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Proceeding Paper

Dark Matter Investigation Using Double Beta Decay Experiments †

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Abstract: Nuclei that are unstable with respect to double beta decay are potentially interesting for a novel Dark Matter (DM) direct detection approach. In particular, a Majorana DM fermion inelastically scattering on a double beta unstable nucleus could stimulate its decay. Thanks to the exothermic nature of the stimulated double beta decay, this detection approach would allow for also investigating light DM fermions, a class of DM candidates that evade the detection capability of the traditional elastic scattering experiments. The upper limits on the nucleus scattering cross sections and the expected signal distribution for different DM masses are shown and compared with the existing data for the case of the ^{76}Ge nucleus.

Keywords: light Dark Matter; Majorana fermions; double beta decay; seesaw model

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1. Introduction

Neutrinoless double beta decay is an important test for Physics beyond the Standard Model; the investigation of this process allows for studying the possible Majorana nature of the neutrino and the possible violation of the Leptonic quantum number [1,2]. In particular, the Seesaw models provide a mechanism to generate small neutrino masses (see, e.g., [3]); moreover, both the problem of baryogenesis [4] and some Dark Matter (DM) candidates [5–7] can be addressed.

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

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

where $l^j_L = \begin{pmatrix} \nu_j \\ l^-_j \end{pmatrix}$ are the SM lepton doublets ($j = e, \mu, \tau$) and H is the SM Higgs doublet. The last two terms are providing a Dirac mass and a Majorana mass term after the spontaneous symmetry breaking of H and, possibly, of the ϕ scalar, respectively. A very large scale of the Majorana mass would naturally generate active neutrinos whose masses are much lighter than the "Dirac" mass scale. The two main classes of DM candidates can be accommodated in this model: a scalar particle, the Majoron [8,9], and the heavy neutrino mass eigenstate, whose composition is dominated by the Majorana fermion N_R, generally called a "sterile" neutrino. We will focus on the Majorana fermion DM candidates (in the following: χ) whose interactions (and self-interactions) are mediated by the Majoron field; in the minimal model of Equation (1), the direct detection of such a DM particle scattering on the charged fermions should be very suppressed. However, the diagram responsible for a possible neutrinoless double beta decay can also be considered for a possible detection mechanism of a fermionic DM inelastically scattering on the meta-stable nucleus, stimulating the neutrinoless double beta decay, as shown in Figure 1.

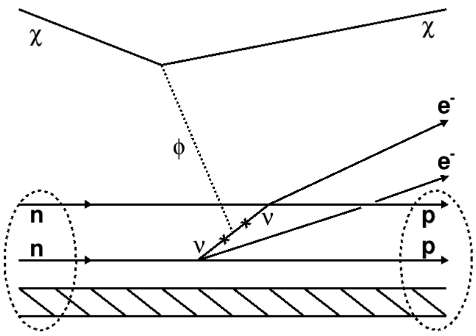

Figure 1. A possible detection diagram for the Majorana DM fermion, χ. The exchange of one or more Majoron fields ϕ could stimulate a neutrinoless double beta decay of the nucleus (A,Z) to the daughter nucleus (A,Z+2). A part of the decay Q-value is lost due to the invisible kinetic energy of the upscattering χ particle. In principle, a measurement of the mass of the χ particle is possible by studying the distribution of the sum of the kinetic energy of the electrons.

In particular, the direct detection of light fermionic DM is very difficult/impossible with the traditional elastic scattering techniques, but, thanks to the exothermic nature of the stimulated decay, a direct detection of a light DM particle is in principle achievable. We note that another detection technique relies in the absorption of a light fermionic DM emitting a neutrino or inducing the beta decay of the nucleus [10–13].

Beyond the case of a sterile neutrino DM, other DM candidates are also expected to be Majorana fermions, such as the supersymmetric Neutralino, Axino, or Gravitino. In this work, we avoid focusing on the details of a specific interaction model, since the diagram shown in Figure 1 is only one example of the possible mechanisms for the DM particle to stimulate a neutrinoless double beta decay; thus, different DM candidates could interact with the nucleus with a similar phenomenology but through different diagrams.

In the following, the expected signature for this novel detection technique will be described and the sensitivity of the current double beta decay experiments to this DM candidate will be investigated.

2. Expected Energy Distribution

When a DM particle, χ, induces a neutrinoless double beta decay of the nucleus (A,Z) to the daughter nucleus (A,Z+2), the available energy in the reaction is the sum of the decay Q-value and the χ particle kinetic energy. However, considering the typical Q-values for the nuclei adopted in the double beta decay searches (MeV scale) and the typical velocity of galactic DM particles, the nucleus recoil energy can be neglected in the detected energy distribution evaluation. In particular, this is a reasonable approximation that is valid for both light and heavy χ candidates. Fermi's Golden Rule can be adopted to evaluate the expected energy distribution:

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

where $E_{(1,2)} = \sqrt{P^2_{(1,2)} + m_e^2}$ is 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 transition matrix element T_{fi} encodes the model dependent details of the DM particle interactions and the assumption of different T_{fi}; thus, different interaction models can modify the expected energy distribution providing a variation of the absolute and relative spectrum. In particular, the absolute spectrum amplitude impacts the expected value of the DM nucleus scattering cross section. This is similar to the case of the neutrino mass limit derived from the double beta decay experiments, which very much depends on the nuclear matrix element considered, with a factor of ∼3–10. On the other hand, the experimental limits on the DM cross sections only depend on the behavior of the sum of the electron's kinetic energy (the quantity experimentally detected) that is mostly defined by the phase space density factor (and by the detector effects). With the aim to investigate the phenomenology of this novel DM detection approach in the following, we assume, for simplicity, a constant value for the transition matrix element.

In Figure 2, as an example, the distribution of the sum of the energies of the two electrons is shown for the case of the ^{76}Ge target nuclei (Q = 2.039 MeV). The shape of the electron energy distributions depend on the amount of invisible energy carried away by the DM particle upscattering. When $M_\chi \ll m_e$ (green line), the expected energy distribution is very similar to the one expected for the neutrinoless double beta decay with a Majoron emission, $0\nu\beta\beta M$ (n = 2) [14,15]. On the other hand, in the case of $M_\chi \simeq m_e$ (magenta line), a distribution very similar to the one expected for the $0\nu\beta\beta M$ (n = 1) decay is evaluated, while, for $M_\chi \gg m_e$, a much harder distribution is expected (blue line).

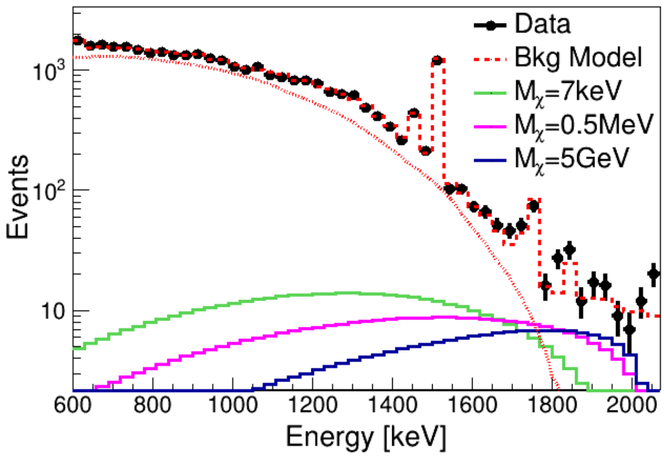

Figure 2. Upper limits on Dark Matter signals allowed by the "golden data-set" 17.9 kg × day exposure collected by Gerda Phase-I (points). The maximum signal allowed at 90% C.L. is shown for M_χ = 7 keV, 0.5 MeV, and 5 GeV (green, magenta, and blue lines), respectively.

It is interesting to compare the energy distribution measured by the Gerda experiment (Phase-I golden data set 17.9 kg × yr, black points) [15] with the distributions expected for DM stimulated double beta decay of Figure 2. In particular, the detector background model is also shown (red dashed line). The background is dominated by the known $2\nu\beta\beta$ decay (red dotted line) and by some radioactive contaminants of the detector and surrounding materials. It is important to note that the energy distribution of the $2\nu\beta\beta$ decay is peaking at relatively low energy; thus, it is quite different when compared with the one expected by the DM-induced events.

In a dedicated study of the Gerda collected events [15], no evidence was found for the $0\nu\beta\beta M$ decay; similarly, only the upper limits of the DM-stimulated double beta decay are obtained when searching for DM-induced double beta decay as shown in Figure 2.

Finally, the expected behaviour of the maximum of the detected energy distribution in ^{76}Ge as a function of M_χ is shown in Figure 3. It is important to note that a direct measurement of the DM particle mass in the range 100 keV–10 MeV could, in principle, be feasible with this approach. In particular, this is due to the deformation of the electron energy distribution caused by the upscattering of the χ particle.

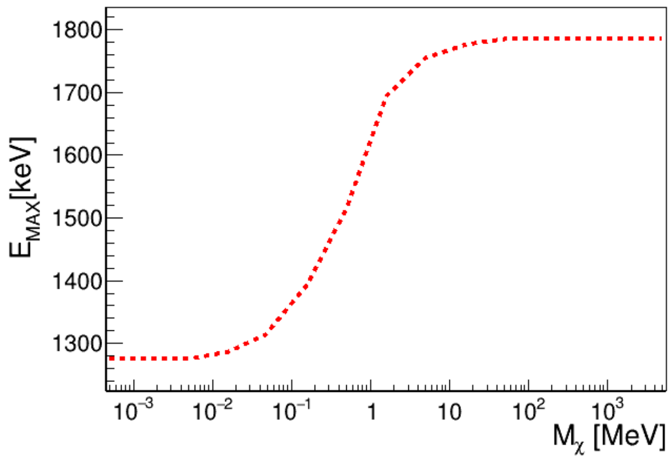

Figure 3. Behaviour of the maximum of the detected energy distribution versus the Dark Matter particle mass inducing a neutrinoless double beta decay in ^{76}Ge.

3. Conclusions and Outlooks

In this work, the possibility to search for DM-induced neutrinoless double beta decay is considered. This novel detection technique could also allow for the investigation of a possible 7.1 keV sterile neutrino DM [16]) or other light DM fermions that are very difficult or impossible to detect using elastic scattering experiments. We found that, for sub-MeV DM, the expected energy distribution for a DM-induced decay is similar to the expected distribution for a $0\nu\beta\beta M$ decay. Thus, in the case of a hypothetical signal, it would be difficult to disentangle the two different processes from the sole measurement of the energy distribution (also considering the large variations of the spectrum that are expected in different Majoron and DM models); however, some important differences among these rare processes can be noticed. A first difference is related to the physics involved in the interaction; in particular, a $0\nu\beta\beta M$ decay requires relatively light Majorons ($M_{\phi} <$ Q-value), while a DM-induced decay could also be mediated by a heavy Majoron. On the other hand, the counting rate due to the DM-induced double beta decay is expected to be modulated thanks to the yearly variation of the DM flux/velocity in the Earth frame. Thus, with a large exposure, the annual modulation could be exploited, in principle, to disentangle the two different rare processes.

Finally, it is interesting to investigate the sensitivity of this approach for the detection of light Dark Matter. Currently, the direct detection of sub-GeV Dark Matter in the underground experiments relies on the "Migdal effect", which is the DM-induced atomic shake-off, pointed out by one of us in [17].

In Figure 4, the upper limits of the total nuclear scattering cross section ($\chi-^{76}$Ge) obtained in this analysis of the Gerda Phase-I golden data set are compared with the current upper limit on the DM–Ge nucleus scattering obtained by considering the "Migdal effect" in the CDMSlite experiment [18]. Despite a deeper comparison being required to detail the χ–nucleus interaction model, the proposed approach could be very effective for the direct detection of a light fermion DM candidate by using the existing or future neutrinoless double beta decay experiments.

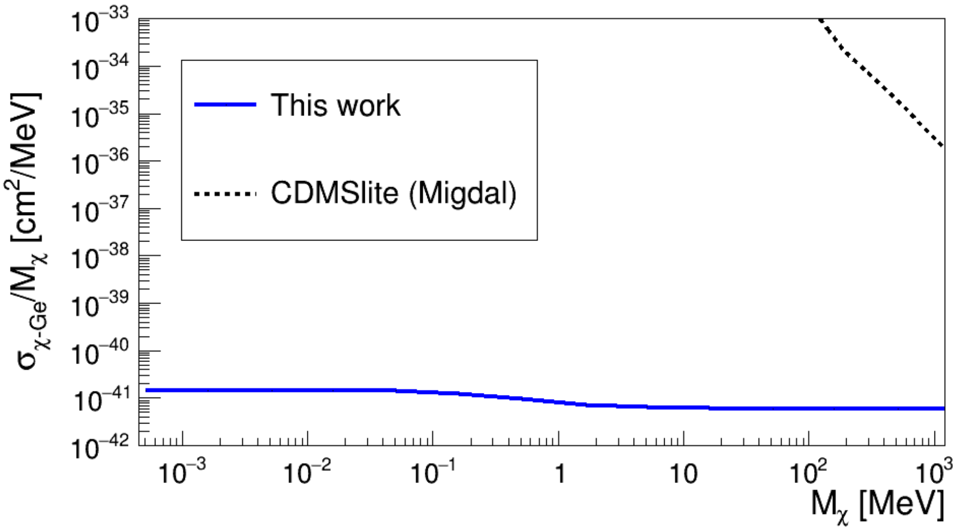

Figure 4. Example of upper limits on the total Dark Matter–Germanium nucleus cross section, obtained in this work considering the 17.9 kg $\times$ day exposure collected by Gerda Phase-I golden data set (blue line). Dotted line shows, as a comparison, the upper limits for the Dark Matter–Germanium nucleus elastic scattering for the very low mass region accessible exploiting the "Migdal effect" [17,18].

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Abbreviations

The following abbreviations are used in this manuscript:

DM	Dark Matter.
SM	Standard Model.

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