

University of Groningen

Radium Ion Spectroscopy

Giri, Gouri Shankar

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version

Publisher's PDF, also known as Version of record

Publication date:

2011

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Giri, G. S. (2011). *Radium Ion Spectroscopy: Towards Atomic Parity Violation in a single trapped Ion*. [Thesis fully internal (DIV), University of Groningen]. s.n.

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

**Radium Ion Spectroscopy
Towards Atomic Parity Violation
in a Single Trapped Ion**

To My Parents

COVER: First ever optical signal of trapped radium ions in a radiofrequency quadrupole trap. This is the fluorescence light at 468 nm which is collected from the trapped $^{212}\text{Ra}^+$ cloud and imaged onto a photomultiplier tube.

This work has been performed as part of the research program of the “Stichting voor Fundamenteel Onderzoek der Materie” (FOM) through programme 114 (TRI μ P), which is financially supported by the “Nederlandse Organisatie voor Wetenschappelijk Onderzoek” (NWO). Additional funding was provided by the European Commission under contract HPRI-CT-2001-50034 (NIPNET) and HPRI-CT-2001-50022 (Ion Catcher).

Druk: Facilitair Bedrijf, University of Groningen, Groningen, August 2011

RIJKSUNIVERSITEIT GRONINGEN

**Radium Ion Spectroscopy
Towards Atomic Parity Violation
in a Single Trapped Ion**

Proefschrift

ter verkrijging van het doctoraat in de
Wiskunde en Natuurwetenschappen
aan de Rijksuniversiteit Groningen
op gezag van de
Rector Magnificus, dr. E. Sterken,
in het openbaar te verdedigen op
maandag 3 oktober 2011
om 16.15 uur

door

Gouri Shankar Giri

geboren op 16 mei 1981
te Nalagaja, India

Promotor: Prof. dr. K. H. K. J. Jungmann

Copromotor: Dr. L. Willmann

Beoordelingscommissie: Prof. dr. R. Morgenstern

Prof. dr. B. P. Das

Prof. dr. G. zu Putlitz

ISBN: 978-90-367-5058-5 (Printed Version)

ISBN: 978-90-367-5057-8 (Digital Version)

Contents

1	Introduction	1
1.1	The Standard Model and its Limits	1
1.2	Outline of the Thesis	2
2	Atomic Parity Violation and Standard Model	7
2.1	Parity Violation	7
2.1.1	The Discrete Symmetries	7
2.1.2	History of Parity Violation	8
2.1.3	Electroweak Unification	9
2.1.4	Experiments Worldwide	11
2.2	Parity Violation Experiments	14
2.2.1	Parity Violation in Atomic Systems	14
2.2.2	APV: Low Energy Test of the SM	16
2.2.3	Principle of APV Experiments	17
3	Measuring Parity Violation in a Trapped Ion	19
3.1	Heavy Alkaline-earth Ions: Ba ⁺ and Ra ⁺	19
3.1.1	Atomic Properties of Ra ⁺	20
3.1.2	Atomic Properties of Ba ⁺	22
3.2	Ra ⁺ : An Ideal Candidate for APV Experiment	23
3.3	Signature of Parity Violation in Ra ⁺	24
4	Experimental Methods and Tools	27
4.1	Radium Isotope Production	27
4.1.1	The AGOR Cyclotron and Ra Production Target Station	28
4.1.2	Double Magnetic Separator	29
4.1.3	Thermal Ionizer	32
4.1.4	Wien Filter	34

4.1.5	Results of Radium Production Experiments	35
4.2	Radium Ion Trapping and Spectroscopy	40
4.2.1	Trapping in a Radio Frequency Quadrupole	40
4.2.2	Spectroscopy of Trapped Radium in RFQ	42
4.2.3	Trapping and Spectroscopy in a Linear Paul Trap	43
4.3	Lasers	49
4.3.1	Lasers for Ra^+	49
4.3.2	Lasers for Ba^+	52
4.3.3	Overlap of Beams and Measurement of Spot Size	53
4.4	Spectroscopy	54
4.4.1	Absolute and Relative Frequency Calibration	54
4.4.2	Imaging System and Optical Detection	57
4.5	Computer Control and Data Acquisition	58
5	Spectroscopy of Short-Lived Radium Isotopes in an Ion Trap	59
5.1	Hyperfine Structure Interval of $6d\ ^2D_{3/2}$ State	59
5.2	Isotope Shifts	64
5.2.1	Isotope Shifts of $6d\ ^2D_{3/2} - 7p\ ^2P_{1/2}$ Transition	65
5.2.2	Isotope Shifts of $6d\ ^2D_{3/2} - 7p\ ^2P_{3/2}$ Transition	67
5.2.3	Data Analysis and Results	69
5.3	Lifetime of Metastable $6d\ ^2D_{5/2}$ State	73
5.4	Conclusion	74
6	Towards Single Ion Parity Violation Measurement	77
6.1	Coupling of States	77
6.2	The AC Stark Shift	80
6.3	A Discussion of Original Proposal	81
6.3.1	The Principle of Measuring the AC Stark Shift	81
6.3.2	Radio Frequency Spectroscopy	83
6.4	Future Directions	85
7	Summary of Results and Conclusion	89
8	Samenvatting van de Resultaten en Conclusies	93

Appendices

A Discussion of Ion Trapping	97
A.1 Paul Trap	97
A.2 Stability of Ions in a Trap	100
A.3 Macromotion and Micromotion	101
B Discussion of Hyperfine Structure	105
B.1 Hyperfine Structure Interval	105
B.2 Spins and Electromagnetic Multipole Moments	105
B.3 The Hyperfine Interaction	106
B.3.1 Magnetic Dipole Interaction	106
B.3.2 Electric Quadrupole Interaction	107
C Discussion of Isotope Shift	109
C.1 Isotope Shift	109
C.2 Mass Effect	110
C.3 Field Effect	111
D Settings of the LEBL	115
Bibliography	117
List of Publications	129
Acknowledgment	131

List of Figures

1.1	TRI μ P facility concept	3
1.2	Layout of this thesis	4
1.3	Level structure of Ra ⁺ relevant for APV experiment	6
2.1	Interference of weak and electromagnetic interaction	10
2.2	The running of the γ -Z ⁰ mixing angle	12
2.3	Feynman diagrams depicting atomic parity violation	14
3.1	Level scheme of Ra ⁺	21
3.2	Level scheme of Ba ⁺	23
3.3	Level structure of Ra ⁺ showing mixing of states	25
4.1	Operating diagram of AGOR cyclotron	28
4.2	Cross section for ²⁰⁴ Pb beam and ¹² C target vs. beam energy	30
4.3	Cross section for ²⁰⁶ Pb beam and ¹² C target vs. beam energy	30
4.4	Pyrolytic graphite target mounted on a rotating wheel	31
4.5	Schematic diagram of TRI μ P separator	32
4.6	Schematic diagram of TRI μ P thermal ionizer	33
4.7	Electrostatic extraction from the thermal ionizer	34
4.8	Characteristic α -energy spectrum of Ra ⁺	36
4.9	Activity for extraction and primary beam on/off measurements	38
4.10	Measured half lives from extraction on/off measurements	39
4.11	Extraction on/off measurements for lighter isotopes	40
4.12	Schematic diagram of TRI μ P RFQ	41
4.13	Trapping region of TRI μ P RFQ	41
4.14	$6d\ ^2D_{3/2} - 7p\ ^2P_{1/2}$ transition in Ba ⁺	43
4.15	Schematic diagram of low energy beam line	45
4.16	Pulsing sequence of drift tubes	46

4.17	Schematic diagram of linear Paul trap	47
4.18	Alignment of beam line by scanning the voltages	48
4.19	Performance curve of the electrostatic mirror	48
4.20	Mechanical set up of diode lasers in Littrow configuration	51
4.21	Optical layout for trapping and laser spectroscopy	54
4.22	Principle behind frequency calibration	55
4.23	Tellurium absorption signal	56
4.24	Imaging system and optical detection	57
5.1	Level schemes of odd isotopes with hyperfine structure	60
5.2	HFS intervals of $6d\ ^2D_{3/2}$ and $7p\ ^2P_{1/2}$ states in $^{213}\text{Ra}^+$	61
5.3	Hyperfine structure intervals of the $6d\ ^2D_{3/2}$ states in $^{209,211}\text{Ra}^+$	62
5.4	Isotope shift of $6d\ ^2D_{3/2} - 7p\ ^2P_{1/2}$ transition in $^{210,212,214}\text{Ra}^+$	65
5.5	Isotope shift of $6d\ ^2D_{3/2} - 7p\ ^2P_{1/2}$ transition in $^{213}\text{Ra}^+$	66
5.6	Isotope shift of $6d\ ^2D_{3/2} - 7p\ ^2P_{1/2}$ transition in $^{209,211}\text{Ra}^+$	66
5.7	Level scheme of $^{213}\text{Ra}^+$ showing a shelving transition	67
5.8	Isotope shift of $6d\ ^2D_{3/2} - 7p\ ^2P_{3/2}$ transition in $^{212,213,214}\text{Ra}^+$	68
5.9	King plot of the 1079 nm line in Ra^+	72
5.10	King plot of the 708 nm line in Ra^+	72
5.11	Lifetime of $6d\ ^2D_{5/2}$ state in $^{212}\text{Ra}^+$	73
5.12	Lifetime of $6d\ ^2D_{5/2}$ state in $^{212}\text{Ra}^+$ at different gas pressures	74
6.1	Two level coupling diagram	78
6.2	Illustration of Stark shift on a two level system.	80
6.3	Principle of light shift measurement	82
6.4	Principle of RF Spectroscopy	83
6.5	Light shift in the $6s\ ^2S_{1/2}$ Zeeman sub-levels in Ba^+	85
6.6	$^{212}\text{Ra}^+$ in a linear Paul trap	86
6.7	An ion trap to confine a single ion	87
7.1	Level schemes of odd isotopes with hyperfine structure	91
8.1	Energieniveaus van oneven isotopen met hyperfijnstructuur	95
A.1	Mechanical model of dynamic stability	98
A.2	Electrode structure for a two dimensional quadrupole trap	99
A.3	Mathieu stability diagrams	101
A.4	Mathieu stability diagram in three dimensional trap	103

List of Tables

2.1	APV experiments from high energy to low energy scales	13
3.1	Atomic properties of barium and radium	20
3.3	Barium isotopes and their atomic properties	22
4.1	Half lives and production rates for $^{212-214}\text{Ra}$	37
4.2	Half lives for $^{209-211}\text{Ra}$ isotopes	37
4.3	A list of the necessary laser systems for Ba^+ and Ra^+	50
5.1	HFS constants $A(6d\ ^2D_{3/2})$ and $A(7p\ ^2P_{1/2})$ of $^{213}\text{Ra}^+$	63
5.2	HFS constants $A(6d\ ^2D_{3/2})$ and $B(6d\ ^2D_{3/2})$ of $^{209,211}\text{Ra}^+$	64
5.3	Hyperfine structure intervals of the $6d\ ^2D_{3/2}$ state in $^{209,211,213}\text{Ra}^+$	64
5.4	Isotope shifts of $6d\ ^2D_{3/2} - 7p\ ^2P_{1/2}$ transition in $^{209-214}\text{Ra}^+$	70
5.5	Isotope shifts of $6d\ ^2D_{3/2} - 7p\ ^2P_{3/2}$ transition in $^{212-214}\text{Ra}^+$	71
7.1	Results of radium isotope production	90
7.2	Results of hyperfine structure from radium ion spectroscopy	92
7.3	Results of isotopes shift from radium ion spectroscopy	92
8.1	Resultaten van de productie van radiumisotopen	94
8.2	Resultaten van de hyperfijnstructuurmetingen aan radiumionen	96
8.3	Resultaten van de metingen van isotoopverschuivingen aan radiumionen	96
D.1	Settings of the low energy beam line	115

