

Contents

1 Sources of ionizing radiation and shielding concepts

1.1	Introduction	1
1.1.1	Description of the volume and its use	1
1.1.2	Ionizing radiation	2
1.1.3	Biological effects	4
1.1.4	Damage to materials	15
1.1.5	Sources of high-energy radiation	23
1.2	Shielding estimations	27
1.2.1	Reduction of harmful effects of the radiation field	27
1.2.2	Attenuation processes	28
1.2.3	Conceptual considerations	29
1.3	Further information	30
1.3.1	General references	30
1.3.2	Useful general data	31
1.3.3	Definitions of quantities and expressions used in this volume	53
1.3.4	List of frequently used symbols	62
1.4	References for 1	64

2 Hadron attenuation

2.1	Introduction	67
2.2	Physical processes	68
2.2.1	Inelastic hadron-nucleus scattering	68
2.2.2	Elastic hadron-nucleus scattering	74
2.2.3	Ionization energy loss, multiple Coulomb scattering	77
2.2.4	Particle production	78
2.2.4.1	Definitions, kinematics	78
2.2.4.2	Exclusive and inclusive particle production cross-sections	79
2.2.4.3	Particle production in hadron-hadron collisions	80
2.2.4.4	Hadron production in hadron-nucleus collisions	86
2.2.4.5	Models for particle production in hadron-nucleus collisions	89
2.2.4.6	A Monte-Carlo chain fragmentation model	92
2.2.4.7	Hadron-hadron and hadron-nucleus collisions at energies below 5 GeV	92
2.2.4.8	Nuclear excitation energies and production of cascade nucleons	96
2.3	The hadron cascade	98
2.3.1	The Boltzmann equation and its analytic solutions	98
2.3.2	Monte-Carlo solutions	100
2.3.2.1	FLUKA	101
2.3.2.2	CASIM	102
2.3.2.3	HETC	103
2.4	Results of the Monte-Carlo calculations	104
2.4.1	Introduction	104
2.4.2	Monte-Carlo calculations of hadron-meson cascades in large beam dumps	106
2.4.3	Results of Monte-Carlo calculations for a target in a cylindrical tunnel	117
2.4.4	Monte-Carlo results for a small target inside a magnet in a tunnel	122
2.5	Empirical shielding formulae	124
2.5.1	Dose equivalent per star in hadron cascade calculations	124
2.5.2	Design of hadron shielding for beam-stops	126
2.5.2.1	Lateral shielding	126

2.5.2.2 Longitudinal shielding	127
2.5.3 Hadron shielding for targets in tunnels	129
2.5.4 Shielding of extended line sources	133
2.6 Estimation of shielding thickness	136
2.6.1 Lateral shielding	137
2.6.2 Forward shielding	146
2.7 Other results from hadron cascade calculations	152
2.7.1 The absorbed dose	152
2.7.2 Radiation heating	156
2.7.3 Energy deposition in standard configurations	157
2.7.3.1 Energy deposition in beam dumps	157
2.7.3.2 Energy deposition in targets	161
2.7.3.3 Energy deposition in a hollow cylinder simulating a target in a magnet	162
2.7.3.4 Reliability of estimates	163
2.7.4 Estimation of remanent dose rates	164
2.8 References for 2	165

3 Electron attenuation

3.1 Introduction	172
3.2 Physical processes	172
3.2.1 Introduction	172
3.2.1.1 Elementary interactions of electrons	172
3.2.1.2 Average quantities	174
3.2.1.3 Collective effects in condensed matter	174
3.2.1.4 Photon interactions	175
3.2.2 Electron processes	175
3.2.2.1 Bremsstrahlung	175
3.2.2.2 Average energy loss by collision (mass stopping power)	225
3.2.2.3 Elastic scattering	226
3.2.2.4 Annihilation of electron-positron pairs	227
3.2.2.5 Møller and Bhabha scattering	228
3.2.2.6 Direct pair production	228
3.2.2.7 Nuclear processes	228
3.2.2.8 Collective effects	228
3.2.3 Photonic processes	229
3.2.3.1 Pair production	229
3.2.3.2 Compton effect	265
3.2.3.3 Photoelectric effect	265
3.2.3.4 Photonuclear reactions	266
3.2.3.5 Rayleigh scattering	266
3.2.3.6 Photon nuclear scattering	266
3.2.3.7 Attenuation of photons	266
3.3 Electromagnetic cascades	267
3.3.1 Introduction	267
3.3.1.1 Description of the phenomenon	267
3.3.1.2 Electron and photon dosimetry in different energy ranges	268
3.3.1.3 Photon and electron transport as a function of energy	269
3.3.1.4 The problem of measurement	269
3.3.2 Characteristics of an electromagnetic shower	270
3.3.2.1 Multiplication	270
3.3.2.2 Shower maximum	271
3.3.2.3 Shower tail	271
3.3.2.4 Transition curve and shower profile on axis	271
3.3.2.5 Radial and angular spread	272
3.3.2.6 Shower track-length and equilibrium spectrum	274
3.3.2.7 Shower moments	274

3.3.2.8 Transition effects	274
3.3.2.9 Other cascade components	275
3.3.3 Shower theory	276
3.3.3.1 Principles of the one-dimensional theory	276
3.3.3.2 The diffusion equations	277
3.3.3.3 Mathematical solutions	278
3.3.3.4 Various approximations	278
3.3.3.5 Formulae and tables used in the description of electromagnetic showers	280
3.3.4 Monte-Carlo simulation of cascades	282
3.3.5 Experimental data	284
3.3.5.1 Transition curves	284
3.3.5.2 Profile on axis	291
3.3.5.3 Radial and angular distribution	291
3.3.6 Photonuclear reactions	291
3.3.6.1 Low-energy region	292
3.3.6.2 Giant Dipole Resonance	293
3.3.6.3 Quasi-Deuteron Effect	301
3.3.6.4 The high-energy region	306
3.4 Shielding against electrons	309
3.4.1 Introduction	309
3.4.2 The beam dump case	310
3.4.2.1 General considerations	310
3.4.2.2 Electromagnetic source terms	314
3.4.2.3 Giant resonance neutrons	316
3.4.2.4 High-energy particles	318
3.4.3 The target case	320
3.4.3.1 General considerations	320
3.4.3.2 The electromagnetic source term	320
3.4.3.3 Giant resonance neutrons	323
3.4.3.4 High-energy particles	324
3.5 Tables of shielding requirements in practical situations	324
3.5.1 Forward shielding of a dump	324
3.5.2 Lateral shielding of a dump	329
3.5.3 Lateral shielding around a target	331
3.6 References for 3	336

4 Muon transport

4.1 Introduction	350
4.1.1 Sources of muons at high-energy accelerators	350
4.1.2 Muons from π and K decay	350
4.1.3 Muons from charm and bottom decay	353
4.1.4 Pair-production of muons	357
4.2 Interaction of muons with matter	358
4.2.1 Ionization energy loss and multiple Coulomb scattering	358
4.2.2 Bremsstrahlung	360
4.2.3 Direct electron pair production	363
4.2.4 Interactions of muons with nucleons	365
4.3 Muon slowing-down	368
4.3.1 Introduction	368
4.3.2 Total energy loss and mean ranges of muons	368
4.3.3 Range straggling	381
4.4 Multiple scattering	384
4.4.1 Comparison of muon scattering processes	384
4.4.2 Multiple scattering with energy loss	388

4.5	Muons from proton-induced cascades	394
4.5.1	Introduction	394
4.5.2	Comparison of various simulation programs	394
4.5.3	Comparison with experimental data	402
4.6	Specification of muon shielding	402
4.6.1	Introduction	402
4.6.2	Conversion of muon fluence to dose equivalent	403
4.6.3	Shielding of proton end-stops	404
4.6.4	Shielding of electron end-stops	404
4.7	References for 4	407

Appendix: Transmission dominated by low-energy phenomena

A.1	Neutron skyshine	411
A.1.1	Introduction	411
A.1.2	Comparison of calculations and experimental data	411
A.1.3	Empirical relations for neutron fluence at large distances	415
A.2	Neutron attenuation in labyrinths, ducts and penetrations	417
A.2.1	Introduction	417
A.2.2	Calculation of transmission through ducts and labyrinths	417
A.2.3	Measurement of the transmission in straight ducts	418
A.2.4	Prediction of transmission in ducts and labyrinths	420
A.2.5	Neutron traps and curved tunnels	422
A.3	Photon attenuation in labyrinths, ducts and penetrations	423
A.3.1	Introduction	423
A.3.2	Calculations	423
A.3.3	Prediction of transmission in ducts and labyrinths	424
A.4	References to appendix	425