Rydberg atom-based single photon detectors for dark matter axion searches

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**Axion Dark Matter**

The QCD axion would solve both the dark matter problem and the Strong CP problem of Quantum ChromoDynamics. Haloscopes attempt to detect them through the inverse Primakoff effect, shown on the right.

**Single Photon Detection for Axion Searches**

Scanning axion parameter space with a standard haloscope becomes intractable at high frequencies due to lower signal and increased quantum noise. Single-photon instrumentation has many benefits over the standard haloscope at higher masses [1]:

- Insensitive to phase; only limited by thermal / shot noise
- Can search at higher masses despite SNR relationship with cavity volume, as experimentally demonstrated in [2]
- Has already been demonstrated in a dark photon search [3]

**Rydberg Atoms**

Rydberg atoms have a high principal quantum number \( n \) and are useful for axion searches because they can have transition frequencies \( > 40 \) \( \mu \)eV. **Right:** Regions of the axion-photon interaction strength versus axion mass. QCD axion region is in yellow and haloscope exclusions are in red. Figure modified from [4].

This technique was pioneered by CARRACK [5]. We are well-positioned to take it further:

- Advantages of measuring at higher frequencies:
  - Smaller cavity requires a smaller dilution refrigerator
  - Shorter Rydberg paths make R&D implementation easier
- Advantages of us doing it now:
  - Rydberg atoms are now being studied for quantum computing
  - New cavity design insulates Rydberg atoms from the Tesla-scale magnetic fields required for the axion-photon conversion
  - Experience translates from HAYSTAC collaboration

**Detection Scheme**

We are building a haloscope setup with Rydberg atom-based single photon detectors.

**Using \(^{39}\text{K}\) Rydberg Atoms**

Our setup will use \(^{39}\text{K}\), which is less susceptible to Stark shift than the Rb used by CARRACK [5]. Rydberg transitions in \(^{39}\text{K}\) were found with electromagnetically induced transparency (EIT) spectroscopy [6].

**Below:** Our EIT setup. The two blue diode lasers are frequency-locked using spectroscopy, so that the \(^{39}\text{K}\) atoms can be raised to the Rydberg state with a two-photon transition using a photon from each laser.

**References:**


**Below:** A detection cavity is coupled to and locked in frequency with the conversion cavity. **Below:** The system is cooled with a dilution refrigerator to reduce thermal noise.

https://wlab.yale.edu/
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