

CONTENTS

PART I

(Reprints)

Chapter I. Introduction	1
Chapter II. The Excitation of the Spectrum	3
2.1. The atomic and the molecular spectrum	3
2.2. Atomic hydrogen	4
2.3. Wood's discharge tubes	4
2.4. The 'ring' discharge	5
2.5. Electron bombardment	6
Chapter III. The Gross Structure	8
3.1. Balmer's formula	8
3.2. Bohr's analysis	8
3.3. Experimental tests	10
3.4. Hydrogen-like spectra	11
3.5. High series members and the continuum	12
Chapter IV. The Fine Structure—Old Quantum Theory	13
4.1. Relativistic effects	13
4.2. Quantum conditions	14
4.3. Energy levels	14
4.4. Intensities and the Correspondence Principle	15

Chapter V. Old Quantum Theory—Comparison with Experiment	16
5.1. The ionized helium lines	17
5.2. The Balmer lines	18
5.3. X-ray spectra	19
5.4. The dilemma	20
Chapter VI. The Fine Structure—New Quantum Theory	20
6.1. Wave and matrix mechanics	20
6.2. Quantum mechanics	21
6.3. Relativity	22
6.4. Electron spin	23
6.5. Spin and relativity corrections to the energy levels	24
6.6. Pauli spin matrices—two-valued wave functions	24
6.7. The Dirac theory of the electron	25
6.8. The Dirac theory of the hydrogen atom	27
6.9. The Breit interaction	28
6.10. Corrections to the Dirac theory	29
6.11. Intensities: new quantum theory	30
Chapter VII. New Quantum Theory—Comparison with Experiment	32
7.1. The H_α line	32
7.1.1. The wavelength	34
7.1.2. The interval ν_{12}	35
7.1.3. The interval ν_{23}	36
7.1.4. Relative intensities of the components	36
7.2. The ionized helium line 4686\AA	37
7.3. Conclusion	37
Chapter VIII. The Experiment of Lamb and Retherford	37

Chapter IX. The New Quantum Electrodynamics	41
9.1. The problem in classical physics	41
9.2. The problem in quantum physics	42
9.3. Re-normalization of mass	44
9.4. Bethe's calculation	45
9.5. Welton's calculation	47
9.6. Re-normalization of charge	48
9.7. Relativistic calculations	48
9.8. Results of the calculations—formulae	49
9.9. Numerical results for hydrogen and deuterium	52
9.10 Development of the radiation theory	52
 Chapter X. Further Measurements of Lamb Shifts	 54
10.1. Optical spectroscopy	55
10.1.1. Deuterium: $n = 2$ and 3	55
10.1.2. Tritium: $n = 2$	56
10.1.3. Helium ⁺ : $n = 3$ and 4	57
10.1.4. Helium ⁺ : $n = 2$ and 3	59
10.1.5. An intensity anomaly	60
10.1.6. Deuterium: $n = 1$	60
10.2. Radiofrequency spectroscopy	61
10.2.1. Helium ⁺ : $n = 2$	61
10.2.2. Hydrogen: $n = 3$	63
10.3. Comments on Table 1	65
 Chapter XI. Hyperfine Structure	 66
11.1. The Fermi formula	66
11.2. The Fermi formula—comparison with experiment	67
11.3. The anomalous magnetic moment of the electron	68
11.4. Further electrodynamic corrections	69
11.5. The corrected formula—comparison with experiment	70

11.6. Compound nuclei 72

11.7. Excited levels in hydrogen and deuterium 74

Chapter XII. Positronium 75

12.1. The gross structure 75

12.2. The fine and hyperfine structure 75

12.3. The annihilation force 76

12.4. The energy levels 77

12.5. The Zeeman effect 78

12.6. Lifetimes 80

12.7. Experimental test 81

Appendix 82

References and Author Index 83

Subject Index 88

PART II

Chapter 1: Advances in Experimental Methods 89

E. A. Hinds and G. W. Series

1.1. Conventional laboratory spectroscopy: gas discharges:
 spontaneous emission 91

1.2. Radiofrequency spectroscopy: atomic beams: Lamb's experiment . 92

1.3. Radiofrequency spectroscopy:
 hyperfine structure of the ground state 92

1.4. Optical spectroscopy: the laser era 93

 1.4.1. Saturated absorption spectroscopy 94

 1.4.2. Two-photon spectroscopy 95

 1.4.3. Polarization spectroscopy 96

 1.4.4. Cross-over resonances 97

1.4.5.	Interaction times: the Ramsey technique: cooling	98
1.5.	Optical pumping: ground states	99
1.6.	Fluorescence spectroscopy: excited states	100
1.6.1.	Optical radiofrequency double resonance	101
1.6.2.	Level-crossing spectroscopy	101
1.6.3.	Anticrossing spectroscopy	102
1.7.	Beam foil spectroscopy	104
1.8.	Production of hydrogenic atoms	105
1.8.1.	Traditional methods	105
1.8.2.	Cold hydrogen beams	105
1.8.3.	Fast hydrogen beams	106
1.8.4.	Hydrogenic ions	106
1.8.5.	Positronium (e^+e^-)	107
1.8.6.	Muonium (μ^+e^-)	108
	References	108
Chapter 2: Quantum Electrodynamics Calculations		111
<i>Peter J. Mohr</i>		
2.1.	Introduction	113
2.2.	Quantum electrodynamics	114
2.3.	Magnetic moment anomaly	115
2.4.	Bound interaction picture QED	117
2.5.	Self-energy	119
2.6.	Vacuum polarization	122
2.7.	Higher order radiative corrections	123
2.8.	Finite nuclear size effects	124
2.9.	Nuclear recoil corrections	125
2.10.	Lamb shift in hydrogenlike atoms	126
2.11.	Hyperfine structure	130
2.12.	Helium energy levels	131
	References	132

Chapter 3: Theory of Transitions, and the Electroweak Interaction . . .	137
<i>G. W. F. Drake</i>	
3.1. Introduction	139
3.2. Theory of spontaneous transitions	140
3.3. Theory of quenching radiation assymetries	145
3.3.1. Basic formalism	145
3.3.2. Hyperfine structure effects for weak quenching fields . . .	155
3.3.3. The Lamb shift anisotropy	158
3.3.4. $E1-E1$ damping interference	165
3.3.5. $E1-M1$ interference	167
3.3.6. The total quench rate	168
3.4. Quantum beats	170
3.4.1. Introduction	170
3.4.2. Theory of field-induced quantum beats	172
3.4.3. The two-state approximation	179
3.4.3.1. Continuous and modulated excitation	184
3.4.4. Comparison with experiment	187
3.5. Two-photon transitions	189
3.5.1. Introduction	189
3.5.2. Theory of two-photon transitions	191
3.5.3. Computational methods and results	196
3.5.4. Other two-photon processes	202
3.5.5. Static field quenching as a two-photon process	203
3.6. The electroweak interaction:	
parity non-conservation in atomic physics	210
3.6.1. Introduction	210
3.6.2. Some basic concepts of weak interactions and their currents	212
3.6.3. The electron-nucleon weak interaction	220
3.6.4. Coupling constants in the standard electroweak model . .	222

3.6.5.	Calculation of matrix elements	226
3.6.6.	Bibliography on weak interactions	231
Appendix:	Hydrogenic perturbation theory and the Stark effect	232
A.1.	Higher order perturbation corrections	232
A.2.	Intermediate state summations	235
Acknowledgements	237
References	237
Chapter 4:	Radiofrequency Spectroscopy	243
<i>E. A. Hinds</i>		
4.	Introduction	245
4.1.	Hyperfine structure	245
4.1.1.	Hydrogen ground state interval	245
4.1.2.	The hydrogen maser	248
4.1.3.	The hyperfine anomaly δ	251
4.1.4.	Comparison of $1S$ and $2S$ hyperfine intervals	251
4.1.5.	Measurement of the ground state interval in $^3\text{He}^+$	253
4.1.6.	Muonium ground state interval	257
4.1.7.	Measurement of muonium ground state interval	258
4.1.8.	Positronium ground state interval	260
4.2.	Fine structure and Lamb shift	262
4.2.1.	Energy levels	262
4.2.2.	The Lamb shift interval	264
4.2.3.	The $2P$ fine structure interval	266
4.2.4.	The slow beam Lamb shift measurements	267
4.2.5.	Fast beam <i>rf</i> Lamb shift measurements	270
4.2.6.	Lamb shift measurements using static electric fields	274
4.2.7.	Present status of the Lamb shift	275
4.2.8.	Measurements of other $n = 2$ intervals:	
the fine structure constant		276
4.3.	Weak interactions	278

4.3.1.	Theory	279
4.3.2.	General principles of parity measurements	281
4.3.3.	Experiments to measure parity violation	281
	References	287
Chapter 5: Optical Spectroscopy		293
<i>G. W. Series and T. W. Hänsch</i>		
5.1.	Before the laser era	295
5.1.1.	Helium ⁺ : resolution of the fine structure	295
5.1.2.	The Rydberg constant: renewed interest	296
5.1.3.	Student laboratories	297
5.2.	Precision laser spectroscopy: first round of experiments	297
5.2.1.	Precision laser spectroscopy (<i>T. W. Hänsch</i>)	297
5.3.	Precision laser spectroscopy: later work	309
5.3.1.	Levels of accuracy; units and standards of measurement	309
5.3.2.	Objectives of experiments and reduction of measurements	310
5.3.3.	Design of experiment	312
5.3.4.	Determinations of the Rydberg constant	315
5.3.4.1.	–at the National Physical Laboratory, UK: Balmer- α	315
5.3.4.2.	–at Yale: Balmer- α and Balmer- β	317
5.3.4.3.	–in Paris: avoid the <i>P</i> -states	318
5.3.4.4.	Further studies to avoid the <i>P</i> -states	319
5.3.5.	The <i>1S</i> - <i>2S</i> transition	320
5.4.	Experimental results: comparison with theory	323
5.4.1.	The Rydberg constant	323
5.4.2.	The <i>1S</i> - <i>2S</i> transition	325
5.4.3.	Spectroscopic isotope shift	326
5.4.4.	Indications for future measurements	327
	References	329

Chapter 6: Spectroscopy of One-Electron Ions of Intermediate and High Z	331
<i>E. Träbert</i>	
6.1. Introduction	333
6.2. Light sources	337
6.2.1. Gas discharges	337
6.2.2. Laser-produced plasmas	338
6.2.3. Ion sources	339
6.2.4. Recoil ions	339
6.2.5. Fast ion beams	340
6.3. More or less classical spectroscopy: $n = 1$ Lamb shift	345
6.4. Application of constant external fields: Quench Experiments	353
6.5. Application of oscillating external fields: resonance experiments	358
6.6. Conclusion	362
References	362
Chapter 7: Hydrogenic Systems in Electric and Magnetic Fields	367
<i>J. C. Gay</i>	
7.1. Introduction	369
7.2. Elementary considerations	371
7.2.1. Coupling constants—orders of magnitude	372
7.2.2. The atomic spectrum in external fields— the three gross regimes	373
7.2.3. Orders of magnitude and further remarks	374
7.2.4. The failure of traditional methods	375
7.3. Basic aspects of experiments	375
7.3.1. The choice of the atomic species and optical state selection	376
7.3.2. Atomic beam experiments	377
7.3.3. Vapour phase experiments	379
7.3.4. Other experimental techniques	381

7.3.5.	The production of fields	382
7.3.6.	About the future	382
7.4.	Electric field structure of one-electron Rydberg atoms	383
7.4.1.	Historical survey	383
7.4.2.	The electric field structure of the hydrogen atom	383
7.4.2.1.	The spectrum of resonances from a physical viewpoint	383
7.4.2.2.	The hydrogen atom in an electric field— the standard treatment	385
7.4.2.3.	The crossing rule of the energy levels	388
7.4.2.4.	The parabolic description of the quasi-bound states	388
7.4.2.5.	Distribution of oscillator strength and photoionization	389
7.4.3.	One-electron Rydberg atoms in electric fields— the role of non-Coulombic corrections	389
7.4.3.1.	The problem to solve—Harmin's solution	389
7.4.3.2.	Energy diagram—the non-crossing rule	390
7.4.3.3.	Fano-profiles and and ionization	390
7.4.4.	Experimental manifestations in Rydberg atoms	391
7.4.4.1.	Linear Stark effect on quasi-hydrogenic species	391
7.4.4.2.	Generation of pseudo profiles in the quasi-bound spectrum	393
7.4.4.3.	The Stark resonance spectrum	394
7.4.4.4.	The mechanisms of ionization	400
7.4.5.	Conclusions	401
7.5.	Magnetic field structure of one-electron Rydberg atoms— the diamagnetic behavior	401
7.5.1.	Historical survey	401
7.5.2.	The magnetic structure of atoms— standard analysis of a non-separable problem	402

7.5.3.	The diamagnetic behavior from experiments	404
7.5.3.1.	The low field inter- l -mixing regime	404
7.5.3.2.	The inter- n -mixing regime—merging of the diamagnetic manifolds ($\gamma^2 \cdot n^7 \gtrsim 1$)	407
7.5.3.3.	The quasi-Landau regime close to the zero field limit	409
7.5.3.4.	The diabatic picture of the building of the magnetic spectra	411
7.6.	Elementary views on the symmetries of the Coloumb interaction	412
7.6.1.	The overview from classical mechanics	413
7.6.2.	The symmetry group of the orbital Coulomb problem	415
7.6.2.1.	The SO(4) symmetry of the bound Coulomb spectrum	415
7.6.2.2.	The SO(4) vectorial model of the orbital problem	416
7.6.2.3.	The two classes of generalized eigenfunctions	417
7.6.2.4.	Conclusions	419
7.6.3.	The Coulomb dynamical group	420
7.6.3.1.	The general background	420
7.6.3.2.	The orbital Coulomb problem as a pair of 2-dimensional oscillators	420
7.6.3.3.	The oscillator dynamics in a 3-dimensional Lorentz space	421
7.6.3.4.	The double vectorial model of the Coulomb dynamics in 3-dimensional Lorentz spaces	422
7.7.	The low field regimes and breaking the Coulomb symmetry	423
7.7.1.	Rydberg atoms in crossed (\mathbf{E} , \mathbf{B}) fields— the low field Pauli quantization	423
7.7.1.1.	Pauli's prediction and the SO(4) analysis	424
7.7.1.2.	Physical meaning of the results	425

7.7.1.3.	The λ angular momentum and the low field (crossed \mathbf{E} , \mathbf{B}) fields spectrum	426
7.7.1.4.	An experiment in the geometry of the Coulomb field	426
7.7.1.5.	The extended tunability of the atom	427
7.7.1.6.	Miscellaneous extensions	429
7.7.2.	The atom in a magnetic field— the low field diamagnetic behavior	430
7.7.2.1.	The effective diamagnetic Hamiltonian in the n Coulomb shell	430
7.7.2.2.	The rovibrational structure of the diamagnetic band	431
7.7.2.3.	Some experimental illustrations	432
7.7.2.4.	Dynamical correlations in the diamagnetic band	433
7.7.2.5.	Miscellaneous corrections	433
7.7.2.6.	Other classes of interactions	433
7.7.3.	Stark effect for quasi-hydrogenic species	434
7.8.	The strong mixing regimes and the Coulomb dynamical group .	434
7.8.1.	The magnetic problem and coupled-oscillators dynamics	435
7.8.2.	The symmetries in the magnetic problem	435
7.8.3.	Classical chaos and its quantum analogue in the magnetic problem	436
7.8.4.	Conclusions	436
7.9.	Conclusions	437
	Acknowledgements	439
	References	439
	Chapter 8: Spectroscopy of Positronium	447
	<i>A. P. Mills, Jr.</i>	
8.1.	Introduction	449
8.2.	Positronium formation methods	450

8.2.1.	Fast positrons	450
8.2.2.	Slow positrons	450
8.3.	Positronium mass	452
8.4.	Positronium charge	452
8.5.	Annihilation rates	452
8.6.	Positronium energy levels	453
8.6.1.	Hyperfine interval	454
8.6.2.	<i>Ps</i> Lamb shift	457
8.6.3.	<i>1S-2S</i> interval	459
References	466
Chapter 9: Temperature-Dependent Level Shifts		469
<i>G. Barton</i>		
9.1.	Introduction	471
9.2.	Nonrelativistic approximation	473
9.2.1.	Free electrons	473
9.2.2.	Atoms	473
9.3.	Approximations for high and low temperatures	474
9.4.	The $n = 2$ Lamb shift	475
9.5.	Hyperfine structure	476
9.6.	Experiment	477
References	478
Chapter 10: Hydrogen and the Fundamental Atomic Constants		481
<i>G. W. Series</i>		
10.1.	The atomic constants, physical theory, and the base units of measurement	483
10.2.	The Rydberg constant	485
10.3.	The fine structure constant	487
10.3.1.	Experimental study of fine structure in hydrogen	488
10.3.2.	Fine structure in helium	489

10.3.3.	Hyperfine structure	490
10.3.4.	The Josephson effect	491
10.3.5.	Muonium hyperfine structure	493
10.3.6.	The electron and the positron: the $g-2$ anomaly	493
	10.3.6.1. Resonance experiments	495
	10.3.6.2. Free precession experiments	497
10.3.7.	Muons: the $g-2$ anomaly	497
10.3.8.	The quantized Hall effect	498
10.3.9.	The values of α	499
10.4.	The electron-to-proton mass ratio	499
10.5.	CODATA	501
	References	501
	Supplementary References	503
	Subject Index	505