NEMO-3 analysis of the double-β decay of ^{96}Zr

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The NEMO-3 detector was searching for neutrinoless double-β decay. A dedicated study on the double-β processes of ^{96}Zr to ^{96}Mo has been performed using an exposure of 49 g·y. ^{96}Zr is a very promising isotope for neutrinoless double-β decay searches thanks to its high $Q_{\beta\beta}$ value of 3.35 MeV. Analysis techniques and status of two-neutrino process half-life measurements to ground state and excited states with the entire NEMO-3 statistics are exposed.

1 The NEMO-3 detector

NEMO-3 was a tracker-calorimeter detector designed to search for neutrinoless double-β decay ($0\nu\beta\beta$). Data taking started on February 14^{th} 2003 and stopped on January 11^{th} 2011.

The full kinematic reconstruction of the two-electron events is one of the crucial and unique assets of the NEMO technique. A double-β event is identified by two electrons arriving in time from the same vertex in the source foil. Three-dimensional tracks are reconstructed combining information from different cell layers in the tracking device. The magnetic field inside the tracker allows electrons to be distinguished from positrons via the track curvature. The e^- energies (individual and total) and their times of arrival are measured in the segmented calorimeter.

The detector is able to discriminate events with γ, α, e^+, e^- and $\mu^\pm$. e^+ and e^- produce long tracks with a curvature due to the magnetic field and γ-particles a hit in the calorimeter without any associated track (see Figure 1).

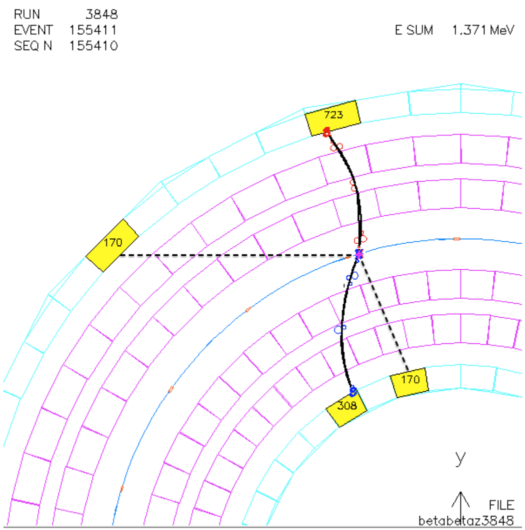

Figure 1 – *Event display from NEMO-3 data with two electrons and two γ-particles.*

2 NEMO-3 analysis of ^{96}Zr

Control samples can be defined thanks to the tracking and calorimetry assets of the NEMO-3 detector. Data and Monte-Carlo simulations are compared in individual analysis channels, enabling independent background measurements and double-β decay searches.

2.1 Two-neutrino double-β decay to ground state

Due to its high $Q_{\beta\beta}$ value, only few background components exist for the $0\nu\beta\beta$ decay of ^{96}Zr. Several measurements of the half-life of the two-neutrino double-β decay ($2\nu\beta\beta$) of ^{96}Zr to the ground state have already been performed . The current best measurement obtained with a shorter dataset of NEMO-3 provided [?]:

$$T_{1/2}^{2\nu\beta\beta}(^{96}Zr \rightarrow ^{96}Mo) = 2.35 \pm 0.14\ (stat.) \pm 0.16\ (syst.) \times 10^{19}\ y \tag{1}$$

A new study has been carried out with the full statistics. In order to optimise the signal to background ratio, an elliptic selection in energy has been done as displayed on Figure **??**. Indeed, ^{40}K appeared to be the dominant background as visible on Figure **??** (left). The kinematics of the decays provided by the detector enabled this two-dimensional study on Monte-Carlo simulations. The two variables were the maximal electron energy as a function of the minimal electron energy, different due to the two electrons production mechanisms. This has the effect of rejecting ^{40}K decays, the main background contribution in the two electron analysis channel. 96 % of ^{40}K events were rejected while keeping 79 % of the signal events.

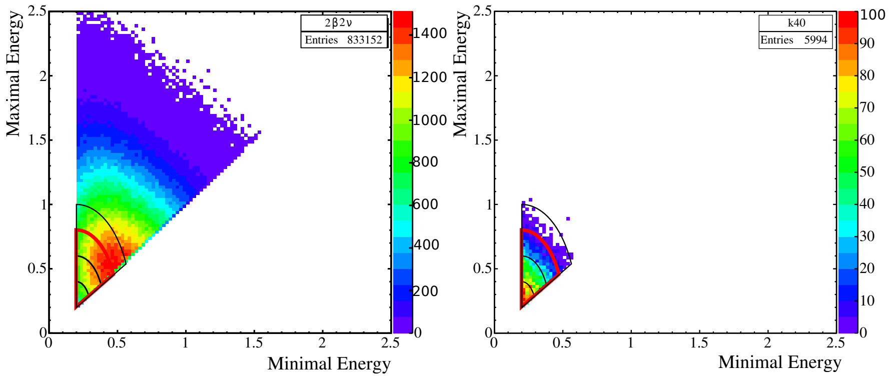

Figure 2 – *Distribution of the maximal energy as a function of the minimal energy in the 2 electrons channel from Monte-Carlo simulations. The signal from two-neutrino double-β decay is on the left and ^{40}K is on the right. Events inside the bold red ellipse are rejected.*

After this selection, the total energy has been fitted with simulations (see Figure **??**, right).

After approval by the collaboration, this $2\nu\beta\beta$ half-life measurement should be the most precise obtained with NEMO-3 and by any other experiment. Compared to the previous result, the signal over background should be improved by a factor of 3-4 and the exposure by 30 %.

2.2 Two-neutrino double-β decay to excited states

^{96}Zr is one of the double-β decay isotopes that can undergo a double-β decay to an excited state. The energy levels of ^{96}Mo, daughter nucleus of ^{96}Zr, are displayed on Figure **??**.

The decay to excited states is expected to be strongly suppressed compared to $2\nu\beta\beta$ to the ground state. Two energy levels exist, 0_1^+ and 2_1^+, but the 2_1^+ level is theoretically more suppressed. Therefore, the study was performed assuming no contribution from the 2_1^+ level.

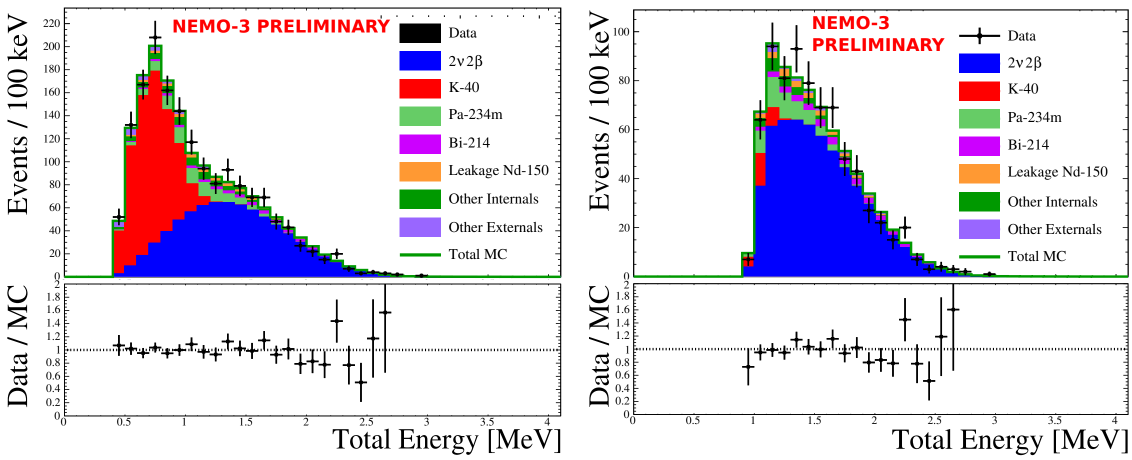

Figure 3 – *Comparison between data and Monte-Carlo simulations for the total energy in the 2 electrons channel before (left) and after (right)* ^{40}K *rejection.*

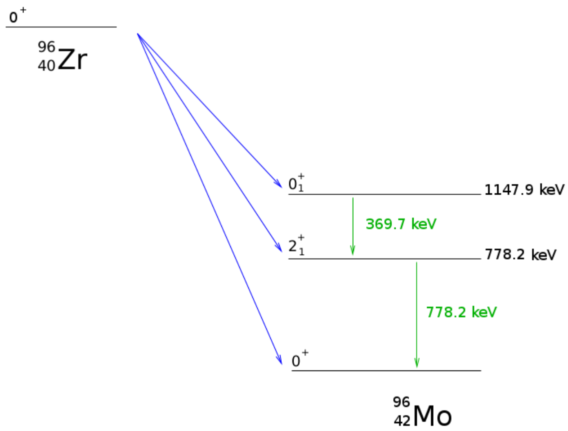

Figure 4 – *Energy scheme for the double-*β *decay of* ^{96}Zr *to* ^{96}Mo *to ground and excited states.*

Given the decay scheme of ^{96}Zr to the 0_1^+ excited state of ^{96}Mo, a cascade of two γ's is expected to be detected along with the two electrons. NEMO-3 is very powerful when considering electron detection. However, the efficiency to detect γ's is approximately of 50 %. It is compensated with a more distinctive event topology and lower background.

A selection optimising signal over background is again realised based on Monte-Carlo simulations for each of the main contributions. The energy of the unique γ-particle or the sum of the energies of the two γ's is compared to the sum of the energies of the electrons. Elliptic selections of events are performed in the plane constituted by these two kinematic variables. The position of the ellipse in the plane (ΣE_γ, ΣE_e) on Figure **??** illustrates the cut performed to optimise the signal over background ratio. In order to strongly reduce the background, this cut selects 17 % of the total number of $2\beta2\nu$ to excited state events. This allows to reject 93.5 % of ^{214}Bi, 97.1 % of ^{208}Tl and 96.1 % of the contribution from $2\nu\beta\beta$ to ground state.

A comparison between data and simulations for the total energy is performed (see Figure **??**). Data and simulations are compatible within a 2 σ background fluctuation hypothesis, estimated from a Poisson probability.

The dotted red line is the distribution of the decay to the 0_1^+ excited state. It illustrates the number of events that would be observed assuming a half-life equal to the current best limit from another experiment [?]. Careful cross-check of background systematics are currently ongoing.

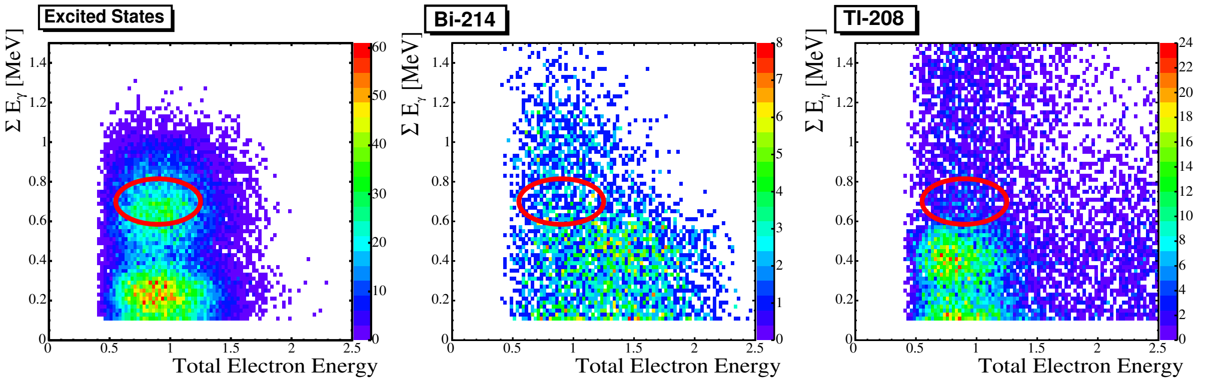

Figure 5 – *Display of the dominant backgrounds and the result of the optimisation of the signal over background for the decay to the 0_1^+ excited state of ^{96}Mo.*

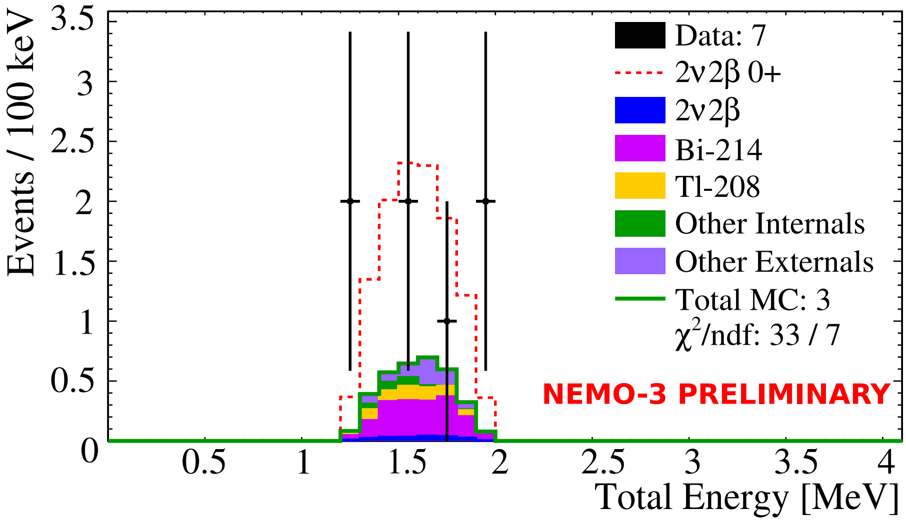

Figure 6 – *Distribution of the total energy in the 2 electrons and N γ-particle channel after strict selection cuts.*

3 Summary

A measurement of the half-life of $2\nu\beta\beta$ of ^{96}Zr to the ground state has been performed with the entire data available from NEMO-3. The half-life measurement is consistent with previously published values. A first search for $2\nu\beta\beta$ of ^{96}Zr to the 0_1^+ state with NEMO-3 data has been carried out. A limit on the half-life of this process should be set close to the current best limit.

Acknowledgments

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References