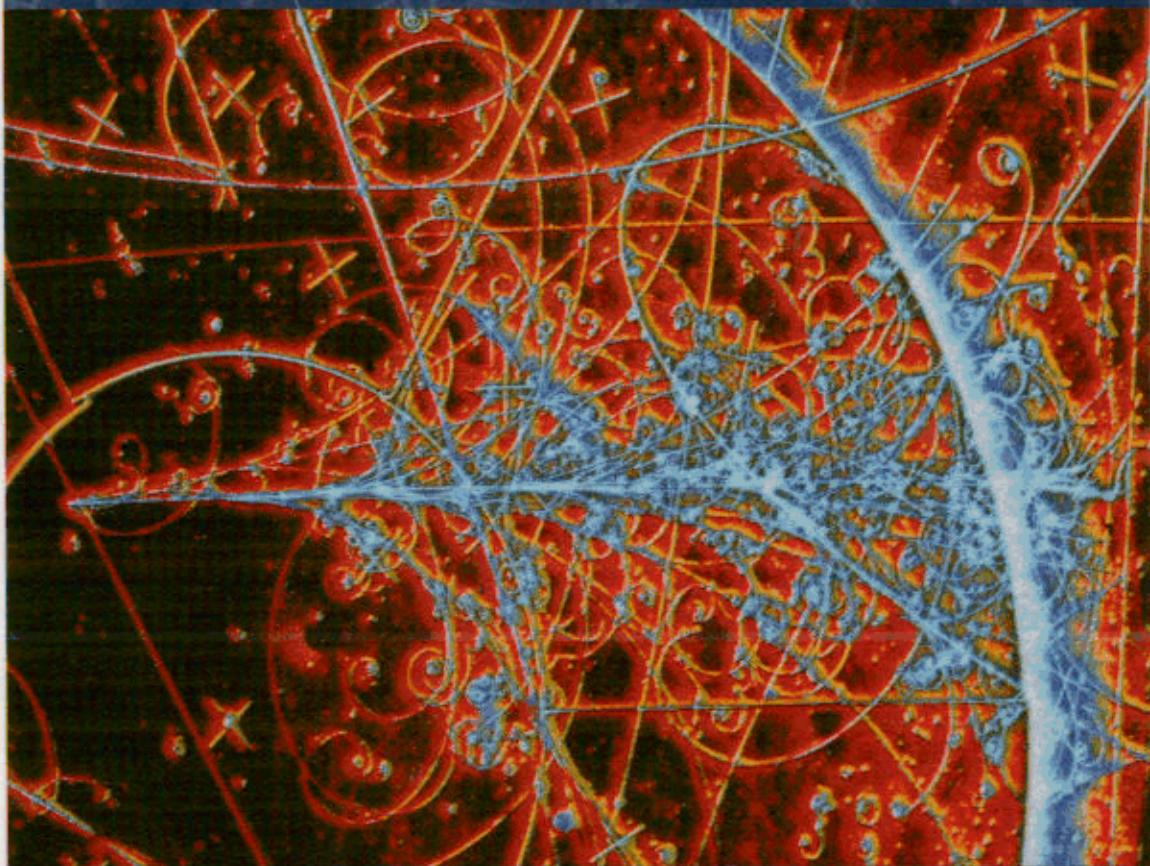


INTERNATIONAL STUDENT EDITION

third edition

# MODERN PHYSICS



SERWAY / MOSES / MOYER

Not for Sale in the  
United States

# Contents

## 1 RELATIVITY I 1

- 1.1 Special Relativity 2
- 1.2 The Principle of Relativity 3
  - The Speed of Light 6
- 1.3 The Michelson–Morley Experiment 7
  - Details of the Michelson–Morley Experiment 8
- 1.4 Postulates of Special Relativity 10
- 1.5 Consequences of Special Relativity 13
  - Simultaneity and the Relativity of Time 14
  - Time Dilation 15
  - Length Contraction 18
  - The Twins Paradox (Optional) 21
  - The Relativistic Doppler Shift 22
- 1.6 The Lorentz Transformation 25
  - Lorentz Velocity Transformation 29
- 1.7 Spacetime and Causality 31
- Summary 35

## 2 RELATIVITY II 41

- 2.1 Relativistic Momentum and the Relativistic Form of Newton's Laws 41
- 2.2 Relativistic Energy 44
- 2.3 Mass as a Measure of Energy 48
- 2.4 Conservation of Relativistic Momentum and Energy 52
- 2.5 General Relativity 53
  - Gravitational Radiation, or a Good Wave Is Hard to Find 56
- Summary 59

*Web Essay* The Renaissance of General Relativity  
*Clifford M. Will*

## 3 THE QUANTUM THEORY OF LIGHT 65

- 3.1 Hertz's Experiments—Light as an Electromagnetic Wave 66
  - 3.2 Blackbody Radiation 68
    - Enter Planck 72
    - The Quantum of Energy 74
  - 3.3 The Rayleigh–Jeans Law and Planck's Law (Optional) 77
    - Rayleigh–Jeans Law 77
    - Planck's Law 79
  - 3.4 Light Quantization and the Photoelectric Effect 80
  - 3.5 The Compton Effect and X-Rays 86
    - X-Rays 86
    - The Compton Effect 89
  - 3.6 Particle–Wave Complementarity 94
  - 3.7 Does Gravity Affect Light? (Optional) 95
  - Summary 98
- Web Appendix* Calculation of the Number of Modes of Waves in a Cavity  
Planck's Calculation of the Average Energy of an Oscillator

## 4 THE PARTICLE NATURE OF MATTER 106

- 4.1 The Atomic Nature of Matter 106
- 4.2 The Composition of Atoms 108
  - Millikan's Value of the Elementary Charge 113
  - Rutherford's Model of the Atom 119
- 4.3 The Bohr Atom 125
  - Spectral Series 126
  - Bohr's Quantum Model of the Atom 130

4.4	Bohr's Correspondence Principle, or Why Is Angular Momentum Quantized? 139	
4.5	Direct Confirmation of Atomic Energy Levels: The Franck–Hertz Experiment 141	
	Summary 143	

## 5 MATTER WAVES 151

5.1	The Pilot Waves of De Broglie 152	
	De Broglie's Explanation of Quantization in the Bohr Model 153	
5.2	The Davisson–Germer Experiment 154	
	The Electron Microscope 159	
5.3	Wave Groups and Dispersion 164	
	Matter Wave Packets 169	
5.4	Fourier Integrals (Optional) 170	
	Constructing Moving Wave Packets 173	
5.5	The Heisenberg Uncertainty Principle 173	
	A Different View of the Uncertainty Principle 175	
5.6	If Electrons Are Waves, What's Waving? 178	
5.7	The Wave–Particle Duality 179	
	The Description of Electron Diffraction in Terms of $\Psi$ 179	
	A Thought Experiment: Measuring Through Which Slit the Electron Passes 184	
5.8	A Final Note 186	
	Summary 186	

## 6 QUANTUM MECHANICS IN ONE DIMENSION 191

6.1	The Born Interpretation 191	
6.2	Wavefunction for a Free Particle 194	
6.3	Wavefunctions in the Presence of Forces 197	
6.4	The Particle in a Box 200	
	Charge-Coupled Devices (CCDs) 205	
6.5	The Finite Square Well (Optional) 209	
6.6	The Quantum Oscillator 212	
6.7	Expectation Values 217	
6.8	Observables and Operators 221	
	Quantum Uncertainty and the Eigenvalue Property (Optional) 222	
	Summary 224	

## 7 TUNNELING PHENOMENA 231

7.1	The Square Barrier 231	
7.2	Barrier Penetration: Some Applications 238	
	Field Emission 239	
	$\alpha$ Decay 242	
	Ammonia Inversion 245	
	Decay of Black Holes 247	
	Summary 248	
Essay	The Scanning Tunneling Microscope <i>Roger A. Freedman and Paul K. Hansma</i> 253	

## 8 QUANTUM MECHANICS IN THREE DIMENSIONS 260

8.1	Particle in a Three-Dimensional Box 260	
8.2	Central Forces and Angular Momentum 266	
8.3	Space Quantization 271	
8.4	Quantization of Angular Momentum and Energy (Optional) 273	
	$L_z$ Is Sharp: The Magnetic Quantum Number 275	
	$ \mathbf{L} $ Is Sharp: The Orbital Quantum Number 276	
	$E$ Is Sharp: The Radial Wave Equation 276	
8.5	Atomic Hydrogen and Hydrogen-like Ions 277	
	The Ground State of Hydrogen-like Atoms 282	
	Excited States of Hydrogen-like Atoms 284	
8.6	Antihydrogen 287	
	Summary 289	

## 9 ATOMIC STRUCTURE 295

9.1	Orbital Magnetism and the Normal Zeeman Effect 296	
9.2	The Spinning Electron 302	
9.3	The Spin–Orbit Interaction and Other Magnetic Effects 309	
9.4	Exchange Symmetry and the Exclusion Principle 312	
9.5	Electron Interactions and Screening Effects (Optional) 316	
9.6	The Periodic Table 319	
9.7	X-Ray Spectra and Moseley's Law 325	
	Summary 328	

<b>10 STATISTICAL PHYSICS 334</b>		<b>12 THE SOLID STATE 404</b>	
10.1	The Maxwell–Boltzmann Distribution 335 The Maxwell Speed Distribution for Gas Molecules in Thermal Equilibrium at Temperature $T$ 341 The Equipartition of Energy 343	12.1	Bonding in Solids 405 Ionic Solids 405 Covalent Solids 408 Metallic Solids 409 Molecular Crystals 409 Amorphous Solids 410
10.2	Under What Physical Conditions Are Maxwell–Boltzmann Statistics Applicable? 344	12.2	Classical Free Electron Model of Metals 413 Ohm's Law 414 Classical Free Electron Theory of Heat Conduction 418
10.3	Quantum Statistics 346 Wavefunctions and the Bose–Einstein Condensation and Pauli Exclusion Principle 346 Bose–Einstein and Fermi–Dirac Distributions 347	12.3	Quantum Theory of Metals 420 Replacement of $v_{rms}$ with $v_F$ 421 Wiedemann–Franz Law Revisited 422 Quantum Mean Free Path of Electrons 423
10.4	Applications of Bose–Einstein Statistics 351 Blackbody Radiation 351 Einstein's Theory of Specific Heat 352	12.4	Band Theory of Solids 425 Isolated-Atom Approach to Band Theory 425 Conduction in Metals, Insulators, and Semiconductors 426 Energy Bands from Electron Wave Reflections 429
10.5	An Application of Fermi–Dirac Statistics: The Free-Electron Gas Theory of Metals 356 Summary 360 <i>Essay</i> Laser Manipulation of Atoms <i>Steven Chu</i> 366	12.5	Semiconductor Devices 433 The <i>p-n</i> Junction 433 Light-Emitting and -Absorbing Diodes—LEDs and Solar Cells 436 The Junction Transistor 437 The Field-Effect Transistor (FET) 439 The Integrated Circuit 441
11.1	<b>11 MOLECULAR STRUCTURE 372</b>	12.6	Superconductivity 443
11.1	Bonding Mechanisms: A Survey 373 Ionic Bonds 374 Covalent Bonds 374 van der Waals Bonds 375 The Hydrogen Bond 377	12.7	Lasers 447 Absorption, Spontaneous Emission, and Stimulated Emission 447 Population Inversion and Laser Action 449 Semiconductor Lasers 451
11.2	Molecular Rotation and Vibration 377 Molecular Rotation 378 Molecular Vibration 381	Summary 454 <i>Web Essay</i> The Invention of the Laser <i>S. A. Marshall</i>	
11.3	Molecular Spectra 385	<i>Web Essay</i> Photovoltaic Conversion <i>John D. Meakin</i>	
11.4	Electron Sharing and the Covalent Bond 390 The Hydrogen Molecular Ion 390 The Hydrogen Molecule 396	<i>Web Chapter</i> Superconductivity	
11.5	Bonding in Complex Molecules (Optional) 397 Summary 399 <i>Web Appendix</i> Overlap Integrals of Atomic Wavefunctions	<b>13 NUCLEAR STRUCTURE 463</b>	
13.1	Some Properties of Nuclei 464 Charge and Mass 465 Size and Structure of Nuclei 466 Nuclear Stability 468 Nuclear Spin and Magnetic Moment 469 Nuclear Magnetic Resonance and Magnetic Resonance Imaging 470		

13.2	Binding Energy and Nuclear Forces	472	15.3	Mesons and the Beginning of Particle Physics	553
13.3	Nuclear Models	476	15.4	Classification of Particles	556
	Liquid-Drop Model	476		Hadrons	556
	Independent-Particle Model	478		Leptons	557
	Collective Model	479		The Solar Neutrino Mystery and Neutrino Oscillations	558
13.4	Radioactivity	479	15.5	Conservation Laws	559
13.5	Decay Processes	484		Baryon Number	560
	Alpha Decay	484		Lepton Number	560
	Beta Decay	487	15.6	Strange Particles and Strangeness	561
	Carbon Dating	489	15.7	How Are Elementary Particles Produced and Particle Properties Measured?	563
	Gamma Decay	491		Resonance Particles	564
13.6	Natural Radioactivity	492		Energy Considerations in Particle Production	568
	Four Radioactive Series	492	15.8	The Eightfold Way	571
	Determining the Age of the Earth	493	15.9	Quarks	574
	Summary	495		The Original Quark Model	574
				Charm and Other Developments	575

## **14 NUCLEAR PHYSICS APPLICATIONS 503**

14.1	Nuclear Reactions	503
14.2	Reaction Cross Section	506
14.3	Interactions Involving Neutrons	508
14.4	Nuclear Fission	510
14.5	Nuclear Reactors	513
	Neutron Leakage	515
	Regulating Neutron Energies	515
	Neutron Capture	515
	Control of Power Level	515
	Safety and Waste Disposal	516
14.6	Nuclear Fusion	517
	Fusion Reactions	518
	Magnetic Field Confinement	521
	Inertial Confinement	523
	Fusion Reactor Design	524
	Advantages and Problems of Fusion	526
14.7	Interaction of Particles with Matter	526
	Heavy Charged Particles	526
	Electrons	528
	Photons	528
14.8	Radiation Damage in Matter	530
14.9	Radiation Detectors	532
14.10	Uses of Radiation	536
	Tracing	536
	Neutron Activation Analysis	537
	Radiation Therapy	538
	Food Preservation	539
	Summary	539

## **15 ELEMENTARY PARTICLES 547**

15.1	The Fundamental Forces in Nature	548
15.2	Positrons and Other Antiparticles	550

15.3	Mesons and the Beginning of Particle Physics	553
15.4	Classification of Particles	556
	Hadrons	556
	Leptons	557
	The Solar Neutrino Mystery and Neutrino Oscillations	558
15.5	Conservation Laws	559
	Baryon Number	560
	Lepton Number	560
15.6	Strange Particles and Strangeness	561
15.7	How Are Elementary Particles Produced and Particle Properties Measured?	563
	Resonance Particles	564
	Energy Considerations in Particle Production	568
15.8	The Eightfold Way	571
15.9	Quarks	574
	The Original Quark Model	574
	Charm and Other Developments	575
15.10	Colored Quarks, or Quantum Chromodynamics	577
	Experimental Evidence for Quarks	578
	Explanation of Nuclear Force in Terms of Quarks	579
15.11	Electroweak Theory and the Standard Model	580
15.12	Beyond the Standard Model	582
	Grand Unification Theory and Supersymmetry	582
	String Theory—A New Perspective	582
	Summary	583
	<i>Essay How to Find a Top Quark</i>	590
	<i>Melissa Franklin and David Kestenbaum</i>	

## **16 COSMOLOGY (Web Only)**

### **APPENDIX A BEST KNOWN VALUES FOR PHYSICAL CONSTANTS A.1**

### **APPENDIX B TABLE OF SELECTED ATOMIC MASSES A.2**

### **APPENDIX C NOBEL PRIZES A.7**

### **ANSWERS TO ODD-NUMBERED PROBLEMS A.12**

### **INDEX I.1**