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Double beta decay with the NEMO experiment : status of the NEMO 3 detector

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The NEMO 3 detector, now mounting in the Fréjus underground laboratory, is devoted to search for neutrinoless double beta decay and will be able to reach the sensitivity to the effective neutrino mass ($< m_\nu >$) in the order of 0.1 eV. The expected performance of the detector for signal detection and both internal and external background rejections are presented. A specific study of the neutron induced background is given.

1. Introduction

Since 1988 the NEMO (Neutrinoless Experiment with Molybdenum) collaboration [1] has started a R&D program to build a detector able to lower the sensitivity on 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 guide-lines to reach this goal are :
- several kilograms of $\beta\beta$ emitters to measure half-lives greater than 10^{24} years,
- source and detector independent, to allow the study of different $\beta\beta$ isotopes 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 made of low radioactivity materials (selected using ultra low background γ-ray Ge spectrometers) to reduce background,
- stability and reliability of the techniques to allow several years of running time with full remote control from each laboratory of the collaboration,
- α and γ detection, Time of Flight criteria and magnetic field to reject the background.

Two prototypes, NEMO 1 [1] and NEMO 2 [2] have proved the technical feasibility and have also permitted the background studies. 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 performances of the final NEMO 3 detector [8], which is under construction in the Fréjus underground laboratory, will be presented in this paper focused on the $\beta\beta(0\nu)$ backgrounds.

2. The NEMO 3 detector

The NEMO 3 detector will house up to 10 kg of double beta decay isotopes. It is cylindrical in design and divided into 20 equal sectors.

A thin (40-50 μm) source foil will be constructed from either a metal film or a powder bounded by an organic glue to mylar strips. This source will hang between two concentric cylindrical tracking volumes consisting of open octogonal drift-Geiger cells. The cells run vertically and are staged in a 4, 2, and 3 rows pattern to optimize the track reconstruction. The design of the 6180 drift cells calls for 50 μm stainless steel anode and cathode wires.

The external walls of these tracking volumes are covered by calorimeters made of 1940 large blocks of plastic scintillators coupled to very low radioactivity 3" and 5" Hammamatsu PMTs. At 1 MeV, the energy resolution which depends on

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Table 1
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

the scintillator shape and 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 daily checked by a laser system.

A solenoid producing a field of 30 Gauss will surround the detector to reject (e^+, e^-) pairs. A 20 cm of iron shielding will reduce gamma ray flux. A supplementary 20 cm polyethylene shielding will be introduced to suppress the contribution of the fast neutrons. This will be detailed in section 4. Radioactivity of all the materials which have gone into the construction of the detector have been measured with HP Ge detectors. The activity in 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 3 detector, a signal from ^{100}Mo $\beta\beta(0\nu)$ decay will be expected between 2.8 and 3.2 MeV depending on the energy resolution due to the energy resolution of the calorimeter and to the energy lost in the source foil. In this energy range the only activities are from ^{214}Bi (Q_β=3.2 MeV) and ^{208}Tl (Q_β=5.0 MeV). In the source, these nuclei can mimic $\beta\beta$ events by β emission followed by Möller effect or by β-γ cascade followed by Compton interaction. Because of the energy resolution, the tail of the $\beta\beta(2\nu)$ signal also contributes to the background.

3.2. Expected contributions

To limit the background due to the $\beta\beta(2\nu)$ decay, some improvements have been done to lower the energy resolution of the calorimeter. The actual performances are 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 are calculated to give a contribution on the same level as the $\beta\beta(2\nu)$ decay. To reach the required activities, several processes of both physical and chemical purification of the source foils have been developed.

The Table 1 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. Note that the energetic decay of ^{150}Nd ($Q_{\beta\beta} = 3.368 MeV$) removes background from ^{214}Bi, but new techniques to enrich Nd will have to be developed.

4. External background

4.1. Description

The external background of $\beta\beta(0\nu)$ signal is due to high energy gamma rays (> 2.6 MeV) crossing the source foil. Their origin is from neutron captures occurring inside the detector. The interactions of these photons in the foil can lead to 2 electrons by e^+e^- pair creation, double Compton scattering or Compton followed by Möller scattering. The low energy photon flux coming from photomultiplier tubes and other surrounding materials doesn't contribute to the background of $\beta\beta(0\nu)$ decay.

4.2. Study of the neutron background

Most of the high energy gamma rays produced by (n,γ) reactions interact in the scintillators and create a Compton electron crossing the detector ("one crossing electron" events or OCE events).

The first effect of the neutron contribution on these events and on the $\beta\beta(0\nu)$ background has been proved by the increase of the number of events recorded with an AmBe source located near the NEMO 2 prototype compared to the data without neutron source (Figure 1).

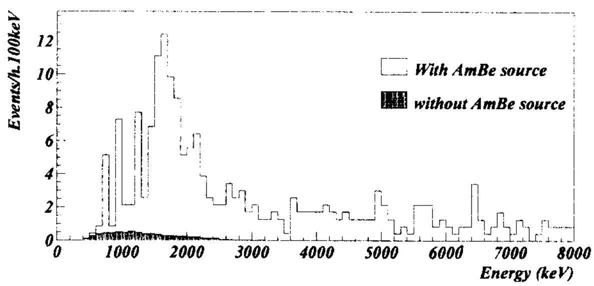

Figure 1. Energy of OCE events for 1 hour of data taking with and without neutron source.

The peak around 1.8 MeV is due to 2.2 MeV gamma rays coming from neutron captures in the hydrogen component of the scintillators. High energy events correspond to neutron captures in iron and copper frames of the detector.

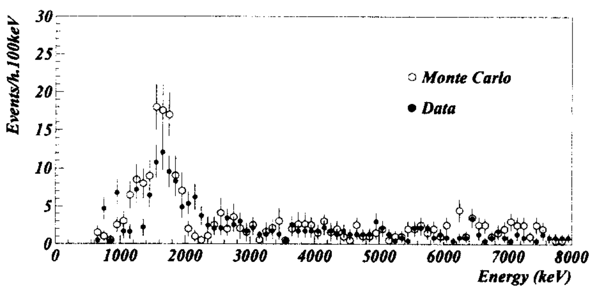

Figure 2. Comparison between simulated and experimental energy spectrum of OCE events for 1 hour of data taking with the AmBe source.

The simulations, based on GEANT/MICAP code with a new photon library developed by the collaboration for γ-rays emitted after (n,γ) captures and inelastic scatterings, rather well reproduce the number and the shape of the spectrum (Figure 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 260 $\pm$ 110 (this error is due to the measured neutron flux uncertainty) two charged tracks events with an energy greater than 2.8 MeV for 5 years of data acquisition and 10 kg of ^{100}Mo. The 30 Gauss magnetic field rejects 95% of (e^+,e^-) pairs. So, the number of events becomes 50 $\pm$ 20. An added neutron shielding of 20 cm of borated polyethylene placed outside the iron shielding allows to reach 0.5 $\pm$ 0.3 events created by the neutrons in 5 years with an energy greater than 2.8 MeV and less than 0.1 event (at 90% CL) in the energy range of $\beta\beta(0\nu)$ signal.

5. Conclusion

With 10 kg of ^{100}Mo and 5 years of data acquisition, a total of 9.5 background events (due to the natural radioactivity inside the source) is expected in the $\beta\beta(0\nu)$ energy region for the NEMO 3 detector. This leads to a sensitivity on the $\beta\beta(0\nu)$ half-life of 2 10^{24} years for a 5 σ $\beta\beta(0\nu)$ signal effect corresponding to an effective neutrino mass between [0.4-0.9] eV depending on the nuclear matrix elements. In terms of limit, the sensitivity is 5.5 10^{24} years which gives a limit in the range [0.2-0.6] eV for $< m_\nu >$. More stringent limits could be reached with the NEMO 3 detector replacing the ^{100}Mo by ^{82}Se or ^{150}Nd. In addition, the NEMO 3 detector will measure the $\beta\beta(2\nu)$ energy spectrum and the angular distribution with very high statistics (10^6 events per year with 10 kg of ^{100}Mo). It will be also sensitive to the $\beta\beta(0\nu)$ decay with Majoron emission at the level of 10^{23} years and up to 10^{22} years for $\beta\beta$ decay to excited states.

The detector is now under construction in the Fréjus underground laboratory and data taking with full detector is planned for summer 2000.

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