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Towards a Precise Measurement of Atomic Parity Violation in a Single Ra^+ Ion

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Abstract A single trapped Ra^+ ($Z = 88$) ion provides a very promising route towards a most precise measurement of Atomic Parity Violation (APV), since APV effects grow faster than Z^3. This experiment promises the best determination of the electroweak coupling constant at the lowest accessible energies. Such a measurement provides a sensitive test of the Standard Model in particle physics. At the present stage of the experiment, we focus on trapping and laser cooling stable Ba^+ ions as a precursor for radioactive Ra^+. Online laser spectroscopy of the isotopes $^{209-214}Ra^+$ in a linear Paul trap has provided information on transition wavelengths, fine and hyperfine structures and excited state lifetimes as test of atomic structure calculations. Additionaly, a single trapped Ra^+ ion could function as a very stable clock.

1 Introduction

There are two different and complementary approaches to search for physics beyond the standard model: (i) the direct observation of new particles or effects, typically in high energy experiments, and (ii) high precision measurements of known quantities and thereby searching for deviations from their Standard Model predicted values, typically at low energy. Searches for Electric Dipole Moments (EDMs) and Atomic Parity Violation (APV) are examples of such precision experiments at low energy. Here we focus on an APV experimental program with Ra^+ using the TRIμP facility at the AGOR cyclotron of KVI.

2 Atomic Parity Violation in Ra^+

APV arises from the exchange of Z_0 boson between the atomic electrons and the quarks inside the nucleons of the atomic nucleus. In this process the nucleus acquires a weak nuclear charge (Q_{weak}) which depends on the Weinberg angle (θ_W)

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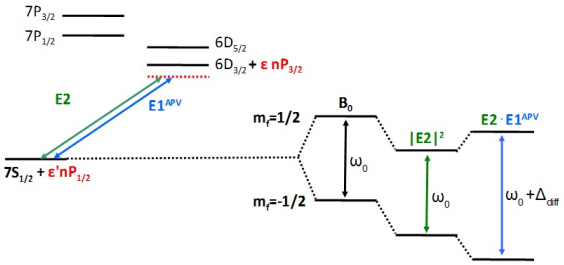

Fig. 1 Atomic parity violation measurement. The interference between E_1^{APV} and E_2 produces differential light shifts of ground state m-levels that can be measured with RF spectroscopy and optical shelving [4,9].

via the relation $Q_{weak} \approx (1 - 4\sin^2\theta_W)Z - N$. The value of the Weinberg angle is a running constant on the scale of momentum transfer. At the lowest accessible momentum transfer, so far one high precision experiment has been performed in Cs to measure θ_W [1,2,3]. The interpretation of this experiment in the nineties is today still limited by the required precise calculations of atomic wave functions in Cs.

A new way to measure APV in single ions of Ba^+ and Ra^+ was proposed by Fortson *et al.* [4]. In an atom, parity violation arises from the mixing of a photon and a Z_0 boson both exchanged between an electron and nucleus. Atomic states acquire thereby a tiny admixture of opposite parity states. In Ra^+ mixing of the $7S_{1/2}$ and $7P_{1/2}$ enables a dipole transition E_1^{APV} between the $7S_{1/2} \rightarrow 6D_{3/2}$ states. Since the E_1^{APV} transition rate is too small to be measured directly, the interference between the dipole E_1^{APV} and the quadrupole E_2 transitions is observed. A differential AC Stark shift of the $m = \pm 1/2$ Zeeman levels of the ground state (Fig. 1) is a consequence of this interference.

The APV signal is strongly enhanced in heavy atoms, stronger than $\propto Z^3$ [5]. The Ra^+ ion ($Z = 88$) is the heaviest alkaline earth ion available. Therefore a single trapped and laser cooled Ra^+ is a superior candidate to measure APV. The E_1^{APV} effect in Ra^+ is 20 times larger than in Ba^+ [10] and 50 times larger than in Cs [6,8,10]. The existence of a long series of different Ra^+ isotopes provides also for ratio measurements where the uncertainties associated with atomic wave functions calculation cancel. An experiment to exploit this APV enhancement in Ra^+ is currently being developed within the TRIμP research program. The experiment aims at 5-fold improved measurement of the weak mixing angle with respect to the sole best APV result from atoms performed with Cs [1,2,3,7].

3 Ra^+ Production and Spectroscopy

In order to extract the Weinberg angle with high accuracy, the atomic wave functions and atomic lifetimes need to be calculated at high level of precision, i.e. subpercent level. The isotopes $^{212-214}$Ra are produced at the TRIμP facility in inverse

kinematics by the fusion and evaporation reaction ^{206}Pb $+^{12}$C$\rightarrow^{(218-x)}$Ra$+x$n, where x is the number of evaporated neutrons [11]. A ^{204}Pb beam is used for the production of $^{209-211}$Ra. The Ra isotopes are separated from the primary beam and other reaction products in a double magnetic separator [12]. Subsequently they are stopped in a Thermal Ionizer (TI) consisting of a stack of 0.75 μm thick tungsten foils in a $\approx$ 2500 K hot tungsten cavity [13]. The atoms are ionized on the hot surfaces. The ions are electrostatically extracted and a singly charged Ra^+ beam are obtained with $> 8\%$ efficiency [11]. The Ra^+ isotopes pass through a Wien Filter which eliminates contaminant ions. Electrostatic deceleration takes place in a gas-filled Radio Frequency Quadrupole (RFQ) cooler that operates at a frequency of 500 kHz with 190 V peak to peak voltage between the opposite electrodes. Ions are trapped at the end of the RFQ that operates as a linear Paul trap (see Fig.2) by an effective potential well of depth 13 eV. The axial potential depth is 10 eV. Ions are thermalized by Ne buffer gas at a pressure of $1-5\times10^{-2}$ mbar.

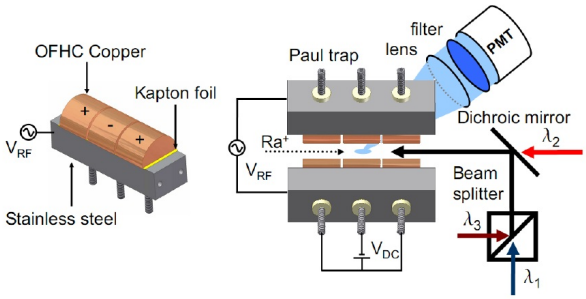

Fig. 2 Schematic diagram of the linear Paul trap. The optical setup necessary for spectroscopy and optical signal detection is shown.

Laser spectroscopy is performed by driving optical transitions at wavelengths $\lambda_1 = 468$ nm and $\lambda_2 = 1079$ nm (Fig. 3). Light from two diode lasers at wavelength λ_1 is overlapped and transported to the ion trap in a single mode optical fiber. A separate single mode optical fiber transports light from a diode laser at wavelength λ_2 to the trap. The laser beams at different wavelengths are overlapped using a polarizing beam splitter and a dichroic mirror. The beams are aligned along the axis of the trap in order to minimize stray-light (Fig. 2). Typical laser intensities at the trap center are 200 μW/mm^2(λ_1) and 600 μW/mm^2(λ_2). The transitions are detected via fluorescence at wavelength λ_1 using an imaging lens system and a photomultiplier tube. A low-pass filter with 80% transmission for light at wavelengths shorter than 500 nm suppresses stray light.

The hyperfine structure intervals of the $6d\,^2\mathrm{D}_{3/2}$ states in the isotopes with $I \neq 0$ have been measured. The isotope shifts of the $6d\,^2\mathrm{D}_{3/2}$ - $7p\,^2\mathrm{P}_{1/2}$ transitions in all the produced isotopes have been determined. The results are shown in Fig. 4; further details are listed in Table 1.

The APV measurement requires the localization of a single ion within one wave-

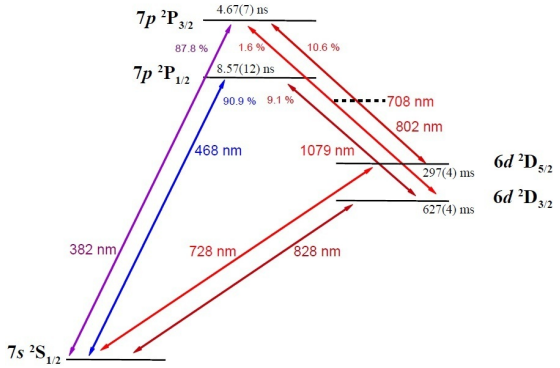

Fig. 3 Level scheme of Ra^+.

Table 1 Isotope shifts of the $6d\,^2D_{3/2} - 7p\,^2P_{1/2}$ transition in $^{209-214}Ra^+$ with the relevant hyperfine constants. The comparatively large uncertainty on the isotope shift of $^{209}Ra^+$ is a consequence of a low signal-to-noise ratio due to a lower yield and the shorter lifetime of the isotope.

Mass Number	A($6d\,^2D_{3/2}$) MHz	B($6d\,^2D_{3/2}$) MHz	A($7p\,^2P_{1/2}$) MHz	Isotope Shifts [16] MHz
214	-	-	-	0
213	528(5) [15]	-	4525(5) [18]	707(14)
212	-	-	-	1025(12)
211	151(2) [17]	103(6) [17]	1299.7(0.8) [18]	1755(14)
210	-	-	-	1884(16)
209	148(10) [17]	104(38) [17]	1276(20)[1]	2645(56)

length of the laser light. In order to achieve single ion detection, a hyperbolic Paul trap has been installed (see Fig. 5). Ba^+ ions are produced by electron beam ionization inside the trap. The laser cooling and single ion detection schemes are presently being developed using Ba^+ in a precursor experiment for the Ra^+ APV measurement.

The spectroscopic data obtained from Ra^+ isotopes are in good agreement with recent calculations [19,20,21,22,23]. For a competitive extraction of $\sin^2\theta_W$ the precision of the atomic theory of the Ra^+ ion needs to be improved further to the sub-percent level. Work towards this is in progress [24]. The experiment is expected to produce an APV signal from a single Ra^+ ion within the coming three years.

4 Ra^+ Optical Clock

We note here that the very same setup which is used for a competitive APV measurement is also well suited for the realization of a single ion optical clock based on Ra^+ [25]. The isotope ^{223}Ra is of particular interest. Here the sensitivity to the quadrupole shifts in the $7s\,^2S_{1/2} - 6d\,^2D_{3/2}$ transitions—which is a major systematic effect limiting present single ion clocks—is minimal. Whereas for the

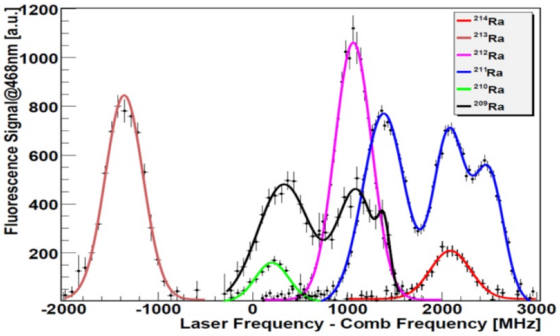

Fig. 4 The solid lines represent fits with a Gaussian lineshape of the measured $6d^2D_{3/2} - 7p^2P_{1/2}$ transition (1079 nm) for the isotope chain $^{209-214}Ra^+$. The horizontal axis represents the laser frequency offset from the reference frequency of a frequency comb line.

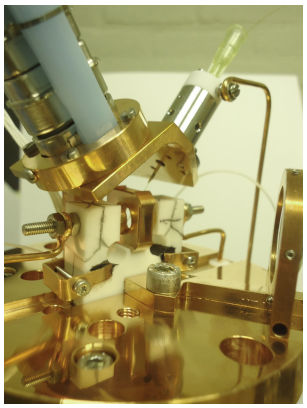

Fig. 5 Hyperbolic Paul trap to confine a single ion. A Ba oven and an electron gun are located above the trap. Ba^+ ions are produced inside the trap assembly by electron beam ionization.

APV measurement the light shift needs to measured as a function of laser intensity very accurately, a clock only requires its stable control [25]. A stability of 10^{-18} or beyond appears feasible for a $^{223}Ra^+$ clock, which makes it very competitive with present clocks. In particular, high precision tests of fundamental symmetries, e.g., a search for the time variation of the fine structure constant α, become possible with unprecedented accuracy.

5 Conclusions

Ra^+ provides an excellent opportunity for an accurate measurement of the Weinberg angle, a clock with highest possible accuracy and thereby searches for the time variation of fundamental constants such as α.

References

1. C. S. Wood et al., Science **275**, 1759 (1997).
2. S. C. Bennett et al., Phys. Rev. Lett. **82**, 2484 (1999).
3. S. G. Porsev et al., Phys. Rev. Lett. **102**, 181601 (2009).
4. N. Fortson. Phys. Rev. Lett.**70**, 2383 (1993).
5. M. A. Bouchiat and C. C. Bouchiat, Phys. Lett. B **48**, 111 (1974).
6. V. A. Dzuba et al., Phys. Rev. A **63**, 062101 (2001).
7. M. A. Bouchiat et al., Phys. Lett. B **117**, 358 (1982).
8. O.O. Versolato et al., CAn. Jour. Phys. **89**, 65 (2011).
9. T. W. Koerber et al., J. Phys. B: At. Mol. Opt. Phys. **36** (2003) 637648.
10. L. W. Wansbeek et al., Phys. Rev. A **78**, 050501 (2008)
11. P. D. Shidling et al., Nucl. Instr. Meth. A **606**, 305 (2009).
12. G. P. A. Berg et al., Nucl. Instr. Meth. A **560**, 169 (2006).
13. P. D. Shidling et al., Nucl. Instr. Meth. A **622**, 11 (2010).
14. E. Traykov et al., Nucl. Instr. Meth. B **266**, 4478 (2008).
15. O. O. Versolato et. al., Phys. Rev. A **82**, 010501 (2010).
16. G. S. Giri et al., Phys. Rev. A , **84**, 020503(R) (2011).
17. O. O. Versolato et al., Phys. Lett. A **375**, 31303133 (2011).
18. K. Wendt et al., Z. Phys. D **4**, 227 (1987).
19. R. Pal et al., Phys. Rev. A **79**, 062505 (2009).
20. S. G. Porsev et al., Phys. Rev. Lett. **102**, 181601 (2009).
21. T. H. Dinh et al., Phys. Rev. A **80**, 044502 (2009).
22. V. A. Dzuba et al., Phys. Rev. A **83**, 052513 (2011).
23. B. K. Sahoo et al., Phys. Rev. A **76**, 040504(R) (2007).
24. L.W. Wansbeek et al., Phys. Rev. C **86**, 015503 (2012).
25. O. O. Versolato et al., Phys. Rev. A **83**, 043829 (2011).