

# Contents

|  |    |
|--|----|
| <b>1. Colored Centers in Ionic Crystals</b> .....              | 1  |
| 1.1 The Mollwo–Ivey Law .....                                  | 2  |
| 1.2 The Jahn–Teller Effect .....                               | 3  |
| 1.3 The Stokes Shift .....                                     | 4  |
| 1.4 Solutions .....  | 5  |
| Further Comments on F-Centers .....                            | 10 |
| <b>2. Unstable Diatomic Molecule</b> .....                     | 11 |
| 2.1 Preliminaries .....  | 11 |
| 2.2 A Molecule Which Is Only Stable in Its Excited State ..... | 12 |
| 2.3 Solutions .....  | 13 |
| <b>3. Neutrino Oscillations</b> .....                          | 17 |
| 3.1 Neutrino Masses and the Associated Oscillations .....      | 17 |
| 3.2 Solutions .....  | 18 |
| <b>4. Colored Molecular Ions</b> .....                         | 21 |
| 4.1 Carbohydrate Ions .....                                    | 21 |
| 4.2 Nitrogenous Ions .....                                     | 22 |
| 4.3 Solutions .....  | 23 |
| <b>5. Schrödinger’s Cat</b> .....                              | 27 |
| 5.1 The Quasi-Classical States of a Harmonic Oscillator .....  | 27 |
| 5.2 Construction of a Schrödinger-Cat State .....              | 28 |
| 5.3 Quantum Superposition Versus Statistical Mixture .....     | 29 |
| 5.4 The Fragility of a Quantum Superposition .....             | 30 |
| 5.5 Solutions .....  | 32 |
| Conclusion .....   | 37 |
| <b>6. Direct Observation of Field Quantization</b> .....       | 39 |
| 6.1 Quantization of a Mode of the Electromagnetic Field .....  | 39 |
| 6.2 The Coupling of the Field with an Atom .....               | 41 |
| 6.3 Interaction of the Atom and an “Empty” Cavity .....        | 42 |

|            |  |           |
|------------|--|-----------|
| 6.4        | Interaction of an Atom with a Quasi-Classical State .....                | 43        |
| 6.5        | Large Numbers of Photons: Damping and Revivals .....                     | 44        |
| 6.6        | Solutions .....  | 45        |
|            | Reference .....  | 52        |
| <b>7.</b>  | <b>Decay of a Tritium Atom .....</b>                                     | <b>53</b> |
| 7.1        | The Energy Balance in Tritium Decay .....                                | 53        |
| 7.2        | Solutions .....  | 54        |
| <b>8.</b>  | <b>The Hydrogen Atom in Crossed Fields .....</b>                         | <b>57</b> |
| 8.1        | The Hydrogen Atom in Crossed Electric<br>and Magnetic Fields .....       | 57        |
| 8.2        | Pauli's Result .....   | 58        |
| 8.3        | Solutions .....  | 59        |
| <b>9.</b>  | <b>Exact Results for the Three-Body Problem .....</b>                    | <b>61</b> |
| 9.1        | The Two-Body Problem .....   | 61        |
| 9.2        | The Variational Method .....   | 61        |
| 9.3        | Relating the Three-Body and Two-Body Sectors.....                        | 62        |
| 9.4        | The Three-Body Harmonic Oscillator .....                                 | 63        |
| 9.5        | From Mesons to Baryons in the Quark Model .....                          | 63        |
| 9.6        | Solutions .....  | 64        |
|            | References .....   | 68        |
| <b>10.</b> | <b>Analysis of a Stern–Gerlach Experiment .....</b>                      | <b>69</b> |
| 10.1       | Preparation of the Neutron Beam .....                                    | 69        |
| 10.2       | Spin State of the Neutrons.....  | 71        |
| 10.3       | The Stern–Gerlach Experiment .....                                       | 71        |
| 10.4       | Solutions .....  | 73        |
| <b>11.</b> | <b>Measuring the Electron Magnetic Moment Anomaly.....</b>               | <b>79</b> |
| 11.1       | Spin and Momentum Precession of an Electron<br>in a Magnetic Field ..... | 79        |
| 11.2       | Solutions .....  | 80        |
| <b>12.</b> | <b>Neutron Interferometry .....</b>                                      | <b>83</b> |
| 12.1       | Neutron Interferences .....  | 84        |
| 12.2       | The Gravitational Effect .....   | 85        |
| 12.3       | Rotating a Spin 1/2 by 360 Degrees.....                                  | 86        |
| 12.4       | Solutions .....  | 88        |
|            | References .....   | 91        |

|   |     |
|---|-----|
| <b>13. The Penning Trap</b> .....                               | 93  |
| 13.1 Motion of an Electron in a Penning Trap .....              | 93  |
| 13.2 The Transverse Motion .....                                | 94  |
| 13.3 Measurement of the Electron Anomalous Magnetic Moment ..   | 95  |
| 13.4 Solutions .....  | 95  |
| Reference .....   | 98  |
| <b>14. Quantum Cryptography</b> .....                           | 99  |
| 14.1 Preliminaries .....  | 99  |
| 14.2 Correlated Pairs of Spins .....                            | 100 |
| 14.3 The Quantum Cryptography Procedure .....                   | 102 |
| 14.4 Solutions .....  | 104 |
| <b>15. Hidden Variables and Bell's Inequalities</b> .....       | 109 |
| 15.1 The Electron Spin .....                                    | 109 |
| 15.2 Correlations Between the Two Spins .....                   | 109 |
| 15.3 Correlations in the Singlet State .....                    | 110 |
| 15.4 A Simple Hidden Variable Model .....                       | 111 |
| 15.5 Bell's Theorem and Experimental Results .....              | 112 |
| 15.6 Solutions .....  | 113 |
| References .....  | 118 |
| <b>16. Hyperfine Structure in Electron Spin Resonance</b> ..... | 119 |
| 16.1 Hyperfine Interaction with One Nucleus .....               | 120 |
| 16.2 Hyperfine Structure with Several Nuclei .....              | 120 |
| 16.3 Experimental Results .....                                 | 121 |
| 16.4 Solutions .....  | 123 |
| <b>17. The Spectrum of Positronium</b> .....                    | 127 |
| 17.1 Positronium Orbital States .....                           | 127 |
| 17.2 Hyperfine Splitting .....                                  | 127 |
| 17.3 Zeeman Effect in the Ground State .....                    | 128 |
| 17.4 Decay of Positronium .....                                 | 129 |
| 17.5 Solutions .....  | 131 |
| References .....  | 134 |
| <b>18. Magnetic Excitons</b> .....                              | 135 |
| 18.1 The Molecule CsFeBr <sub>3</sub> .....                     | 135 |
| 18.2 Spin-Spin Interactions in a Chain of Molecules .....       | 136 |
| 18.3 Energy Levels of the Chain .....                           | 136 |
| 18.4 Vibrations of the Chain: Excitons .....                    | 138 |
| 18.5 Solutions .....  | 140 |
| Reference .....   | 145 |

|  |     |
|--|-----|
| <b>19. Probing Matter with Positive Muons</b> .....          | 147 |
| 19.1 Muonium in Vacuum .....                                 | 148 |
| 19.2 Muonium in Silicon .....                                | 149 |
| 19.3 Solutions .....   | 151 |
| <b>20. Spectroscopic Measurement on a Neutron Beam</b> ..... | 157 |
| 20.1 Ramsey Fringes .....                                    | 157 |
| 20.2 Solutions .....   | 159 |
| Reference .....  | 163 |
| <b>21. The Quantum Eraser</b> .....                          | 165 |
| 21.1 Magnetic Resonance .....                                | 165 |
| 21.2 Ramsey Fringes .....                                    | 166 |
| 21.3 Detection of the Neutron Spin State .....               | 168 |
| 21.4 A Quantum Eraser .....                                  | 169 |
| 21.5 Solutions .....   | 170 |
| <b>22. Molecular Lasers</b> .....                            | 179 |
| 22.1 Preliminaries .....                                     | 179 |
| 22.2 Molecular Lasers .....                                  | 180 |
| 22.3 Solutions .....   | 182 |
| <b>23. Energy Loss by Ions in Matter</b> .....               | 187 |
| 23.1 Energy Absorbed by One Atom .....                       | 188 |
| 23.2 Energy Loss in Matter .....                             | 188 |
| 23.3 Solutions .....   | 190 |
| <b>24. Properties of a Bose–Einstein Condensate</b> .....    | 195 |
| 24.1 Particle in a Harmonic Trap .....                       | 195 |
| 24.2 Interactions Between Two Confined Particles .....       | 196 |
| 24.3 Energy of a Bose–Einstein Condensate .....              | 197 |
| 24.4 Condensates with Repulsive Interactions .....           | 197 |
| 24.5 Condensates with Attractive Interactions .....          | 198 |
| 24.6 Solutions .....   | 199 |
| Further Comments .....                                       | 204 |
| <b>25. Quantum Reflection of Atoms from a Surface</b> .....  | 205 |
| 25.1 The Hydrogen Atom–Liquid Helium Interaction .....       | 205 |
| 25.2 Excitations on the Surface of Liquid Helium .....       | 207 |
| 25.3 Quantum Interaction Between H and Liquid He .....       | 208 |
| 25.4 The Sticking Probability .....                          | 208 |
| 25.5 Solutions .....   | 209 |
| References .....   | 215 |

**26. Laser Cooling and Trapping** ..... 217

    26.1 Optical Bloch Equations for an Atom at Rest ..... 217

    26.2 The Radiation Pressure Force ..... 218

    26.3 Doppler Cooling ..... 219

    26.4 The Dipole Force ..... 220

    26.5 Solutions ..... 220

**27. Quantum Motion in a Periodic Potential** ..... 227

    27.1 Band Structure in a Periodic Potential ..... 227

    27.2 Bloch Oscillations ..... 228

    27.3 Solutions ..... 230

**Author Index** ..... 239

**Subject Index** ..... 241