STAX

An improved detection scheme for axion-like particles

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Axion-like particle searches with sub-THz photons

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ABSTRACT

We propose a variation, based on very low energy and extremely intense photon sources, on the well established technique of Light-Shining-through-Wall (LSW) experiments for axion-like particle searches. With radiation sources at 30 GHz, we compute that present laboratory exclusion limits on axion-like particles might be improved by at least four orders of magnitude, for masses $m_a \leq 0.01$ meV. This could motivate research and development programs on dedicated single-photon sub-THz detectors.

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Axion to photon conversion

- Light pseudo scalar $J^P = 0^-$ can solve both the dark matter problem and the CP symmetry puzzle in QCD

- $m_a < 3 \times 10^{-3}$ eV from SN1987

- Axion, like neutral pion couples to two photons via fermion loop (Primakoff effect)
Axion in magnetic field

Axion-B field interaction can be treated quasi-classically as an interaction of a photon with an external field with a photon-axion transition.
Axion-Photon conversion probability

\[ P_{\gamma \rightarrow a} = P_{a \rightarrow \gamma} = G^2 H^2 \frac{\sin^2(q_x L_x/2)}{q_x^2} \frac{\epsilon_\gamma}{\sqrt{\epsilon_\gamma^2 - m_a^2}} \]

with the transferred momentum

\[ q_x = \frac{m_a^2}{2 \epsilon_\gamma} \]

G is the axion-gamma coupling constant < 10^{-10} GeV^{-1} from astrophysics

2 key points: very high H field
very intense source
Axions Experiments

- Three types: Haloscopic, Helioscopic, LSW
- Halo often use cavities: High sensitivity but limited mass window

Only experiments hitting Peccei-Quin region

Ex: ADMX Livermore

Exclusion plot for axion-like particles as described in the text.

In the DFSZ model \[17\], the tree-level coupling coefficient to electrons is

\[ C_e = \cos^2 \beta \]

where \( \tan \beta \) is the ratio of two Higgs vacuum expectation values that are generic to this and similar models.

For nucleons, \( C_{n,p} \) are related to axial-vector current matrix elements by generalized Goldberger-Treiman relations,

\[
C_p = (C_u - \eta) \Delta u + (C_d - \eta z) \Delta d + (C_s - \eta w) \Delta s,
\]

\[
C_n = (C_u - \eta) \Delta d + (C_d - \eta z) \Delta u + (C_s - \eta w) \Delta s.
\]

Here, \( \eta = (1 + z + w)^{-1} \) with \( z = m_u/m_d \approx z \) and the \( \Delta q \) are given by the axial vector current matrix element

\[
\Delta q_S \mu = \langle p | \bar{q} \gamma^\mu \gamma^5 q | p \rangle
\]

with \( S_{\mu} \) the proton spin.

Neutron beta decay and strong isospin symmetry considerations imply

\[
\Delta u - \Delta d = F + D = 1 \pm 0.003, \quad \text{whereas hyperon decays and flavor SU(3) symmetry imply}
\]

\[
\Delta u + \Delta d - 2 \Delta s = 3 F - D = 0 \pm 0.031 \ [21].
\]
Axions Experiments

- Three types: Halosscopic, Helioscopic, LSW
- Helioscopic depend on stellar/galactic models

\[ \Phi_a \sim 4 \times 10^{11} \cdot g_{10}^2 \text{ cm}^{-2} \text{ s}^{-1}, \quad g_{10} \equiv g_{a\gamma\gamma}/10^{-10} \text{ GeV}^{-1} \]

Ex: CAST (best limit at the moment) and IAXO (CERN) use LHC dipoles

\( <E> \sim 4.2 \text{ KeV} \)
**LSW: Light Shining through the Wall**

\[ \dot{N} \propto \dot{N}_{\text{source}} \times P_{\gamma \rightarrow a} P_{a \rightarrow \gamma} \approx \dot{N}_{\text{source}} \times g^4 H^4 L_x^4 \]

Sensitivity on \( g \) turns out to be:
- Linear with magnetic field \( H \) and path
- Quartic root of time and flux

The first such experiment was carried out by Ruoso et al. in the early 1990s using two Brookhaven CBA dipoles (4.4 m long each, 3.7 T), and an argon ion laser (1.5 W, 200 traversals in an optical cavity). A limit of $g^{5.6.7 \times 10^{-6}}$ GeV was established, for $m_a = 3 \times 10^{-7}$ eV [53].

The original PVLAS results, however, prompted a tremendous resurgence of activity in laboratory experiments which could unambiguously confirm or refute the particle interpretation of the unexpectedly large vacuum dichroism and birefringence data. At least half a dozen photon-regeneration experiments were launched, some still in the planning phase, and two of which have already taken data and published their results. The first of them, by the BMV collaboration at LULI, utilised a novel short pulsed-field magnet [54]. The other, the GammeV collaboration, employed a standard Tevatron dipole magnet (6 m long, 5 T field) with the optical barrier in the middle (Figure 15) [55]. Both BMV and GammeV conclusively confirmed the non-existence of a pseudoscalar in the original PVLAS allowed region (Figure 16).

It is reasonable to ask why would one encourage several competing efforts to continue when none of them would be competitive with the solar or astrophysical limits many orders of magnitude stronger, i.e. $g^* = 10^{-7} \times 10^{-1}$. A new and compelling motivation for a major campaign in photon regeneration has recently been published, which demonstrates that the basic photon regeneration experiment (Figure 14(a)) can be resonantly enhanced by encompassing both the production and regeneration magnets in matched Fabry–Peţrot optical resonators, which are actively locked to one another in frequency (Figure 14(b)) [56].

It is shown that if the reflectivity of the end-mirrors in the production and regeneration cavities are $Z, Z_0$, respectively, then the resonantly enhanced probability is given by

$$P_{res}(g_a^m) = \frac{2Z_0}{F F_0} P_{non-res}(g_a^m),$$

where $F, F_0$ represent the finesse of the two cavities, roughly equivalent to the number of passes the light makes in each. It is important to note that while the...
Up to $m_a \approx 0.1 \varepsilon_\gamma$, photon-axion conversion probability depends on luminosity, not on photon energy $\Rightarrow$ **sub-THz photons** sources have the largest luminosity

**Very intense photon source:** gyrotrons up to 1 MW @ 30 GHz $\rightarrow 10^{28}$ photons / s
for the first lab set up $P \approx 100$ kW, $\Phi_\gamma = 10^{27}$ s$^{-1}$, $\varepsilon_\gamma = 120$ μeV ($\nu \approx 30$ GHz)

**High dipole magnetic field** of $\sim 15$ T and $L_x = 50$ cm

**Sub-THz single-photon detector:** based on TES technology, $\eta \approx 1$, dark count negligible

30-100 GHz is the optimal point
For reference 1 GHz = 4.1 μeV
STAX: gyrotrons

For reference 1 GHz = 4.1 μeV

30-100 GHz is the optimal point

As discussed above, in a LSW setup the total number of photons per time unit detected after the wall is, in general, proportional to the power \( P \) of the primary photon source according to the relation

\[
\frac{\dot{N}}{PE} \propto P^4 H^4 L^4 x \]

Therefore, the efficiency of a LSW experiment, beyond the \((HL)\) factor appearing in the product of the photon-axion and axion-photon conversion probabilities, stems mainly from the number of photons hitting the wall, i.e., from the source luminosity \( PE \), and from the sensitivity of the radiation detector at the relevant frequency.

For the first time in the field of LSW experiments, STAX will use specific photon sources emitting in the microwave or sub-THz regime (i.e., exploiting, for instance, masers) allowing extremely high fluxes of incident photons. As displayed in Fig. 3, the sub-THz spectral range is where the maximum photon source luminosity is achievable (values on the y axis are obsolete, exceeding nowadays the MW. However the power scale is still valid).

Figure 3: Average power versus emitted frequency for common photon sources available on the market. Different power values have to be considered as relative, since nowadays gyrotrons working points exceed the power of 1 MW.
The operating region of gyrotrons

Now beyond 1 MW power
**STAX: TES detectors**

**Transition Edge Sensor (TES):** *ultra-low* critical temperature superconductor between two superconducting electrodes. TES coupled to antenna.

**TES operated within its superconducting transition.** DC bias voltage applied. When TES absorbs an incoming photon, it heats up above critical temperature $T_c$. Change of resistance and current flowing in the circuit, measured by a SQUID.

**efficiency ~ 1**

**Negligible background / dark count**

![Diagram of a TES detector](image)
Sub -THz TES for STAX

R&D goal: implement TES sensors in the working region between 30-100 GHz through 4 drivers

Material: choice of a Superconductor with low critical temperature \((T_c \approx 15 \text{ mK})\) to have a good energy resolution \((\sim T^{3/2})\) use \(\alpha\)-tungsten (or Ti based bi-layers) for implementation of TES with \(T_c \approx 15 \text{ mK}\).

\(\alpha\)-W, bilayer Ti-Au or Ti-Cu

Tailoring TES active volume to reduce thermal capacitance

\((10^{-3}-10^{-4} \mu\text{m}^3)\)

low-noise SQUID readout electronics optimization (operating at 100 mK)

Efficient New log-periodic spiral antenna with planar design to enhance the efficiency
STAX potential exclusion reach

cit. Phys. Dark Univ. 12, 37 (2016)

- Exclusion limits STAX may achieve in case of null result
- **STAX** limits compared to
  - **ALPS LSW** results
  - **CAST** results
  - Calculated limits of **ALPS II**
    JINST 8, T09001 (2013)
    arXiv:1309.3965
  - **QCD Axion models** predictions
    (Inclusion limits)

**STAX**: 1 month exposure time \( P = 100 \text{KW} \)

**STAX2**: \( P = 1 \text{MW} \) and Fabry-Perot \( Q \sim 10^4 \) cavities to enhance the luminosity

**STAX2 option B**: new concept \( Q \sim 10^6 \div 10^8 \) cavities with lower source power of \( P = 100 \text{W} \div 1 \text{KW} \) and highest purity
### STAX vs ALPS

<table>
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<th>Parameter</th>
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<th>STAX</th>
<th>( \frac{G_{\text{ALPS}}}{G_{\text{STAX}}} )</th>
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<td>( 10^{-9} \text{ s}^{-1} )</td>
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<tr>
<td>Combined Improvement</td>
<td></td>
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<td>( \sim 10^4 )</td>
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Enhanced gyrotron power up to 1 MW

A second cavity installed in the magnetic field region behind the wall
A coherent axion beam excite the cavity electromagnetic modes
enhanced axion-photon conversion  P. Sikivie, D.B. Tanner and K. Van Bibber, 
Exclusion Plot Axion–Like Particle.

STAX: Time: $2.6 \cdot 10^6$ s, $H = 15$ T, $L_x = 0.5$ m

$Q = 10^4, E_\gamma = 118 \mu eV, \dot{N} = 10^{27} \gamma/s, P = 100$ kW

**STAX**

- $Q_{\text{reg}} = 10^4$
- $P = 1$ MW

**CAST**

**ALPS(LSW)**

**ALPS II**

Axions Search exclusions

STAX potential

QCD Axion Inclusion
Exclusion limits STAX may achieve in case of null result

**STAX** limits compared to
- **ALPS LSW** results
- **CROWS** results
- **Spring-8** results
- **XENON10** results

Constraints on dark photons from measurements of the **CMB**

Searches for modifications of **Coulomb's Law**
Conclusions

We propose an improved detection scheme for axion-like particles searches based on a Light-Shining-Through-Wall (LSW) experiment in a photon frequency domain never explored before and a relative low cost (~ 5Meu).

The aim is that of setting the most stringent exclusion limits on axion-like particles ever reached in this kind of experiments.

To pursue the final objective we need to undergo an intermediate phase of R&D on the basic unit of the apparatus we have in mind to build: a TES detector for sub-THz photons.

The antenna and the cavities implementation will be other important milestone
BACK-UP

Wavelength associated to virtual axion $\lambda = 1/p_x \approx L_x$
Uncertainty principle: $\Delta x \approx L_x \rightarrow \Delta p \geq 1/L_x$
In more details, if $\lambda/2 < L_x$ the entire process takes place in the $H \neq 0$ region

Consider $\varepsilon_\gamma \neq m_\alpha$, so that $q_1 \geq m_\alpha + 1/2L$, $q_2 \leq m_\alpha - 1/2L$
Poles coincide when $\varepsilon_\gamma = m_\alpha$ ($p^* = 0$)
Minimum distance between poles must satisfy: $\min(q_1 - q_2) = 1/L$

We argue the formula

$$P_{\gamma \rightarrow \alpha} \approx G^2 H^2 \frac{\sin^2(q_x L_x/2)}{q_x^2} \frac{\varepsilon_\gamma}{L_x} + \sqrt{\varepsilon_\gamma^2 - m_\alpha^2}$$

to be used when $\varepsilon_\gamma \approx m_\alpha$ to avoid unphysical divergences
**Axion-like particles**

\[ \mathcal{L}_I = \frac{i}{\hbar} \bar{a}_\mu \tilde{F}_\mu \tilde{F}^{\mu \nu} \]

\[ \tilde{F}_{\mu \nu} = \frac{i}{2} \epsilon_{\mu \nu \alpha \beta} F_{\alpha \beta} \]

\[ \square a = \frac{i}{\hbar} \tilde{H}_{\text{ent}} \cdot \frac{2}{\hbar} \tilde{A} - m^2 a \]

Cfr. Poisson eq. in electricity:

\[ \Delta \phi + k^2 \phi = -4 \pi \rho \]

\[ \phi = \int \rho \left( \vec{r}', t - \frac{R}{c} \right) \frac{e^{ikR}}{R} \, dV' \]
Photon-Axion Conversion

\[ \gamma \ \rightarrow \Downarrow \ \rightarrow \ \rightarrow \ \rightarrow \ \rightarrow \ \rightarrow \ \rightarrow \ \rightarrow \ \rightarrow \ \rightarrow \ \rightarrow \ \rightarrow \ a \]

Unstable in H

\[ a = f \frac{e^{i k \tau}}{r} \]

\[ |M_{\gamma \rightarrow a}|^2 = \frac{1}{4\pi^2} \left| \int \frac{e^{i q \cdot r}}{r} \cdot \vec{H}(\vec{r}) \cdot \vec{E}(\vec{k}_\gamma, \lambda) \, dV \right|^2 \]

Max when \( \vec{k}_g \perp \vec{H} \)

Formula holds for \( \vec{E}_g = \vec{E}_a \)

Notice \( |\vec{k}_g| = |\vec{k}_a| \) and \( \vec{q} = \vec{k}_g - \vec{k}_a \)
Conversion Probability

In the $I$ plane $H$ extends over long dist. wrt $1/q_y$ & $1/q_x$. In the $II$ direction we assume $L_x \lesssim 1/q_x$.

\[
P_{x\rightarrow 2a} = \frac{H^2}{\mu^2} \frac{\sin^2 \left( \frac{q_x L_x}{2} \right)}{q_x^2} \left( \frac{\xi_y}{k_x} \right)
\]

\[
q_x = \frac{m_a^2}{2E_y}
\]

\[
|\vec{K}_a| = E_y^2 - m_a^2 = E_y^2 - m_a^2 \sim E_y \text{ as } E_y \gg m_a
\]
Massive vectors of hidden $U(1)_h$

Visible and hidden-sector photons Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + e J_{\text{em}}^\mu A_\mu + e_h J_h^\mu B_\mu - \frac{1}{2} \mu^2 B^\mu B_\mu$$

$F^{\mu\nu}$ = field strength tensor for $A^\mu$; $B^{\mu\nu}$ = field strength tensor for $B^\mu$ (paraphoton)

A and B rotated into $B_1$ and $B_2$; mixing angle $\chi < 10^{-2}$

$B_1$ and $B_2$ acquire masses $m_1 = \mu \chi$, $m_2 = \mu$

Photon field evolve as:

$$A(r) = \frac{1}{\chi^2 + 1} e^{-i(\epsilon \gamma t - k_1 r)} \left[ A(1 + \chi^2 e^{-iqr}) + \chi B(e^{-iqr} - 1) \right]$$

$$k_1 \approx \epsilon \gamma$$

$$k_2 \approx \sqrt{\epsilon^2 \gamma^2 - \mu^2}$$

$$q = k_1 - k_2$$
Dark photons


\begin{itemize}
  \item Conversion probability: \( P_{\gamma \rightarrow \gamma'}(r) = 4 \chi^2 \sin^2 \left( \frac{q r}{2} \right) \)
  \item \( P_{\gamma \rightarrow \gamma' \rightarrow \gamma} = P_{\gamma \rightarrow \gamma'}(L_1) P_{\gamma' \rightarrow \gamma}(L_2) = 16 \chi^4 \left[ \sin \left( \frac{q L_1}{2} \right) \sin \left( \frac{q L_2}{2} \right) \right]^2 \)
  \item Rate: \( \frac{dN_\gamma}{dt} = \eta \Phi_\gamma \left[ \frac{N_{\text{pass}} + 1}{2} \right] P_{\gamma \rightarrow \gamma' \rightarrow \gamma} \)
\end{itemize}

\( \Phi_\gamma = \text{photon flux (s}^{-1}) , \ \eta = \text{detector efficiency} \)
Dark count and other bkg sources

Dark count rate (phonon noise) \( \sim 6 \times 10^{-13} \text{ s}^{-1} \)

\[ N_d = \frac{\beta_{\text{eff}}}{\sqrt{2\pi}} \int_{E_T/\delta E}^{\infty} \exp(-x^2/2) \, dx \]

\( \beta_{\text{eff}} = 1/\tau_{\text{eff}} \) is the effective detection bandwidth, and \( E_T \) is the discrimination threshold energy.

Black Body: at 10mK peaked around 0.6 GHz with a negligible rate of \( 10^{-30} \text{ m}^{-2} \text{ s}^{-1} \) photons irradiated

Cosmic bkg: 1mu/cm\(^2\)/min with 10 eV released in 10nm of material saturates the TES, bkg. under control translated in a negligible dead time of the TES \( \sim 0.1\% \)

Environmental radioactivity: negligible with similar estimates

Dark count negligible at these sub THz frequencies
Facilities located between INFN-Pisa and NEST-Pisa possibility to use INFN S.Piero Labs
### Financial Plan and Requests

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