Lifetime of the potassium $5P_{1/2}$ state

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(Received 27 August 2004; published 16 August 2005)

We have measured the natural decay lifetime of the $5P_{1/2}$ state in potassium by pulsed excitation followed by nonresonant photoionization to monitor the state population. The result for the lifetime is $\tau = 137.6 \pm 1.3$ ns, an improvement compared to previous results in the literature.

DOI: 10.1103/PhysRevA.72.024501 PACS number(s): 32.70.Cs, 31.15.Ar, 32.80.Fb

I. INTRODUCTION

We have measured the lifetime of the $5P_{1/2}$ state in potassium with improved accuracy. Measurements of lifetimes of atomic alkali states provide useful tests [1–3] of many-body *ab initio* wavefunctions [4]. Transitions to higher-lying fine structure $P_{1/2}$ and $P_{3/2}$ doublets can have different dipole matrix elements apart from the expected statistical factors, a phenomenon known as the oscillator strength anomaly [5]. For example, detailed *ab initio* calculations of the reduced dipole matrix elements for the $4S–5P_{3/2}$ and $4S–5P_{1/2}$ transitions in atomic potassium exist, and the ratio of their squares is 2.18 [4], quite different from the statistical value of 2. In contrast, the calculated ratio for the $5S–5P_{3/2}, 5S–5P_{1/2}$ doublet is 1.993 [4]. We know of no detailed calculation of the other decay branch, 5P–3D, although equivalent transitions have been calculated in heavier alkali atoms [6].

II. EXPERIMENT

We trap between 3×10^6 and 3×10^7 atoms of nuclear spin $I=3/2$ ^{39}K in the second magneto-optical trap (MOT) of a two-MOT apparatus [7] (see Fig. 1). We excite the $4S_{1/2}F=1$ to $5P_{1/2}F=2$ transition with light from a 405 nm narrow-frequency diode laser locked by saturation spectroscopy. The 405 nm light is pulsed on and off using an acousto-optic modulator (AOM). We measure the 5P population as a function of time after the pulse by using nonresonant photoionization at 763 nm, which has enough energy to ionize the 5P state but not the lower-lying states (see Fig. 2). The intensity of the 763 nm beam is 0.5 W/cm^2, so two-photon ionization from lower-lying levels is entirely negligible. The 763 nm photoionization beam is left on at all times, and it copropagates with the 405 nm excitation beam.

The duty cycle is 5 μs long. First the MOT 766.5 nm beams are turned on for 2 μs to confine the atoms and then turned off for the rest of the cycle. The 405 nm light is turned on for 0.8 μs to populate the $5P_{1/2}$ state. Then the 405 nm light is switched off, 100 ns is allowed for the 405 nm AOM to extinguish the light, and then the photoions are counted for the remainder of the cycle, 2.2 μs.

We accelerate the ions with an electric field to a microchannel plate (MCP) detector, and measure the resulting count rate as a function of time. The system time resolution was measured separately using a pulsed photoionization laser to be 5 ns, limited by the cloud size. The MCP also has a resistive anode readout with 0.25 mm position resolution. The photoionization light is tuned to the blue of the 4P resonances to avoid complications due to photoassisted molecular ionization [8].

Using maximum likelihood, we fit an exponential with a constant background to the number of counts as a function of time. The result for the sum of all of the data used to determine the lifetime is shown in Fig. 3.

Figure 3 also shows the result of a measurement of the 405 nm AOM pulsing time (Fig. 3, bottom). We measured this separately in the same geometry by leaving the MOT light on at all times and tuning the 405 nm light well off-resonance. The 405 nm light has sufficient energy to photoionize the excited $4P_{3/2}$ state of the MOT, so this creates a photoionization rate directly proportional to the power of the 405 nm light. This technique directly measures the time dependence of the 405 nm pulse without distortion from atomic lifetimes. By focusing the 405 nm light into the AOM and passing through it twice, we achieve 0.3% extinction at 40 ns and better than 10^{-4} extinction at 100 ns, where we begin our fits.

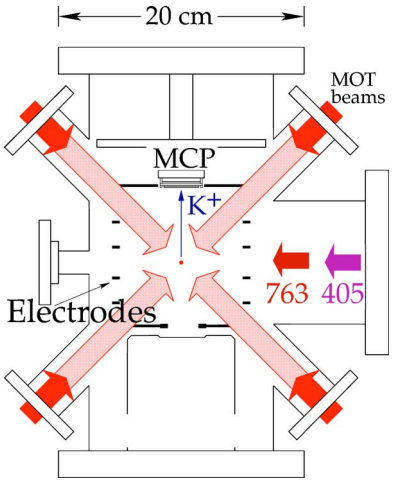

FIG. 1. (Color online) Top view of the experimental apparatus. Atoms trapped in the MOT are excited to the $5P_{1/2}$ state by the pulsed 405 nm beam and nonresonantly photoionized by the 763 nm beam. The ions are accelerated with the ring electrodes to the microchannel plate (MCP) and detected.

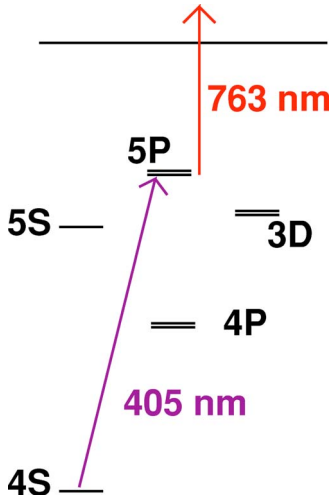

FIG. 2. (Color online) Potassium atom energy level diagram, approximately to scale. The 763 nm light has enough energy to only ionize the $5P_{1/2}$ state. Hyperfine structure is not shown. The $4S_{1/2}F=1$ to $5P_{1/2}F=2$ transition is excited.

The sample is insignificantly depleted by the nonresonant photoionization process during the decay times measured. Absolute measurements of the 405 fluorescence imply that an average of between 30 and 300 atoms are excited into the 5P state by the relatively weak laser (≈ 0.3 mW/cm^2) and transition. Our highest ion production rates are 3000 ions per second, or an average of 6×10^{-3} atoms during the 2 μs inspection time, decreasing the apparent lifetime by 1.4×10^{-6} of its value.

III. DETAILED ERROR DISCUSSION

Table I shows our errors. We consider them in detail.

A. Quantum beats in photoionization detection

For careful discussions of quantum beats, see e.g., [9]. A detailed experimental example of quantum beats in fluorescence can be found in [10].

If fluorescence detection were used, there would be no quantum beats for $P_{1/2}$ decay. Since $J=1/2$ cannot be aligned, the angular distribution of radiation remains isotropic as long as the polarization of spontaneously emitted light is not selected [9]. In contrast, our use of photoionization to measure the state population has the possibility of quantum beats occurring, because the photoionization cross section can change as a function of the polarization of the atoms and the photoionizing laser. The final continuum state for photoionization from the $P_{1/2}$ state can be either $S_{1/2}$ or $D_{3/2}$ [11]. As an extreme example, if circularly polarized light were used to excite a completely vector polarized $J=1/2$, $M_J=+1/2$ state, and the photoionization light were pure σ^+, then the $S_{1/2}$ partial wave would be completely suppressed. If the vector polarization oscillates with time, e.g., by Larmor precession in nonzero stray B field, beats would be produced as the photoionization cross-section changed.

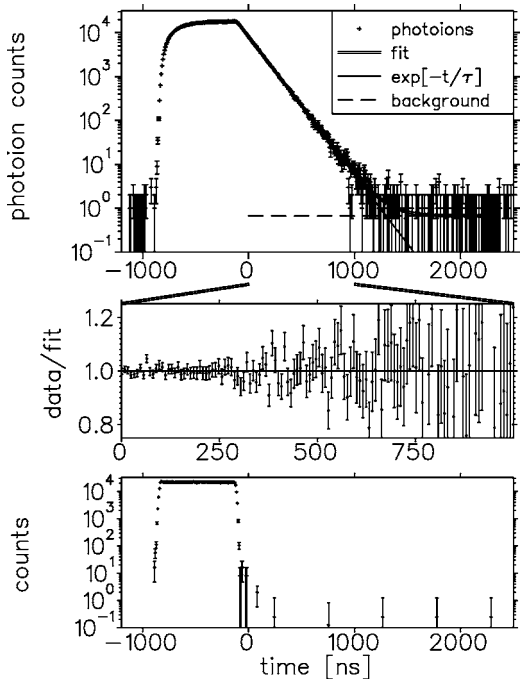

FIG. 3. Top: Results of the fit (double solid line) of the number of photoions, proportional to the $5P_{1/2}$ population. Also shown is the decomposition into an exponential decay (single solid line) plus a random background (dashed line). The χ^2 per degree of freedom is 1.1, and the confidence level of the fit is 9%. All the data used in Fig. 4 is shown here. Middle: Data divided by fit for the first microsecond of the fit region. Bottom: Separate data showing the intensity as a function of time of the switched 405 nm light. This is measured by tuning the 405 nm light well off the $5P_{1/2}$ resonance, and leaving MOT light on at all times. The fit is begun at $t=0$ ns, which is 100 ns after the AOM is switched off, after which the 405 nm light has been attenuated by more than 10^{-4}.

In the absence of coherences, if purely linearly polarized light is used for photoionization, then parity conservation implies that the cross section would not depend on the vector polarization of a $J=1/2$ state. Thus the presence of both vector polarization of the $P_{1/2}$ state and a circularly polarized component of the photoionizing light is necessary for the cross section to change with time and produce quantum beats.

TABLE I. List of systematic and statistical errors and how they were estimated. The errors shown are from independent physical processes and so are added in quadrature.

Potential physics sources of quantum beats:	
(1) 763 nm linear polarization	0.80 ns
(2) Cloud position in B field (Zeeman)	0.38 ns
(3) Truncation error (hyperfine, other)	0.44 ns
Other errors:	
(4) Statistical and fit	0.36 ns
(5) Radiation trapping (0.51ns correction)	0.73 ns
(6) Cloud expansion	0.02 ns
Total (summed in quadrature)	1.3 ns

If coherent superpositions of $M_J = \pm 1/2$ were formed by the linearly polarized 405 nm light, beats could be produced even by linearly polarized photoionization light, with phase determined by the relative linear polarization of excitation and photoionizing light [12].

We determine errors from the possible experimental sources of quantum beats below.

1. Photoionization polarization dependence

We suppress vector polarization of the $5P_{1/2}$ state by using linearly polarized 405 nm light to excite the atoms. Since in finite B field this can still produce a nonzero vector polarization, we also use linearly polarized photoionization light. Birefringence of the vacuum window can in principle cause a very small circular polarization in either beam. We measured the resulting Stokes parameter to be $S_3 < 0.05$. So we test for the presence of quantum beats by varying the polarization of the 763 nm photoionization beam between linear parallel to the polarization of the 405 nm beam, linear perpendicular to the polarization of the 405 nm beam, and circular. The lifetime deduced from use of circularly polarized photoionization light differs from linear light by a possibly significant 2.8 ± 0.9 ns statistical error. We therefore do not use the circularly polarized light data in the lifetime determination. The lifetime fits to the two different linear polarizations agree to within 0.20 ± 0.80 ns statistical error, and we assign a systematic error of 0.80 ns to this source.

2. Cloud position and Zeeman quantum beats

The MOT cloud spatial distribution has a full width at half maximum of 2 mm, and the quadrupole B field vertical gradient is 20 G/cm, so the cloud samples fields of several Gauss. Residual polarization of the cloud from the 405 nm beam could produce Zeeman quantum beats with periods of a few hundred nanoseconds. As the ions from the trap cloud follow straight paths to the MCP in the 800 V/cm field, the trap cloud is imaged on the MCP. We investigated possible Zeeman beats by measuring the dependence of the fit lifetime on atom position within the trap cloud and, therefore, the local B field. There is no effect above statistics, and we assign the variance of the resulting distribution of measured lifetimes, 0.38 ns, as a systematic error.

3. Truncation error and hyperfine quantum beats

Pulsed lasers can excite coherent superpositions of excited states, which then evolve periodically in time at rates determined by their frequency splitting. The 405 laser pulse is 0.8 μs long, which widens the laser linewidth by a negligible 0.1 MHz. The 405 nm laser light has intensity ≈ 0.3 mW/cm^2, much less than saturation, so there is negligible power broadening. However, the width of our saturation spectroscopy peaks only puts an upper limit of 4 MHz on the laser linewidth, while the $5P_{1/2}$ hyperfine splitting in ^{39}K is 18 MHz. So although we are locked to the $F=1 \rightarrow F'=2$ transition, we can in principle excite a superposition of $F'=2$ and $F'=1$ excited states.

The fit residuals (see Fig. 3) show no evidence of a sinusoid. To quantify this, we investigated the dependence of the fit τ on the start time of the fit. This truncation error is sensitive to a number of possible errors including quantum beats [2,3]. There is no systematic trend of the lifetime values for start times varied by three lifetimes. We conservatively take the standard deviation of the resulting Gaussian distribution of lifetimes, 0.44 ns, as the truncation error.

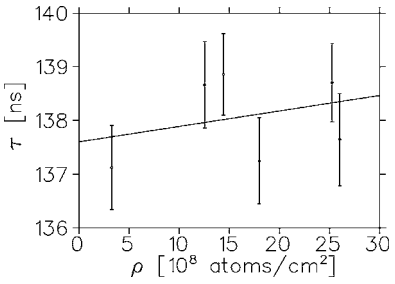

FIG. 4. Measured lifetime τ as a function of the column density of atoms, showing that the effect of radiation trapping is small.

B. Other errors

4. Random background

There is a background in the microchannel plate that is constant with time. We reduced the natural background to approximately 2×10^{-5} of the peak count rate by making a software cut on MCP position, allowing only events in a tight area surrounding the impact region of imaged ions from the trap cloud. In addition, raising the software threshold on the MCP pulse height preserved most of the ion pulses while eliminating a large fraction of the natural background from radioactivity. A background of 1×10^{-4} of the peak count rate remains, and examination of the MCP position profile implies $\sim 2/3$ of this is from photoions rather than random background counts. We accurately determined this background by continuing to count for 2 μs after the 405 nm AOM was pulsed off, and fitting the sum of a constant background and an exponential to the data (see Fig. 3). This fit is also consistent with our direct measurement of the background produced by taking the 405 nm light far off-resonance, and we attribute it to a small leakage of 405 nm light through the double-pass AOM. Correctly including the background decreases the deduced lifetime by 0.5 ns compared to fits with no background. The error due to the uncertainty of the background is naturally included in the fit error.

5. Radiation trapping

There is a finite probability for 405 nm fluorescence to be absorbed by other trapped atoms, which would then perturb the time dependence of the 5P population. To lowest order, such radiation trapping preserves a pure exponential, with an increase in lifetime that scales with column density. To test for the presence of radiation trapping, we vary the number of atoms in the trap between 3×10^6 and 3×10^7, with highest column density 3×10^9/cm^2, and measure the apparent lifetime. The results are shown in Fig. 4. There is no conclusive evidence for radiation trapping. The upper limit we place on the effect at the highest density measured is consistent with

an estimate from the measured trap density and the known transition strengths. We deduce identical results if we either extrapolate linearly to zero column density as in Fig. 4, or if we fit the sum of all the runs and then correct for the radiation trapping effect deduced from Fig. 4. The latter procedure lets us explicitly show the separate errors, and as the radiation trapping is potentially our largest error we choose to present it separately. The result is $\tau=138.11\pm0.36$ ns for the total fit, minus a correction of 0.51 ± 0.73 ns for radiation trapping, producing the result $\tau=137.60\pm0.81$ ns.

6. Cloud expansion

The photoionization beam has $1/e$ diameter of ≈1.2 cm, and the trap has spatial FWHM diameter of 0.20 cm. During the 2 μsec counting time, we can measure the cloud size expansion by using the MCP position information. We measure no expansion in this very short time to within 0.005 cm error, and the resulting change in overlap with the photoionizing beam would produce an error of less than 0.02 ns on the lifetime, which is negligible.

C. Summary and independence of errors

We summarize the errors in Table I. These are random independent errors and so we add them in quadrature. We have considered in detail above how the radiation trapping error can either be included in an extrapolation to zero column density or be added separately in quadrature with identical result. The cloud expansion error is bounded by experimentally determined parameters to be negligibly small. The three distinct physical sources of quantum beats are found to produce corrections consistent with zero, with errors estimated by variances of subsets of the data in a statistically random determination. Since the truncation error may include contributions from all sources of quantum beats, it is possible we are doubly counting and slightly overestimating the total error.

IV. CONCLUSION

Our result for the $5P_{1/2}$ lifetime is $\tau=137.6\pm1.3$ ns. This has improved accuracy compared to a previous measurement done by pulsed excitation and fluorescence detection, $\tau=137\pm2$ ns [13].

There is a discrepancy in the literature for the lifetime of the $5P_{3/2}$ state. A measurement using the Hanle effect [14] produced $\tau=140.8\pm1.0$ ns, while Ref. [13] cited above measured $\tau=134\pm2$ ns. A resolution of that discrepancy would be necessary to comment on the oscillator strength anomaly.

ACKNOWLEDGMENTS

We thank R. Pitcairn for physics discussions. This work was supported by the National Research Council of Canada through TRIUMF and by the Natural Sciences and Engineering Research Council of Canada.

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