Dear Editor,

We thank the Referee for reviewing our paper and furnishing this report.

We have considered all comments, and we have applied changes to the original version of the paper to address the issues raised. In addition, we have made a few changes.
First, we include one more figure (Fig. 2 in this updated manuscript) to help the readers to have a better overview of the experimental setup and the different components of the dilution refrigerator. Second, the limits on the axion-two-photon couplings are updated due to an improved calculation of the cavity form factor in the Ansys HFSS microwave simulation. Third, we add one more citation to a theory paper and update Equation 3 by including the permittivity constant. More details of these additional changes are presented at the end of this letter.

We are at your disposal for any further clarifications.

Sincerely,

TASEH Collaboration

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Color code:

Black: the original text of the referee comments

Blue: our response

Green: quoted original text

Bold green: changes to the paper

Red: explanation regarding the additional changes

Report of Referee A -- LS18220

Summary:
This paper describes experimental results for a narrowband microwave resonator based haloscope search for dark matter axions at 19.6 micro-eV mass. The experiment used a copper microwave cavity at a physical temperature of 155 mK along with a low-noise receiver chain that included a low noise HFET amplifier for the first amplification stage. Experimental and analysis details were referenced in two accompanying arXiv articles (presumably both are currently undergoing peer

review). The paper represents exploration in a new frequency range, much of which is currently unexplored by axion haloscopes. Though its sensitivity is still too low to detect plausible axion masses it is only an order a magnitude away from the KSVZ benchmark and had discovery potential for either Axion-Like-Particles or to QCD axions if there happened to be a local overabundance of dark matter. As such I would recommend publication in PRL once the below comments are taken into account.

General Comments, Critiques and Suggestions:

1. This was a very well organized and clearly written paper which did an excellent job of describing the experimental setup, the month-long data taking operations and the analysis in a search for dark matter axions in the 19.6 micro-eV mass range. It was easy to read with a logic progression and I commend the authors on the conciseness balanced with just the right amount of details needed.
2. One general issue that I noticed which needs to be rectified is that this experiment claims to be the first axion haloscope experiment to probe the region at 19.6 micro-eV. However, the authors failed to acknowledge previous work described in: arXiv:2110.10262v1 [hep-ex] 15 Oct 2021 which explored this exact frequency range of 4.796.7-4799.5 MHz, albeit with a lower sensitive (few x 10^-13 GeV^-1 as opposed to this works 4.9 x 10^-14 GeV^-1 for 90% confidence) and overall frequency coverage (2.8 MHz vs this works 90 MHz). Please correct this omission in the updated draft.

   We have added citations to the searches performed by ADMX and CAPP that have a small overlap with our mass window. Instead of quoting the full mass window 19.4687 < ma < 19.8436 μeV, now we emphasize that the range 19.4687 < ma < 19.7639 μeV has never been explored by haloscope experiments before. The changes have been applied to the abstract and the main text.

   The original abstract

   The experiment excludes models with the axion-two-photon coupling $|g_{a\gamma\gamma}| > 8.2 \times 10^{-14}$ 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 $19.4687 < m_a < 19.8436$ μeV. It is also the first time that a haloscope-type experiment places constraints on $g_{a\gamma\gamma}$ in this mass region.

   is modified to:

   The experiment excludes models with the axion-two-photon coupling $|g_{a\gamma\gamma}| > 8.1 \times 10^{-14}$ GeV^{-1}, a factor of eleven above the benchmark KSVZ model, in the mass range $19.4687 < m_a < 19.8436$ μeV. It is also the first time that a haloscope experiment places constraints on $g_{a\gamma\gamma}$ in the mass region of $19.4687 < m_a < 19.7639$ μeV, reaching a sensitivity three orders of magnitude better than the limits obtained by non-haloscope experiments.

   The main text on page 1

   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-aγ (QUAX- aγ) [41]. This Letter presents the first results of a search for axions in the mass range of 19.4687–19.8436 μeV, from the Taiwan Axion Search Experiment with Haloscope (TASEH).

is now replaced by:

Others include the Haloscope at Yale Sensitive to Axion Cold dark matter (HAYSTAC) [36– 38], the Center for Axion and Precision Physics Research (CAPP) [39–42], and the QUest for AXions-aγ (QUAX- aγ) [43]. This Letter presents the first results of a search for axions in the mass range of 19.4687–19.8436μeV from the Taiwan Axion Search Experiment with Haloscope (TASEH). This mass region is largely unexplored by haloscope experiments and has only a small overlap with the previous searches performed by ADMX [44] and CAPP [42].

The main text on page 4

The sensitivity on $|g_{a\gamma\gamma}|$ reached by TASEH is three orders of magnitude better than the existing limits in the same mass range. It is also the first time that a haloscope-type experiment places constraints in this mass region. The target of TASEH is to search for axions in the mass range of 16.5–20.7μeV corresponding to a frequency range of 4–5 GHz. With the upcoming upgrades of the experimental setup and several years of data taking, TASEH is expected to probe the QCD axion band in the target mass range.

is modified to:

The sensitivity on $|g_{a\gamma\gamma}|$ reached by TASEH is three orders of magnitude better than the limits obtained by helioscope experiments. It is also the first time that a haloscope experiment places constraints in the mass region of $19.4687 < m_a <$ 19.7639μeV. The target of TASEH is to search for axions in the mass range of 16.5–20.7 μeV corresponding to a frequency range of 4– 5 GHz. With the upcoming upgrades of the experimental setup, including: the use of a quantum-limited Josephson parametric amplifier, a new dilution refrigerator that has a stronger magnetic field and a larger bore size, and a new cavity with a significantly larger effective volume, and several years of data taking, TASEH is expected to probe the QCD axion band in the target mass range.

3. I appreciate that the cavity overall dimensions were given but I didn't see what the dimensions of the tuning rod were. Please include that.

   Thanks for pointing this out to us. The dimensions and the location of the tuning rod have been added in the text.

   The original text

   The resonant frequency can be tuned via the rotation of an off-axis OFHC copper tuning rod.

   is modified to:

   The resonant frequency can be tuned via the rotation of an off-axis OFHC copper tuning rod with a diameter of 0.4 cm and a length of 11.4 cm. The rotation axis of the tuning rod is 1.9 cm away from the center of the cavity.

4. There is no discussion in equation 5 of any attenuation between the cavity and the HEMT amplifier. Given the components in between everything I would be surprised if there wasn't at least of order 0.2-0.3 dB or so. Can you comment on the expected upper bound on the attenuation between

cavity and/or the blackbody radiation source and the HEMT form the receiver components in between?

The attenuation between the cavity or the blackbody radiation source and the HEMT could be estimated from the calibrated added noise temperature T_a' and the nominal noise temperature of the HEMT T_a: $T_a' = T_a / A$ where A is the attenuation.

In addition to the original text

The added noise Ta obtained from the calibration is about 1.9 − 2.2 K, with a frequency dependence.

we have added the text below:

The difference between the calibrated Ta and the nominal 1.5 K noise temperature of the HEMT amplifier indicates an overall attenuation of 1.0–1.7 dB, contributed from the cables, switch, and circulator, between the noise source and the HEMT amplifier.

5. The y-axis on figure 2 seemed strange as plotted on a linear scale. Typically plots of the y-axis are shown in log scale so that other experiments (such as CAST, which this work beats by several orders of magnitude) can be shown. In addition it seems odd to have the coupling on the inserted wider band go below 0. This is really just a stylistic suggestion though.

   Thanks for your suggestion. We have modified Fig. 3 (Fig. 2 in the first manuscript) by making the y-axis of the inset shown in log scale. We also added the results from CAST, CAPP[42], RBF, and UF experiments in the inset for comparison.

Additional changes

1. The detector-related text on page 1 has been modified to refer to Fig. 2 in the updated version of manuscript.

   The original text

   Figure 1 shows a simplified diagram of the TASEH apparatus.

   is now modified to:

   Figure 1 shows a simplified diagram of the TASEH apparatus while Fig. 2 shows the schematic diagram of the DR system and a photo of the experimental setup.

   The two subfigures in Fig. 2 are referenced individually in the following text.

   The DR has multiple flanges at different temperatures for the required cooling: 50 K, 4 K, still, and mixing flanges [Fig. 2 (a)], among which the mixing flange could reach the lowest temperature at ≃ 20 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 [Fig. 2 (b)].

2. We have updated the limits and the corresponding text due to an improved calculation of form factors. We noticed recently that in the Ansys HFSS microwave simulation software using the curvilinear mesh option for a model with rounded surfaces gives more accurate results. We redo the simulation for the cavity using the curvilinear mesh. The difference of form factor between the simulated results with the original mesh and with the curvilinear mesh is 3%, which results in a 1.3-1.4% change in the limits. Note the changes do not alter the understanding of the cavity. The limits reported in the text and Fig. 3 (Fig. 2 in the original manuscript) have been modified. Note the ADMX-style limit increases rather than decreases because an inconsistent form factor was used in the previous calculations. The new calculations now use the same form factors as those for the central values.

   The original text on page 3

   The form factor C for the TM_{010} mode varies from 0.60 to 0.61 over the operational frequency range.

   is now modified to:

   The form factor C for the TM_{010} mode varies from 0.614 to 0.630 over the operational frequency range.

   The limits reported on page 4 (page 3 of the old manuscript)

   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};

   ADMX paper [56], rather than using the 5σ target SNR, the average limit on $|g^{a\gamma\gamma}|$ will be $\approx 4.9\times10^{-14}$ GeV^{-1}.

   are now modified to:

   The limits on $|g_{a\gamma\gamma}|$ range from 5.2×10^{-14} GeV^{-1} to 8.7×10^{-14} GeV^{-1}, with an average value of 8.1×10^{-14} GeV^{-1};

   ADMX paper [56], rather than using the 5σ target SNR, the average limit on $|g^{a\gamma\gamma}|$ will be $\approx 5.1\times10^{-14}$ GeV^{-1}.

3. We have added one more citation [26] to a theory paper by M. Gorghetto, E. Hardy, and G. Villadoro. It is added near the end of the first paragraph on page 1.

   In the post-inflationary PQ symmetry breaking scenario, current calculations suggest a mass range of O(1–100) μeV for axions so that the cosmic axion density does not exceed the observed cold DM density [13–26].

4. One of the comments for the manuscript DS13038 is to include the permittivity constant. We have updated Equation 3 and added a citation.

   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 $\vec{B}$ [53]:

$$C = \frac{\left[\int \left(\vec{\boldsymbol{B}} \cdot \vec{\boldsymbol{E}}\right) d^3\boldsymbol{x}\right]^2}{B_0^2 V \int \epsilon_0 E^2 d^3\boldsymbol{x}}.$$

[53] P. Sikivie, Rev. Mod. Phys. 93, 015004 (2021). Here, the vacuum permittivity in Heaviside-Lorentz units ε0=1 is used.