The ORGAN Experiment

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Motivation for high frequency haloscope

- Beck result: potential signal of axions at \( \sim 26.6 \text{ GHz (~10}^{-4}\text{ eV)} \)
- Higher frequency than typical haloscopes…or easily accessible
- Considered a spurious result by many
- Beck's hypothesis:
  Shapiro step-like features in Josephson Junctions could be as a result of axions

DOI: [http://dx.doi.org/10.1103/PhysRevLett.111.231801](http://dx.doi.org/10.1103/PhysRevLett.111.231801)

- No direct test of this candidate signal has been performed – seems like as good a place as any to start looking
Motivation for high frequency haloscope

- Shapiro step-like features observed in experiments [C. Homann et al. PRB 70, 180503(R) (2004)]

Beck’s Proposal: Axion entering WL region, transport of excess Cooper pairs

Motivation for high frequency haloscope

- Curiosly: $g$ cancels

\[
B = \frac{8\pi^2 \Gamma f_a^2 d}{g \gamma \hbar c^3 e}.
\]

\[
Pa \rightarrow \gamma = \frac{1}{4\beta_a} (g \text{ Bec } L)^2 \frac{1}{4\pi \alpha} \left( \frac{\sin \frac{qL}{2\hbar}}{\frac{qL}{2\hbar}} \right)^2
\]

\[
Pa \rightarrow \gamma = \frac{1}{\beta_a h^2 c^4} (f_a \Gamma dL)^2 4\pi \alpha
\]

\[
L = \frac{\hbar c^2}{\sqrt{4\pi \alpha}} \sqrt{\beta_a} \frac{1}{f_a \Gamma d}
\]

- $L \sim 10^{-22}$ m

- We are left with a mass/frequency range: $110\pm 2$ micro-eV, or $26.6 \pm 0.5$ GHz
High Frequency Haloscope Design

- High frequency haloscope at UWA (~26 GHz), known as ORGAN

- Multi-stage project:
  - Direct test of Beck result
  - Wider scan at high frequency
  - Novel resonators

- Designing a haloscope at high frequency is difficult

- TM Mode frequency inversely proportional to cavity size
  - Lower volume
  - Lower sensitivity
  - Lossier material

- Quantum noise limit increases

- Harder to tune, and couple to modes
High Frequency Haloscope Design

- TM010 mode almost always employed in haloscopes due to highest form factor

\[ C_E = \frac{\left| \int dV \mathbf{E}_c \cdot \hat{z} \right|^2}{V \int dV | \mathbf{E}_c |^2} \]

- Measure of mode overlap with axion induced EM field
- TM010 \( \sim 0.69 \)
- High frequency \( \rightarrow \) very low volume

- We explored the possibility of higher order modes
High Frequency Haloscope Design

- $TM_{010}$ mode offers the greatest form factor, but the lowest volume for given cavity length and frequency

- Essentially no change for given cavity length

- Other considerations:
  - Higher order modes have higher G factors at a given frequency
  - Aspect ratio problem $\rightarrow$ Likely to be more spurious modes
  - We chose $TM_{020}$ as the detecting mode
High Frequency Haloscope Design

- Mode crowding gets worse at higher frequency
- But, worth considering in a given length, depending on required tuning range

<table>
<thead>
<tr>
<th>Mode</th>
<th>C</th>
<th>V (cm^3)</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM010</td>
<td>0.69</td>
<td>1.45</td>
<td>386.5</td>
</tr>
<tr>
<td>TM020</td>
<td>0.13</td>
<td>7.783</td>
<td>744.6</td>
</tr>
<tr>
<td>TM030</td>
<td>0.053</td>
<td>18.87</td>
<td>1244.3</td>
</tr>
</tbody>
</table>
• Cavity dimensions:
  ~1 cm radius
  ~5 cm length
• \( \text{TM}_{020} \) Mode frequency ~26.5 GHz
• First “path-finding run” complete
  – Stationary frequency, single cavity
  – Traditional HEMT amplification
  – 4 K
  – 7 T
  – Commercial FFT
• Successful test of entire system, ready for tunable run
• Scale up sensitivity
ORGAN
Future of search

- Federal funding for 7 years, can scale up experiment
- ARC Centre of Excellence for Engineered Quantum Systems (EQuS) – expertise and assistance
- 14 T magnet
- Multiple cavity search
- Quantum or near-quantum limited amplification (JPAs, NQL HEMTs)
- Other areas we are exploring:
  - Signal processing techniques
  - Methods to increase Q factor (superconductivity, 3D printing, Bragg resonators)
  - Novel resonators (as per Mike’s talk)
Tuning

- Exploring tuning options
  - Next stage will utilize regular copper post tuning (~ 1 GHz)
  - Later stages may utilize dielectrics (ie sapphire disk)
  - Coupling of mode to other, highly tunable resonances (ie magnon modes in YIG)
Reduction in C and G makes about a factor of 2

Slightly more sensitive near the centre

Possibility of re-design moving to larger cavity numbers
Sensitivity Projection

![Graph showing sensitivity projection for axion mass vs. coupling constant](image)
Sensitivity Projection

- Aa is the search we have just run
- Ab is a planned search for the Beck range with current technology and equipment
- B, C, D, X, Y, Z represent various stages of scale-up to the experiment
- Generous scale-up projection:
  - 14 T magnet
  - 8 cavities
  - Quantum noise limited amplifier
  - Q to 1 million (axion linewidth)
Bragg Resonators

- Dielectric walls in cavity
- Air gap
- Confine modes, virtual boundary conditions
- Improve Q factor
Bragg Resonators
Bragg Resonators
Cross-correlation techniques

- High frequency cavities very small
  - Would like to combine multiple cavities
- Cross-correlation measurements are two-channel measurements which reject uncorrelated noise sources

- Cross-correlate signals from two cavities
  - Reject the uncorrelated thermal cavity noise and amplifier noise
  - Retain correlated axion signal
Cross-correlation techniques

- Define SNR as signal divided by spread of background noise, for purpose of scheme comparison

- With cross-correlation spread (standard deviation) of background noise goes down proportional to \( \frac{1}{2\sqrt{n}} \)

- Compared with \( \frac{1}{\sqrt{n}} \) for single channel

- Factor of 2 reduction in background spread, same improvement as doubling signal power by combining two cavities

- Downside: need two readouts, amps etc
Cross-correlation techniques
Cross-correlation techniques

- Real benefit achieved when synchronizing larger numbers of cavities
- Can compute “averaged cross spectrum”
- For n cavities we can compute \( \frac{n(n-1)}{2} \) independent cross spectra
- Averaging these cross-spectra produces a new spectrum
  - WISP signal of interest retained
  - Mean of thermal noise reduced
  - Standard deviation of thermal noise reduced
- Achieve \( 2 \cdot \sqrt{\frac{n(n-1)}{2}} \) reduction in spread of background noise, compared with \( n \) from power combining
Cross-correlation techniques
Cross-correlation techniques

- This is not magic or free \(\rightarrow\) We have a tonne more data/readouts, this is all post-processing
- We need \(n\) readouts, rather than one
- \(n\) digitization channels
- \(n\) times as much data
- Equivalent to averaging a Wilkinson system for longer in terms of data, but we do it simultaneously
Cross-correlation techniques

- Synchronizing 4+ cavities is a long term goal of ORGAN

**Cross-correlation has other uses than increasing SNR:**
- Power summation of multiple cavities is difficult
- Cavities need to be inside same system, in phase
- CC measurements can be performed with cavities spatially well separated
- Characterize WISP signals e.g. coherence length

*See arXiv:1510.05775v2 for more information on these techniques, update forthcoming*
Conclusion

● UWA EQuS node developing multi-stage haloscope (ORGAN)
  – Direct test of Beck result at 26.6 GHz
  – Wide scanning at high frequency
  – TM_{020} mode employed
  – Search now underway
  – Planned future phases rely on experimental scale-up, new technologies and ideas

● Novel experimental techniques will improve sensitivity
  – Synchronize multiple cavities and employ cross-correlation techniques

References:
  – ORGAN Experiment: arXiv:1611.08082
  – Cross-correlation schemes: arXiv:1510.05775v2 (update forthcoming)