Title
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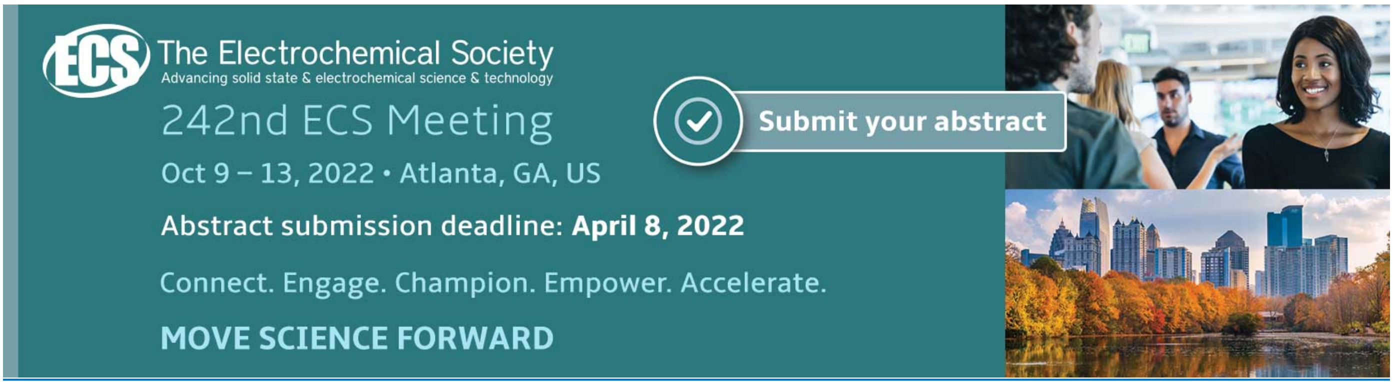

Search for charged excitations of dark matter by KamLAND-Zen experiment

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Abstract. There are many scenarios in which dark matter is a part of a multiplet with an electrically charged state. If WIMP dark matter is accompanied by a charged state separated by a small mass difference, it can form stable bound states with nuclei. The region of observable energy deposition via this process of bound state formation is $O(1{\sim}10\ \mathrm{MeV})$. KamLAND-Zen is a large scintillator detector designed for neutrino-less double-beta decay search. This detector is also useful to detect dark matter bound state formations with nuclei. The result from the KamLAND-Zen 400 dataset is reported.

1. Introduction

Dark matter is one of the most important problems in particle physics [1]. It is expected to be a new particle(s) beyond the Standard Model. One strong candidate for dark matter is the weakly interacting massive particle (WIMP). The neutralino in SUSY is a good example of a WIMP. It has neutral charge and is stable relative to the age of the Universe. WIMPs are expected to interact with ordinary matter with a strength weaker than the weak nuclear force.

There are a lot of scenarios in which the WIMP is a part of a multiplet with an electrically charged excited state. It enables us to naturally control the dark matter's abundance through coannihilation. If the mass difference is sufficiently small, the WIMP can form a stable bound state with a nucleus. In this process, the observable energy is $O(1{\sim}10\ \mathrm{MeV})$. Detectors for neutrino-less double-beta decay $(0\nu\beta\beta)$, for example, are suitable to detect events in this energy region.

2. Observables

The bound state formation process is written as [2]

$$N_Z + X^0 \to (N_Z X^-) + e^+. \tag{1}$$

N_Z, X^0 and X^- represent a target nucleus with an atomic number Z, the WIMP like the neutralino and the excited state of the WIMP like the stau ($\tilde{\tau}$), respectively. If the bound state $(N_Z X^-)$ is not in its ground state, it will de-excite by emitting γ-rays. Besides the de-excitation γ-rays and the positron (e^+), the annihilation γ-rays would be observed in this process. The observable energy is written as

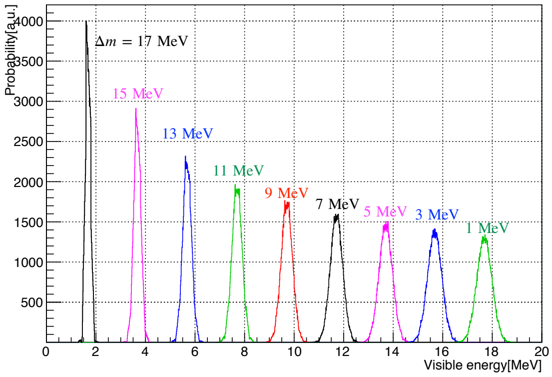

Figure 1. The expected energy spectrum in the KamLAND-Zen detector for several Δm.

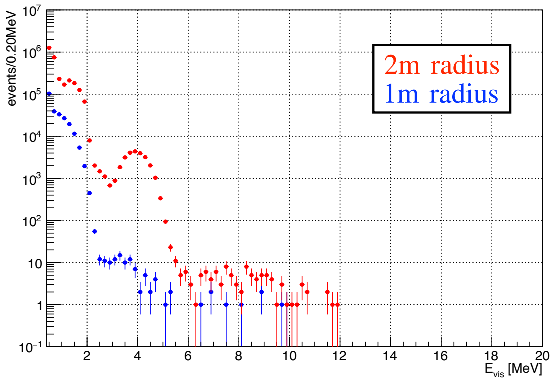

Figure 2. The observed energy spectra in the KamLAND-Zen 400 Phase-II.

$$E_{tot} = E_{e^+} + E_\gamma + 2m_e, \quad (2)$$
$$= E_b^{(0)} - \Delta m + m_e, \quad (3)$$
$$E_{e^+} = E_b^{(n,l)} - \Delta m - m_e, \quad (4)$$
$$E_\gamma = E_b^{(0)} - E_b^{(n,l)}. \quad (5)$$

The Coulomb binding energy E_b of $(N_Z X^-)$ enables to bridge the mass difference $\Delta m \equiv m_{X^-} - m_{X^0}$. $E_b^{(0)}$ is the ground-state energy and has a value of 18.4 MeV for the N_Z = Xe case. Increasing Z increases $E_b^{(0)}$ and enlarges the searchable Δm region. $E_b^{(n,l)}$ is the excited-state energy with the usual initial principal and the orbital quantum numbers of the capture (n,l). The energy distributions of the positrons and the γ-rays change with its value. However, the total energy deposition $E_{\rm vis}$ would be monochromatic, regardless of the capture level. The signal shape is basically determined only by the energy response of the detector.

Once Δm and the WIMP mass m_{X^0} are chosen, the induced signal in a detector can be translated into a constraint on the recombination cross section with the incoming dark matter velocity $\langle \sigma v \rangle$ or the combination of the Yukawa couplings $(|g_{eL}|^2 + |g_{eR}|^2)$. They are traded off against a constraint on the stau's decay width $\Gamma_{\tilde{\tau}} = \tau_{\tilde{\tau}}^{-1}$. This enables us to compare our result with the limit obtained in collider experiments [4].

3. Search for the WIMPs using KamLAND-Zen

KamLAND-Zen 400 is a $0\nu\beta\beta$ search experiment in the Kamioka mine[3]. It is a 1 kton liquid scintillator (LS) detector with Xe-loaded LS located in a 3.08-m-diameter spherical nylon balloon located at the center of the detector. The bound state formation search was performed by using the KamLAND-Zen 400 phase-II dataset. The total Xe amount (all isotopes) is 378.4 ± 2.2 kg. The livetime of the KamLAND-Zen 400 phase-II is 534.5 days. The exposure is 139.3 or 554.7 [kg·yr], when a 1 or 2 m-radius fiducial volume is used for analysis, respectively.

Figure 1 shows the expected energy spectra for several Δm values. The energy non-linearity and the energy resolution ($\sigma_E = 7.3\%/\sqrt{E(\mathrm{MeV})}$) are taken into account. Only single atomic de-excitation γ-ray emission with the total energy E_γ is assumed. Figure 2 shows the observed energy spectra including the higher energy region not used in the $0\nu\beta\beta$ analysis. The radius

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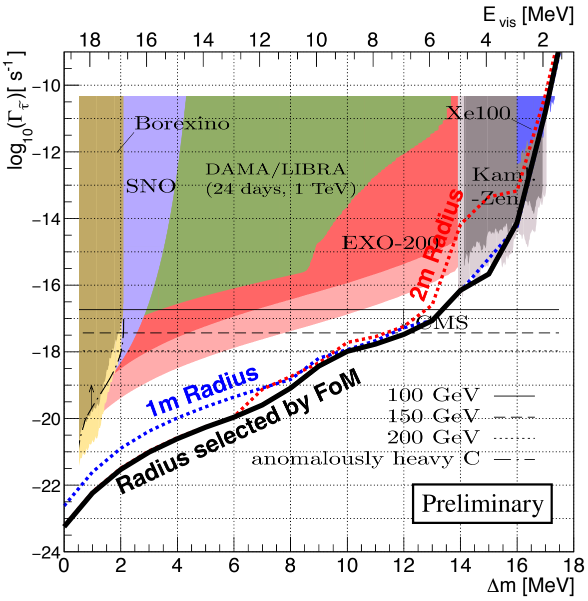

Figure 3. The decay width of $\tilde{\tau}$ as a function of Δm. The black solid curve shows 90% C.L. upper limits from the KamLAND-Zen 400 Phase-II. The filled regions are the expected sensitivity for several other experiments[2].

was selected using a figure of merit (FoM) in order to enlarge the fiducial volume as much as possible. The FoM was defined as

$$\mathrm{FoM}(r, \Delta m) \equiv \frac{S}{\sqrt{B}} \equiv \frac{\mathrm{FV}(r) \times \epsilon_{\mathrm{det}}(r, \Delta \mathrm{m})}{\sqrt{\mathrm{N}_{\mathrm{obs}}^{90\%}}}, \tag{6}$$

where $\mathrm{FV}(r)$ is the volume of the Xe-loaded LS, $\mathrm{N}_{\mathrm{obs}}^{90\%}$ is 90% C.L. upper limit on the number of the observed events and $\epsilon_{\mathrm{det}}(r, \Delta \mathrm{m})$ is the spatial detection efficiency estimated by a Monte-Carlo simulation. The radius with highest FoM was chosen at 1 MeV Δm intervals. The results of this study are shown in Figure 3. The black solid curve corresponds to a fiducial volume selected by the FoM. The results from analyses in which the 1 or 2 m-radius fiducial volume is chosen, are shown by the blue and red dotted curves. Zero the background and $m_{X^0} = 100$ GeV is assumed. For $\Delta m \gtrsim 12$ MeV, the present analysis provides a better limits than the CMS experiment [4].

4. Summary

A search for a WIMP dark matter was performed by using the dataset from the $0\nu\beta\beta$ detector KamLAND-Zen 400. It provides a better limit than the CMS experiment for the low Δm region. The sensitivity of this search will be improved by a background subtraction obtained from the best-fit of the energy spectrum in the $0\nu\beta\beta$ search [3].

References

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