SUMMARY OF RESEARCH: INDIUM SINGLE–ION FREQUENCY STANDARD

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1 Introduction

A single laser-cooled indium ion is a promising candidate for an ultimate resolution optical time or frequency standard. It can be shown [1] that single ions from group IIIA of the periodic table (indium, thallium, etc.) can have extremely small systematic errors. In addition to being free from Doppler, transit-time and collisional shifts, these ions are also quite insensitive to perturbations from ambient magnetic and electric fields (mainly due to the use of a J=0–0 transition for spectroscopy). Of all group IIIA ions, indium seems to be the most practical, since it is heavy enough to have a tolerable intercombination cooling transition rate and (unlike thallium) has transitions which are easily accessible with frequency multiplied continuous-wave lasers. A single indium ion standard has a potential inaccuracy of one part in 10^{18} for integration times of 10^6 seconds.

We have made substantial progress during the grant period in constructing a frequency standard based upon a single indium ion. At the beginning of the grant period, single indium ions were being successfully trapped, but the lasers and optical systems were inadequate to achieve the desired goal. We have considerably improved the stability of the dye laser used to cool the ions and locked it to a molecular resonance line, making it possible to observe stable cooling-line fluorescence from a single indium ion for reasonable periods of time, as required by the demands of precision spectroscopy. We have substantially improved the single-ion fluorescence signal with significant benefits for the detection efficiency of forbidden transitions using the "shelving" technique. Finally, we have constructed a compact, efficient UV "clock" laser and observed "clock" transitions in single indium ions using this laser system. We will elaborate below on these accomplishments.

2 Accomplishments During Grant Period

Single indium ions are routinely trapped in a single-ring Paul-Straubel trap whose ring diameter is 1.0 mm. The trapping drive consists of about 700 V of 10 MHz RF applied to the ring, resulting in a secular frequency of about 1 MHz. The trapping is very robust: it is not unusual for an ion to stay in the trap overnight without laser cooling and one ion actually lasted for 27 days in the trap (with occasional cooling).

Reasonable fluorescence signals (Fig. 2) are obtained when the $5^0S_0-5^3P_1$ transition (at 231 nm, see Fig. 1) is driven with a frequency-doubled dye laser. The dye laser is frequency stabilized in the short term to an external cavity and in the long term to a saturated molecular tellurium line. The short-term stabilization system provides a short-term linewidth of less that 50 kHz and includes a "redundant" locking system, which considerably improves the robustness of the lock by automatically switching to the laser's internal reference cavity if the lock from the external, much narrower cavity is momentarily lost. The tellurium system provides a long-term locking error of less than 1 MHz. An AO-modulator in the tellurium saturation spectrometer allows the laser to be tuned over the cooling transition while being locked. The locking system provides optimum fluorescence for several hours while the laser sits on the cooling side of the relatively narrow (360 kHz [4]) cooling transition.

The narrow "clock" transition is the $5^0S_0-5^3P_0$ "forbidden" transition at 236 nm (Fig. 1). The 5^3P_0 level contains a very small admixture (due to the nuclear magnetic moment) of $^{3,1}P_1$ levels,
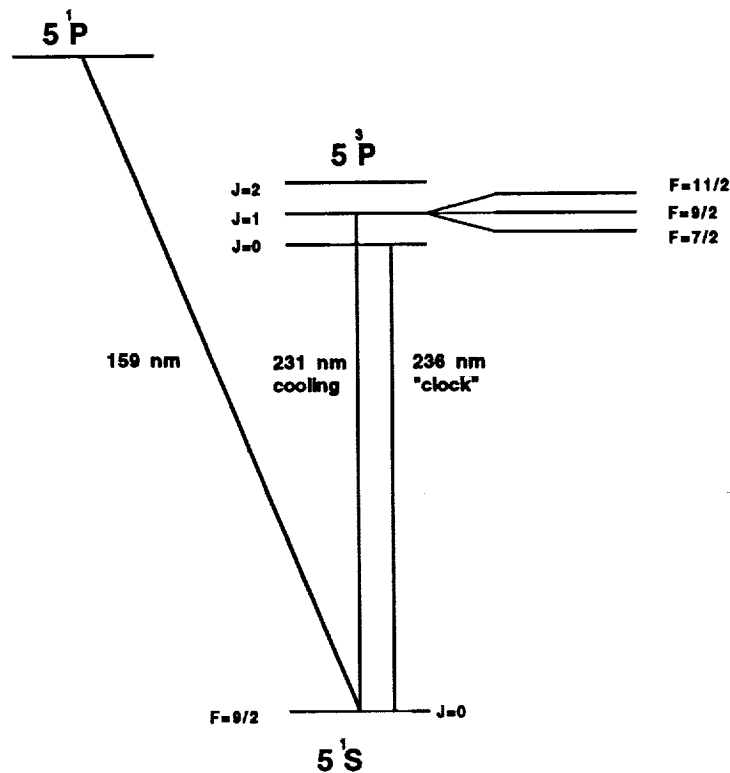
5 ^{1}P

5 ^{3}P

J=2   F=11/2
J=1   F=9/2
J=0   F=7/2

159 nm   231 nm cooling   236 nm "clock"

F=9/2   J=0

5 ^{1}S

Figure 1: Level diagram of In$^+$, showing cooling and "clock" transitions..

which allows the transition to take place. The lifetime[4] of the 5^3P_0 state is .15 s, giving the transition a 1 Hz natural width (a Q of about 10^{15}).

This transition is driven by a frequency quadrupled solid-state laser system. The laser source is a small commercial tunable "master-oscillator power-amplifier" (MOPA), which generates up to 500 mW of CW power and is tunable from 925 nm to 968 nm. The laser's linewidth is about 2 Mhz, with most of the frequency jitter being at low audio frequencies (less than 1 kHz).

The 946 nm output of the MOPA is frequency doubled in two stages to 236 nm. Both doublers employ "build-up" cavities to multiply (by up to a factor of 100) the intensity of the radiation focused into the inefficient doubling crystals, resulting in an enhancement of the frequency-doubled power by a factor of up to 10,000. The first stage uses a potassium niobate crystal and converts more than half of the 946 nm radiation to 473 nm. The second stage uses a BBO crystal to generate more than 10 mW of UV at 236 nm. The cavities are resonant devices and are locked to their input beams using the Hänsch-Couillaud polarization scheme.[5] Extremely good locks are achieved, particularly in the first stage, whose amplitude fluctuations are less than .1% (a poor lock would convert frequency noise to amplitude noise). The entire system fits inside a 19"x25"x8" box and the power draw is several hundred watts. A schematic of the complete system appears in Fig. 3.

The reduction of the "clock" laser linewidth is achieved using two reference cavities. Originally, it was intended to narrow the laser in two steps; recent results have led to a modification of this strategy (see below). The first resonator is a small integral reference cavity which narrows the laser to a few kHz (relative to the cavity) and the second resonator is a larger optically-contacted Zerodur cavity which should narrow the laser to a width of 1 Hz or less. Both cavities have been
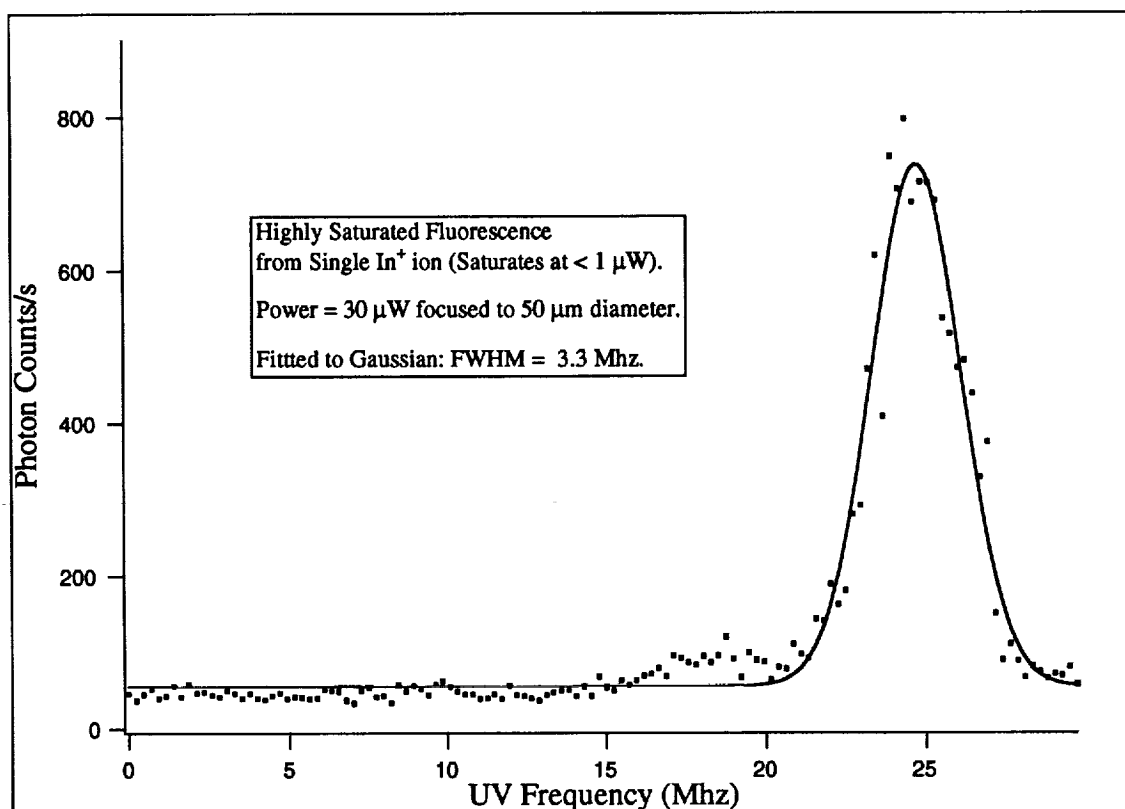
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Figure 2: Fluorescence at 231 nm obtained by excitation of the $5^0S_0-5^3P_1$ transition of In^+ with a frequency doubled dye laser.

constructed and the first is currently in use. It is a small, temperature stabilized and hermetically sealed cavity (linewidth 160 kHz) which is coupled to a small sample of the 946 nm laser beam using a single-mode optical fiber whose ends are cleaved for very low reflection. The cavity is suspended by short springs (resonant frequency of 5 Hz), which, together with the use of an optical fiber (and using very fine wires for all connections), provides some isolation from ambient vibrations. Using the Pound-Drever [6] locking scheme, the laser is frequency locked to this small cavity. Analysis of the error signal using a digital spectrum analyzer demonstrates that the locked rms linewidth of the laser is under 2 kHz (relative to the cavity). This reference cavity fits entirely within the 19"x25"x8" enclosure of the UV source. The larger cavity has a measured linewidth of 16 kHz.

The "clock" transition was recently observed (Fig. 4). The search for the narrow transition was facilitated by the availability of several mW of UV power which allowed us to broaden the laser to about 1 MHz and scan rapidly over a region within 600 MHz of the expected resonance frequency. The size of this search region was dictated by the ±300 MHz uncertainty in the commercial digital wavemeter used to set the laser frequency. A somewhat lower power "clock" laser would have made the search much more tedious, as a smaller laser linewidth would have been necessary in order to obtain a reasonable transition rate (A narrower laser linewidth would require a slower search).

A plot of the "clock" laser resonance appears in Fig. 4. The 8.9 Mhz linewidth is much larger than the "clock" laser linewidth relative to the cavity and is due almost entirely to jitter in the small reference cavity. Using a tellurium saturation spectrometer as a frequency discriminator, we investigated this jitter (Fig. 5). As can be seen in the plot, the jitter is quite large - we believe it is
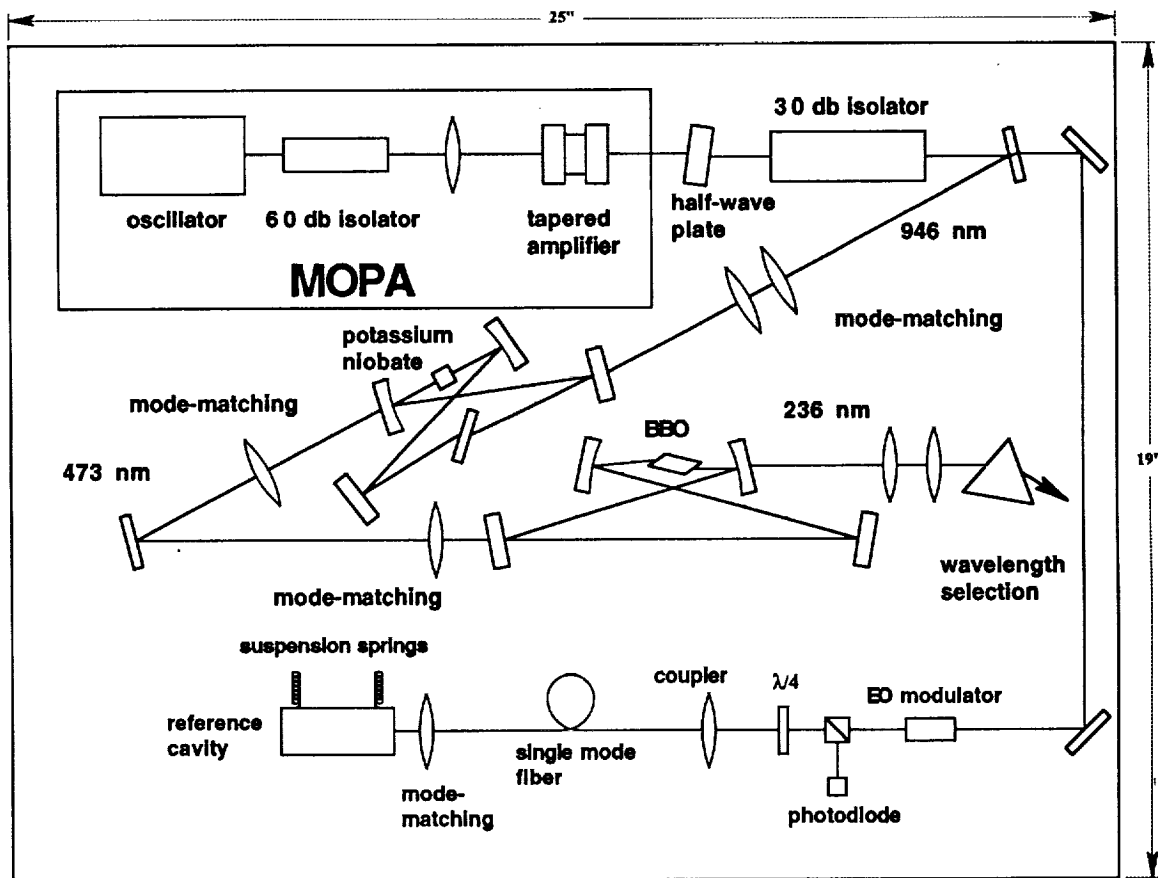
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Figure 3: Schematic of UV laser system used to excite the "clock" transition of In$^+$ at 236 nm.

due to "position noise" (perhaps having a 1/f character) of the PZT used to sweep one of the cavity mirrors. Noise in the mirror position is especially conducive to frequency jitter since this cavity is very short: the mirror spacing is 1.5 cm. The cavity temperature stability and PZT voltage stability are quite good and make very little contribution to the observed linewidth.

As a result of this (unexpectedly) large cavity jitter, the function of the small cavity will be changed: rather than serving as the first stage in a two stage locking system, it will be used as a "redundant" locking cavity which will aid in re-locking the laser if it breaks lock from the large, very narrow cavity. The latter will be highly isolated from the environment and constructed of a Zerodur spacer with Zerodur mirrors optically contacted at each end. The stability of this resonator should be extremely good and it will, of course, be free from the jitter which plagued the small cavity.

3 Conclusions

We feel that continuing advancement of the state of the art of single ion trapping and flywheel laser technology will make a single laser-cooled ion a viable candidate for an ultimate resolution optical frequency standard. We are very close to being able to observe very narrow resonances in In$^+$ and should be able to construct a frequency standard in the near future. The recent achievements in the use of femtosecond "comb" lasers to bridge the optical-microwave gap are very important steps in
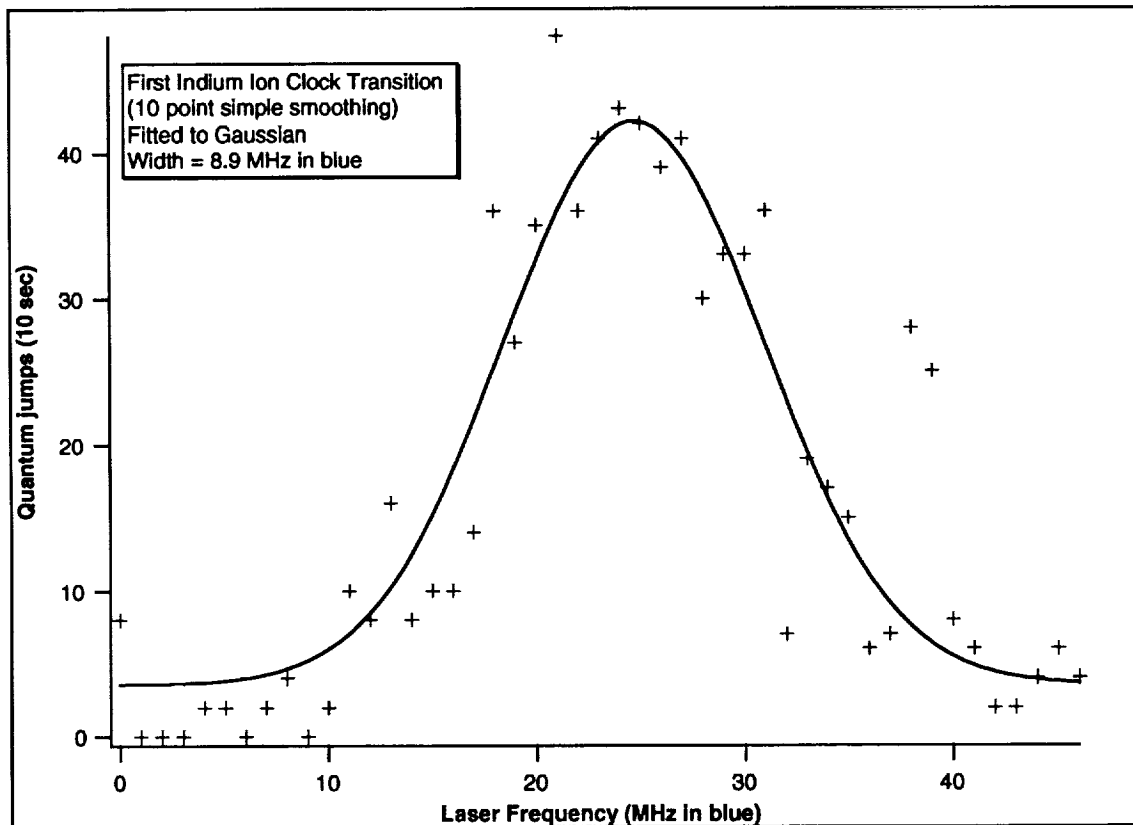
Figure 4: Plot of "clock" resonance at 236 nm. The frequency scale is for the blue light at 474 nm.
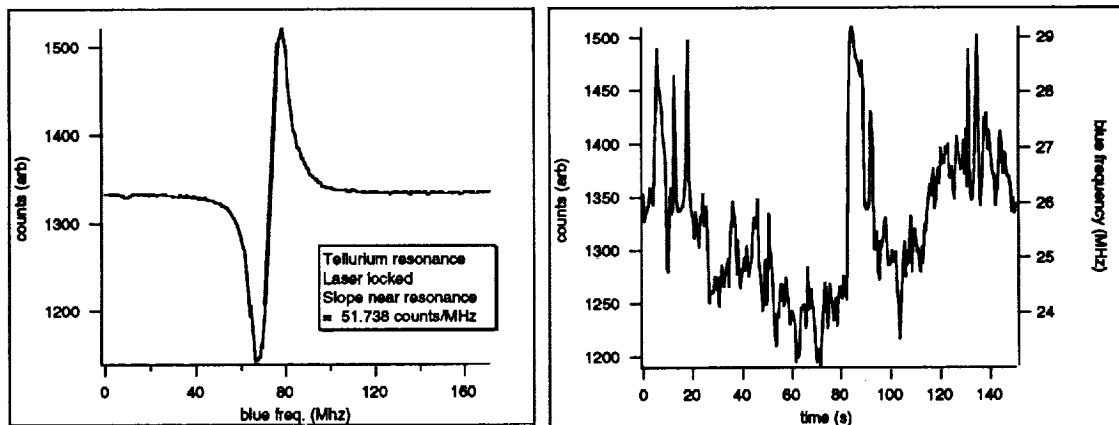

Figure 5: Plot (on right) of locked "clock" laser frequency drift versus time, using tellurium resonance as a discriminant (left).

converting a frequency standard into a time standard. These advances together with the well-known single-ion advantages of an optical frequency and small systematics should make the prospects for a single-ion time standard very favorable indeed.

4   References

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