Lifetime measurement of the $5d^2D_{5/2}$ state in $\text{Ba}^+$

Amita Mohanty¹ · Elwin A. Dijck¹ · Mayerlin Núñez Portela¹ · Nivedya Valappol¹ · Andrew T. Grier¹ · Thomas Meijknecht¹ · Lorenz Willmann¹ · Klaus Jungmann¹

Published online: 21 April 2015
© The Author(s) 2015. This article is published with open access at Springerlink.com

Abstract The lifetime of the metastable $5d^2D_{5/2}$ state has been measured for a single trapped $\text{Ba}^+$ ion in a Paul trap in Ultra High Vacuum (UHV) in the $10^{-10}$ mbar pressure range. A total of 5046 individual periods when the ion was shelved in this state have been recorded. A preliminary value $\tau_{D_{5/2}} = 26.4(1.7)$ s is obtained through extrapolation to zero residual gas pressure.

Keywords Single ion spectroscopy · Electron shelving · Atomic lifetime

1 Introduction

The accurate determination of the transition probability of transitions in heavy alkali earth systems is an important step in the research program to measure Atomic Parity Violation (APV) in such systems [1–9]. In the research reported here, a single trapped $\text{Ba}^+$ ion has been investigated and the lifetime of its $5d^2D_{5/2}$ state has been measured. This provides essential input for testing atomic structure and, in particular, the atomic wavefunctions of the involved states at percent level accuracy. Such measurements are highly sensitive to...

---

Amita Mohanty holds M.Sc. degree at University of Groningen.
Elwin A. Dijck holds M.Sc. at University of Groningen.
Mayerlin N. Portela holds M.Sc. at University of Groningen.
Nivedya Valappol holds M.Sc. at University of Groningen.
Andrew T. Grier holds Ph.D at University of Groningen.
Thomas Meijknecht holds B.Sc at University of Groningen.

© Amita Mohanty
a.mohanty@rug.nl; mohanty.amita18@gmail.com

¹ Van Swinderen Institute, FMNS, University of Groningen, 9747AA Groningen, The Netherlands
Table 1  Calculations and measurements of the lifetime of the 5d\textsuperscript{2}D\textsubscript{5/2} state in Ba\textsuperscript{+} (see also Fig. 6)

| Theory | Experiments |
|--------|-------------|
| Value[s] | Year | Reference | Value[s] | Year | Reference |
| 29.8(3) | 2012 | [5, 6] | 31.2(0.9) | 2014 | [15] |
| 30.3(4) | 2008 | [19] | 32.0(2.9) | 2007 | [13] |
| 30.8 | 2007 | [21] | 32.3 | 1997 | [16] |
| 31.6 | 2007 | [14] | 34.5(3.5) | 1990 | [11] |
| 30.3 | 2001 | [18] | 32(5) | 1986 | [10] |
| 37.2 | 1991 | [20] | 47(16) | 1980 | [12] |

Note, some of the values have been reported without error bars

variations of parameters that determine the experiment’s performance during long periods (i.e. several hours) and which may cause systematic uncertainties. In particular, such effects may arise from interactions of the ion with background gas.

There are two main reasons for choosing single trapped Ba\textsuperscript{+} ion in UHV to perform precise lifetime measurements. Firstly, Barium (Ba) is a heavy alkaline earth metal. The Ba\textsuperscript{+} ion has a rather simple electronic configuration. Precise measurements provide for accurate tests of the atomic wavefunctions. Secondly, systematic errors due to collisions with other particles (such as different species) are highly suppressed.

The lifetime of the metastable 5d\textsuperscript{2}D\textsubscript{5/2} state in Ba\textsuperscript{+} has been measured earlier in different experiments [10–16]. Calculations are presently performed by different independent theory groups [5, 6, 17–21]. All the measurements to date as well as calculated values for the lifetime of 5d\textsuperscript{2}D\textsubscript{5/2} state in Ba\textsuperscript{+} have been compiled in Table 1.

2 Experimental setup

The trap for Ba\textsuperscript{+} in this experiment is a hyperbolic Paul trap [22]. It consists of a ring electrode and two end caps made of copper. The electrodes are mounted on a Macor holder. The chosen geometry results in a harmonic pseudopotential at the center of the trap when AC voltages are applied between the ring and the two endcaps. The latter are grounded. The operating RF frequency for the trap is $\Omega_{RF} = 5.44 \text{ MHz}$. The trap with its Macor holder is mounted on Oxygen Free High Conductivity (OFHC) copper base plate. In order to trap ions, there is a Ba oven (0.9 mm diameter $\times$ 40 mm length resistively heated stainless steel tube) which contains a mixture of BaCO\textsubscript{3} and Zr. This oven produces a flux of order of $10^6$ thermal Ba atoms/s.

A laser at wavelength 413 nm is used to produce Ba\textsuperscript{+} ions in the trap by two-photon photoionisation. We use laser light at $\lambda_1 = 493$ nm (frequency doubled from a Coherent MBR-110 Ti:Sa laser) for driving the 6s\textsuperscript{2}S\textsubscript{1/2}-6p\textsuperscript{2}P\textsubscript{1/2} cooling transition and laser light at $\lambda_2 = 649$ nm (produced from Coherent CR-699 ring dye laser) for the 6p\textsuperscript{2}P\textsubscript{1/2}-5d\textsuperscript{2}D\textsubscript{3/2} repump transition (see Fig. 2). In the experiments reported here, the power of $\lambda_1$ is between 6 $\mu$W and 50 $\mu$W and that of $\lambda_2$ is between 6 $\mu$W and 45 $\mu$W. The Gaussian radius of the laser beams is about 60 $\mu$m at the position of the ion for all the measurements. Fluorescence from the 6s\textsuperscript{2}S\textsubscript{1/2}-6p\textsuperscript{2}P\textsubscript{1/2} transition in the Ba\textsuperscript{+} ion is detected with a photomultiplier tube
Lifetime measurement of $5d^2D_{5/2}$ state in Ba$^+$

Fig. 1 Hyperbolic Paul trap of Ba$^+$ ion. On top, images of 3, 2 and 1 ion are given.

(PMT) and an EMCCD camera. Figure 1 shows our hyperbolic Paul trap together with the image of ions that are trapped and localized at the potential minimum of the trap.

3 Electron shelving technique

Ba$^+$ ions have a closed three-level system. One of the excited states, the $5d^2D_{5/2}$ state, is long-lived (see Fig. 2). Simultaneous laser radiation at $\lambda_1$ and $\lambda_2$ is therefore needed to cool the ion in the center of the trap. When the ion is exposed to the light of two laser beams at wavelengths $\lambda_1$ and $\lambda_2$ (see Fig. 2), there is a closed cycle of $6s^2S_{1/2}$-$6p^2P_{1/2}$-$5d^2D_{3/2}$ transitions. Observing the fluorescence from the $6p^2P_{1/2}$-$6s^2S_{1/2}$ transition implies that the ion is “not shelved” in the $5d^2D_{5/2}$ state. The electron shelving technique is employed in our experiment to determine the lifetime of the $5d^2D_{5/2}$ state. With an additional fiber-coupled
Fig. 2 Level scheme of Ba\(^+\) ion. The lowest \(^2S_{1/2}, ^2P_{1/2}\) and \(^2D_{3/2}\) electronic states form a closed three level system.

Fig. 3 Quantum Jumps observed in single Ba\(^+\) ion. Left PMT count rate as a function of time. Right EMCCD image of the ion in the unshelved state (top) and shelved state (bottom).

High power LED (M455F1) at \(\lambda_3 = 455\) nm wavelength the ion can be “shelved” to the \(5d^2 D_{5/2}\) state via excitation to the \(6p^2 P_{3/2}\) state and this state’s subsequent decay. The direct observation of “quantum jumps” in a single Ba\(^+\) ion between the \(5d^2 D_{5/2}\) and \(6s^2 S_{1/2}\) states has been first demonstrated by Nagourney et al. \[10\]. The decay of the \(6p^2 P_{3/2}\) state is the start of a shelving period which ends with a quantum jump from the \(5d^2 D_{5/2}\) state to \(6s^2 S_{1/2}\) state. Figure 3 displays the highest PMT count rate (2200 cnts/s) when the ion is not shelved and the lowest count rate (600 cnts/s) as background when it is shelved to the metastable \(5d^2 D_{5/2}\) state. The “on/off” and “off/on” transitions in the fluorescence signal corresponds to the start and end of one single interval, when the ion was in the \(5d^2 D_{5/2}\) state.

4 Measurements

In order to measure the lifetime \(\tau_{D_{5/2}}\), a total of 5046 individual shelved periods have been recorded in 71 data samples and analysed. They were taken under in part significantly different conditions to enable observing and correcting for systematic errors \[23\]. Figure 4 represents one example of the analysed samples. It shows an exponential decay. Such a decay function is fitted to each data set using a binned log-likelihood method. The lifetime
Lifetime measurement of 5d²D₅/₂ state in Ba⁺

Fig. 4 One sample of the lifetime measurements in single Ba⁺ ion with 96 shelved periods

Fig. 5 Lifetime of the 5d²D₅/₂ state versus residual gas pressure in a single Ba⁺ ion. 68 % and 95 % confidence intervals are given

τ₅/₂ is obtained for each data sample from the corresponding fit parameters. We note that experimental situations can be created where ion heating results in longer measured durations of individual dark periods than the actual dwell time of the ion in the D₅/₂ state. This can be seen in the slow recovery of the fluorescence light.

Collisions with background gas can reduce the lifetime of the metastable state. In order to extrapolate the absolute value for the lifetime to zero pressure, the lifetime τ₅/₂ was measured at different background pressures. Figure 5 displays the results for a selection of 1600 out of 5046 shelved periods. The uncertainty for the lifetime in each value corresponds to the statistical error from fitting an exponential decay to the data. A range of pressures between 2.5 × 10⁻¹⁰ and 8.7 × 10⁻¹⁰ mbar was explored by changing the temperature of the vacuum chamber in the range from 289 K to 296 K and by adjusting the pumping speed of the ion pump. For the small change in temperature needed here, changes in the collision cross-sections between the ion and the residual gas atoms can be neglected. A linear function is fitted to the data. The lifetime of the 5d²D₅/₂ state is found to be τ₅/₂ = 26.4(1.7) s. 3446 shelved periods are used to check for systematics, such as potentially arising from laser intensities, laser frequency detunings, rf voltages for trap and effects from the operating conditions of the ion pump. No significant effects have been observed.
Fig. 6  Lifetime of the 5d^2D_5/2 state in a single Ba^+ ion versus time within the last four decades. Squares represent measurements and triangles represent calculated values. Note, the result Guet2 [21] differs from Guet1 [20] by an omitted term.

5 Conclusions

In summary, the lifetime of the metastable 5d^2D_5/2 has been measured for a single Ba^+ ion. The measured value is preliminary because cross checks for systematics are still ongoing. Our result agrees within 2σ with the most recent theoretical value τ_{D_5/2} = 29.8(3) s [6] and with the latest independent experimental value of τ_{D_5/2} = 31.2(9) s [15]. Figure 6 displays the time evolution of the measurements and the theory values for the lifetime of the 5d^2D_5/2 state in a Ba^+ ion.

Acknowledgments  We thank Leo Huisman, Oliver Böll, and Otto Dermois for their technical assistance. We acknowledge the financial support from FOM Programme 114 (TRμP/AGOR) and FOM programme 125 (Broken Mirrors and Drifting Constants).

Open Access  This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

1. Nuñez Portela, M., Dijck, E.A., Mohanty, A., Bekker, H., van den Berg, J.E., Giri, G.S., Hoekstra, S., Onderwater, C.J.G., Schlessor, S., Timmermans, R.G.E., Versolato, O.O., Willmann, L., Wilschut, H.W., Jungmann, K.: Ra^+ ion trapping: Toward an atomic parity violation measurement and an optical clock. Appl. Phys. B 114(1–2), 173–182 (2014)

2. Wansbeek, L.W., Sahoo, B.K., Timmermans, R.G.E., Jungmann, K., Das, B.P., Mukherjee, D.: Atomic parity nonconservation in Ra^+. Phys. Rev. A 78(5), 050501(R) (2008)

3. Willmann, L., Jungmann, K., Onderwater, C.J.G., Timmermans, R.G.E., Wilschut, H.W.: Trapped radioisotopes for fundamental symmetry investigations. EXA 2011, 315–319 (2012)

4. Nuñez Portela, M., van den Berg, J.E., Bekker, H., Böll, O., Dijck, E.A., Giri, G.S., Hoekstra, S., Jungmann, K., Mohanty, A., Onderwater, C.J.G., Santra, B., Schlessor, S., Timmermans, R.G.E., Versolato, O.O., Wansbeek, L.W., Willmann, L., Wilschut, H.W.: Towards a precise measurement of atomic parity violation in a single Ra^+ ion. Hyperfine Interact. 214(1–3), 157–162 (2013)

5. Sahoo, B.K., Chaudhuri, R., Das, B.P., Mukherjee, D.: Relativistic coupled-cluster theory of atomic parity nonconservation: Application to ^{137}Ba^+. Phys. Rev. Lett. 163003, 96 (2006)
6. Sahoo, B.K., Das, B.P.: Ba\(^+\) quadrupole polarizabilities: Theory versus experiment. Phys. Rev. A 86, 022506 (2012)
7. Sahoo, B.K., Mandal, P., Mukherjee, M.: Parity nonconservation in odd isotopes of single trapped atomic ions. Phys. Rev. A 83, 030502(R) (2011)
8. Geetha, K.P., Singh, A.D., Das, B.P., Unnikrishnan, C.S.: Nuclear-spin-dependent parity-nonconserving transitions in Ba\(^+\) and Ra\(^+\). Phys. Rev. A 58, R16(R) (1998)
9. Roberts, B.M., Dzuba, V.A., Flambaum, V.V.: Nuclear-spin-dependent parity nonconservation in s-d\(^3/2\) and s-d\(^5/2\) transitions. Phys. Rev. A 89, 012502 (2014)
10. Nagourney, W., Sandberg, J., Dehmelt, H.: Shelved optical electron amplifier: Observation of quantum jumps. Phys. Rev. Lett. 56, 2797–2799 (1986)
11. Madej, A.A., Sankey, J.D.: Quantum jumps and the single trapped barium ion: Determination of collisional quenching rates for the 5d\(^2\)D\(^5/2\) level. Phys. Rev. A 41, 2621–2630 (1990)
12. Plumelle, F., Desaintfuscien, M., Duchene, J.L., Audoin, C.: Laser probing of ions confined in a cylindrical radiofrequency trap. Opt. Commun. 34(1), 71–76 (1980)
13. Royen, P., Gurell, J., Lundin, P., Norlin, L.O., Mannervik, S.: Monitoring the weak collisional excitation of a stored ion beam reveals the radiative decay rate of extremely long-lived metastable levels. Phys. Rev. A 76, 030502(R) (2007)
14. Gurell, J., Biémont, E., Blagoev, K., Fivet, V., Lundin, P., Mannervik, S., Norlin, L.O., Quinet, P., Rostohar, D., Royen, P., Schef, P.: Laser-Probing Measurements and Calculations of Lifetimes of the 5d\(^2\)D\(^3/2\) and 5d\(^2\)D\(^5/2\) metastable Levels in Ba II. Phys. Rev. A 75, 052506 (2007)
15. Aucbtcr, C., Noel, T.W., Hoffman, M.R., Williams, S.R., Blinov, B.B.: Measurement of the Branching Fractions and Lifetime of the 5d\(^2\)D\(^5/2\) Level of Ba\(^+\). ArXiv e-prints:1409.0873
16. Yú, N., Nagourney, W., Dehmelt, H.: Radiative lifetime measurement of the Ba\(^+\) metastable D\(^3/2\) state. Phys. Rev. Lett. 76, 4898–4901 (1997)
17. Sahoo, B.K., Islam, Md.R., Das, B.P., Chaudhuri, R.K., Mukherjee, D.: Lifetimes of the metastable 2D\(^3/2\), 2D\(^5/2\) states in Ca\(^+\), Sr\(^+\) and Ba\(^+\). Phys. Rev. A 74, 062504 (2006)
18. Dzuba, V.A., Flambaum, V.V., Ginges, J.S.M.: Calculations of Parity-Nonconserving sd Amplitudes in Cs, Fr, Ba\(^+\) and Ra\(^+\). Phys. Rev. A 63(6), 062101 (2001)
19. Iskrenova-Tchoukova, E., Safronova, M.S.: Theoretical study of lifetimes and polarizabilities in Ba\(^+\). Phys. Rev. A 78, 012508 (2008)
20. Gurell, C., Johnson, W.R.: Relativistic many-body calculations of transition rates for Ca\(^+\), Sr\(^+\) and Ba\(^+\). Phys. Rev. A 44, 1531–1535 (1991)
21. Gurell, C., Johnson, W.R.: Erratum: Relativistic many-body calculations of transition rates for Ca\(^+\), Sr\(^+\) and Ba\(^+\). Phys. Rev. A 76, 039905(E) (2007)
22. Paul, W.: Electromagnetic traps for charged and neutral particles. Rev. Mod. Phys. 62(3), 531–540 (1990)
23. Nuñez Portela, M.: Single Ion Spectroscopy in Preparation of an Atomic Parity Violation Measurement in Ra\(^+\), PhD thesis, University of Groningen (2015)