Snowmass2021 - Letter of Interest

Dark photon detection with Rydberg atom single photon counting

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: (IF7) Quantum Sensors

Contact Information: (authors listed after the text)
Submitter Name/Institution: Sumita Ghosh/Yale University & Elizabeth Ruddy/University of Colorado, Boulder
Collaboration: Rydberg Atoms at Yale (RAY)
Contact Email: sumita.ghosh@yale.edu, elru9923@colorado.edu

Abstract: The dark photon was proposed as an additional U(1) symmetry in the Standard Model in 1986, and since then has been a rising candidate for dark matter. Recently, many haloscope and haloscope-like experiments have dabbled in searching for dark photons en route to an axion result. In contrast, the more traditional light-shining-through-wall (LSW) method uses two microwave cavities and requires the ability to send photons into one cavity and detect photons in the other cavity. The versatile experiment described in this letter is able to do all three: search for dark photons as a field-free haloscope, measure converted dark photons as an LSW system, and search for axions. Here we focus on the contribution we can make to dark photon parameter space.

Background Traditionally, dark matter has been modeled as a single as-yet-unidentified particle. Popular candidates for the elementary dark matter particle include axions[1–3] and WIMPs.[4–6] However, the visible matter that comprises $\sim$5% of the universe is complex. The Standard Model has three gauge interactions and multiple categories of particles, including quarks, charged leptons, and gauge bosons. Assuming that the other 85% of matter invisible to us is similarly complex, there may exist an entire *hidden sector* of matter[7;8] that contains many different types of particles with their own self-interactions.

These self-interactions would imply the existence of dark forces and their corresponding mediators. The canonical example is a dark electromagnetic force mediated by a dark photon.[9;10] If we consider the dark photon as a vector boson that stems from an added U(1) symmetry to the Standard Model, there may be extremely weak interactions between the dark photon and the Standard Model photon.[11] The Lagrangian for the interaction includes a kinetic mixing term which suggests that dark photons can oscillate into Standard Model photons with a mixing parameter χ, in a similar way to how neutrinos spontaneously oscillate into one another.

Traditional dark photon searches have used a light-shining-through-wall (LSW) mechanism. For this technique, a beam of photons is shined onto a wall with the goal that the photons will convert into dark photons, travel through the wall, and then reappear as photons beyond the wall.[12] This suppresses any dark photon signal by χ^2 but is independent of its abundance.[13] Another way to detect dark photons involves detecting photons converted from a slowly decaying relic abundance of dark photons in the universe, assuming that dark photons comprise the majority of dark matter.[14] Detection of a relic abundance requires only one conversion from dark photons to photons, so the signal is only suppressed by one factor of χ. The former technique can span a large range of masses, while the latter has deep sensitivity to the mixing parameter between dark photons and photons, but can be very slow depending on the mass range being covered. The remainder of this LOI outlines an experiment that can use both techniques in order to fully take advantage of each.

Beyond the quantum limit The HAYSTAC (Haloscope At Yale Sensitive to Axion CDM) experiment's latest run[15] has surpassed the quantum limit that had until now limited dark matter detection. HAYSTAC's use of a squeezed state receiver, which manipulates quantum states to partially bypass the standard quantum limit, represents the first time that quantum metrology techniques have been used in the search for dark matter. This becomes increasingly necessary at larger masses due to the fact that higher frequencies lead to a lower signal to noise ratio. The dark matter mass range is enormous, so our methods of searching must be dynamic to keep pace with the newest results using the latest advances in technology.

Single photon detection is one technique in development that holds great promise for accelerating the search. While the squeezed state receiver allows for measurements with uncertainty *below* the standard quantum limit, single photon detection circumvents the problem completely, eliminating quantum noise from the measurement altogether.[16] By counting single photons using Rydberg atoms or superconducting transmons as detectors, one can determine the amplitude of a given signal with absolute certainty while giving up any knowledge of phase. Eliminating quantum noise in the relevant observable will allow us to search through parameter space more rapidly. This is advantageous in the high-frequency regime $\geq 10\,\mathrm{GHz}$ because searching for a higher-frequency signal means combating increased quantum noise and decreasing cavity volume – both of which require longer measurement times. By eliminating quantum noise, scanning for particles with frequencies above $10\,\mathrm{GHz}$ using a haloscope would become tractable for the first time.

This technique becomes even more powerful if we employ quantum non-demolition (QND). Single photon detection without QND requires absorbing the photon into the single photon detector, thus destroying the signal. QND allows for more sensitive measurement because the photon can be measured multiple times rather than only once. This merely requires detuning the single photon detection frequency from the cavity frequency. 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[17]. This means not only can we eliminate quantum noise but we can also make our probability of success higher in our measurements. These two systems in conjunction are described in another LOI entitled *Rydberg Atoms as Quantum Sensors for New Physics*.[18]

A two-cavity system To achieve single photon detection, our experiment will involve separating the photon conversion and detection into separate cavities coupled together by a mixer.[19] A beam of Rydberg atoms will run through the detection cavity, acting as discrete photon counters that can be selectively field ionized and detected if excited by a photon in the cavity. While the two-cavity setup is modeled after the early CARRACK experiments,[20–23] the mixer allows the detection and conversion cavities to be at different frequencies, which means that we can tune the conversion cavity through frequency space while the detection cavity and the Rydberg atom transition frequency are fixed. This versatile setup can be used to search for dark photons from both a relic abundance[14] and from conversion from photons (in the LSW method).[12]

To search for dark photons from the relic abundance, we connect the two detuned cavities using a mixer. Dark photons that enter the tunable conversion cavity and spontaneously convert into photons are measured in the readout cavity due to the mixing process. This method has deep sensitivity to χ at the expense of only being able to search at the mass frequency of the conversion cavity. To change our detector to an LSW setup, we set the cavities on resonance with each other and the Rydberg atoms, then disconnect the mixer. We then send a strong beam of light into the conversion cavity. A subsequent signal in the readout cavity would suggest that a photon converted into a dark photon, passed unimpeded through the walls of the cavities, and re-converted into a regular photon in the readout cavity. This LSW search method would be able to make exclusions in a large range of masses, even while the cavity remains at a single frequency.[12] In this way, the two-cavity setup will allow us to make multiple types of exclusions in dark photon parameter space from the same detection device.

Conclusion Observation of dark photons would provide a non-gravitational window into dark matter's existence. With the prioritization of newer tabletop dark matter detectors, a more flexible setup that can search for dark matter in many different ways is increasingly desirable. The proposed experiment described in this letter involves two cavities and a Rydberg atom beam or other single photon detector. This setup is versatile enough to use the two most popular methods for searching for dark photons while also completely bypassing quantum noise. Its effectiveness in axion detection is described in a separate Rydberg atom setup LOI.[18]

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Authors: (names and institutions)

Sumita Ghosh, Yale University

Elizabeth Ruddy, University of Colorado, Boulder

Danielle H. Speller, Johns Hopkins University

Reina Maruyama, Yale University