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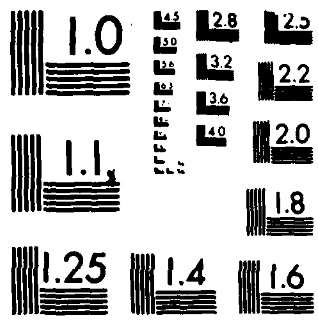

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Atomic spectroscopy; Doppler narrowing; Doppler shifts; Frequency standards; High resolution spectroscopy; Ion storage; laser spectroscopy; Penning trap; Radiation pressure.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second and residual first-order Doppler shifts. To this end we study suitable frequency reference transitions in ions which are stored on electromagnetic traps and cooled by radiation pressure to < 1K.

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Summary of Work on

"COOLED ION FREQUENCY STANDARD"

(FY 84)

ONR Contract No. N00014-84-F-0003

Project Leader:

D. J. Wineland

Frequency & Time Standards Group

524.11

National Bureau of Standards

Boulder, Colorado 80303

FTS: 320-5286

(303) 497-5286

Contract Description

The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second and residual first-order Doppler shifts. To this end, we study suitable frequency reference transitions in ions which are stored in electromagnetic traps and cooled by radiation pressure to < 1K.

Scientific Problem

The scientific problems are (1) to greatly suppress second order and residual first order Doppler shifts in atomic frequency standards in a fundamental way--by substantially reducing the kinetic energy of ions stored ion electromagnetic traps, (2) to study suitable reference transitions in ions that can be used as frequency standards, and (3) to study the problems generic to all stored ion frequency standards. The goal is to achieve at least a factor of 100 improvement in accuracy over the present best device, the Cesium beam frequency standard, which has an accuracy of approximately one part in 10^{13}.

Scientific and Technical Approach

We will continue studies of laser cooling. We can now obtain ion temperatures near .1K in ion clouds--temperatures near 10^{-3}K should be possible. We will continue work to develop better traps for spectroscopic studies. We are completing experiments on Be^{+} and will soon make improvements in trap design. We are developing a separate experiment for $^{201}Hg^{+}$ ions. This experiment has the goal of realizing a prototype microwave frequency standard with 10^{-15} accuracy.

III. PROGRESS DURING LAST CONTRACT PERIOD

A. Hg^+ studies

1. Storage and fluorescence detection of $^{198}Hg^+$ in a Penning trap. We have now observed 194 nm laser fluorescence scattering from $^{198}Hg^+$ ions which are stored in a Penning trap. In addition we have measured the electronic g-factor for Hg^+ (to 3 ppm accuracy) which was an important step in the project because of the necessity of microwave "mixing" the ground state energy levels. This latter measurement involved a lengthy search compounded by the fact that a previous, less accurate measurement (500 ppm) from the literature was in error by 15 σ from the quoted error. $^{198}Hg^+$ ions were chosen for this initial study of stored mercury ions because the structure is simpler than that of $^{201}Hg^+$ (two ground state levels as opposed to eight). The last big step before setting up a frequency standard based on $^{201}Hg^+$ is to achieve laser cooling of Hg^+. This work, presently underway, may necessitate the use of cryogenic cooling to reduce the pervasive background pressure of neutral Hg at room temperature and may require higher laser power.

2. 194 nm generation. $^{201}Hg^+$ has been chosen as a prototype frequency standard because it appears to have the best potential performance of any ion that might conceivably be used in a microwave frequency standard. One of its chief drawbacks is that the coherent

194 nm radiation required for laser cooling/optical pumping is difficult to produce. Therefore a significant effort has gone into the continued development of this source. Recently we have increased the effective power for cooling from 3 μW to about 25 μW by constructing a build up cavity around the trap apparatus. We are hopeful that this should provide enough power to achieve laser cooling since approximately 5 μW of power was sufficient in the case of Mg^+ and Be^+.

B. $^9Be^+$ experiments

1. Cloud studies In order to optimize conditions for the $^{201}Hg^+$ experiments, we study the general ion storage problems using $^9Be^+$ ions where the required radiation (λ=313 nm) for optical pumping and laser cooling experiments is easier to produce. We have undertaken a careful study of ion cloud dynamics since it is expected that the largest systematic effect in a microwave frequency standard based on ions stored in a Penning trap will be due to a second order Doppler effect due to cloud rotation. To this end we have developed a sensitive way to measure cloud size and density from which rotation velocity can be accurately determined. The size of the cloud was determined by using a second probe laser which is moved spatially across the cloud. The density was determined by measuring the space charge shifted $\vec{E} \times \vec{B}$ cloud rotation frequency (dependent on density) via the change in Doppler shift across the cloud using the probe laser.

By using an optical depopulation technique, the steady state behavior of the ion cloud is undisturbed by the probe laser. From the linewidth of these optical depopulation signals, the overall temperature of the cloud is determined.

From these measurements we have not only characterized the Doppler shift due to the rotation, but have also identified two sources of general heating. We note that when the cooling laser is on, temperatures are low enough to cause a second order Doppler shift of only about 10^{-15}. The laser must be turned off, however, when the clock transition is driven in order to avoid light shifts. During this time the cloud heats up due to (1) collisions with background gas and (2) plasma heating. We anticipate that the background gas heating can be made negligible by using cryopumping. The second effect appears to be due to "resonant particle transport" heating - an effect which causes plasma instability in tandem mirror fusion machines.

2. $^{9}Be^{+}$ clock studies.

We have set up a "model" clock based on $^{9}Be^{+}$ where laser cooling is easier to achieve than in Hg^{+}. Two key features of this system are (1) an inaccuracy only slightly worse than the best laboratory Cesium clocks. (2) This system facilitates studies of generic stored ion frequency standard systematic effects. The general heating discussed in the preceeding paragraph gives a second order Doppler shift error of about 1-2 parts in 10^{13} (only a factor of 2 or 3 worse than the best laboratory primary Cesium standards.) This appears to be the largest systematic effect by an order of magnitude. Other effects studied include magnetic field fluctuations, gyroscopic effect due to the earth's rotation, servo offsets, rf "chirping" (i.e. phase shifts of the rf when it is turned on and off), pulling from spurious signals, stark shifts, first order Doppler effects, collisions of background gas, background slopes and rf coherence between cycles.

C. Laser development

The cooling and interrogation of positive ions requires continued development of ultraviolet laser techniques beyond the present state of the art. At present, this work is concentrated on increasing the 194 nm laser power. Example byproducts of this work is the invention of a low loss Mach-Zehnder "thick" etalon for dye lasers, a study of external ring cavities for non-linear optical mixing, and a study of laser frequency offset locking systems using Schottky barrier mixers.

D. Basic physics applications

As a result of frequency standard systematic effect searches, two physically interesting side effects have been investigated: (1) Strongly coupled plasmas - density and temperature measurements indicate that the ion clouds should be liquid. Transition to a solid (Wigner crystallization) should also be observable. (2) Search for spatial anisotropies of a cosmological origin. This work which only involves an evaluation of frequency stability data has for example already improved the result of the "Hughes-Drever" search for spatial mass anisotropy by a factor of 100.

E. Future apparatus development

A NMR based system for shimming and characterizing our superconducting magnet has been completed. Computer designs of advanced traps have continued to be studied and a new apparatus based on these designs should be under construction by this next fiscal year.

F. Ion storage publications in preparation or published since May '83.

1. "High Resolution Spectroscopy of Stored Ions," D. J. Wineland, Wayne M. Itano and R. S. Van Dyck Jr., in Advances in Atomic and Molecular Physics, Vol. 19 ed. by Bederson & Bates, (Academic Press, Aug. 1983). p. 135.

2. "Laser Cooled $^{9}Be^{+}$ Accurate Clock", J. J. Bollinger, Wayne M. Itano, and D. J. Wineland, Proc. 37th Annual Symp. Freq. Control, 1983, p. 37 (copies available from Systematics General Corp., Brinley Plaza, Rt. 38, Wall Township, NJ 07719.

3. "Spectroscopy of Stored Ions Using Fluorescence Techniques," D. J. Wineland, Wayne M. Itano, J. C. Bergquist, and H. Hemmati, S.P.I.E. Vol. 426-Laser Based Ultrasensitive Spectroscopy and Detection V, Society of Photo-Optical Instrumentation Engineers, 1983, p. 65.

4. "Frequency Standard Research Using Stored Ions", D. J. Wineland, Wayne M. Itano, J. C. Bergquist, J. J. Bollinger, and H. Hemmati, in Laser Cooled and Trapped Atoms, (Proc. of the Workshop on Spectroscopic Applications of Slow Atomic Beams, NBS, Gaithersburg, MD, April 1983. Ed. W. D. Phillips, NBS (US) Spec. Publ. 653 (1983) p. 19.

5. "Precision Measurements of Laser Cooled $^{9}Be^{+}$ Ions", J. J. Bollinger, D. J. Wineland, Wayne M. Itano, and J. S. Wells, in Laser Spectroscopy VI, ed. by H. P. Weber and W. Lüthy, (Springer-Verlag, 1983) p. 168.

6. "Sum Frequency Generation of Narrowband cw 194 nm Radiation in Potassium Pentaborate," H. Hemmati, J. C Bergquist, Wayne M. Itano, Proceedings of the 6th International Conference on Laser Spectroscopy, 1983.

7. "A Wideband Frequency-Offset Locked Dye Laser Spectrometer Using a Schottky Barrier Mixer", J. C. Bergquist and H. -U. Daniel, Optics Comm. 48 (1984) 327.

8. "Demonstration of Broadband Schottky Barrier Mixers for Visible Laser Light and Application to High Resolution Spectroscopy," J.C. Bergquist, H. -U. Daniel, B. Maurer, M. Steiner, and H. Walther, Proceedings of the 6th International Conference on Laser Spectroscopy, 1983.

9. "Efficient Single Mode Operation of a cw Ring Dye Laser with a Mach-Zehnder Inferometer", J. C. Bergquist and Lee Burkins, submitted to Optics Comm., Jan. 1984.

10. "External Ring Cavities for Nonlinear Mixing", J. C. Bergquist in preparation.

11. "Strongly Coupled One Component Ion Plasma", J. J. Bollinger and D. J. Wineland submitted to Phys. Rev. Lett.

12. "Hyperfine Structure of the $2p^2P_{\frac{1}{2}}$ State in $^9Be^+$", J. J. Bollinger, J. S. Wells, D. J. Wineland, to be submitted to Phys. Rev.

13. "Trapped Ions, Laser Cooling, and Better Clocks", D. J. Wineland, accepted for Science magazine.

Abstracts

1. "Laser Spectroscopic Studies of Cold, Trapped Ions," W. M. Itano, Invited paper for D.E.A.P. meeting, Storrs, CT, May/June, 1984.

2. "A Frequency Standard Based on Laser-Cooled Ions Stored in a Penning Trap," W. M. Itano, J. J. Bollinger, and D. J. Wineland, "Abstract for Workshop on Controlling Atoms, Storrs, CT, May 28, 1984.

3. "Strongly Coupled One Component Ion Plasma" J. J. Bollinger, D. J. Wineland and J. D. Prestage, ibid.

4. "Measurements of Hg^+ g-factors", W. M. Itano, J. C. Bergquist, and D. J. Wineland, Abstract for Int. Conf. Atomic Physics, Seattle, 1984.

5. "Laser Cooled Atomic Frequency Standard", D. J. Wineland, J. J. Bollinger, W. M. Itano, and J. D. Prestage, ibid.

6. "Strongly Coupled Non-Neutral Ion Plasma", J. J. Bollinger, D. J. Wineland, and J. D. Prestage, ibid.

7. "Tests of Spatial Anisotropy Using Trapped $^{9}Be^{+}$ Ions," J. D. Prestage, J. J. Bollinger, W. M. Itano, and D. J. Wineland, ibid.

F. Invited talks on ion storage since May 1983

1. Sixth International Conf. Laser Spectroscopy nterlocken, Switzerland, June '83 (Bollinger and Hemmati).

2. Gordon Conf. on Atomic Physics, New London, NH July, 1983 (Itano).

3. Conference of the Society of Photo-Optical Instrumentation Engineers (S.P.I.E.) San Diego, CA, August '83 (Wineland).

4. Univ. of California, San Diego, Aug. '83 (Wineland).

5. Symposium on Atomic Spectroscopy, Berkeley, Calif. Sept. '83 (Wineland).

6. Sixth International Conf. on Lasers and Applications, Lasers '83, San Francisco, CA, Dec. 1983 (Bollinger and Wineland).

7. NBS Workshop on Precision Measurement May, 1984 (Wineland).

8. Workshop on Controlling Atoms, Storrs, CT May '84, (Itano and Wineland).

9. D.E.A.P. Annual Meeting, Storrs CT, May/June, 1984 (Itano).

10. Int. Conf. on Atomic Phys., Seattle, WA. July '84 (Wineland).

11. Amer. Chem. Soc. Meeting, Philadelphia, PA, Aug. 1984 (Bergquist).

12. 1984 Federation of Analytical Chem. and Spectroscopy Soc., Philadelphia, PA, Sept. 1984 (Bergquist).

Miscellaneous

A. All FY84 funds will be spent by end of contract year.

B. Other contract support of principal investigators:

David J. Wineland and Wayne M. Itano

AFOSR $150K "Precision Frequency Metrology Using Laser Cooled Ions."

KEY PERSONNEL (FY84)

Co-Principal Investigators	D. J. Wineland	(50%)
	Wayne M. Itano	(50%)
Senior Staff Scientists	J. C. Bergquist	(35%)
	C. Manney	(35%)
	E. Beaty	(35%)
	J. J. Bollinger	(50%)
Research Associate	J. D. Prestage	(50%)