Snowmass2021 - Letter of Interest

Rydberg Atoms as Quantum Sensors for New 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

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Abstract: For decades, the unique properties of Rydberg atoms have been exploited for precision tests of new physics. Recent progress on the use of Rydberg atoms as single-photon detectors in the areas of quantum computing and quantum information has also opened exciting new possibilities for their use as quantum sensors in probes of new fundamental physics, particularly in searches for light dark matter candidates such as axions and hidden photons. In many cases, full sensitivity to these candidates requires the use of quantum non-demolition (QND) techniques, wherein the photon being detected is kept in the cavity for many measurements rather than being absorbed by the atom as in selective field ionization (SFI). This is currently possible for some types of hidden photon searches, but at the high frequencies and magnetic field strengths required for axion searches, there are stringent technical challenges, some of which cannot yet be achieved with the current technology. Developing the full potential of current technologies and driving R&D to enable the robust application of QND techniques to a wider range of fundamental searches is an important step for the next generation of quantum sensors for new physics.

Rydberg atoms have been employed in photon detection since the early stages of the development of quantum computing systems[1]. The CARRACK collaboration[2;3] pioneered the use of Rydberg atoms for single photon detection in axion haloscopes[4;5]. The successful measurement of the blackbody spectrum by CARRACK II[6] demonstrated the power of this technique: an ultra low-noise measurement with extraordinary sensitivity to small fields and thermal noise fluctuations near the level of the standard quantum limit (SQL). Despite that result, the use of Rydberg atoms as quantum sensors in searches for new fundamental particles has been under-utilized. This technique is highly synergistic with the current congressional mandate for federally funded quantum information science (QIS), the computational frontier, the rare processes and precision frontier, and the instrumentation frontier. The usage of Rydberg atoms as single photon detectors is also complementary to other ongoing searches and R&D projects to search for physics beyond the Standard Model.

A separate LOI submitted by the HAYSTAC collaboration provides motivation for the axion as a dark matter candidate and the exploration of its large, mostly unexplored parameter space. In addition to those efforts, this proposal is to focus on the fact that single photon detection is a promising way to completely eliminate quantum noise from the detection of light-mass dark matter candidates[7]. Single photon detection exploits the Heisenberg uncertainty principle to give infinite uncertainty to the phase measurement in exchange for absolute certainty in the amplitude. This allows us to search through parameter space much more quickly, which is essential at higher frequencies since the time it takes to resolve a hypothetical signal in a haloscope increases with frequency. Because of these issues, traditional haloscopes have stuck to regions below $10\,\mathrm{GHz}$ in axion frequency. By eliminating quantum noise, scanning this higher mass region becomes tractable.

Haloscopes use the Primakoff effect to probe the relic abundance of dark matter axions in the universe. This requires the presence of a strong magnetic field, such as HAYSTAC's $9\,\mathrm{T}$ magnet[8]. Magnetic fields are detrimental to any qubit, and in the case of the Rydberg atom, the frequencies of the photons it can detect will fluctuate with the magnetic field. As a result, it is important to isolate the Rydberg atoms from the field, and the best way to do this is to separate the photon conversion and detection into separate cavities coupled together using a mixer[9]. The mixer allows the detection and conversion cavities to be at different frequencies, which means that the conversion cavity can be tunable while the detection cavity and the Rydberg atom transition frequency can be fixed. While we develop this experiment, we will also have the ability to probe the relic abundance of another dark matter candidate, dark photons, detailed in a separate LOI[10]. Because dark photon detection does not require a magnet, we will be able to make a dark photon exclusion immediately once the system is running.

One challenge in using a Rydberg beam as a dark matter detector is that the atoms must be able to stay at the Rydberg state while traversing the entire length of the conversion cavity. A $10\,\mathrm{GHz}$ cavity must be at least $15\,\mathrm{mm}$ in length. In order for the single photon detectors to work throughout the length of the cavity, the Rydberg atom lifetime needs to be long enough to traverse the length of the cavity. For ^{39}K, the lifetime of the $68\mathrm{S}_{1/2}$ state is $0.335\,\mathrm{ms}$[11], and this grows with the energy level. CARRACK used a Rydberg beam with a velocity of 350 m/s[5], so an atom can cross the cavity in one tenth of its lifetime.

CARRACK used selective field ionization (SFI) to detect their photons[6] which meant that they needed the Rydberg atoms that had absorbed a photon to stay at the excited state long enough to be ionized. Quantum non-demolition (QND) is even more compelling than SFI both because atoms only need to stay in their state long enough to be measured and because the photon can be measured multiple times rather than only once. Using QND in our dark matter measurements is possible as long as the lifetime of the photon in the cavity is much much longer than the time it takes to measure the change in the state of the atom due to the presence of the photon[12]. The RAY collaboration is in the process of exploring the feasibility of such an experiment. Because the photon needs to survive long enough to be transferred from the conversion cavity to the detection cavity, the conversion cavity must maintain a Q as high as the detection cavity Q. This is challenging because in an axion experiment, the conversion cavity is permeated by a large magnetic field which would lower the Q of the cavity. The QIS-MET collaboration at Fermilab is developing cavities that meet the above requirements and is submitting its own LOI.

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