Axion Quasiparticles for Axion Dark Matter Detection

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Outline

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Condensed Matter Axions

- Axion QuasiParticles (AQPs) may exist in certain materials. (F. Wilczek, 1987; Gooth *et al*, 1906.04510)
- AQPs are collective excitations of electrons that behave like an axion: $\mathcal{L} \supset \theta_Q \mathbf{E} \cdot \mathbf{B}$.
- AQPs may be used to detect axion Dark Matter (D. Marsh *et al*,1807.08810; J. Schütte-Engel *et al*, 2102.05366; S. Chigusa *et al*, 2102.06179).

Topological Insulators

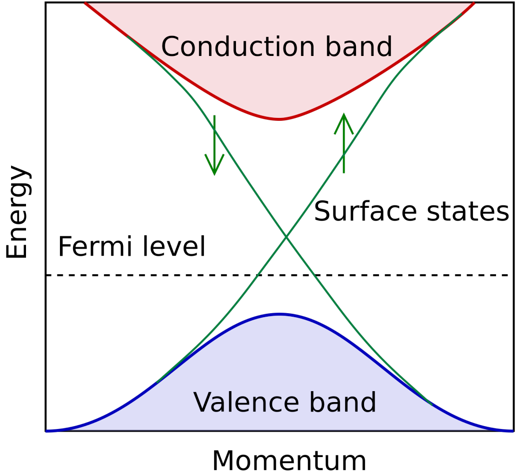


Diagram by A13ean

Insulating in the bulk but conducting at the surface.

Topological Insulators

- The electrodynamics at the surface of topological insulators is described by the addition $\mathcal{L} \supset \theta \mathbf{E} \cdot \mathbf{B}$ with $\theta = \pi$.
- The resulting Maxwell equations are only sensitive to the gradient in theta at the surface of the material.
- Time Reversal symmetry requires $\theta = 0$ or $\theta = \pi$.

Anti-ferromagnetic Topological Insulators

- In anti-ferromagnetic topological insulators, time reversal symmetry is broken and θ can take different values.
- In some such materials, θ may be a dynamical axion quasi-particle (AQP) (Li *et al*, 0908.1537).
- In the materials we consider, the AQP is a longitudinal magnon mode.

The Axion QuasiParticle

$$S_{\rm topo} = \frac{\alpha}{\pi} \int \mathrm{d}^4 x \left(\delta\Theta + \Theta^0 \right) \boldsymbol{E} \cdot \boldsymbol{B},$$

$$S_\Theta = \frac{f_\Theta^2}{2} \int d^4 x \left[(\partial_t \delta\Theta)^2 - (v_i \partial_i \delta\Theta)^2 - m_\Theta^2 \delta\Theta^2 \right].$$

f_Θ and m_Θ can be predicted from known material properties and measured using transmission spectroscopy.

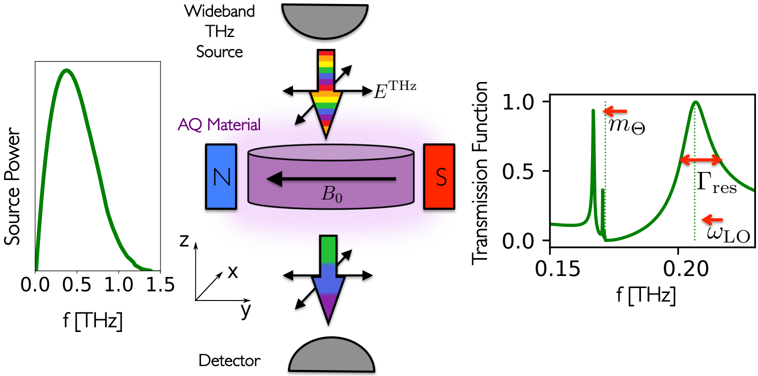
The Axion QuasiParticle

$$f_\Theta = 30\mathrm{eV}\left(\frac{M_0}{0.03\mathrm{eV}}\right)^{0.5}\left(\frac{V_{\mathrm{u.c}}}{440\mathring{A}^3}\right)^{-0.5}\left(\frac{t}{0.04\mathrm{eV}}\right)^{-1.5}\left(\frac{\mathcal{I}_1}{4\times 10^{-7}}\right)^{0.5}$$

$$m_\Theta = 2\mathrm{meV}\left(\frac{S}{4.99}\right)\left(\frac{U}{3\mathrm{eV}}\right)\left(\frac{\mathcal{I}_2/\mathcal{I}_1}{4\times 10^{-8}}\right)^{0.5}$$

- M_0 = bulk band gap
- $V_{\mathrm{u.c}}$ = unit cell volume
- t = nearest neighbour hopping
- S = magnetic moment of ion
- $\mathcal{I}_1$, $\mathcal{I}_1$ are energy integrals over the Brillouin zone
- U = Hubbard term (interactions between spins on the same site)

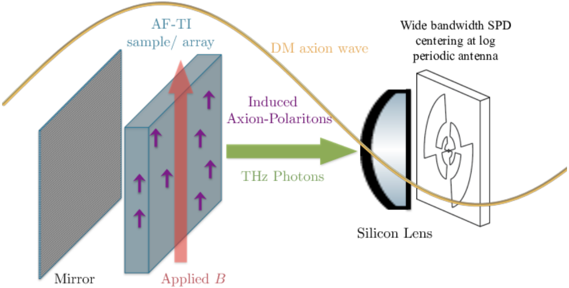
Transmission Spectroscopy



The AQP and Axion Dark Matter

- Both the AQP and the Dark Matter axion couple to $\mathbf{E} \cdot \mathbf{B}$.
- In an applied magnetic field, the AQP and electric field mix, giving the axion-polariton propagating degrees of freedom.
- Dark matter axions can resonantly mix with the axion-polariton - the resonant frequency is *tuneable* via the applied magnetic field.
- The three way mixing produces a detectable photon at the bounding of the material.

Axion Dark Matter Detection



TOORAD: Topological Resonant Axion Detection

Linearized Equations of Motion

$$\left(\partial_z^2 - n^2\partial_t^2 - \sigma\mu\partial_t\right) E_y = \mu B_e \partial_t^2 \left(\frac{\alpha}{\pi}\delta\Theta + g_{a\gamma} a\right)$$
$$\left(v_z^2\partial_z^2 - \partial_t^2 - m_\Theta^2\right) \delta\Theta = -\Lambda B_e E_y$$
$$\left(\partial_z^2 - \partial_t^2 - m_a^2\right) a = -g_{a\gamma} B_e E_y$$

- Axion Dark Matter drives the system at frequency m_a.
- Mixing of E and $\delta\Theta$ gives the photon an effective mass $\sim m_\Theta$.

Interface Conditions

- $\boldsymbol{n} \cdot (\nabla a_1 - \nabla a_2) = 0$
- $a_1 - a_2 = 0$
- $\boldsymbol{n} \times (\boldsymbol{H}_{\Theta,2} - \boldsymbol{H}_{\Theta,1}) = 0$
- $\boldsymbol{n} \times (\boldsymbol{E}_2 - \boldsymbol{E}_1) = 0$

$$\boldsymbol{H}_\Theta = \boldsymbol{H} - \frac{\alpha}{\pi}\Theta^0 \boldsymbol{E}$$

Resonance

In the lossless case, the material has an effective refractive index

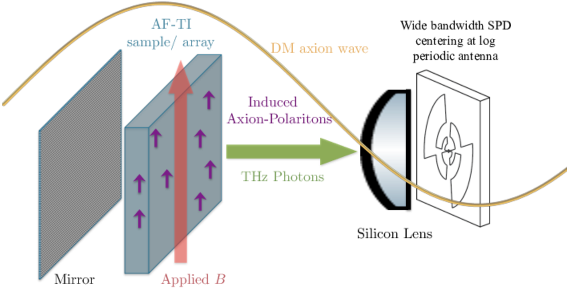
$$n_\Theta^2 = n^2 \left(1 - \frac{b^2}{\omega^2 - m_\Theta^2}\right),$$

where $b = \frac{\alpha}{\pi\sqrt{2}} \frac{B_0}{\sqrt{\epsilon} f_\Theta}$.
A resonance in the emitted power occurs when

$$n_\Theta(\omega)\omega d = (2n+1)\pi,$$

where d is the material thickness.

TOORAD

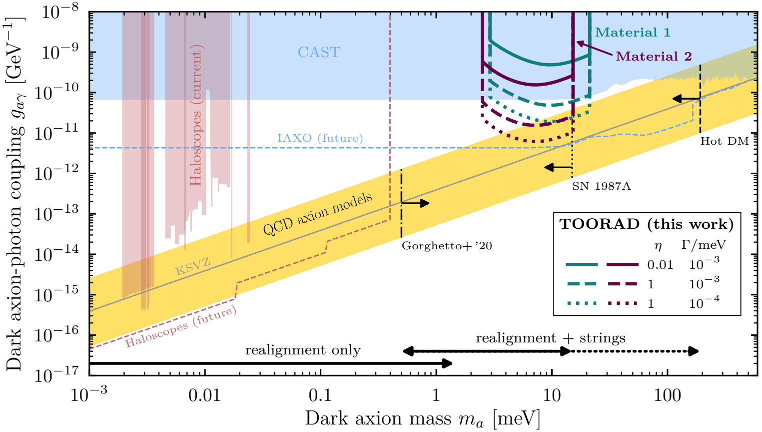


- The resonant frequency can be tuned independently of the material volume.
- This allows detection of higher mass axions $m \sim 1 - 10$ meV.

TOORAD

- Reach depends on available photon detectors.
- We must take into account damping of the axion-polariton.
- Losses are dominated by the material resistivity and AQP scattering from impurities and domain boundaries.

Axion Dark Matter Detection



Material 1: $(Bi_{1-x}Fe_x)_2Se_3$; Material 2: $Mn_2Bi_2Te_5$