RESULTS FROM THE NEMO 3 EXPERIMENT

L. VÁLA*

IEAP, Czech Technical University in Prague,
Horská 3a/22, Prague, CZ – 128 00, Czech Republic
E-mail: ladislav.vala@utef.cvut.cz

The aim of the NEMO 3 experiment is the search for neutrinoless double beta decay and precise measurement of two-neutrino double beta decay of several isotopes. The experiment has been taking data since 2003. Since no evidence for neutrinoless double beta decay of $^{100}$Mo and $^{82}$Se has been found, a 90% C.L. lower limit on the half-life of this process and corresponding upper limit on the effective Majorana neutrino mass are derived. The data are also interpreted in terms of alternative models, such as weak right-handed currents or Majoron emission. In addition, NEMO 3 has performed precision measurements of the two-neutrino double beta decay for seven different isotopes. The most recent experimental results of NEMO 3 are presented in this paper.

*on behalf of the NEMO Collaboration

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1. Introduction

The neutrino oscillation experiments demonstrated in the last decade convincing evidence for neutrino oscillations proving the finite neutrino masses and mixing. However, these experiments are only sensitive to the difference in the square of the neutrino masses, $\Delta m^2_{ij} = |m_i^2 - m_j^2|$, therefore they do not provide information on the absolute scale of the neutrino masses and are not sensitive to the nature of neutrinos. Nevertheless, the detection and study of neutrinoless double beta decay is the only way able to answer the following fundamental questions: (i) neutrino nature (Majorana or Dirac particle?), (ii) absolute neutrino mass scale, (iii) type of neutrino mass hierarchy (degenerated, inverted, or normal?), (iv) CP violation in the lepton sector.

Double beta decay ($\beta\beta$) is a transition from nucleus $(A, Z)$ to $(A, Z + 2)$ and it can occur in different channels: (a) two-neutrino double beta
decay ($2\nu\beta\beta$) with emission of two $e^-$ and two $\bar{\nu}_e$, (b) neutrinoless double beta decay ($0\nu\beta\beta$) with emission of two $e^-$ and (c) neutrinoless double beta decay with Majoron emission ($0\nu\chi\beta\beta$) with two $e^-$ and Majoron $\chi$ (massless Goldstone boson) in the final state. The mode (a) is a process of second order allowed in the Standard Model (SM) which has been observed for several nuclei. Nevertheless, processes (b) and (c) are violating lepton number conservation by two units and involve new physics beyond the SM.

The NEMO 3 experiment (NEMO = Neutrino Ettore Majorana Observatory) is devoted to the search for $0\nu\beta\beta$ decay and to the accurate measurement of $2\nu\beta\beta$ decay. For this goal, the experiment combines two detection techniques: calorimetry and tracking. Such approach allows us at the same time unambiguous identification of $e^-$, $e^+$, $\gamma$, and $\alpha$-particles provided by a wire tracking chamber and energy and time measurements of particles with a calorimeter.

2. NEMO 3 detector

The NEMO 3 detector [1] is installed and currently running in the Fréjus Underground Laboratory (4800 m w.e.) in France. The experimental set-up is cylindrical in design, is divided into twenty equal sectors and with $\gamma$ and neutron shielding it has about 6 m in diameter and 4 m in height.

The tracking wire chamber is made of 6180 open octagonal drift cells operating in Geiger mode (Geiger cells). It is filled with a gas mixture of 95% He, 4% ethyl-alcohol and 1% Ar. The Geiger cells provide a three-dimensional measurement of the charged particle tracks by recording the drift time and the two plasma propagation times.

The calorimeter, which surrounds the wire chamber, is composed of 1940 plastic scintillators coupled by light-guides to very low-radioactivity PMTs. The energy resolution $\sigma_E/E$ of the calorimeter ranges from 6.0% to 7.5% for 1 MeV electrons, while the time resolution is 250 ps.

Seventeen sectors of NEMO 3 accommodate almost 10 kg of the following, highly enriched (95% – 99%) $\beta\beta$ decay isotopes: $^{100}$Mo (6914 g), $^{82}$Se (932 g), $^{116}$Cd (405 g), $^{130}$Te (454 g), $^{150}$Nd (34 g), $^{96}$Zr (9 g), and $^{48}$Ca (7 g). In addition, three sectors are also used for external background measurement and are equipped with pure Cu and natural Te. All these isotopes are produced in the form of thin foils and are placed in the central vertical plane of each sector.

For the $e^-/e^+$ recognition, the detector is surrounded by a solenoidal coil which generates a vertical magnetic field of 25 Gauss. Moreover, NEMO 3 is covered by two types of shielding against external $\gamma$-rays and
neutrons. Finally, the whole experimental set-up is closed inside a “tent”, which is supplied with radon-free air from a radon trapping facility. Radon is trapped and then decays inside a tank filled with 1 ton of charcoal cooled down to $-50^\circ$C. This facility decreases the radon level of the air from the laboratory (15 – 20 Bq/m$^3$) by a factor of $\sim$ 1000. The radon trapping facility has been operating in the laboratory since October 2004.

3. Measurement of $\beta\beta$ decay and backgrounds

A candidate for a $\beta\beta$ decay is a two-electron event which is defined with the following criteria: two tracks coming from the same vertex in the source foils, the curvature of the tracks corresponds to a negative charge, each track has to be associated with a fired scintillator, and the time-of-flight has to correspond to the case of two electrons emitted at the same time from the same vertex. In addition a threshold of 200 keV is applied on energy of each electron. Finally, it is also required that there is no delayed Geiger cell hit close to the event vertex in order to suppress background from $^{214}$Bi decay inside the tracking detector.

The energy window of interest for the $0\nu\beta\beta$ decay for both $^{100}$Mo and $^{82}$Se is set to $(2.8 - 3.2)$ MeV and the complete study of background contribution in this window has been performed. The level of each background component has been directly measured from data using different analysis channels. The dominant background during the first running period from February 2003 to September 2004, Phase I, was due to radon diffusion into the tracking wire chamber. Nevertheless, during Phase II (since November 2004 up to now), the radon level inside NEMO 3 has been reduced by a factor of ten thanks to the radon trapping facility. Remaining low radon activity inside NEMO 3 is due to degasing of detector components.

4. NEMO 3 results

4.1. $2\nu\beta\beta$ decay

The $2\nu\beta\beta$ decay of $^{100}$Mo and $^{82}$Se is measured with high accuracy with NEMO 3. The obtained half-lives for Phase I data (389 d) are $T_{1/2} = [7.11\pm0.02(stat)\pm0.54(syst)]\times10^{18}$ y for $^{100}$Mo and $T_{1/2} = [9.6\pm0.3(stat)\pm1.0(syst)]\times10^{19}$ y for $^{82}$Se [2]. The half-lives for the other five $\beta\beta$ isotopes have been also derived from data and are summarised in Tab. 1. Measurements of this process are important for nuclear theory as they allows us to reduce the uncertainties on the nuclear matrix elements (NME).
4.2. $0\nu\beta\beta$ decay

In the case of $^{100}$Mo, there are 14 events observed in the energy window of interest while 13.4 events were expected from backgrounds for combined Phase I and II data (693 d). The situation is similar for $^{82}$Se as 7 events are observed and 6.2 expected for the same period. Thus, resulting half-life limits at 90% C.L. are $T_{1/2} > 5.8 \times 10^{23}$ y for $^{100}$Mo and $T_{1/2} > 2.1 \times 10^{23}$ y for $^{82}$Se. If using the NME from Refs. [3–5], the following limits on the effective neutrino mass are derived: $(m_\nu) < (0.6 - 0.9)$ eV for $^{100}$Mo and $(m_\nu) < (1.2 - 2.5)$ eV for $^{82}$Se. We determined also limits for alternative models assuming weak right-handed currents (V+A) and the $0\nu\chi\beta\beta$ decay channel [6]. All these results are given in Tab. 2.

### Table 2. Limits at 90% C.L. for different $0\nu\beta\beta$ decay modes for $^{100}$Mo and $^{82}$Se.

| Decay mode | $^{100}$Mo | $^{82}$Se |
|------------|------------|-----------|
| $0\nu\beta\beta$ (V − A) (g.s. → g.s.) | $T_{1/2} > 5.8 \times 10^{23}$ y | $T_{1/2} > 2.1 \times 10^{23}$ y |
| $(m_\nu) < (0.6 - 0.9)$ eV | $(m_\nu) < (1.2 - 2.5)$ eV |
| $0\nu\beta\beta$ (V − A) (g.s. → $0^+_2$) | $T_{1/2} > 8.9 \times 10^{22}$ y | |
| $0\nu\beta\beta$ (V − A) (g.s. → $2^+_1$) | $T_{1/2} > 1.6 \times 10^{23}$ y | |
| $0\nu\beta\beta$ (V + A) (g.s. → g.s.) | $T_{1/2} > 3.2 \times 10^{23}$ y | $T_{1/2} > 1.2 \times 10^{23}$ y |
| $0\nu\chi\beta\beta$ (n = 1) | $T_{1/2} > 2.7 \times 10^{22}$ y | $T_{1/2} > 1.5 \times 10^{22}$ y |
| $0\nu\chi\beta\beta$ (n = 2) | $T_{1/2} > 1.7 \times 10^{22}$ y | $T_{1/2} > 6.0 \times 10^{21}$ y |
| $0\nu\chi\beta\beta$ (n = 3) | $T_{1/2} > 1.0 \times 10^{22}$ y | $T_{1/2} > 3.1 \times 10^{21}$ y |
| $0\nu\chi\beta\beta$ (n = 7) | $T_{1/2} > 7.0 \times 10^{19}$ y | $T_{1/2} > 5.0 \times 10^{20}$ y |

However, these results date back to 2006 because the NEMO Collaboration decided to perform blind analysis with mock data. We plan to open the box and update the results by the summer of 2008 and once again after...
the end of the experiment by 2010.

4.3. Double beta decay of $^{100}$Mo to excited states

The $\beta\beta$ decay of $^{100}$Mo to excited $0^+_1$ and $2^+_1$ states of $^{100}$Ru has been also studied with the NEMO 3 detector. The obtained half-life for the $2\nu\beta\beta$ decay to the $0^+_1$ state is $T_{1/2} = [5.7^{+1.3}_{-0.9}(\text{stat}) \pm 0.8(\text{syst})] \times 10^{20}$ y [7]. This value is in a good agreement with previous measurements [8,9]. In addition, the $T_{1/2}$ limits have been determined for the $0\nu\beta\beta$ and $2\nu\beta\beta$ decay to the $2^+_1$ state and for the $0\nu\beta\beta$ decay to the $0^+_1$ state (see Tabs. 1 and 2).

5. Conclusions

The NEMO 3 detector has been routinely taking data since February 2003. The $2\nu\beta\beta$ decays of $^{100}$Mo and $^{82}$Se have been measured with very high statistics and better precision than in previous experiments. The $2\nu\beta\beta$ half-lives have been obtained also for $^{116}$Cd, $^{130}$Te, $^{150}$Nd, $^{96}$Zr, and $^{48}$Ca.

No evidence for $0\nu\beta\beta$ decay has been found in combined data for Phase I and II corresponding to 693 days. The $T_{1/2}$ limits at 90% C.L. for different modes of this decay are summarised in Tab. 2. We obtained currently the best limits for the $0\nu\chi\beta\beta$ decay of $^{100}$Mo and $^{82}$Se.

At present time, the analysis of the Phase II data without radon is in progress and improved $2\nu\beta\beta$ and $0\nu\beta\beta$ results will be published in 2008. The expected half-life limits for the $0\nu\beta\beta$ decay by the end of the experiment in 2010 are $T_{1/2} > 2 \times 10^{24}$ y for $^{100}$Mo and $> 8 \times 10^{23}$ y for $^{82}$Se.

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