Part I

Introduction

The subject of particle detectors covers those devices by which the existence and attributes of particles in a detecting medium is made manifest to us. The full and complete understanding of these devices requires a good understanding of basic physics. Without that knowledge we are simply 'mechanics' without the capacity to advance the state of the art of detector technology. On the other hand, a rigorous understanding from first principles is also not an optimal approach. The 'useful' understanding of a given device proceeds from an understanding of what approximations to full rigor are possible. That understanding can only come from experience and it is the purpose of this volume to communicate that experience. The aim of this text is to steer a perilous course between the purely descriptive and the purely theoretical.

The role of detectors can be visualized by assuming that an interesting interaction occurs at a point in space and time. From that point several secondary particles of different masses are emitted with various angles and momenta as shown in Fig. I.1. It is the job of the detector designer to measure the time of interaction, t, and the vector momenta, $\mathbf{p}_i$, and masses, M_i, of those emitted particles. The text is organized so as to show the ensemble of tools available to the designer. Typically, mathematical detail and topics outside the main scope of the text are relegated to the Appendices.

A list of the topics covered is given in the Table of Contents. The first chapter is an introduction devoted to a numerical description of the appropriate size, energy scales, and cross sections for different processes. The numerical data given in the tables of Chapter 1 will constantly be referred to in later chapters.

There then follow eight chapters on 'non-destructive' measurements, or those which do not appreciably change the measured particle's position or momentum. The first subtopic concerns the measurement of time and velocity. Chapter 2 starts with the basic physics of the photoelectric effect and leads into photomultiplier tubes, scintillator and time of flight measurement.

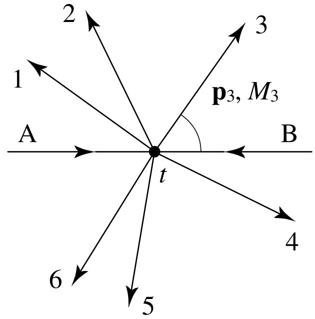

Fig. I.1. A schematic representation of the reaction A + B → 1 + 2 + 3 + 4 + 5 + 6. The reaction is specified when the vector momentum and mass of each particle is determined.

Chapter 3 describes velocity measurement by way of the emission of optical photons in the Cerenkov process. Chapter 4 follows with a discussion of the closely related emission of x-ray photons in transition radiation which also determines the velocity of a particle.

The second subtopic within non-destructive readout first lays the physics groundwork of elastic scattering in Chapter 5. Chapter 6 then covers the application of single scattering to scattering off atomic electrons and the resulting energy loss. Detection of the energy lost is the physical basis of many of the techniques used in charged particle detection. The third subtopic then follows up with the non-destructive measurement of the position and momentum of charged particles. Chapter 7 contains a derivation of the particle trajectory in a magnetic field and the consequent measurement of momentum. Those measurements have intrinsic limitations which are explored first in Chapter 8 in studying diffusion in gases and wire chambers. Chapter 9 looks at faster and higher spatial resolution silicon detectors for more accurate position measurements.

The text then switches to destructive measurements, where the particle to be measured loses a significant fraction of its energy or is fully absorbed in the detector. First, in Chapter 10, the physics foundation is laid by exploring radiation and photon scattering. Then these concepts are applied in exploring the topic of destructive energy measurements. Chapter 11 describes measurements of electron and photon energy, while Chapter 12 describes the measurement of the energy of strongly interacting particles.

Finally, a general-purpose high energy physics detector using all the previously described techniques is sketched in Chapter 13. The concept of multiple redundant measurements is introduced and several examples are given.

The full set of material in the text is suitable for a one year course. If a one semester course is desired, the algebraic details in the Appendices can be skipped as well as Chapter 1, the first half of Chapter 2 and Chapters 5, 6, and 10 assuming that no supplementary physics background was required.

Note that the subjects covered in the text are strongly limited to detectors themselves. Exceptions are a brief description of coincidence circuits in Chapter 2 and front end noise processing in Chapter 9. These brief forays were made since these special topics were tightly connected to the detectors themselves. However, there is no other discussion of front end electronics, trigger systems, data acquisition, or computer programming. In addition, the vital area of detector modeling and Monte Carlo techniques is only sketched in Appendix K. Probability theory and statistical analysis appear only briefly in Appendix J. References to these vital areas are given at the end of the text for readers who want to go beyond the scope of this volume.

The aim of this text is to describe the full ensemble of particle detectors from first principles. The goal is to strike a balance between simply presenting the final result and a full and rigorous derivation and thus to extract the relevant physics in a clear fashion. Intuition and order of magnitude numerical estimates are stressed throughout in an attempt to communicate the insights garnered from experience.

> Ah, but a man's reach should exceed his grasp, or what's a heaven for?
>
> *Robert Browning*

> Curiosity is, in great and generous minds, the first passion and the last.
>
> *Dr Samuel Johnson, 1750*

General references – A

Mechanics, electricity and magnetism and quantum mechanics

[1] *The Feynman Lectures in Physics*, R. Feynman, R. Leighton, and M. Sands, Addison-Wesley Publishing Co., Inc. (1963).
[2] *Classical Mechanics*, H. Goldstein, Addison-Wesley Publishing Co., Inc. (1950).
[3] *Classical Electricity and Magnetism*, W.K.H. Panofsky and M. Phillips, Addison-Wesley Publishing Co., Inc. (1962).
[4] *Quantum Mechanics*, E. Merzbacher, John Wiley & Sons, Inc. (1961).

General references – B

Textbooks on particle detectors

[1] *Detectors for Particle Radiation*, K. Kleinknecht, Cambridge University Press (1987).

[2] *Experimental Techniques in High Energy Physics*, T. Ferbel, Addison-Wesley Publishing Co., Inc. (1987).
[3] *Instrumentation in High Energy Physics*, Ed. F. Sauli, World Scientific Publishing Co. (1992).
[4] *Instrumentation in Elementary Particle Physics*, J.C. Anjos, D. Hartill, F. Sauli, and M. Sheaf, Rio de Janeiro, 1990, World Scientific Publishing Co. (1992).
[5] *Instrumentation in Elementary Particle Physics*, C.W. Fabjan and J.E. Pilcher, Trieste 1987, World Scientific Publishing Co. (1988).
[6] C.W. Fabjan and H.F. Fisher, 'Particle detectors', *Rep. Prog. Phys.* **43** 1003 (1980).

1

Size, energy, cross section

Beauty depends on size as well as symmetry.

Aristotle

Energy is eternal delight.

William Blake

Textbooks on detectors often jump directly into a description of the devices themselves. The relevant descriptive formulae are then simply given without derivation and readers are instead referred to the relevant texts. A complementary approach is taken here. A 'derivation' of the relevant physics is always attempted first. Armed with the derivations, the reader is then introduced to the detector where the approximations which are made are explained along with the reasons why they are valid. In order to contain the length of the text, all 'derivations' are heuristic and thus either compressed or left to the Appendices. Numerical examples are given at regular intervals in order that the reader be firmly connected to real devices and have a firm grasp of the appropriate orders of magnitude. We note that 'intuition' is largely the result of experience. The judgement that allows a simplifying approximation to be made usually comes with an appreciation of orders of magnitude of the quantities involved. In this text, that hard won 'intuition' is, it is hoped, passed on to the student.

Detectors function by causing a particle to interact with some detecting medium. For example, a charged particle might ionize a gas in a device and the freed charge might be collected as an electrical signal localized in time, a 'pulse', on a detector electrode. To characterize the detector it is fundamental to understand the probability of interaction of the particle with the device. The aim of Chapter 1 is to provide the basic numerical data needed to later characterize the interaction probability of the different particles which we wish to detect.

1.1 Units

It is traditional in high energy physics to work in dimensionless units where $\hbar$ and c are defined to be equal to 1. In those units momentum (pc), energy (ε), mass (mc^2), inverse time ($\hbar/t$) and inverse length ($\hbar c/x$) all have the same dimensions, which we take to be energy. Units for energy are taken to be the electron volt, where one electron volt, eV, is the energy, ΔU, gained by an electron of charge e, in dropping through a potential difference, ΔV, of 1 volt, $\Delta U = e\Delta V$. A tabulation of many of the physical quantities used throughout the text is given in Table 1.1[1]. In that table, the speed of light, the Planck constant, the electron charge, the masses of elementary particles, the fine-structure constant, the classical electron radius, the Compton wavelength of the electron etc. are gathered together in electron volt and in MKS units. This table and Table 1.2 contain sufficient numerical information for the needs of this text. Kinematics, the constraints imposed by energy–momentum conservation, are worked out in Appendix A.

1.2 Planck constant

In going from the dimensionless calculations of high energy physics to dimensional quantities, it is necessary to know the Planck constant and be able to use it. (See Table 1.1.)

$$\begin{aligned} \hbar c &= 0.2 \text{ GeV fm} = 2000 \text{ eV Å} \\ 1 \text{ GeV} &= 10^{9} \text{eV} \\ 1 \text{ Å} &= 10^{-8} \text{cm} = 10 \text{nm} \\ 1 \text{ fm} &= 10^{-13} \text{cm} \end{aligned} \tag{1.1}$$

The Planck constant is given for two different distance scales, the angstrom and the fermi. Those two distance scales are characteristic of the size of an atom and the size of a nucleus respectively. The conversion of size to energy leads us to the immediate conclusion that nuclear energy scales are GeV whereas atomic energy scales are of order a few electron volts. The ratio of one angstrom to one fermi is 100 000 to 1.

1.3 Electromagnetic units

In the body of the text we will most often use CGS units in symbolic manipulations and we will freely convert back and forth to MKS units. It is a fact of life that practicing physicists must acquire a facility with both systems of units since experimentalists have connections to both theory and engineering. (See the beginning of Chapter 3 for a full explanation.) We will later explicitly give a prescription for converting between MKS and CGS units.

Table 1.1. *Fundamental physical constants*

Quantity	Symbol, equation	Value	Uncert. (ppm)
Speed of light in vacuum	c	299 792 458 m s^{-1}	exact[a]
Planck constant	h	6.626 075 5(40) $\times 10^{-34}$ J s	0.60
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 572 66(63) $\times 10^{-34}$ J s	0.60
		$=$ 6.582 122 0(20) $\times 10-^{22}$ MeV s	0.30
Electron charge magnitude	e	1.602 177 33(49) $\times 10^{-19}$ C $=$ 4.803 206 8(15) $\times 10^{-10}$ esu	0.30, 0.30
Conversion constant	$\hbar c$	197.327 053(59) MeV fm	0.30
Conversion constant	$(\hbar c)^2$	0.389 379 66(23) GeV^2 mbarn	0.59
Electron mass	m_e	0.510 999 06(15) MeV/c^2 $=$ 9.109 389 7(54) $\times 10^{-31}$ kg	0.30, 0.59
Proton mass	m_p	938.272 31(28) MeV/c^2 $=$ 1.672 623 1(10) $\times 10^{-27}$ kg	0.30, 0.59
		$=$ 1.007 276 470(12) u $=$ 1836.152 701(37) m_e	0.012, 0.020
Deuteron mass	m_d	1875.613 39(57) MeV/c^2	0.30
Unified atomic mass unit (u)	(mass ^{12}C atom)/12 $=$ (1g)/(N_A mol)	931.494 32(28) MeV/c^2 $=$ 1.660 540 2(10) $\times 10^{-27}$ kg	0.30, 0.59
Permittivity of free space	ϵ_0 } $\epsilon_0 \mu_0 = 1/c^2$	8.854 187 817 . . . $\times 10^{-12}$ F m^{-1}	exact
Permeability of free space	μ_0 }	$4\pi \times 10^{-7}$ N A^{-2} $=$ 12.566 370 614 . . . $\times 10^{-7}$ N A^{-2}	exact
Fine-structure constant	$\alpha = e^2/4\pi\epsilon_0 \hbar c$	1/137.035 989 5(61)[b]	0.045
Classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 92(38) $\times 10^{-15}$ m	0.13
Electron Compton wavelength	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e \alpha^{-1}$	3.861 593 23(35) $\times 10^{-13}$ m	0.089
Bohr radius ($m_{nucleus} = \infty$)	$a_\infty = 4\pi\epsilon_0 \hbar^2/m_e e^2 = r_e \alpha^{-2}$	0.529 177 249(24) $\times 10^{-10}$ m	0.045
Wavelength of 1 eV/c particle	hc/e	1.239 842 44(37) $\times 10^{-6}$ m	0.30
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi e_0)^2 \hbar^2 = m_e c^2 \alpha^2/2$	13.605 698 1(40) eV	0.30
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.655 246 16(18) barn	0.27
Bohr magneton	$\mu_B = e\hbar/2m_e$	5.788 382 63(52) $\times 10^{-11}$ MeV T^{-1}	0.089
Nuclear magneton	$\mu_N = e\hbar/2m_p$	3.152 451 66(28) $\times 10^{-14}$ MeV T^{-1}	0.089
Electron cyclotron freq./field	$\omega^e_{cycl}/B = e/m_e$	1.758 819 62(53) $\times 10^{11}$ rad s^{-1} T^{-1}	0.30
Proton cyclotron freq./field	$\omega^p_{cycl}/B = e/m_p$	9.578 830 9(29) $\times 10^{7}$ rad s^{-1} T^{-1}	0.30

Table 1.1. (*cont.*)

Quantity	Symbol, equation	Value	Uncert. (ppm)
Gravitational constant	G_N	$6.672\,59(85) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	128
		$= 6.707\,11(86) \times 10^{-39}\ \hbar c\ (\text{GeV}/c^2)^{-2}$	128
Standard grav. accel., sea level	g	$9.806\,65$ m s^{-2}	exact
Avogadro constant	N_A	$6.022\,136\,7(36) \times 10^{23}$ mol^{-1}	0.59
Boltzmann constant	k	$1.380\,658(12) \times 10^{-23}$ J K^{-1}	8.5
		$= 8.617\,385(73) \times 10^{-5}$ eV K^{-1}	8.4
Molar volume, ideal gas at STP	$N_A k(273.15\text{ K})/(101\,325\text{ Pa})$	$22.414\,10(19) \times 10^{-3}$ m^3 mol^{-1}	8.4
Wien displacement law constant	$b = \lambda_{max} T$	$2.897\,756(24) \times 10^{-3}$ m K	8.4
Stefan–Boltzmann constant	$\sigma = \pi^2 k^4 / 60\hbar^3 c^2$	$5.670\,51(19) \times 10^{-8}$ W m^{-2} K^{-4}	34
Fermi coupling constant	$G_F/(\hbar c)^3$	$1.166\,39(2) \times 10^{-5}$ GeV^{-2}	20
Weak mixing angle	$\sin^2\hat{\theta}(M_Z)\ (\overline{\text{MS}})$	0.2319(5)	2200
$W^{\pm}$ boson mass	m_W	80.22(26) GeV/c^2	3200
Z^0 boson mass	m_Z	91.187(7) GeV/c^2	77
Strong coupling constant	$\alpha_s(m_Z)$	0.116(5)	43 000

$\pi = 3.141\,592\,653\,589\,793\,238$ $\quad e = 2.718\,281\,828\,459\,045\,235$ $\quad \gamma = 0.577\,215\,664\,901\,532\,861$

1 in ≡ 0.0254 m	1 G ≡ 10^{-4} T	1 eV = $1.602\,177\,33(49) \times 10^{-19}$ J	kT at 300 K = $[38.681\,49(33)]^{-1}$ eV
1 Å ≡ 10 nm	1 dyne ≡ 10^{-5} N	1 eV/c^2 = $1.782\,662\,70(54) \times 10^{-36}$ kg	0 °C ≡ 273.15 K
1 barn ≡ 10^{-28} m^2	1 erg ≡ 10^{-7} J	$2.997\,924\,58 \times 10^9$ esu = 1C	1 atmosphere ≡ 760 torr ≡ 101 325 Pa

Notes:

[a] The meter is defined to be the length of path traveled by light in vacuum in 1/299 792 458 s. See B. W. Petley, *Nature* **303**, 373 (1983).

[b] At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is approximately 1/128.

Source: From Ref. 1.1.

Table 1.2. *Atomic and nuclear properties of materials*

Material	Z	A	Nuclear total cross section σ_T (barn)	Nuclear inelastic cross section σ_I (barn)	Nuclear collision length λ_T (g/cm^2)	Nuclear interaction length λ_I (g/cm^2)	$dE/dx\|_{min}$ $\left(\frac{MeV}{g/cm^2}\right)$ ( ) is for gas	Radiation length X_0 (g/cm^2) ( ) is for gas	Radiation length X_0 (cm)	Density (g/cm^3) ( ) is for gas (g/ℓ)	Refractive index n ( ) is $(n-1)\times10^6$ for gas
H_2 gas	1	1.01	0.0387	0.033	43.3	50.8	(4.103)	61.28	865	(0.0838) [0.090]	[140]
H_2 (B.C., 26K)	1	1.01	0.0387	0.033	43.3	50.8	4.045	61.28	865	0.0708	1.112
D_2	1	2.01	0.073	0.061	45.7	54.7	(2.052)	122.6	757	0.162 [0.177]	1.128
He	2	4.00	0.133	0.102	49.9	65.1	(1.937)	94.32	755	0.125 [0.178]	1.024 [35]
Li	3	6.94	0.211	0.157	54.6	73.4	1.639	82.76	155	0.534	—
Be	4	9.01	0.268	0.199	55.8	75.2	1.594	65.19	35.3	1.848	—
C	6	12.01	0.331	0.231	60.2	86.3	1.745	42.70	18.8	2.265	—
N_2	7	14.01	0.379	0.265	61.4	87.8	(1.825)	37.99	47.0	0.808 [1.25]	1.205[300]
O_2	8	16.00	0.420	0.292	63.2	91.0	(1.801)	34.24	30.0	1.14 [1.43]	1.22 [266]
Ne	10	20.18	0.507	0.347	66.1	96.6	(1.724)	28.94	24.0	1.207 [0.900]	1.092 [67]
Al	13	26.98	0.634	0.421	70.6	106.4	1.615	24.01	8.9	2.70	—
Si	14	28.09	0.660	0.440	70.6	106.0	1.664	21.82	9.36	2.33	—
Ar	18	39.95	0.868	0.566	76.4	117.2	(1.519)	19.55	14.0	1.40 [1.782]	1.233 [283]
Ti	22	47.88	0.995	0.637	79.9	124.9	1.476	16.17	3.56	4.54	—
Fe	26	55.85	1.120	0.703	82.8	131.9	1.451	13.84	1.76	7.87	—
Cu	29	63.55	1.232	0.782	85.6	134.9	1.403	12.86	1.43	8.96	—
Ge	32	72.59	1.365	0.858	88.3	140.5	1.371	12.25	2.30	5.323	—
Sn	50	118.69	1.967	1.21	100.2	163	1.264	8.82	1.21	7.31	—
Xe	54	131.29	2.120	1.29	102.8	169	(1.255)	8.48	2.77	3.057 [5.858]	[705]
W	74	183.85	2.767	1.65	110.3	185	1.145	6.76	0.35	19.3	—
Pt	78	195.08	2.861	1.708	113.3	189.7	1.129	6.54	0.305	21.45	—
Pb	82	207.19	2.960	1.77	116.2	194	1.123	6.37	0.56	11.35	—
U	92	238.03	3.378	1.98	117.0	199	1.082	6.00	≈0.32	≈18.95	—

Table 1.2. (*cont.*)

Material	Nuclear collision length λ_T (g/cm^2)	Nuclear interaction length λ_I (g/cm^2)	$dE/dx\|_{min}$ $\left(\frac{MeV}{g/cm^2}\right)$ ( ) is for gas	Radiation length X_0 (g/cm^2)	Radiation length X_0 (cm) ( ) is for gas	Density (g/cm^3) ( ) is for gas (g/ℓ)	Refractive index n ( ) is $(n-1)\times10^6$ for gas
Air, (20 °C, 1atm), [STP]	62.0	90.0	(1.815)	36.66	[30 420]	(1.205) [1.29]	(273) [293]
H_2O	60.1	84.9	1.991	36.08	36.1	1.00	1.33
CO_2	62.4	90.5	(1.819)	36.2	[18 310]	[1.977]	[410]
Shielding concrete	67.4	99.9	1.711	26.7	10.7	2.5	—
Borosilicate glass (Pyrex)	66.2	97.6	1.695	28.3	12.7	2.23	1.474
SiO_2 (fused quartz)	67.0	99.2	1.697	27.05	11.7	2.32	1.458
Methane (CH_4)	54.7	74.0	(2.417)	46.5	[64 850]	0.423 [0.717]	[444]
Ethane (C_2H_6)	55.73	75.71	(2.304)	45.66	[34 035]	0.509 (1.356)	(1.038)
Propane (C_3H_8)	—	—	(2.262)	—	—	(1.879)	
Isobutane ($(CH_3)_2CHCH_3$)	56.3	77.4	(2.239)	45.2	[16 930]	[2.67]	[1900]
Octane, liquid ($CH_3(CH_2)_6CH_3$)	—	—	2.123	—	—	0.703	
Paraffin wax ($CH_3(CH_2)_nCH_3$, $\langle n\rangle \approx 25$)	—	—	2.087	—	—	0.93	
Nylon, type 6	—	—	1.974	—	—	1.14	
Polycarbonate (Lexan)	—	—	1.886	—	—	1.200	
Polyethylene terephthlate (Mylar) ($C_5H_4O_2$)	60.2	85.7	1.848	39.95	28.7	1.39	—
Polyethylene (monomer $CH_2{=}CH_2$)	56.9	78.8	2.076	44.8	≈47.9	0.92–0.95	—
Polyimide film (Kapton)	—	—	1.820	—	—	1.420	
Polymethylmethacrylate (Lucite, Plexiglas) (monomer ($CH_2{=}C(CH_3)CO_2CH_3$))	59.2	83.6	1.929	40.55	≈34.4	1.16–1.20	≈1.49
Polystyrene, scintillator (monomer $C_6H_5CH{=}CH_2$)	58.4	82.0	1.936	43.8	42.4	1.032	1.581