

THE PHYSICS OF PARTICLE DETECTORS

DAN GREEN

Fermilab



CAMBRIDGE
UNIVERSITY PRESS

Contents

	<i>Acknowledgments</i>	<i>page</i> xiii
I	Introduction	1
1	Size, energy, cross section	5
1.1	Units	5
1.2	Planck constant	6
1.3	Electromagnetic units	6
1.4	Coupling constants	12
1.5	Atomic energy scales	12
1.6	Atomic size	15
1.7	Atomic spin effects	17
1.8	Cross section and mean free path	17
1.9	Partial waves and differential cross section	19
1.10	Nuclear scales of energy and size	22
1.11	Nuclear cross section	23
1.12	Photon cross section	25
	Exercises	27
	References	28
II	Non-destructive measurements	29
IIA	Time and velocity	29
2	The photoelectric effect, photomultipliers, scintillators	31
2.1	Interaction Hamiltonian	31
2.2	Transition amplitude and cross section	32
2.3	The angular distribution	38
2.4	The photomultiplier tube	38
2.5	Time of flight	39
2.6	Scintillators and light collection	41
2.7	Gain and time structure	43
2.8	Wavelength shifting	47

2.9	Coincidence logic and deadtime	50
	Exercises	53
	References	53
3	Cerenkov radiation	55
3.1	Units	55
3.2	Index of refraction	58
3.3	Optical theorem	59
3.4	Conducting medium and skin depth	59
3.5	Plasma frequency	61
3.6	Two 'derivations' of the Cerenkov angle	62
3.7	A 'derivation' of the frequency spectrum	69
3.8	Examples and numerical values	70
	Exercises	73
	References	74
4	Transition radiation	75
4.1	Cerenkov radiation for a finite length radiator	75
4.2	Interference effects	77
4.3	The vacuum phase shift	79
4.4	The frequency spectrum	79
4.5	Dependence on γ and saturation	81
4.6	TRD foil number and thickness	83
4.7	TRD data	85
	Exercises	85
	References	87
IIB	Scattering and ionization	89
5	Elastic electromagnetic scattering	91
5.1	Single scattering off a nucleus	91
5.2	The scattering cross section	93
5.3	Feynman diagrams	94
5.4	Relativistic considerations	95
5.5	Multiple scattering	96
5.6	The radiation length	97
5.7	Small angle, three dimensional multiple scattering	98
5.8	Maximum momentum transfer	100
5.9	Energy transfer	103
5.10	Delta rays	103
5.11	Other force laws	104
	Exercises	105
	References	105

6	Ionization	106
6.1	Energy loss	106
6.2	Minimum ionizing particle	107
6.3	Velocity dependence	108
6.4	Range	111
6.5	Radioactive sources	115
6.6	The logarithmic dependence and relativistic rise	117
6.7	Fluctuations	119
6.8	The critical energy	121
	Exercises	125
	References	125
IIC	Position and momentum	127
7	Magnetic fields	129
7.1	Solenoidal fields	129
7.2	Dipole fields – fringe fields	130
7.3	Particle motion in a uniform field	133
7.4	Momentum measurement and error	135
7.5	Exact solutions – Cartesian and cylindrical coordinates	138
7.6	Particle beam and quadrupole magnets	140
7.7	The quadrupole doublet	146
	Exercises	148
	References	150
8	Drift and diffusion in materials, wire chambers	151
8.1	Thermal and drift velocity	151
8.2	Mobility	153
8.3	Pulse formation in ‘unity gain’ detectors	154
8.4	Diffusion and the diffusion limit	158
8.5	Motion in \mathbf{E} and \mathbf{B} fields, with and without collisions	161
8.6	Wire chamber electrostatics	165
8.7	Pulse formation in a wire chamber	167
8.8	Mechanical considerations	169
8.9	The induced cathode signal	172
	Exercises	175
	References	175
9	Silicon detectors	177
9.1	Impact parameter and secondary vertex	177
9.2	Band gap, intrinsic semiconductors and ionization	181
9.3	The silicon diode fields	182
9.4	The silicon diode: signal formation at depletion	186

9.5	Noise sources – thermal and shot noise	190
9.6	Filtering and the ‘equivalent noise charge’	194
9.7	Front end transistor noise	196
9.8	Total noise charge	197
9.9	Hybrid silicon devices	199
	Exercises	200
	References	201
III	Destructive measurements	203
IIIA	Radiation	203
10	Radiation and photon scattering	205
10.1	Non-relativistic radiation	205
10.2	Thomson scattering	207
10.3	Thomson scattering off objects with structure	209
10.4	Relativistic photon scattering	210
10.5	Compton scattering	211
10.6	Relativistic acceleration	213
10.7	Circular and linear acceleration	216
10.8	Angular distribution	217
10.9	Synchrotron radiation	219
10.10	Synchrotron applications	221
10.11	Photon emission kinematics	224
10.12	Photon frequency spectrum	224
10.13	Bremsstrahlung and pair production	225
10.14	The radiation length	227
10.15	Pair production by photons	229
10.16	Pair production by charged particles	230
10.17	Strong and electromagnetic interaction probabilities	231
	Exercises	231
	References	232
IIIB	Energy measurements	235
11	Electromagnetic calorimetry	237
11.1	Radiation length and critical energy	237
11.2	The electromagnetic cascade	238
11.3	Energy – linearity and resolution	241
11.4	Profiles and single cascades	243
11.5	Sampling devices	245
11.6	Fully active devices	247
11.7	Transverse energy flow	251
11.8	Calibration methods	254
	Exercises	256
	References	257

12	Hadronic calorimetry	258
12.1	Properties of single hadronic interactions	259
12.2	The hadronic cascade – neutrals	262
12.3	Binding energy effects	264
12.4	Energy resolution	266
12.5	Profiles and single cascades	268
12.6	elh and the ‘constant term’	273
12.7	Transverse energy flow	278
12.8	Radiation damage	280
12.9	Energy leakage	281
12.10	Neutron radiation fields	284
12.11	Neutron detection	286
	Exercises	288
	References	289
IV	The complete set of measurements	291
13	Summary	293
13.1	Fundamental particles	293
13.2	Detection of fundamental particles	294
13.3	General purpose detectors	298
13.4	The jumping off point	300
	References	301
	Appendices	303
A	Kinematics	305
B	Quantum bound states and scattering cross section	311
C	The photoelectric effect	317
D	Connecting cables	320
E	The emission of Cerenkov radiation	324
F	Motion in a constant magnetic field	328
G	Non-relativistic motion in combined constant E and B fields	331
H	Signal generation in a silicon diode for point ionization	333
I	Ideal operational amplifier circuits	336
J	Statistics introduction	342
K	Monte Carlo models	348
	<i>Glossary of symbols</i>	353
	<i>Index</i>	357