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SUPPLEMENTS

Results from the NEMO experiment

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The NEMO collaboration is building a detector to search for neutrinoless double beta decay. The main results of the second prototype NEMO 2 are presented as well as the expected performance of the final detector NEMO 3.

1. Introduction

In 1989 the NEMO (Neutrinoless Experiment with Molybdenum) collaboration[1] started a R&D program to build a detector able to lower the sensitivity to the effective neutrino mass down to about 0.1 eV by looking for the neutrinoless double beta decay process ($\beta\beta0\nu$). The observation of such a process will prove the existence of a massive Majorana neutrino.

The experimental setup has been designed with a removable source in order to study different $\beta\beta$ emitters. It must also be able to reconstruct trajectories and to measure the energy and the time of flight of the emitted electrons. Two prototypes, NEMO 1 and NEMO 2, have been built to test the techniques of detection and to study the background. This paper reports the main results obtained in 6 years of running with the NEMO 2 prototype detector installed in the Fréjus Underground Laboratory (4800 m.w.e.). A brief description and the expected performance of the final detector NEMO 3 currently under construction are also given.

2. The NEMO 2 detector

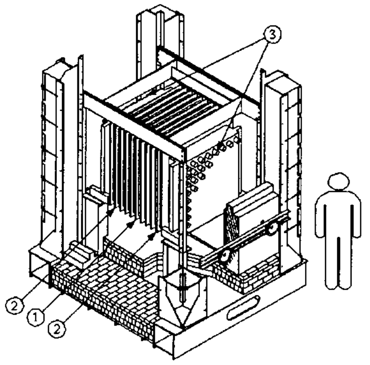

Figure 1. The NEMO 2 prototype without shielding. (1) Central frame with the source plane capable of supporting plural source foils. (2) tracking device of 10 frames, each consisting of two perpendicular planes of 32 geiger cells. (3) Two scintillator arrays of 8 by 8 counters each.

A more detailed description can be found in Ref. [1]. Only the main characteristics of the detector will be presented here. The NEMO 2 detector (Figure 1) is made of a 1 m^2, 50 μm source foil sandwiched by two tracking volumes composed of Geiger cells and two plastic scintillator arrays. The tracking volumes are filled with a mixture of helium gas and 4% ethyl alcohol in order to miminize multiple scattering effects. The detector is able to track electrons with energy as low as 100 keV. A delayed trigger allows the possibility of detecting alpha particles.

The calorimeter part is made of two arrays of plastic scintillators coupled to photomultiplier tubes (PMT). These counters allow energy and time of flight measurements. The resolution is 17.4 % (FWHM) in energy and 250 ps (σ) in time at 1 MeV. The detection threshold is 50 keV. Time and energy calibrations were checked daily.

The shielding is composed of an internal 5 cm

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Table 1
Comparison between measured and expected number of events in the $\beta\beta$ 0ν energy region for ^{100}Mo, ^{116}Cd, ^{82}Se.

	^{100}Mo	^{116}Cd	^{82}Se
Windows (MeV)	[2.6-3.0]	[2.3-2.8]	[2.4-3.1]
Running time (h)	6140	5960	10357
Mass (g)	172	152	157
Measured events	1	0	1
Expected background events	2	0.2	1

lead layer surrounded by 20 cm of iron. All materials used in the construction were selected using low background Ge detectors.

The signature of any $\beta\beta$ decay event is given by the pure electron-electron channel. However, other channels like electron-gamma or electron-delayed alpha channels have shown to be very important for background studies. For example, delayed alpha emission is a good signature of a ^{214}Bi contamination in the foil [2].

3. NEMO 2 results

3.1. Background studies near $Q_{\beta\beta}$ energy

The main goal of the NEMO 2 prototype was to study and to understand the components of the background in the $\beta\beta0\nu$ energy region for several nuclei: ^{100}Mo ($Q_{\beta\beta}$=3.034 MeV) [3], ^{116}Cd ($Q_{\beta\beta}$=2.805 MeV) [4] and ^{82}Se ($Q_{\beta\beta}$=2.995 MeV) [5]. Two origins of background called *internal* and *external* components are identified.

The *internal* background corresponds to the events coming from radioactive contaminations in the foil. In the energy region of interest for $\beta\beta0\nu$, the only activities are from ^{214}Bi and ^{208}Tl. These nuclei decay by β emission and a secondary electron can be produced by internal conversion, by the Compton effect from photons of the cascades or by Möller scattering. The tail of the $\beta\beta2\nu$ spectrum contributes also because of the energy resolution.

The *external* background is due to high energy gamma rays (> 2.6 MeV)crossing the source foil. Their origin is from neutron capture occuring inside the detector. The interactions of these photons in the foil can lead to the production of 2 electrons by e^+e^- pair creation, double Compton effect or Compton + Möller effect. To understand this background component, several tests with different types of shielding have been performed . The low energy photon flux coming from photomuplier tubes and other surrounding materials don't contribute to the background at the $\beta\beta0\nu$ energy.

The results of the background measurements are summarized in Table 1 . The number of expected events is calculated by simulation taking into account all known sources of background. The good agreement between measured and expected number of events in the energy window of the $\beta\beta0\nu$ decay makes us confident in our ability to control the background in the final NEMO 3 detector.

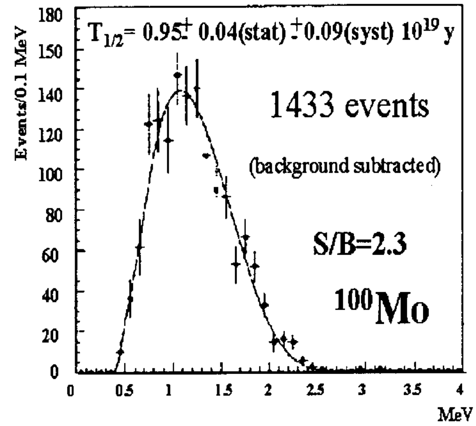

Figure 2. Experimental energy spectrum of 2e events for ^{100}Mo (6140 h), background subtracted.

Table 2
Measured $\beta\beta2\nu$ half-lifes with NEMO 2 detector and Signal/Background (Sig/Back) ratio.

	$T_{1/2}^{\beta\beta2\nu}$ (y)	Sig/Back
^{100}Mo	0.95 ± 0.04(stat)±0.09(syst) 10^{19}	2.3
^{116}Cd	3.75 ± 0.35(stat)±0.21(syst) 10^{19}	4
^{82}Se	0.83 ± 0.10(stat)±0.07(syst) 10^{20}	3
^{76}Zr (preliminary)	$2.1^{+0.8}_{-0.4}$(stat)±0.1(syst) 10^{19}y	

3.2. $\beta\beta2\nu$ results

Even if the NEMO 2 prototype was first of all dedicated for the $\beta\beta0\nu$ background studies, its performance also allowed measurement of the half-life of the $\beta\beta2\nu$ process. As an exemple, Figure 2 shows for ^{100}Mo the measured 2e energy sum spectrum after background subtraction. The removed background below 2.6 MeV is essentially due to the photon flux coming from the photomultiplier tubes. The contamination of the source (measured with Germanium detector and NEMO 2 itself) in ^{214}Bi, ^{208}Tl and ^{234}Pa gives a negligible contribution.

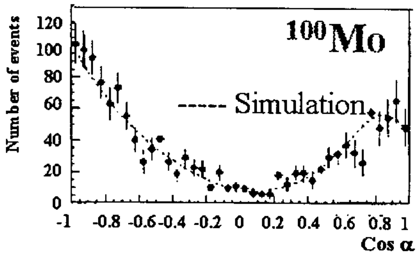

Figure 3. Angular distribution of 2e events for ^{100}Mo (6140 h, background subtracted). The broken line corresponds to the simulation.

The experimental value of the $\beta\beta2\nu$ half-life, reported on the figure 2, is obtained by a fit of the data with the expected $\beta\beta2\nu$ shape (solid line).The results for several isotopes are reported in Table 2 together with the corresponding signal/background ratio.

As shown in Figure 3, the detector also allows measurement of the angular distribution between the 2 emitted electrons. This distribution is significantly distorted by the detector geometry and the multiple scattering in the foil. The simulation (dashed line) is in good agreement with the data. Detailed analysis can be found in Ref [3],[4] and [5].

4. The NEMO 3 detector

4.1. Structural design of NEMO 3

The NEMO 3 detector, Figure 4, will be similar in function to the earlier detector, NEMO 2. More specifically, the NEMO 3 detector will also operate in the Fréjus Underground Laboratory and will house up to 10 kg of double beta decay isotopes. To date, much attention has been focused on 10 kilograms of enriched Mo samples (97% ^{100}Mo). Also currently available are the following isotopes: 1 kg of ^{82}Se; 1 kg of ^{116}Cd; and 1 k

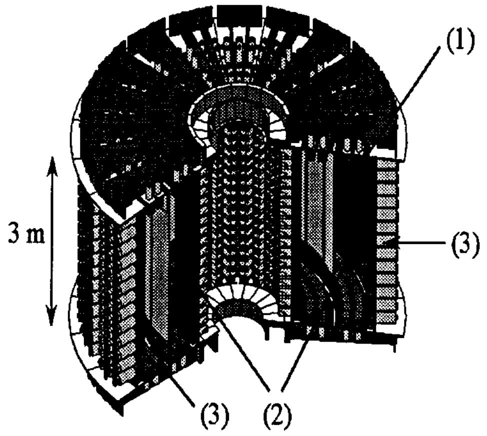

Figure 4. NEMO 3 detector. (1) Source foil, (2) tracking volumes consisting of 3 m vertical Geiger cells, (3) calorimeter made of plastic scintillators coupled to photomultiplier tubes.

The detector is cylindrical in design and divided into 20 equal sectors. A thin (40-50 μm) cylindrical source foil will be constructed from either a metal film or powder bound by an organic

Table 3
NEMO 3 Expected background rate and maximum acceptable activities (mBq/kg) in ^{214}Bi and ^{208}Tl.

Isotope	Events/year			mBq/kg	
	^{214}Bi	^{208}Tl	$\beta\beta 2\nu$	^{214}Bi	^{208}Tl
^{100}Mo	0.4	0.4	1.1	0.3	0.02
^{82}Se	0.1	0.1	0.1	0.07	0.005
^{150}Nd	none	0.4	1.1	none	0.02

glue to mylar strips. The source will hang between two concentric cylindrical tracking volumes consisting of open octagonal drift cells operating in Geiger mode. These cells run vertically and are staged in a 4, 2, and 3 row pattern to optimize track reconstruction. The design of the drift cells calls for 50 μm anode and cathode wires to prevent rapid aging.

The external walls of these tracking volumes are covered by calorimeters made of large blocks of plastic scintillator coupled to very low radioactivity 3" and 5" Hammamatsu PMTs . The energy resolution depends on the scintillator shape and the associated PMT. It ranges from 11% to 14.5% (FWHM) for 1 MeV electrons.

The complete detector contains 6180 Geiger cells and 1940 scintillators.

Additionally, a solenoid capable of producing a 30 Gauss field will surround the detector to reject pair production events. Finally, external shielding in the form of 20 cm of low activity iron will reduce gamma ray fluxes and thermal neutrons. If needed, additional shielding will be introduced to suppress the contribution of fast neutrons. More details on this are given below.

4.2. Neutrons and radioactivity requirements

At the depth of the experimental hall in the Frejus Underground Laboratory any effect of cosmic rays has been found negligible. Vigorous flushing of the air in the hall reduces the radon levels to 10-20 Bq/m^3. The presence of ^{214}Bi decays in the detector from this level of radon contamination is below that introduced by the PMTs.

Thermal and fast neutrons fluxes in the hall have been measured at levels of 1.6×10^{-6} neutrons/s·cm^2 and 4×10^{-6} neutrons/s·cm^2, respectively [6]. From NEMO 2 studies, it appears that the effects of photons coming from neutron capture are expected to be negligible. The magnetic field will be used to study the pair production and confirm the prediction of a negligible contribution.

Radioactivity of the materials which have gone into the construction of the detector have been measured with HP Ge detectors at the Fréjus Underground Laboratory or at the CENBG laboratory in Bordeaux. The activity in the mechanical pieces which frame the detector are required to be less than 1 Bq/kg.

As expected, the radioactive contamination in the experiment is dominated by the low radioactivity glass in the PMTs. The total activity of all of the 0.6 tons of PMTs is 800 Bq, 300 Bq and 18 Bq for ^{40}K, ^{214}Bi, and ^{208}Tl, respectively. These levels are three orders of magnitude below standard PMT levels. In the energy region of interest for $\beta\beta 0\nu$ decays i.e., around 3 MeV, the above external background component doesn't give any contribution.

However, the internal component from ^{214}Bi, ^{208}Tl contaminations in the source foil and tail of the $\beta\beta 2\nu$ decays have to be seriously minimized. The $\beta\beta 2\nu$ decays ultimately define the half-life limits to which the $\beta\beta 0\nu$ decays can be studied. To insure that $\beta\beta 2\nu$ defines these limits, maximum acceptable activities of ^{214}Bi and ^{208}Tl in the source foil were calculated (Table 3). For ^{100}Mo it is believed that these limits can be reached, whereas for Se with a longer $\beta\beta 2\nu$ decay half-life, more stringent levels are sought and will require some additional research. Note that the energetic decay of ^{150}Nd removes concerns of contamination by ^{214}Bi, but new techniques to enrich Nd will have to be developed for this to be realized.

4.3. Expected performance of NEMO 3

In Figure 5, the projected performance of the NEMO 3 detector with 10 kg of isotopes (^{100}Mo, ^{82}Se, ^{150}Nd) and 5 years of data are compared to the other double beta decay experiments or projects in terms of the effective neutrino mass limit.

For the running experiments with ^{76}Ge (Heidelberg-Moscow, IGEX) or ^{136}Xe (Neuchatel-Caltech), the neutrino mass has been deduced from the already published $\beta\beta0\nu$ half-life limits.

In case of the recent proposal GENIUS (see this proceedings) with 1 ton of ^{76}Ge, the two limits have been calculated using the published background level of the Heidelberg-Moscow experiment and assuming 2 or 3 orders of magnitude background reduction.

The broad range of results for the effective neutrino mass results from the use of various nuclear matrix elements (nme's) calculations. In Figure 5 calculations for the above experiments have been performed with QRPA, Shell model, and SU(3) nme's. It is worth noting that there seems to be a movement towards greater acceptance of shell model nme's.

4.4. Status of the NEMO 3 detector

12 sectors over 20 are already built. The placement of completed sectors on the frame in Frejus laboratory will start in December 1998. This final stage of the construction is expected to continue until January 1, 2000. Presently, it is planned to start operating with 7 kg of ^{100}Mo and 1 kg of ^{82}Se, with some sectors filled with foils especially designed to check background.

REFERENCES

1. R. Arnold et al.,*Nucl. Instr. Meth.* **A354** (1995)338.
2. R. Arnold et al.,*Nucl. Instr. Meth.* **A401** (1997)144.
3. D. Dassie et al.,*Phys. Rev.* **D 51** (1995)2090.
4. R. Arnold et al.,*Z. Phys.* **C 72** (1996)239.
5. R. Arnold et al.,*Nucl. Phys.* **A636** (1998)209.
6. V. Chazal, Thesis, Université de Lyon (1996).

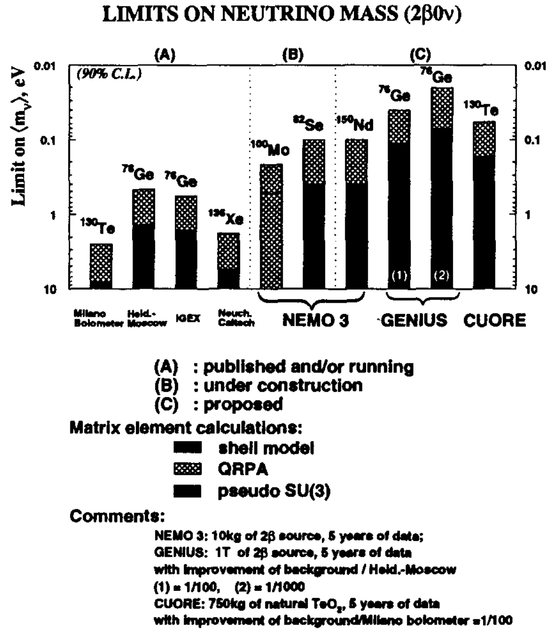

Figure 5. Projected performance of NEMO 3 detector in terms of limit on neutrino effective mass $< m_\nu >$ for 10 kg of 2β source and 5 years of data, compared to published and/or running experiment: Heidelberg-Moscow, IGEX, Neuchatel-Caltech and to the proposed GENIUS and CUORE experiments. GENIUS numbers are given for 1 ton of 2β source, 5 years of data with the hypothesis of 2 or 3 orders of magnitude improvement of their present background (respectively (1) and (2) on the figure) and CUORE numbers for 750 kg of natural TeO$_2$, 5 years of data with an improvement of the background of 2 order of magnitude compared to Milano bolometer.