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Scholars Electives 2200E - Interim Report

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ABSTRACT

This research investigates the experimental realization of steady-state quantum subradiance in a disordered molecular gas as a potential explanation for non-luminous dark matter. Unlike previous studies confined to transient decay in cold atomic clouds, we utilize millimeter-wave radiation to continuously drive the $J = 3 \rightarrow 2$ transition of Carbon Monoxide (CO) at 345.796 GHz within a custom-built vacuum chamber. We demonstrate a significantly refined experimental platform, including a butt-welded KF-flange chamber capable of high-vacuum retention and a Python-based data acquisition pipeline optimized for a a minumum of 4% instrumental dead-time. These advancements establish the necessary sensitivity to observe the suppression of thermal emission, potentially providing a first-principles quantum optical mechanism for the ”invisible” mass in astrophysical halos.

1 BACKGROUND & MOTIVATION

The mystery of dark matter remains one of the most enduring challenges in modern astrophysics, arising from the observed discrepancy between the gravitational mass and the luminous matter in galaxies. Standard cosmological models frequently invoke Weakly Interacting Massive Particles (WIMPs) or other exotic, non-baryonic candidates to explain this phenomenon. However, despite decades of searching, direct experimental evidence for such particles remains elusive or disproven by newer studies (Bernabei et al. (2008), Carlin et al. (2025)). This project explores an avant-garde approach to dark matter proposed by Houde and Rajabi (2025), postulating that it may not be a new species of particle, but rather a manifestation of collective quantum effects in ordinary baryonic matter.

The theoretical foundation for this work lies in the concept of subradiance, first predicted in Dicke (1954). Dicke demonstrated that when atoms or molecules interact through a common electromagnetic field, they should not be treated as independent entities but as a single, entangled quantum system. While much research has focused on superradiance, the cooperative enhancement of radiation,

subradiance represents the inverse process: the suppression of specific photonic emission modes through destructive interference. In subradiant states, matter can supress all modes of electromagnetic expression, resulting in a material which effectively becomes 'dark', similarly to what is expected in Cold Dark-Matter (CDM) theories, as first proposed in Peebles (1982).

Previous experimental observations of subradiance have typically been confined to transient regimes in cold, dilute atomic clouds (e.g., ^{87}Rb) Guerin et al. (2016), where subradiant states are inherently short-lived as the system relaxes toward the ground state via non-collective decay. Our project at Western University's Submillimetre Astronomy Laboratory differs fundamentally by investigating steady-state subradiance in a driven-dissipative regime. We propose that in astrophysical environments, a radiation field from a host galaxy can continuously repopulate these dark states, maintaining a steady-state equilibrium that renders the gas effectively dark and collisionless over cosmological timescales Houde and Rajabi (2025). Our laboratory setup targets the J=3→2 transition of CO at 345.796 GHz. By irradiating a custom-built aluminum cylindrical gas chamber with a millimetre-wave beam, we aim to observe the suppression of thermal emission in the direction perpendicular to the incident radiation. Using a spectrum analyzer, we will seek to "see" the gas go dark in real-time.

The implications of a positive result are profound. It would demonstrate a mechanism where ordinary hydrogen gas can exhibit the defining characteristics of dark matter: a lack of detectable radiation. This would provide a first-principles explanation for the "invisible" mass in the universe using established quantum optics, offering a novel perspective on the non-luminous behavior of matter in dark matter halos.

2 EXPERIMENTAL OVERVIEW

Experimental verification occurs in the Submilimeter Astronomy Lab, where the design of the overall experiment can be defined in three parts: chamber design, radio-frequency (RF) setup, and measurement.

2.0.1 Chamber Design

Firstly, the chamber containing the CO which will be irradiated has undergone multiple iterations to ensure vacuum capability. Initially the chamber contained three orifices, one for CO injection, one for vacuum gauge connection and CO detector, and one for vacuum pump connections. This initial setup was secured with NPT fittings and PTFE tape, with NPT threads machined directly into the chamber wall. Extended re-pressurization time experiments found that the prior setup was only capable of sustaining sub 1 mbar pressures for only a few seconds, major improvements were required. These came in the form of replacing all previous NPT fittings with vacuum-rated KF flange connectors, which required butt-welding a kf flange directly into the walls of the chamber, avoiding the previous setup's issue of impefect mating between the chamber and external NPT fittings. The new setup can be seen in 1, The gas cell containing the CO sample has undergone significant structural refinement to achieve the vacuum stability and pressure required. The initial iteration utilized NPT fittings and PTFE tape threaded directly into the chamber walls; however, re-

pressurization tests demonstrated that this configuration could only sustain pressures below 1 mbar for several seconds. To rectify these leak rates, the chamber was refitted with vacuum-rated KF flange connectors. This involved butt-welding KF flanges directly to the chamber body to eliminate imperfect mating surfaces associated with the machined NPT threads. The new chamber design can be seen in figure 1,

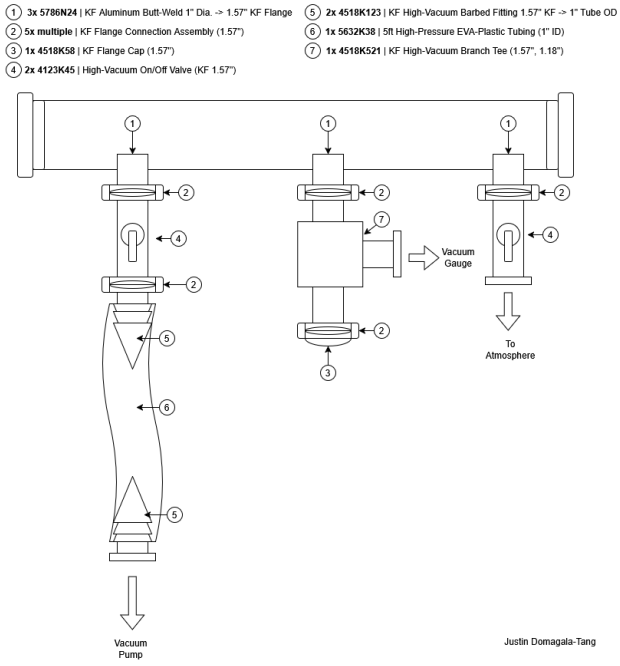


Figure 1. A full diagram of the new chamber setup, with McMaster Carr codes for each component.

where major improvements in vacuum retention come in the form of all flange-type connection, a directly weleded connection from the chamber to externals, and an upgrade from natural-gas line rated valves to specifically high-vacuum valves. Following the minimum pressure for the individual parts, the new setup should hypothetically be rated to a minimum of $1.33 \cdot 10^{-8}$ mbar, far exceeding the experimental requirement of 0.01-0.1 mbar.

2.0.2 Radio-Frequency Setup

As the radio frequency setup has undergone no changes within the current scholars-electives research cycle, it will be very briefly be reviewed. The full RF diagram can be seen in figure 2,

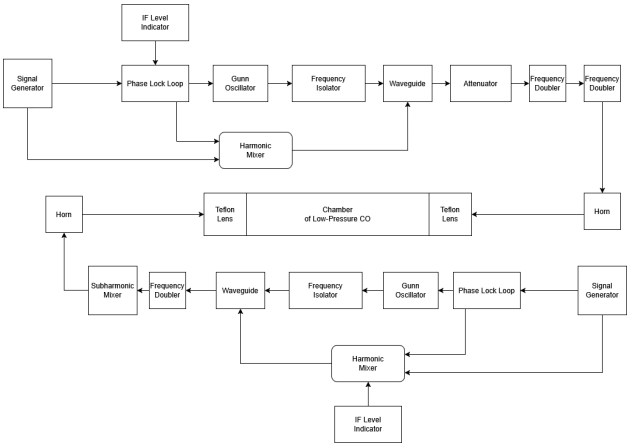


Figure 2. A full diagram displaying each component in the radio-frequency generation and measurement pipeline.

though in short, a low-frequency signal (typically around 20GHz) is directed from a signal generator into a series of RF components which have two main objectives: isolate the desired signal; and increase the signal frequency to the desired frequency. Prior to entering the chamber, the initial signal would have been cleaned and increased to the exact frequency required to irradiate the CO propertly, and be received by a similar setup at the other end of the chamber which will obtain the signal difference and deliver the data to the spectrum analyzer.

2.0.3 Measurement Apparatus

The largest point of change has been the method of retrieving data from the individual apparti. Previously, data was retrieved using a 20 year-old Windows machine utilizing LabView, which both made future improvements difficult, and posed issues regarding measurement cadence and instrumental dead-time. As such the system was replaced with a newer PC, and LabView discarded in favor of Python code and direct communication with each instrument. Firstly, the vacuum gauge is communicated with using a specific serial protocal outlined by the vacuum gauge manufacturater, and PySerial. Second, the spectrum analyzer is communicated with using PyVisa and the specific communication protocols outlined by the manual for the instrument. The display for data is as seen in figure 3,

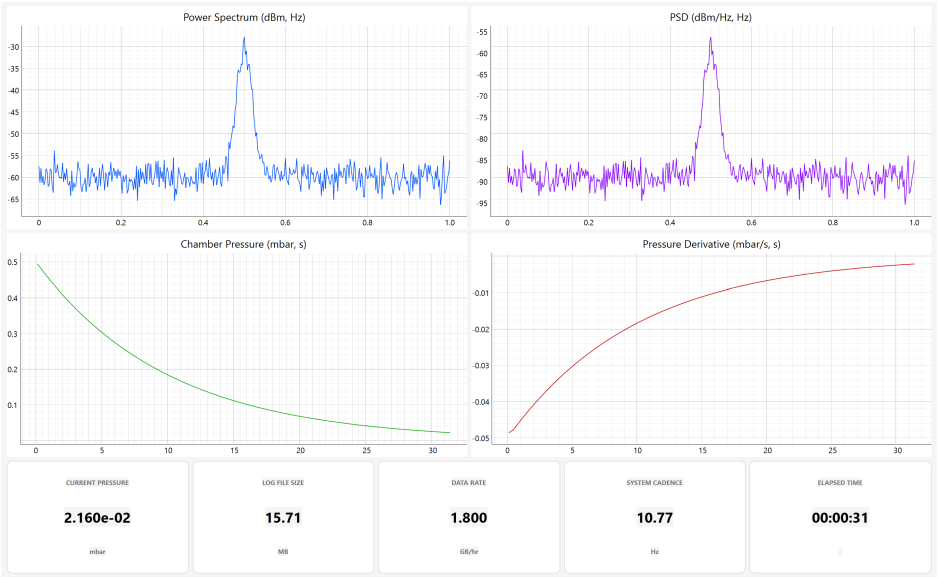


Figure 3. A screenshot of simulated data from the GUI given by the measurement code.

which provides useful information regarding the spectrum and pressure whilst the experiment is ongoing. Besides the front-end, the code was heavily optimized to reduce processing latency in order to reduce the instrumental dead-time between read/write cycles, eventually maximizing the integration time of the spectrum analyzer to approx. 96% of the total reading time. Finally the data is continuously written to a csv, both ensuring data is consistently being dumped to the disk, and avoids memory leakages.

3 CONCLUSIONS & FUTURE STEPS

This research cycle has successfully established an experimental platform prepared for the detection of steady-state subradiance in Carbon Monoxide. The transition from NPT-threaded interfaces to a fully welded KF-flange architecture has improved the chamber's theoretical vacuum limit to 1.33×10^{-8} mbar, ensuring the low-pressure environment (0.01–0.1 mbar) required for this experiment. Furthermore, the development of a custom PyVISA and PySerial data pipeline has virtually eliminated the instrumental dead-time inherent in the previous legacy system, allowing for the long-duration integration necessary to resolve faint signals. In the coming weeks, the new vacuum chamber is posed to be constructed, where new re-pressurization tests will occur. After vacuum has been confirmed, the RF system will be analyzed and optimized, where-after initial trails of the experiment will occur.

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