**Investigation of hydrogen hyperfine spin-exchange shift at 0.5 K**


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### Hydrogen maser basics

The hydrogen maser is among the most stable atomic frequency standards available today. Its applications include:

1. Astronomy (VLBI, deep space tracking)
2. Local oscillators for absolute time standards (for atomic fountain clocks)
3. Precision tests of fundamental physics
4. Precision tests of atomic physics

### Why a cryogenic maser?

**Decreased noise at low T**

Thermal noise limits the stability of room temperature hydrogen masers for short times (t < 1000 s). During this time, the Allan variance scales with temperature as:

\[ \sigma^2 \propto T \]

For a maser operating < 1 K, the operating temperature is reduced by ~ 500.

**Increased power at low T**

Spin-exchange broadening limits the maximum atomic flux at which oscillation can occur. This limits the maximum output power:

\[ \text{Power} \propto \frac{1}{\Delta \nu} \]

At T < 1 K, spin-exchange line broadening is reduced by ~ 3 orders of magnitude. Therefore, a cryogenic maser could be operated at much higher flux and higher output powers.

### Experimental setup

Unfortunately, there are large, temperature dependent frequency shifts due to H-He collisions at the wall and in the vapor. At ~ 0.5 K, however, the wall and vapor shift offset:

\[ \text{Wall shift} = \text{Vapor shift} \approx 0 \]

Thus, fluctuations in atomic density could significantly degrade cryogenic maser stability.

### Spin-exchange effects

Spin-exchange collisions shift the oscillation frequency of a hydrogen maser. The magnitude of this shift is density dependent, therefore density fluctuations can limit the stability of a hydrogen maser.

At low temperature (< 1 K), quantum mechanical effects due to the hyperfine splitting (~ 0.3 K) become important. A fully quantum-mechanical treatment predicts a new, hyperfine-induced maser shift caused by spin-exchange collisions.

\[ \Delta \nu = \frac{g_F}{\Delta \nu_0} \]

The quantum mechanical shift is proportional to the atomic broadening due solely to spin-exchange collisions. Since it is not proportional to the total atomic linewidth, there is no maser cavity tuning where the maser frequency is density-independent.

Thus, fluctuations in atomic density could significantly degrade cryogenic maser stability.

### Measurement of semi-classical spin-exchange parameter [2]

**Measurement procedure:**

The broadening was varied by applying a set of static magnetic field gradients across the maser ensemble. The gradients broadened but did not shift the hyperfine transition.

**Results:**

The maser cavity detuning was determined by measuring the reflection of cw microwave power off of the maser cavity:

\[ \text{Reflection} \propto \text{Masercavity detuning} \]

and by recording the decay of a microwave pulse reflected off of the cavity:

\[ \text{Decay} \propto \text{Wall resonance} \]

These two methods disagreed, revealing the dominant source of systematic error.

### Measurement of semi-classical spin-exchange parameter [2]

**Comparison to previous 0.5 K results:**

- **Original theory result:**
  \[ \Delta \nu = -11.86 \text{ A}\text{D} \]
- **Previous experiment:**
  \[ \Delta \nu = -2.17 \pm 2.8 \text{ A}\text{D} \]
- **This work:**
  \[ \Delta \nu = +56.7 \pm 13.5 \text{ A}\text{D} \]

**Dominant error is systematic uncertainty in detuning [1].**

Until this is resolved, the SAO CHM cannot address existing discrepancy between theory and experiment.