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A novel approach for the direct detection of light Dark Matter in Double Beta decay experiments.

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Francesco Nozzoli[a,*]

[a] *Istituto Nazionale Fisica Nucleare INFN-TIFPA,*
Via Sommarive 14, Trento, Italy

E-mail: francesco.nozzoli@unitn.it

The direct detection of light fermionic Dark Matter (DM) is a technological challenging task. In this work the nuclei that are unstable against the 2β decay are considered as a target for the direct detection of a class of light Dark Matter candidates. In particular, the same diagram responsible for the hypothetical neutrinoless double beta decay could be considered for the detection of a Majorana DM fermion. In this detection approach, the interaction of the DM fermion with the unstable nucleus causes the nucleus decay. The relatively large energy provided by the nucleus decay provides an experimental signature for this class of light DM fermion. The expected signal distribution for various DM masses is evaluated and compared with the current data available from the experiments using ^{76}Ge and ^{136}Xe target nuclei. The upper limits on the total cross sections for this inelastic nucleus scattering are shown.

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[*] Speaker

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1. Introduction

The search for neutrinoless double beta decay is an important tool for the exploration of Physics beyond the Standard Model. This process is potentially able to test the Majorana nature of neutrinos and the violation of Leptonic quantum numbers [1, 2]. A mechanism to naturally solve the problem of small neutrino masses is given by Seesaw models (see e.g. [3]). These models can explain the baryon asymmetry in the Universe [4] and foreseen various Dark Matter (DM) candidates [5–7].

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

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

where H is the SM Higgs doublet and $l^j_L = \binom{\nu_j}{l^-_j}$ are the SM lepton doublets ($j = e, \mu, \tau$). The symmetry breaking of H and ϕ scalar fields is providing a Dirac mass and a Majorana mass term, respectively. 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.

On the other hand, the sterile neutrino, the heavy mass neutrino eigenstate whose composition is dominated by the Majorana fermion N_R, is a good DM candidate. The other DM candidate provided by this model is the scalar Majoron, when the ϕ mass is in the MeV scale [8, 9].

The expected interactions (and self-interactions) of the Majorana fermion DM candidates (in the following: χ) are mediated by the Majoron, thus the direct detection of such a DM particle elastically scattering on charged fermions could be very suppressed. However, on the basis of the hypothetical diagram expected for the neutrinoless double beta decay, a possible detection technique for this Majorana fermion DM is the inelastic scattering on a double beta unstable nucleus, stimulating its decay. This is shown left diagram of fig. 1.

Thanks to the energy provided by the nucleus decay, the direct detection of a light DM fermion is feasible with this approach. This is a class of DM candidates that are difficult or impossible to investigate with current experiments based on the traditional elastic scattering techniques[1].

The Lagrangian considered in eq.1 would provide the process shown in the Left Panel of fig.1, however this is just one example of the possible detection mechanisms involving a neutrinoless double beta decay of the target nucleus. In the Right Panel of fig.1 another example is shown, this involves an heavy scalar ϕ' exchanged by the effective interaction vertex of χ with the electron and the nucleons. In particular, beyond the sterile neutrino provided by the model of eq.1, also other popular DM candidates are expected to be Majorana fermions (like, e.g., the supersymmetric Neutralino, Axino or Gravitino) and they could interact the nucleus with similar phenomenology but different diagrams. Therefore in

[1] A detection possibility of a light DM fermion requires the absorption of the particle inducing the beta decay of the nucleus or emitting a neutrino in the final state [10–13].

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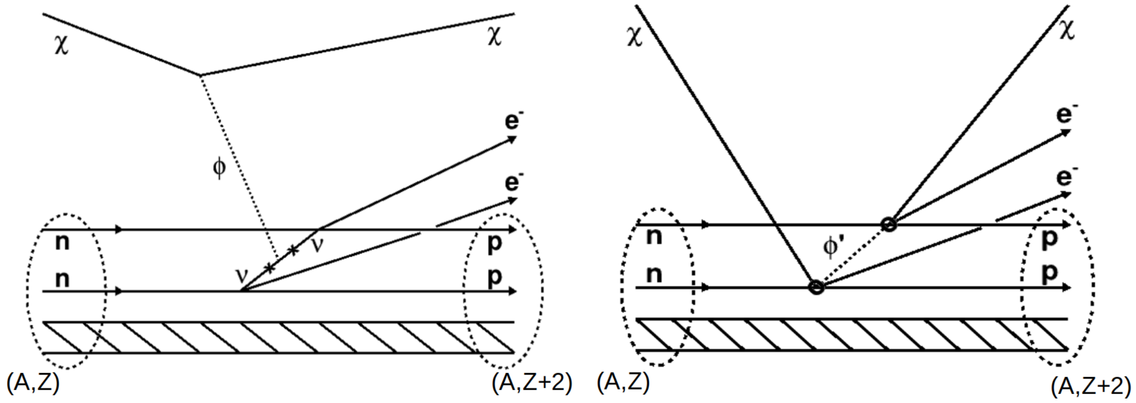

Figure 1: Example of possible detection diagrams for the Majorana DM fermion, χ. The exchange of one or more Majoron fields ϕ could stimulate a neutrinoless double beta decay of the nucleus (A,Z) to the daughter nucleus (A,Z+2) in the framework of the Seesaw models (Left panel). Other different diagrams can be considered, as the possible exchange of a heavy scalar ϕ' among the effective vertex of χ with the electron and the nucleons (Right panel). In both cases the kinetic energy of the two electrons is detected.

the following the expected signature for this novel detection technique will be summarized and the implication of current experimental results of neutrinoless double beta decay experiments will be investigated, avoiding strong assumptions on the specific DM interaction model.

2. Expected energy distribution

Considering the diagrams of fig.1, when a DM induces a neutrinoless double beta decay of the nucleus (A,Z) to the daughter nucleus (A,Z+2), the detected energy is provided by the electron recoils and the nucleus recoil. The available energy in the detection process are the decay Q-value and a fraction of the χ initial kinetic energy. Considering the non relativistic nature of galactic DM particles, the nucleus recoil energy can be neglected in the detection, however the target nucleus still plays an important role in the momentum conservation. This approximation is valid for light DM candidates up to TeV mass, since the MeV scale Q-values of the typical nuclei adopted in double beta decay searches are much larger than the χ initial kinetic energy.

In this framework, the expected energy distribution can be evaluated following the Fermi's Golden Rule:

$$d\Gamma = \frac{|T_{fi}|^2}{4\pi^2\hbar}\frac{d^3P_1}{(2\pi)^3}\frac{d^3P_2}{(2\pi)^3}\frac{d^3P_\chi}{(2\pi)^3}\delta(K_1+K_2+K_\chi-Q) \quad (2)$$

where $K_{(1,2)} = \sqrt{P^2_{(1,2)}+m_e^2} - m_e$ are the kinetic energies of the electrons and $K_\chi = \sqrt{P_\chi^2+M_\chi^2} - M_\chi$ is the kinetic energy carried away by the DM particle. The transition matrix element, T_{fi}, is describing all the model dependent details of the DM particle interactions and is potentially energy dependent. However, the overall behavior of the detected

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energy distribution is dominated by the phase space density factor (convoluted with the detector efficiency/resolution effects).

In the following the example of a "contact" interaction, assuming a constant matrix element, is considered. This is interesting for the case of $M_\phi > Q$ when the neutrinoless double beta with Majoron emisison, $0\nu\beta\beta M$, is energetically forbidden. Different DM interaction models can slightly modify the behaviour of the detected energy distribution, however the global mass/energy dependencies and the phenomenology of this DM detection approach will be similar.

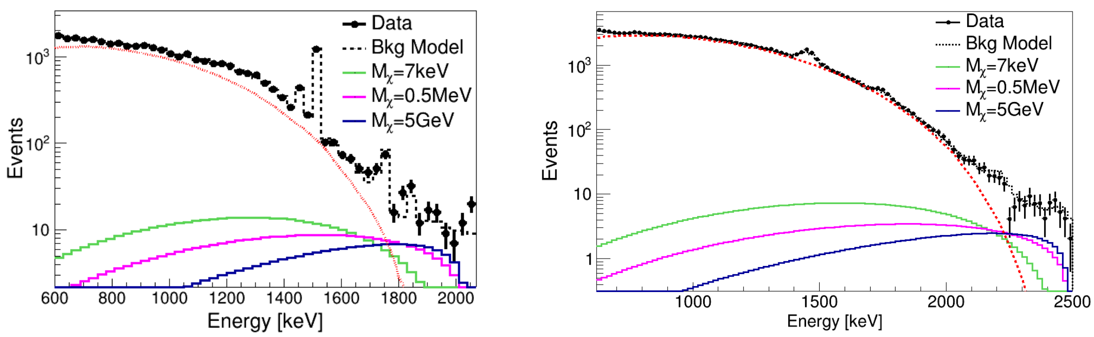

Figure 2: Example of upper limits on Dark Matter signals inferred for: 17.9 kg x day exposure collected by Gerda Phase-I, ^{76}Ge (Left Plot) [14] and 116.7 kg x day exposure collected by EXO-200 Phase-II, ^{136}Xe (Right Plot) [15]. Black points are the measured event distributions, black dotted lines are the models of the detector background that are dominated by the $2\nu2\beta$ decay (red dotted lines). The Maximum DM signals allowed at 90% C.L. for M_χ=7 keV, 0.5 MeV and 5 GeV are shown as green, magenta and blue lines.

In figure 2 the expected energy distributions are shown for the case of ^{76}Ge target nuclei (Q=2.039 MeV, Left Plot) and ^{136}Xe target nuclei (Q=2.48 MeV, Right Plot).

The up-scattered DM particle removes a part of the available energy from the system, thus the expected energy distributions are dependent on M_χ. The case of $M_\chi \ll m_e$ (green lines in fig.2) provides an energy distribution similar to the one expected for the Majoron emitting neutrinoless double beta, $0\nu\beta\beta M$ (n=2) decay [15, 16]. On the other hand, increasing the value of M_χ an harder electron energy distribution is expected. The case of $M_\chi \simeq m_e$ (magenta lines) provides a spectrum 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 energy distribution (blue lines). Figure 2 also shows, as a comparison, the experimental energy distributions measured by the Gerda detector (Phase-I, 17.9 kg x day) [14] and EXO-200 detector (Phase-II, 116.7 kg x yr) [15]. The model of the detector background are also superimposed (black dotted lines). The detector background are due to radioactive contaminants within the set-up and in the surrounding materials, as an example, the large peak at 1461 keV is due to ^{40}K decay. However, the large background contribution below the Q-value, it is dominated by the known $2\nu\beta\beta$ decay (red dotted lines). It is important to note that the energy distribution of this last process is very different and much softer as compared with the one expected by DM induced events. No evidence for the $0\nu\beta\beta M$ decay was found so far in the analysis of

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the Gerda and EXO-200 data [14, 15], for the same reason, only upper limits to the DM induced neutrinoless double beta decay are obtained and shown in fig. 2.

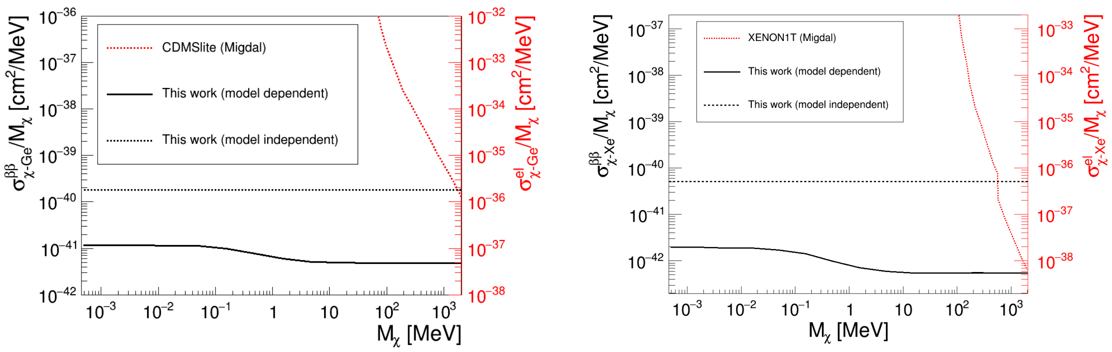

Figure 3: Example of upper limits on the total Dark Matter - nucleus cross sections, $\sigma^{\beta\beta}_{\chi-Ge}$ and $\sigma^{\beta\beta}_{\chi-Xe}$, (black continuous lines). A "model independent", cautious, upper limit is obtained by attributing to a possible DM signal all the events in excess with respect to the known $2\nu\beta\beta$ decay (horizontal dashed black lines). Red dotted line shows, as a comparison, the upper limits for the Dark Matter-nucleus elastic scattering, $\sigma^{el}_{\chi-Ge}$ and $\sigma^{el}_{\chi-Xe}$, for the very low mass region accessible by exploiting the atomic shake-off "Migdal effect" [17–19].

3. Discussion and conclusion

This work summarizes a possible approach for the detection of light DM fermions by using existing double beta decay experiments. This approach could allow the investigation of light fermionic DM (like the 7.1 keV sterile neutrino [20]) that is very difficult or impossible to detect with the elastic scattering technique. The expected energy distribution for a sub-MeV DM induced decay, is similar to the one expected for $0\nu\beta\beta M$ decay (due to the many possibilities in Majoron and DM models). However there are some important differences among these rare processes. From the phenomenological point of view, 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, from experimental point of view, a characteristics of the DM induced double beta decay is the possible annual modulation due to the yearly variation of the DM flux/velocity. In principle, this signature might be exploited to disentangle the two different rare processes.

Currently, the direct detection of sub-GeV dark matter relies in the so called "Migdal effect", the DM induced atomic shake-off, pointed out in [17].

Assuming a DM density of 0.3 GeV/cm^3 and the DM average velocity in the Solar System frame of 250km/s it is possible to test the sensitivity of the approach of this work for the detection of light dark matter.

In figure 3 the upper limits on the total nuclear scattering cross section ($\chi-^{76}$Ge and $\chi-^{136}$Xe) obtained in this analysis of Gerda Phase-I and EXO-200 Phase-II data are compared with the current upper limits on the DM-Ge and DM-Xe nucleus scattering obtained by considering the "Migdal effect" in the CDMSlite and XENON1T experiments [18, 19].

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Obviously a deeper comparison requires to model the χ-nucleus interactions, however the approach suggested in this work 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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