Search for a Scalar Axion–like Particle at 34 GHz

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DOI: will be assigned

Light axion–like particles (ALPs) that couple to two photons are allowed in a number of proposed extensions to the Standard Model of elementary particles. Of particular interest from a theoretical and observational standpoint is the energy regime near 0.1 meV. We present results from a pilot experiment to search for a signal from a 0.14 meV scalar ALP by way of its coupling to two photons. Using a copper resonant cavity cooled to four degrees Kelvin while immersed in a seven Tesla magnetic field, and coupled to a low noise cryogenic amplifier and room temperature receiver, we exclude an ALP–driven excess of 34 GHz photons with \( g > 10^{-8}/\text{GeV} \) with 5\( \sigma \) confidence. We discuss the ramifications of this initial measurement as well as planned modifications to the experiment for increased sensitivity.

1 Introduction

Several theories of particle physics as well as cosmology predict the existence of at least one sub–eV scalar, that is, spin-zero, boson [1, 2, 3, 4, 5]. Correspondingly, many theories of physics beyond the Standard Model (SM) can accommodate scalars with very small masses and feeble couplings to SM fields [6, 7]. An intriguing possibility in astrophysics and cosmology is that these weakly interacting, sub–eV particles (WISPs) may constitute at least some component of the cold dark matter in the universe [8, 9, 10]. It has been shown that these arguments apply for both pseudoscalar, namely axion [8, 9], and scalar [10] WISPs, e.g. axion–like particles (ALPs) that couple to two photons.

The current experimental programs that explore the parameter space of weakly interacting, light, spin-zero bosons include sensitive searches that make use of resonant cavities [11, 12, 13, 14]. Scalar ALPs may be detected by stimulation of the conversion to photons in a magnetic field, similar to the way that axion conversion may take place [15]. This conversion can occur in a suitable cavity that is properly tuned to the mass of the ALP.

While it should be noted that scalar couplings to two photons are strongly excluded by fifth force experiments [16], it is possible that a low energy form factor could relax these constraints in some models [16]. The Lagrangian that describes the coupling of a light scalar particle to two photons in the presence of an external magnetic field takes the form:

\[ \mathcal{L} = \frac{\lambda}{4m} \phi \mathcal{F} \phi \phi^\dagger \mathcal{F} \]

\[ \mathcal{F} = \epsilon_{\mu\nu\rho\sigma} B^\mu \partial^\nu A^\rho J^\sigma \]

Here, \( \lambda \) is the coupling constant, \( m \) is the mass of the ALP, and \( J^\sigma \) is the energy density current induced by the ALP. The magnetic field \( B^\mu \) and the electric field \( \mathcal{E}^\mu \) are related by the Maxwell equation \( \mathcal{E}^\mu = \partial_\mu \mathcal{B} \) with \( \mathcal{B} = \mu_0 B \).

Patras 2012
\[ L_{S\gamma\gamma} = \frac{1}{4}g_{S\gamma\gamma}S^0 F_{\mu\nu} F^{\mu\nu} = -g_{S\gamma\gamma}S^0 B \cdot B_{\text{ext}} \]

where \( F_{\mu\nu} \) is the electromagnetic field strength tensor, \( g_{S\gamma\gamma} \) is the strength of the coupling between the scalar particle \( S^0 \) and two photons, \( B \) is the magnetic field of the incident photon, and \( B_{\text{ext}} \) is the external magnetic field. From this Lagrangian, the equations of motion that result may be used to write the power \( P_{S\gamma} \) that results from axion to photon conversion on resonance in the microwave cavity as \[ P_{S\gamma} = g^2 S_{\gamma\gamma} V B^2_{\text{ext}} \rho_a C_{lmn} Q. \] (1)

Here, \( V \) is the cavity volume, \( C_{lmn} \) is the form factor associated with the cavity mode, \( Q \) is the quality factor of the cavity, and \( \rho_a \) is the assumed scalar ALP density. The results presented here are the first from a search for primordial scalar particles coupling to a strong external magnetic field using resonant cavities in the mass range of 0.14 meV corresponding to 34 GHz frequency.

2 Experiment

The apparatus \([15, 18, 19]\) consists of a tunable, 34 GHz resonant cavity (\( Q \sim 10^4 \)) made from oxygen-free copper and a high electron mobility transistor (HEMT) cryogenic amplifier \([20]\) located at the bottom of a cold gas cryostat that is oriented vertically and cooled to approximately 4 K. The cavity and cryogenic amplifier are coupled by approximately 10 cm of WR28 waveguide. The cryostat rests inside the vertical bore of a 7 T cryomagnet. The temperature inside the cryostat is monitored at multiple locations with cryogenic thin film resistance temperature sensors.

The resonant cavity has one critically coupled and one weakly coupled port, each connected to WR28 waveguide. The critically coupled waveguide terminates at the input to the HEMT amplifier, after which both waveguides feed out of the cryostat. The air in the cavity is pumped out through the weakly coupled waveguide. The \( Q \) of the cavity is measured prior to each data run using a network analyzer connected to both waveguides.

The cavity is tuned with an adjustable plunger that is vacuum tight at 4 K. A fiberglass G-10 rod is threaded through the top of the cryostat and fastened to the tuning plunger with a horizontal lever. When the G-10 rod is turned, the plunger moves vertically. The range of tuning in the cavity is \( \pm 5 \) mm which corresponds to approximately \( \pm 0.8 \) GHz.

The signal from the cryogenic amplifier terminates outside the cryostat at a waveguide–to–coaxial adapter and triple heterodyne microwave receiver \([15]\). After the receiver the voltages from the in–phase and quadrature components are digitized for the complex Fast Fourier Transform (FFT) and further analysis offline. The sensitivity of the experiment is limited by the system noise temperature \( T_{\text{sys}} \) according to the Dicke radiometer equation \([21]\). \( \sigma_T = \frac{T_{\text{sys}}}{\sqrt{\Delta f T}} \)

3 Measurements and Results

Typical power spectra measured with the cryogenic amplifier held at 6 K are shown in the left panel of Figure \([1]\). The resonance of the cavity appears as a dip in the spectrum. This dip is
Figure 1: Left panel: Two power spectra measured with the first HEMT cryoamplifier held at T = 6 K. The spectrum marked *cavity* shows a raw measurement of the power at the output of the receiver chain with the cold resonant cavity tuned to 34.409 GHz (6-7 MHz on the plot). The trace labeled *terminator* shows the power measured at the output of the receiver with a cold 40 GHz 50-ohm terminator at the input to the first HEMT. In both measurements the shape of the spectrum is driven by the last bandpass filter in the electronics chain. Right panel: Exclusion limit on $S^{0\gamma\gamma}$ coupling from data similar to those shown in the left panel. In this initial result the measurements are centered at 34.29 GHz (0.142 meV) and span across the width of the last bandpass filter (30 MHz). The gap in the center of the plot corresponds to frequencies at or near 0 Hz in the baseband and have been excluded from this analysis.

qualitatively consistent with the combination of two effects: A frequency-dependent reflection of noise power coming from the input of the HEMT, and a change in the gain of the HEMT as the impedance of the source decreases (e.g. [22, 23]). The width of the dip is approximately 3-4 MHz which is in accordance with the cavity’s Q of $10^4$.

The expected power from couplings between a scalar ALP and 2 photons is given in Equation 1 [17]. The cavity form factor $C_{lmn}$, adapted from [17] for the case of a scalar ALP, is

$$C_{lmn} = \left| \frac{\int_V d^3 x B \cdot \hat{B}_{ext}}{V \int_V d^3 x \frac{1}{\mu} |B|^2} \right|^2,$$

where $B e^{i\omega t}$ is the oscillating magnetic field in the cavity, $\hat{B}_{ext}$ is the static magnetic field, and $\mu$ is the magnetic permeability. For the configuration used in these measurements $C_{lmn} = 10^{-6}$ is lower than would be desirable, but the cavity geometry was dictated by the constraints of a different experiment [18]. Using a limited set of measurements similar to those in the left panel of Figure 1 and assuming a primordial ALP density $\rho_a$ of $10^{13}$/cm$^3$ [24], the right panel shows that we exclude couplings with $g > 10^{-8}$/GeV between 0.14 meV scalar particles and two photons with 5$\sigma$ confidence.

Although the sensitivity of the present measurement does not exceed model-dependent limits on $g_{S\gamma\gamma}$ set in previous searches for solar ALPs [23], by astrophysical observations [26], and by fifth force experiments [16], it is the first glimpse into this energy regime with a technique that has mass resolution. It is also the first direct search for ALPs as cold dark matter at 0.1 meV. Immediate plans for the experiment include a cavity in a transverse magnetic mode which will
allow coupling to pseudoscalar ALPs and will be 3 orders of magnitude more sensitive than
the present measurement. A wider mass range will also be searched by tuning the receiver.
In conclusion although this measurement is primarily a first step toward the goal of a more
sensitive experiment, it is still an unprecedented, narrow band test of $S^0\gamma\gamma$ coupling limits that
are otherwise model-dependent.

4 Acknowledgments

This work was supported by the Office of Naval Research award N00014–09–1–0481.

5 Bibliography

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