Investigation of hydrogen hyperfine spin-exchange shift at 0.5 K

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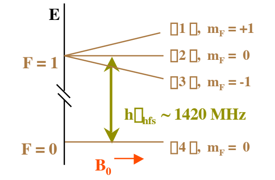
Hydrogen maser basics

The hydrogen maser is among the most stable **atomic frequency standards** available today. It's 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

Hydrogen hyperfine structure

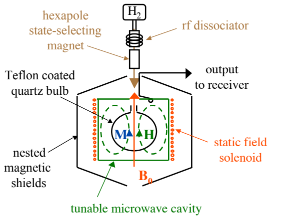


In a hydrogen maser, a beam of state selected |1□and |2□ hydrogen atoms is focused into a storage bulb centered inside a TE_{011} mode microwave cavity. The cavity is tuned near the hyperfine frequency of 1420 MHz.

The microwave cavity field **H** stimulates hyperfine transitions in the atomic ensemble, and the coherently radiating atoms build up a macroscopic magnetization **M** which acts to increase the microwave field.

This positive feedback between the field and the atoms leads to self sustained maser oscillation at a frequency near 1420 MHz.

Hydrogen maser schematic



The output oscillation frequency is extremely stable. This stability is attributed to:

1. Long atomic storage time (~1 s) }
2. Minimal wall relaxation } □ **narrow resonance line**
3. No first-order Doppler effects
4. No first-order Zeeman effects
5. Significant shielding from environment (thermal, magnetic, vacuum)
6. Low intrinsic noise, set by:
   - **thermal** microwave field □ **incoherent transitions**
   - **thermal** noise in receiver

Why a cryogenic maser?

Decreased noise at low T

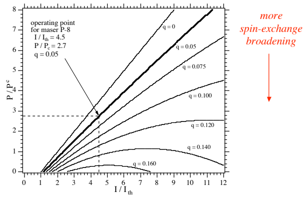
Thermal noise limits the stability of room temperature hydrogen masers for short times (t < 1000 s). During this time, the Allan variation scales with temperature as:

$$\square \quad \sqrt{T}$$

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

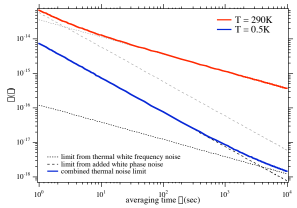
Increased power at low T

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



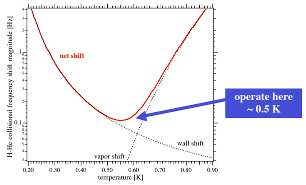
At T < 1 K, spin-exchange line broadening is reduced by ~ 3 orders of magnitude. Therefore, a cryogenic maser could be operated at much higher flux and higher output powers.

Through increased signal and decreased noise, a cryogenic hydrogen maser could be up to 3 orders of magnitude more stable than a room temperature maser:

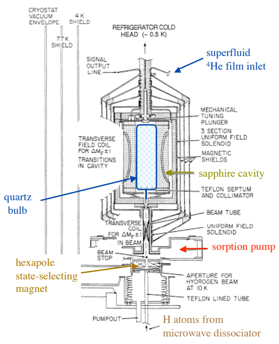


Experimental setup

Unfortunately, there are large, temperature dependent frequency shifts due to H-^{4}He collisions at the wall and in the vapor. At ~ 0.5 K, however, the wall and vapor shift offset:



Maser apparatus



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 (~ 0.1 K) become important. A fully quantum-mechanical treatment predicts a new, **hyperfine-induced maser shift** caused by spin-exchange collisions.

quantum mechanical spin-exchange shift parameter

$$\boxed{\square = \square_0 + [\square + \square\bar{\square}_0(1+\square^2)]\square\square\square\square_H}$$

semi-classical spin-exchange shift parameter

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 *n* could significantly degrade cryogenic maser stability

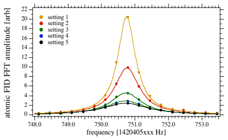
Measurement of semi-classical spin-exchange parameter $\square_0$

We determined $\square_0$ by measuring the spin-exchange maser frequency shift induced by increased hyperfine broadening.

$$\boxed{\square_0 = \frac{d\square/d\square_2\,\square\square}{\square(1+\square^2)}}$$

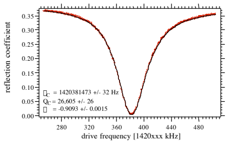
The broadening was varied by applying a set of static magnetic field gradients across the masing ensemble. The gradients **broadened** but **did not shift** the hyperfine transition.

The magnetic-gradient-induced broadening was measured using **free-induction decays** with the maser cavity detuned to quench active oscillation:

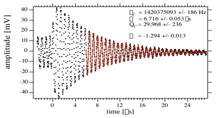


The maser cavity detuning was determined by measuring the reflection of cw microwave power off of the maser cavity:

$$\square = \frac{2Q_C}{\square_{24}}(\square_C \square\square_{24})$$

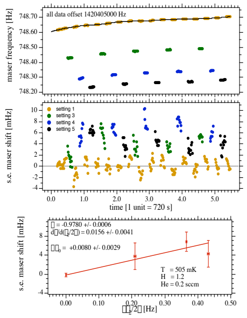


and by recording the decay of a microwave pulse reflected off of the cavity:

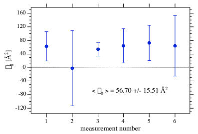


These two methods disagreed, revealing the dominant source of systematic error.

Measurement **procedure**:

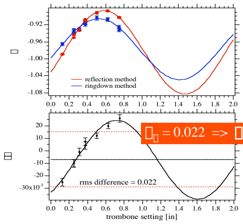


and **results**:



Result **independent** of maser temperature, superfluid film flow, hydrogen flux, and cavity detuning.

We estimated the **systematic uncertainty** in □ as the rms value of the difference in measured □ between the two measurement techniques (over one microwave wavelength along the transmission line):



$\square_\square$ = 0.022 => $\square_{\square_0}$ **= 81 Å^2**

Comparison to previous 0.5 K results:

Original **theory** result *(Koelman et al., PRA **38**, 3535 (1988)*	$\square_0 = -11.86$ Å^2
Previous **experiment** *(Hayden et al., PRA **53**, 1589)1996)*	$\square_0 = -21.7 \pm 2.8$ Å^2
this work	$\square_0 = +56.7 \pm 15.5 \pm 81$ Å^2 15.5: statistical error; 81: systematic error

- Dominant error is **systematic uncertainty in detuning □.**
- Until this is resolved, the SAO CHM cannot address existing discrepancy between theory and experiment.