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Abstract. In the past few years, attention has been drawn to the fact that a precision analysis of two-neutrino double beta decay ($2\nu\beta\beta$) allows the study of interesting physics cases like the emission of Majoron bosons and possible Lorentz symmetry violation. These processes modify the summed-energy distribution of the two electrons emitted in $2\nu\beta\beta$. CUPID is a next-generation experiment aiming to exploit ^{100}Mo-enriched scintillating Li_2MoO_4 crystals, operating as cryogenic calorimeters. Given the relatively fast half-life of ^{100}Mo $2\nu\beta\beta$ and the large exposure that can be reached by CUPID, we expect to measure with very high precision the ^{100}Mo $2\nu\beta\beta$ spectrum shape, reaching great sensitivities in the search for distortions induced by the physics beyond the Standard Model. In this contribution, we present the CUPID exclusion sensitivity for such New Physics processes, as well as the preliminary projected background of CUPID.

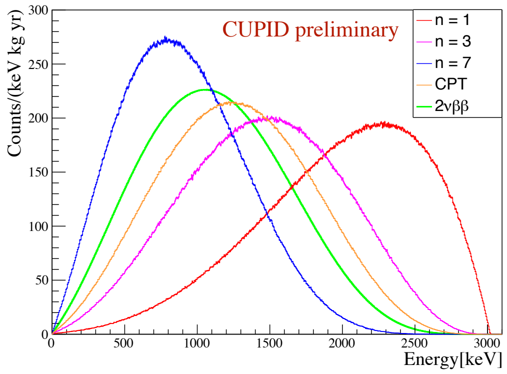

Figure 1: Standard $2\nu\beta\beta$ decay compared to bSM spectra.

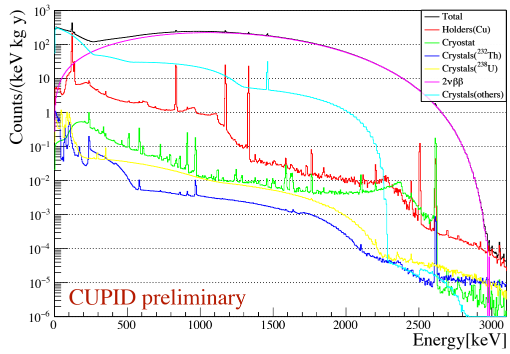

Figure 2: CUPID projection of the β/γ spectrum.

1. Introduction

Although the discovery of neutrinoless double beta decay ($0\nu\beta\beta$) is the primary target of CUPID [1], other interesting physics cases can be investigated, in particular those beyond the Standard Model (bSM) processes that can induce a deviation of the $2\nu\beta\beta$ spectral shape. Indeed, the phase space factor G depends on the spectral index n through the relation $G \sim (Q_{\beta\beta} - T)^n$ where $Q_{\beta\beta}$ is the Q-value of the decay and T is the summed kinetic energies of the two emitted electrons. For *standard* 2νDBD $n = 5$, while for bSM processes the spectral index assumes different values inducing a shift of the maximum of the spectrum as shown in Fig. 1. An accurate background projection of CUPID is crucial to perform the sensitivity studies on the $2\nu\beta\beta$ spectral shape. In Sec 2 the preliminary CUPID Background Budget is shown in details, while in Sec 3 we explain the analysis method used to evaluate the CUPID exclusion sensitivity for the CPT violating $2\nu\beta\beta$ and for several Majoron emitting decays.

2. The CUPID Background Budget

The Background Budget (BB) is composed by a series of Monte Carlo simulations aiming to predict the CUPID background spectrum. We simulate radioactive contaminations using a Geant4 [2] based software. Our knowledge about radioactive contaminants in CUPID comes mainly from material assays, previous bolometric experiments and cosmogenic activation calculations. Since CUPID will be hosted in the same cryogenic infrastructure of CUORE, the CUORE background budget [3] provides a clear picture of contaminations in the detector holders and the cryostat, while the CUPID-Mo data describe the impurities of Li_2MoO_4 crystals [4]. Combining these models, we have the possibility to assess almost all the background sources, having a reliable estimate of the CUPID background in a wide energy region. Besides, we introduced in the BB also contaminations due to cosmogenic activation in the Li_2MoO_4 crystals and copper holders that were calculated with the ACTIVIA code [5]. The simulations are then processed with a custom software to implement experimental features on simulated data, like the energy and the time resolution, the coincidence window and the particle identification. The projection of the CUPID β/γ spectrum is shown in Fig. 2.

3. Exclusion sensitivity results

Using the same software tools, we simulate the energy spectrum of bSM processes starting from the exact phase space calculation for $2\nu\beta\beta$ [6], obtaining the results reported in Fig. 1. To evaluate the CUPID sensitivity for a given bSM process after 1 yr of data-taking, we simulate the corresponding statistics according to the BB. Performing a combined Bayesian fit on CUPID-like

Table 1: List of decays with one (χ^0) and two ($\chi^0\chi^0$) Majoron emission.

n	mode	exclusion sensitivity on $T_{1/2}$ [yr]	current limit [yr] (NEMO-3)
1	χ^0	7.4×10^{23}	4.4×10^{22} [8]
3	χ^0	2.4×10^{21}	4.4×10^{21} [9]
3	$\chi^0\chi^0$	2.4×10^{21}	4.4×10^{21} [9]
7	$\chi^0\chi^0$	7.3×10^{21}	1.2×10^{21} [9]

data including the New Physics hypotheses, we set limits on the half-life of bSM processes. The fitting procedure is accurately described in Ref. [7]. One of the critical points in this fit is represented by the pure β-decaying isotopes which can correlate with $2\nu\beta\beta$ and bSM spectra in the fit. ^{90}Sr is an anthropogenic radioactive isotope that decays with a half-life of 28.8 yr in $^{90}\mathrm{Sr} \rightarrow {}^{90}\mathrm{Y} \rightarrow {}^{90}\mathrm{Zr}$ emitting two subsequently β-decays with Q-values, respectively, of 546 keV and 2.3 MeV. The preliminary CUPID-Mo background model assessed that the ^{90}Sr activity in Li_2MoO_4 crystals is $\sim 10^{-4}$ Bq/kg, but the presence of ^{90}Sr in the actual CUPID crystals is not certain. To estimate the effect of the pure β-decays on the sensitivity, the analysis was repeated in two cases: the ^{90}Sr is included in the simulated spectrum but not considered in the fit (underestimation) and, on the contrary, the ^{90}Sr is considered in the fit but not included in the simulated spectrum (overestimation).

Several grand unification theories predict that one or two Majorons could be emitted in the $0\nu\beta\beta$ [10] producing a continuum spectrum similar to $2\nu\beta\beta$ but with different spectral indexes. The preliminary exclusion sensitivities are shown in Tab. 1. We report the less stringent exclusion sensitivity obtained for each process in the ^{90}Sr overestimated and underestimated fits.

The Standard Model Extension (SME) provides a general framework for Lorentz Invariance Violation (LIV) [11]. The parameter $\mathring{\mathbf{a}}^{(3)}_{\mathrm{of}}$ is related to the time-like component of the LIV operator in the neutrino sector. The preliminary predicted exclusion limit of the Lorentz-violating term is $\mathring{\mathbf{a}}^{(3)}_{\mathrm{of}} \lesssim 10^{-8}$ GeV at 90% C.I., while the current limit was set by NEMO-3 $\mathring{\mathbf{a}}^{(3)}_{\mathrm{of}} < 3.5 \times 10^{-7}$ GeV at 90% CL. [9].

References

[1] Armstrong W R *et al.* (CUPID) 2019 (*Preprint* 1907.09376)

[2] Agostinelli S *et al.* (GEANT4) 2003 *Nucl. Instrum. Meth. A* **506** 250–303

[3] Alduino C *et al.* (CUORE) 2017 *Eur. Phys. J. C* **77** 543 (*Preprint* 1704.08970)

[4] Armengaud E *et al.* 2020 *Eur. Phys. J. C* **80** 674 (*Preprint* 1912.07272)

[5] Back J J and Ramachers Y A 2008 *Nucl. Instrum. Meth. A* **586** 286–294 (*Preprint* 0709.3472)

[6] Kotila J and Iachello F 2012 *Phys. Rev. C* **85** 034316 (*Preprint* 1209.5722)

[7] Alduino C *et al.* (CUORE) 2017 *Eur. Phys. J. C* **77** 13 (*Preprint* 1609.01666)

[8] Arnold R *et al.* (NEMO-3) 2015 *Phys. Rev. D* **92** 072011 (*Preprint* 1506.05825)

[9] Arnold R *et al.* (NEMO-3) 2019 *Eur. Phys. J. C* **79** 440 (*Preprint* 1903.08084)

[10] Georgi H M, Glashow S L and Nussinov S 1981 *Nucl. Phys. B* **193** 297–316

[11] Kostelecky V A and Samuel S 1989 *Phys. Rev. D* **39** 683