Inverse Primakoff Scattering as a Probe of Solar Axions at Liquid Xenon Direct Detection Experiments

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We show that XENON1T and future liquid xenon (LXe) direct detection experiments are sensitive to axions through the parameter space of the axion-electron 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. This result modifies the couplings required to explain the XENON1T excess in terms of solar axions, opening a large region of parameter space that is not ruled out by the CAST helioscope experiment and reducing the tension with the astrophysical constraints. We also explore the sensitivity to solar axions for future generations of LXe detectors which can exceed future helioscope experiments, such as IAXO, for a large region of parameter space.

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 couplings to Standard Model particles (SM) [1–7]. Examining electronic recoils within the detector volume produced by a solar axion flux, these searches have probed a variety of $a$-SM couplings including axion-electron, axion-photon, and axion-nucleon.

Recently, the XENON1T collaboration announced an observed excess of electron recoils in their low energy (1–30 keV) data [8], with a rise above the background-only model occurring below 7 keV. The collaboration showed that a solar axion model can fit the data with a 3.5$\sigma$ significance, which is reduced to 2.1$\sigma$ if an unconstrained tritium background is introduced in the fitting.

XENON1T placed constraints in a three-dimensional confidence limit volume in the parameter space of the axion-electron coupling, $g_{ae}$, along with the products $g_{ae}g_{\gamma\gamma}$ and $g_{ae}g_{\text{eff}}$, where $g_{\gamma\gamma}$ and $g_{\text{eff}}$ characterize the strength of axions coupling to photons and nucleons, respectively. These constraints were shown to be competitive with (or exceeding in some regions) the axion helioscope experiment CAST [9] and the xenon-based dark matter direct detection experiments LUX [1] and PandaX-II [2]. The preferred region for the solar axion interpretation of the XENON1T result is in severe tension with astrophysical bounds, as discussed in [10] (see [11] for a recent review that includes updated astrophysical bounds).

The analysis calculated the expected event rates produced by a solar axion flux consisting of three components, which we describe in more detail in Sec. II, arising from each of the couplings mentioned above, which would scatter off of electrons within the XENON1T detector through the axioelectric effect. This scattering process depends only on the $g_{ae}$ axion coupling, and not on either $g_{\gamma\gamma}$ or $g_{\text{eff}}$.

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. In Primakoff scattering (also called the inverse Primakoff effect), shown in Fig. 1, an incident axion scatters off of a charged particle through the $g_{ae}$ coupling, producing an outgoing photon and recoil of the target particle. This channel occurs through a coherent interaction with external electromagnetic fields. The inverse Primakoff scattering process has been considered in several works [12–17], including a recent analysis of the sensitivity of reactor neutrino experiments to axion-like particles with low-threshold detectors [18].

In this work, we first describe the inverse Primakoff channel for axion detection in XENON1T (which can be applied to any direct detection experiments). We then explore the axion model parameter space for regions which can fit the XENON1T excess through Primakoff scattering within the detector. We demonstrate
that the current XENON1T excess can be well-fit purely through a $g_{a\gamma}$ coupling (for both solar production and experimental detection). We show that there are regions of coupling and axion mass parameter space which fit the excess and are not ruled out by the CAST experiment. This region has constraints from HB stars which, however, can be evaded in the context of particle physics models [19–25]. If this excess is instead due to an un-modelled background, we show the constraint emerging from this inverse Primakoff channel at the ongoing and future detectors.

I. MODELS

Peccei and Quinn (PQ) introduced a new global chiral symmetry into the Standard Model in order to solve the strong CP problem [26]. This symmetry is broken dynamically and the resulting pseudo Nambu-Goldstone boson is the axion [27, 28]. Although axion couplings to all Standard Model particles can be considered, in the present work we examine the couplings to photons and leptons within the interaction Lagrangian

$$\mathcal{L} \supset -\frac{1}{4}g_{a\gamma}F_{\mu\nu}F^{\mu\nu} + ig_{ae}a\bar{\psi}\gamma^5\psi$$  \hspace{1cm} (1)

These couplings are model dependent, with some models allowing lepton couplings only beginning at one-loop order. Within a given model, these couplings are not strictly independent, as loop effects can correlate them. However, in the present work we allow these parameters to be independently fit to the data. We will also comment on the common QCD axion models of Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) [29, 30], and Kim-Shifman-Vainshtein-Zakharov (KSVZ) [31, 32], which provide specific, model dependent forms for $g_{a\gamma}$ and $g_{ae}$. In addition, effective couplings to nucleons (of a similar form as the electron interaction term [33]) will be included in the next section.

The explicit coupling correlations can be made to connect our phenomenological axion model to specific DFSZ and KSVZ QCD axion models in the analysis. For these we make use of the following relations, omitting uncertainties on constants [34–36]:

$$g_{DFSZ}^{ae} = \frac{2\pi m_e\sin^2\beta}{3\alpha C_{a\gamma}}g_{a\gamma}$$

$$g_{KSVZ}^{ae} = 3\alpha m_e C_{a\gamma}g_{a\gamma} \left( \frac{E}{N} \ln \frac{\alpha C_{a\gamma}}{2\pi m_e g_{a\gamma}} - 1.92 \ln \frac{\Lambda}{m_e} \right)$$

$$g_{a\gamma} = 10^{-9}\text{GeV}^{-1}(0.203\frac{E}{N} - 0.39)\left(\frac{m_a}{\text{eV}}\right)$$

$$C_{a\gamma} = \frac{E}{N} - 1.92$$  \hspace{1cm} (2)

where $E$ and $N$ are model dependent and related to the electromagnetic and color anomalies. We will display the bands in the $g_{a\gamma} - m_a$ parameter space for benchmark $E/N$ values. We take the scale factor $\Lambda \sim 1\text{ GeV}$ and for the DFSZ parameter we provisionally use $\tan\beta = 140$ (DFSZ I) and $\tan\beta = 0.28$ (DFSZ II) taken from fits to accommodate unitarity and stellar cooling [36]. Various additional instances of these models have been explored over a range of $E/N$ values [37].

II. SOLAR AXION FLUX

There are three sources of solar axion flux that we consider, each with a dependence on a different axion coupling parameter. First is the the ABC flux (Atomic de-excitation and recombination, Bremsstrahlung, and Compton scattering), which is dependent upon the axion-electron coupling as $\Phi_a \propto g_{ae}^2$. We adopt the flux as calculated in [38].

Next is the Primakoff production process occurring through photons scattering with electrons or ions in the solar interior. This production mechanism depends on the axion-photon coupling, $g_{a\gamma}$, with the analytic form for the differential flux given by [39, 40]

$$\frac{d\Phi_a}{dE_a} = 6 \cdot 10^{30} \left( \frac{g_{a\gamma}}{\text{GeV}^{-1}} \right)^2 \left( \frac{E_a}{\text{keV}} \right)^{2.481} \times \exp \left[ - \frac{E_a}{1.205\text{keV}} \right] \text{cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$$  \hspace{1cm} (3)

Finally, de-excitation of $^{57}$Fe in the sun can produce a monoenergetic axion population at 14.4 keV [33, 41, 42]. This flux would arise from an effective axion-nucleon coupling $g_{an}^{\text{eff}} = -1.19g_{an}^0 + g_{an}^{0(3)}$, where $g_{an}^{0(3)}$ are the isoscalar (isovector) coupling constants for the nucleons [33, 43]. Its analytic form is

$$\Phi_a^{^{57}\text{Fe}} = \left( \frac{E_a}{E_{^{57}\text{Fe}}} \right)^3 \times 4.56 \times 10^{21} \left( g_{an}^{\text{eff}} \right)^2 \text{cm}^{-2}\text{s}^{-1}$$  \hspace{1cm} (4)

III. ANALYSIS

We consider two possibilities of solar axion production and subsequent scattering within the XENON1T volume. First, we examine Primakoff production in the sun, followed by photon production through Primakoff scattering in the detector (this combination is purely dependent on $g_{a\gamma}$). We note here that solely using this coupling approximates the phenomenology of KSVZ-type axion models, for which axion-electron interactions happen through loop-induced processes, and would be suppressed. Second, we analyze a non-zero $g_{ae}$ in conjunction with a non-zero $g_{a\gamma}$, which allows for both ABC and Primakoff solar production, along with axioelectric and Primakoff scattering detection. This analysis is complementary to that of XENON1T which allowed for the possibility of Primakoff production, but only detection through the axion-electron scattering controlled by the $g_{ae}$ coupling.
Inverse Primakoff scattering may allow solar axions to coherently scatter with the Xe atomic electric field and back-convert into photons in the detector volume; $e \gamma \rightarrow \gamma Z$, proceeding through a $t$-channel photon exchange (Fig. 1). Since electromagnetic conversion of the final state photon in the LXe TPC may produce light yields within the region of interest, it is possible that inverse Primakoff scattering would contribute to the axion hypothesis. For an axion of momentum $k_a$, the inverse Primakoff cross-section is given by \[ \sigma(k_a) = \frac{Z^2 \alpha g_{ae}^2}{2} \left( \frac{2r_0^2k_a^2 + 1}{4\sqrt{2}k_a^2} \ln \left( 1 + \frac{4r_0^2k_a^2}{1} \right) - 1 \right) \]  
where $r_0$ is the screening length for which we take as the Wigner-Seitz radius in LXe, 2.45 Å.

We consider inverse Primakoff scattering in addition to the axioelectric absorption process outlined in the analysis performed by XENON1T. Also, it is possible that axions undergo inverse Compton scattering off electrons at rest in LXe, $ae^- \rightarrow \gamma e^-$, but this is a subdominant process. If both axion-photon and axion-electron couplings are present, there are interference terms present in the total matrix element of the combined processes, which are also subdominant, but we include as a matter of completeness.

To predict the event spectra from axions produced through ABC, Primakoff, and $^{57}$Fe, we convolve the fluxes in each case with the total cross-sections, for inverse Primakoff scattering or axioelectric absorption, and multiply by the detector efficiency reported in [8]. In addition, we approximate the detector response for the energy resolution by passing the simulated differential event distribution through a Gaussian filter and matched empirically to the energy resolution [44]. The event distribution for Primakoff-produced axions that undergo inverse Primakoff scattering in the LXe fiducial volume over a ton-year exposure is shown in Figure 2.

We perform a likelihood analysis given the data and "$\mathcal{B}_0$" background hypothesis taken in [8] and our axion signal hypotheses using the Bayesian inference package MultiNest [45-47]. A binned log-gaussian likelihood is constructed over bins $i$, with signal event rates $\{\mu_i\}$ and observed events $\{n_i\}$ ranging from 1 to 29 keV, taken with errors $\sigma_i$ reported by XENON1T.

We wish to investigate several scenarios of signal and background models in the context of the excess: (I) Primakoff-produced axions detected through solely inverse Primakoff scattering, (II) Primakoff-produced and scattered axions with an additional $^3$H component and (III) the $^3$H component alone, repeating the methods used in the XENON1T analysis, (IV) all production mechanisms (ABC, Primakoff, $^{57}$Fe) and all scattering channels (Primakoff, axioelectric, Compton) allowed in the detector, and (V) all flux components and scattering channels along with an unconstrained $^3$H component. For each of these cases we will assume flat priors on free parameters in the likelihood scan.

Finally, we will also consider the possibility that the low energy excess disappears with more exposure at XENONnT experiments or that the background model becomes more well-understood and shows no excess. We can simulate these possibilities to forecast future exclusions in parameter space. Future limits and the five cases that we consider for the analysis of the excess are discussed in the next section.

IV. FIT RESULTS

After checking all five cases described in Section III with the likelihood-ratio test statistic, we find that the $^3$H unconstrained model rejects the background-only hypothesis at a 2.3σ level, in agreement with the XENON1T result. When Primakoff production and detection mechanisms are added to the signal model that includes the unconstrained $^3$H component, we find a significance of 2.6σ, while if we remove the $^3$H component and just include Primakoff production and detection, we reject the background-only hypothesis at 3.1σ, slightly less significant than the XENON1T result which omitted the inverse Primakoff detection component. This may be intuitively understood by the shape difference between the Primakoff flux with inverse Primakoff response, shown as
the red dotted curve in Fig. 2, and the response from the ABC-produced axioelectric absorption which is peaked at lower energies more than the inverse Primakoff response. Finally, if we allow for all fluxes and detection channels that we considered to be present in the likelihood scan, we find a rejection of the background at a level of 3.7σ, mildly higher than the XENON1T result, while if we also include an unconstrained 3H, the significance is reduced to 2.95σ.

For the purely Primakoff production and detection scenario, in Fig. 3 we display our best fit region in the \( g_{a\gamma} - m_a \) parameter space for the XENON1T excess, as well as the current limits from the CAST helioscope and astrophysical bounds. The CAST limits [48] provide a bound of \( g_{a\gamma} < 0.66 \times 10^{-1} \text{GeV}^{-1} \) (95% C.L.) for \( m_a < 0.02 \text{eV} \), and \( g_{a\gamma} < 2 \times 10^{-1} \text{GeV}^{-1} \) (95% C.L.) for \( m_a < 0.7 \text{eV} \). The excess explanation evades the CAST constraint for \( m_a > 0.03 \text{eV} \).

Bounds from the \( R \)-parameter - the ratio between the number of horizontal branch (HB) stars and red giant branch (RGB) stars in older stellar clusters [49] - also sets a very stringent bound of \( g_{a\gamma} < 0.66 \times 10^{-10} \text{GeV}^{-1} \) (95% C.L.), but extends to higher axion masses than the CAST bound. However, since HB and RGB stars have much higher density (two to four orders of magnitude) and higher core temperatures (by a factor of seven) compared to the sun, mechanisms exist in the context of specific particle physics models which could allow the evasion of the bounds emerging from the null observation of axions associated with these astrophysical objects, e.g. [19–25].

The evasion could involve additional scalar degrees of freedom around the HB star temperature by invoking a phase transition [24], or the axion as a chameleon-type field with its mass depending on the environmental matter density \( \rho \) [20, 25]. In addition, the possibility that the axion is a composite particle with a form factor has been explored [21–23], leading to a suppression of the production in the HB stars, as well as models with a paraphoton where the axion-like particles are trapped in the HB star interior thus evading the stellar bounds.

Another possibility involves considering a population of axions gravitationally bound to the Sun. In [50], it is shown that stellar emission of axions into gravitationally bound orbits can significantly increase the flux of axions on Earth. This additional flux reduces the coupling required to explain the XENON1T excess (\( g_{a\gamma} \sim 10^{-13} \)) and thus reduces tension with the astrophysical constraints. Further work is required to determine if this scenario can indeed provide a robust explanation of the XENON1T excess.

In Fig. 4, 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 \( g_{a\gamma} = 10^{-16} \text{GeV}^{-1} \). In the limit of small \( g_{ae} \) the inverse

![Figure 3](image3.png)

**FIG. 3.** The 2σ credible bands for Primakoff-produced solar axions undergoing solely inverse-Primakoff scattering in XENON1T (blue band) is compared against the 2σ limit when \( ^3H \) is included as a background as well as the signal hypothesis (hatched band). We also show the 2σ bound from the Primakoff signal hypothesis tested against the \( B_0 \) background, simulating a no-excess scenario. We discuss the CAST and HB stars constraints in the text.

![Figure 4](image4.png)

**FIG. 4.** 2σ credible contours are shown for fits to the XENON1T excess for all axion flux components with (i) only axioelectric scattering (red) and (ii) with both inverse-Primakoff and axioelectric scattering (blue). 1σ contours are also shown with dark shading. HB stars and white dwarf exclusions are indicated by the arrows. Here we consider \( m_a = 0.7 \text{ eV} \) for the plot. However the plot does not change for any \( m_a < 100 \text{ eV} \). The CAST constraints get evaded for \( m_a > 0.03 \text{ eV} \).
Primakoff channel provides flat sensitivity that is especially improved for KSVZ-type models. Constraints from white dwarf luminosity function (WDLF) place bounds on $g_{ae} < 2.8 \times 10^{-13}$ [51].

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; in Fig. 3, we show the constraint in $g_{ae}$ 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. 5, we show the future XENONnT constraint (with a 1 kton-year exposure) and find that the 2σ (∼95% CL) can overcome even the HB stars constraint 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 order of magnitudes. We also find that our projected sensitivity for a 1 kton-year exposure at XENONnT is competitive with future helioscope experiments. We compare the 1 kton-year XENONnT projection against the projected sensitivities for IAXO+ with masses $m_a > 0.1$ eV, where sensitivity begins to diminish for larger masses [52] in Fig. 5. 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.

V. CONCLUSION

In this work, we investigated inverse Primakoff scattering as a new detection channel at liquid xenon based direct detection experiments. We showed that use of the sole coupling $g_{ae}$ 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 better than the CAST limit. The future XENONnT experiment can also overcome the HB stars limit (if it is not already evaded by the particle physics models) 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 $m_a \gtrsim 0.1$ eV.

**Note Added:** During the completion of this work, a study [53] appeared that also investigated the effect of the inverse Primakoff effect on solar axion detection.

## Acknowledgements

The authors thank Nicole Bell for discussions related to this work. JLN is supported in part by the Australian Research Council. JBD acknowledges support from the National Science Foundation under Grant No. NSF PHY182080. BD and AT acknowledge support from DOE Grant DE-SC0010813. AT also thanks the Mitchell Institute for Fundamental Physics and Astronomy for support.

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