PROCEEDINGS OF SCIENCE

Methodology for sterile neutrino searches in CUPID-0

Sylvie Pietrarota[a,b,*] **on behalf of the CUPID-0 collaboration**

[a] *Dipartimento di Fisica, Sapienza Università di Roma, P.le Aldo Moro 2, 00185, Roma, Italy*
[b] *INFN, Sezione di Roma, P.le Aldo Moro 2, 00185, Roma, Italy*

E-mail: sylvie.pietrarota@roma1.infn.it

Searches for sterile neutrinos in nuclear processes rely on the identification of subtle deviations from Standard Model expectations in precisely measured energy spectra. In this contribution, we present the analysis methodology adopted by the CUPID-0 experiment to investigate sterile neutrino emission in double beta decay. We discuss the characterization of the expected spectral shapes, the construction of a model including the signal hypothesis, and the Bayesian statistical framework used to extract constraints on the active-sterile mixing angle $\sin^2\theta$. Particular emphasis is given to the treatment of spectral correlations and systematic effects, which play a key role in spectral-shape studies.

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[*] Speaker

1. Introduction

Since the observation of neutrino oscillations, which demonstrated that they are massive, several fundamental questions in neutrino physics remain unresolved. Among these are the origin of neutrino masses and the mechanism responsible for their smallness. In addition, a number of oscillation experiments have reported anomalies that cannot be fully accommodated within the three-flavor mixing framework, suggesting the presence of additional neutrino states [1–3]. These open problems can be addressed by introducing massive neutrinos that do not interact with any of the Standard Model (SM) gauge bosons, therefore commonly referred to as *sterile* neutrinos [4]. In fact, such states would play a central role in the generation of neutrino masses through the so-called see-saw mechanism [5] and could also mix with the SM *active* flavors. Moreover, the absence of SM gauge interactions and their free mass scale make them compelling candidates for dark matter [6].

As sterile neutrinos would not be directly detectable, their presence could be probed through deviations from SM expectations in mixing parameters and in weak processes involving active neutrinos. One such process is double beta decay ($2\nu\beta\beta$), one of the rarest nuclear decays observed in nature, in which two electrons and two electron anti-neutrinos are emitted. Then, if the electron anti-neutrino has an admixture of a sterile mass eigenstate N, the decay can produce N in the final state, modifying the phase space in a way that depends on the sterile neutrino mass. This exotic channel, denoted as N$\nu\beta\beta$, would occur with probability ruled by the active-sterile mixing angle [7], a free parameter of the theory.

Double beta decays are measured with high precision in experiments dedicated to the search for the neutrinoless double beta decay ($0\nu\beta\beta$), a hypothetical process that, if observed, would establish the Majorana nature of neutrinos [8]. In this context, CUPID-0 [9, 10] was primarily conceived as a demonstrator to CUPID, the next-generation experiment aimed at searching for $0\nu\beta\beta$ with unprecedented sensitivity [11]. However, the excellent data reconstruction and the α/β particle discrimination capability achieved in CUPID-0 also open the possibility to explore physics beyond the SM. In this contribution, we discuss the analysis strategy adopted to search for sterile neutrino signatures in double beta decay of ^{82}Se with the CUPID-0 data, with particular emphasis on the statistical methods and on spectral correlations.

2. Sterile neutrino signature in the CUPID-0 detector

The CUPID-0 detector, which collected data from June 2017 to February 2020 at the Laboratori Nazionali del Gran Sasso, consisted of an array of scintillating ZnSe crystals enriched in the $2\nu\beta\beta$-decaying isotope ^{82}Se. The absorbers were operated as cryogenic calorimeters, measuring the temperature rise consequent to an energy deposit. CUPID-0 proved for the first time the possibility to simultaneously detect the scintillation light emitted, with dedicated cryogenic light detectors. This double read-out mechanism enables an efficient discrimination between α and β/γ events, which is crucial for rejecting the dominant background for the $0\nu\beta\beta$ search due to surface contamination.

The existence of sterile neutrinos N coupling to the SM neutrinos can lead to an alternative double beta decay final state, involving the emission of a sterile particle. In the case of ^{82}Se investigated by CUPID-0, the process is: $^{82}\text{Se} \rightarrow ^{82}\text{Kr} + 2e^- + \bar{\nu}_e + N$.

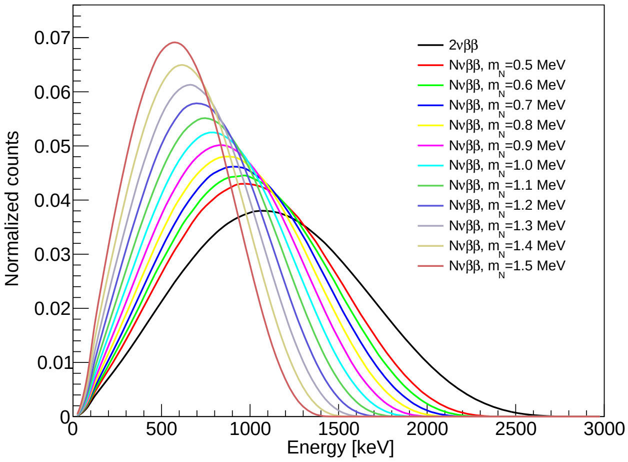

Figure 1: Summed-electron energy spectra from the Monte Carlo simulations of the $2\nu\beta\beta$ and of the N$\nu\beta\beta$ decays of ^{82}Se in the CUPID-0 detector, for sterile neutrino masses in the (0.5–1.5) MeV range. All spectra are normalized to unity.

If the decay channel is kinematically allowed, i.e. if the sterile neutrino mass is smaller than the reaction Q-value $Q_{\beta\beta} \simeq 3$ MeV, the total double β decay rate can be written as the incoherent sum of the purely SM and beyond SM decay rates [12]:

$$\Gamma_{\beta\beta} \simeq \cos^4\theta\,\Gamma_{2\nu\beta\beta} + 2\cos^2\theta\,\sin^2\theta\,\Gamma_{N\nu\beta\beta} \tag{1}$$

where the emission probability of two sterile states is assumed negligible and $\sin^2\theta$ represents the mixing probability between electronic and sterile neutrinos. This is the parameter of interest in the search for the exotic decay mode and it is related to the N$\nu\beta\beta$ and $2\nu\beta\beta$ decay rates via the relation:

$$\sin^2\theta = \frac{G_{2\nu\beta\beta}}{2\,G_{N\nu\beta\beta}(m_N)} \cdot \frac{\Gamma_{N\nu\beta\beta}}{\Gamma_{2\nu\beta\beta}} \tag{2}$$

where G represents the phase-space factors of each process. The presence of a massive fermion in the final state changes the endpoint of the summed-electron energy distribution, which is shifted at $Q_{\beta\beta} - m_N$, leading to a shift of the peak, as illustrated in Fig. 1 for $m_N \in [0.5, 1.5]$ MeV.

This mass window, optimized for studying spectral distortions with respect to the $2\nu\beta\beta$ of ^{82}Se, is complementary to regions probed by other sterile neutrino searches. Oscillation experiments, such as MicroBooNE [13] and PROSPECT [14], probe mass-squared differences at the eV level and are sensitive to light sterile neutrinos. Kinematic searches exploiting single β decay endpoints, such as KATRIN [15], extend the sensitivity to the keV region. By contrast, the sub-MeV to MeV range has been comparatively less constrained by direct laboratory searches based on spectral distortions, although bounds exist from beta decay studies and solar neutrino experiments [16]. Double beta decay experiments offer a complementary approach in this mass regime, as CUPID-Mo [17] and GERDA [18] already demonstrated using ^{100}Mo and ^{76}Ge, respectively. The present study extends this program to an exposure of 5.58 kg·year of ^{82}Se, further strengthening the complementarity of nuclear decay probes.

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3. Analysis method

A prerequisite for the search for rare processes is an accurate modeling of the experimental background. Indeed, small deviations can be disentangled from the data only if the SM spectrum with all relevant background contributions is precisely understood. The fundamental idea of the analysis is to model the observed energy spectrum as a linear combination of simulated spectra of background and signal components. The coefficients of the sum represent the scaling parameters quantifying how much each spectrum contributes to the data. Therefore, the number of events associated with each source can be inferred from the known total number of simulated events, once the scaling parameters have been determined. In this search we are interested in the ratio of number of events (or decay rates) between the N$\nu\beta\beta$ and $2\nu\beta\beta$ processes in order to obtain $\sin^2\theta$ (see Eq. (2)). The extraction of the scaling parameters can be performed via a multivariate Bayesian fit. In particular, in CUPID-0 we can exploit multiple spectral categories δ corresponding to different particles and event topologies, to improve the separation among signal and background components. Moreover the detector response is propagated to the Monte Carlo templates via the ARES software, which models energy calibration and resolution effects, so that the simulated events resemble real data acquired with the detector.

The Bayesian framework requires as a first step the construction of a likelihood function. Given $C^{\text{exp}}_{i,\delta}$ the observed number of counts in the i-th bin of the experimental spectrum δ, the likelihood function is the product of Poisson probability over bins and spectral classes:

$$\mathcal{L}(\text{data}|\vec{a}) = \prod_{i,\delta} \frac{e^{-\mu_{i,\delta}}\mu_{i,\delta}^{C^{\text{exp}}_{i,\delta}}}{C^{\text{exp}}_{i,\delta}!} \tag{3}$$

Here, $\mu_{i,\delta}$ represents the expectation value of the counts in bin i of spectrum δ, $\mu_{i,\delta} = \sum_j a_j\, C^{\text{MC}}_{ij,\delta}$, where $C^{\text{MC}}_{ij,\delta}$ denotes the number of counts in the i-th bin of spectrum of type δ for the simulation of the j-th component of the model, and a_j is the j-th scaling parameter. The posterior probability distributions of the coefficients a_j is then reconstructed by combining the likelihood with the priors $\pi(a_j)$ assigned to each source: $P(\vec{a}|\text{data}) \propto \mathcal{L}(\text{data}|\vec{a}) \prod_j \pi(a_j)$. This method allows the derivation of the marginal posterior distributions of the individual a_j and, most importantly, to convert them in a posterior distribution for the parameter of interest $\sin^2\theta$. In addition, we can derive correlations among pairs of parameters, discussed in Section 4.

The systematic uncertainties can be accounted for by repeating the Bayesian fit varying some choices in the data modeling. These can for instance concern the adopted binning, the energy calibration or the list of background sources to take into account. Suppose we are interested in s systematic tests, describing different ways to model the observed spectrum, which we refer to as model M_s; in each case a different posterior distribution $P(\sin^2\theta|M_s, \text{data})$ is obtained, thus we can combine them according to the law of total probability:

$$P(\sin^2\theta|\text{data}) = \sum_s P(\sin^2\theta|M_s, \text{data})P(M_s|\text{data}) \tag{4}$$

i.e. they are weighted with the posterior probability density of the corresponding model, given by:

$$P(M_s|\text{data}) \propto \pi(M_s)P(\text{data}|M_s) = \pi(M_s)\int \mathcal{L}(\text{data}|\vec{a}, M_s)\prod_j \pi(a_j)\text{d}a_j \tag{5}$$

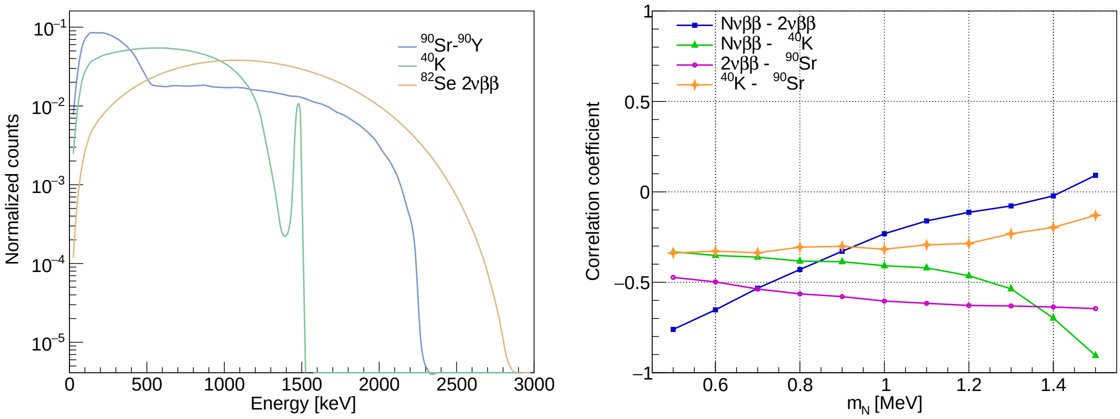

Figure 2: *Left*: Simulated spectra of β/γ events for selected background components exhibiting correlations with the $2\nu\beta\beta$ and with the N$\nu\beta\beta$ (see Fig. 1). *Right*: Correlation coefficients $\rho_{ij} = \frac{\text{cov}_{ij}}{\sigma_i \sigma_j}$ between the N$\nu\beta\beta$ and $2\nu\beta\beta$ and the considered backgrounds, evaluated from the posterior covariance matrix of the Bayesian fit for sterile neutrino masses between 0.5 and 1.5 MeV.

Here $\mathcal{L}(\text{data}|\vec{a}, M_s)$ represents the likelihood function for the model M_s and $\pi(M_s)$ its prior, and the index j runs over the spectral components included in the specific model.

4. Spectral correlations

An important aspect of this analysis is the presence of correlations among spectral components, arising from similarities in their energy distributions. The most relevant sources of correlation affecting the sterile neutrino search are shown in Fig. 2, where their energy spectra are displayed together with the correlation coefficients as a function of the sterile neutrino mass in the (0.5–1.5) MeV range.

As can be inferred from Eq. (1), the presence of the N$\nu\beta\beta$ decay implies a decrease of the $2\nu\beta\beta$ by a factor $\cos^4\theta$. Therefore we expect an intrinsic anti-correlation between the two competing processes. As the sterile neutrino mass increases, the N$\nu\beta\beta$ spectral shape progressively departs from the $2\nu\beta\beta$ case, reducing the degeneracy between the two spectra and causing the correlation coefficient to approach zero.

^{90}Sr is a product of nuclear fission and decays into ^{90}Y, which in turn undergoes beta decay. The resulting spectrum is a featureless beta spectrum that resembles the shape of the $2\nu\beta\beta$ one, explaining the anti-correlation displayed in Fig. 2. A similar effect is observed for the ^{40}K background: the decay of ^{40}K [19] produces a continuous electron energy spectrum extending up to ~1.5 MeV, whose overlap with the N$\nu\beta\beta$ increases with the sterile neutrino mass hypothesis.

5. Summary

We presented the analysis strategy adopted by the CUPID-0 experiment to search for sterile neutrino emission in double beta decay of ^{82}Se. The methodology relies on a detailed modeling of the observed energy spectrum as background and signal components; a multivariate Bayesian fit then allows the extraction of the posterior probability distribution of the active-sterile mixing angle. Particular attention was devoted to to the treatment of systematic effects through model averaging and to the study of correlations among the N$\nu\beta\beta$ and background contributions entering the fit, representing one of the dominant limitations in distinguishing the signal from SM processes.

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