Cavity Ring-Down Spectroscopy for Ultra-trace Determination of Chemical Impurities in Noble Gases

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Abstract

Many searches for rare event physics located in deep underground laboratories rely on time projection chambers filled with liquid noble gases. These detectors require extremely low levels of chemical impurities in these liquids. After being moved between labs at Black Hills State University, a Cavity Ring-Down Spectroscopy (CRDS) system was set up and aligned for the detection of chemical impurities in liquid noble gas samples taken from the boil off from the time projection chambers.

Dark Matter

There is little known about dark matter due to the difficulty in directly detecting it, since it doesn't interact with the electromagnetic spectrum, neither optical nor radio astronomy can detect it. However indirect observations have been made that predict the existence of dark matter. Two of these observations are orbital speed of planetary bodies (Fig. 1) and gravitational lensing (Fig. 2) [1].

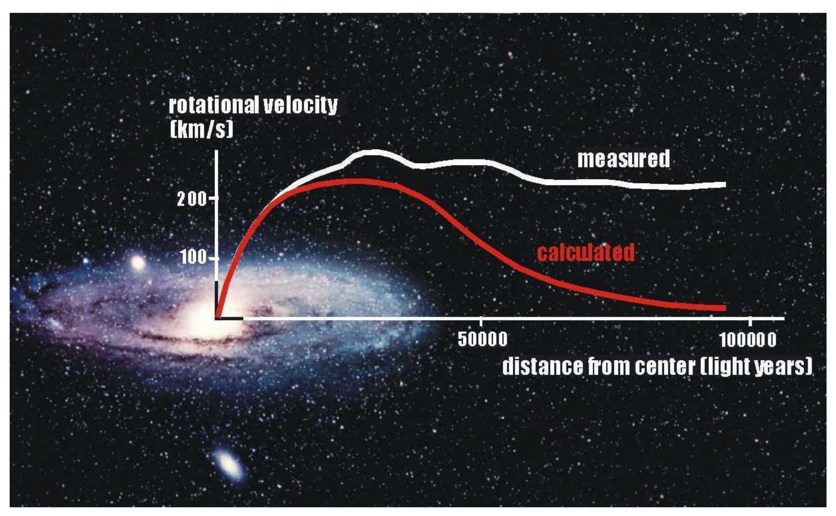

Figure 1. Rotational speed of planetary objects in galaxies [2]

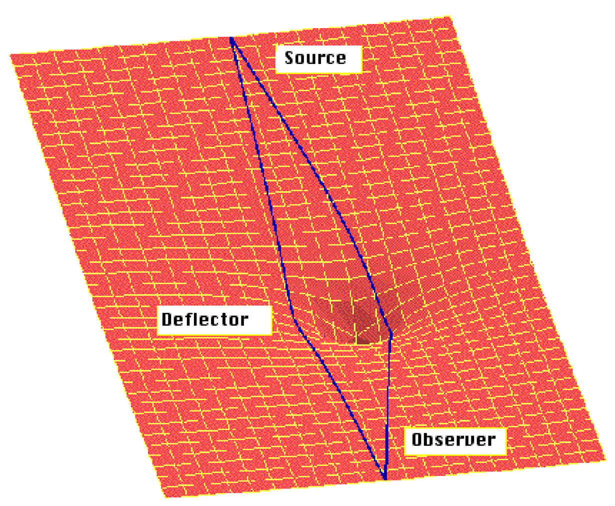

Figure 2. Paradigm of gravitational lensing [3]

Time Projection Chamber

Several particle astrophysics experiments implement large scale noble gas time projection chambers (Fig. 3) to be able to observe phenomenon such as neutrinoless double beta decay, dark matter, and long baseline neutrino oscillations [4]. For these experiments the noble gas needs to be purified and maintained at sup ppb ranges, a failure to do so would result in several problems ranging from quenching the scintillation light to disruption of the ionization signal.[5]

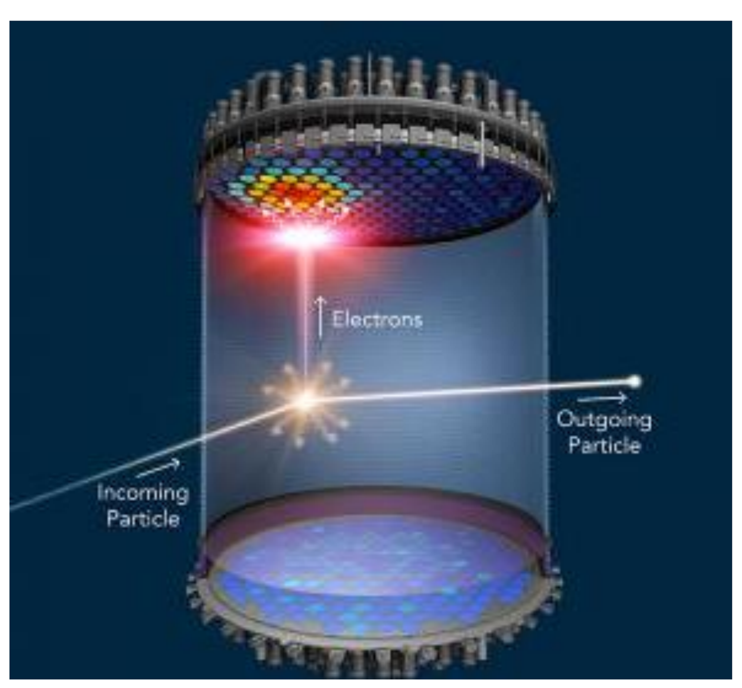

Figure 3. Time Projection Chamber (TPC) [6]

Cavity Ring-Down Spectroscopy (CRDS)

CRDS is an absorption spectroscopy technique in which a laser beam enters the absorption cavity and is reflected multiple times off of highly reflective supermirrors. This creates the equivalent of a pathlength of tens of kilometers through the gas sample. After the power within the cavity builds up to a pre-determined threshold, the beam is directed away from the cavity and the light intensity inside the cavity exponentially decreases as a small potion of it escapes the mirrors due to transmission and is picked up on the detector after each reflection. Ring-down time (Fig. 4) is defined as the amount of time it takes for the transmitted light to decrease by a factor of *1/e* (Fig. 4).

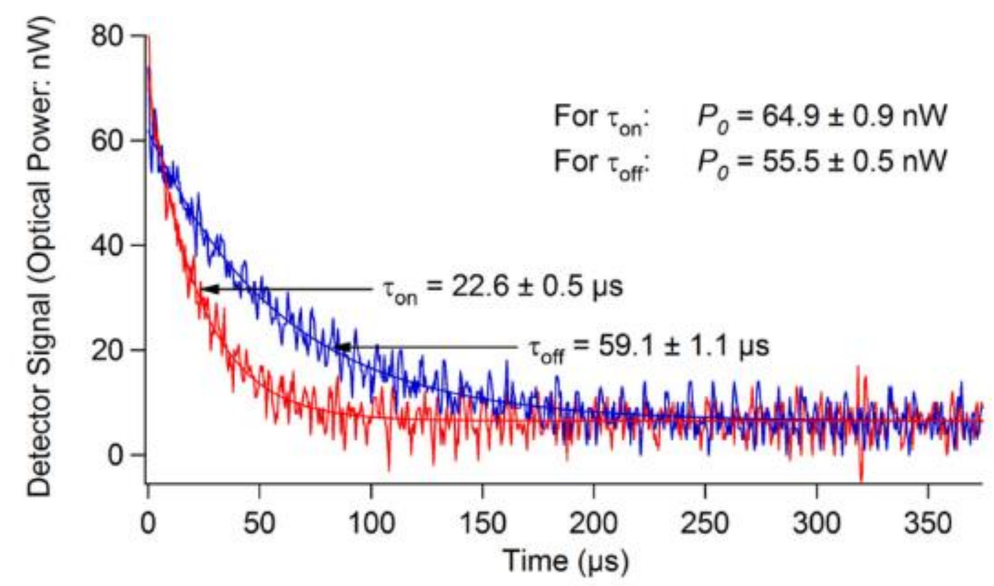

Figure 4. Simulated ring-down for a 0.4m cavity with mirrors of 0.997 reflectivity

Theory

The equation that determines the concentration of the gas particles inside the optical cavity is:

$$N = \frac{1}{c\sigma}\left(\frac{1}{\tau_{on}} - \frac{1}{\tau_{off}}\right)$$

where c is the speed of light, σ is the cross section and τ is the ringdown time. The difference between the ringdown times of the laser tuned on and off resonance allows to calculate for the concentration of the contaminate particles.

Alignment of System

The process of aligning the beam with the cavity consisted of several steps. Starting with a laser beam being directed into an Acousto-Optic Modulator (AOM) which when powered, splits the beam into two beams allowing one to be turned on and off easily by powering or depowering the AOM. By adjusting the AOM, the strength of the secondary beam that will continue into the cavity is maximized. Next the beam goes through a first optic lens which serves the purpose to focus the laser. Afterwards the beam is reflected off two adjustable mirrors and finally the beam goes through one more lens (similar to the first) before it enters the cavity. Walking the beam into the cavity ensures the beam enters and exits the cavity exactly in the middle, requiring the fine adjustment of the two mirrors seen in Figure 5 as well as the supermirrors so that their reflections followed the same path as the initial beam to be able to create a standing wave.

Figure 5. laser system setup containing laser, AOM, optical lenses, reflective mirrors, and one side of the optical cavity with a supermirror attached

Modes

Modes are displayed on an oscilloscope to indicate the presence of a standing wave within the cavity, however modes themselves vary based on the alignment of the cavity. Finesse is a measurement of the quality of resolution[8] inside the cavity which indicates how much constructive interference there is. In a situation where the laser beam is perfectly aligned with the cavity the equation to calculate finesse is listed below, in which R is the reflectance of the mirrors.

$$F = \pi\frac{\sqrt{R}}{1-R} \qquad F = \frac{\Delta v_{fsr}}{\Delta v_{1/2}}$$

The higher the finesse the taller and skinnier the modes are and the wider the gaps in between the modes and this is solely dependent on the reflectivity of the mirrors.

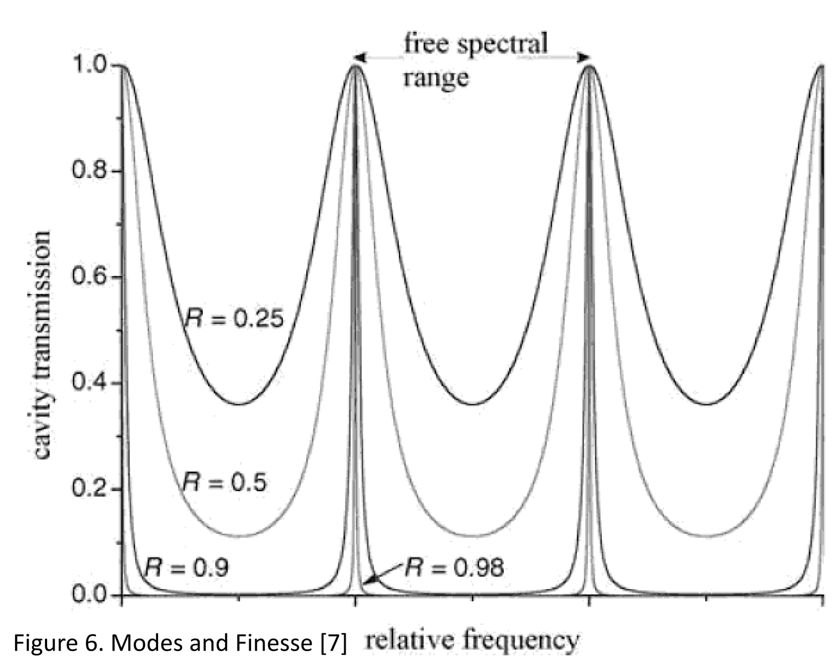

Figure 6. Modes and Finesse [7]

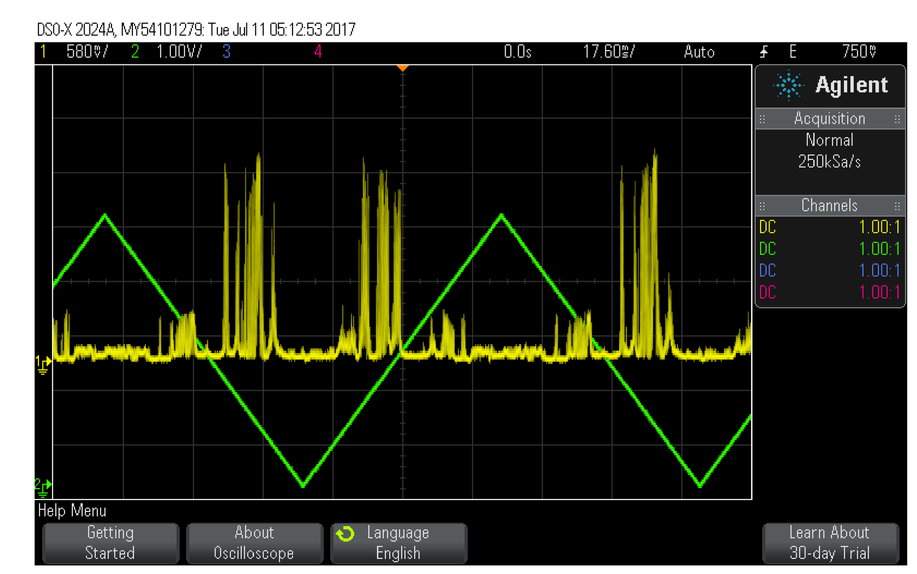

Figure 7. Modes with 1550 nm laser

The goal of the BHSU CRDS team this summer was to set up a CRDS system after the system had recently moved locations. The group started with setting up all of the optics and walking the laser beam through the whole setup, then focused on adjusting the supermirrors and looking for modes. The process was to find modes with a low finesse system, using a 1550 nm laser and supermirrors optimized for a 1392 nm wavelength. The purpose of using a laser with a higher wavelength initially was to find modes more easily using the low finesse system. This was achieved this summer (see Fig. 7). Future goals include evacuating air out of the cavity to be able to switch to the 1392 nm laser (which has higher finesses modes), as this wavelength is absorbed by water.

Acknowledgments

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