

Search for light fermionic Dark Matter with Double Beta decay experiments

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This work focuses on the investigation of double beta decay unstable nuclei, with the aim of exploring a new approach for the direct detection of Dark Matter (DM). Specifically, the study considers the diagram associated with neutrinoless double beta decay as a potential technique for detecting a Majorana DM fermion. This detection method involves the inelastic scattering of the DM fermion on a double beta unstable nucleus, thereby inducing its decay. By exploiting the exothermic nature of the stimulated double beta decay, it becomes possible to directly detect a light DM fermion. This is particularly significant as traditional elastic scattering technique is not able to investigate light fermion DM candidates. The paper presents the expected signal distribution for various DM masses and compares them with the current data available for the ^{136}Xe nucleus, establishing upper limits on the cross sections of nucleus scattering.

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1. Introduction

Neutrinoless double beta decay plays a significant role in the exploration of Physics beyond the Standard Model. This process investigates the detected energy distribution in the decay to potentially identify the Majorana nature of neutrinos and the violation of Leptonic quantum numbers [1, 2]. The Seesaw models offer a compelling mechanism for naturally generating the small neutrino mass (see e.g. [3]). Furthermore, these models can address important issues such as the baryon asymmetry in the Universe [4] and various Dark Matter (DM) candidates [5–7].

A minimal approach requires the inclusion of a right-handed neutrino field N_R and a Majoron scalar field ϕ , to the Standard Model (SM) Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{N}_R\gamma^\mu\partial_\mu N_R + (\partial_\mu\phi)^\dagger(\partial^\mu\phi) - V(\phi) - y_j\bar{l}_L^j H N_R - \frac{\lambda}{2}\bar{N}_R^c\phi N_R + h.c. \quad (1)$$

where $l_L^j = \begin{pmatrix} \nu_j \\ l_j^- \end{pmatrix}$ are the SM lepton doublets ($j = e, \mu, \tau$) and H is the SM Higgs doublet. After spontaneous symmetry breaking of H and, possibly, of the ϕ scalar, the last two terms are providing a Dirac mass and a Majorana mass term, respectively. In the Seesaw mechanism, a very large value of the Majorana mass scale would naturally generate active neutrinos whose masses are much lighter than the (Dirac-) mass scale of the charged fermions. Such a Lagrangian also provides two types of DM candidate: the Majoron that is a scalar particle [8] and the sterile neutrino, the heavy mass eigenstate whose composition is dominated by the Majorana fermion N_R . Focusing on the Majorana fermion DM candidates (in the following: χ) the expected interactions (and self-interactions) are mediated by the Majoron, thus the direct detection of such a DM particle scattering on charged fermions could be very suppressed. On the other hand, the same diagram responsible for the possible neutrinoless double beta decay can be considered also for a possible detection technique of a Majorana fermion DM inelastically scattering on a double beta unstable nucleus, stimulating its decay, as shown in fig. 1.

In particular the exothermic nature of the stimulated double beta decay would allow the direct detection also of a light DM fermion, a class of DM candidates that are difficult/impossible to investigate with current experiments based on the traditional elastic scattering techniques¹.

It is important to note that the diagram shown in fig.1 is just one of the possible mechanisms for the DM particle to trigger a neutrinoless double beta decay of the nucleus. In this work we avoid focusing in the details of a specific interaction model, since beyond the sterile neutrino also other popular DM candidates are expected to be Majorana fermions (like, e.g. , the supersymmetric Neutralino, Axino or Gravitino) thus they could interact the nucleus with similar phenomenology but different diagrams. Therefore we will focus on the expected signature for this novel detection technique and we will study the implication of current experimental results of neutrinoless double beta decay experiments.

¹Another detection possibility relies in the absorption of a light fermionic DM emitting a neutrino or inducing the beta decay of the nucleus [9–12].

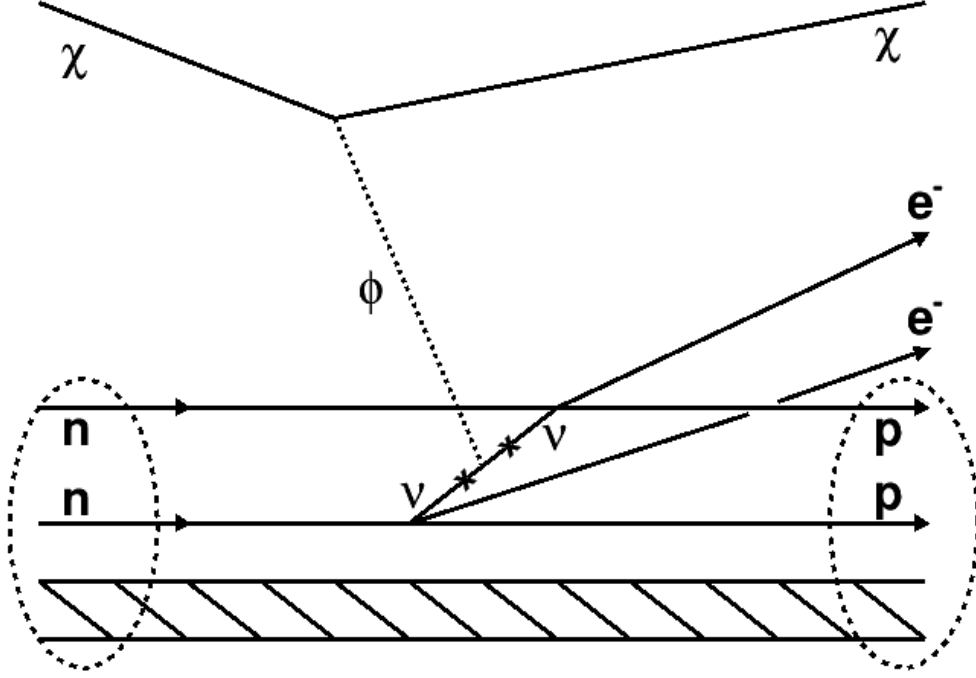


Figure 1: Example of a possible detection diagram for the Majorana DM fermion, χ . The exchange of one or more Majoron fields ϕ could stimulate a neutrinoless double beta decay of the nucleus (A,Z) to the daughter nucleus $(A,Z+2)$. The kinetic energy of the two electrons is detected. A fraction of the decay Q-value is lost due to the upscattering χ particle, this would allow a possible measurement of the mass of χ particle from the energy distribution of the electrons.

2. Expected energy distribution

The available energy of a stimulated neutrinoless double beta decay of the nucleus (A,Z) to the daughter nucleus $(A,Z+2)$ is provided by the reaction Q-value and by χ kinetic energy. Due to the non relativistic nature of galactic DM particles, for simplicity we follow the approximation where the nucleus recoil contributes to momentum conservation but provides a negligible contribution to the detected energy. Considering the MeV scale of Q-values for the typical nuclei adopted in double beta decay searches, these approximations holds with a reasonable accuracy both for light and heavy χ candidates. Thus, the expected energy distribution can be evaluated following the Fermi's Golden Rule:

$$d\Gamma = \frac{|T_{fi}|^2}{4\pi^2\hbar} \frac{d^3P_1}{(2\pi)^3} \frac{d^3P_2}{(2\pi)^3} \frac{d^3P_\chi}{(2\pi)^3} \delta(E_1 + E_2 + E_\chi - Q - 2m_e - M_\chi) \quad (2)$$

where $E_{(1,2)} = \sqrt{P_{(1,2)}^2 + m_e^2}$ are the total energy of the electrons and $E_\chi = \sqrt{P_\chi^2 + M_\chi^2}$ is the invisible total energy carried away by the DM particle. The model dependent details of the DM particle interactions are encoded in the transition matrix T_{fi} , however, the

overall behavior of the expected distribution of the sum of electron's kinetic energy (that is experimentally detected) is shaped mainly by the phase space density factor (and also by detector effects).

In the following, with the aim to study the phenomenology of this DM detection approach, the approximation of a constant matrix element is applied; the assumption of different interaction models can modify the details of the detected energy distribution while preserving the global mass/energy dependencies.

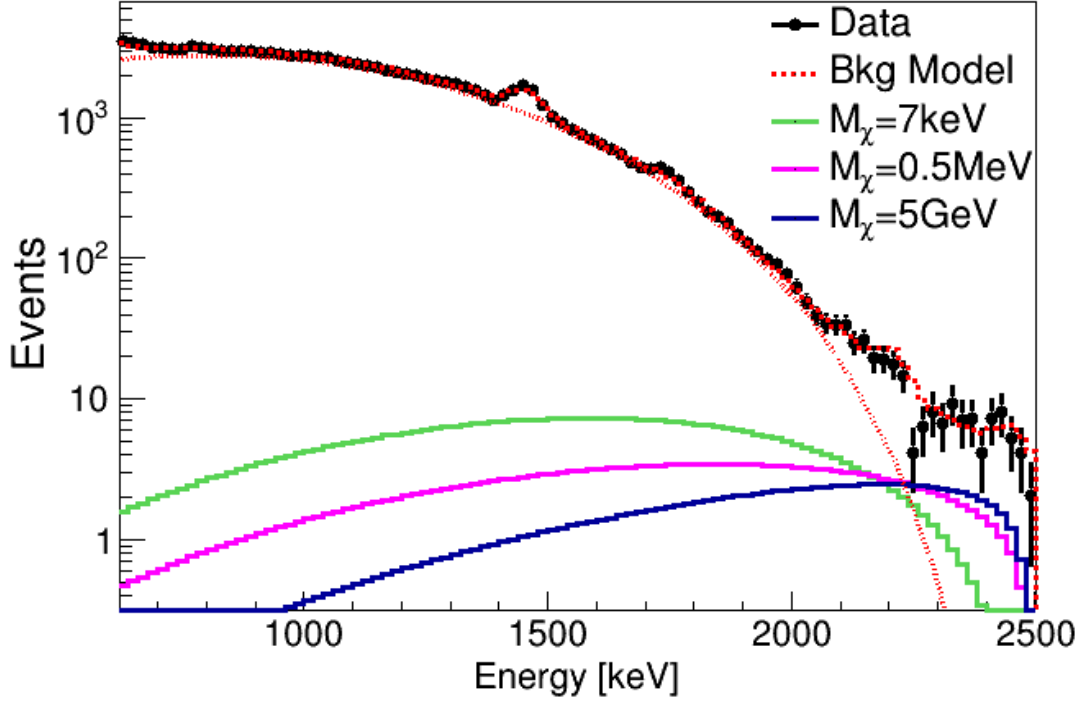


Figure 2: Example of upper limits on Dark Matter signals inferred analysing the 116.7 kg x day exposure collected by EXO-200 Phase-II (points). Maximum signals allowed at 90% C.L. for $M_\chi=7\text{keV}$, 0.5MeV , 5GeV are shown as green, magenta and blue lines, respectively.

In figure 2 the example of expected (sum-) energy distributions for the case of ^{136}Xe target nuclei ($Q=2.48\text{MeV}$) is shown. In particular, the expected energy distributions are dependent on M_χ ; the case of $M_\chi \ll m_e$ (green line) provides a distribution very similar to the one expected for the Majoron emitting neutrinoless double beta, $0\nu\beta\beta M$ ($n=2$) decay [13, 14]. Increasing the value of M_χ an harder electron energy spectrum is expected. In particular, the case of $M_\chi \simeq m_e$ (magenta line) provides a distribution very similar to the one expected for the $0\nu\beta\beta M$ ($n=1$) decay, while the case $M_\chi \gg m_e$ provides a much harder distribution (blue line).

Figure 2 also shows, as a comparison, the energy distribution measured by the EXO-200 experiment (Phase-II 116.7 kg x yr, black points) [14]. The published model of the detector background is also superimposed (red dashed line). The detector background is generally

due to radioactive contaminants of the detector and surrounding materials, however, below the Q-value, it is dominated by the known $2\nu\beta\beta$ decay. It is important to note that the energy distribution of this last process (red dotted line) is very different as compared with the one expected by DM induced events, peaking at much lower energy.

No evidence for the $0\nu\beta\beta M$ decay was found so far in a dedicated study of the EXO-200 data [14], for the same reason, only upper limits to the DM induced neutrinoless double beta decay are shown in fig. 2.

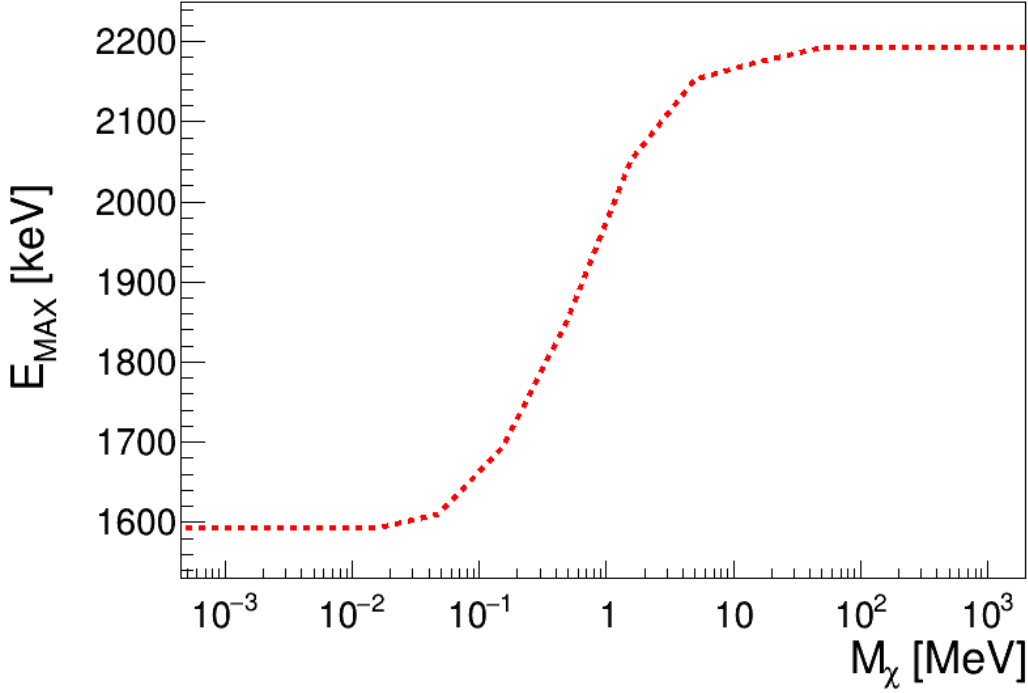


Figure 3: Expected behavior of maximum of the detected energy distribution versus the Dark Matter particle mass inducing a neutrinoless double beta decay in ^{136}Xe .

Finally, the expected behavior of the maximum of the detected energy distribution in ^{136}Xe as a function of M_χ is shown in fig. 3. Thanks to the deformation of the electrons energy distribution caused by the upscattering of χ particle, a direct measurement of the Dark Matter particle mass could be feasible, in principle, for DM masses in the range 100keV-10MeV.

3. Conclusion and Outlooks

The possibility of a DM induced neutrinoless double beta decay is considered in this work, this could allow the investigation of light fermionic DM (like the 7.1 keV sterile neutrino [17]) that is very difficult or impossible to detect with the elastic scattering technique.

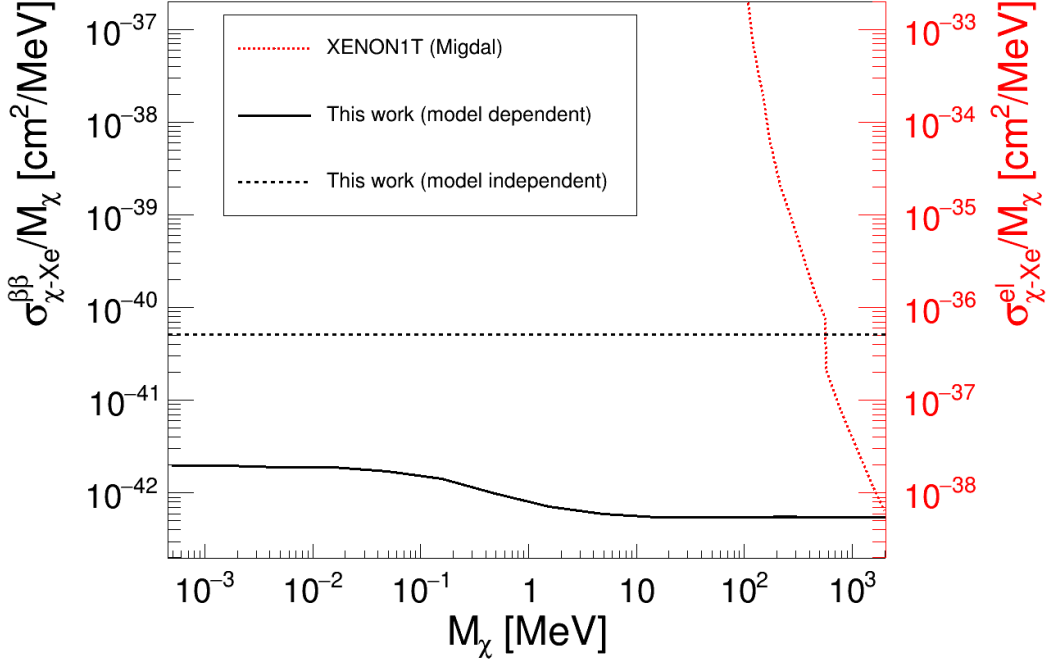


Figure 4: Example of upper limits on the total Dark Matter - Xenon nucleus cross section, $\sigma_{\chi-Xe}^{\beta\beta}$, obtained in this work by considering the 116.7 kg x day exposure collected by EXO-200 Phase-II (black continuous line). A "model independent", very cautious, upper limit is obtained by attributing to a possible DM signal all the EXO-200 events in excess with respect to the known $2\nu\beta\beta$ decay (horizontal dashed black line). Red dotted line shows, as a comparison, the upper limits for the Dark Matter-Xenon nucleus elastic scattering, $\sigma_{\chi-Xe}^{el}$, for the very low mass region accessible by exploiting the atomic shake-off "Migdal effect" [15, 16].

For sub-MeV DM, the expected energy distribution for a DM induced decay, is similar to the expected distribution for $0\nu\beta\beta M$ decay (due to the large variations possible in Majoron and DM models) however some important differences among these rare processes can be noticed. The first difference is based on the phenomenological point of view, in particular the $0\nu\beta\beta M$ decay is allowed only for relatively light Majorons ($M_\phi < Q$ -value) while the DM induced decay could be mediated also by an heavy Majoron. On the other hand, a characteristic of the DM induced double beta decay is the possible annual modulation due to the yearly variation of the DM flux/velocity; this effect, in principle, might be exploited to disentangle the two different rare processes.

Finally, it is interesting to focus in the sensitivity of this approach for the detection of light dark matter assuming a DM density of 0.3 GeV/cm^3 and the DM average velocity in the Solar System frame of 250 km/s .

The direct detection of sub-GeV dark matter in the current underground experiments relies in the so called "Migdal effect", the DM induced atomic shake-off, pointed out by one of us in [15].

In figure 4 the upper limits on the total nuclear scattering cross section ($\chi-^{136}\text{Xe}$)

obtained in this analysis of EXO-200 Phase-II data are compared with the current upper limit on the DM-Xe nucleus scattering obtained by considering the "Migdal effect" in the XENON1T experiment [16]. Despite a deeper comparison requires to detail the χ -nucleus interaction model, the proposed approach could be very effective for the direct detection of light fermionic DM using the existing or future neutrinoless double beta decay experiments.

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