Neutrinoless double beta decay and the NEMO experiments

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Abstract

The search for neutrinoless double beta decay ($\beta\beta0\nu$) is a very attractive field of particle physics concerning the Majorana nature and absolute mass scale of neutrinos. The NEMO 3 detector, operating in the Fréjus Underground Laboratory since February 2003 has been designed to identify and measure the ($\beta\beta0\nu$) process using ^{100}Mo and ^{82}Se sources (10 kg). Preliminary results have been obtained for the first phase of data taking (2003-2004, 384 days). Significative improvements concerning the reduction of radon contamination has been performed in 2004. The expected sensitivity in 2009 is $T_{1/2}(\beta\beta0\nu) \simeq 2\ 10^{24}$ yr for ^{100}Mo, corresponding to an upper limit of the Majorana neutrino effective mass $< m_\nu >$ in the 0.3-1.3 eV range. More, the NEMO collaboration is now involved in the R&D phase of SuperNEMO, a next generation large experiment to search for ($\beta\beta0\nu$) process at the $T_{1/2}(\beta\beta0\nu) \simeq 2\ 10^{26}$ yr level.

1 Neutrinoless double beta decay

The observation of the neutrinoless double beta decay (1) 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 scale of the neutrinos. The experimental searches for neutrinoless double beta decay are motivated by this very attractive new physics discovery potential.

$$(A, Z) \rightarrow (A, Z + 2) + 2\ e^- \qquad (\Delta L = 2) \tag{1}$$

The ideal experimental approach consists in accomodating some source of $\beta\beta0\nu$ emitter in a detector designed to identify both emitted electrons and measure their energy. The expected total electron energy spectrum is peak-shaped 1. In realistic conditions, only a few even-even isotopes are of experimental interest (table 1).

Because of the typical energy range of beta decay processes, the natural (or artificial) radioactivity of the experimental setup and its environment may induce backgrounds that mimic the $\beta\beta0\nu$ process. As a consequence, this main experimental issue is solved using very low radioactivity experimental setup and $\beta\beta$ sources, a detector with energy resolution as good as possible and the ability to identify low energy particles in the 1-5 MeV energy range (electrons, positrons, gamma rays, alpha particles…). $\beta\beta$ decay experiments are always hosted in underground laboratories to protect against background induced by cosmic rays.

$\beta\beta$ experiments may be separated in two main categories. Calorimetry based experiments measure the energy of particles emitted through radioactive decays in the source, regardless of their nature (electrons, gammas…). These experiments usually benefits of an extremely good

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energy resolution (FWHM∼5-10keV at 1 MeV). The detector itself is used as the $\beta\beta$ source (HP Ge detector enriched with ^{76}Ge or bolometer using Te cristals with 30% of ^{130}Te), thus the whole experimental setup is rather compact. Significant efforts have been done during the last decade to try to distinguish electrons, alpha particles and gamma rays using pulse-shape analysis techniques (PSA). The Heidelberg-Moscow [1] and IGEX [2] experiments, both using ^{76}Ge enriched HPGe detectors, have obtained the best results during the 1990-2000 period. Limits for $\beta\beta0\nu$ process were obtained at the level of $T_{1/2} \gtrsim 1.5\ 10^{25}$ y which corresponds to an upper limit for the effective neutrino mass in the $< m_\nu >$=0.4-1.0 eV range (depending on the nuclear matrix element calculations).

The other type of $\beta\beta$ experiments uses some calorimeter coupled with a tracking device in order to identify the particles. The source is designed in shape of thin foils at the center of the tracking and calorimetry devices. This technique induces some large experimental setup and some relative energy resolution (FWHM) at the 10-20% level in 1 MeV region. On the other side, the tracking device gives the ability to discriminate among particles and to measure the kinematics of the decay. More, this kind of detector may accomodate different $\beta\beta$ emitter isotopes. Other hybrid techniques may also be used, like gaseous or liquid TPC.

2 The NEMO 3 experiment

The NEMO 3 detector [3], installed in the Fréjus underground laboratory (LSM, France), is searching for $\beta\beta0\nu$ decay by the direct detection of the two electrons with a combination of tracking and calorimeter information. 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). On both sides of the sources, there is a gaseous tracking detector which consists of 6180 open drift cells operating in the Geiger mode allowing three-dimensional track reconstruction. The electron multiple scattering is minimized using a gas mixture of helium (95%), ethyl alcohol (4%), argon (1%) and water (0.1%). The wire chamber is surrounded by a calorimeter made of 1940 plastic scintillator blocks coupled to very low radioactivity photomultipliers. The energy resolution (FWHM) of the calorimeter is 14% and 17% at 1 MeV for the scintillators equipped respectively with 5" (external wall) and 3" PMTs (internal wall). The resolution of the summed energy of the two electrons in the $\beta\beta0\nu$ decay is mainly the convolution of the calorimeter energy resolution and the electron energy loss fluctuation in the source foil. The FWHM of the expected two-electron energy spectrum of the $\beta\beta0\nu$ decay is 350 keV. A solenoid surrounding the detector produces a 25 gauss magnetic field in order to distinguish electrons from positrons. To reduce the external γ and neutron flux, the detector is covered by an external shield of low radioactivity iron (18 cm), water and wood.

Figure 2 demonstrates the ability of the NEMO 3 detector to measure very rare $\beta\beta$ events. The number of $\beta\beta2\nu$ decays detected during the first period of data collection (7.369 kg.yr exposure) was 219000 with a signal-to-noise ratio of 40. Figures 2-(a) and 2-(b) show respectively the $\beta\beta2\nu$ energy sum spectrum and the angular distribution of the two electrons for ^{100}Mo. Background has been computed by Monte Carlo simulation and subtracted. The values of the measured half-lives are $T_{1/2}(\beta\beta2\nu) = \left[7.11 \pm 0.02(stat) \pm (0.54(syst)\right] \times 10^{18}\big]$ yr for ^{100}Mo and $T_{1/2}(\beta\beta2\nu) = \left[9.6 \pm 0.3(stat) \pm (1.0(syst)\right] \times 10^{19}\big]$ yr for ^{82}Se. More, the NEMO 3 detector is able to measure all sources of radioactive backgrounds using independant analysis channels like (e^-,γ), (e^-,2γ), (e^-,γ,α)... This features compensates the poor energy resolution of the calorimeter and the large size of the setup compared to calorimetry experiments, making NEMO 3 a very attractive and competitive experiment.

Concerning $\beta\beta0\nu$, the dominant background in the first period of data was radon gas (^{222}Rn) inside the tracking chamber due to a low rate of diffusion of radon from the laboratory into the detector. This level is 3 times higher than the $\beta\beta2\nu$ background for ^{100}Mo. This radon contamination has been measured at the level of 25±5 mBq/m^3. This corresponds to an expected level of background in the $\beta\beta0\nu$ energy window of $\sim$1 count.kg^{-1}.y^{-1}.

Figures 4-(a) and 4-(b) show the tail of the two-electron energy sum spectrum in the $\beta\beta0\nu$ energy window for ^{100}Mo and ^{82}Se. The number of $2e^-$ events observed in the data is in agreement with the expected number of events from $\beta\beta2\nu$ and radon simulation. As no other background but radon is expected above 2.5 MeV for copper and tellurium foils, figure 4-(c) confirms our understanding of the radon contamination. With 389 effective days of data collection, limits at 90% C.L. obtained with a likelihood analysis are $T_{1/2}(\beta\beta0\nu) > 4.6 \times 10^{23}$ yr for ^{100}Mo and $T_{1/2}(\beta\beta0\nu) > 1.0 \times 10^{23}$ yr for ^{82}Se.

A radon-tight tent enclosing the detector and a radon-trap facility have operated since December 2004, starting a second running period. Preliminary analysis demonstrates that the background originating from radon has now been significantly reduced by a factor $\sim$10. After five year of data collection, the expected sensitivity at 90% C.L. is $T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24}$ yr for ^{100}Mo and $T_{1/2}(\beta\beta0\nu) > 8 \times 10^{23}$ yr for ^{82}Se corresponding to $< m_\nu >$<0.3-1.3 eV for ^{100}Mo and $< m_\nu >$<0.6-1.7 eV for ^{82}Se. These results are detailed in [4]. New results for the low radon 2005-2006 period will be presented in summer 2006 conferences.

3 The SuperNEMO project

The NEMO collaboration is now involved in the R&D phase of a next generation $\beta\beta$ decay experiment using calorimeter/tracking techniques: SuperNEMO. The aim of the future SuperNEMO experiment is to observe the $\beta\beta0\nu$ process within 5 years at the sensitivity of $T_{1/2}(\beta\beta0\nu) > 2 \times 10^{26}$ yr, using isotopes such as ^{82}Se or ^{150}Nd. To reach this goal, SuperNEMO will be a modular ultra low background detector, able to accomodate 50-100 kg of enriched isotope. The main experimental constraints have been identified and constitute the backbone of the R&D phase during 2006-2008. First of all, it is of crucial importance to be able to make a large mass of enriched source foils ($\sim$100 m^2) with contamination less than 10μBq/kg and 2μBq/kg for ^{214}Bi and ^{208}Tl respectively. Both ^{82}Se and ^{150}Nd are studied. It is necessary to develop new techniques for radioactivity measurements due to limitations of current measurement setups. A significant effort is done to develop new large HPGe detectors and dedicated planar detector using NEMO techniques (BiPo). More, it is necessary to improve the energy resolution of the calorimeter by a factor two in order to reduce the background induced by the $\beta\beta2\nu$ process in the $\beta\beta0\nu$ energy window. An important study concerns new scintillators materials and “ultra low radioactivity/high energy and time resolution” photomultipliers. Another issue consists in the control of the contamination by radon of the gas and wires in the tracking chamber which should be less than 0.1 mBq/m^3. This level is extremely difficult to achieve and measure, thus new radon measurement techniques are under study. Finally, the hosting underground site of such a large experiment ($\sim$1000 m^3) have still to be determined. This R&D phase will last until 2008, the SuperNEMO experiment could start in 2011.

4 Conclusion

The search for evidence of neutrinoless double beta decay is very active all over the world. Many experienced groups are now involved in the next generation $\beta\beta$ experiments (2010-2020). Different experimental approaches and techniques are used. With the NEMO 3 detector, the NEMO collaboration has proven that the calorimetry/tracking techniques is very attractive and competitive. The new SuperNEMO project aims to improve the sensitivity of NEMO 3 to $\beta\beta0\nu$ decay by two orders of magnitude. A R&D program has started in 2005. New contributors are welcome.

[1] Klapdor *et al.*, Eur. Phys. J. 12 (2001) 147

[2] Gonzales *et al.*, Nucl. Phys. B (P.S.) 87 (2000) 278

[3] Arnold *et al.*, Nucl. Instrum. Methods Phys. Res. A 536, 79 (2005)

[4] Arnold *et al.*, Phys. Rev. Lett. 95, 182302 (2005)

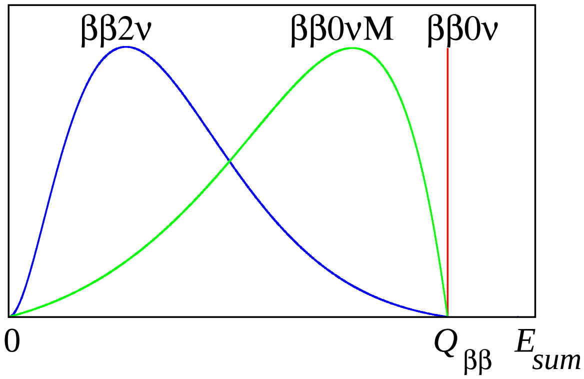

Figure 1: Expected energy sum spectrum of the two electrons for $\beta\beta 2\nu$ (two neutrinos double beta decay allowed process), $\beta\beta 0\nu M$ (neutrinoless double beta decay with Majoron emission) and $\beta\beta 0\nu$process. The $\beta\beta 0\nu$ signal is expected to be a peak centered at the $\beta\beta$ decay Q value.

Isotope	$Q_{\beta\beta}$ (keV)	Abundance (%)
^{48}Ca	4271	0.187
^{76}Ge	2039	7.8
^{82}Se	2995	9.2
^{100}Mo	3034	9.6
^{130}Te	2530	34.5
^{136}Xe	2478	8.9
^{150}Nd	3200	5.6

Table 1: Nuclei of experimental interest for $\beta\beta 0\nu$ experiments.

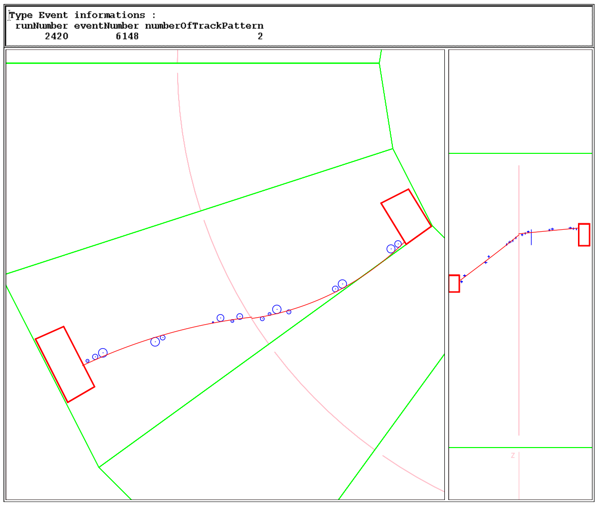

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Figure 2: Transverse (left) and longitudinal (right) view of a reconstructed $\beta\beta$ event selected from the data.

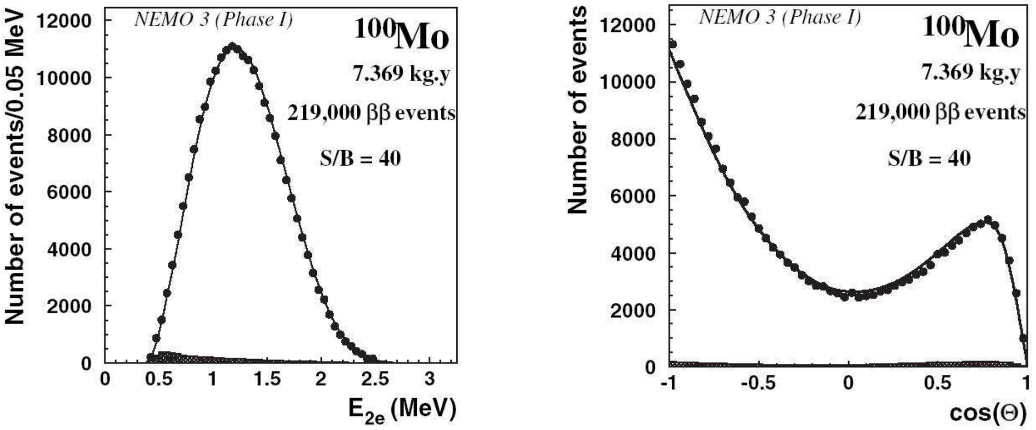
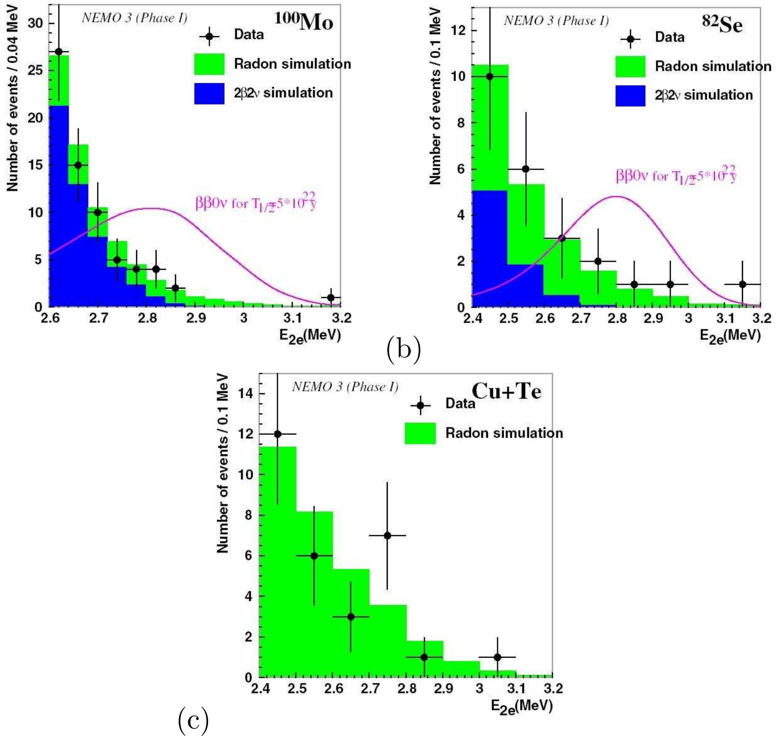


Figure 3: (a) Energy sum spectrum of the two electrons, (b) angular distribution of the two-electrons, after background subtraction for ^{100}Mo with 7.369 kg.yr exposure. Solid line: expected spectra from simulation, shaded: subtracted background.



(a) (b)

(c)

Figure 4: Spectra of the energy sum of the two electrons in the $\beta\beta0\nu$ energy window after 389 effective days of data collection from February 2003 until September 2004 (phase 1): (a) ^{100}Mo; (b) ^{82}Se; (c) with copper and tellurium foils. The shaded histograms are the expected backgrounds computed by Monte Carlo simulations: dark (blue) part is the $\beta\beta2\nu$ contribution and light (green) part is the radon contribution. The solid line corresponds to the expected $\beta\beta0\nu$ signal if $T_{1/2}(\beta\beta0\nu) = 5 \times 10^{22}$ yr.