Snowmass2021 - Letter of Interest

Radio Frequency Quantum Upconverters: Precision Metrology for Fundamental Physics

Thematic Areas: (check all that apply ☐/■)
☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) IF1 Quantum Sensors
☐ (Other) AF7 Accelerator Technology R&D

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Abstract:

We propose a comprehensive program to investigate the advantages of quantum metrology techniques in the frequency range between DC and 300MHz. The work will be based on the Radio Frequency Upconverter (RQU), which is a flexible and adaptable platform for precision metrology of a variety of quantum systems including electromagnetic circuits and polarized nuclear spin ensembles. The immediate application of the RQU to fundamental physics is in searches for the QCD axion via interactions with electromagnetism and nuclear spin. These experiments are poised to search for the QCD axion over approximately 6 orders of magnitude in mass, spanning from approximately 1 peV to 1μeV.

1 Introduction

Advances in precision measurement have often led to breakthroughs in scientific understanding. Sensors, including electromagnetic resonators and spin ensembles, have grown in size and sophistication, allowing more sensitive probes of fundamental physics. At the same time, breakthroughs in quantum information science and the physics of measurement provide a path to continued improvement. Engineering the uniquely quantum properties of sensors can create states with useful quantum correlations, including squeezed and entangled states. These quantum correlations enable enhanced precision and better science reach.

Several fundamental physics experiments have demonstrated the enhanced precision available with engineered quantum states, including the search for the QCD axion (1; 2), measurement of gravitational waves (3), and the search for a nonzero electron electric dipole moment (4). QCD axion searches in the range of 1-10 μeV are poised to take advantage of existing quantum techniques from Circuit Quantum Electrodynamics (Circuit QED) that manipulate the quantum properties of microwave photons, which have frequencies from approximately 1-100 GHz. In this frequency range, a variety of techniques have already been developed to enhance measurement sensitivity, including squeezing of microwave states (2) and photon counting (1). These techniques build on the progress of the field of Circuit Quantum Electrodynamics (Circuit QED), which has been driven in large part by the desire to build a universal quantum computer.

Unfortunately, the advantages from photon counting do not directly extend to lower frequencies, and squeezed states are challenging to generate at lower frequency. Comparatively little work has been done to develop other quantum metrology techniques for electromagnetic modes at frequencies between dc and the Very High Frequency (VHF) band (below 300 MHz). Primarily this is because, even at typical dilution refrigerator temperatures near 10 mK, a VHF mode is still in a thermal state, containing approximately $hf/k_BT \gtrsim 1$ thermal excitations, where f is the frequency of the mode. The high number of thermal excitations means that common Circuit QED techniques like photon counting do not significantly enhance the sensitivity of the experiment, since the photon number in a VHF circuit is still subject to thermal fluctuations.

Nevertheless, there are compelling reasons to develop appropriate quantum metrology techniques for axion searches at lower frequencies, below 300 MHz. Quantum sensors (e.g. high-Q resonant circuits or highly polarized spin samples) operating in this frequency range can still be highly sensitive probes of fundamental physics, even with a high thermal excitation number. These quantum sensors can carry useful information at frequencies significantly detuned from their resonant frequency, where the thermal fluctuations are suppressed to below the level of a single photon per second per Hz of bandwidth (5; 6). This off-resonant information can only be accessed by a readout technique operating beyond the Standard Quantum Limit (SQL). In this case, improving the readout performance beyond the SQL does not substantially improve the signal to noise ratio (SNR) on resonance (which is limited by equilibrium thermal fluctuations), but instead allows constant SNR to be maintained over a much broader bandwidth, which dramatically increases the axion search rate. In this way, up-conversion would allow quantum metrology techniques adapted from Circuit QED to accelerate the search for the QCD axion.

2 The RQU: An Optimized Upconverter for Quantum Metrology Below 300MHz

The work proposed in this LOI would be based on the RF Quantum Upconverter (RQU), a flexible device that enables quantum metrology of dc-VHF circuits. The RQU uses the nonlinearity of Josephson junctions to parametrically upconvert signals from the sensor frequency to microwave frequencies. This upconversion paradigm allows the RQU to take advantage of several mature microwave Circuit QED technologies, including high coherence microwave resonators (7), Josephson Parametric Amplifiers (JPAs) (8), and microwave squeezers (9), while extending the frequency range of quantum measurement techniques to lower frequencies. The RQU is optimized for quantum metrology of electromagnetic signals in practical experiments, with an interferometer design that isolates the RQU's microwave drive signals from the axion receiver.

The RQU can be operated in a variety of modes, which can be set by choosing the frequencies, phases, and amplitudes of the microwave drive signals. A variety of quantum metrology techniques, including sideband cooling, two-mode squeezing, and backaction-evading (BAE) readout are possible. BAE readout is especially desirable for sub-μeV axion searches, as it can reduce the noise associated with the upconversion process below the Standard Quantum Limit, allowing for broader bandwidth in axion searches. This technique enables 'quantum-accelerated' axion searches, which achieve a sensitivity better than would be possible with any classical detector.

The work proposed here is a systematic program of optimization of several quantum metrology protocols, resulting in lower sensor temperatures (for sideband cooling), stronger entanglement between the microwave mode and sensor mode (for two-mode squeezing) and a higher degree of backaction evasion. In order to maximise the practical benefits of quantum metrology in axion searches, the optimization follows a multi-pronged approach. Iterative improvements to the physical RQU devices yield longer coherence times, better control of undesired coupling terms, and stronger interactions between the sensor and microwave modes. These improvements increase the cooperativity of the physical system, boosting the performance of all quantum metrology techniques. Meanwhile, improvements to the microwave drive tones and readout allow for better control of spurious microwave tones, which can limit the fidelity of quantum operations. Finally, improvements to data analysis allow for reduced systematic errors and better-characterized device Hamiltonians. This information can in turn be fed back into the improvements of the physical devices and the microwave drive schemes, further improving the performance of quantum metrology with RQUs. This multi-pronged approach mirrors the process of research and development in the field of quantum computing, which has yielded rapid, "Moore's law type" progress towards high-performance multi-qubit systems (10).

Early RQU devices capable of realizing a modest degree of BAE immediately improve the science reach of sub-μeV axion searches like DMRadio-50L, DMRadio-m^3, and CASPEr. As quantum metrology improves, more dramatic enhancements are possible. Combined with larger and more sophisticated axion detectors like DMRadio-GUT, impressive science reach is possible, with the ultimate goal of probing GUT-scale QCD axion models at frequencies near 100kHz with a 10-cubic-meter-scale, 12-Tesla axion detector and an RQU achieving 20dB of backaction evasion.

Axion searches are not the only experiments which stand to benefit from improved quantum metrology below 300MHz: experiments with polarized nuclear spin ensembles can probe a variety of physical and chemical processes in addition to axion interactions. Several important experimental techniques using nuclear spins are limited by the sensitivity with which the ensemble's magnetization can be detected. In low-field Nuclear Magnetic Resonance (low-field NMR) (11; 12; 13; 14), and Spin Noise Spectroscopy (SNS) (15; 16; 17; 18), the net magnetization of the spin ensemble is extremely weak, so it is important that the readout add as little noise as possible. Low-field NMR and SNS offer a variety of advantages over conventional NMR, including simplified magnet construction, enhanced T_1 and T_2 coherence times, enhanced T_1 contrast for imaging applications, and faster experimental cycles. However, low-field NMR and SNS are challenging due to the weak magnetization signal, and benefit from sensitive readout. Reading out low-field NMR and SNS experiments with RQUs and quantum metrology techniques enables smaller sample sizes, lower polarizing fields, or faster experiments. RQU-enabled spin metrology will have a variety of benefits beyond axion searches, in analytical chemistry and condensed-matter systems. Thus, developing quantum metrology for axion searches may ultimately provide benefits across a broad range of disciplines.

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