Snowmass2021 - Letter of Interest

The Oscillating Resonant Group AxioN (ORGAN) Experiment

Thematic Areas: (check all that apply □/■)

■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors

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Abstract: The ORGAN Experiment is a high mass, (Sikivie-style) axion haloscope hosted at the University of Western Australia nodes of the ARC Centre of Excellence for Engineered Quantum Systems (EQUS), and the ARC Centre of Excellence for Dark Matter Particle Physics. The experiment will run for 7 years, from 2020 - 2026, as funded by the ARC, continuing the work which has already been done with the ORGAN pathfinding project. The ORGAN axion mass range of interest is $\sim$60-200 μeV, corresponding to roughly 15-50 GHz in photon frequency. To overcome the significant technical challenges associated with operating a traditional resonant cavity haloscope, we pursue four avenues of research and development. Firstly, we consider novel resonator designs based on higher order modes in resonant cavities and dielectric materials, to increase form factors and volumes at high frequency. Secondly, we investigate novel schemes for combining multiple resonators, such as cross-correlation, to increase effective detector volume. Thirdly, we consider high critical field superconducting coatings to increase quality factors of resonators. Finally, we propose to implement promising single photon counting technologies, and/or sub-quantum limited linear amplification. The experiment will consist of 2 phases, each broken down into stages. Phase 1 will consist of two targeted scans at 15 - 16 GHz and 26.1 - 27.1 GHz, whereas Phase 2 will consist of the entire 15-50 GHz region, broken down into 5 GHz stages.

Background and Prior Work

In recent years interest has grown in searching the high mass ($>\sim50$ μeV) range for dark matter axions[1;2]. The interest is due to a range of promising theoretical proposals[3;4] suggesting axions could exist in this range, along with the non-discovery of axions at lower masses[5], and a series of anamolous experimental observations which have offered hints of possible axion signals[6;7]. Despite this, there are few experiments which propose to scan this range, owing in part to a host of technical difficulties associated with conducting axion detection experiments at higher frequencies. Since 2016 we have conducted R&D, prototyping, path-finding, planning and commissioning for The ORGAN Experiment, which will probe this range[1]. This work culminated in the first experiment in this mass region in 2017. Subsequently, we have undertaken future planning for the experiment, and will commence long-term operation in 2020, operating until 2026.

Novel Resonator Designs

A key pillar of ORGAN is novel resonant design. At high frequencies traditional haloscope detectors based on TM_{010} modes become infeasibly tiny, necessitating new designs. ORGAN will likely employ a higher frequency resonant mode, with dielectric material present to modify the field structure of the resonance, to maximize the product of form factor and cavity volume. A handful of dielectric resonator designs are being prototyped and characterized, for potential application in the high mass region[8;9].

Resonator Combination

Most resonant cavity haloscope experiments propose to combine many resonators in the push to higher frequencies, in an effort to combat the reduction of volume at high frequency. Typical schemes for combination rely on precise phase and frequency matching of multiple cavities. For ORGAN, we propose to implement alternate methods of cavity combination, such as cross-correlation, and frequency multiplexing[10].

Superconducting Coatings

At higher frequencies, the surface losses of conductors such as copper become higher, reducing the quality factor of resonators, impacting haloscope sensitivity. To combat this, we are conducting research into the application of high critical-field superconducting coatings on to the interior surfaces of resonant cavities, increasing their quality factors[11]. At the same time, we are investigating new methods for characterizing the magnetic field penetrating inside a cavity with a superconducting layer on the walls, rather than simply assuming it is equal to the external field[12].

Single Photon Counting/Quantum Amplifiers

It has been shown that for haloscopes at frequencies >10 GHz, single photon counters become preferable over quantum-limited linear amplifiers[13]. Unfortunately, as yet, no single photon counters in the GHz frequency range have been reliably demonstrated. We are working with world leaders in quantum technology, both inside the EQUS collaboration and elsewhere, to develop such GHz single photon counters. We are pursuing multiple avenues of research, including cavity-qubit hybrid systems[14], and current-biased Josephson junctions[15]. Additionally, we are exploring the development of Josephon parametric squeezed-state amplifiers, should the single photon counter work prove unfruitful.

Run Plan

All phases of the run plan will operate at mK temperatures, in a 14 T (or higher) magnetic field, at UWA. The scans will use a SNR of 4 as the target for searching, and will achieve different levels of sensitivity depending on success of various aspects of R&D during the 7 years of the experiment.

Phase 1a and Phase 1b

Phases 1a and 1b, to commence in late 2020 and run for 12 months, will consist of targeted, 1 GHz scans over specific mass ranges. Phase 1a will cover the mass range 15 - 16 GHz, and serve as a test bed for various ORGAN technologies and techniques. We are currently testing a potential 15 - 16 GHz single photon counter which, if proven to be reliable and efficient, will be employed in the search. Failing that, a low noise HEMT-based amplifier will be employed, whilst research into quantum-limited amplifiers and single photon counters continues for future phases. Phase 1b will operate on the same principles as Phase 1a, but covering the range 26.1-27.1 GHz, to test the range of axion masses proposed by the Beck result[6]. If high efficiency

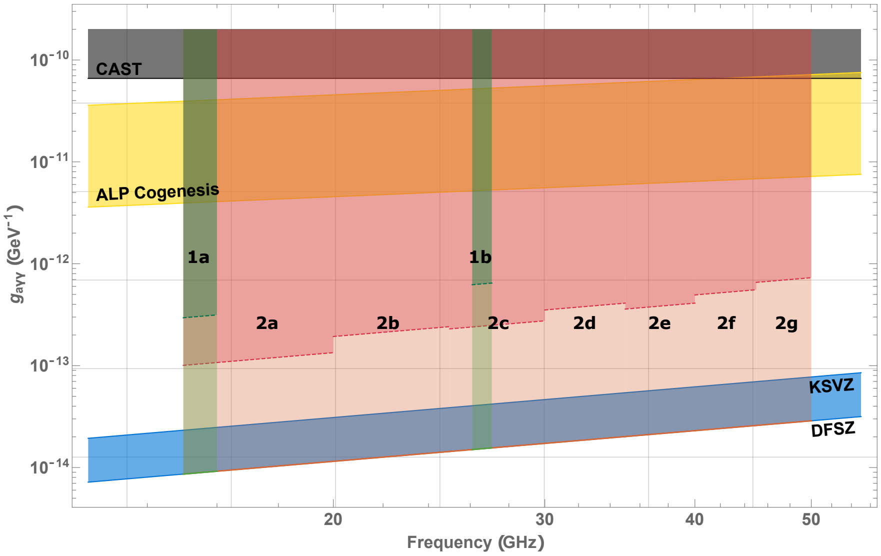

Figure 1: Projected exclusion limits based on different assumed parameters. For Phase 1, the darker green limits represent what can be achieved using HEMT-based amplifiers, and TM_{010}, tuning rod-based resonators, assuming a form factor of 0.4, and a loaded Q of 30,000. The lighter green limits represent what can be achieved with single photon counters. Phase 2 assumes a moderate scale up, utilizing dielectric resonators with a form factor of 0.45, a loaded quality factor of 50,000, and 50% greater volume than the Phase 1 resonators at the same frequency. The darker red limits represent what can be achieved with quantum limited linear amplifiers, whereas the lighter red limits represent what can be achieved with novel single photon counters with efficiencies on the order of 0.5, and dark count rates on the order of 1000 photons/second. The higher frequency limits assume combination of multiple (2-4) cavities. Also shown are the common axion model bands[16–18], and the exclusions from CAST[19].

single photon counters are utilized, it will suffice to employ simple, TM_{010} based tuning-rod resonators to achieve DFSZ sensitivity in both Phase 1a and 1b. In this instance, 12 months of averaging time will be more than sufficient. 12 months are afforded to account for a stop-start run, allowing time for maintenance, and to address issues expected to arise given the novel, experimental nature of the photon counting technology. If HEMTs are used, a lower level of sensitivity will be attained, and it is likely that more complex dielectric resonators will be employed for Phase 1b, serving as an additional test of these technologies for Phase 2.

Phase 2

Phase 2 will commence in 2022, and be broken down into 5 GHz stages, each lasting $\sim$ 9 months. The stages will begin at 15 GHz, and end at 50 GHz. Phase 2 will employ single photon counters if available by 2022, or quantum limited amplifiers if not. R&D for Phase 2 stages will be on a rolling basis, where Phase 2a cavities and detectors will be developed during Phase 1, and later Phase 2 stages will be developed during earlier Phase 2 stages. Phase 2 will likely employ a dielectric resonator design, and consist of multiple cavities combined via cross-correlation, or another technique. If single photon counters are implemented in Phase 1, this will save scan time in Phase 2, since 2 GHz of the range will have already been covered at similar sensitivity. As with Phase 1, the use of efficient single photon counters will afford access to DFSZ sensitivity over the entire range, within the planned timeline, allowing time for expected maintenance and unplanned stops. If more traditional quantum-limited linear amplification is employed, a lower level of sensitivity will be attained, and efforts will be made to employ sub-quantum limited amplification.

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