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Radium Ion Spectroscopy

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Chapter 7

Summary of Results and Conclusion

Here we present a list of achievements and a compilation of final results achieved in the laser spectroscopy of Ra^+. This provides an indispensable ground work towards a high precision atomic parity violation experiment in this system.

- We have set up a dedicated laboratory to investigate trapping and cooling of Ba^+ which is indispensable for the work towards Ra^+. Several ion traps have been built, commissioned, and tested. Laser systems necessary for Ba^+ spectroscopy have been set up in this laboratory. Ba^+ ions have been gas cooled and trapped as a cloud. Trapping and laser cooling of a single Ba^+ ion is underway.

- A low energy beam line consisting of an electrostatic mirror, a drift tube, several lenses, several steering plates, and a linear Paul trap has been built and successfully commissioned to investigate trapping and cooling of Ra^+. Several commissioning measurement have been performed to test the integrity of this apparatus. Such measurements enable to draw conclusions about possible future upgrades in order to optimize the functionality of various parts of the apparatus.

- An independent data acquisition system has been set up for the experiment. This is an essential requirement for the online Ra^+ experiment followed by offline analysis of the experimental data.

- An isotopic chain of radium isotopes with different nuclear spins has been produced using the AGOR cyclotron and the TRIμP facility. A rotating target wheel has been developed to enhance the lifetime of the production target. The produced isotopes were thermalized and ionized to Ra$^+$ using a thermal ionizer and were extracted as a singly charged Ra$^+$ ion beam which was mass separated by a Wien filter system. The Ra$^+$ ion species were quantitatively characterized with a calibrated silicon detector. The results of radium production are listed in Table 7.1. The amount of radium ions produced are sufficient to carry out further experiments with their trapping and spectroscopy.

Table 7.1: An isotopic chain of radium isotopes was produced by shooting a $^{204/206}$Pb beam on a ^{12}C target.

Isotope	I	$T_{1/2}$ (s)	Nuclear Reaction	Beam Energy (MeV/u)	Production Rate (ions/s)
^{209}Ra$^+$	5/2	4.6(1.5)	^{204}Pb^{28+}+^{12}C	10.3	200
^{210}Ra$^+$	0	3.66(18)	^{204}Pb^{28+}+^{12}C	10.3	500
^{211}Ra$^+$	5/2	12.61(5)	^{204}Pb^{28+}+^{12}C	10.3	1000
^{212}Ra$^+$	0	12.5(1.0)	^{206}Pb^{27+}+^{12}C	8.5	800
^{213}Ra$^+$	1/2	162.0(1.7)	^{206}Pb^{27+}+^{12}C	8.5	2600
^{214}Ra$^+$	0	2.42(14)	^{206}Pb^{27+}+^{12}C	8.5	1000

- The Ra$^+$ ion beam was injected into a gas-filled radio frequency quadrupole operated in trapping mode. Transverse cooling and trapping of ions were realized here. Laser spectroscopy was performed on the trapped ion cloud which yielded new and high quality spectroscopic information on hyperfine structures, isotope shifts, and lifetime. Such results are important input to test the accuracy of atomic theory which is indispensable for the planned parity violation experiment. The results of the precision spectroscopy measurements are listed in Table 7.2 and 7.3. The relevant level schemes are displayed in Fig. 7.1 which are supplementary to the results presented.

- For laser cooling of Ra$^+$, the Ra$^+$ ion beam from thermal ionizer was transported to a linear Paul trap via the newly commissioned low energy beam line and trapping of Ra$^+$ in a buffer gas free environment was investigated.

- In conlusion, this work provides indispensable building blocks for a parity violation measurement in single trapped radium ion.

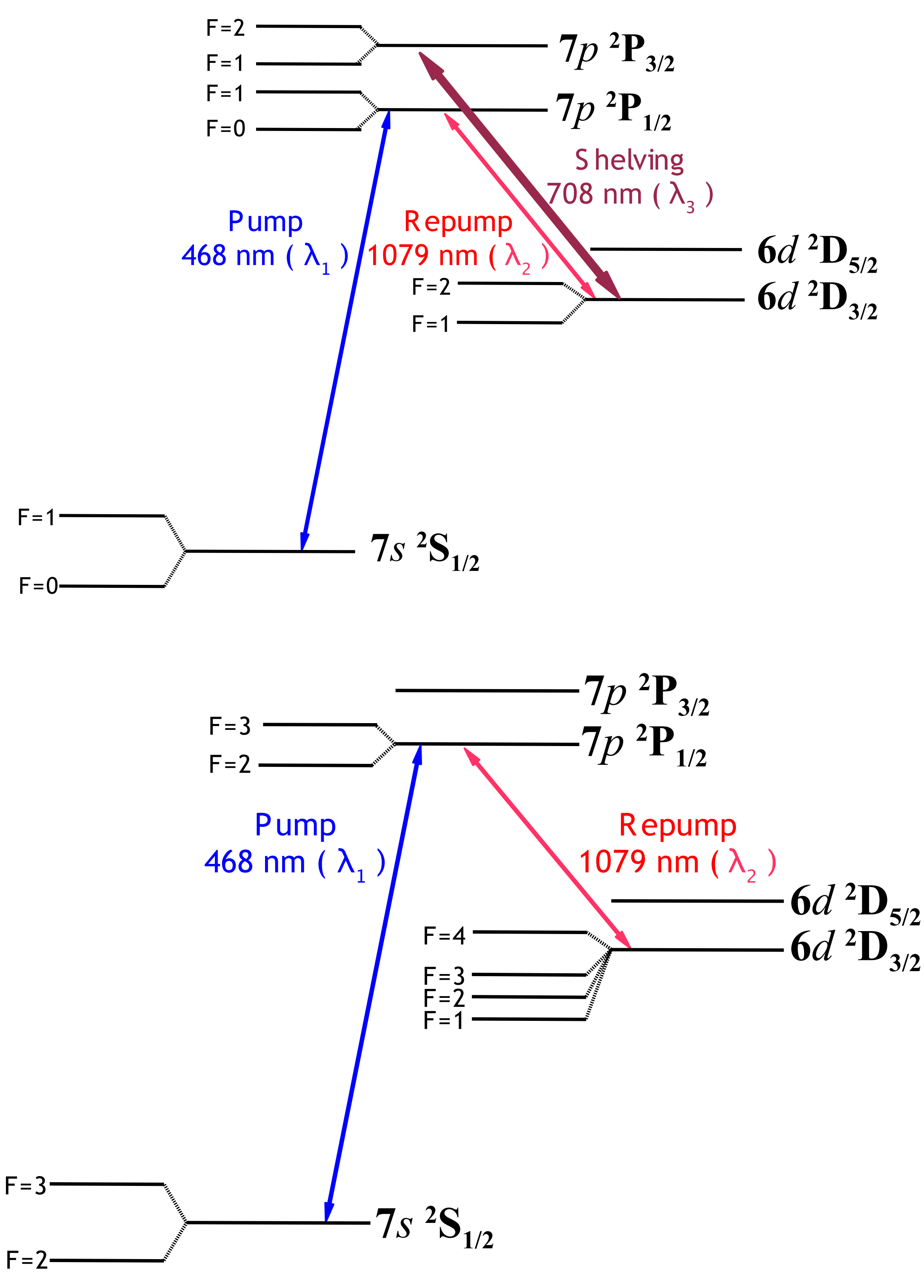

Fig. 7.1: Level schemes of odd isotopes with hyperfine structures. The upper figure corresponds to ^{213}Ra^{+} (I=1/2) and the lower figure corresponds to ^{209,211}Ra^{+} (I=5/2).

Table 7.2: Newly obtained results of hyperfine structure from precision laser spectroscopy of trapped radium ions. The hyperfine structure constants A and B for the odd isotopes were extracted for the $6d\ ^2D_{3/2}$ states. The measured hyperfine structure interval of the $7p\ ^2P_{1/2}$ state is in good agreement with a previous measurement [79].

Isotope	Nuclear Spin	Hyperfine Structure Constants (MHz)			Hyperfine Structure Interval (MHz)			
		$A(6d\ ^2D_{3/2})$	$B(6d\ ^2D_{3/2})$	$A(7p\ ^2P_{1/2})$	$6d\ ^2D_{3/2}$			$7p\ ^2P_{1/2}$
					F=4−F=3	F=3−F=2	F=2−F=1	F=1−F=0
^{209}Ra$^+$	5/2	148(10)	104(38)	-	673(28)	396(49)	-	-
^{211}Ra$^+$	5/2	151(2)	103(6)	-	687(9)	407(7)	-	-
^{213}Ra$^+$	1/2	528(5)	-	4542(7)	-	-	1055(10)	4542(7)

Table 7.3: Newly obtained results of isotope shift and lifetime from precision laser spectroscopy of trapped radium ions. The isotope shifts of the $6d\ ^2D_{3/2}$ - $7p\ ^2P_{1/2}$ and $6d\ ^2D_{3/2}$ - $7p\ ^2P_{3/2}$ transitions were determined with respect to ^{214}Ra$^+$. Lifetime of $6d\ ^2D_{5/2}$ state was measured only for ^{212}Ra$^+$.

Isotope	Isotope Shifts (MHz)		Absolute Frequency (MHz)		Lifetime (ms)
	$6d\ ^2D_{3/2}$ - $7p\ ^2P_{1/2}$	$6d\ ^2D_{3/2}$ - $7p\ ^2P_{3/2}$	$6d\ ^2D_{3/2}$ - $7p\ ^2P_{1/2}$	$6d\ ^2D_{3/2}$ - $7p\ ^2P_{3/2}$	$6d\ ^2D_{5/2}$
^{209}Ra$^+$	2645(56)	-	277,803,011(55)	-	-
^{210}Ra$^+$	1884(16)	-	277,803,772(11)	-	-
^{211}Ra$^+$	1755(14)	-	277,803,901(9)	-	-
^{212}Ra$^+$	1025(12)	707(50)	277,804,631(5)	423,434,288(44)	232
^{213}Ra$^+$	707(14)	453(34)	277,804,949(9)	423,434,536(25)	-
^{214}Ra$^+$	0	0	277,805,656(11)	423,434,989(23)	-