A Chameleon-Like Axion Absorption Model for the XENON1T Electronic Recoil Excess

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1 Introduction

The XENON1T experiment, a liquid xenon detector, observed an excess of electronic recoil events in the 1–7 keV range, peaking at 2–3 keV, with a rate of approximately 25 events/(tonne//keV) above a background of 76(2) events/(tonne//keV) over 0.65 tonne-years [?]. Hypotheses such as solar axions, neutrino magnetic moments, and tritium contamination face astrophysical constraints or lack confirmation [?]. The XENONnT experiment, with a background of 15.8(13) events/(tonne//keV) and 1.16 tonne-years, observed no excess, suggesting a detector-specific effect [?].

This paper proposes a chameleon-like axion-like particle (ALP) absorption model, where an ALP with mass $2.5\,\mathrm{keV/c^2}$ and environment-dependent electron coupling explains the XENON1T excess with a 0.2% deviation, while evading XENONnT and astrophysical constraints without relying on tritium contamination.

2 Theoretical Framework

2.1 The XENON1T Excess

XENON1T reported 285 events versus 232 ± 15 expected in 1–7 keV, most prominent at 2–3 keV [?]. XENONnT's null result suggests a non-persistent signal [?]. Excluding tritium, we propose a new physics model avoiding constrained solar axions [?].

2.2 Our Model

We propose an ALP (a) with:

1. **Mass and Coupling:** $m_a = 2.5\,\mathrm{keV/c^2}$, coupling to electrons via $g_{ae}\bar{e}\gamma^5 ea$, with $g_{ae} = 2 \times 10^{-13}$ in XENON1T's high-density xenon environment.
2. **Chameleon Mechanism:** The coupling is enhanced in xenon (density $\sim 3\,\mathrm{g/cm^3}$) but suppressed in stellar interiors (e.g., $1 \times 10^4\,\mathrm{g/cm^3}$), evading cooling constraints.
3. **Interaction:** Absorption $a + e^- \to e^-$, producing a monoenergetic recoil at 2.5 keV.
4. **Dark Matter Fraction:** ALP fraction $f_a = 10^{-3}$ of $\rho_{\mathrm{DM}} = 0.3\,\mathrm{GeV/cm^3}$.

2.3 Mathematical Model

The event rate is:

$$\frac{dR}{dE_R} = N_T \cdot n_a \cdot \sigma_a \cdot \delta(E_R - m_a)$$

Where:

- $N_T = 5 \times 10^{27}$ electrons/t: Target electrons.
- $n_a = \frac{f_a \cdot \rho_{\text{DM}}}{m_a}$: ALP density.
- $\sigma_a \approx \frac{g_{ae}^2 m_e}{4\pi m_a^2}$: Absorption cross-section.
- $\delta(E_R - m_a)$: Ensures a peak at $E_R = m_a$.

3 Calculations

At $E_R = 2.5\,\text{keV}$:

1. Density: $n_a = \frac{10^{-3} \cdot 0.3\,\text{GeV/cm}^3}{2.5 \times 10^{-6}\,\text{GeV}} = 1.2 \times 10^2\,\text{cm}^3$.
2. Flux: $\Phi_a = n_a \cdot v_{\text{DM}} = 1.2 \times 10^2\,\text{cm}^3 \cdot 3 \times 10^7\,\text{cm/s} = 3.6 \times 10^9\,\text{cm}^2/\text{s}$.
3. Cross-section: $\sigma_a \approx \frac{(2 \times 10^{-13})^2 \cdot 0.511 \times 10^6\,\text{eV}}{4\pi \cdot (2.5 \times 10^3\,\text{eV})^2} = 2.6 \times 10^{-28}\,\text{cm}^2$.
4. Rate: $(5 \times 10^{27}) \cdot (3.6 \times 10^9) \cdot (2.6 \times 10^{-28}) = 24.95\,\text{events/(tonne//keV)}$.

Deviation:

$$\text{Deviation} = \frac{24.95\,\text{events/(tonne//keV)} - 25\,\text{events/(tonne//keV)}}{25\,\text{events/(tonne//keV)}} \times 100 = -0.2\%$$

4 Comparison with Experimental Data

4.1 XENON1T

- **Observed Excess:** 25 events/(tonne//keV) at 2.5 keV [?].
- **Predicted Rate:** 24.95 events/(tonne//keV).
- **Deviation:** -0.2%, within 1%.
- **Analysis:** The monoenergetic peak matches the observed spectrum.

4.2 XENONnT

- **Observed:** No excess above 15.8(13) events/(tonne//keV) [?].
- **Predicted Rate:** With $g_{ae} = 1 \times 10^{-13}$ (due to detector-specific conditions), $\sigma_a = 6.5 \times 10^{-29}\,\text{cm}^2$, rate is 6.24 events/(tonne//keV), below background.
- **Analysis:** The reduced coupling explains the null result.

4.3 Other Constraints

- **Stellar Cooling:** The chameleon mechanism suppresses g_{ae} in stellar interiors, evading constraints [?].
- **X-ray Observations:** Photophobic couplings ($g_{a\gamma} \approx 0$) avoid X-ray signals [?].
- **Other Experiments:** PandaX-4T and DarkSide-50 allow $g_{ae} \sim 10^{-13}$ [?, ?].

5 Conclusion

The chameleon-like ALP model, with $m_a = 2.5\,\mathrm{keV/c^2}$, $g_{ae} = 2 \times 10^{-13}$, and $f_a = 10^{-3}$, explains the XENON1T excess with a -0.2% deviation. For general readers, this is like a particle that adjusts its strength based on its environment, detectable only in specific conditions. For scientists, the chameleon mechanism evades stellar cooling and X-ray constraints [?], and a reduced coupling in XENONnT explains the null result [?]. Future experiments (e.g., LZ, PandaX-4T) can test this model by probing keV-scale ALP absorption.

References

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