Constraints on Dark Matter Axion-Like-Particles with Inelastic Inverse Primakoff Interactions

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Axions are hypothetical particles introduced to solve the strong CP-problem with the spontaneous breaking of the Peccei-Quinn symmetry. In recent years, there has been remarkable progress evolved from the original "QCD axions" to their variants generically called "Axion-Like-Particles"(ALPs). The ALPs naturally appear in many extensions of the Standard Model of particle physics, and are viable candidates to Dark Matter (DM).

The interaction Lagrangian of axion with photons is given as

$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4}\, g_{a\gamma\gamma}\, \phi_\alpha\, F_{\mu\nu}\, \widetilde{F}^{\mu\nu} \quad , \qquad (1)$$

where $g_{a\gamma\gamma}$ is the coupling strength, ϕ_α is the axion field, $\widetilde{F}^{\mu\nu}$ is antisymmetric tensor, and $F^{\mu\nu}$ is the field strength of the photon field A_μ. There is an analogous term for axion couplings with electrons(g_{aee}). A wide spectrum of experimental projects are being pursued to measure both the couplings (g_{aee}, $g_{a\gamma\gamma}$) including micro-wave cavity experiments, solar axion helioscopes, direct DM searches, indirect searches of γ-rays from the universe, as well as constraints from cooling of astrophysical objects.

The intereaction of ALPs with matter via inelastic Inverse Primakoff (IP) scattering was recently studied in the context of solar ALPs [1]. We extend the studies to non-relativistic ALPs which are relevant to the case of DM [2]. The following three different data sets are selected to derive constraints on the $(m_a, g_{a\gamma\gamma})$ parameter space:

1. TEXONO low threshold data with point-contact germanium detector from 300 eV_{ee} to 12 keV_{ee} [3].

2. TEXONO high energy (MeV_{ee}) reach data with high-purity germanium detector from 12 keV_{ee} to 3000 keV_{ee} [4].

3. XENON1T "S2-only" data with liquid xenon from 1.5 keV_{ee} to 207 keV_{ee} [5].

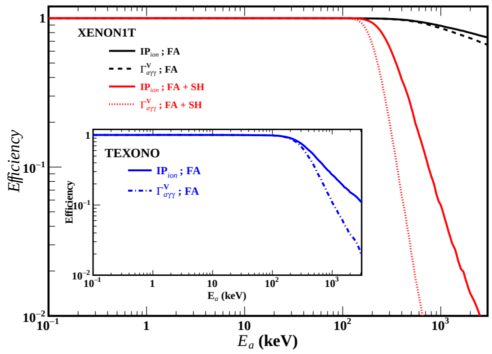

FIG. 1: Signal detection efficiency for DM-ALPs for the leading $\Gamma^V_{a\gamma\gamma}$ and IP_{ion} channels as function of E_a in XENON1T and TEXONO (inset) experiments.

The DM-ALPs are non-relativistic and interact pre-dominantly via the vacuum decay and inelastic IP ionization channels. These two channels differ among each other by their final-states: vacuum decay has two γ's each having energy $E_a/2$ and inelastic IP ionization has an electron and a photon each with energy $E_a/2$.

The differential cross section of inelastic IP ionization channel is derived with full electromagnetic fields of atomic charge and current

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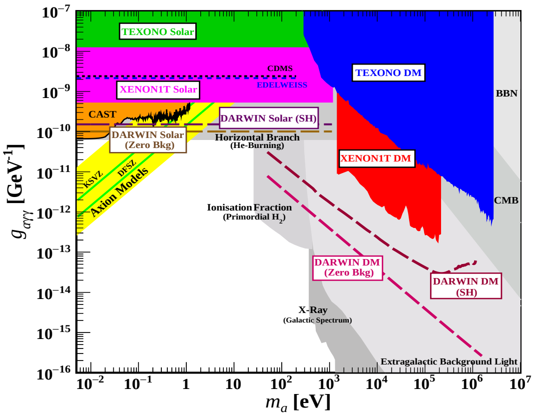

FIG. 2: Exclusion regions at 90% C.L. in $(m_a, g_{a\gamma\gamma})$ parameter space, showing the solar-ALPs and DM-ALPs bounds from TEXONO and XENON1T experiments. Cosmological and astrophysical bounds are also superimposed [6]. The current constraints from solar-ALPs with Bragg scattering and helioscope experiments, as well as the sensitivity reaches of the DARWIN project are shown.

densities [2]. The signatures of DM-ALPs are Gaussian peaks at m_a on the total energy depositions over the continuum background spectra, which offers the smoking-gun signatures for DM-ALPs. Signal efficiencies of final-state emissions with full absorption (FA) in the detectors is evaluated with Geant4 simulation package. In the case of liquid xenon detector, for single hit (SH) event requires the final states to be fully absorbed within the spatial resolution of the detector, ($\sigma_{x,y}$=0.8 cm and σ_z=0.3 cm at 1 MeV$_{\rm ee}$ away from the vertices. The energy dependence of signal efficiencies of both channels are depicted in Figure 1.

Elastic IP scattering with a single photon final state is the dominant channel for relativistic solar-ALPs, the signal of which are continuously distributed over measurable energy. The detection efficiencies for single-hit events are close to unity at this low (<20 keV$_{\rm ee}$) energy.

Figure 2 shows the exclusion regions at 90% confidence level (CL) of the leading channels (vacuum decay and inelastic IP ionization for DM-ALPs; elastic IP scattering for solar-ALPs) for the TEXONO and XENON1T experiments together with astrophysical and cosmological bounds. The predictions from QCD-axion models are also depicted. The elastic IP scattering channel for solar-ALPs improves on $g_{a\gamma\gamma}$ over the Bragg-scattering constraints from CDMS and EDELWEISS. It also extends m_a range to be probed from 1 eV to $\mathcal{O}$(keV) beyond the reach of the CAST helioscope experiment. In DM-ALPs searches, new regions not accessible to other laboratory experiments in $\mathcal{O}$(keV)<m_a<$\mathcal{O}$(MeV) are probed and excluded by inelastic IP ionization and vacuum decay.

The leading inelastic IP ionization channel in DM-ALPs searches offers very distinct signatures: an electron and a photon with equal energy originated from a common vertex. This can be used for further background suppression while retaining good signal efficiency. The projected sensitivities of the next generation liquid xenon project DARWIN at 200 ton-year exposure and 50 eV$_{\rm ee}$ threshold are superimposed in Figure 2, showing one with typical SH selection with the projected background subtracted, and another with an idealized zero-background all-multiplicity measurement.

Acknowledgments

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