Technical Note 1380

Trapped Ions and Laser Cooling IV

Selected publications of the Ion Storage Group of the Time and Frequency Division

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PREFACE

This collection of papers represents the work of the Ion Storage Group, Time and Frequency Division, National Institute of Standards and Technology, from May 1992 to January 1996. It follows the collections of papers contained in NBS Technical Note 1086, *Trapped Ions and Laser Cooling* (June 1985), NIST Technical Note 1324, *Trapped Ions and Laser Cooling II* (September 1988), and NIST Technical Note 1353, *Trapped Ions and Laser Cooling III* (April 1992). Although the primary goal of this work has been the development of techniques necessary for achieving high resolution spectroscopy, we have also been able to investigate related areas of research.

Papers listed on page viii were published or prepared during the period May 1992 to January 1996 but are not included here. Copies can be obtained on request. We intend to update this publication periodically to include new work. We hope this collection of papers will be useful to our colleagues in this and related fields.

We acknowledge the contributions of many colleagues to this collection. In particular, we thank Amy Barton, Ed Bell, Dana Berkeland, Flavio Cruz, Dan Dubin, Ulli Eichmann, Jon Gilligan, Phil Gould, Dan Heinzen, Steve Jefferts, Brana Jelenković, Brian King, Dawn Meekhof, John Miller, Fred Moore, Martin Poitzsch, Mark Raizen, Norman Ramsey, Max Rauner, Andy Steinbach, Carl Weimer, and Joseph Tan. We gratefully acknowledge the continued support of the U.S. Office of Naval Research and the U.S. Army Research Office. We thank Wendy Ortega Henderson for assembling this collection.

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ADDITIONAL PUBLICATIONS

The following publications were published or prepared during the period between May 1992 and January 1996, but are not included in this technical note.

1. "Experimental results on normal modes in cold, pure ion plasmas," J. J. Bollinger, D. J. Heinzen, F. L. Moore, C. S. Weimer, W. M. Itano, and D. J. Wineland, in *Strongly Coupled Plasma Physics*, ed. by Van Horn and Ichimaru (University of Rochester Press, Rochester, NY, 1993), pp. 393-398.

2. "Quantum measurements of trapped ions," W. M. Itano, J. C. Bergquist, J. J. Bollinger, J. M. Gilligan, D. J. Heinzen, F. L. Moore, M. G. Raizen, and D. J. Wineland, Proc., Intl. Symp. on Quantum Physics and the Universe, Waseda Univ., Tokyo, Japan, Aug. 19-22, 1992, ed. by M. Namiki, K. Maeda, and I. Ohba, Vistas in Astronomy 37, 169-183 (1993).

3. "Precise spectroscopy for fundamental physics," W. M. Itano, J. C. Bergquist, J. J. Bollinger, J. M. Gilligan, D. J. Heinzen, F. L. Moore, M. G. Raizen, and D. J. Wineland, Hyperfine Interactions 78, 211-220 (1993).

4. "Non-neutral ion plasmas and crystals, laser cooling, and atomic clocks," J. J. Bollinger, D. J. Wineland, and D. H. E. Dubin, Phys. Plasmas 1, 1403-1414 (1994).

5. "Interference in the resonance fluorescence of two trapped atoms," U. Eichmann, J. C. Bergquist, J. J. Bollinger, J. M. Gilligan, W. M. Itano, M. G. Raizen, and D. J. Wineland, *Laser Spectroscopy*, Proc., XIth Intl. Conf., ed. by L. Bloomfield, T. Gallagher, and D. J. Larson (AIP Conf. Proc. 290, New York, NY, 1994), pp. 43-48.

6. "Paul trap for optical frequency standards," S. R. Jefferts, C. Monroe, A. S. Barton, and D. J. Wineland, IEEE Trans. Instrum. Meas. 44, 148-150 (1995).

7. "Progress on a cryogenic linear trap for $^{199}Hg^{+}$ ions," M. E. Poitzsch, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Proc., 1994 IEEE Intl. Frequency Control Symp., pp. 744-746, June 1994.

8. "Nonneutral ion plasmas and crystals in Penning traps," J. J. Bollinger, J. N. Tan, W. M. Itano, D. J. Wineland, and D. H. E. Dubin, Proc. Nobel Symp. on Trapped Charged Particles and Related Fundamental Physics, Lysekil, Sweden, August 1994, Physica Scripta T59, 352-359 (1995).

9. "Cooling methods in ion traps," W. M. Itano, J. C. Bergquist, J. J. Bollinger, and D. J. Wineland, ibid, pp. 106-120.

10. "Quantum effects in measurements on trapped ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, and W. M. Itano, ibid, pp. 286-293.

11. "Quantum mechanics with one, two, and many atoms," W. M. Itano, J. C. Bergquist, J. J. Bollinger, and D. J. Wineland, in *Group Theoretical Methods in Physics*, Proc., XX Intl. Colloquium (Yamada Conference XL, "Quantum mechanics with one, two, and many atoms,"), Toyonaka, Japan, 1994, ed. by A. Arima, T. Eguchi, and N. Nakanishi (World Scientific, Singapore, 1995), pp. 10-18.

12. "Laser-cooled trapped-ion experiments at NIST," J. N. Tan, J. J. Bollinger, A. S. Barton, and D. J. Wineland, in *Non-neutral Plasma Physics II*, ed. by J. Fajans and D. H. E. Dubin, AIP Conf. Proc. 331 (AIP Press, New York, NY, 1995), pp. 215-228.

13. "A cryogenic linear ion trap for $^{199}Hg^{+}$ frequency standards," J. Miller, M. E. Poitzsch, F. C. Cruz, D. J. Berkeland, J. C. Bergquist, W. M. Itano. and D. J. Wineland, Proc., 1995 IEEE Intl. Frequency Control Symp., June 1995, pp. 110-112.

14. "Quantum mechanically correlated states and atomic clocks," C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, J. J. Bollinger, and D. J. Wineland, Proc. 1995 Moriond Workshop (Editions Frontieres, Gif-sur-Yvette, France, 1996).

15. "Experiments at NIST with trapped ions: 3-D zero-point cooling, quantum gates, Bragg scattering, and atomic clocks," C. Monroe, A.S. Barton, J.C. Bergquist, D. J. Berkeland, J.J. Bollinger, F. Cruz, W.M. Itano, S.R. Jefferts, B.M. Jelenković, B.E. King, D.M. Meekhof, J.D. Miller, M.E. Poitzsch, J.N. Tan, and D.J. Wineland, Proc., 12th Intl. Conf. on Laser Spectroscopy, Capri, Italy, June 1995 (World Scientific), to be published.

16. "Minimizing time dilation in Penning trap ion clocks," J. N. Tan, J. J. Bollinger, W. M. Itano, and D. J. Wineland, Proc. 5th Symp. on Frequency Standards and Metrology, Woods Hole, MA, Oct. 1995 (World Scientific) to be published.

17. "Primary atomic frequency standards: New developments," R. E. Drullinger, S. L. Rolston, and W. M. Itano, in *Review of Radio Science*, in press.

18. "CW second harmonic generation with elliptical Gaussian beams," A. Steinbach, M. Rauner, F. C. Cruz, and J. C. Bergquist, Opt. Commun., in press.

19. "Generation of non-classical motional states of a trapped atom," D. M. Meekhof, C. Monroe, B. King, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett., in press.

20. "A 'Schrödinger Cat' superposition state of an atom," C. Monroe, D. M. Meekhof, B. E. King, and D. J. Wineland, submitted to Science.

21. "Optimal frequency measurements with maximally correlated states," J. J. Bollinger, W. M. Itano, D. J. Wineland, and D. J. Heinzen, submitted to Phys. Rev. Lett.