Measurement of the $6p\ ^2P_{3/2}$ State Lifetime in Atomic Cesium

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We present a precision experimental test of atomic many-body theory that is currently applied to the interpretation of recent parity-nonconservation experiments in atomic cesium. We report the first measurement of the ^{133}Cs $6p\ ^2P_{3/2}$ state lifetime using resonant diode-laser excitation of a fast atomic beam. The lifetime result of 30.55 ± 0.27 ns determines the absorption oscillator strength for the $6s\ ^2S_{1/2}$–$6p\ ^2P_{3/2}$ transition in cesium to be 0.7133 ± 0.0064, and establishes the accuracy of recent relativistic many-body calculations of the dipole transition matrix element to 0.5%.

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Interpretation of atomic parity-nonconservation (PNC) experiments in terms of fundamental weak interaction coupling constants requires accurate atomic structure calculations that include sums over many radial integrals [1]. At low interaction energies, atomic PNC measurements probe the weak interaction in a regime that is inaccessible to high-energy accelerators. In atomic cesium, PNC measurements [2] are approaching a sensitivity which can test the standard model at the level of radiative corrections, making it possible to look for new physical effects predicted by high-mass-scale supersymmetric and technicolor models [3]. In order to obtain precise weak interaction information from cesium PNC experiments, the atomic radial matrix elements between low-lying states must be known to an accuracy of better than 1% [4]. We report in this Letter a 0.9% measurement of the $6p\ ^2P_{3/2}$ state lifetime in the cesium atom. This result provides a direct test at the 0.5% level of recent relativistic many-body calculations [4,5] of the $6S$-$6P$ transition matrix element.

The measurement of an atomic lifetime using laser excitation of a fast beam [6] offers an exceptional combination of excitation selectivity, intense unperturbed fluorescence, and a precise spatial time scale. Earlier beam-laser measurements for light atoms [7,8] have demonstrated the capability of lifetime uncertainties as low as 0.2%. We have extended the application of the beam-laser excitation method to the precise measurement of a lifetime in a heavy neutral atom, and we report here the first application of this technique to a measurement of the lifetime of the $6p\ ^2P_{3/2}$ fine-structure state in atomic cesium. This measurement also introduces the new technology of diode lasers [9] into the field of fast-beam spectroscopy.

The lifetime measurement was performed using diode-laser excitation of a fast cesium atomic beam and detection of the decay in flight of the beam fluorescence (see Fig. 1). A beam of several microamperes of 50-keV Cs^+ ions was produced using the BLASE accelerator at Argonne National Laboratory. The beams ions were neutralized with $> 90\%$ efficiency by electron capture during passage through a heated rubidium vapor cell. The neutral cesium beam was collimated to ~ 2 mrad, yielding $\sim 10^{12}$ atoms/sec traversing the interaction region 1 m beyond the charge exchange cell. Light from a stabilized diode laser was directed perpendicular to the fast beam to excite the $6s\ ^2S_{1/2}$–$6p\ ^2P_{3/2}$ (D_2) transition in CsI at 852 nm within an interaction region of volume ~ 30 mm^3. Scattered laser light was reduced using light baffles and by retroreflecting the laser beam out of the vacuum chamber. The laser provided about 20 mW power on target, in a bandwidth of about 30 MHz, and was tuned to the D_2 transition frequency using a thermal cesium reference cell. The 300-MHz-width Doppler-broadened beam fluorescence signal was monitored by two detectors: One stationary detector provided the normalization signal, the other detector was capable of being translated parallel to the atomic beam and provided the decay signal. Each detector consisted of a 6-mm-diam light-shielded, flexible fiber-optic bundle oriented perpendicular to the beam at a distance of 7 mm from the beam center. Each fiber-optic bundle was coupled to a cooled, red-sensitive photomultiplier located outside the vacuum. Photon-count signals for both detectors were sent to a small computer, which also controlled a stepping-motor drive for the translating detector. The total excitation and collection efficiency in the experiment was estimated to be $\sim 1 \times 10^{-7}$.

Decay curves of the fluorescence intensity were measured by accumulating photon-count signals at 28 equally spaced positions along the fast beam over a distance of 4 decay lengths (130 ns or 35 mm). A typical decay curve

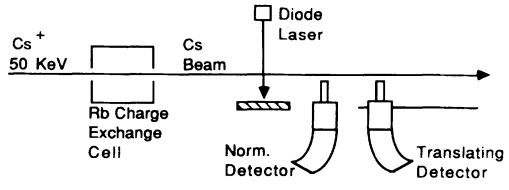

FIG. 1. Schematic diagram of the experiment.

is shown in Fig. 2. Peak signal rates of up to 90 kHz provided $\sim 2\times 10^8$ total counts among the 26 decay curves recorded for this experiment. Sequential decay-curve measurements of the simultaneous position-dependent and normalization signals were performed for the laser tuned first on resonance and then a few GHz off resonance to provide background corrections for the fluorescence decay. Periodic measurements were made with the atomic beam and/or laser beam blocked in order to monitor possible systematic variations in the excitation and detection efficiencies and in the individual background contributions. Atomic-beam-induced scattered light produced a background signal of about 7 kHz; both the scattered laser light and the detector dark count rates were <1 kHz. The few percent residual Cs^+ ion beam was electrostatically deflected after the excitation chamber, and the ion current was measured in a Faraday cup to provide an additional beam monitor.

The 26 on-resonance decay curves were corrected for background with the off-resonance signals. These decay data were normalized to the corrected stationary-detector signals, and each normalized decay was fitted by a single exponential plus constant background. The very small residual background resulted from slight variations in scattered laser light and beam-induced scattered light during sequential measurements. The diode-laser frequency was initially tuned to the $6S_{1/2}$-$6SP_{3/2}$ resonance of the $6S_{1/2}(F=4)$ hyperfine state, and a total of 17 decays were recorded for the unresolved hyperfine transitions from $6P_{3/2}(F'=5,4,3)$ to $6S_{1/2}(F=4,3)$. The laser frequency was then increased by the 9.2-GHz ground-state hyperfine interval to excite from the $6S_{1/2}(F=3)$ state, and 9 decays were recorded for the transitions from $F'=4,3,2$ to $F=4,3$. The mean fitted lifetimes were 30.543 ns for the $F=4$ data and 30.552 ns for the $F=3$ data, with a standard deviation in the mean lifetime of 0.04% for all 26 decays.

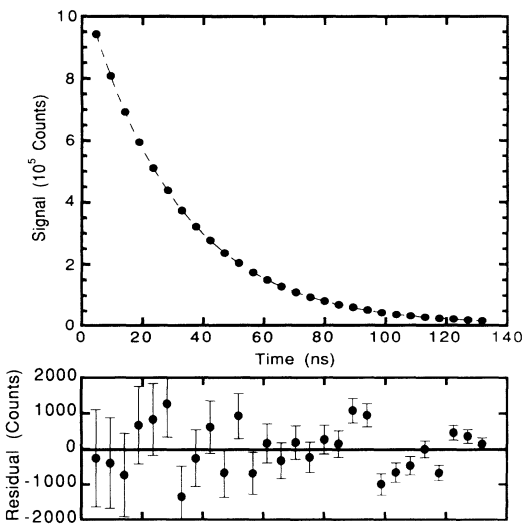

FIG. 2. Typical decay curve of the normalized signal and the residuals to the fit, with statistical error bars.

The precision of our final lifetime result is determined by systematic uncertainties resulting from possible beam instabilities, the beam-detector alignment geometry, and several smaller contributions. Small neutral-beam intensity variations between the on-resonance and off-resonance measurements were only approximately accounted for by the blocked-beam measurements and by the ion-beam Faraday cup monitor, yielding an estimated 0.5% lifetime uncertainty due to inexact background corrections. Imprecise knowledge of the parallelism between the beam trajectory and the detector translator accounts for 0.5% uncertainty due to solid angle considerations. The spread of fitted decay constants resulting from various data point truncation analyses produces 0.3% uncertainty, part of this probably already included in the beam variation uncertainty. Nonlinearities in the stepping-motor driven precision translator screw assembly contribute 0.1% uncertainty. Hyperfine beats [10] of frequency 150–250 MHz in the time-resolved decay due to the coherent nature of the beam-laser excitation for the $6P_{3/2}$ hyperfine states would have a spatial period of 1–2 mm along the beam, and would be averaged out by the combined spread of the excitation and detection geometries. However, Zeeman beats [7,8] due to the Earth's magnetic field would produce an intensity modulation of ~ 10-cm period, and could account for an uncertainty of 0.3% in the lifetime. Additional small effects such as pressure and temperature changes in the target chamber and possible variations in laser power are estimated to contribute no more than 0.2% uncertainty. Finally, the atomic beam velocity directly links the decay measurements to the lifetime. The accelerator voltage was stable to within $\pm 2\times 10^{-4}$ during the entire experiment. We determined the neutral cesium beam velocity to be $(2.700\pm 0.005)\times 10^5$ m/s by measuring the Doppler shift of collinear excitation of the $6S_{1/2}$-$6P_{3/2}$ transition using a second diode laser. Locating the centroid of the collinearly excited resonance and measuring its 317-GHz frequency shift relative to the cesium reference cell resulted in the velocity uncertainty of 0.2%. We consider all the above error estimates to be conservatively large, and we combine them in quadrature to produce a total uncertainty of 0.9%. Our final result for the cesium $6p\,^2P_{3/2}$ state lifetime is 30.55 ± 0.27 ns.

Previous measurements of the $6P_{3/2}$ lifetime in cesium are compared with our result in Fig. 3. Both the most precise level crossing value [11] (29.9 ± 0.2 ns) and the most recent measurement using time-resolved spectroscopy [12] (31.8 ± 0.7 ns) differ significantly from our fast-beam-laser result, as well as from each other. Earlier measurements, primarily using level crossing and phase shift techniques, show similar scatter, usually with larger uncertainties.

Relativistic many-body calculations [4,5] of the $6S$-$6P$

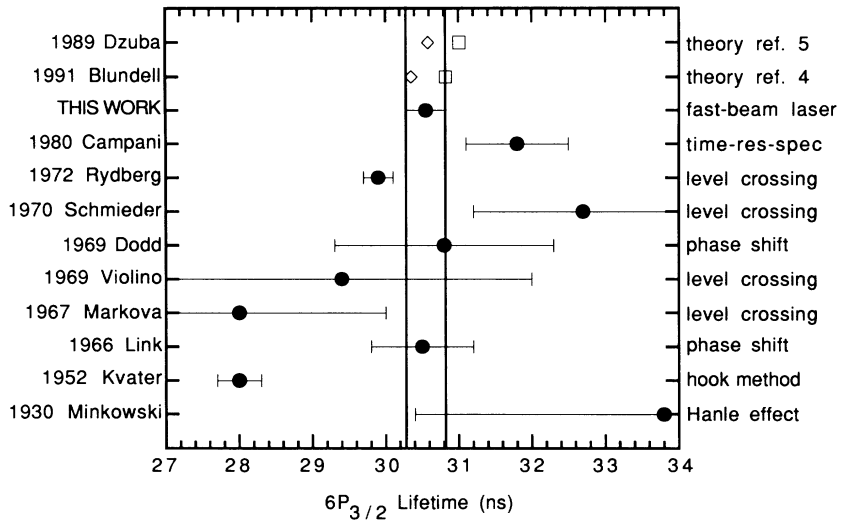

FIG. 3. Comparison of the present result with theory [4,5] and with previous measurements of the $6p\,^2P_{3/2}$ lifetime in the cesium atom. The theoretical values shown are the *ab initio* (squares) and energy-scaled (diamonds) results. The references to previous experiments are Campini (Ref. [12]); Rydberg (Ref. [11]); R. W. Schmieder, A. Lurio, W. Happer, and A. Khadjavi, Phys. Rev. A **2**, 1216 (1970); J. N. Dodd, E. Enemark, and A. Gallagher, J. Chem. Phys. **50**, 4838 (1969); P. Violino, Can. J. Phys. **47**, 2095 (1969); G. Markova, G. Khvostenko, and M. Chaika, Opt. Spektrosk. **23**, 456 (1967); J. K. Link, J. Opt. Soc. Am. **56**, 1195 (1966); G. S. Kvater and T. G. Meister, Vestn. Leningrad Univ. Fiz. Khim. **9**, 137 (1952); R. Minkowski and W. Mühlenbruch, Z. Phys. **63**, 198 (1930).

transition probability in cesium are sensitive at about the 1% level to the form of the dipole operator used and to energy-dependent factors. The velocity form of the operator yields a transition probability 1.3% lower than the length form [4], although the length form is more appropriate for valence-electron radial matrix elements. Terms involving valence-electron binding energies that are omitted in the many-body calculations of the matrix element [4] are estimated to decrease the transition probability by 0.7%. Also, using experimental energies, the factor of the transition energy cubed that relates line strength (dipole length form) to transition probability is larger by about 2% than the corresponding theoretical energy factor [4,5]. We compare our experimental value in Fig. 3 with the *ab initio* (energy-scaled) many-body lifetime results of 30.82 (30.35) ns from Ref. [4], and 31.01 (30.58) ns from Ref. [5]. Earlier calculations of the $6p\,^2P_{3/2}$ lifetime in cesium are discussed in Ref. [13].

Our 0.9% lifetime measurement establishes the accuracy of the two energy-scaled many-body calculations of the transition matrix element in cesium to be about 0.5%, which is consistent with their mutual agreement. We also note that this precise measurement of the $6S$-$6P$ transition probability is important for calibrating the strength of the electric field induced $6S_{1/2}$-$7S_{1/2}$ transition, which is specifically used to measure PNC in atomic cesium.

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