



# Contents

|  |    |
|--|----|
| <b>1. Introduction</b>   |    |
| By J. Christiansen and W. Witthuhn (With 11 Figures) .....                       | 1  |
| 1.1 Perturbed Angular Distribution Techniques .....                              | 3  |
| 1.1.1 Magnetic Hyperfine Interaction .....                                       | 3  |
| 1.1.2 Electric Quadrupole Hyperfine Interaction .....                            | 6  |
| 1.1.3 The Stroboscopic Method .....  | 8  |
| 1.2 Perturbed Angular Correlation Techniques .....                               | 10 |
| 1.3 Nuclear Magnetic Resonance on $\beta$ -Emitting Nuclei .....                 | 13 |
| References .....   | 14 |
| <br>   |    |
| <b>2. Hyperfine Interactions of Excited Nuclei in Atomic Systems</b>             |    |
| By G.D. Sprouse (With 21 Figures) .....  | 15 |
| 2.1 Free Atoms in Flight—The Recoil Distance Method .....                        | 15 |
| 2.1.1 Calculation of the Perturbation Function $G^{kk}(t)$ .....                 | 17 |
| 2.1.2 Fine-Structure Beats .....   | 18 |
| 2.1.3 Hyperfine Interactions in Free Atoms .....                                 | 18 |
| 2.1.4 Hydrogenlike Atoms .....   | 19 |
| 2.1.5 He-Like Atoms .....  | 22 |
| 2.1.6 Li-Like Atoms .....  | 24 |
| 2.1.7 Na-Like Atoms .....  | 25 |
| 2.1.8 Other Atomic Systems in Vacuum .....                                       | 26 |
| 2.2 Atoms in Gases .....   | 28 |
| 2.2.1 Fast Atoms in Gases .....  | 28 |
| 2.2.2 Statistical Approach .....   | 29 |
| 2.2.3 Nuclear Spin Dependence .....  | 30 |
| 2.2.4 Relaxing the Condition $\langle \omega^2 \rangle^{1/2} \tau_c \ll 1$ ..... | 31 |
| 2.2.5 The Approach to Thermal Equilibrium-Chemical Effects .....                 | 31 |
| 2.2.6 Thermalized Atoms in Rare-Gas Hosts .....                                  | 33 |
| 2.2.7 Pressure Dependence of the Alignment .....                                 | 34 |
| 2.2.8 Magnetic Field Dependence .....  | 34 |
| 2.3 Magnetic Decoupling Measurements in Vacuum .....                             | 36 |
| 2.3.1 Fields Parallel to the Quantization (Beam) Axis .....                      | 36 |
| 2.3.2 Strong Magnetic Fields Transverse to the Beam Direction .....              | 36 |

|           |   |     |
|-----------|---|-----|
| 2.4       | New Methods and Future Directions .....                             | 39  |
|           | References .....  | 41  |
| <b>3.</b> | <b>Hyperfine Interaction Studies in Nuclear Physics</b>             |     |
|           | By O. Häusser and I.S. Towner (With 24 Figures) .....               | 45  |
| 3.1       | Overview .....  | 45  |
| 3.2       | Hyperfine Hamiltonian and Nuclear Moments .....                     | 47  |
| 3.2.1     | Atomic Isotope Shifts and Nuclear Mean-Square Radii .....           | 48  |
| 3.2.2     | Quadrupole Interactions and Nuclear Quadrupole Moments .....        | 52  |
| a)        | Quadrupole Interactions in Atoms .....                              | 53  |
| b)        | Quadrupole Interaction Non-Cubic Lattices .....                     | 54  |
| c)        | Calibration of Electric Field Gradients .....                       | 58  |
| 3.2.3     | Magnetic Interactions and Nuclear Magnetic Moments .....            | 63  |
| a)        | Magnetic Interactions in Atoms .....                                | 64  |
| b)        | Magnetic Interactions in Solids .....                               | 66  |
| 3.3       | Laser Spectroscopy and Hyperfine Structure of Exotic Nuclear States | 75  |
| 3.4       | Nuclear Moments of High-Spin States .....                           | 81  |
| 3.4.1     | The Deformation of High-Spin Yrast Isomers .....                    | 82  |
| 3.4.2     | The $g$ Factors of Collective High-Spin States .....                | 88  |
| 3.5       | Magnetic Moments of Simple Shell-Model Configurations .....         | 90  |
| 3.5.1     | Meson Exchange Currents .....                                       | 93  |
| 3.5.2     | First-Order Core Polarization .....                                 | 95  |
| 3.5.3     | High-Spin Isomers of Two-Particle Configuration .....               | 98  |
| 3.5.4     | Single-Particle States in Other Mass Regions .....                  | 102 |
| 3.5.5     | Core-Polarization Blocking .....                                    | 103 |
| 3.5.6     | Second-Order Core Polarization .....                                | 106 |
| 3.5.7     | Magnetic Moments of $\beta$ Emitters .....                          | 109 |
| 3.6       | Hyperfine Interactions in Nuclear $\beta$ Decay .....               | 110 |
| 3.6.1     | Theoretical Position .....  | 110 |
| 3.6.2     | Experimental NMR Techniques for $\beta$ Emitters .....              | 118 |
| 3.6.3     | Experimental Results .....  | 122 |
| 3.6.4     | Discussion .....  | 125 |
|           | References .....  | 128 |
| <b>4.</b> | <b>Hyperfine Interactions of Defects in Metals</b>                  |     |
|           | By E. Recknagel, G. Schatz, and Th. Wichert (With 47 Figures) ..... | 133 |
| 4.1       | Relevant Solid State and Nuclear Physics Aspects .....              | 134 |
| 4.1.1     | Defects in Metals .....   | 134 |
| a)        | Defects After Irradiation .....                                     | 134 |
| b)        | Defects in Thermal Equilibrium .....                                | 137 |
| c)        | Vacancy and Interstitial Configurations .....                       | 139 |
| d)        | Migration of Defects .....  | 139 |

|  |     |
|--|-----|
| e) Interaction of Lattice Defects with Impurity Atoms .....                  | 141 |
| f) Some Experimental Aspects in the Determination of Defect Properties ..... | 142 |
| 4.1.2 Hyperfine Interaction Parameters .....                                 | 144 |
| a) Electric Hyperfine Interaction .....                                      | 144 |
| b) Magnetic and Combined Hyperfine Interaction .....                         | 149 |
| 4.1.3 Nuclear Probes .....   | 149 |
| 4.2 Hyperfine Investigations of Defects .....                                | 152 |
| 4.2.1 Experiments with Radioactive Sources .....                             | 152 |
| a) Diamagnetic fcc Metals .....  | 159 |
| b) Diamagnetic bcc Metals .....  | 173 |
| c) Ferromagnetic Cubic Metals .....  | 179 |
| d) Hcp Metals .....  | 182 |
| e) Summary .....   | 184 |
| 4.2.2 In-Beam Experiments .....  | 187 |
| a) Cubic Metals .....  | 189 |
| b) Noncubic Metals .....   | 194 |
| c) Summary of Nuclear Reaction Experiments .....                             | 198 |
| References .....   | 200 |
| <br>5. Electric Quadrupole Interaction in Noncubic Metals                    |     |
| By W. Witthuhn and W. Engel (With 39 Figures) .....                          | 205 |
| 5.1 Electric Quadrupole Hyperfine Interaction .....                          | 206 |
| 5.2 Experimental Methods .....   | 209 |
| 5.2.1 Energy Methods .....   | 210 |
| a) Specific Heat Measurements .....  | 210 |
| b) Nuclear Orientation .....   | 212 |
| c) Mössbauer Effect .....  | 214 |
| 5.2.2 Precession Methods .....   | 215 |
| a) Nuclear Resonance Methods .....   | 216 |
| b) Perturbed Angular Correlation (Distribution) Methods .....                | 218 |
| 5.3 Experimental Data and Systematic Trends .....                            | 225 |
| 5.3.1 The Universal Correlation .....  | 227 |
| 5.3.2 The Temperature Dependence of the EFG .....                            | 229 |
| 5.3.3 The Pressure Dependence of the EFG .....                               | 232 |
| 5.3.4 Impurity Valence Effects of the EFG .....                              | 234 |
| 5.4 The EFG in Metals .....  | 235 |
| 5.4.1 Antishielding .....  | 236 |
| 5.4.2 The Lattice Sum .....  | 240 |
| 5.4.3 Wave Function Approaches .....   | 241 |
| a) Wannier Functions .....   | 242 |

|  |     |
|--|-----|
| b) Augmented Plane Waves .....   | 242 |
| c) Orthogonalized Plane Waves .....  | 243 |
| d) Fermi Surface Electrons .....   | 244 |
| 5.4.4 Potential Approaches .....   | 246 |
| 5.4.5 Temperature Dependence .....   | 250 |
| a) Fermi Surface Electrons .....   | 251 |
| b) Wave Function Approach .....  | 252 |
| c) Potential Approach .....  | 254 |
| 5.4.6 Pressure and Concentration Dependence .....  | 258 |
| 5.5 Conclusion .....   | 259 |
| 5.6 Appendix .....   | 260 |
| Table of Experimental Data on Quadrupole Interaction in Noncubic<br>Metals .....   | 260 |
| References .....   | 280 |
| <br>6. $\beta$ Emitters and Isomeric Nuclei as Probes in Condensed Matter<br>By H. Ackermann, P. Heitjans, and H.-J. Stöckmann (With 30 Figures) ..... | 291 |
| 6.1 Theory .....   | 292 |
| 6.1.1 Hamiltonian and Energy Levels .....  | 292 |
| 6.1.2 Reorientation in Electromagnetic Fields .....  | 294 |
| 6.1.3 Relaxation .....   | 298 |
| a) Nuclear Relaxation by Magnetic Coupling to Conduction<br>Electrons .....  | 301 |
| b) Relaxation by Fluctuating Nuclear Dipole-Dipole<br>Interactions .....   | 301 |
| c) Quadrupolar Relaxation Induced by Atomic Motion .....   | 302 |
| d) Relaxation by Quadrupolar Spin-Phonon Coupling .....  | 302 |
| 6.2 Experimental Methods .....   | 303 |
| 6.2.1 Experiments Using $\beta$ Emitters .....   | 303 |
| a) Probe Creation by Capture of Polarized Thermal Neutrons .....   | 304 |
| b) Probe Creation by Fast Particle Reactions with Selected<br>Recoil Angle .....   | 307 |
| c) Probe Creation by Reactions with Polarized Fast Particles .....   | 308 |
| d) Probe Creation by Fast Particle Reactions and Subsequent<br>Polarization in the Stopper .....   | 308 |
| 6.2.2 Experiments Using Isomeric $\gamma$ Emitters .....   | 309 |
| 6.3 Metals .....   | 310 |
| 6.3.1 Static Interactions, NMR Spectra .....   | 311 |
| a) Magnetic Energy Splitting .....   | 311 |
| b) Energy Splitting in the Presence of Quadrupole Interactions .....   | 313 |

|  |            |
|--|------------|
| 6.3.2 Relaxation of Nuclear Orientation .....                        | 316        |
| a) Solid Metals .....  | 318        |
| b) Liquid Metals .....   | 324        |
| 6.4 Insulators .....   | 331        |
| 6.4.1 Static Interactions, NMR Spectra .....                         | 332        |
| a) Lithium Compounds .....   | 332        |
| b) Fluorine Compounds .....  | 334        |
| c) Probe Nuclides in the Mass Number Range $24 \leq A \leq 39$ ..... | 338        |
| d) Indium and Silver Compounds .....                                 | 339        |
| 6.4.2 Relaxation of Nuclear Orientation .....                        | 341        |
| a) Lithium and Fluorine Compounds .....                              | 341        |
| b) Indium and Silver Compounds .....                                 | 343        |
| 6.5 Tabular Summary .....  | 345        |
| References .....   | 356        |
| <b>Subject Index .....</b>   | <b>363</b> |