
Contents

General Notations	XIX
-------------------------	-----

Part I General

1 Introduction	3
1.1 Brief Historical Survey	3
1.1.1 Particle Penetration	3
1.1.2 Radiation Effects	9
1.2 Applications	10
1.2.1 Fundamental Physics Research	11
1.2.2 Astrophysics and Space Science	11
1.2.3 Plasma Physics and Fusion Research	12
1.2.4 Materials Research and Engineering	12
1.2.5 Analytical Chemistry	16
1.2.6 Biomedical Research	17
1.3 Measurements and Experimental Tools	18
1.3.1 Sources of Energetic Charged Particles	18
1.3.2 Targets and Detecting Devices	19
1.4 General-Physics and Related Aspects	20
1.5 Literature	21
1.6 Nomenclature	22
Problems	22
References	24
2 Elementary Penetration Theory	27
2.1 Introductory Comments	27
2.2 Collision Statistics	28
2.2.1 Definition of Cross Section	28
2.2.2 Multiple Collisions; Poisson's Formula	31
2.2.3 Energy Loss	33

2.2.4	Energy-Loss Straggling	34
2.2.5	Differential Cross Section	36
2.2.6	Range	36
2.3	Electronic and Nuclear Stopping	38
2.3.1	General Considerations	38
2.3.2	Free-Coulomb Collision	39
2.3.3	Stopping and Straggling	42
2.3.4	Adiabatic Limit to Electronic Stopping	44
2.3.5	Relativistic Extension	46
2.3.6	Validity of Classical-Orbit Picture	47
2.3.7	Screening in Nuclear Stopping	49
2.4	Multiple Scattering	51
2.4.1	Small-Angle Approximation	51
2.4.2	Statistics	52
2.4.3	Nuclear and Electronic Scattering	54
2.5	Estimates	56
2.5.1	Alpha Particles	56
2.5.2	Preview: Energy and Z_1 dependence	57
2.6	Electron and Positron Penetration	58
2.7	Discussion and Outlook	60
Problems		61
References		64
3	Elastic Scattering	67
3.1	Introductory Comments	67
3.2	Conservation Laws	68
3.2.1	Nonrelativistic Regime	68
3.2.2	Relativistic Regime	71
3.3	Classical Scattering Theory	74
3.3.1	The Scattering Integral	74
3.3.2	Runge-Lenz Vector and Rutherford's Law	76
3.3.3	Scaling Relations	79
3.3.4	Time Integral (*)	80
3.3.5	Relativistic Scattering Integral (*)	82
3.3.6	Perturbation Theory (*)	84
3.4	Quantum Theory of Elastic Scattering	85
3.4.1	Laboratory and Center-of-Mass Variables	85
3.4.2	Scattering Amplitude and Differential Cross Section	86
3.4.3	Born Approximation	88
3.4.4	Partial-Wave Expansion	92
3.5	Coulomb Scattering	97
3.5.1	Phase Shifts	97
3.5.2	Cross Section (*)	98
3.5.3	Relativistic Extension	100
3.6	Discussion and Outlook	101

Problems	101
References	104

Part II Stopping

4 Stopping of Swift Point Charge I: Bohr and Bethe Theory	109
4.1 Introductory Comments	109
4.2 Classical Perturbation Theory	110
4.2.1 Energy Transfer to Harmonic Oscillator	110
4.2.2 Distant Collisions: Dipole Approximation	112
4.2.3 Relativistic Extension	114
4.3 Semiclassical Theory	115
4.3.1 General Considerations	115
4.3.2 Time-Dependent Perturbation Theory	116
4.3.3 Distant Collisions	117
4.3.4 Excitation Cross Section	119
4.4 Plane-Wave Born Approximation	120
4.4.1 General Considerations	120
4.4.2 Stationary Perturbation Theory	120
4.4.3 Excitation Cross Section	122
4.4.4 Coulomb Interaction	124
4.5 The Stopping Cross Section	124
4.5.1 Bohr Stopping Formula	124
4.5.2 Semiclassical Theory: Harmonic Oscillator	129
4.5.3 Plane-Wave Born Approximation	131
4.5.4 Bethe Stopping Formula	132
4.5.5 Mean Logarithmic Excitation Energy	135
4.6 Discussion and Outlook	135
Problems	137
References	138
5 Dielectric Stopping Theory	141
5.1 Introductory Comments	141
5.2 Electrodynamics	142
5.2.1 Field Equations in Vacuum	142
5.2.2 Linear Response	144
5.2.3 Connection to Stopping Force	145
5.3 Gaseous Medium	146
5.3.1 Dielectric Function	147
5.3.2 Bethe Stopping Formula	148
5.3.3 Nonrelativistic Density Effect	149
5.4 Static Electron Gas	151
5.4.1 Dielectric Function	151
5.4.2 Relativistic Extension (*)	152

5.4.3	Stopping Force	153
5.4.4	Oscillator Strength, Equipartition Rule and Differential Cross Section	155
5.4.5	Plasmon-Pole Approximation (*)	157
5.5	Assembly of Harmonic Oscillators (*)	157
5.5.1	Dielectric Function	157
5.5.2	Excitation Spectrum	158
5.5.3	Stopping Force	159
5.6	Relativistic Bethe Stopping Theory (*)	159
5.6.1	Regimes of Momentum Transfer	159
5.6.2	Transverse Field: Low Momentum Transfers	160
5.6.3	High Momentum Transfers	163
5.6.4	Relativistic Density Effect	164
5.7	Fermi Gas	170
5.7.1	Electronic States	170
5.7.2	Lindhard Function	171
5.7.3	Degenerate Fermi Gas	172
5.7.4	Stopping Force at High Projectile Speed	174
5.8	Discussion and Outlook	176
Problems		178
References		179
 Stopping of Swift Point Charge II: Extensions		181
6.1	Introductory Comments	181
6.2	Bare and Dressed Projectiles	183
6.2.1	Bohr Screening Criterion	183
6.3	Bloch Theory	184
6.3.1	Bloch Formula	184
6.3.2	Derivation	186
6.3.3	Inverse-Bloch Correction	188
6.3.4	Impact-Parameter Dependence	188
6.4	Barkas-Andersen Effect	190
6.4.1	Overview	190
6.4.2	Dimensional Arguments	192
6.4.3	Binding and Screening	193
6.4.4	Higher-Order Perturbation Theory	194
6.4.5	Beyond Perturbation Theory	201
6.5	Stopping Medium in Internal Motion	206
6.5.1	Nonrelativistic Regime	206
6.5.2	Relativistic Extension (*)	207
6.5.3	A Useful Transformation	209
6.5.4	High-Speed Expansion: Nonrelativistic	209
6.5.5	Relativistic Orbital Speed (*)	210
6.6	Shell Correction	210
6.6.1	Introduction	210

6.6.2	Bohr Theory	211
6.6.3	Bethe Theory	212
6.6.4	Kinetic Theory	215
6.6.5	Is the Shell Correction Purely Kinematic?	216
6.7	Relativistic Projectile Speed	217
6.7.1	General Observations	217
6.7.2	Lindhard-Sørensen Theory (*)	218
6.7.3	Additional Effects	221
6.8	Discussion and Outlook	221
	Problems	222
	References	223
7	Arriving at Numbers	229
7.1	Introductory Comments	229
7.2	Stopping Models I: Statistical Method	230
7.2.1	Thomas-Fermi Model of the Atom	230
7.2.2	Scaling Properties	230
7.2.3	Charge and Velocity Distributions	232
7.2.4	The Lindhard-Scharff Model and its Implementation	234
7.2.5	Generalizations	239
7.3	Stopping Models II	240
7.3.1	Shell and Subshell Splitting	240
7.3.2	Kinetic Theory	243
7.3.3	Harmonic-Oscillator Model	243
7.3.4	Binary-Collision Models	246
7.3.5	Numerical Simulations	248
7.4	Remarks on Stopping Measurements	249
7.4.1	Energy-Loss Spectra in Transmission	249
7.4.2	Other Measurements on Thin Foils	250
7.4.3	Reflection Geometry	250
7.4.4	Doppler-Shift Attenuation	251
7.4.5	Pitfalls	251
7.4.6	Range Measurements	251
7.5	Extraction of Input Parameters from Stopping Measurements	251
7.5.1	<i>I</i> -Values and Shell Correction	252
7.5.2	Barkas-Andersen and Bloch Correction	252
7.5.3	Z_2 Structure	254
7.6	Input Parameters from Other Sources	254
7.6.1	Theory	254
7.6.2	Optical and X-Ray Data	256
7.7	Compound Materials and Bragg Additivity	256
7.8	Data Compilations and Codes	260
7.9	Discussion and Outlook	261
	Problems	268
	References	268

Part III Straggling

8	Energy-Loss Straggling: Variance and Higher Cumulants	277
8.1	Introductory Comments	277
8.2	Classical versus Quantum Theory	278
8.3	Bohr Theory	280
8.4	Born Approximation	283
8.4.1	Harmonic oscillator	283
8.4.2	Bethe Approximation	283
8.4.3	Relativistic Extension (★)	286
8.4.4	Density Effect	288
8.5	Fermi Gas (★)	288
8.5.1	Expression for Straggling	288
8.5.2	Static Electron Gas	289
8.5.3	Degenerate Fermi Gas: High Projectile Speed	290
8.6	Shell Correction: Kinetic Theory (★)	292
8.6.1	High-Speed Expansion	293
8.6.2	Relativistic Extension	293
8.6.3	Bohr Theory	293
8.6.4	Bethe Theory	294
8.6.5	Quantum Oscillator	294
8.6.6	Bloch Theory	294
8.6.7	Fermi Gas	295
8.6.8	Full Integration	295
8.7	Barkas-Andersen Correction (★)	295
8.8	Relativity: Lindhard-Sørensen Theory (★)	299
8.9	Bunching	300
8.9.1	Classical Estimate	300
8.9.2	Bunching in Helium	302
8.9.3	Molecular Gas	304
8.9.4	Dense Matter	307
8.10	Straggling Measurements	312
8.10.1	Gas Targets	312
8.10.2	Solid Targets	315
8.11	Third- and Higher-Order Moments (★)	317
8.11.1	Moments and Cumulants	317
8.11.2	Free-Coulomb Scattering	318
8.11.3	Bohr Theory	318
8.11.4	Born Approximation	319
8.11.5	Relativistic Extension	320
8.11.6	Fermi Gas	321
8.11.7	Kinetic Theory	321

8.12	Discussion and Outlook	322
	Problems	322
	References	324
9	Energy-Loss Spectra	327
9.1	Introductory Comments	327
9.2	General Aspects	327
9.2.1	Bothe-Landau Formula	329
9.2.2	Bunching	332
9.2.3	Moments and Cumulants to Arbitrary Order	332
9.2.4	Diffusion Approximation	333
9.2.5	An Integrable Energy-Loss Spectrum	334
9.3	Thin Targets	337
9.3.1	Bohr-Williams Approach	337
9.3.2	Landau's Solution	340
9.3.3	Lindhard's Solution (*)	342
9.3.4	Glazov's Solution	344
9.4	Moderately Thick Targets	346
9.4.1	Vavilov Scheme (*)	346
9.4.2	Method of Steepest Descent	349
9.4.3	Applications	353
9.4.4	Straight Convolution	355
9.5	Transport Equations	357
9.5.1	Derivation by Two-Layer Argument	357
9.5.2	Forward and Backward Equations	358
9.6	Very Thick Targets (*)	359
9.6.1	Continuous Slowing-Down Approximation	360
9.6.2	Ionization Yield	360
9.6.3	Stopping Measurement on a Thick Target	361
9.6.4	Straggling According to Symon (*)	362
9.6.5	Nonstochastic Broadening and Skewing	365
9.6.6	Method of Moments	367
9.7	Simulation	367
9.7.1	Monte Carlo Schemes	367
9.7.2	Procedure	368
9.7.3	Equivalence with Transport Theory (*)	369
9.8	Discussion and Outlook	369
	Problems	371
	References	373

Part IV Appendices

Selected Tutorials	377
A.1 Units	377
A.1.1 Electromagnetic Units	377
A.1.2 Atomic Units	379
A.1.3 Length Measures	379
A.2 Calculus	380
A.2.1 Poisson Statistics	380
A.2.2 Fourier Transform	382
A.2.3 Spherical Harmonics and Legendre Polynomials	384
A.2.4 Dirac Function	387
A.2.5 Green Functions	390
A.3 Mechanics	395
A.3.1 Classical Perturbation Theory	395
A.3.2 Relativity	399
A.4 Quantum Mechanics	402
A.4.1 Gaussian Wave Packets	402
A.4.2 Time-Dependent Perturbation Theory	404
A.4.3 Generalized Oscillator Strengths for the Harmonic Oscillator	406
A.4.4 Sum Rules	408
A.4.5 Dirac Equation	410
A.5 Dispersion and Absorption	412
A.5.1 Drude Theory for a Dilute Gas	412
A.5.2 Quantum Theory for a Dilute Gas	413
A.5.3 Dense Media	415
A.5.4 Lindhard Function of the Fermi Gas	415
References	416
Books and Reviews	419
References	422
Author Index	425
Subject Index	429