2. The extraction of the observable $\langle m_{\beta\beta}\rangle$ depends on the computation of the corresponding nuclear matrix elements. Even with the recent calculations [14–19] large uncertainties are remaining (column 3). Nevertheless, a conservative upper limit for $\langle m_{\beta\beta}\rangle$ of 1 eV (90% C.L.) seems to be a reasonable value.

Two other experiments, Cuoricino and NEMO3, are in operation with a double beta decay source of $\simeq 10$ kg each.

3.2. Cuoricino experiment

Cuoricino is based on the technique of cryogenic detectors (Fig. 4). When operated at low temperature $\simeq 10$ 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. Cuoricino is located in the Gran Sasso underground laboratory. It is an array of 44 crystals, each of $Te0_2$ $5\times5\times5$ cm, and 18 crystals $3\times3\times6$ cm 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 (34%) of the double beta decay candidate ^{130}Te no isotopic enrichment is performed, but only two of the $3\times3\times6$ cm crystals are enriched in ^{130}Te and two in ^{128}Te to investigate $2\nu\beta\beta$. In only six months of operation Cuoricino obtained a limit on neutrinoless double beta decay of 2×10^{24} yr [20] 90% C.L. The experimental background spectrum summed over all the 5 cm cube detectors is shown on Fig. 5. This limit is not very far from the best limit obtained from the searches of double beta decay period of ^{76}Ge with the enriched semi-conductor detectors.

3.3. NEMO3 experiment

The NEMO3 detector [21], installed in the Fréjus Underground laboratory (LSM, France) is devoted to searching for $\beta\beta0\nu$ decay with the direct detection of the two electrons by a combination of a tracking device and a calorimeter (Fig. 6). The two main isotopes present inside the detector in the form of very thin foils (40–60 mg/cm^2) are ^{100}Mo (6914 g) and ^{82}Se (932 g). The sources have been purified to reduce their content of ^{214}Bi and ^{208}Tl. On both sides of the sources, there is a gaseous tracking detector. It consists of 6180 open drift cells operating in the Geiger mode regime which gives three-dimensional track reconstruction. To minimize the multiple scattering, the gas is a mixture of 95% helium, 4% ethyl alcohol, 1% argon and 0.1% of water. The wire chamber is surrounded by a calorimeter which consists of 1940 plastic scintillator blocks coupled to very low radioactive photomultipliers (PMTs) developed by Hamamatsu. A solenoid surrounding the detector produces a 25 gauss

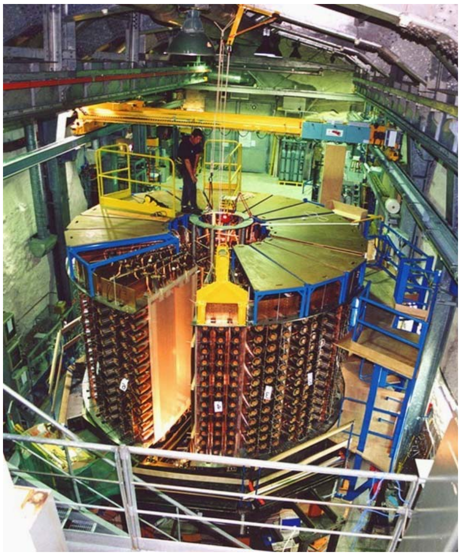

Fig. 6. View of the NEMO3 detector in the LSM before the installation of the last sector.

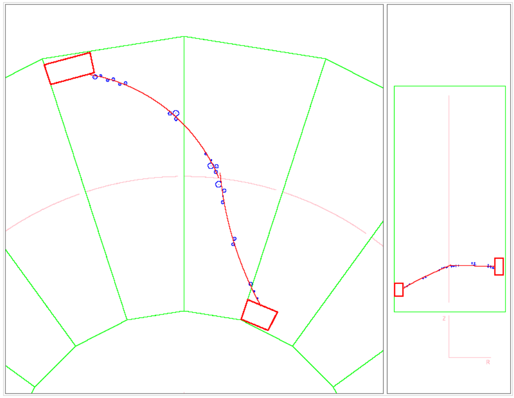

Fig. 7. Transversal (left) and longitudinal (right) view of a $\beta\beta$ event selected in data: two tracks (small circles represent the hit drift cells) coming from the same vertex on the source foil and associated each one to a hit scintillator (rectangular boxes) with an internal time of flight.

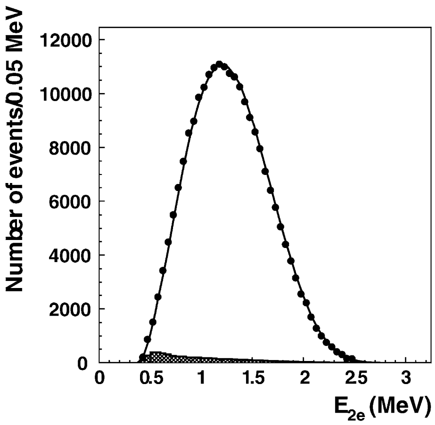

Fig. 8. NEMO3 energy sum spectrum of the two electrons of ^{100}Mo.

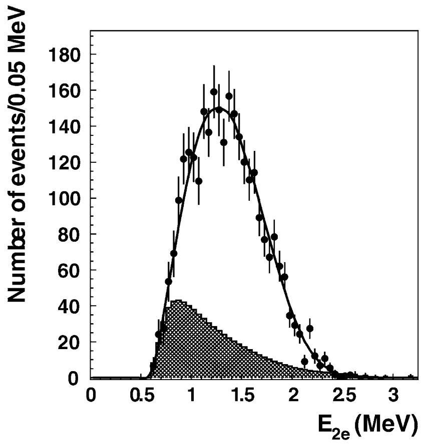

Fig. 9. NEMO3 energy sum spectrum of the two electrons of ^{82}Se.

magnetic field in order to distinguish electrons from positrons. An external shield of 18 cm of low radioactivity iron, a water shield and a wood shield cover the detector to reduce external γ and neutrons. Since October 2004, a radon-tight tent encloses the detector. This detector allows the identification of electrons, positrons, γ and α particles.

The expected performance of the tracking detector, the calorimeter and the trigger has been successfully achieved and is given in [21].

A $\beta\beta$ event (Fig. 7) is an event with two tracks coming from the same vertex on the foil. Each track is identified with a fired scintillator with a positive internal time-of-flight hypothesis, and its curvature corresponds to a negative charge. After 389 days of data collection, about 219 000 and 2 750 $2\nu\beta\beta$ events from $\sim$ 7 kg of ^{100}Mo and $\sim$ 1 kg of ^{82}Se, respectively, have been recorded. Figs. 8 and 9 show the spectrum of the summed energy of two electrons for ^{100}Mo and ^{82}Se respectively after background subtraction. These spectra are in agreement with the expected spectra from $2\nu\beta\beta$ simulations. Figs. 10 and 11 show the angular distribution of the two electrons and the single energy spectrum for ^{100}Mo, also in agreement with simulations. The subtracted backgrounds are very low, corresponding to the very high signal-to-background ratio of 40 for ^{100}Mo and 4 for ^{82}Se.

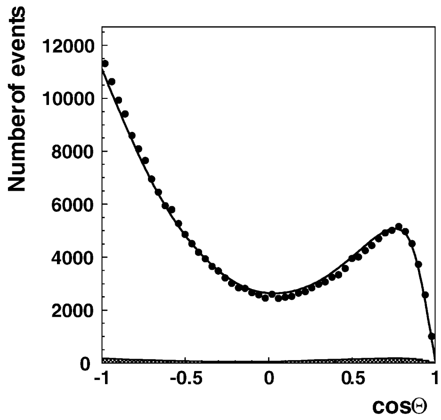

Fig. 10. NEMO3 angular distribution of the two electrons of ^{100}Mo.

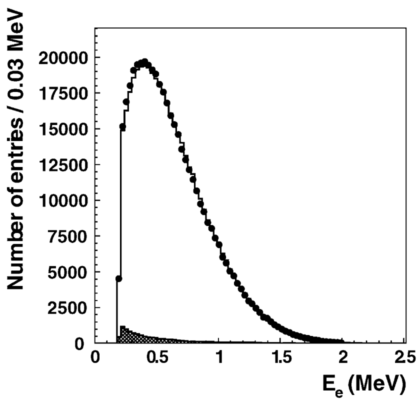

Fig. 11. NEMO3 single energy spectrum of ^{100}Mo.

The preliminary values of the measured half-life are:

^{100}Mo $\quad T_{1/2} = [7.11 \pm 0.02\ \text{(stat.)} \pm 0.54\ \text{(syst.)}] \times 10^{18}$ y.

^{82}Se $\quad T_{1/2} = [9.6 \pm 0.3\ \text{(stat.)} \pm 1.0\ \text{(syst.)}] \times 10^{19}$ y.

Additionally 2 kg of various foils were placed in the detector to study $2\nu\beta\beta$ decay and backgrounds. The preliminary values of the measured half life $2\nu\beta\beta$ are:

^{116}Cd $\quad T_{1/2} = [2.8 \pm 0.1\ \text{(stat.)} \pm 0.3\ \text{(syst.)}] \times 10^{18}$ y.

^{150}Nd $\quad T_{1/2} = [9.7 \pm 0.7\ \text{(stat.)} \pm 1.0\ \text{(syst.)}] \times 10^{18}$ y.

^{96}Zr $\quad T_{1/2} = [2.0 \pm 0.3\ \text{(stat.)} \pm 0.2\ \text{(syst.)}] \times 10^{19}$ y.

The data permit, for the first time, a precise study of the energy spectra (Fig. 10) and of the angular distribution (Fig. 11) and demonstrate that a $2\nu\beta\beta$ transition of ^{100}Mo is primarily through a single intermediate state [22,23].

3.4. $2\nu\beta\beta$ decays and nuclear matrix elements

The calculation of the allowed double beta decay matrix element in the framework of QRPA (quasi random phase space approximation) could be used to measure the relevant parameter of this model. Recent theoretical work [24] has been proposed for many candidates. The idea is the use the value of this parameter obtained from the experimental $2\nu\beta\beta$ rates to compute the nuclear matrix elements for the neutrinoless double beta decay of the same candidates. Even if the hypothesis of the model is questionable, a 10% accuracy of the $2\nu\beta\beta$ rate obtained by the NEMO3 experiment for five nuclei with the same device could be a strong experimental input to the $0\nu\beta\beta$ nuclear matrix element computations, another approach [4] in the framework of the shell model seems to be promising; but the comparison of the two methods is very difficult.

3.5. First results on the limit of $0\nu\beta\beta$ decay with ^{100}Mo and ^{82}Se with NEMO3

After one year of data the level of each component of the background has been directly measured using different channels in the data. The total expected background in the $0\nu\beta\beta$ energy window [2.8–3.2] MeV is 0.1 count/kg.y. The expected level of background due to the tail of the $2\nu\beta\beta$ is 0.3 count/kg.y in the same energy window. The dominant background in the first year of data was the radon inside the tracking chamber due to a very low rate of diffusion of radon from the laboratory (~ 15 Bq/m^3) into the tracking detector. The radon level in the detector was measured in two independent way and found to be 20 mBq/m^3. The radon contamination corresponds to an expected number of $0\nu\beta\beta$ like events of ~ 1 count/kg.y in the energy window. A radon-trapping facility has been installed and has reduced the contamination by a factor of 10 since October 2004.

Figs. 12 and 13 show the spectrum of the energy sum of the two electrons in the $\beta\beta0\nu$ energy window after 389 days of data collection with 6.914 kg of ^{100}Mo and 0.932 kg of ^{82}Se respectively. The number of two electron events observed in the data is in agreement with the expected number of events from $\beta\beta2\nu$ and the radon simulations. From ^{100}Mo, in the energy window [2.8–3.2] MeV, the expected background is 8.1 ± 2.0 (error dominated by the uncertainty on the radon activity) and 7

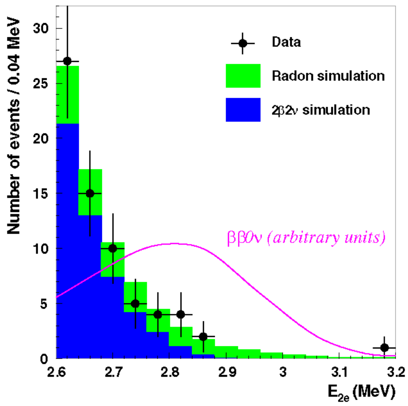

Fig. 12. NEMO3 spectrum of the energy sum of the two electrons above 2.6 NeV of ^{100}Mo.

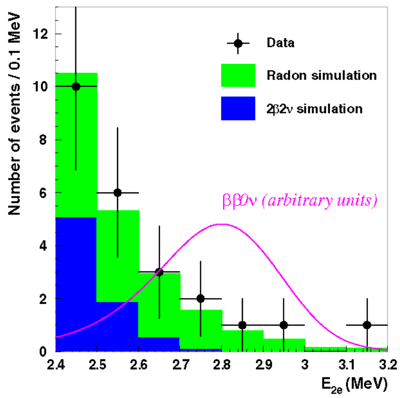

Fig. 13. NEMO3 spectrum of the energy sum of the two electrons above 2.4 MeV of ^{82}Se.

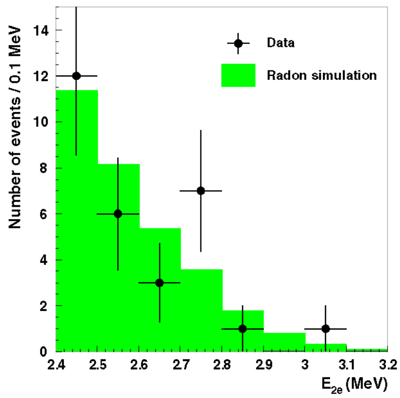

Fig. 14. NEMO3 spectrum of the energy sum of the two electrons above 2.6 MeV from copper and tellurium foils.

events have been observed. From ^{82}Se, in the energy window [2.8–3.2] MeV, the expected background is 3.1 ± 0.8 and 5 events have been observed. In order to independently check the dominant radon contribution above 2.8 MeV, the energy sum spectrum (Fig. 14) has been plotted for the two electrons emitted from the copper and tellurium foils where no background except radon is excepted. The data is in agreement with the radon simulations.

The NEMO3 detector is able to measure not only the energy sum (E_{tot}) of the $2e^-$ events but also the single energy of each electron (E_{min} the minimum single energy) and the angle between the two tracks ($\cos\theta$). Moreover, the level of each component of background can be measured through studies of different channels, as explained above. Therefore a maximum likelihood analysis has been applied to $2e^-$ events above 2 MeV using the three variables identified above [25]. A three-dimensional probability distribution function, P^{3D}, can be written as:

$$P^{3D} = P(E_{tot})P(E_{min}/E_{tot})P(\cos\theta/E_{min})$$

where $P(E_{min}/E_{tot})$ and $P(\cos\theta/E_{min})$ are two conditional probability distribution functions.

With 389 days of data, limits obtained with the likelihood analysis are $T_{1/2}(0\nu) > 4.6 \times 10^{23}$ years at 90% C.L. for ^{100}Mo and 1.0×10^{23} years for ^{82}Se. Similar limits have been obtained using an analysis of Poisson process with background in the [2.8–3.2] sum energy window. The corresponding upper limits for the effective Majorana neutrino mass range from 0.7 to 2.8 eV for ^{100}Mo and 1.7 to 4.8 eV for ^{82}Se depending on the nuclear matrix element calculations [14–18].

4. Experimental prospects for $0\nu\beta\beta$ decay searches

There are many proposals to search for $0\nu\beta\beta$ decay. Table 2 shows a list of the experiments, some of them have been funded for a research and development program and some for the experiment itself. Only these categories will be briefly described

Table 2
Neutrinoless double beta decay projects for the next ten years and the expected sensitivities to $\langle m_{\beta\beta} \rangle$

Experiment	Nucleus	Mass kg	FWHM at $Q_{\beta\beta}$ (keV)	Background counts/FWHM.kg.y	$T_{1/2}^{0\nu}$ limit (year)	$\langle m_\nu \rangle$ meV
MOON	^{100}Mo	1000	350	~ 0.2	$2. \times 10^{27}$	30–80
EXO	^{136}Xe	160	50	0.95	$3. \times 10^{25}$	90–550
GERDA phase I	^{76}Ge	15	4	0.04	$3. \times 10^{25}$	25–780
GERDA phase II	^{76}Ge	100	4	0.004	$2. \times 10^{26}$	100–290
GERDA phase III	^{76}Ge	300	4	0.004	6×10^{27}	25–80
MAJORANA I	^{76}Ge	180	4	0.003	$3. \times 10^{26}$	90–250
MAJORANA II	^{76}Ge	540	4	0.003	4.0×10^{27}	20–65
SuperNEMO	^{82}Se	100	210	0.01	$2. \times 10^{26}$	35–105
CUORE	^{130}Te	203	5	0.05	2.1×10^{26}	35–120
			5	0.005	6.6×10^{26}	20–65

here. The status reported here for CUORE, MAJORANA, GERDA and SuperNEMO is based on the presentations at the recent NANP'05 conference in Dubna (June 2005); EXO and MOON status have been found in the literature.

4.1. *CUORE* [26]

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 Te 0_2 crystals each $5 \times 5 \times 5$ cm for a total of 988 crystals with a total mass of 741 kg of Te 0_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 $T_{1/2} \sim 2 \times 10^{26}$ years.

An ultimate background of 1 count/ton.keV.y is the goal of the experiment; then $T_{1/2} \sim 6 \times 10^{26}$ years could be measured. The device would be in operation in 2011.

4.2. *MAJORANA* [27]

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 $0\nu\beta\beta$. 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 a sensitivity of 4×10^{27} years to be reached, with an ultimate expected background of 1 count/ton.keV.y. The experiment will be installed in the Sudbury 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 should be in operation in 2012.

4.3. *GERDA* [28]

The experimental concept of the GERDA experiment is to operate bare Ge diodes in high purity liquid nitrogen or liquid argon shield. In the liquid argon case, an active anticoincidence with scintillation light for argon could be used. The ultimate goal is to reach a background free regime. The GERDA Collaboration has proposed three phases for the experiment. In phase I, 15 kg of ^{76}Ge crystals will be installed in the final cryostat. The aim is to control the level of experimental background at a level of 0.1 count/keV.kg.y and to measure a period in the range of a few 10^{25} years to check the claim of Ref. [6]. In the next step, phase II, the segmentation of the crystals and the pulse shape analysis to discriminate the local energy deposition would allow the decrease of the background to a level at 0.01 count/keV.kg.y with a total mass of 100 kg of enriched ^{76}Ge crystals to be sensitive to a period of 2×10^{26} years. In the final configuration with a cosmic ray veto and an active shield the ultimate expected background would be 1 count/keV.ton.y. The phase III would operate a 300 kg ^{76}Ge detector and the sensitivity would be 6×10^{27} years. The experiment will be located in the Gran Sasso underground laboratory. The phase I will start in 2007, the second phase is planned for 2010.

4.4. EXO [29]

The EXO experiment proposes to search for the $0\nu\beta\beta$ 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 illuminate the location where a candidate decay has occurred. In the liquid phase case the $^{136}Ba^{+}$ ion candidate must be extracted and brought into an 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 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 $T_{1/2} \sim 3 \times 10^{25}$ years with a background in the range of 0.02 counts/keV.kg.y. The recent [30] lower limit of the $2\nu\beta\beta$ period is 8×10^{21} years (90% C.L.) is encouraging for the remaining $2\nu\beta\beta$ background in the $0\nu\beta\beta$ region of interest.

4.5. MOON [31]

MOON (Molybdenum Observatory of Neutrinos) is a ‘hybrid’ $\beta\beta$ 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). The expected background in the region of interest is 0.01 count/keV.kg.y. A prototype is in progress of installation in Otto Underground Laboratory in Japan. The final design of a 1 ton source of ^{100}Mo would allow to measure a period of 2×10^{27} years. Such a detector has the potentiality to study several candidates to $0\nu\beta\beta$ decay.

4.6. SuperNEMO [32]

The SuperNemo experiment is an extrapolation by a factor of ten of the NEMO3 experiment which is currently running with an experimental background of 0.4 count/kg.y in the energy region of interest [2.8–3.2] MeV for the search of the neutrinoless double beta decay of ^{100}Mo and ^{82}Se which corresponds to 0.001 count/keV.kg.y. for the calorimetric experiments. The collaboration is involved in a R & D program for a period of three years. The goal is to design a detector which is a combination of a tracking detector and a calorimeter with a double beta source of at least 100 kg of enriched ^{82}Se to be sensitive to a period of a few 10^{26} years. The NEMO3 experiment proved that the techniques are reliable. The aim of the R & D program is to improve the energy resolution of the calorimeter to 4% at 3 MeV (FWHM). This could be achieved by improving the scintillation yield of the plastic scintillator, the light collection and the photocathode efficiency of the PMTs. The global efficiency of the detection

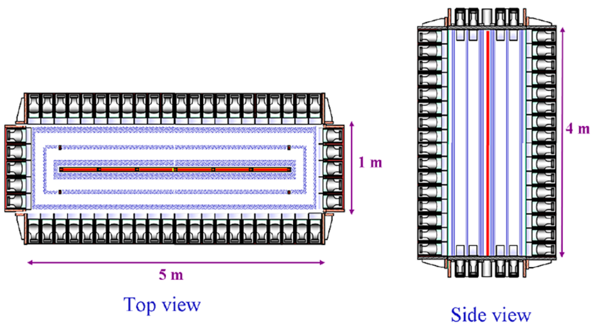

Fig. 15. Scheme of the SuperNEMO module.

of the two electrons will be improved by a tracking detector with carbon wires instead of stainless steel. Finally, the radiopurity of the double beta decay sources should be improved by at least a factor of 10. The residual radio-impurities have to be less then 20μ Bq/kg for ^{214}Bi and 2μ Bq/kg for ^{208}Tl. These radiopurity requirements are a real challenge especially for ^{208}Tl. A new dedicated device has to be built to measure the radiopurity. A program for the production of 5 kg of enriched ^{82}Se has recently been funded by the European Infrastructure ILIAS, the aim is to start the chemical purification in the U.S.A. and to measure the radiopurities. The gas of the tracking detector has to be radon free at a level of 100μ Bq/m^3 which imposes a severe selection of all the components of the tracking device and a new radon detector sensitive at this level. A scheme of the detector is shown in Fig. 15. It is modular and consists of 20 identical modules equipped with a 5 kg double beta decay source. The SuperNEMO experiment has the $\beta\beta$ source separated from the detector therefore in principle other $\beta\beta$ isotopes like ^{116}Cd, ^{150}Nd, ^{100}Mo, ^{130}Te and ^{76}Ge could be studied.

The experiment would be installed in a new cavity in the Modane Underground laboratory or in the Gran Sasso Laboratory.

5. Conclusions

Presently the conservative value of the upper limit for the effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle$ is 1 eV. Cuoricino and NEMO3 experiments are taking data for the next four years. These two experiments have a sub eV sensitivity depending on the nuclear matrix element calculations. In a near future, $\simeq 10$ years, other experiments will be in operation observing double beta decay sources of a few hundred kg. The sensitivity should be beyond a half life of a few 10^{26} years. The potentiality of discovery of a few tens of meV Majorana neutrino mass is the ultimate goal of this new generation of experiments. If one of the experiment observes the $0\nu\beta\beta$ decay it will have large physics implications. Such an important result will require a strong experimental proof. One must require important statistical significance (5σ). This will require a large signal to noise ratio. Calorimetric experiments provide little information beyond just the energy measurement. How does an experiment prove that the observed peak is actually due to $0\nu\beta\beta$ decay and not some unknown radioactivity? At least two calorimetric experiments with two different nucleus are needed to confirm the discovery. The experiments that provide an additional signature of the signal, for example, demonstrating that only two electrons are present in the final state or identifying the daughter nucleus of the decay may give further credibility to a discovery. The neutrinoless double beta decay could be one of the experimental key for a better understanding of the neutrino physics. It will be a long way but likely very promising. In this paper we used results reported in references [33].

Acknowledgements

The author would like to thank Corinne Augier and Xavier Sarazin for their contributions, Jocelyne Brosselard for her marvelously cooperative secretarial help. He is grateful to Dominique Lalanne and Georges Szklarz for reviewing the manuscript.

References

[1] M. Shiozawa, et al., Phys. Rev. Lett. 81 (1998) 3319;
Y. Hayato, et al., Phys. Rev. Lett. 83 (1999) 1529.
[2] J. Schechter, J. Valle, Phys. Rev. D 25 (1982) 2951.
[3] S. Pascoli, S.T. Petcov, Phys. Lett. B 580 (2004) 280;
S. Pascoli, et al., hep-ph/0505226.
[4] E. Caurier, A. Gniady, F. Nowacki, Beyond NEMO3, Orsay, December 2003;
E. Caurier, G. Martinez-Pinedo, F. Nowacki, A. Poves, P. Zuker, nucl-th/0402046.
[5] I. Ogawa, et al., CANDLES Collaboration, Nucl. Phys. A 730 (2004) 215.
[6] H. Klapdor-Kleingrothaus, et al., Nucl. Instrum. Methods A 522 (2004) 371.
[7] D. Gonzales, et al., Nucl. Instrum. Methods A 515 (2003) 634.
[8] C. Arnaboldi, et al., Cuoricino Collaboration, hep-ex/0501034.
[9] R. Luescher, et al., Phys. Lett. B 434 (1998) 407.
[10] A. De Silva, et al., Phys. Rev. C 56 (1997) 2451.
[11] P.G. Bizzeti, et al., Izv. Ross. Akad. Nauk. 67 (2003) 630;
F.A. Danevich, et al., Nucl. Phys. B (Proc. Suppl.) 138 (2005) 230.
[12] R. Arnold, et al., NEMO Collaboration, Nucl. Phys. A 658 (1999) 299.
[13] X. Sarazin, et al., NEMO Collaboration, Nucl. Phys. B (Proc. Suppl.) 143 (2005) 221;
R. Arnold, et al., hep-ex/0507083.

[14] V.A. Rodin, et al., nucl-th/0503063; Phys. Rev. C, in press.
[15] F. Simkovic, et al., Phys. Rev. C 60 (1999) 055502.
[16] S. Stoica, et al., Nucl. Phys. A 694 (2001) 269.
[17] M. Aunola, et al., Nucl. Phys. A 643 (1998) 207.
[18] J. Suhonen, et al., Nucl. Phys. A 723 (2003) 271.
[19] E. Caurier, et al., Phys. Rev. Lett. 77 (1996) 1954.
[20] C. Arnaboldi, et al., Cuoricino Collaboration, Phys. Lett. B 584 (2004) 260;
O. Cremonesi, in: NANP'05, June 2005, http://www.nanp.ru/.
[21] R. Arnold, et al., NEMO Collaboration, Nucl. Instrum. Methods A 536 (2005) 79.
[22] Y. Shitov, et al., in: NANP'05, June 2005, http://www.nanp.ru/.
[23] F. Simkovic, J. Phys. G 27 (2001) 2233.
[24] A. Faessler, in: NANP'05, June 2005, http://www.nanp.ru/.
[25] A.I. Etienvre, PhD Thesis, University Paris-Sud (2003), LAL 03–13.
[26] CUORE Collaboration, Technical Design Report, CUORE: a cryogenic underground observatory for rare events, hep-ex/0501010.
[27] C.E. Aalseth, H.S. Miley, Nucl. Phys. B (Proc. Suppl.) 110 (2002) 392.
[28] I. Abt, et al., GERDA Proposal, hep-ph/0404049;
S. Schoenert, in: NANP'05, June 2005, http://www.nanp.ru/.
[29] D. Akimov, et al., EXO Collaboration, Nucl. Phys. B (Proc. Suppl.) 138 (2005) 224.
[30] A. Gangapshev, et al., in: NANP'05, June 2005, http://www.nanp.ru/.
[31] M. Nomachi, et al., Nucl. Phys. B (Proc. Suppl.) 138 (2005) 221.
[32] F. Piquemal, et al., in: NANP'05, June 2005, http://www.nanp.ru/.
[33] C. Augier, Mémoire d'habilitation à diriger des recherches, LAL 05–36;
F.T. Avignone, et al., New J. Phys. 7 (2005) 6;
C. Aalseth, et al., hep-ph/0412300.