

Contents

1	Precise Matter and Antimatter Tests of the Standard	
	Model with e^-, e^+, p, \bar{p} and \bar{H}	1
	G. Gabrielse, S. Fogwell Hoogerheide, J. Dorr and E. Novitski	
1.1	Overview Summary	1
1.2	Magnetic Moments	6
1.3	One-Electron Quantum Cyclotron	9
1.3.1	A Homemade Atom	9
1.3.2	Cylindrical Penning Trap Cavity	11
1.3.3	100 mK and 5 T	14
1.3.4	Stabilizing the Energy Levels	15
1.3.5	Motions and Damping of the Suspended Electron	17
1.4	Non-destructive Detection of One-Quantum Transitions	17
1.4.1	QND Detection	17
1.4.2	One-Electron Self-Excited Oscillator	19
1.4.3	Inhibited Spontaneous Emission	20
1.5	Elements of a Electron $g/2$ Measurement	22
1.5.1	Quantum Jump Spectroscopy	22
1.5.2	The Electron as Magnetometer	24
1.5.3	Measuring the Axial Frequency	24
1.5.4	Frequencies from Lineshapes	25
1.5.5	Cavity Shifts	26
1.6	Results and Applications	28
1.6.1	Most Accurate Electron $g/2$	28
1.6.2	Most Accurate Determination of α	30
1.6.3	Testing the Standard Model and QED	32
1.6.4	Probe for Electron Substructure	35
1.6.5	Comparison to the Muon $g/2$	35
1.7	Prospects and Conclusion	36
	References	37

2	Theory of Anomalous Magnetic Dipole Moments of the Electron	41
	Masashi Hayakawa	
2.1	Introduction	41
2.2	QED and Anomalous Magnetic Dipole Moment	44
2.2.1	Perturbation Theory of QED	44
2.2.2	Feynman Diagrams and Feynman Rule	46
2.2.3	Anomalous Magnetic Dipole Moment	48
2.2.4	Renormalization and Counter-Terms	49
2.2.5	Classification of Perturbative Dynamics	50
2.3	Non-QED Contribution to $g - 2$	51
2.4	Numerical Approach to Perturbative QED Calculation	54
2.4.1	Classification of Feynman Diagrams	54
2.4.2	Parametric Representation of Feynman Diagrams	57
2.4.3	Subtraction of UV and IR Divergences	61
2.5	Result for QED Contribution	67
	References	69
3	Magnetic Moment of the Bound Electron	73
	Manuel Vogel and Wolfgang Quint	
3.1	The Case of the Bound Electron	73
3.2	Why the Bound Electron is Interesting	75
3.3	A Brief Look Back	77
3.4	The Continuous Stern-Gerlach Effect	79
3.5	Measurement Principle and Ion Confinement	81
3.5.1	Measurement Principle and Ideal Confinement	81
3.5.2	Imperfections	82
3.5.3	Magnetic Bottle	90
3.6	Experimental Setups and Techniques	96
3.6.1	Ion Cooling and Oscillation Frequency Measurement	99
3.6.2	Larmor Frequency Measurement	102
3.6.3	Spin State Determination	103
3.6.4	Double-Trap Technique	106
3.6.5	Mode Coupling Techniques	108
3.7	Results	111
3.7.1	Larmor Resonances	111
3.7.2	Resulting Magnetic Moments and Uncertainties	112
3.8	Double-Resonance Spectroscopy	114
3.8.1	Application to Highly Charged Ions	115
3.8.2	Double-Resonance Spectroscopy and the Zeeman Effect	121
3.9	Comment on Trap-Specific Spectroscopy	122

3.10	Relation of the Bound Electron Magnetic Moment to Other Quantities	123
3.10.1	Fine Structure Constant	123
3.10.2	Electron Mass	125
3.10.3	Relations to Nuclear Properties	125
	References	127
4	QED Theory of the Bound-Electron Magnetic Moment	137
	D. A. Glazov, A. V. Volotka, V. M. Shabaev and G. Plunien	
4.1	Introduction	137
4.2	Furry Picture of QED	138
4.2.1	Screening Potential	141
4.2.2	Effective Hamiltonian	142
4.2.3	One-Electron QED Effects	143
4.2.4	Many-Electron QED Effects	149
4.3	Nuclear Recoil Effect	153
4.4	Nuclear Size and Polarization Effects	154
4.5	Zeeman Splitting in Few-Electron Ions	155
4.5.1	Non-linear in Magnetic Field Effects	156
	References	158
5	The Magnetic Moments of the Proton and the Antiproton	165
	Stefan Ulmer and Christian Smorra	
5.1	Introduction	165
5.2	CPT Tests	167
5.3	The Magnetic Moments of the Proton and the Antiproton	170
5.4	Antiproton Magnetic Moment and Antihydrogen Hyperfine Structure	173
5.5	g -Factor Measurements	174
5.6	The Penning Trap	174
5.7	Experimental Setup	177
5.8	Measurement of the Eigenfrequencies	178
5.8.1	Peak Detection	178
5.8.2	Dip Detection	179
5.8.3	Sideband Coupling	181
5.9	Advanced Frequency Measurements	182
5.10	Continuous Stern Gerlach Effect	184
5.11	Larmor Frequency Measurement	186
5.12	Line Profile and Transition Rates	187
5.13	Statistical Detection of Spinflips	189
5.14	Feedback Cooling: Reduction of Linewidth	191
5.15	Determination of the g -Factor	192

5.16	Double Penning Trap Technique.	193
5.17	Towards a High Precision Measurement of the Antiproton Magnetic Moment.	195
5.18	Summary.	196
	References	197
6	Fundamental Physics with Antihydrogen.	203
	J. S. Hangst	
6.1	Some History	203
6.2	Producing Antihydrogen: ATHENA	204
6.3	Detecting Antihydrogen: ATHENA.	205
6.4	Antihydrogen and Ion Trap Physics	206
6.5	Trapping Antihydrogen for Spectroscopy: ALPHA.	208
	6.5.1 ALPHA Configuration.	209
	6.5.2 Detecting Trapped Antihydrogen	211
	6.5.3 Antihydrogen Trapping	212
	6.5.4 Holding Antihydrogen.	212
	6.5.5 Measuring Trapped Antihydrogen.	214
	6.5.6 Trapped Antihydrogen and Ion Trap Physics	215
6.6	Autoresonant Injection of Antiprotons into a Positron Plasma.	215
6.7	Evaporative Cooling of Charged Antimatter Plasmas	216
6.8	Towards Antihydrogen Spectroscopy.	217
	6.8.1 Dropping Antihydrogen.	219
	References	220
7	High-Precision Mass Measurements of Radionuclides with Penning Traps	223
	Michael Block	
7.1	Importance of Masses of Radionuclides.	223
7.2	Mass Measurements at On-line Facilities.	225
7.3	Penning-Trap Mass Spectrometry	227
7.4	Production of Radionuclides at On-line Facilities	227
	7.4.1 Typical Layout of a Penning Trap Mass Spectrometer	229
7.5	Beam Preparation	230
	7.5.1 Beam Preparation with an RFQ Cooler and Buncher.	231
	7.5.2 Penning Traps	234
	7.5.3 Contributions to the Systematic Uncertainty in PTMS	238
	7.5.4 Applications of High-Precision Mass Measurements	243

7.6	Conclusions	246
	References	246
8	Quantum Information Processing with Trapped Ions.	253
	Christian Roos	
8.1	Introduction	253
8.2	Storing Quantum Information in Trapped Ions	256
8.3	Preparation and Detection of a Qubit Encoded in a Single Ion	257
8.4	Coherent Manipulation of a Qubit	259
	8.4.1 Laser-Ion Interactions	259
	8.4.2 Laser Cooling of Single Ions	262
	8.4.3 Single-Qubit Gates	266
8.5	Entangling Quantum Gates	268
	8.5.1 Cirac-Zoller-Type Gate Interactions	270
	8.5.2 Quantum Gates Based on Bichromatic Light Fields	272
	8.5.3 Conditional Phase Gates	273
	8.5.4 Mølmer-Sørensen Gates.	274
8.6	Quantum State Tomography.	275
8.7	Entangled States and Elementary Quantum Protocols	279
	8.7.1 Deterministic Quantum Teleportation	280
8.8	Quantum Simulation	282
8.9	Quantum Information for Precision Measurements	283
8.10	Decoherence and Scalability Issues.	284
	8.10.1 Decoherence in Trapped-Ion Experiments	285
	8.10.2 Increasing the Number of Qubits	286
8.11	Outlook	287
	References	288
9	Optical Transitions in Highly Charged Ions for Detection of Variations in the Fine-Structure Constant.	293
	A. Ong, J. C. Berengut and V. V. Flambaum	
9.1	Introduction	293
9.2	Sensitivity of Atomic Transitions to α -Variation.	296
9.3	Level Crossings in Highly Charged Ions	298
9.4	Hole Crossings	300
9.5	Scaling Laws for Atomic Clocks Based on Highly Charged Ions.	301
	9.5.1 Scaling of the Sensitivity to α -Variation.	302
	9.5.2 Scaling of EJ and MJ Transition Matrix Elements	304
	9.5.3 Scaling of Polarizability and Blackbody Radiation Shift	305

9.5.4	Scaling of the Hyperfine Structure	305
9.5.5	Summary of Scaling Laws	306
9.6	Atomic Calculations for Highly Charged Ions	307
9.6.1	Hartree-Fock and Relativistic Hartree-Fock	307
9.6.2	Configuration Interaction	308
9.6.3	Combining Many-Body Perturbation Theory with Configuration Interaction	308
9.6.4	Cf ¹⁶⁺ : A Sample Calculation	309
	References	312
10	Emission and Laser Spectroscopy of Trapped Highly Charged Ions in Electron Beam Ion Traps	315
	José R. Crespo López-Urrutia and Zoltán Harman	
10.1	Introduction	315
10.2	Quantum Electrodynamics Studies with Trapped HCl	316
10.3	Historical Development of Experiments with Electron Beam Ion Traps	317
10.4	Production and Trapping of Highly Charged Ions by Electron Beams	320
10.5	Physical Processes in the Trap Region	323
10.5.1	Electron Impact Ionization	324
10.5.2	Electron Impact Excitation	324
10.5.3	Radiative Recombination	325
10.5.4	Dielectronic Recombination	326
10.6	Photon Spectroscopy Under Electron Beam Excitation	327
10.6.1	The X-ray Region: Lyman- α Transitions of Hydrogen-Like Ions	328
10.6.2	The Heliumlike Sequence: A Test for Interelectronic Correlation	333
10.6.3	The QED-Sensitive $2s_{1/2} \rightarrow 2p_{3/2,1/2}$ Transitions in Lithiumlike Ions	335
10.6.4	Spectroscopy of Forbidden Transitions in the Visible Range	336
10.6.5	The Hyperfine Structure of Hydrogenlike Ions	339
10.7	Resonant Photorecombination Processes	341
10.7.1	Dielectronic Recombination	342
10.7.2	Higher-Order Interactions in Photorecombination: Trielectronic and Quadreelectronic Terms	344
10.7.3	The Effect of the Breit Interaction in the Dielectronic Process	346
10.7.4	Quantum Interference Terms Between Dielectronic and Radiative Recombination	347
10.7.5	Resonant Photo-Ionization Processes	348

10.8	Photonic Excitation: Laser Spectroscopy from the Visible to the X-ray Range	349
10.8.1	Laser Spectroscopy in the Soft X-ray Region at Free-Electron Lasers	350
10.8.2	Extending Laser Spectroscopy into the X-ray Domain	351
10.8.3	Laser Excitation of Forbidden Transitions in the Visible Range	353
10.9	Ion Cooling Schemes for Spectroscopy with HCI	355
10.10	Summary and Future Directions	358
	References	359
11	Tests of Theory in Rydberg States of One-Electron Ions	375
	Joseph N. Tan and Peter J. Mohr	
11.1	Introduction	375
11.2	The Rydberg Constant	378
11.3	The Proton Radius Puzzle: Is QED in Trouble?	379
11.3.1	Spectroscopic Data and the Rydberg Constant	379
11.3.2	Scattering Determinations of the Radii	379
11.3.3	Proton Radius from Muonic Hydrogen	381
11.3.4	Comparison of the Determinations of the Proton Radius	382
11.3.5	Comparison of the Determinations of the Rydberg Constant	384
11.4	Optical Transitions Between Rydberg States	385
11.5	Theory of Rydberg States	386
11.5.1	Simplification of Nuclear Size and Higher-Order QED Effects	386
11.5.2	High- ℓ -State Energy Levels in Hydrogen-Like Atoms	387
11.5.3	Transition Frequencies and Uncertainties	390
11.5.4	Natural Line Widths	391
11.6	Experiment	392
11.6.1	Source of Fully-Stripped Ions	393
11.6.2	Capturing Bare Nuclei in a Compact Penning Trap	395
11.6.3	Charge-Exchange Recombination: One-Electron Rydberg Ions	400
11.7	Summary	401
	References	402
	Index	405

Fundamental Physics in Particle Traps

Quint, W.; Vogel, M. (Eds.)

2014, XXI, 411 p. 166 illus., Hardcover

ISBN: 978-3-642-45200-0