First Results from the Taiwan Axion Search Experiment with Haloscope at 19.6 μeV

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This Letter reports on the first results from the Taiwan Axion Search Experiment with Haloscope, a search for axions using a microwave cavity at frequencies between 4.70750 and 4.79815 GHz. Apart from the non-axion signals, no candidates with a significance more than 3.355 were found. The experiment excludes models with the axion-two-photon coupling $|g_{a\gamma\gamma}| \gtrsim 8.2 \times 10^{-14} \text{ GeV}^{-1}$, a factor of eleven above the benchmark KSVZ model, reaching a sensitivity three orders of magnitude better than any existing limits in the mass range $19.4687 < m_a < 19.8436 \mu\text{eV}$. It is also the first time that a haloscope-type experiment places constraints on $g_{a\gamma\gamma}$ in this mass region.

Various astrophysical and cosmological observations indicate that dark matter (DM) exists and makes up 26.4% of the total energy density of the universe [1–5]. One of the viable dark matter candidates is the axion, which arises from the spontaneous breaking of a new global $U(1)_{\text{PQ}}$ symmetry [6] introduced by Peccei and Quinn to solve the strong CP problem [6–8]. Axions are abundantly produced during the QCD phase transition in the early universe and may constitute the DM [9–12]. In the post-inflationary PQ symmetry breaking scenario, current calculations suggest a mass range of $\mathcal{O}(1–100) \mu\text{eV}$ for axions so that the cosmic axion density does not exceed the observed cold DM density $\Omega_{\text{DM}} h^2$ [13–15].

Axions could be detected and studied via their two-photon interaction, of which the strength is described by the coupling constant $g_{a\gamma\gamma}$. The detectors with the best sensitivities to axion DMs with a mass of $m_a \approx \mu\text{eV}$, as first proposed by Sikivie [20, 24], are haloscopes consisting of a microwave (MW) cavity immersed in a strong static magnetic field and operated at a cryogenic temperature. In the presence of an external magnetic field, the ambient oscillating axion field drives the cavity and they resonate when the frequencies of the electromagnetic modes in the cavity match the MW frequency $f$, where $f$ is set by the total energy of the axion: $hf = E_a = m_a c^2 + \frac{1}{2} m_a v^2$. The axion signal power is further delivered to the readout probe followed by a low-noise linear amplifier.

Several haloscope experiments have actively carried out axion searches. The most significant efforts are from the Axion Dark Matter eXperiment (ADMX), placing tight constraints on $g_{a\gamma\gamma}$ within the mass range of $1.9–4.2 \mu\text{eV}$ [23, 24]. Others include the Haloscope at Yale Sensitive to Axion Cold dark matter (HAYSTAC) [35, 37], the Center for Axion and Precision Physics Research (CAPP) [38, 40], and the QUEST for AXions-γ (QUAX-γ) [41]. This Letter presents the first results of a search for axions in the mass range of $19.4687–19.8436 \mu\text{eV}$, from the Taiwan Axion Search Experiment with Haloscope (TASEH).

The detector of TASEH is located at the Department of Physics, National Central University, Taiwan and housed within a cryogen-free dilution refrigerator (DR) from BlueFors. Figure 1 shows a simplified diagram of the TASEH apparatus. An 8-Tesla superconducting solenoid with a bore diameter of 76 mm and a length of 240 mm is integrated with the DR. The DR has multiple flanges at different temperatures for the required cooling: 50 K, 4 K, still, and mixing flanges, among which the mixing flange could reach the lowest temperature at $\sim 20 \text{ mK}$. During the data taking, the MW cavity with two coupling probes sits in the center of the magnet bore and is connected via holders to the mixing flange. The 0.234-L cylindrical cavity, made of oxygen-free high-conductivity (OFHC) copper, has an inner radius of 2.5 cm and a height of 12 cm and is split into two halves along the axial direction to reduce the loss from the seam [22]. The resonant frequency can be tuned via the rotation of an off-axis OFHC copper tuning rod. The axion-photon conversion signal from the readout probe is directed to an impedance-matched amplification chain (thick lines in Fig. 1). The first-stage amplifier is a low noise high-electron-mobility-transistor (HEMT) amplifier mounted on the 4 K flange. A circulator, anchored at the mix-

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The simplified diagram of the TASEH apparatus.

The signal power extracted from a MW cavity on resonance is given by [35, 44]:

$$P_s = \left( g_{a\gamma\gamma} \frac{\hbar^3 c^3 \rho_a}{m_a^2} \right) \times \left( \omega_c \frac{1}{\mu_0} B_0^3 V C Q L \beta \frac{1}{1+\beta} \right).$$

The first set of parentheses contains $g_{a\gamma\gamma}$, $m_a$, physical constants, and the local dark-matter density $\rho_a = 0.45 \text{ GeV/cm}^3$ [5, 15]. For the QCD axions, $g_{a\gamma\gamma}$ is related to the axion mass $m_a$:

$$g_{a\gamma\gamma} = \left( \frac{g_s \alpha}{\pi \Lambda^2} \right) m_a,$$

where $g_s$ is a dimensionless model-dependent parameter, with numerical values -0.97 and 0.36 in the Kim-Shifman-Vainshtein-Zakharov (KSVZ) [40, 47] and the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) [48, 49] benchmark models, respectively. The symbol $\alpha$ is the fine-structure constant and $\Lambda = 78 \text{ MeV}$ is a scale parameter that can be derived from the mass and the decay constant of the pion and the ratio of the up to down quark masses. The second set of parentheses contains parameters related to the experimental setup: the angular resonant frequency of the cavity $\omega_c$, the vacuum permeability $\mu_0$, the nominal strength of the external magnetic field $B_0$, the effective volume of the cavity $V$, and the loaded quality factor of the cavity $Q_L = Q_0/(1+\beta)$, where $Q_0$ is the unloaded, intrinsic quality factor and $\beta$ is the coupling coefficient which determines the amount of coupling of the signal to the receiver. The form factor $C$ is the normalized overlap of the electric field $\vec{E}$ for a particular cavity resonant mode, with the external magnetic field $\vec{B}$:

$$C = \frac{\int (\vec{B} \cdot \vec{E}) d^3x}{B_0^2 V \int E^2 d^3x}.$$ (3)

The magnetic field $\vec{B}$ in TASEH points mostly along the axial direction of the cavity. For cylindrical cavities, the largest form factor is from the TM$_{010}$ mode. The expected signal power derived from the experimental parameters of TASEH is $P_s \approx 1.4 \times 10^{-24} \text{ W}$ for a KSVZ axion with a mass of 19.6 $\mu$eV.

In the haloscope experiments, the figure of merit that determines the design of the experimental setup is the signal-to-noise ratio (SNR), i.e. the ratio of the signal power $P_s$ to the fluctuation in the averaged noise power spectrum $\sigma_n$ [50], given by:

$$\text{SNR} = \frac{P_s}{\sigma_n} = \frac{P_s}{k_B T_{\text{sys}}} \sqrt{\frac{t}{\Delta f}},$$

where $T_{\text{sys}}$ is the system noise temperature, an effective temperature associated with the total noise of the system, $t$ is the data integration time, and $\Delta f$ is the resolution bandwidth. Here, one assumes that all the axion signal power falls within $\Delta f$.

The system noise temperature $T_{\text{sys}}$ has three major components:

$$T_{\text{sys}} = T_{\text{mx}} + \left( T_c - T_{\text{mx}} \right) L(\omega) + T_a,$$

where $\omega$ is the angular frequency. The last term $T_a$ is the effective temperature of the noise added by the receiver (mainly from the first-stage amplifier). The sum of the first two terms is equivalent to the sum of the reflection of the incoming noise from the attenuator anchored to the mixing flange (Fig. 1) and the transmission of the noise from the cavity body itself. The symbol $T_i = \left( \frac{1}{e^{\hbar \omega/k_B T_i}-1} + \frac{1}{2} \right) \hbar \omega/k_B$ refers to the effective temperature due to the blackbody radiation at a physical temperature $T_i$ and the vacuum fluctuation. The difference of the effective temperatures $T_i - T_{\text{mx}}$ is modulated by a Lorentzian function $L(\omega)$. If the physical temperatures of the cavity $T_c$ and of the mixing flange $T_{\text{mx}}$ are identical, the thermal noise spectrum from the cavity is
flat. The derivation of the first two terms in Eq. (5) can be found in Ref. 51.

The calibration for the amplification chain is performed by connecting the HEMT to a blackbody radiation source (Fig. 1) instead of the cavity via a cryogenic switch. Various values of input currents are sent to a nearby resistor heater to change its temperature $T_b$ monitored by a thermometer. The output power is fitted to a first-order polynomial, as a function of the source temperature, to extract the overall gain and added noise $T_a$.

The data for the analysis presented here were collected by TASEH from October 13, 2021 to November 15, 2021, and are termed as the CD102 data, where CD stands for “cool down”. The CD102 data cover the frequency range of 4.70750–4.79815 GHz. In this Letter, most of the frequencies in unit of GHz are quoted with five decimal places as the absolute accuracy of frequency is $\approx 10$ kHz.

It shall be noted that the frequency resolution is 1 kHz. During the CD102 data run, the temperature of the cavity stayed at $T_c \simeq 155$ mK, higher with respect to the mixing flange $T_{mx} \simeq 27$ mK; it is believed that the cavity had an unexpected thermal contact with the radiation shield in the DR. As a result, $\Delta T$ and $T_{mx}$ are 0.18 K and 0.11 K, respectively. The form factor $C$ for the TM$_{4010}$ mode varies from 0.60 to 0.61 over the operational frequency range. The intrinsic quality factor $Q_0$ at the cryogenic temperature is $\approx 60700$. The insertion depth of the readout probe is set for $\beta \simeq 2$ since this value, for a given amount of time and a fixed value of SNR, maximizes the frequency coverage. In this case, the cavity line width, $\omega_c/2\pi Q_L$, is about 240 kHz.

The analysis that merges bins without assuming a signal line shape results in the upper limits at 95% confidence level (C.L.) on $|g_{a\gamma\gamma}|$ are derived by setting the maximum SNR equal to five, with the assumption that axions make up 100% of the local dark matter density. Figure 2 shows the $|g_{a\gamma\gamma}|$ limits of TASEH and the ratios relative to the KSVZ benchmark value, together with those from the previous searches. The limits on $|g_{a\gamma\gamma}|$ range from 5.3×$10^{-14}$ GeV$^{-1}$ to 8.9×$10^{-14}$ GeV$^{-1}$, with an average value of 8.2×$10^{-14}$ GeV$^{-1}$; the lowest value comes from the frequency bins near the external magnetic field. No limits are placed for the above two frequency ranges.

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The analysis that merges bins without assuming a signal line shape results in $\approx 5.5\%$ larger values on the $|g_{a\gamma\gamma}|$ limits. If a Gaussian signal line shape with an FWHM of 2.5 kHz is assumed instead, the limits will be $\approx 3.8\%$ smaller than the central results. If the $|g_{a\gamma\gamma}|$ lim-
its are derived from the observed SNR as described in the ADMX paper [51], rather than using the 5σ target SNR, the average limit on $|g_{a\gamma\gamma}|$ will be $\approx 4.9 \times 10^{-14}$ GeV$^{-1}$.

After the collection of the CD102 data, synthetic axion signals were injected into the cavity via the transmission input line (Fig. 1) and read out via the same amplification chain. The procedure to generate axion-like signals is summarized in Ref. [43] and the analysis of the synthetic axion data is described in Ref. [51]. The analysis results demonstrate the capability of the experimental setup and the analysis strategy to discover an axion signal with $|g_{a\gamma\gamma}| \approx \mathcal{O}(10|g_{a\gamma\gamma}^{KSVZ}|)$.

In summary, a search for axions in the mass range $19.4687 < m_a < 19.8436 \mu$eV was performed by the TASEH Collaboration. Apart from the non-axion signals, no candidates with a significance more than 3.355 were found. The experiment excludes models with the axion-two-photon coupling $|g_{a\gamma\gamma}| \gtrsim 8.2 \times 10^{-14}$ GeV$^{-1}$ at 95% C.L., a factor of eleven above the benchmark KSVZ axion-two-photon coupling.

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FIG. 2. The 95% C.L. limits on $|g_{a\gamma\gamma}|$ and the ratio of the average limit with respect to the KSVZ benchmark value from the CD102 data (red band in the inset). The results from the previous searches performed by the ADMX, CAPP, and HAYSTAC Collaborations are also shown (inset). The blue error band indicates the systematic uncertainties. The gray band in the inset shows the allowed region of $|g_{a\gamma\gamma}|$ vs. $m_a$ from various QCD axion models, while the blue and red dashed lines are the values predicted by the KSVZ and DFSZ benchmark models, respectively.
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