Master Seminar: Atomic Clocks

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Introduction

From sundials to mechanical clocks, over electrical to atomic clocks—as technology advanced over the last centuries and decades, so did the measurement of frequencies, particularly in the context of clocks.
To keep time, a clockwork counts recurring events, therefore, at its heart every clock needs a frequency standard. This seminar writeup describes how atomic transitions can be used as frequency standards. This is beneficial because their fast frequencies allow for a low relative uncertainty of the time measurement and the well-defined atomic structure permits construction of stable and reproducible clocks.

Microwave Atomic Clocks

Atomic transitions—approximated with a two-level system—can be be stimulated with external oscillating electromagnetic fields. While interacting with the external field, the system oscillates between the two states with the Rabi frequency Ω. The (maximum) probability to change states depends on the detuning Δ of the oscillating field (ω) compared to the atomic transition frequency ω_0. A beam of atoms in the ground state will, after a time T in an interaction zone (IZ) with the external field, have a population in the excited state depending on Δ. Measuring the population of the states for different ω, one obtains a resonance curve centered at ω_0 [1]. The resonance width decreases with larger T, however the IZ is difficult to extend very far because it introduces technical problems, such as inhomogeneities [2].
In 1950 Ramsey developed this method further by separating the oscillating field IZ into two with a field free propagation in the middle [3]. The IZs apply a $\pi/2$–pulse to the atom, which generates a superposition state from a pure state. For the resonant case ($\Delta = 0$) the external field and the superposition will oscillate in phase and the 2nd IZ will produce the excited state with 100% certainty. For a detuning there will be a phase shift accumulated between the field and the superposition, resulting in a non-zero ground state population. The width of the central peak of the resulting interference pattern decreases with larger free time of flight, which is a lot easier to increase and has the benefit of being field free, hence less perturbative.
Based on this method the first caesium beam atomic clock was built in 1955, using the hyperfine (HF) splitting in the ^{133}Cs ground state as the referenced atomic transition frequency [4, 5]. A U-shaped microwave (mw) cavity supplies the two IZs, the frequency of which is read out electronically. Due to the definition of the second at the time, the precision of atomic clocks was limited by necessary comparison to astronomical observations [6], before the SI second was redefined and based on the Cs HF transition of 9.2 GHz [7].
A more current setup of the same Ramsey principle is a caesium fountain [8]. Here the setup is vertical, the Cs atoms are accelerated upwards through a mw IZ, are slowed by gravity and fall through the IZ a second time. This makes the field free time of flight a lot longer, and only requires a single mw IZ which is tuned around the transition frequency to read out the detuning.

Optical Atomic Clocks

Larger frequencies such as optical frequencies ($\sim 100\,$THz) allow a potentially higher precision in their measurement and in clocks. With the invention of the laser in 1960 [9] one gained control over optical transitions, however, measurements of optical frequencies were still confined to measurements of the corresponding wavelength—insufficient and unsuitable for clocks—for a long time. The invention of the frequency comb 1998 makes optical frequency measurement possible [10]. The spectrum of this mode-locked femtosecond laser consists of narrow equidistant lines under an envelope. Offset and repetition frequency of the comb are in the microwave regime and provide a link to the optical regime where a monochromatic (clock) laser can be compared to the teeth of the comb [11].
For a clock setup with optical frequency measurement there are typically single ions trapped in a Paul trap or several atoms trapped in an optical lattice [12]. A clock laser drives the optical transition of interest as the mw cavity did previously, and the detuning is determined as before with the Ramsey method while the frequency is measured with a comb. The best precision possible yet is 3.2×10^{-18} for a single ion clock with a ^{171}Yb$^+$ ion [13] and 2.1×10^{-18} for a Sr optical lattice clock [14].

Outlook

To improve this precision further new atomic frequency standards have been proposed. Nuclear transitions as well as HF transitions in highly charged ions are not very susceptible to external perturbations which makes them good candidates for clocks. Either of these new atomic clock designs could achieve a precision on the order of 10^{-19} [15, 16].

References

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