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FREQUENCY STANDARD RESEARCH USING STORED IONS

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ABSTRACT

We summarize research undertaken to develop time and frequency standards based on stored ions. The ion storage method for high resolution spectroscopy is also briefly compared to the methods for stored neutrals and slow atomic beams.

Key Words: atomic clocks, atomic spectroscopy, frequency standards, high resolution spectroscopy, laser spectroscopy.

1. Introduction

The possibility of producing very cold atomic beams and stored neutrals is exciting. Certainly these experiments are interesting by themselves but they also point the way to some new experiments in high resolution spectroscopy and may result in new schemes for atomic frequency standards. The technique of stored ions also has great promise in these applications and therefore it is useful to compare these techniques so that potential problems can be addressed in the future. In the case of trapped ions, practical frequency standards techniques have already been demonstrated. Stabilities comparable to or better than some commercial standards have been achieved and the potential is clear to obtain long term stability and accuracy of 10^{-15} in a practical device. This paper is biased toward the stored ion technique but certainother hand seeks the region of zero electric field; for cooled ions the average magnitude of electric field can be below 1mV/cm [6]. Perhaps the chief limitation of the atomic beam method is caused by the net linear motion of atoms; even if Doppler cancellation schemes are used, residual first order Doppler shifts can be the limiting systematic effect. This is, for example, true for the cesium beam frequency standard, the most accurate frequency and time standard available. For the case of trapped ions, the same ions can be confined nearly indefinitely; therefore the net velocity averages to zero and first order Doppler shifts are nearly absent.

The primary disadvantage of the stored ion technique is that the number of trapped ions is typically small--approximately 10^6 ions or less for a trap of centimeter dimensions. Therefore one is usually restricted to use simple atomic systems where signal to noise can be maximized.

1.2 Scope of Paper

The remainder of the paper discusses stored ion experiments whose goal is very high resolution spectroscopy--i.e. stored ion frequency standards: present status and future goals.

2. Stored Ions and Frequency Standards

2.1. Microwave Frequency Standards

At present, the most accurate (reproducible) frequency standards are based on microwave transitions of atoms or molecules. The stability of a frequency standard increases with increased Q (transition frequency divided by linewidth) and increased signal to noise ratio. The reproducibility depends upon control of environmental factors. Standards based on narrow optical transitions have the advantage of higher Q for a given interaction time, for cases where the linewidth is limited by interaction time. However, the use of such a frequency standard to generate precise time, one of the chief applications of frequency standards, is very difficult with current technology. The main difficulty is dividing an optical frequency down to the RF region. Also, high-stability optical sources are not easy to produce.

dilation) shift, which is relatively high (about 10^{-11}) because the average ion kinetic energy is a few eV. In a similar experiment on trapped $^{171}Yb^+$ ions, Blatt et al. [14] have observed a 0.06 Hz linewidth on a 12.6 GHz hyperfine transition, corresponding to a Q of 2×10^{11}, the highest yet obtained in microwave spectroscopy.

2.2 Laser Cooling and Microwave Frequency Standards

Perhaps the chief advantage of applying laser cooling to stored ions is the suppression of Doppler effects. Even without laser cooling, first order Doppler effects are highly suppressed because of the long term storage. However, without laser cooling, second order Doppler shifts can be relatively large (approximately 2×10^{-13} for room temperature Hg^+ ions) and since the velocity distributions are non-Maxwellian -- these shifts are difficult to precisely characterize.

With laser cooling, temperatures < 1K are easily obtained. The lowest temperatures (approximately 0.01 K) have been obtained for single ions [15-17]. However for a microwave frequency standard, many ions are required in order to keep the signal to noise ratio high enough to maintain desired stability [6,8]. So far the only reported experiments with the goal of a laser cooled microwave frequency standard are those of NBS [18,19]. These experiments are based on the storage of many ions (10^2-10^5) in a Penning trap where residual heating mechanisms [20] are apparently much less than in the rf trap. The Penning trap [20] requires static electric and magnetic fields for trapping. Since the required magnetic fields are rather large (∿ 1T), one uses extremum points in the clock transition frequency vs. magnetic field; for these conditions, stabilities below 10^{-15} should be obtained [8,18,19]. Linewidths of approximately 0.01 Hz have been obtained on 300 MHz nuclear spin flip hyperfine transitions in $^{25}Mg^+$ [21] and an oscillator has been locked to a similar transition in $^9Be^+$, giving a stability approaching 10^{-13}. Operation on a 26 GHz transition in $^{201}Hg^+$ is anticipated; inaccuracy of $< 10^{-15}$ and stabilities better than 10^{-16} appear possible [8].

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