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**PRECISION MEASUREMENTS OF ATOMIC
LIFETIMES
IN
ALKALI LIKE SYSTEMS**

Progress Report

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I. RESEARCH PROGRAM

Precision measurements of atomic lifetimes are important to the analysis of data from many areas of physics and provide fundamental atomic structure information. Scientists in the fields of astrophysics, geophysics, and plasma fusion all depend on oscillator strengths to determine the relative abundances of elements. Assessing the operation of discharge lamps and atomic resonance line filters also depends on knowing accurately atomic oscillator strengths. Often relative values of oscillator strengths are measured precisely, but accurate atomic lifetimes are needed to obtain absolute values. In addition, the interpretation of parity nonconservation (PNC) experiments [3] requires accurate knowledge of the atomic structure including radial matrix elements. Many of these scientific needs are addressed theoretically with sophisticated many-electron atomic structure calculations. In this program we address these needs experimentally with a precision that surpasses current theoretical accuracy. Our lifetime measurements also play the important roles of assessing the accuracy of many-electron atomic structure calculations and of guiding further theoretical development. Alkali like atoms, with a single electron outside of a closed shell, provide the simplest open shell systems for detailed comparisons between experiment and theory. To date, our research has focused on measurements of excited state lifetimes in neutral alkali systems along with the development of the necessary equipment and techniques for studying alkali-like ionic systems.

The accomplishments of this program are summarized in Section II and are supported by the reprints and preprints that appear in the Appendix. The development of new techniques and technologies has played an important role in this program and will allow us to expand our work to other atomic systems. Graduate and undergraduate student participation in the research projects has been crucial to the success of this program to date and will continue to be so in the future. The experimental atomic physics group at the University of Notre Dame is very fortunate to have frequent interactions with atomic theorists at Notre Dame, Profs. Walter Johnson and Jonathan Sapirstein, and this project has benefited greatly from their presence. The motivations for much of our experimental research parallel their interests in fundamental atomic structure.

II. SIGNIFICANT RESULTS

This research program has been supported by the DOE for approximately three years. The work accomplished during this period has resulted in three papers that have already appeared in print and two preprints which have been submitted for publication. These papers are listed in the bibliography and appear as copies in the Appendix of this report. The work to date has also resulted in several conference presentations at national and international conferences the abstracts of which also appear in the Appendix. One Ph. D. dissertation has resulted from this work, a second Ph. D. student is near completion of her thesis, and a third Ph. D. project is in progress.

Funding from the DOE has made it possible to introduce new technologies into our research program and has significantly expanded our experimental research capabilities. Technologies which we have developed as part of our fast-beam laser lifetime measurements are diode lasers, a fiber optic position sensitive light collection system, and a precise technique for direct measurement of the beam velocity. Our technological base also includes Ar-ion laser pumped dye lasers and Ti-sapphire lasers which cover the visible and near infra-red spectrum. We have also developed the capabilities for pulsed laser delayed coincidence measurements, and the capability of producing highly collimated beams of neutral alkali atoms.

A. Technological Developments

1. Diode Lasers

Stabilized diode lasers are used for the excitation of resonance transitions in the fast atomic beam. We have developed a temperature and current controller system to ensure long term frequency stability of the single mode diode lasers. Some details of our diode laser system are described in Reference [6]. External optical feed back has also been implemented on some of our diode lasers for reducing the laser line width. We use diode lasers for both transverse and longitudinal excitation of the fast atomic beam. The exceptional intensity and frequency stability of our diode lasers have been important to the success of our fast beam lifetime measurements. Diode lasers are used for precise measurements of the beam velocity by observation of Doppler shifted resonance lines and for characterizing the longitudinal energy spread of the beam by observing the hyperfine structure of the resonance lines. We have also developed the ability to rapidly shutter the lasers on and off with a rise time of a few nanoseconds. We plan to use this capability for making pulsed measurements of medium to long lived

atomic states where the fast beam technique is not applicable. The capability to rapidly shutter the lasers has also led to a collaboration with a DOE funded condensed matter project in our department [11].

2. Precision velocimetry of fast beams

A precise technique for measuring our fast beam velocity has also been developed. We observe the Doppler shift of a known atomic resonance transition as the atomic beam is excited longitudinally, and the frequency shift is directly related to the beam velocity. We now determine the overall shift of several hundred gigahertz using a temperature stabilized and calibrated solid etalon by essentially counting the number of fringes between the unshifted and shifted resonance lines. We have demonstrated the technique by measuring the velocity of a fast lithium beam to a precision of 0.03%. The details of our technique were published recently [4,10], and a copy of the paper appears in the Appendix. This approach will also be implemented in future fast beam lifetime experiments.

3. Fiber-optic collection system

The demand for higher precision in lifetime measurements has led us to develop a unique fiber optic light collection system. Our constraints included a high degree of directionality, a large collection solid angle, the ability to couple the light out of the vacuum system, and the ability to translate the system without changes in solid angle or transmission. We addressed these issues by constructing our own multi-fiber optical collection device. Six bundles with polished facets are arranged in a 360 degree annular ring around the atomic beam axis. Then the approximately 70,000 optical fibers are combined into a single vacuum feedthrough that allows all fibers to continuously pass through the vacuum wall. On the outside, the complete bundle is geometrically matched to a remote photo detector. The advantages of the new system are the improved collection and transmission efficiencies and the reduction of systematic uncertainties because of its enhanced symmetry. The details of the collection system and its implementation in upcoming experiments are discussed in the proposal.

4. Improvements to data collection and analysis

Important aspects for obtaining high precision in lifetime measurements are the stability of the laser power and the atomic beam. We began our fast beam lifetime measurements using diode lasers for excitation of cesium [1]. The diode lasers have exceptionally high output power stability. Since then we have begun to investigate

other atomic systems such as lithium [4]. For some systems, diode lasers can be found near the desired wavelengths. However, many of our planned experiments call for the use of a dye laser where output power fluctuations can be much larger. In addition, the ion source intensity can vary and fluctuate differently for each element. Random independent fluctuations in both the laser and ion beam intensity on a time scale comparable to the integration time of our data collection can lead to inexact background subtractions. Therefore, we have added additional detectors to the data collection system. We now simultaneously monitor four signals: decay fluorescence, normalization fluorescence, laser power, and ion beam intensity. The analysis of lifetime data now includes not only background subtraction, but scaling for intensity fluctuations. The details of this approach are described in [2] which appears in the Appendix. With our preliminary measurements in lithium, we have demonstrated that this more sophisticated approach reduces the random deviations in the decay residuals which lie outside of the photon counting statistics.

B. Precision measurements of atomic lifetimes

1. Laser excitation of fast atomic beams

Laser excitation of a fast atomic beam is a versatile technique for measuring a variety of lifetimes in both neutral and ionic systems. The potential precision of this technique has been demonstrated by our measurements of the cesium $6p\ ^2P_{1/2, 3/2}$ state lifetimes, details of which can be found in Ref. [1,2]. Briefly, Cs^+ is accelerated through a 50 kV potential, energy selected in a magnetic field, then neutralized in a charge exchange cell containing rubidium vapor. A diode laser excites either the $6s\ ^2S_{1/2} \rightarrow 6p\ ^2P_{1/2}$ or the $6s\ ^2S_{1/2} \rightarrow 6p\ ^2P_{3/2}$ transition thereby populating the selected excited state for observation. Fiber optic bundles collect and couple the emitted light into two photomultiplier tubes. One fiber bundle remains stationary, and the signal is used for normalization. A pair of fiber bundles translates and observes the decay of the fluorescence as a function of position. With a second laser aligned antiparallel to the atomic beam, the Doppler shift of the $6s\ ^2S_{1/2} \rightarrow 6p\ ^2P_{3/2}$ transition is measured to determine the velocity of the atoms and convert the decay from a function of position to a function of time.

Since the $6p\ ^2P_{1/2, 3/2}$ states decay without branching, their lifetimes can be compared directly with those calculated using the relativistic MBPT techniques of Blundell *et al.* and Dzuba *et al.* (References to these works can be found in [1,2].) At present, our lifetime measurements in cesium establish the experimental precision of 6s-

6p radial matrix elements at the 0.12% level. Our results also demonstrate the significance of correlation effects that have not been included thus far in many-body atomic-structure calculations for cesium. Motivated by precision measurements such as ours, theorists at Notre Dame are incorporating the next level of accuracy into their calculations.

During the grant period, we have also made improvements to our collection system and velocity measurements as described above. Our fast-beam-laser technique is different from other fast beam experiments. First, fiber optic bundles are arranged to collect the decay fluorescence such that the collection solid angle is insensitive to small misalignments between the mechanical translation stage and the direction of the atomic beam. Second, the velocity of the atomic beam is measured directly, eliminating possible systematic errors introduced by inferring the velocity of the atoms from either the accelerating voltage or the velocity of the ions.

Also during the grant period, the experimental atomic physics group at Notre Dame collaboratively constructed and installed a new 30-200 kV accelerator at Notre Dame. New measurements planned for this facility are described in the proposal. The laboratory also includes a new data acquisition system and new laser systems. The completed facility is now called the Atomic Physics Accelerator Laboratory at Notre Dame (APALaND). The following plot is the first decay fluorescence scan observed at our new facility.

First decay fluorescence scans of the Cs 6p $2P_{3/2}$ state taken at APALaND.

2. Pulsed laser excitation

We have initiated an investigation into the lifetimes of the 5d $2D_{5/2,3/2}$ states in atomic cesium [5]. This investigation has also led to a measurement of the highly excited 11s $2S_{1/2}$ state lifetime. We began these investigations because of a reported

discrepancy between the measured lifetimes of the $5d\ ^2D_{5/2}$ state reported Hoeling *et al.* and a many body perturbation theory calculation by Dzuba *et al.* The states are of interest not only for testing atomic theory in cesium, but also because cesium is isoelectronic to Ba⁺ in which a new type of PNC experiment has been proposed which utilizes the 6s-5d transition. The 5d and 11s states of cesium have decay constants of order 1 μ s and are easily addressed using pulsed laser excitation with delayed coincidence photon counting. We performed these measurements in collaboration with A. Sieradzan at Central Michigan University using a Nd:YAG pumped dye laser that allowed a great deal of flexibility with regard to wavelength selection. We plan to continue using the delayed coincidence approach for measuring the lifetimes of these longer lived states and other neutral systems.

III. PERSONNEL

This DOE grant has provided partial support for the PI, partial support of one postdoctoral research associate, full support of one graduate student, partial support of two graduate students, and partial support of two undergraduates. Undergraduates supported by the NSF-Research Experience for Undergraduates program have also participated in this program.

POSTDOCTORAL RESEARCH ASSOCIATE:

Kris W. Kukla completed his Ph.D. Thesis at Notre Dame in June 1996 with Professor Livingston and participated in this program both as a graduate student and as a postdoctoral research associate.

GRADUATE STUDENTS:

Robert J. Rafac completed his Ph. D. Thesis in August of 1997 and is currently a National Research Council (NRC) postdoctoral research associate in the Time and Frequency Division of NIST at Boulder.

Diana DiBerardino is expected to complete her Ph. D. Thesis in May of 1997.

Vladislav Gerginov is a first year graduate student who recently joined this project.

UNDERGRADUATES:

Germain Linares is presently a senior undergraduate student who is both laboratory and electronics technician through the work study program at Notre Dame.

Asling McKenna is presently a junior foreign exchange student from Northern Ireland who is an electronics technician also through the work study program.

Joseph Riley participated as an NSF-REU student and graduated from Notre Dame with a B.A. in Physics.

Tess Napili participated as an NSF-REU student and returned to Reed College Oregon for her senior year.

David M. Glantz also participated as an NSF-REU student and returned to South Western College in Kansas to complete his undergraduate degree.

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11. "Wavelength-Dependent Photoresponse in YBCO Thin-Film Systems," S. T. Ruggiero, C. E. Tanner, A. J. Wilson, L. R. Vale, and D. A. Rudman, Materials Research Society Meeting, Boston, November 1997.
12. "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, and A. Sieradzan, submitted to DAMOP, May 1998.

V. APPENDIX

The papers and conference presentations referred to in this report and listed in the bibliography are the result of work accomplished during this program. One paper [3] was not supported by DOE, but was included here because of its strong coupling to the motivation for our work for DOE. Copies of the items listed in the bibliography appear in this appendix.

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