

DOE/ER/14579-1

Final Technical Report for DOE Grant No. DE-FG02-95ER14579

PRECISION MEASUREMENTS OF ATOMIC LIFETIMES
AND HYPERFINE ENERGIES

IN
ALKALI LIKE SYSTEMS

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Apr 11 2005
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Financial support of this research project has led to advances in the study of atomic structure through precision measurements of atomic lifetimes, energy splittings, and transition energies. The interpretation of data from many areas of physics and chemistry requires an accurate understanding of atomic structure. For example, scientists in the fields of astrophysics, geophysics, and plasma fusion depend on transition strengths to determine the relative abundances of elements. Assessing the operation of discharges and atomic resonance line filters also depends on accurate knowledge of transition strengths. Often relative transition strengths are measured precisely, but accurate atomic lifetimes are needed to obtain absolute values. Precision measurements of atomic lifetimes and energy splittings also provide fundamentally important atomic structure information. Lifetimes of allowed transitions depend most strongly on the electronic wave function far from the nucleus. Alternatively, hyperfine splittings give important information about the electronic wave function in the vicinity of the nucleus as well as the structure of the nucleus.

Our main focus throughout this project has been the structure of atomic cesium because of its connection to the study of atomic parity nonconservation (PNC). The interpretation of atomic PNC experiments in terms of weak interaction coupling constants requires accurate knowledge of the electronic wave function near the nucleus as well as far from the nucleus. It is possible to address some of these needs theoretically with sophisticated many-electron atomic structure calculations. However, this program has been able to address these needs experimentally with a precision that surpasses current theoretical accuracy. Our measurements also play the important role of providing a means for testing the accuracy of many-electron calculations and guiding further theoretical development. Atomic systems such as cesium, with a single electron outside of a closed shell, provide the simplest open shell systems for detailed comparisons between experiment and theory.

This program initially focused on measurements of excited state atomic lifetimes in alkali atomic systems. Our first measurements of atomic lifetimes in cesium surpassed the precision and accuracy of previous measurements and sparked renewed interest in the need for greater precision in lifetime measurements throughout the atomic physics community. After enhancing the capabilities of the laser systems built for these initial measurements, we began a study hyperfine energy splittings in cesium using a thermal

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atomic beam. The results surpassed previous measurements by more than an order of magnitude and lead to the first observation of the nuclear magnetic octupole moment in cesium demonstrating the inadequacy of the nuclear shell model for predicting high order nuclear moments. The laser system and atomic beam apparatus developed for these endeavors turned out to be perfectly suited for exploring the possibility of making absolute optical frequency measurements of atomic transitions. We initiated collaboration with researchers at NIST so that the desired optical frequencies could be reference with respect to the primary microwave frequency standard (Cs atomic fountain NIST-F1) via a femtosecond laser frequency comb. Our first absolute optical frequency measurement, of the cesium D2 line, surpassed the accuracy of a previous measurement by more than an order of magnitude. An absolute optical frequency measurement of the cesium D1 line, now near completion, also surpasses previous results and places us in a position to be able to report a new value for the fine structure constant which is the fundamental dimensionless constant that underlies all electromagnetic interactions.

The research conducted under this grant is described in numerous publications, conference presentations, and invited talks that are all listed below.

PUBLICATIONS

"Precision Lifetime Measurements Using Laser Excitation of a Fast Atomic Beam," C.E. Tanner, A.E. Livingston, R.J. Rafac, K.W. Kukla, H.G. Berry, C.A. Kurtz, NIM B **99**, 117-120 (1995).

"Laser Doppler Velocimetry of a Fast Beam with a Temperature Stabilized Solid Etalon," D. DiBerardino, R.J. Rafac, D.M. Glantz, C.E. Tanner, Opt. Com. **143**, 118 (1997).

"Lifetime Measurements of Cesium $5d\ ^2D_{5/2, 3/2}$ and $11s\ ^2S_{1/2}$ States using Pulsed-Laser Excitation," D. DiBerardino, C.E. Tanner, A. Sieradzan, Phys. Rev. A **57**, 4204 (1998).

"Wavelength Dependent Photoresponse in YBCO Thin-Film Systems," S.T. Ruggiero, M.P. Mischke, C.E. Tanner, A.J. Wilson, L.R. Vale, and D.A. Rudman, IEEE Trans. Appl. Superconductivity **9**, 3182-3185 (1999).

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"Diode Lasers for Fast-beam Laser Experiments," V. Gerginov, B. Laughman, D. DiBerardino, R.J. Rafac, S.T. Ruggiero, C.E. Tanner, Optics Communications **187** (2001) 219-230, 1 Jan. 2001.

"High-precision Frequency Measurements in Thermal ^{133}Cs Cell," Vladislav Gerginov and Carol E. Tanner, Proc. SPIE vol. 4397, p. 166-170, 2001.

"Imperfect Detectors in Linear Optical Quantum Computers", S. Glancy, J.M. LoSecco, H.M. Vasconcelos, and C.E. Tanner, Phys. Rev. A **65**, 062317-1 through 7, June 2002.

"Fiber-Optic Bundle Light-Collection Systems and Calculations of Collection Efficiency," D. DiBerardino, R.J. Rafac, S. Boone, V. Gerginov, and C.E. Tanner, *Opt. Com.* **210** (2002) 233-243, 15 September 2002.

"The $^{199}\text{Hg}^+$ Single Ion Optical Clock: Recent Progress," U. Tanaka, S. Bize, C. E. Tanner, R. E. Drullinger, S. A. Diddams, L. Hollberg, W. M. Itano, D.J. Wineland, J. C. Bergquist, *J. Phys. B: At. Mol. Opt. Phys.* **36** (2003) 545-551, 23 January 2003.

"Heterodyne Frequency Calibration of High Resolution Cesium Spectra Using Diode Lasers," V. Gerginov and C.E. Tanner, *Optics Communications* **216** (2003) 391-399, 15 February 2003.

"Optical Frequency Standards Based on the $^{199}\text{Hg}^+$ Ion," U. Tanaka, J.C. Bergquist, S. Bize, S.A. Diddams, R.E. Drullinger, L. Hollberg, W.M. Itano, C.E. Tanner, and D.J. Wineland, *IEEE Transactions on Instrumentation and Measurement* **52**, No. 2, p. 245-249, April 2003.

"Testing the Stability of Fundamental Constants with the $^{199}\text{Hg}^+$ Single Ion Optical Clock," S. Bize, S.A. Diddams, U. Tanaka, C.E. Tanner, W.H. Oskay, R.E. Drullinger, T.E. Parker, T.P. Heavner, S.R. Jefferts, L. Hollberg, W.M. Itano, and J.C. Bergquist, *Phys. Rev. Lett.* **90**, 150802-1 through 4, 18 April 2003.

"Fluorescence of a Highly Collimated Atomic Cesium Beam: Theory and Experiment," V. Gerginov and C.E. Tanner, *Optics Communications* **222** (2003) 17-28, 6 May 2003.

"Magneto-optic Effects in Spin-injection Devices," S.T. Ruggiero, T. Williams, C.E. Tanner, S. Potashnik J. Moreland, and W.H. Rippard, *Appl. Phys. Lett.* **82**, 4599-4601 (2003), 23 June 2003. {Also selected for inclusion in the June 30, 2003 issue of the *Virtual Journal of Nanoscale Science & Technology*.}

"Observation of the Nuclear Magnetic Octupole Moment of ^{133}Cs ," V. Gerginov, A. Derevianko, and C.E. Tanner, *Phys. Rev. Lett.* **91**, 072501-1 through 4, 15 August 2003.

"The Mercury-Ion Optical Clock: Towards a Measurement of the Quadrupole Shift," W.H. Oskay, A. Bartels, S.A. Diddams, C.W. Oates, G. Wilpers, L. Hollberg, D.J. Wineland, W. M. Itano, C.E. Tanner, and J.C. Bergquist, proceedings of the 18th European Frequency and Time Forum (EFTF), University of Surrey, Guildford, UK. 5-7 April 2004, (CDROM), 4P.

"Optical Frequency Measurements of $6s\ ^2S_{1/2} \rightarrow 6s\ ^2P_{3/2}$ Transition in a ^{133}Cs Atomic Beam Using a Femtosecond Laser Frequency Comb," V. Gerginov, C.E. Tanner, S. Diddams, A. Bartels, L. Hollberg, submitted to *Phys. Rev. A* April 2004.

"Off-diagonal Hyperfine Interaction Between the $6p_{1/2}$ and $6p_{3/2}$ Levels in ^{133}Cs ," W.R. Johnson, H.C. Ho, C. E. Tanner, A. Derevianko, accepted for publication Phys. Rev. A, May 2004.

CONTRIBUTED CONFERENCE PRESENTATIONS (posters and talks)

"Precision Lifetime Measurements by Laser Excitation of Fast Ion Beams," J. Riley, A. Vasilyev, H.G. Berry, C. Tanner, A.E. Livingston, DAMOP May 1996.

"Precision Measurements of Atomic Lifetimes by Laser Excitation of Fast Atomic Beams," C.E. Tanner, A. Vasilyev, H.G. Berry, A.E. Livingston, Fifteenth International Conference on Atomic Physics 5-9 August 1996.

"Precision Lifetimes and Hyperfine Structures Using Laser Excitation of Fast Ion Beams," A. Vasilyev, H.G. Berry, C.E. Tanner, A.E. Livingston, Fifteenth International Conference on Atomic Physics 5-9 August 1996

"Absorption Measurement of the Ratio of Cesium 6^2P_j Oscillator Strengths," R.J. Rafac and C.E. Tanner, APS and DAMOP, April 1997.

"Laser Doppler Velocimetry of a Fast Atomic Lithium Beam," D. DiBerardino, R.J. Rafac, and C.E. Tanner, APS and DAMOP, April 1997.

"Wavelength Dependent Response in YBCO Thin-Film Systems," S.T. Ruggiero, C.E. Tanner, and A.J. Wilson at the Fall Meeting of the Materials Research Society, Boston, MA, December 1997.

"Lifetime Measurements of Cesium $5d^2D_{5/2, 3/2}$ and $11s^2S_{1/2}$ States Using Pulsed-Laser Excitation," D. DiBerardino and C.E. Tanner, DAMOP, May 1998.

"Wavelength-Dependent Photoresponse in YBCO Thin-Film Systems," S.T. Ruggiero, N. Crain, M. Mischke, C.E. Tanner, A.J. Wilson, L.R. Vale, and D.A. Rudman, Applied Superconductivity Conference (1998).

" ^{133}Cs ($I=7/2$) $6^2P_{3/2}$ Hyperfine Structure Measurements," Vladislav Gerginov and Carol Tanner, Centennial APS and DAMOP, April 1999.

"Decay Lifetime Measurement for Cs $7P_{1/2}$ and $7P_{3/2}$ States," A.A. Vasilyev, H.G. Berry, and C.E. Tanner, Centennial APS and DAMOP, April 1999.

"Cs Atomic Structure Studies Using Diode Lasers", V.P. Gerginov and C.E. Tanner, DAMOP Storrs, Connecticut, 14-17 June 2000.

"High Precision Frequency Measurements in Thermal ^{133}Cs Cell," V. Gerginov and C. Tanner, Eleventh International School on Quantum Electronics, 18-22 September 2000, Varna, Bulgaria. (Selected for inclusion in the SPIE proceedings.)

"Thermal Beam Spectroscopy of ^{133}Cs ," Vladislav Gerginov and C.E. Tanner, DAMOP 2001, London Ontario, May 2001.

"Imperfect Detectors in Linear Optical Quantum Computers", S. Glancy, J.M. LoSecco, H.M. Vasconcelos, and C.E. Tanner, Fourth annual meeting of the Southwestern Quantum Information and Technology network (SQUINT) NIST, Boulder, CO, March 8-10, 2002

"Wavelength-Dependent Photoresponse in $\text{YBa}_2\text{CuO}_{7-\delta}$ ", M.P. Mischke, S.T. Ruggiero, C.E. Tanner, L.R. Vale, Indianapolis, IN, APS March Meeting, March 18-22, 2002.

"Hyperfine Spectroscopy of Cesium at the kHz Level," V. Gerginov and C.E. Tanner, DAMOP 2002, Williamsburg, VA, May 28-June 1, 2002.

"Construction of Fiber-optic Light Collection Systems and Calculations of Collection Efficiency," D. DiBerardino, S. Boone, V. Gerginov, R.J. Rafac, C.E. Tanner, DAMOP 2002, Williamsburg, VA, May 28-June 1, 2002.

"Laser Heterodyne Frequency Measurements of the ^{133}Cs $6p\ ^2P_{3/2}$ State Hyperfine Splitting," V. Gerginov and C.E. Tanner, 34 Conference of the European Group for Atomic Spectroscopy (EGAS 34), Sofia Bulgaria, 9-12 July 2002.

"Investigation into the Nuclear Moments of ^{133}Cs ," V. Gerginov and C.E. Tanner, XVIII International Conference on Atomic Physics (ICAP 2002), Cambridge, MA, 28 July-2 August 2002.

"Magneto-optic Effects in Ferromagnetic-based Spin Injection Devices Films," S.T. Ruggiero, T. Williams, C.E. Tanner, S. Potashnik, J. Moreland, and W.H. Rippard, Bull. Am. Phys. Soc. **48**, 313 (2003), APS March Meeting 2003.

"High Resolution Spectroscopy Reveals the Nuclear Magnetic Octupole Moment of ^{133}Cs ," C.E. Tanner and V. Gerginov, Topical Group on Precision Measurements and Fundamental Constants, APS Meeting, April 5-8, 2003, Philadelphia, Pennsylvania.

"The Mercury-Ion Optical Clock and the Search for Temporal Variation of Fundamental Constants," W.H. Oskay, S. Bize, S.A. Diddams, R.E. Drullinger, T.P. Heavner, L. Hollberg, W.M. Itano, S.R. Jefferts, T.E. Parker, U. Tanaka, C.E. Tanner, and J.C. Bergquist, Joint Meeting of the IEEE International Frequency Control Symposium and 17th European Frequency and Time Forum, 5-8 May 2003, Tampa, FL.

"Testing the Stability of Fundamental Constants with the $^{199}\text{Hg}^+$ Single-ion Optical Clock", W.H. Oskay, S. Bize, S.A. Diddams, U. Tanaka, C.E. Tanner, T. Parker, R.E. Drullinger, T. Heavner, S.R. Jefferts, L. Hollberg, W.M. Itano, J.C. Bergquist, DAMOP May 2003, Boulder, CO.

"Nuclear Magnetic Octupole Moment of ^{133}Cs Through High Resolution Laser Spectroscopy" V. Gerginov and C.E. Tanner, DAMOP May 2003, Boulder, CO.

"The Mercury-Ion Optical Clock," W.H. Oskay, T. Rosenband, U. Tanaka, C.E. Tanner, S.A. Diddams, L. Hollberg, W.M. Itano, J.C. Bergquist, 18th European Frequency and Time Forum (EFTF), 5-7 April 2004, University of Surrey, Guildford, UK.

"Optical Frequency Measurements of $6s\ ^2S_{1/2} \rightarrow 6s\ ^2P_{3/2}$ Transition in ^{133}Cs Using an Atomic Beam and a Femtosecond Laser Frequency Comb," V. Gerginov, C.E. Tanner, S. Diddams, A. Bartels, L. Hollberg, CLEO/IQEC sponsored by OSA/LEOS/APS-DLS May 16-21, 2004, San Francisco, CA.

"Optical Frequency Measurements of D2 Line in ^{133}Cs ," V. Gerginov, C.E. Tanner, S. Diddams, A. Bartels, L. Hollberg, DAMOP May 24-29, 2004, Tucson, AZ

"The Mercury Ion Optical Clock," W.H. Oskay, T. Rosenband, U. Tanaka, C.E. Tanner, S.A. Diddams, L. Hollberg, W.M. Itano, J.C. Bergquist, DAMOP May 24-29, 2004, Tucson, AZ

"Precise Frequency Measurements of $6s\ ^2S_{1/2} - 6s\ ^2P_{3/2}$ Transition in ^{133}Cs Using a Femtosecond Laser Frequency Comb," V. Gerginov, C.E. Tanner, S. Diddams, A. Bartels, L. Hollberg, Conference on Precision Electromagnetic Measurements (CPEM), 27 June-2 July 2004 London, UK.

"Absolute Optical Frequency Measurements of the D1 and D2 Lines in ^{133}Cs ," K.G. Calkins, V. P. Gerginov, C.E. Tanner, S. A. Diddams, A. Bartels, L. Hollberg, *Frontiers in Optics 2004/Laser Science XX* sponsored by OSA/APS-DLS, October 10-14, 2004 Rochester, NY.

INVITED COLLOQUIA, SEMINARS, AND CONFERENCE PRESENTATIONS

"Precision Measurements of Atomic Lifetimes," Atomic Physics Seminar, State University of New York-Stony Brook, March 15, 1996.

"Inside Cesium," C.E. Tanner, presented at *Atoms, Photons, and Their Interaction: A Symposium in Honor of W.D. Phillips* (1997 recipient of a Nobel Prize in Physics) at the National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, June 17-19, 1998.

"Journey to the Center of Cesium," Physics Colloquium, Central Michigan University, Mount Pleasant, Michigan, November 19, 1998.

"Hyperfine Structure of the $\text{Cs } 6p\ ^2P_{3/2}$ state: Can we measure a nuclear magnetic octupole moment?" Invited oral presentation at Workshop on the Tests of Fundamental Symmetries in Atoms and Molecules at the Institute for Theoretical Atomic and

Molecular Physics at Harvard-Smithsonian Center for Astrophysics, Boston, workshop rescheduled for November 29-December 1, 2001.

“Measuring a Nuclear Magnetic Octupole Moment,” NIST, Time and Frequency Division, Ion Storage Group Seminar, December 14, 2001.

“High Resolution Spectroscopy of Atomic Hyperfine Structure Reveals the Nuclear Magnetic Octupole Moment of ^{133}Cs ,” Seminar at European Laboratory for Non-linear Spectroscopy (LENS) in Firenze, Italy, July 8, 2003.

“Journey to the Center of ^{133}Cs : Observation of the Nuclear Magnetic Octupole Moment of ^{133}Cs ,” Physics Department Colloquium, University of Washington, Seattle, WA, February 23, 2004.

“The $^{199}\text{Hg}^+$ Optical Clock,” Atomic Physics Seminar, University of Washington, Seattle, WA February 24, 2004.

“Absolute Optical Frequency Measurements in ^{133}Cs and the Fine Structure Constant,” Department of Physics Colloquium, Western Michigan University, Kalamazoo, MI November 8, 2004.