Search for $\beta\beta$ decay with NEMO 3 and SuperNEMO experiments

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Abstract. NEMO 3 is a double beta decay experiment. A part of low background data was analysed, preliminary result on $\beta\beta_{2\nu}$ decay of ^{130}Te obtained:
$T^{2\nu}_{1/2}(^{130}\mathrm{Te}) = 7.6 \pm 1.5(\mathrm{stat}) \pm 0.8(\mathrm{syst}) \times 10^{20}$y. No $\beta\beta_{0\nu}$ signal was observed: $T^{0\nu}_{1/2}(^{100}\mathrm{Mo}) > 5.8 \times 10^{23}$ y and $T^{0\nu}_{1/2}(^{82}\mathrm{Se}) > 2.1 \times 10^{23}$ y (90% C.L.). SuperNEMO project R&D has started.

PACS. 23.40.-s β decay; double β decay; electron and muon capture – 14.60.Pq Neutrino mass and mixing – 21.10.Tg Lifetimes, widths

1 Introduction

Neutrinoless double decay ($\beta\beta_{0\nu}$) is the most sensitive process for the search of lepton number violation and its discovery would prove that the neutrino is a massive 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 determination of the mass scale of the neutrinos [1].

In the minimal supersymmetric standard model (MSSM) lepton number violation is forbidden by imposing the additional discrete symmetry, R-parity. However, MSSM extensions with broken R-parity is another way of lepton number violation in addition to the Majorana neutrino mass term. These models lead to $\beta\beta_{0\nu}$ decay via exchange of superparticles [1], squark mixing [2] or neutrino mass generation via SUSY radiative corrections [3].

The NEMO 3 is a double beta decay experiment running in the Fréjus Underground Laboratory in Modane, France. Its goal is to look for neutrinoless double beta decay of ^{100}Mo and ^{82}Se, as well as to measure two neutrino double beta decay, $\beta\beta_{2\nu}$, for these and five other isotopes: ^{116}Cd, ^{150}Nd, ^{96}Zr, ^{48}Ca and ^{130}Te. A facility to remove radon from the air around the detector was completed in October 2004. About a year of low background data is being analysed now. A new preliminary result on $\beta\beta_{2\nu}$ decay of ^{130}Te is reported.

An R&D program is being carried out to produce a TDR for a new detector, SuperNEMO. It will have a tracker, based on NEMO 3 design, and a calorimeter to fully reconstruct the events. It will have ≈100 kg of isotopes as a source. It is planned to reach a sensitivity of ~ 1–2×10^{26} y for neutrinoless mode of the decay.

2 The NEMO 3 detector [4]

The NEMO 3 has a tracker to reconstruct the tracks of the two electrons from the $\beta\beta$ final state. It also has a calorimetery to measure their energy. This allows good discrimination between signal and background events.

The detector is cylindrical. A thin source foil (~ 50 mg/cm^2) is placed between two tracking volumes restricted by walls of plastic scintillator blocks read out by photomultipliers (PMT). In total about 10 kg of $\beta\beta$ isotopes are installed in NEMO 3: 6.9 kg of ^{100}Mo, 0.93 kg of ^{82}Se, 0.4 kg of ^{116}Cd, 0.45 kg of ^{130}Te, 37 g of ^{150}Nd, 9 g of ^{96}Zr and 7 g of ^{48}Ca.

The tracking volume consists of 6180 drift cells operating in Geiger mode. It provides track vertex resolution of about 1 cm for 1 MeV electrons. The calorimeter has 1940 blocks with an energy resolution at FWHM of 14–17%/$\sqrt{E}$. Its time resolution (250 ps) allows excellent suppression of crossing electron background with time of flight analysis.

There is a vertical magnetic field of 25 G to reject e^+e^- pair production in the source. The whole detector is covered with 18 cm thick iron passive shielding and 30 cm thick tanks with boron water solution as neutron shield. The detector is capable of identifying e^-, e^+, γ and α particles.

2.1 Background model

Background in NEMO 3 can be classified into three groups: (1) external from incoming γ, (2) radon (Rn) in the tracker volume and (3) internal radioactive contamination of the source. All three were estimated with event topologies other then e^-e^- (i.e. e^-, $e^-\alpha$, $e^-\gamma$, $e^-\gamma\gamma$ etc.) using NEMO 3 data itself and verified with HPGe measurements and Rn detector measurements.

In the beginning of the NEMO 3 experiment it was found that the Rn level inside the tracking gas is higher

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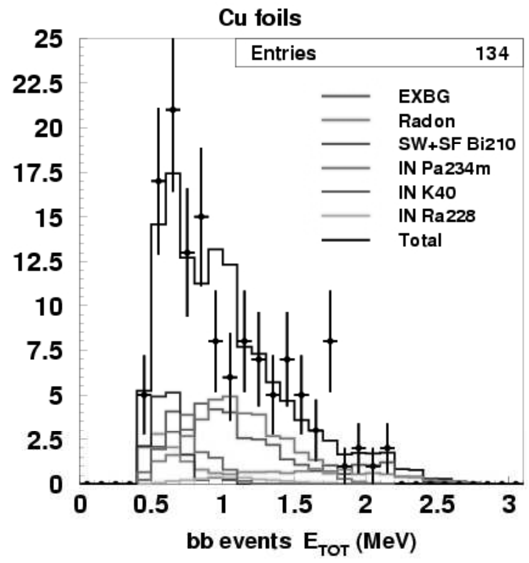

Fig. 1. Background two electron events spectrum in Cu foil, Phase II data

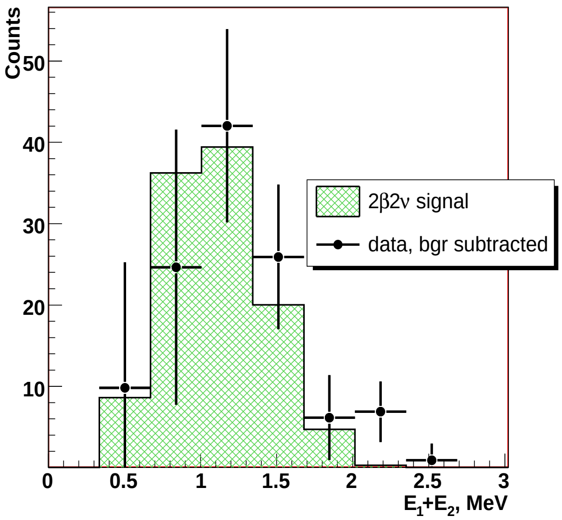

Fig. 2. ^{130}Te $\beta\beta_{2\nu}$ Phase II spectrum, background subtracted.

then initial requirements. It was identified that the main source of radon is the laboratory air, which can penetrate the volume through small leaks. As a solution a facility was built to purify the air surrounding the detector from Rn. This facility started to operate in October 2004. Later we will refer to the data before that date as "high background", or "Phase I" data. And to "low background" or "Phase II" data for the period after October 2004.

To control the background, a blank Cu foil (621 g) was installed in the detector. In Fig. 1 a spectrum of two electron events measured in Cu as well as the MC prediction according to the background model is shown. It is an important check for our understanding of the background in the experiment.

3 NEMO 3 results

3.1 $\beta\beta_{2\nu}$ decay of ^{130}Te

A preliminary measurement of ^{130}Te half-life has been reported. Due to its extremely low decay rate, only the low background data was used. In total, 534 days of data was processed. The number of events observed from the Te source foil is 607, while predicted background is 492 $\beta\beta$ events. A binned maximum likelihood method was used to analyse the data. A $\beta\beta_{2\nu}$ signal equal to 109 ± 21.5(stat) events was found, Fig. 2. This corresponds to a half-life of $T^{2\nu}_{1/2}(^{130}\mathrm{Te}) = 7.6 \pm 1.5(\mathrm{stat}) \pm 0.8(\mathrm{syst}) \times 10^{20}$ y.

This result is an improvement compared to the previous attempt of ^{130}Te decay direct measurement [5]. It is also in agreement with prediction based on the geochemical ^{82}Se/^{130}Te ratio and present ^{82}Se decay rate from direct experiments [6].

This result is of particular interest, because there is a disagreement between geochemical measurements. One group of authors found $T_{1/2} \approx 8 \times 10^{20}$ y [7], while the other gives $T_{1/2} \approx 2.5 - -2.7 \times 10^{21}$ y [8]. Also it was noticed that smaller $T_{1/2}$ value was obtained in the experiments with "young" ores (< 100 million years). This lead to the hypothesis that the differences can be accounted for variations of Fermi constant $\mathrm{G_F}$ with time [9]. NEMO 3 measurement reported is not in contradiction of this hypothesis and suggests that possible $\mathrm{G_F}$ variation should be tested using geochemical methods for other $\beta\beta$ decaying nuclei.

3.2 ^{100}Mo results

A measurement of $\beta\beta_{2\nu}$ decay was done with Phase I data, see Table 1 and Fig. 3 [10]. It is the biggest in the world number fo events was collected (219000 events) with a signal to background ratio (S/B) of 40. $T^{2\nu}_{1/2}(^{100}\mathrm{Mo}) = 7.11 \pm 0.02(\mathrm{stat}) \pm 0.54(\mathrm{syst}) \times 10^{18}$ y.

No evidence for $\beta\beta_{0\nu}$ signal was found (Fig. 4). The results for Phase I and Phase II data were combined. A preliminary counting analysis shows 14 events in the window of interest [2.78–3.20] MeV, the expected background is 13.4 events, and $\beta\beta_{0\nu}$ efficiency is 8.2%. The effective time analysed is 13 kg·y yielding a lower limit on the half-life of $T_{1/2} > 5.8 \times 10^{23}$ y (90% C.L.).

This corresponds to the effective Majorana neutrino mass $\langle m_\nu \rangle < 0.8 - -1.3$ eV according to the most recent QRPA NME calculations [12].

On the assumption of neutralino or gluino exchange, one can also derive the limit on supersymmetric trilinear coupling $\lambda'_{111} < 1.5 \times 10^{-4}$ [13].

3.3 ^{82}Se results

2570 $\beta\beta_{2\nu}$ events from ^{82}Se source were registered during Phase I of the experiment, with a S/B ratio equal to 4, and a half-life given in Table 1.

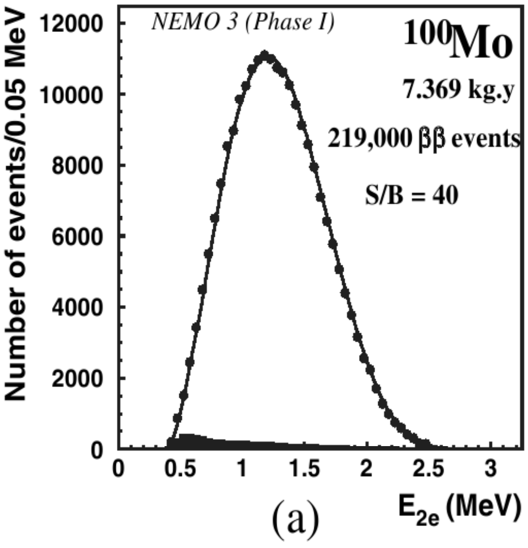

Fig. 3. ^{100}Mo Phase I $\beta\beta_{2\nu}$ spectrum.

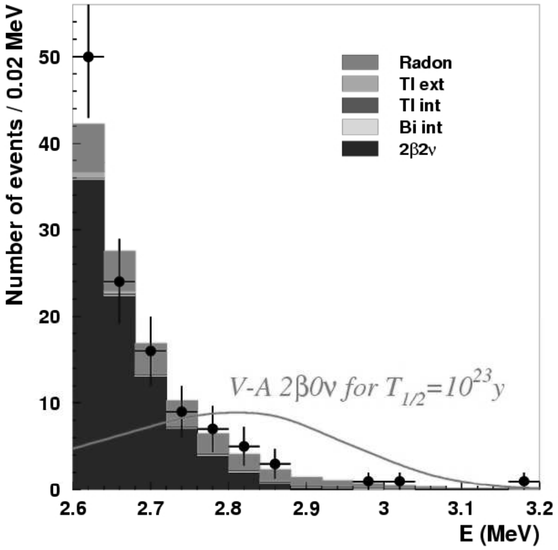

Fig. 4. ^{100}Mo Phase I and Phase II spectrum at $Q_{\beta\beta}$.

After the preliminary analysis of 1.76 kg·y of Phase I and Phase II data, 7 events were found in the window [2.62–3.20] MeV, with the expected background 6.4 events, $\beta\beta_{0\nu}$ efficiency of 14.4% yielding a lower limit on the half-life of $T_{1/2} > 2.1 \times 10^{23}$ y (90% C.L.), which corresponds to an upper mass limit of $\langle m_\nu \rangle < 1.4 - -2.2$ eV [12].

3.4 $\beta\beta_{2\nu}$ decay

Phase I data for four other isotopes were analysed and their half-lives measured, see Table 1 with preliminary results reported. This is a very important input for nuclear theory, because $\beta\beta_{2\nu}$ decay rate is used to fix some free parameters in QRPA nuclear models. Since all isotopes are measured with the same device, the half-life ratio has a very small systematic uncertainty, while statistical errors will reach few per cent at the end of the experiment.

Table 1. Main results on $\beta\beta_{2\nu}$ decays. S/B is a signal to background ratio.

Nuclei	S/B	$T_{1/2}$, y
^{100}Mo	40	$[7.11 \pm 0.02(\text{stat}) \pm 0.54(\text{syst})] \times 10^{18}$
^{82}Se	4	$[9.6 \pm 0.3(\text{stat}) \pm 1.0(\text{syst})] \times 10^{19}$
^{116}Cd	7.5	$[2.8 \pm 0.1(\text{stat}) \pm 0.3(\text{syst})] \times 10^{19}$
^{150}Nd	2.8	$[9.7 \pm 0.7(\text{stat}) \pm 1.0(\text{syst})] \times 10^{18}$
^{96}Zr	1	$[2.0 \pm 0.3(\text{stat}) \pm 0.2(\text{syst})] \times 10^{19}$
^{48}Ca	∼10	$[3.9 \pm 0.7(\text{stat}) \pm 0.6(\text{syst})] \times 10^{19}$
^{130}Te	0.25	$[7.6 \pm 1.5(\text{stat}) \pm 0.8(\text{syst})] \times 10^{20}$

Table 2. Constraints on $T_{1/2}$ in years for exotic processes from NEMO 3 data (90% C.L.). λ is a (V+A) Lagrangian parameter, g is a Majoron to neutrino coupling strength; NME calculations from [12] were used. See [14] for explanation of spectral index n.

Nuclei	^{100}Mo	^{82}Se
(V+A) current	$> 3.2 \times 10^{23\,a}$	$> 1.2 \times 10^{23}$
$n = 1$	$> 2.7 \times 10^{22\,b}$	$> 1.5 \times 10^{22}$
$n = 2$	$> 1.7 \times 10^{22}$	$> 6.0 \times 10^{21}$
$n = 3$	$> 1.0 \times 10^{22}$	$> 3.1 \times 10^{21}$
$n = 7$	$> 7.0 \times 10^{19}$	$> 5.0 \times 10^{20}$

[a] $\lambda < 1.8 \times 10^{-6}$
[b] $g < (0.4 - 1.8) \times 10^{-4}$

3.5 Search for exotic processes

Along with mass mechanism, there are other possibilities to generate $\beta\beta_{0\nu}$ decay, e.g. if there is an explicit right-handed current (V+A) term in the Lagrangian, or if there are neutrino coupled axions (Majorons). In the first case one expects the angular and single electron energy distributions to differ from $\beta\beta_{0\nu}$ driven by the mass mechanism. Only a tracking detector like NEMO 3 allows the use of this signature. In the second case axions are emitted in the decay, thus forming specific energy spectrum, characterised by spectral index n [14]. One can look for deviations in the $\beta\beta_{2\nu}$ spectrum shape to restrict Majoron models and NEMO 3 is one of the best experiments for this work, taking into account purity and high number of $\beta\beta_{2\nu}$ events collected. In Table 2 results for (V+A) and Majoron search are summarised.

4 SuperNEMO project

The SuperNEMO collaboration has been formed in 2005 and started to study the feasibility of an extrapolation of the NEMO technique to a detector with a mass of at least 100 kg of enriched $\beta\beta$ isotope. The goal is to reach a sensitivity of 50 meV on the effective Majorana neutrino mass.

SuperNEMO would use the NEMO 3 technical choices: a thin source between two tracking volumes surrounded by a calorimeter. The performance characteristics to improve, relative to the NEMO 3, are: the energy resolution (FWHM 7–10%/$\sqrt{E}$ depending on final design is needed), geometrical acceptance and $\beta\beta_{0\nu}$ detection efficiency, the source radiopurity (factor > 10 compared to NEMO 3) and the background rejection techniques.

The collaboration focuses on two possible $\beta\beta$ sources: ^{82}Se and ^{150}Nd. ^{150}Nd case has a number of attractive features as 8 times bigger phase space factor and Q value above ^{222}Rn daughters β-decay [1]. However, it is difficult to enrich. Collaboration is studying the possibility to use MENPHIS facility in France for ^{150}Nd enrichment.

It is planned that the detector will have a modular structure. Each module containing 5–7 kg of enriched isotopes, around 20 modules in total. If funded, the first module can start taking data as soon as 2010, with the whole detector finished by 2012–2013.

A three years R&D program was approved in the UK, France and Spain to achieve all these goals and make a detailed technical design proposal by the end of 2008.

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