The NEMO-3 detector installed in the Modane Underground Laboratory (LSM, France) is running to search for neutrinoless double beta decay ($\beta\beta_0\nu$) with an expected sensitivity for the effective Majorana neutrino mass down to 0.1 eV. New preliminary limits (90% CL), $T_{1/2}(\beta\beta_0\nu) > 1.0 \cdot 10^{23}$ y (right-handed currents) and $T_{1/2}(\beta\beta_0\nu) > 1.9 \cdot 10^{23}$ y (massive mechanism) were established analyzing $^{100}$Mo data collected during 3800h of measurements in 2003. This is the world’s best result for $^{100}$Mo. New preliminary half-lives of $\beta\beta_2\nu$-mode for $^{100}$Mo, $^{82}$Se, $^{116}$Cd, $^{150}$Nd are also reported as well as the results of background studies. The future progress and plans of the NEMO-3 project are discussed.

1. Introduction

Recent observations of neutrino oscillations reported by a number of experiments1 2 3 have proved the existence of non-zero neutrino mass. This outstanding progress has triggered a renewed interest in neutrino physics. The search for neutrinoless double beta decay ($\beta\beta_0\nu$) together with new generation neutrino oscillation experiments will help solve the neutrino mass puzzle. The discovery of this process would confirm the Majorana nature of neutrinos as well as it will determine the absolute mass scale and the pattern of neutrino eigenstates. Moreover, the $\beta\beta_0\nu$-search seems to be now the only method which could give the answers on the question of neutrino mass nature and full lepton number non-conservation.

2. The NEMO-3 detector

The main goal of the NEMO-3 experiment4 is to search for neutrinoless double beta decay with a sensitivity to the half-life of up to $10^{25}$ years. The NEMO-3 detector was built in the Fréjus Underground Laboratory (LSM)
which has an overburden of 4800 m.w.e. to reduce the cosmic ray flux.

Details of the detector’s technical design have been already reported by the NEMO collaboration\textsuperscript{5} and will be published soon\textsuperscript{6}. We will only briefly describe here the basic principles of the setup shown in Figure 1. The electrons emitted from the thin foils of a $\beta\beta$-source go through the tracking chamber and hit scintillators of the calorimeter. A separate registration of tracks and energies of both $\beta\beta$-electrons is the main advantage of the so-called ”tracko-calo” method exploited by the NEMO-3 detector. It allows a real observation of $\beta\beta$-decay measuring all its characteristics. Some important information, such as the angular correlation between $\beta\beta$-electrons and single $\beta$-spectra, can not be extracted from other types of $\beta\beta$-measurements.

![Figure 1. Schematic view of the NEMO-3 detector core without external shielding: (1) source foil, (2) 1940 plastic scintillators coupled to (3) low activity photomultiplier tubes, (4) tracking volume with 6180 drift cells operating in Geiger mode](image)
At the same time the background is tagged, monitored, and rejected by
the tracko-calo technique with a very high efficiency using several mecha-
nisms:

- Time-of-flight (TOF) analysis allows the rejection of external elec-
trons crossing the tracking volume;
- tracking information allows the rejection of events without common
vertex;
- A magnetic field of $\sim 25$ Gauss directed along the detector axis allows
the rejection of electron-positron pairs created by external photons
interacting in the source foil;
- Explicit identification of electrons, gammas and delayed-alphas
gives a unique opportunity to monitor and reject different back-
ground events;

The main isotopes under study to search for $\beta\beta^0\nu$-decay are $^{100}$Mo (6.9
kg) and $^{82}$Se (0.9 kg), $^{110}$Cd (0.4 kg), $^{130}$Te (0.5 kg), $^{150}$Nd (37 g), $^{96}$Zr (9
g) and $^{48}$Ca (7 g) are used to study two-neutrino double beta decay ($\beta\beta_2\nu$).
Other sources (0.6 kg of natural Tellurium oxide and 0.6 kg of Copper) are
installed to study the background. Some of the sources have been purified
to reduce their contamination with $^{214}$Bi and $^{208}$Tl, which are the main
two isotopes with a large $Q_\beta$-value, that can potentially contribute to the
background in the $\beta\beta^0\nu$ energy window.

The design allows radioactive sources to be introduced inside the
NEMO-3 detector for calibration purposes. $^{207}$Bi and $^{90}$Sr are used for the
absolute energy calibration ($\sigma/E \sim 6\%$ for 1 MeV electrons) while the time
calibration is performed with $^{60}$Co, $^{207}$Bi, and neutron sources placed out-
side the detector. The neutron runs are also used to check the performance
of the tracking chamber using high energy electrons crossing the tracking
volume. The transverse and longitudinal vertex resolutions obtained at 1
MeV are 0.2 and 0.7 cm, respectively. A laser-based light injection system
is used for a daily survey of the calorimeter (relative energy calibration).

The detector core is surrounded by multi-layer shielding, which includes
a solenoid’s copper coil, 18 cm of iron to suppress gamma flux, and finally
35 cm of water in tanks or wood against neutrons. All components of the
detector have been tested to have extra low radioactivity.

First tests confirmed that the performance of the NEMO-3 detector
corresponds to that claimed in the proposal$^4$. 
3. Results of analysis of 2003 data

3800 h of data collected between February and October 2003 have been analyzed.

3.1. Background studies

A great advantage of the NEMO-3 detector is its ability to measure various backgrounds by detecting electrons, gammas and delayed alphas in any combination with different multiplicities.

Our studies were specially concentrated on the backgrounds, which could contribute to the $\beta\beta0\nu$-mode. In addition to unavoidable background from $\beta\beta2\nu$-tail these are $^{208}$Tl (located in the source foil) and $^{214}$Bi (on the foil’s surface or close to it in the gas) originated from the $^{222}$Rn decay chain.

A $\beta\beta$-like event may come from a ($\beta$, $\gamma$) decay of $^{214}$Bi or $^{208}$Tl followed by the production of the second electron either by the photon via the Compton effect, or by the electron via the Möller scattering or alternatively as a result of a conversion electron emitted instead of the photon.

$\beta\gamma$, $\beta\gamma\gamma$, and $\beta\gamma\gamma\gamma$ channels have been studied to estimate the $^{208}$Tl contamination in the source foils. The TOF and high-energy cuts for electrons and photon(s) were used to isolate $^{208}$Tl-events from other backgrounds. The $^{208}$Tl activities in composite and metallic foils of $^{100}$Mo were found to be $140 \pm 40$ and $50 \pm 40 \mu$Bq/kg, respectively. This is in good agreement with the limit obtained with a Ge detector ($<100 \mu$Bq/kg). The accuracy of the $^{208}$Tl activity estimate will be improved in the future with higher statistics.

$^{214}$Bi is a daughter isotope of the $^{222}$Rn decay chain. Radon penetrates into the NEMO-3 inner volume from the laboratory air. The $^{214}$Bi contamination is estimated from $\beta\alpha$-events with one electron track followed by an alpha track (delayed Geiger hits) originated from the same vertex. The time distribution of the delayed alphas corresponds to the decay constant of $^{214}$Po ($T_{1/2}=164 \mu$s) confirming the efficient selection of $^{214}$Bi-events. The $^{222}$Rn activity reconstructed from the $\beta\alpha$-channel is at the level of 30 mBq/m$^3$ and oscillates with time. This value is in agreement with the results of independent measurements of the NEMO-3 tracking chamber gas made by a special radon detector at the detector’s gas outlet. A daily survey of $^{222}$Rn activity inside NEMO-3 is performed now using the method described. Higher statistics will allow us to determine relative activities of $^{214}$Bi in the foil, Geiger wires and gas volume.

A few $\beta\beta0\nu$-like events per year are expected from the $^{214}$Bi decay.
given the current contamination of radon inside NEMO-3, which is by far more than other background contributions. In order to reach the expected sensitivity for $\beta\beta_{0\nu}$, the radon level in NEMO-3 must be reduced by a factor of $10^{-100}$. To achieve this the detector was surrounded by an anti-radon tent. A radon free air factory analogous to one used by SuperKamiokande is currently being built in LSM. It is expected that the anti-radon tent will be purged with a purified air stream starting from this summer.

3.2. Two-neutrino double beta decay

The $\beta\beta$-event selection criterion requires two electron tracks originated from a common vertex in the source and associated with two scintillator hits. To suppress the $^{214}\text{Bi}$-contribution, events with delayed hits ($\alpha$ particle) near the vertex are rejected.

![Figure 2](image_url)

Figure 2. Distribution of total energy of electrons (a) and cosine of angle between two electrons (b) for $^{100}\text{Mo}$ $\beta\beta$-events after 3800 h of data taking. The points represent data with background subtracted while the histograms show $2\beta2\nu$-simulations.

80000 events were selected in the $^{100}\text{Mo}$ sources with a signal-to-background (S/B) ratio of 40. This statistics is seven times the one collected by the NEMO-2 detector. The energy sum of the two electrons as well as the angular distribution between them are shown in Figure 2.

The preliminary value of the $\beta\beta2\nu$ decay half-life for $^{100}\text{Mo}$ is:

$$T_{1/2}^{\beta\beta2\nu} = 7.3 \pm 0.025\text{(stat)} \pm 0.7\text{(syst)} \times 10^{18}\text{y}. $$
Due to uncertainties in the detector efficiency, a conservative 10% systematic error has been used.

Other isotopes were analyzed in the same way. The spectra of the electron energy sum are shown in Figure 3, while the preliminary values of the $\beta \beta 2\nu$ half-lives are given below:

- $^{82}\text{Se}$: $T_{1/2}^{\beta \beta 2\nu} = 9.5 \pm 0.3(\text{stat}) \pm 0.9(\text{syst}) \times 10^{19}\text{y}$.
- $^{116}\text{Cd}$: $T_{1/2}^{\beta \beta 2\nu} = 2.7 \pm 0.1(\text{stat}) \pm 0.3(\text{syst}) \times 10^{19}\text{y}$.
- $^{150}\text{Nd}$: $T_{1/2}^{\beta \beta 2\nu} = 7.5 \pm 0.3(\text{stat}) \pm 0.7(\text{syst}) \times 10^{18}\text{y}$.

### 3.3. Neutrinoless double beta decay

The $\beta \beta 0\nu$ decay can be produced by V-A or V+A currents. These two modes can be distinguished by studying the angular distribution of the emitted electrons. An analysis with a likelihood method which took into
account the minimal single electron energy, total energy and the angular distribution of $\beta\beta$-electrons has been performed.

The limits (90 % CL) obtained for $^{100}\text{Mo}$ are:

$$V{-}A: T_{1/2}^{\beta\beta0}\nu > 1.9 \cdot 10^{23}\text{y}. $$

$$V{+}A: T_{1/2}^{\beta\beta0}\nu > 9.8 \cdot 10^{22}\text{y}. $$

These limits improve the best current results obtained for $^{100}\text{Mo}$.

4. Discussion and conclusion

The first data collected by NEMO-3 has shown the detector to perform within the original specifications. Since February 2003 the data has been taken routinely. After a few months of data taking the NEMO-3 experiment has already produced the world’s best limit for the $\beta\beta0\nu$-mode of $^{100}\text{Mo}$. After 5 years of measurements we expect to reach a sensitivity to the effective Majorana neutrino mass of 0.1 eV.

It should be emphasized, that 0.1 eV is the first milestone on the current road map of the $\beta\beta0\nu$-search and a short-term (5 years) goal for current $\beta\beta$-experiments. If $\beta\beta0\nu$-decay is not found at this level, the degenerated hierarchy pattern can be excluded for Majorana neutrinos.

According to current theoretical assumptions the second milestone is the sensitivity at the level of 0.02-0.04 eV corresponded to the inverted hierarchy of neutrino eigenstates. This is a longer-term ($\geq 10-20$ years) goal of many ambitious projects (EXO, MOON, MAJORANA, etc.) with hundreds, and possibly tons, of kilograms of enriched $\beta\beta$-isotopes. In the end of 2003 the NEMO collaboration launched a R&D program to study the feasibility of a NEMO-like detector with $\sim 100$ kg of isotope and improved energy resolution in order to reach this sensitivity (SUPERNEMO). Such a project would represent the culmination of two decades of development which has provided three previous NEMO experiments. Because of the modest R&D needed and very well known technology, this future project can potentially have a significant head start on the competition.

Acknowledgments

The authors would like to thank the Fréjus Underground Laboratory staff for their technical assistance in building and running the experiment.

This work was partially supported by INTAS Grant No 03051-3431.
8

References
1. Y. Fukada et al. (SuperKamiokande Collaboration), Phys. Rev. Lett. 81 (1998) 1562.
2. Q. R. Ahmad et al. (SNO Collaboration), Phys. Rev. Lett. 89 (2001) 11301.
3. K. Eguchi et al. (KamLand Collaboration), Phys. Rev. Lett. 90 (2003) 21802.
4. NEMO Collaboration, Preprint LAL 94-29, LAL Orsay, 1994
5. H. Ohsumi, and the NEMO Collaboration Nucl.Phys. A721 (2003) 529.
6. R. Arnold, et al, physics/0402115; accepted to be published at Nucl. Instrum. Methods A.
7. R. Arnold et al., Nucl. Instr. Meth., A503 (2003) 649.
8. D. Dassié et al, Phys. Rev., D51 (1995) 2090.
9. H. Ejiri et al., Phys. Rev. C63, (2001) 065501.