First results of the search for neutrinoless double beta decay with the NEMO 3 detector

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The NEMO 3 detector, which has been operating in the Fréjus underground laboratory since February 2003, is devoted to the search for neutrinoless double beta decay (0νββ). The half-lives of the two neutrino double beta decay (2νββ) have been measured for 100Mo and 82Se. After 389 effective days of data collection from February 2003 until September 2004 (Phase I), no evidence for neutrinoless double beta decay was found from ~7 kg of 100Mo and ~1 kg of 82Se. The corresponding limits are $T_{1/2}(\nu\beta\beta) > 4.6 \times 10^{25}$ years for 100Mo and $T_{1/2}(\beta\beta\nu) > 1.0 \times 10^{24}$ years for 82Se (90% C.L.). Depending on the nuclear matrix element calculation, the limits for the effective Majorana neutrino mass are $m_\nu < 0.7 - 2.8$ eV for 100Mo and $m_\nu < 1.7 - 4.9$ eV for 82Se.

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I. INTRODUCTION

The positive results obtained in the last few years in neutrino oscillation experiments [1, 2, 3, 4] have demonstrated that neutrinos are massive particles and that lepton flavor is not conserved. In parallel, tritium double beta decay (0νββ) has demonstrated that neutrinos are massive particles and that global lepton number violation. In particular the see-saw model [5] 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 [6] which could explain the observed baryon-antibaryon asymmetry in the universe. The observation of neutrinoless double beta decay (0νββ) 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 NEMO 3 detector [3], installed in the Fréjus underground laboratory (LSM, France) is searching for β0ν 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/cm²) are 100Mo and 82Se. After 389 years data collection from February 2003 until September 2004 (Phase I), no evidence for neutrinoless double beta decay was found from ~7 kg of 100Mo and ~1 kg of 82Se. The corresponding limits are $T_{1/2}(\nu\beta\beta) > 4.6 \times 10^{25}$ years for 100Mo and $T_{1/2}(\beta\beta\nu) > 1.0 \times 10^{24}$ years for 82Se (90% C.L.). Depending on the nuclear matrix element calculation, the limits for the effective Majorana neutrino mass are $m_\nu < 0.7 - 2.8$ eV for 100Mo and $m_\nu < 1.7 - 4.9$ eV for 82Se.
III. MEASUREMENT OF $\beta^2\nu$ DECAYS

A two-electron ($2e^-$) event (see Fig. 1) candidate for a $\beta$ decay 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 and the time-of-flight must correspond to the two electrons being emitted from the same source position. For each electron an energy threshold of 200 keV for $^{100}$Mo and 300 keV for $^{82}$Se is applied. Fig. 2(a) and Fig. 3 show the two-electron energy sum spectra after background subtraction obtained after 389 effective days of data collection with $^{100}$Mo and with $^{82}$Se respectively. The angular distribution of the two electrons and the single energy spectrum are also presented in the case of $^{100}$Mo in Fig. 2(b) and (c). All these spectra are in good agreement with the $\beta^2\nu$ simulations. The values of the measured half-lives are $T_{1/2}(\beta^2\nu) = [7.11 \pm 0.02{_{(stat)}} \pm 0.54{_{(syst)}}] \times 10^{18}$ y for $^{100}$Mo (with a Single State Dominance decay) and $[9.6 \pm 0.3{_{(stat)}} \pm 1.0{_{(syst)}}] \times 10^{19}$ y for $^{82}$Se. These values are in agreement with, but have a higher precision than the previous measurements [10].

IV. STUDY OF THE BACKGROUND IN THE $\beta\beta^0\nu$ ENERGY WINDOW

A complete study of the background in the $\beta\beta^0\nu$ energy window has been performed. The level of each background component has been directly measured using different analysis channels in the data.

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 $\gamma$. For $^{208}$Tl, a total activity of $\sim 40$ 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 $\sim 300$ 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 $\beta\beta^0\nu$-like events due to this background is negligible, $< 10^{-3}$ counts.kg$^{-1}$y$^{-1}$ in the [2.8 – 3.2] MeV energy window where the $\beta\beta^0\nu$ signal is expected.

External neutrons and high energy $\gamma$ backgrounds have been measured by searching for crossing electron events above 4 MeV. This corresponds to a negligible expected level of background of $\sim 3 \times 10^{-5}$ counts.kg$^{-1}$y$^{-1}$ in the $\beta\beta^0\nu$ energy window. The level of $^{208}$Tl impurities inside the sources has been measured by searching for internal ($e^-\gamma\gamma$) and ($e^-\gamma\gamma\gamma$) events. The measured activity is $80 \pm 20$ $\mu$Bq/kg in molybdenum and $300 \pm 50$ $\mu$Bq/kg in Selenium. It is in agreement with the previous HPGe measurements which gave an upper limit of 100 $\mu$Bq/kg for Molybdenum and a positive measurement of $400 \pm 100$ $\mu$Bq/kg for Selenium. This corresponds to an expected level of background in the $\beta\beta^0\nu$ energy window of $\sim 0.1$ counts.kg$^{-1}$y$^{-1}$ for Molybdenum and $\sim 0.3$ counts.kg$^{-1}$y$^{-1}$ for Selenium. The measurement of $^{214}$Bi impurities inside the sources could not be achieved in this first period of data due to Radon contamination (see later). However the previous HPGe measurements gave an upper limit of 350 $\mu$Bq/kg for Molybdenum and a positive measurement of 1.2 $\pm 0.5$ nBq/kg for Selenium, corresponding to a negligible expected level of background.

The expected level of background due to the tail of the $\beta^2\nu$ distribution in the $\beta\beta^0\nu$ energy window is $\sim 0.3$ counts.kg$^{-1}$y$^{-1}$ for Molybdenum and $\sim 0.02$ counts.kg$^{-1}$y$^{-1}$ for Selenium.

The dominant background in this first period of data was Radon gas inside the tracking chamber due to a low rate of diffusion of Radon from the laboratory ($\sim 15$ Bq/m$^3$) into the detector. Two independent measurements of the Radon level in the detector were carried out. The first used a high sensitivity Radon detector similar to the one developed by the Super-Kamiokande collaboration [12]. The second was done by searching for ($e^-, delayed-\alpha$) events in the NEMO 3 data. Indeed the tracking detector allows the detection of the delayed tracks (up to 700 $\mu$s later) in order to tag delayed-\alpha emitted by $^{214}$Po in the Bi-Po process.
ββ Carolo simulations. The signal contains 219,000 events to the expected spectrum from ββ and for 82 Se respectively. The number of 2e− events observed in the data is in agreement with the expected number of events from ββ2ν and the Radon simulations. For 100Mo, in the energy window [2.8 − 3.2] MeV, the expected background is 8.1 ± 1.3 (error dominated by the uncertainty on the Radon activity) and 7 events have been observed. For 82Se, in the energy window [2.7 − 3.2] MeV, the expected background is 3.1 ± 0.6 and 5 events have been observed. In order to independently check the dominant Radon contribution above 2.8 MeV, the energy sum spectrum (Fig. 3c) has been plotted for the two electrons emitted from the Copper and Tellurium foils where no background except radon is expected. The data are in agreement with the Radon simulations.

In order to make the optimum use of all the information from the NEMO 3 detector, a maximum likelihood analysis has been applied to the 2e− event sample above 2 MeV using the three available variables: the energy sum (Etot) of the two electrons, the energy of each electron (Emin is the minimum electron energy) and the angle between the two tracks (cosθ). A three-dimensional probability distribution function, P3D, 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. The likelihood is defined as

\[
L = \prod_{k=1}^{N_{tot}} \left( \sum_{i=1}^{8} x_k P_{k}^{3D} \right)
\]

where \(k\) corresponds to one of the eight contributions: \(\beta\beta0\nu, \beta\beta2\nu,\) Radon, external and internal 214Bi and 208Tl, and neutrons. Here \(x_k\) is the ratio of the number of 2e− events due to the process \(k\) relative to the total number of observed events \(N_{tot}\). Finally \(P_{k}^{3D}\) is built using simulated events of contribution \(k\).

With 389 effective days of data collection, limits at 90% C.L. obtained with the likelihood analysis are \(T_{1/2}(\beta\beta0\nu) > 4.6 \times 10^{23}\) years for 100Mo and 1.0 \times 10^{23} years for 82Se. These limits are about 10 times higher than the previous limits obtained with 100Mo and 82Se [1, 12]. The corresponding upper limits for the effective Majorana neutrino mass range from 0.7 to 2.8 eV for 100Mo and 1.7 to 4.9 eV for 82Se depending on the nuclear matrix element calculation [13, 16, 17, 18, 19, 20]. Results for each calculation are given in Table I. For 100Mo, since an incorrect value of the phase-space factor has been used in reference [20], the value calculated in reference [21] has been used. The claim of a positive ββ0ν signal observed with 76Ge [24] gives an allowed effective mass range
In the hypothesis of a right-handed weak current, the upper limit on the coupling constant of the trilinear R-parity-violating supersymmetric coupling elements calculated in reference [22], limits obtained on overlaps this range. In the hypothesis of gluino or 100 Mo and 82 Se, the ββ0ν contribution and light (green) is the Radon contribution. The solid line corresponds to the expected ββ0ν signal if \( T_{1/2}(\beta\beta0\nu) = 5 \times 10^{23} \) y.

![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 backgrounds 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 \( T_{1/2}(\beta\beta0\nu) = 5 \times 10^{23} \) y.]

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**TABLE I:** Limits (in eV) on the effective neutrino mass \( \langle m_\nu \rangle \) obtained from different theoretical calculations of nuclear matrix elements with \( T_{1/2}(\beta\beta0\nu) > 4.6 \times 10^{23} \) y for 100 Mo and 82 Se.

| Nuclear matrix elements | 100 Mo | 82 Se |
|-------------------------|--------|-------|
| Shell model             |        |       |
| Caurier 1996            | < 4.9  |       |
| Rodin 2005              | < 2.7 - 2.8 | < 4.1 - 4.5 |
| Simkovic 1999           | < 1.0  | < 3.3 |
| Suhonen 2003            | < 1.1  | < 2.8 - 4.2 |
| Stoica 2001             | < 0.7 - 1.1 | < 1.7 - 3.7 |

0.1 - 0.9 eV. Our limit obtained with 100 Mo slightly overlaps this range. In the hypothesis of gluino or neutralino exchange, and using the nuclear matrix elements calculated in reference [22], limits obtained on the trilinear R-parity-violating supersymmetric coupling are \( \lambda_{111} < 1.6 \times 10^{-4} \) for 100 Mo and 3.0 \times 10^{-4} for 82 Se. In the hypothesis of a right-handed weak current, the limits are \( T_{1/2}(\beta\beta0\nu) > 1.7 \times 10^{23} \) years at 90% C.L. for 100 Mo and 0.7 \times 10^{23} years for 82 Se, corresponding to an upper limit on the coupling constant of \( \lambda < 2.5 \times 10^{-6} \) for 100 Mo and 3.8 \times 10^{-6} for 82 Se using the nuclear calculations from references [18, 22].

**VI. CONCLUSIONS**

In conclusion, the NEMO 3 detector has been running reliably since February 2003. The ββ2ν decay has been measured for 82 Se and 100 Mo with very high statistics and better precision than the previous measurements. The two-electron energy sum spectrum, the single energy spectrum and the angular distribution are all in good agreement with the ββ2ν simulations. 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, no evidence for ββ0ν decay has been found in 100 Mo or 82 Se. The limits at the 90% C.L. are \( T_{1/2}(\beta\beta0\nu) > 4.6 \times 10^{23} \) y for 100 Mo and 1.0 \times 10^{23} y 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 \( T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24} \) y for 100 Mo and 8 \times 10^{23} y for 82 Se, corresponding to \( \langle m_\nu \rangle < 0.3 - 1.3 \) eV for 100 Mo and \( \langle m_\nu \rangle < 0.6 - 1.7 \) eV for 82 Se.

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