Snowmass2021 - Letter of Interest

Axion-Like Particles from the Sun at Dark Matter Experiments using Inverse-Primakoff Scattering

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: The solar axion search at direct detection experiments so far has neglected the inverse-Primakoff scattering at the detector utilizing $g_{a\gamma} aF\tilde{F}$ operator. Inclusion of this previously neglected channel at the ongoing XENON1T experiment significantly improves the sensitivity to the axion-photon coupling, with a reach extending to $g_{a\gamma} \sim 10^{-10}$ GeV^{-1} for axion masses up to a keV, thereby extending into the region of heavier QCD axion models. The sensitivity to solar axions for future generations of LXe detectors can exceed future helioscope experiments, such as IAXO, for a large region of parameter space. As a followup to this recent finding, we plan to work out various associated details which include the electron and nuclear recoils, along with extending this analysis to include the upcoming SuperCDMS SNOLAB experiment.

Introduction

Dark matter direct detection experiments, initially designed to search for WIMP-like dark matter, have been adapted more broadly as detectors of Beyond Standard Model (BSM) physics. Notable among the wide class of BSM physics searches at direct detection facilities is the extraordinary sensitivity to possible axion or axion-like particles (a) coupling to Standard Model particles (SM)[1–7]. By examining electronic recoils produced by a solar axion flux through the detector, these searches have probed a variety of a–SM couplings including axion-electron (g_{ae}), axion-photon ($g_{a\gamma}$), and axion-nucleon (g_{aN}) interactions. Each coupling could give rise to a solar axion population that is searched for in terrestrial experiments. The direct detection experiments including CDMS, Edelweiss, COGENT, LUX, XENON1T have utilized the direct g_{ae} coupling in the electron scattering process within the detector, allowing constraints on the axion parameter space m_a vs g_{ae} or the products $g_{ae}g_{a\gamma}$ and $g_{ae}g_{aN}$. Until recently, however, these searches have overlooked an important detection channel: the inverse Primakoff process shown in Fig. 1.

Recently, the XENON1T collaboration announced an observed excess of electron recoils in their low energy (1-30 keV) data, with a rise above the background-only model occurring below 7 keV[8]. The solar axion flux is predicted to reside mostly in this energy range, making it a well-motivated hypothesis for the excess. The collaboration showed that a solar axion model can fit the data with a 3.5σ significance, which is reduced to 2.1σ if an unconstrained tritium background is introduced in the fitting.

There is an alternative means of producing electron recoils through axion scattering that does not rely on the g_{ae} coupling - namely through Primakoff scattering which is overlooked in the direct detection experiments[9]. In Primakoff scattering (also called the inverse Primakoff effect), shown in Fig. 1, an incident axion scatters off a charged particle through the $g_{a\gamma}$ coupling, producing an outgoing photon and recoil of the target particle. This channel occurs through a coherent interaction with the entire atomic form factor, not to be confused with a similar process involving the coherent interaction with external electromagnetic fields. The inverse Primakoff scattering process has been considered in several works[10–15], including a recent analysis of the sensitivity of reactor neutrino experiments to axion-like particles with low-threshold detectors[16].

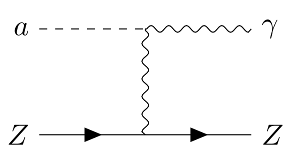

Figure 1: The inverse Primakoff process, where the axion a coherently scatters with the electric fields of the entire atomic system $Z \equiv (e^-, N)$.

Constraints from DM experiments In Fig. 2 (left), we plot $g_{a\gamma}$ vs. g_{ae} where contributions from both axion-electron and axion-photon couplings are included. The red shaded regions show the XENON1T excess fit without considering inverse Primakoff while the blue shaded region utilizes inverse Primakoff. We find that the improvement in $g_{a\gamma}$ due to inverse Primakoff is quite significant for $g_{ae} \lesssim 10^{-12}$, and one can see that the transition from the g_{ae}-dominated signal to the $g_{a\gamma}$-dominated signal occurs around $g_{ae} = 10^{-12}$ and $g_{a\gamma} = 10^{-10}\text{GeV}^{-1}$. In the limit of small g_{ae} the inverse Primakoff channel provides flat sensitivity that is especially improved for the widely studied KSVZ-type models of the QCD axion. Another bound of $g_{ae} < 2.8 \cdot 10^{-13}$ comes from the white dwarf luminosity function (WDLF) constraints[17].

If the excess is due to a background phenomenon, the current data constrain the axion parameter space. We compute this constraint by testing our signal hypothesis against the B_0 model at various exposures; we show the constraint in $g_{a\gamma}$ as a function of m_a and we find that the constraint is already better than the CAST constraint for $m_a > 0.04$ eV. In Fig. 2 (right), we show the next-generation xenon (G3 Xe) constraint (with a 1 kilotonne-year exposure[18]) and find that the 2σ (∼95% CL) can overcome even the HB stars constraint

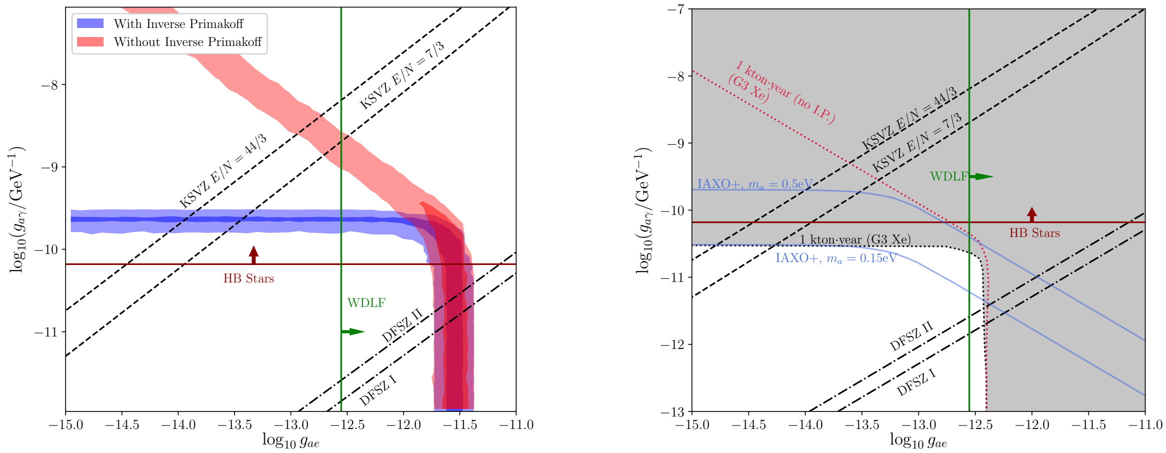

Figure 2: *left*: 2σ credible contours are shown for fits to the XENON1T excess for all axion flux components with only axioelectric scattering (red) and with both inverse-Primakoff and axioelectric scattering (blue). 1σ contours are also shown with dark shading. Here we consider $m_a = 0.7$ eV, however, the plot does not change for any $m_a < 100$ eV and the CAST constraints are evaded for $m_a > 0.03$ eV. *right*: Projections of the 2σ future exclusions (gray) set by G3 Xe over a 1 kilotonne·year exposure given background-only observations. The exclusion line for 1 kilotonne·year without inverse Primakoff (I.P.) scattering is shown for comparison (dotted red). We also show the IAXO+ projection (blue) which begins to lose sensitivity for $m_a \gtrsim 0.01$ eV.

and start exploring the mild hint (2.4σ) region of stellar cooling within 1σ. Interestingly, this is only possible with the inclusion of the inverse Primakoff channel since without this channel the constraint could be worse by a few orders of magnitude. We also find that our projected sensitivity for a 1 kilotonne·year exposure at a G3 LXe experiment is competitive with future helioscope experiments. The proposed DARWIN detector would achieve a 200 tonne-year exposure [19], thereby covering the current HB Stars constraint. We compare the 1 kilotonne·year projection against the projected sensitivities for IAXO+ with masses $m_a > 0.1$ eV, where sensitivity begins to diminish for larger masses [20]. Additionally, future direct detection experiments with directional sensitivity would be able to use the directional information to reduce backgrounds and further increase their sensitivity to solar axions. This is especially useful in the Primakoff channel, where the axion's incoming direction is approximately preserved by the photon in the relativistic limit.

Summary: We point out that the inverse Primakoff scattering is a new detection channel at direct detection experiments. It inclusion broadens the reach of current and future direct detection experiments, allowing sensitivity in the previously unexamined (by direct detection experiments) $g_{a\gamma} - m_a$ parameter space. We showed that sole use of the coupling $g_{a\gamma}$ (on both the solar production and terrestial detection sides) can fit the recent XENON1T excess. The fitting of the excess is free of the leading helioscope CAST constraint for $m_a \gtrsim 0.03$ eV. If this excess is due to the background we find that the 95%CL exclusion limit is also stronger than the CAST limit in this region. Additionally, next-generation xenon experiments can overcome the HB stars limit, and for $g_{ae} = 10^{-13}$, the 2.4σ hint region of stellar cooling can be probed within 1σ. In addition, these future bounds would be applicable for masses $m_a < 1$ keV, covering complementary regions of parameter space for which future helioscopes, such as IAXO, start to lose sensitivity near $m_a \gtrsim 0.01$eV. Further, the KSVZ model can now be probed at the direct detection experiments. A similar region of the $g_{a\gamma} - m_a$ space will also can be investigated at LZ [21] and SuperCDMS SNOLAB [22]. We plan to investigate the inverse Primakoff in more details with additional enhancements at SuperCDMS.

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