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Double-Beta Decay with the Nemo Experiment: Status of the Nemo 3 Detector*

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Abstract—The NEMO 3 detector, devoted to search for the neutrinoless double-beta decay, will be able to reach the sensitivity to $\langle m_\nu \rangle$ of the order of 0.1 eV. The expected performance of the detector for signal detection and both internal and external background rejection is presented. A specific study of the neutron-induced background is given. The NEMO Collaboration is now mounting the detector in the Fréjus underground laboratory.

1. INTRODUCTION

Since 1988, the NEMO (Neutrinoless Experiment with Molybdenum) collaboration started a R& D program to build a detector able to lower the sensitivity of the effective neutrino mass down to about 0.1 eV by looking for the neutrinoless double-beta-decay process $\beta\beta(0\nu)$. The observation of such a process will prove the existence of a massive Majorana neutrino.

The guidelines to reach this goal are the following:

Several kilograms of $\beta\beta$ emitters to measure half-lives greater than 10^{24} yr.

Source and detector are independent, to allow the study of different $\beta\beta$ isotopes and to take into account nuclear matrix element uncertainties.

Full characterization of two electron decays by direct detection of the emitted electrons, including reconstruction of trajectories, time-of-flight and energy measurements.

All detector parts, including the shielding, are made of low radioactivity materials (selected with ultralow background γ-ray Ge spectrometers) to reduce background.

Stability and reliability of the used techniques to allow several years of running with full control from each laboratory of the collaboration.

α and γ detection, time-of-flight criteria, and magnetic field in order to reject the remaining background.

Two prototypes, NEMO 1 [1] and NEMO 2 [2], have proved the technical feasibility and have also permitted background studies (natural radioactivity, radon, cosmics, neutrons, etc.). In addition, the NEMO 2 prototype has shown enough sensitivity to measure $\beta\beta(2\nu)$ half-lives of ^{100}Mo [3, 4], ^{116}Cd [5], ^{82}Se [6], and ^{96}Zr [7]. The expected performance of the final detector NEMO 3 [8], which is under construction in the Fréjus underground laboratory, will be presented in this paper with a focus on the $\beta\beta(0\nu)$-neutron-induced background.

2. THE NEMO 3 DETECTOR

The NEMO 3 detector will house up to 10 kg of double-beta-decay isotopes. 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 bounded by an organic 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 patterns to optimize track reconstruction. The design of the drift cells calls for 50-μm stainless steel anode and cathode wires to have a good transparency of the detector. The tracking volumes are filled with a mixture of helium gas and 4% ethyl alcohol in order to minimize multiple scattering effects. The detector is able to track electrons with energy as low as 100 keV. The electronics of Geiger cells allows the possibility of detecting delayed alpha particles.

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. At 1 MeV, the energy resolution, which depends on the scintillator shape and on the associated PMT, ranges from 11 to 15% (FWHM) and the time resolution is 250 ps (σ). The detection threshold is 30 keV. Time and energy calibrations will be checked daily by a laser and fiber optics system. The

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complete detector contains 6180 Geiger cells and 1940 scintillators.

Additionally, a solenoid capable of producing a field of 30 Gs will surround the detector to reject pair-production events. An external shielding in the form of 20 cm of low activity iron will reduce gamma-ray flux. Finally an additional 20-cm polyethylene shielding will be introduced to suppress the contribution of neutrons. This will be detailed in Section 4.

The radioactivity of the materials which have gone into the construction of the detector has been measured with HPGe detectors at the Fréjus underground laboratory or at the CENBG laboratory in Bordeaux. The activities of the mechanical pieces which frame the detector are required to be less than 1 Bq/kg.

3. BACKGROUND INDUCED BY NATURAL RADIOACTIVITY INSIDE THE SOURCE

3.1. Description

In the NEMO detector, a signal from ^{100}Mo $\beta\beta(0\nu)$ decay is expected between 2.8 and 3.2 MeV depending on the energy resolution of the calorimeter as well as the energy loss by the electrons inside the source foil. In this energy range the only natural activities are from ^{214}Bi (Q_β = 3.2 MeV) and ^{208}Tl (Q_β = 5.0 MeV). These nuclei present in the source 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 simulating a $\beta\beta(0\nu)$ emission. The $\beta\beta(2\nu)$ decays ultimately define the half-life limits to which the $\beta\beta(0\nu)$ decays can be studied. Indeed, the tail of the $\beta\beta(2\nu)$ decays contributes due to the energy resolution, which is the sum of two effects: energy resolution of the calorimeter and energy lost in the source foil.

3.2. Expected Contributions

To limit the contribution of $\beta\beta(2\nu)$ events in the energy range of neutrinoless double-beta decay, some improvements have been made to lower the energy resolution of the calorimeter. The actual performance is closed to the final limit imposed by the thickness of the source foil.

The internal component from ^{214}Bi and ^{208}Tl contaminations in the source foil are seriously minimized. The maximum acceptable activities of ^{214}Bi and ^{208}Tl in the source foil are calculated to be at the same contribution level as the $\beta\beta(2\nu)$-background events. To reach the required activities, several processes of both physical and chemical purification of the source foils have been developed.

The table summarizes the expected background for the considered $\beta\beta$ isotopes. For ^{100}Mo, it is believed that these limits can be reached, whereas, for ^{82}Se with a longer $\beta\beta(2\nu)$-decay half-life, more stringent levels are sought and will require some additional research.

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

Isotope	Events/yr			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

Note that the energetic decay of ^{150}Nd ($Q_{\beta\beta}$ = 3.368 MeV) removes the background from ^{214}Bi, but new techniques to enrich Nd will have to be developed for this to be realized.

4. EXTERNAL BACKGROUND

4.1. Description

The external background of a $\beta\beta(0\nu)$ signal is due to high-energy gamma rays (>2.6 MeV) crossing the source foil. Their origin is from neutron capture occurring inside the detector. The interactions of these photons in the foil can lead to the production of two electrons by e^+e^- pair creation, double Compton effect, or Compton effect following by a Möller scattering. To understand this background component, several tests with different types of shielding have been performed. The low-energy photon flux coming from photomultiplier tubes and other surrounding materials does not contribute to the background at the $\beta\beta(0\nu)$ energy.

4.2. Study of the Neutron-Induced Background

Most of the high-energy gamma rays produced by (n, γ) reactions interact in the scintillators and create Compton electrons crossing the detector ("one crossing electron" events). This has been proved by putting an AmBe source near the NEMO 2 prototype and comparing to the data with and without a neutron source. The number of events increases as shown in Fig. 1. A peak around 2 MeV can be noticed, due to 2.2 MeV gamma

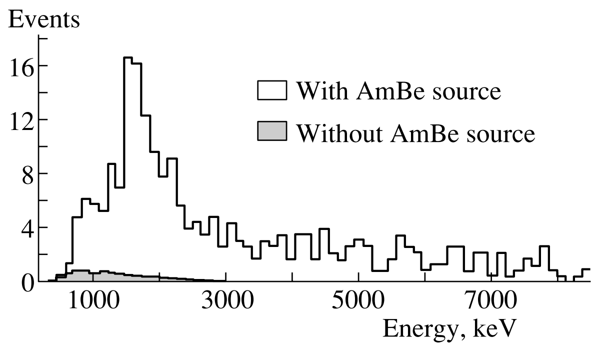

Fig. 1. Energy sum of "one crossing electron" events recorded with and without neutron source during 1 h.

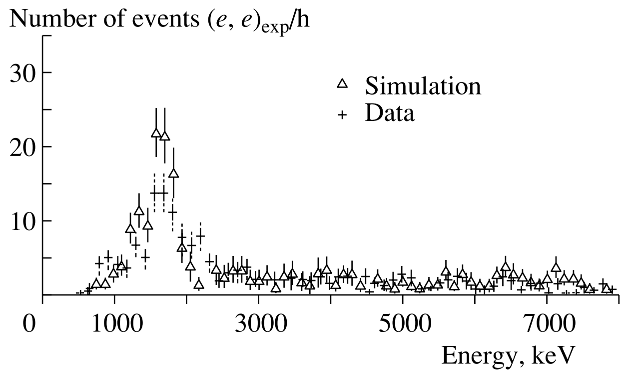

Fig. 2. Comparison of simulated and experimental energy spectrum of "one crossing electron" events for 1 h with the AmBe source located near the NEMO 2 prototype.

rays coming from neutron captures in hydrogen. High-energy events correspond to neutron captures in iron and copper frames of the detector.

The simulations based on the GEANT/MICAP code with a new photon library developed by the collaboration for γ rays emitted after (*n*, γ) captures and inelastic scattering reproduce well the number and the shape of the spectrum (Fig. 2) of the recorded events.

4.3. Expected Neutron Background in the NEMO 3 Detector

The simulations of the neutrons in the NEMO 3 detector achieved with 20 cm of iron shielding lead to a rate of 260 ± 110 (this error is due to the measured neutron flux uncertainty) for charged tracks events (similar to ββ(0ν) events) with an energy greater than 2.8 MeV for 5 yr of data taking and 10 kg of ^{100}Mo. The 30-Gs magnetic field permits one to reject 95% of (e^+, e^-) pairs. So, the number of remaining events becomes 50 ± 20.

An added neutron shielding of 20 cm of borated polyethylene placed outside the iron shielding allows us to reach 0.5 ± 0.3 events in 5 yr with an energy greater than 2.8 MeV corresponding to less than 0.1 event (at 90% C.L.) in the energy range of a ββ(0ν) signal (2.8–3.2 MeV for ^{100}Mo).

5. CONCLUSION

It has been shown that with 10 kg of ^{100}Mo and 5 yr of data acquisition, a total of 9.5 background events is expected in the NEMO 3 detector in the ββ(0ν)-energy region. This leads to a sensitivity of 2×10^{24} yr for a 5σ-ββ(0ν) signal effect corresponding to an effective neutrino mass between 0.4 and 0.9 eV, depending on the nuclear matrix elements. In terms of a limit, the sensitivity is of 5.5×10^{24} yr, which gives a limit in the range 0.2–0.6 eV for $\langle m_\nu \rangle$. More stringent limits could be reached with the NEMO 3 detector by replacing the ^{100}Mo with ^{82}Se or ^{150}Nd. In addition, the NEMO 3 detector will measure ββ(2ν)-energy spectrum and angular distribution with very high statistics (10^6 events/yr with 10 kg of ^{100}Mo). It will also be sensitive to the ββ(0ν) decay with Majoron emission at the level of 10^{23} yr and up to 10^{22} yr for double-beta decay to excited states.

Data taking with the full detector, now under construction in the Fréjus underground laboratory, is planned for summer 2000.

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