Radium Ion Spectroscopy

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Chapter 3

Measuring Parity Violation in a Trapped Ion

3.1 Heavy Alkaline-earth Ions: Ba^+ and Ra^+

Laser spectroscopy has evolved to be a very powerful technique to determine atomic and nuclear properties of an element including but not limited to the information on the electron shell, the lifetime of excited atomic levels, the nuclear spin, the charge distribution, and the electric/magnetic multipole moment of nuclei. A better knowledge of these properties is essential for a better understanding of the atomic and nuclear structures. For example, hyperfine structures and isotope shifts depend on atomic and nuclear properties respectively. The hyperfine structure intervals enable one to understand the atomic wave functions better. Similarly the isotope shifts enable one to understand the shape and size of atomic nuclei.

Towards a competitive APV experiment, all the atomic and nuclear properties need to be determined for the atomic system of interest in order to extract the small contributions from parity violating weak effects to the atomic structure. The singly charged radium ion (Ra^+) has been identified as an ideal system. However, an extensive study of this system through laser spectroscopy is indispensable to determine the missing atomic and nuclear properties. Since radium is scarce, precious, radioactive and is known to have no stable isotope, it is impossible to investigate them on a daily basis. Hence we developed the experiment with singly charged barium ions (Ba^+), which are chemically homologous to Ra^+ (Table 3.1). Though Ba^+ is a well understood system, very limited spectroscopic information about Ra^+ is available in the literature. In this section, we give an overview of

Table 3.1: Atomic properties of the ionic heavy alkaline-earth elements Ba^+ and Ra^+.

Atomic Property	Ba^+	Ra^+
Atomic number	56	88
Melting point (K)	1000	1196
Electronic configuration	[Xe]$6s^1$	[Rn]$7s^1$
Ground state	$6s\ ^2S_{1/2}$	$7s\ ^2S_{1/2}$
Most abundant isotope	^{138}Ba (71.7%)	^{226}Ra (90%)
Nuclear spin	Even: 0, Odd: 1/2, 3/2	Even: 0, Odd: Many
Number of stable isotopes	7	None[a]

[a]The longest lived radium isotope with $I \neq 0$ is ^{225}Ra (I=1/2) and the lifetime is 14.9(2) days. The longest lived radium isotope with I=0 is ^{226}Ra and the lifetime is 1600(7) years.

the known properties of the Ra^+ system and we discuss the informations needed for measuring parity violation in this system.

3.1.1 Atomic Properties of Ra^+

The radioactive element radium was discovered by M. Curie in 1898 and subsequently many short-lived isotopes of radium were found. Ra^+ is an alkaline earth ion. Its atomic number is 88 and the electronic configuration is [Rn] $7s^1$. It is a single valence electron system and the ground state LS configuration is $7s\ ^2S_{1/2}$. Radium has an important role in the understanding of the physics of radioactivity. The activity of one gram of ^{226}Ra is defined as the unit of radioactivity (Ci). The important physical properties of radium are listed in Table 3.1.

Four decades after the discovery of radium, E. Rasmussen in 1933 was the first to perform arc emission spectroscopy of radium atoms [77] and radium ions [76] using a discharge lamp and a grating monochromator. A total of 62 transitions were identified in radium ions [76]. The lines were recorded on a photographic film and the level structure was extracted. These measurements together with the measurements for radium atoms [77,78] confirmed the identification of radium as an alkaline-earth element. The level structure of Ra^+ is shown in Fig. 3.1.

After a long gap of about 50 years, laser spectroscopy of Ra^+ was resumed at the ISOLDE facility of CERN. Radioactive radium isotopes with half life

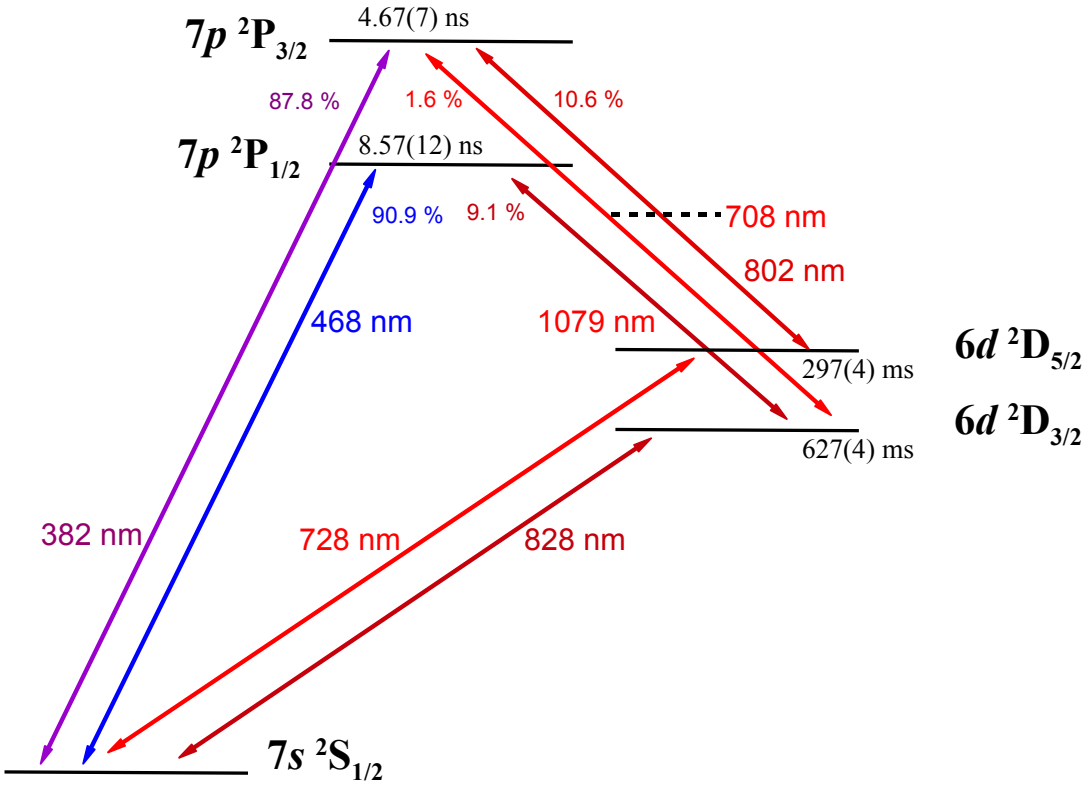

Fig. 3.1: Level diagram of Ra^+. Calculated lifetimes and branching ratios are taken from [75]. Wavelengths are taken from [76].

between 23 ms and 1600 y were produced. On-line collinear fast-beam laser spectroscopy was performed on the strong ionic $7s\ ^2S_{1/2}$ - $7p\ ^2P_{1/2}$ transition to measure the hyperfine structures and isotope shifts in a series of radium isotopes in the mass range of $208 \leq A \leq 232$ [79]. These measurements enabled the determination of nuclear spins, magnetic dipole moments, and electric quadrupole moments of those isotopes [79, 80]. Later on, the hyperfine structure and isotope shift measurements were continued for the $7s\ ^2S_{1/2}$ - $7p\ ^2P_{3/2}$ transition [81]. From these measurements the mean square charge radii were extracted [82]. A direct measurement of nuclear magnetic moments of ^{213}Ra and ^{225}Ra was also performed [83].

Due to the unique atomic and nuclear properties, radium isotopes are considered as promising candidates for several high precision experiments. This is the motivation for performing high precision calculations of the necessary atomic wave functions in this system, because precise calculations of many atomic properties such as hyperfine structure, transition rates, excited state lifetimes etc, have a strong dependence on the knowledge of atomic wave functions. The rel-

Table 3.3: Barium isotopes with their nuclear spins, atomic masses, isotopic abundances, and lifetimes [86].

Isotope	Spin	Mass (amu)	Abundance (%)	Lifetime
^{130}Ba	0	129.906282	0.11	Stable
^{132}Ba	0	131.905042	0.10	Stable
^{133}Ba	1/2	132.906008	-	10.5 y
^{134}Ba	0	133.904486	2.42	Stable
^{135}Ba	3/2	134.905665	6.59	Stable
^{136}Ba	0	135.904553	7.85	Stable
^{137}Ba	3/2	136.905812	11.23	Stable
^{138}Ba	0	137.905232	71.70	Stable

ativistic nature of this system makes the calculation challenging. The results of such calculations have serious impact on the interpretation of experimental results and also on the evaluation of sensitivity to symmetry breaking effects. On the other hand, highly precise experimental determination of these quantities provide reliable input for atomic structure calculations.

Several atomic properties such as the transition rates, hyperfine structures, isotope shifts, excited state lifetimes and branching ratios of several states etc. have been calculated by several groups using different theoretical approaches [25, 26, 65, 75, 84, 85]. The calculated results have very little physical significance until they undergo experimental verification. Any possible discrepancy will require physical explanation and further investigation.

3.1.2 Atomic Properties of Ba^+

Barium was discovered by H. Davy in 1808. Ba^+ is also an alkaline earth ion. Its atomic number is 56 and the electronic configuration is [Xe] $6s^1$. It is a single valence electron system and the ground state LS configuration is $6s\ ^2S_{1/2}$. The level structure of Ba^+ is shown in Fig. 3.2.

Ba^+ has a similar atomic structure as Ra^+. Hence we use Ba^+ as a precursor to develop the necessary experimental tools and the laser spectroscopic techniques which we can apply to Ra^+. Barium has seven stable isotopes and they are readily available in nature. All the stable barium isotopes with their isotopic abundances are listed in Table 3.3. Ba^+ is a well understood system and a large

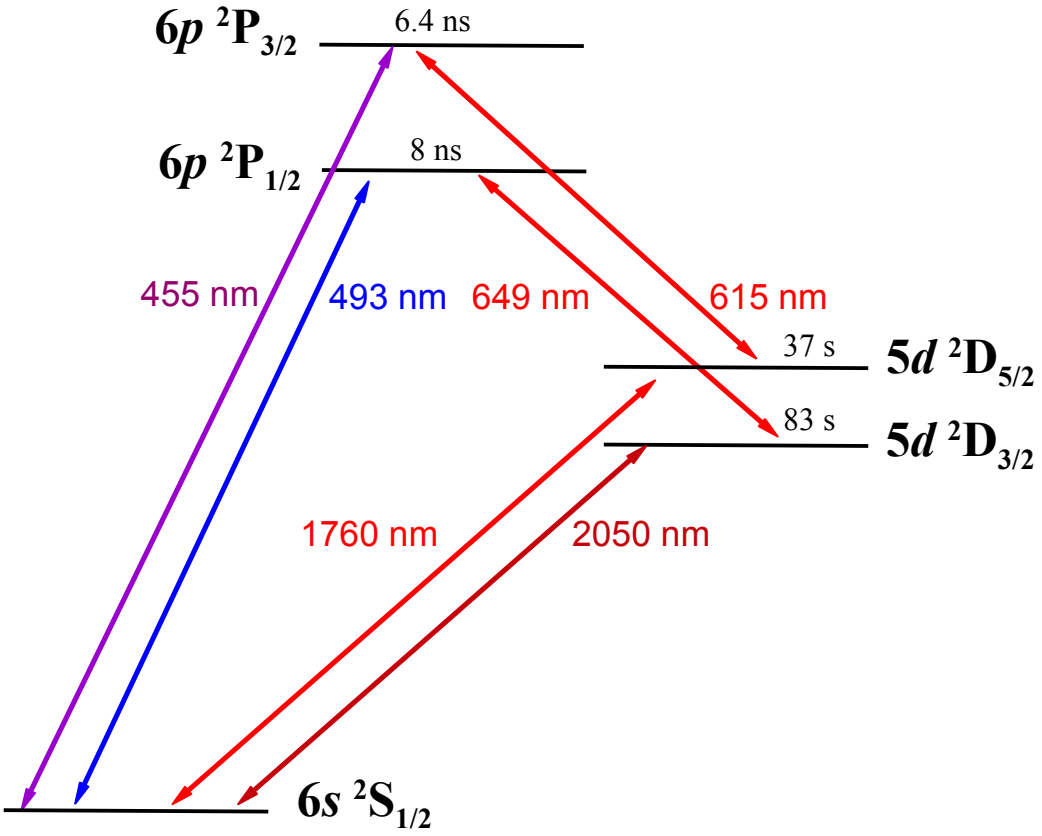

Fig. 3.2: Level diagram of Ba^+. Wavelengths and lifetimes are taken from [32, 44–46, 52, 87]

pool of experimental data is readily available in the literature. This enables us to understand the theoretical and experimental aspects on the trapping and cooling of Ra^+.

3.2 Ra^+: An Ideal Candidate for APV Experiment

A novel experimental method to measure atomic parity violation in a single trapped ion was proposed by E.N. Fortson [31]. Crucial steps have been taken and certain proof-of-principles have been demonstrated towards a single ion parity violation experiment using a single ^{138}Ba ion [44, 52]. This concept can be extended to Ra^+.

A high precision APV experiment is not self sufficient for a precise extraction

of weak nuclear charge. The interpretation of experimental data requires a precise atomic theory. The existing *ab initio* methods in atomic theory to calculate atomic wave functions require experimental input to assess the accuracy of these methods. A heavy atomic system with a single valence electron is preferred for which the atomic wave function is comparatively easier to calculate and the APV signal would be bigger because of the Z^3 law [43]. The heaviest alkali systems like cesium atom (Z=55) and francium atom (Z=87) or the heaviest earth-alkali systems like Ba^+(Z=56) and Ra^+(Z=88) meet these requirements. Recently Yb^+ (Z=70) has been chosen as a potential candidate for a similar experiment [88]. But Ra^+ is the heaviest among others and hence it is expected to have comparatively larger parity violation. The relevant parity violating $7s\ ^2S_{1/2}$ - $6d\ ^2D_{3/2}$ amplitude is expected to be about a factor of 20 and 50 larger in Ra^+ than that in Ba^+ and Cs respectively [26, 65, 88], resulting in less stringent requirements for the theory while the statistical sensitivity would be larger. About 1 hour of data collection can lead to a statistical resolution of 1 Hz and about 10 days of data collection can lead to a 5 fold improvement of over the cesium result. Moreover, all the relevant transitions which are useful for probing parity violation in Ra^+ are in the visible or near infrared regime and hence they are accessible by commercial semiconductor diode lasers with narrow linewidth, which is certainly advantageous compared to Ba^+ (*cf.* Figs. 3.1 and 3.2). Being a heavy element, Ra^+ can be confined to a comparatively smaller trapping volume than Ba^+, since the Lamb-Dicke parameter is inversely proportional to the square root of mass of the ion. This will lead to the reduction of systematic uncertainties due to stray electric fields. Also the relative statistical uncertainty for Ra^+ is expected to be smaller compared to Ba^+. Thus, Ra^+ seems to be the superior candidate for a competitive parity violation experiment.

3.3 Signature of Parity Violation in Ra^+

A determination of the weak charge requires a robust and strong experimental signature. Here we discuss how atomic parity violation manifests itself in Ra^+. The exchange of Z^0 bosons between the electron and the quarks of an ion results in a mixing of the opposite parity states. The magnitude of mixing is maximum for S and P states.

In case of Ra^+, the $7s\ ^2S_{1/2}$ state gets a tiny admixture from the $np\ ^2P_{1/2}$ states

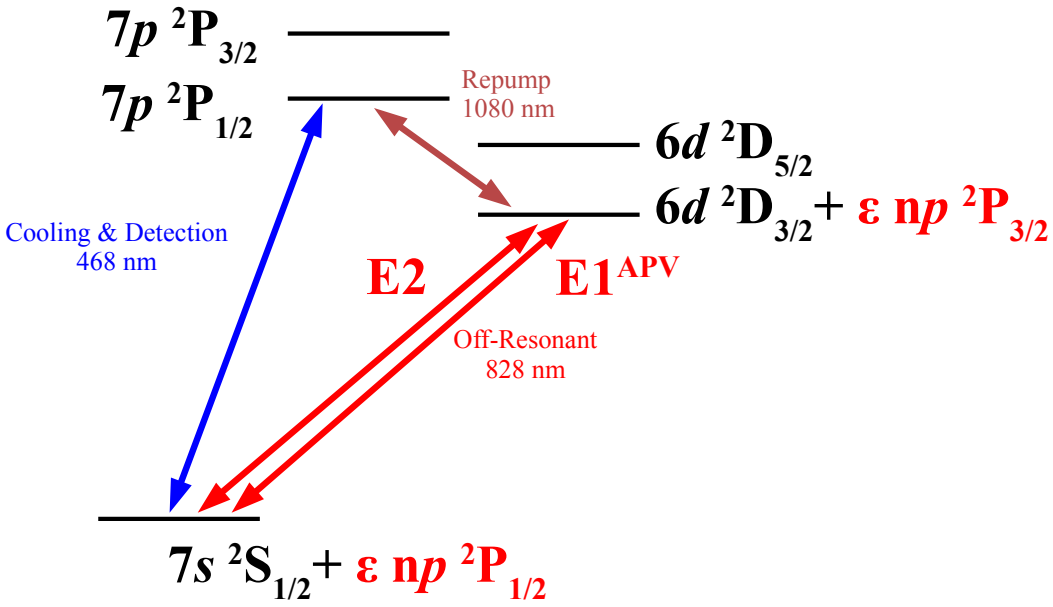

Fig. 3.3: Level diagram of Ra^+ with emphasis given to the admixture of P states with the low lying S and D states.

and no longer remains in a state of definite parity,

$$| 7s\ ^2\tilde{S}_{1/2}\rangle = | 7s\ ^2S_{1/2}\rangle + \varepsilon\ | np\ ^2P_{1/2}\rangle \tag{3.1}$$

$$= | 7s\ ^2S_{1/2}\rangle + \sum_n | np\ ^2P_{1/2}\rangle \frac{\langle np\ ^2P_{1/2} \mid H_W \mid 7s\ ^2S_{1/2}\rangle}{E_{7s\ ^2S_{1/2}} - E_{np\ ^2P_{1/2}}}, \tag{3.2}$$

and the $6d\ ^2D_{3/2}$ state also gets a tiny admixture from the $np\ ^2P_{3/2}$ states,

$$| 6d\ ^2\tilde{D}_{3/2}\rangle = | 6d\ ^2D_{3/2}\rangle + \varepsilon\ | np\ ^2P_{3/2}\rangle \tag{3.3}$$

$$= | 6d\ ^2D_{3/2}\rangle + \sum_n | np\ ^2P_{3/2}\rangle \frac{\langle np\ ^2P_{3/2} \mid H_W \mid 6d\ ^2D_{3/2}\rangle}{E_{6d\ ^2D_{3/2}} - E_{np\ ^2P_{3/2}}}, \tag{3.4}$$

where the Weak Hamiltonian H_W is given by,

$$H_W = Q_W \times \frac{G_F}{\sqrt{8}} \gamma_5 \rho_n(r). \tag{3.5}$$

An electric quadrupole transition (E2) between the $7s\ ^2S_{1/2}$ and the $6d\ ^2D_{3/2}$ states is allowed by the parity selection rule. But the admixture from P states makes a small dipole transition (E1) possible between these energy eigenstates which is otherwise forbidden by the parity selection rule. The strength of the parity

violating E1 amplitude is given by,

$$E1^{APV} = \langle 7s\ ^2\tilde{S}_{1/2} \mid D \mid 6d\ ^2\tilde{D}_{3/2}\rangle \tag{3.6}$$

$$= \sum_n \frac{\langle 7s\ ^2S_{1/2} \mid H_W \mid np\ ^2P_{1/2}\rangle\langle np\ ^2P_{1/2} \mid D \mid 6d\ ^2D_{3/2}\rangle}{E_{7s\ ^2S_{1/2}} - E_{np\ ^2P_{1/2}}} \tag{3.7}$$

$$+ \sum_n \frac{\langle 7s\ ^2S_{1/2} \mid D \mid np\ ^2P_{3/2}\rangle\langle np\ ^2P_{3/2} \mid H_W \mid 6d\ ^2D_{3/2}\rangle}{E_{6d\ ^2D_{3/2}} - E_{np\ ^2P_{3/2}}}. \tag{3.8}$$

Substitution of the weak Hamiltonian from Eq. 3.5 gives,

$$E1^{APV} = Q_W \times \frac{G_F}{\sqrt{8}} \sum_n \frac{\langle 7s\ ^2S_{1/2} \mid \gamma_5\rho_n(r) \mid np\ ^2P_{1/2}\rangle\langle np\ ^2P_{1/2} \mid D \mid 6d\ ^2D_{3/2}\rangle}{E_{7s\ ^2S_{1/2}} - E_{np\ ^2P_{1/2}}} \tag{3.9}$$

$$+ Q_W \times \frac{G_F}{\sqrt{8}} \sum_n \frac{\langle 7s\ ^2S_{1/2} \mid D \mid np\ ^2P_{3/2}\rangle\langle np\ ^2P_{3/2} \mid \gamma_5\rho_n(r) \mid 6d\ ^2D_{3/2}\rangle}{E_{6d\ ^2D_{3/2}} - E_{np\ ^2P_{3/2}}} \tag{3.10}$$

$$= Q_W \times k. \tag{3.11}$$

While $E1^{APV}$ can be experimentally measured, k arises from theoretical calculations using atomic theory. A detailed treatment on the calculation can be found in [89]. Since $E1^{APV}$ is extremely small, it must be measured using an indirect approach. The interference between the parity conserving E2 amplitude and the parity violating E1 amplitude leads to a measurable signal which can be observed as a small shift of the two ground state Zeeman sub-levels. This shift is a vector like AC Stark shift or differential light shift. From the differential light shift the parity violating E1 amplitude can be distinguished from the electromagnetic contribution, and the weak charge Q_W for the ion can be inferred.

In conlusion, Ra^+ is a sensitive system for probing parity violation. The sensitivity to parity violating weak interaction effects in this system is 50 times larger than that in cesium where the best such experiment was performed till date. Ra^+ is preferred over all other possible candidates based on the theoretical and experimental requirements for extracting the weak charge from a parity violation experiment. Spectroscopic information on hyperfine structures, isotope shifts and lifetimes in this system can yield the E1 and E2 matrix elements which are necessary for a parity violation measurement. Such information is scarce in literature. Hence an extensive study of this system through laser spectroscopy is indispensable.