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Search of the $0\nu\beta\beta$ decay with the SuperNEMO demonstrator

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Thèse présentée et soutenue à Orsay, le ***, par

Cloé Girard-Carillo

Composition du Jury :

*** ***	Président
*** ***	Rapporteur
*** ***	Rapporteur
Christine Marquet CENBG - Bordeaux-Gradignan	Examinateur
*** ***	Examinateur
*** ***	Examinateur
Laurent Simard LAL - Orsay	Directeur de thèse
Mathieu Bongrand LAL - Orsay	Co-directeur de thèse

Thèse de doctorat

Contents

Chapter 6

Sensitivity of the SuperNEMO demonstrator to the $0\nu\beta\beta$

In this chapter, we present the SuperNEMO sensitivity to the $0\nu\beta\beta$ decay half-life, and the corresponding effective neutrino masses, for several isotopes. The SuperNEMO final detector is expected to exclude $0\nu\beta\beta$ half-lives up to 1.2×10^{26} y (90% CL) if $0\nu\beta\beta$ decays through the mass mechanism, with a detector exposure of 500 kg.y [7]. The sensitivity is given as a limit, in case we do not observe the expected signal. In 2010 began the demonstrator installation at the Laboratoire Souterrain de Modane. With an exposure of 17.5 y, the demonstrator could set a limit on the $0\nu\beta\beta$ process of 5.35×10^{24} y (90% CL) [8].

This study aims to explore the impact on the sensitivity of the presence of a magnetic field, and will participate in the final decision on the installation of the coil. In a context of investigating the demonstrator and final detector capabilities, different internal source contamination levels are explored. The topology of interest is the two electrons topology, and we use the $2e$ energy sum to discriminate the signal from the background events. Thanks to SuperNEMO tracking capabilities, topological informations are exploited to improve the SuperNEMO sensitivity.

6.1 Signal and background simulations

A full simulation for the SuperNEMO demonstrator was perfomed, in order to determine the longest $0\nu\beta\beta$ half-life that can be probed with SuperNEMO using the distribution of the sum of electron energies, in the case where the $0\nu\beta\beta$ decay were not observed. In the Tab. 6.1 is summarised the expected number of signal and background events, both for the SuperNEMO demonstrator and final detector, and we present the size of Monte-Carlo simulations for each isotope.

The $0\nu\beta\beta$ signal

In the following, the assumed underlying mechanism for the $0\nu\beta\beta$ decay is the mass mechanism (MM), as it is the most natural and widespread mechanism. The hypotetical $0\nu\beta\beta$ signal would be detected as an excess of events in the region of interest, with respect to the predicted background contamination level. The

	Expected decays		Simulated decays
	Demonstrator	Final detector	
$0\nu\beta\beta$ ($T^{0\nu}_{1/2} = 2.5\,10^{23}$ y)	$3.6\,10^{2}$	$1.0\,10^{4}$	$1.0\,10^{7}$
$2\nu\beta\beta$	$9.5\,10^{5}$	$2.7\,10^{7}$	$1.0\,10^{7}$
^{208}Tl	$5.5\,10^{3}$	$1.6\,10^{5}$	$1.0\,10^{7}$
^{214}Bi	$1.1\,10^{3}$	$3.1\,10^{4}$	$1.0\,10^{7}$
^{222}Rn	$1.8\,10^{5}$	$7.2\,10^{6}$	$1.0\,10^{7}$

Table 6.1: Expected and simulated decays for different processes, both for the demonstrator (17.5 kg.y) and for the final detector (500 kg.y), assuming target background ativities are reached.

10^7 $0\nu\beta\beta$ Monte-Carlo events are generated using the DECAY0 software [9]. The simulations are normalised assuming a $T^{0\nu}_{1/2} = 6.0\,10^{24}$ y half-life [citation].

Inside detector backgrounds

In the region where a signal of neutrinoless $\beta\beta$ decay is expected, the allowed $2\nu\beta\beta$ decay stands as the dominant internal background type. Its contribution depends on the $2\nu\beta\beta$ half-life and the energy resolution of the detector. The total energy brought by the two electrons is a continuum presenting a reduced number of events in the region of interest, due to electron energy losses before reaching the calorimeter (mainly inside the dense source material, as well as inside the wire chamber). To adress this, we simulated 10^7 $2\nu\beta\beta$ events with a total energy > 2 MeV, in addition of the normal $2\nu\beta\beta$ decays, and we normalised the total $2\nu\beta\beta$ spectrum.

Trace quantities of naturally-occurring radioactive isotopes can occasionally produce two-electron events and thus can mimic $\beta\beta$-decay events. The largest contributions come from isotopes of decay chains of ^{238}U, ^{232}Th and ^{40}K, which disintegration occur inside the source foils, as well as inside the tracking volume. As described in Sec. 3.2.1, source foil contaminations by isotopes such as ^{208}Tl or ^{214}Bi constitute the principal internal backgrounds with the $2\nu\beta\beta$ decay. These backgrounds are processed by the same detector simulation as the $0\nu\beta\beta$ signal, using DECAY0. Since internal backgrounds have very low efficiencies in the $2e$ topology, we simulated an important amount of Monte-Carlo events.

A component of the external background producing events similar to the internal background is caused by the presence of ^{222}Rn inside the tracking detector volume, and constitute a separate background category. If such an decay occurs on or near a foil and appears with a $2e$ topology, it becomes hard to distinguish from a double beta decay candidate. This isotope being distributed throughout the whole tracking detection volume, it was therefore necessary to simulate a large quantity of this isotope in the detector to maximise the amount of ^{222}Rn events in the region of interest.

The target background activities detailed in Sec. 3.2 were defined so that each background has a similar contribution to that of the $2\nu\beta\beta$ in the region of interest [10]. We remind these nominal activities in Tab. 6.2, and give a comparison with the measured activities of the demonstrator source foils contaminations, as well as a calculated limit for the ^{222}Rn activity inside the tracker volume.

	Nominal activities	Real activities
^{208}Tl	$10\,\mu$Bq.kg^{-1}	$54\,\mu$Bq.kg^{-1}
^{214}Bi	$2\,\mu$Bq.kg^{-1}	$< 290\,\mu$Bq.kg^{-1}
^{222}Rn	0.15 mBq.m^{-3}	0.15 ± 0.02 mBq.m^{-3} [11]

Table 6.2: Real and targeted nominal activities for the SuperNEMO detector.

Outside detector backgrounds

This background category is due to the external γ-ray flux produced by radioactive isotope decays in detector components or surrounding laboratory rocks, as well as neutron interactions in the shield and of the detector's material. The limit on external background number of counts set by the NEMO-3 experiment was < 0.2 in the $2e$ total energy range $[2.8 - 3.2]$ MeV, for an exposure of 34.3 kg·y [12]. Thus, we consider all external backgrounds from outside the foil, apart from ^{222}Rn in the tracking volume, are expected to be negligible and were not simulated.

We select only events matching the $2e$ toplogy. As a reminder, a reconstructed particle is tagged as an electron if it has a negatively curved track with a vertex on the source foils and an associated calorimeter hit. In the following we present an optimisation of the event selection and of the region of interest.

- Justifier bdf externe avec article nemo3 (plus diff roi et meilleure eff)
- Demie vie 2nu à jusifier
- The dominant two neutrino $2\nu\beta\beta$ background and the background due to foil contaminations were normalised assuming a demonstrator exposure of 17.5 kg.y.

6.2 Optimisation of event selection

Most of the double beta exteriments are only sensitive to the total electron energy sum. Such a variable is presented in Fig. 6.1 in logarithmic scale, for each simulated process detailed in Sec. 6.1. These energy spectra are not normalised, therefore the total number of events for each decay represent the amount of selected $2e$ topologies. The $0\nu\beta\beta$ spectrum is peaked around 2.8 MeV, the $Q_{\beta\beta} = 2.99$ MeV energy being degraded by electron energy losses, explaining the asymetric energy distribution.

Tab. 6.3 sums up the expected number of counts in the full energy range as well as in the region of interest.

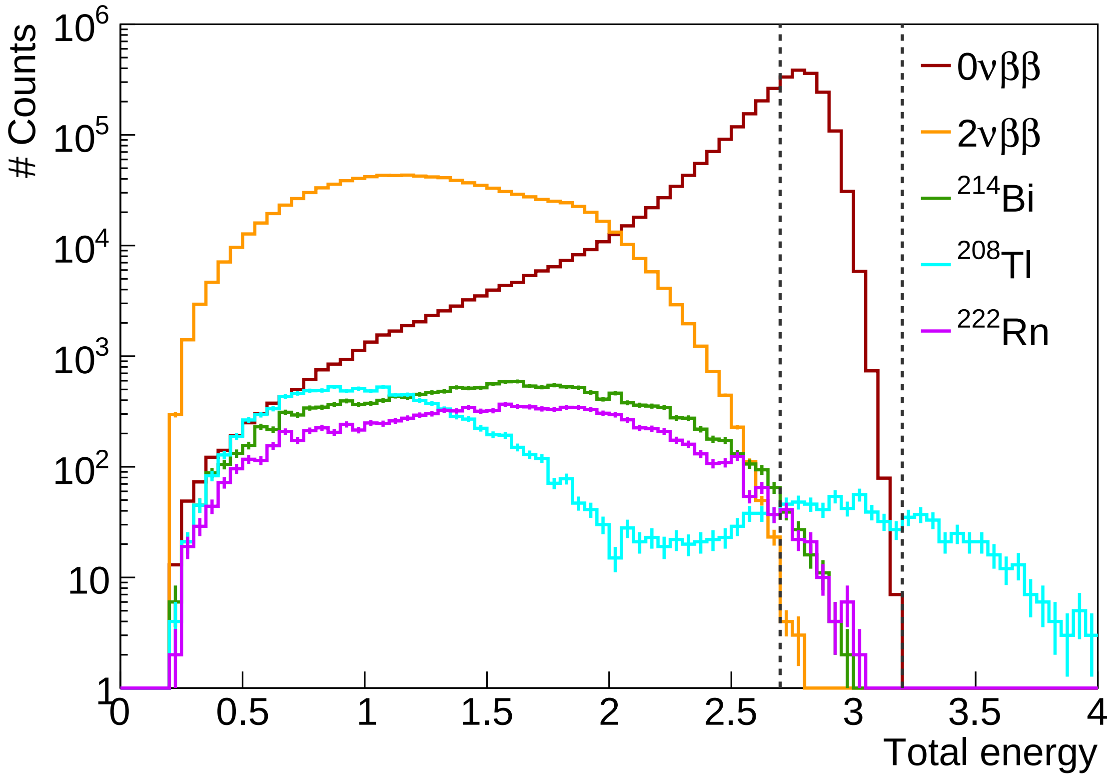

Figure 6.1: Energy spectra for the $0\nu\beta\beta$ signal and for the main backgrounds. The region of interest is matarialised by two dashed vertical lines. ^{208}Tl events dominate in the ROI.

	Full energy range	[2.75;2.85] MeV
$0\nu\beta\beta$	$2.7\,10^6$	$9.5\,10^{-2}$
$2\nu\beta\beta$	$9.1\,10^5$	$1.1\,10^{-1}$
^{208}Tl	$1.7\,10^4$	9.9^{-3}
^{214}Bi	$1.1\,10^4$	$2.7\,10^{-2}$
^{222}Rn	$1.1\,10^4$	

Table 6.3: Real and targeted nominal activities for the SuperNEMO detector.

- plot S/sqrt(B) en fonction E¿Emin
- Quel est le signal qu'on cherche
- présentation des cuts
- efficacité des cuts/ signal + bkg
- cuts premier et second ordre

6.3 Expected number of background events

- plot energy tot
- plus dans région intéret

6.4 Demonstrator sensitivity

- Résultats $B = 0$, avec activités nominales, puis avec activités caca
- Efficiency spretra
- Energy spectra
- Influence des quantités de contaminations sur la sensibilité

6.4.1 avec B

Parler du champ non uniforme/attenuation ROI optimization: avec variation coupure énergie

6.4.2 sans B

avec variation coupure énergie

6.4.3 Champ mappé

6.5 HyperNEMO

results for 500kg.y exposure

6.6 Other isotopes

distribution t1/2 avec différents échantillons de simus (17.5 kg.y)

6.7 Conclusion

- Etude plus générale avec bkg externe+lab (reprendre chiffres NEMO3) + neutrons (cf NEMO3)
- Plot général récap tous résultats

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