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Physics foundations

1.1 Range of application for radiation detectors

1.1.1 *Natural sources of radiation*

Ionizing radiation originates either from our natural environment or from artificial sources. In both cases, the primary radiation consists of massive charged particles or of massless neutral quanta, i.e. photons or neutrinos.

If we observe radiation from our environment, two main origins are in evidence. One is the cosmic and solar radiation which comes from space and impinges on the outer part of the earth's atmosphere. It consists mainly of protons, light nuclei and electrons. By interacting with the terrestrial atmosphere, it produces secondary particles, including short-lived π mesons and muons. The study of the composition and energy distribution of primary cosmic radiation is best achieved above the atmosphere. Balloon flights, satellites and Space Shuttle flights are used for this research.

The most intensive source of radiation near to our planet is, of course, the sun. Apart from the visible light from its surface and the neutrinos from the cyclic nuclear fusion reactions in the core, it also emits massive particles; these are mainly electrons and protons ejected during eruptions and flares from the surface. When arriving at the earth, they cause zodiacal light and magnetic storms. This 'solar wind' of particles is also responsible for the radiation belts around the earth.

The other natural source of radiation, as discovered by Becquerel in 1896 in uranium ores, is natural α-, β- or γ-radioactivity. The phenomenon of α-decay is common amongst heavy nuclei. Such a nucleus can emit an α-particle (or ^{4}He nucleus) which penetrates the Coulomb barrier of the heavy nucleus by tunnelling. It is mono-energetic with a kinetic energy in the range of 2–10 MeV. In β-decay we have the transformation of a nucleus ${}^{A}_{Z}\mathrm{X}$ with Z protons and $A - Z$ neutrons into another one, ${}_{Z+1}^{A}\mathrm{X}$, thereby emitting an electron e^- and an antineutrino $\bar{\nu}$. The energy spectrum of the electrons is continuous, ranging from zero to the endpoint energy, which is given by the difference between the energies of the nuclear levels of the mother and daughter nuclei. Endpoint energies up to few MeV are observed. In γ-decay an excited nuclear state ${}^{A}_{Z}\mathrm{X}^*$ decays into another state of the same nucleus ${}^{A}_{Z}\mathrm{X}$. In this process, mono-energetic hard γ-rays with energies in the MeV range are emitted.

Natural radioactivity is of crucial importance for the interior energy balance of the earth. The only radioactivity accessible for measurement is that in the crust of the earth, which is explored by drillings up to a depth of 5 km. Such measurements can give information about beds of certain minerals and are used in searches for uranium ores or petroleum.

Natural radioactivity can also be used for age determination of minerals in terrestrial rocks, meteorites and material from the moon. They fix the age of our planet at about 4.5×10^9 years. For organic matter, dating can be achieved by measuring the β-activity of the carbon isotope ${}^{14}\mathrm{C}$. In the atmosphere, the concentration of ${}^{14}\mathrm{C}$ is kept in equilibrium by its continuous production through cosmic radiation and its decay with a half-life of 5730 years. If a plant or animal dies, the exchange of CO_2 with the atmosphere ceases and the concentration of ${}^{14}\mathrm{C}$ in it decreases with the half-life of the decay.

1.1.2 *Units for radiation measurements*

The *energy* of radiation is usually measured in electronvolts (eV). This unit is defined as the energy gained by the electron when it is accelerated through a potential difference of 1 volt. Multiples of the unit are $1\,\mathrm{keV} = 10^3\,\mathrm{eV}$, $1\,\mathrm{MeV} = 10^6\,\mathrm{eV}$ and $1\,\mathrm{GeV} = 10^9\,\mathrm{eV}$. The relation between the SI unit joule and the electronvolt is

$$1\,\mathrm{eV} = 1.602 \times 10^{-19}\,\mathrm{J} \tag{1.1}$$

The *rest mass m* of a particle is measured by using the relation $E = mc^2$, in units of eV/c^2. Its relation to the SI unit kg is

$$1\,\mathrm{eV}/c^2 = 1.78 \times 10^{-36}\,\mathrm{kg} \tag{1.2}$$

The *momentum P* of a particle can also be measured in a unit related to the electronvolt. Since the total energy E of the particle is given by $E^2 = P^2c^2 + m^2c^4$, the unit is eV/c. Again its relation to the SI unit is

$$1\,\mathrm{eV}/c = 0.535 \times 10^{-27}\,\mathrm{kg\,m/s} \tag{1.3}$$

The *flux* I of particles is defined as

$$I = \frac{n}{tf} \tag{1.4}$$

if n particles penetrate an area f in a time interval t. The unit is particles/(m^{2}s). The same unit is used for the intensity of a particle beam.

The *activity* of a radioactive source is defined as the number of decays per second; the unit is the curie (Ci), where

$$1\,\mathrm{Ci} = 3.7 \times 10^{10}\ \text{decays per second} \tag{1.5}$$

or the becquerel (Bq), where

$$1\,\mathrm{Bq} = 1\ \text{decay per second} = 2.70 \times 10^{-11}\,\mathrm{Ci} \tag{1.6}$$

The activity is related to the *decay constant* λ by the decay law

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda N \tag{1.7}$$

such that λ is measured in units of s^{-1}.

The *mean lifetime* τ of a radioactive isotope or particle is defined as the interval after which the initial number N_0 of decaying nuclei or particles has decreased to the value N_0/e. It is related to the decay constant by

$$\tau = \frac{1}{\lambda} \tag{1.8}$$

In nuclear physics, it is customary to use instead of τ the *half-life* $t_{\frac{1}{2}}$ after which half of the initial nuclei have decayed:

$$t_{\frac{1}{2}} = \tau \ln 2 = 0.693\tau \tag{1.9}$$

The effects of radiation on matter are measured by three quantities.

(1) The *energy dose* D ('absorbed dose') is defined as the energy W_D absorbed in a sample of the material of volume V and density ρ: $D = \mathrm{d}W_D/(\rho\,\mathrm{d}V)$. The unit for D is

$$1\,\mathrm{rad} = 10^{-2}\,\mathrm{J/kg} \tag{1.10}$$

or

$$1\,\mathrm{gray} = 1\,\mathrm{J/kg}$$

(2) The *ion dose* D_I ('exposure') is given by the charge Q liberated in a volume V by the radiation in air of density ρ_A:

$$D_\mathrm{I} = \frac{\mathrm{d}Q}{\rho_\mathrm{A}\,\mathrm{d}V} \tag{1.11}$$

The unit of ion dose is the roentgen (R)

$$1\,\mathrm{R} = 2.58 \times 10^{-4}\,\mathrm{C/(kg\ of\ air)} \tag{1.12}$$

An ion dose of 1 R in air corresponds to a number $1\,\mathrm{R}/e = 1.61 \times 10^{15}$ of ions/kg and an energy dose $1\,\mathrm{R}\,W_\mathrm{i}/e$, where W_i is the mean effective energy needed for liberating one ion–electron pair in air. Since $W_\mathrm{i} = 33.7\,\mathrm{eV}$ for air, we obtain the energy dose $D = 0.87$ rad. The number of ion pairs liberated in 1 cm^3 of air at standard conditions is 2.08×10^9.

(3) The *equivalent dose* is a measure of the effect of radiation on the human body. It is defined as

$$D_q = qD \tag{1.13}$$

where q is a quality factor for the biological effect of different types of radiation on human tissue. The unit of the equivalent dose is the Rem (roentgen equivalent man); $1\,\mathrm{Rem} = q \times 1\,\mathrm{rad}$. More recently, the SI unit sievert (Sv) has been introduced: 1 Sv = 100 Rem. The quality factors are approximately as follows: $q = 1$ for γ-rays and electrons, $q = 10$ for protons and deuterons, $q = 20$ for α-particles and heavy nuclear fragments and $2 < q < 10$ for neutrons, depending on their energy.

1.1.3 *Artificial radioactivity*

Energetic particles coming from accelerators or nuclear reactors impinging on stable nuclei can undergo nuclear reactions in such a way that unstable radioactive nuclei are produced.

In this way, neutrons from reactors are used to produce β-active isotopes with half-lives between fractions of a second and 10^5 years. Most β-emitters are also γ-ray sources since the β-decay leads to an excited state of the daughter nucleus, which in turn decays by a γ-transition to the ground state. A few β-decays lead directly to the ground state of the daughter nucleus, and some of these 'pure' β-emitters are listed in table 1. The electron energy varies between zero and the endpoint energy E_0^β.

More useful for calibration purposes are mono-energetic electrons from internal conversion. These are electrons from one of the shells of the atom which are emitted as a consequence of a nuclear de-excitation process if γ-ray emission is suppressed by selection rules. Some examples of such conversion electron sources are $^{137}\mathrm{Cs}$ (625 keV), $^{110\mathrm{m}}\mathrm{Ag}$ and $^{110}\mathrm{Ag}$ (656 keV, 885 keV) and $^{113\mathrm{m}}\mathrm{In}$ (393 keV).

The most common way of decay for an excited nuclear state is the emission of γ-radiation. The excited states are frequently the decay products of a β-transition, such that the half-life of these γ-ray sources is determined by the half-life of the β-decay. Also, K capture is a possible weak

Table 1. *Pure β-sources*

Isotope	Endpoint energy (keV)	Half-life $t_{\frac{1}{2}}$
^{3}H	18.6	12.26 years
^{14}C	156	5730 years
^{33}P	248	24.4 days
^{90}Sr	546	27.7 years
^{90}Y	2283	64 hours
^{99}Tc	292	2.1×10^{5} years

interaction process leading to excited nuclear states. A few examples of such nuclides are listed in table 2.

Mono-energetic photon radiation in the keV range can also be obtained from X-ray transitions in the atomic shells. A very useful example of such a source is ^{55}Fe, with an energy of 5.9 keV from the K_α X-ray transition in its daughter nucleus ^{55}Mn. This energy corresponds to the ionization energy loss of a minimum ionizing charged particle along a path of a few centimetres in gases at standard conditions. The photoelectrons liberated by a photon of this energy can therefore be used for calibration purposes.

Another decay mode useful for calibration purposes is α-decay. The reaction is ${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{X} + \alpha$, and the decay rate is determined by the tunnelling probability of the α-particle through the potential barrier of the remaining nucleus. This mechanism implies an exponential dependence of the decay rate on the energy E_α of the α-particle emitted. Half-lives range from 10^{10} years at $E_\alpha = 4\,\mathrm{MeV}$ to days at $E_\alpha = 6.5\,\mathrm{MeV}$.

Table 2. *γ-ray sources*

Parent nucleus of β-decay	Half-life $t_{\frac{1}{2}}$	Decay mode	E_0^{β} (keV)	Daughter nucleus	E_γ (keV)
^{22}Na	2.6 years	β^+	540	^{22}Ne	1274
^{57}Co	272 days	K	—	^{57}Fe	14.4 122.1
^{60}Co	5.27 years	β^-	316	^{60}Ni	1173.2 1332.5
^{137}Cs	30.0 years	β^-	1514	^{137}Ba	661.6
^{55}Fe	2.7 years	K	—	^{55}Mn	5.89 X 6.49 X
^{207}Bi	32.2 years	K	—	^{207}Pb	570.0

For laboratory purposes, an intermediate half-life is indicated. A useful source is, e.g., ^{241}Am with a half-life of 433 years and two α-lines at 5.49 MeV (85%) and 5.44 MeV (13%).

1.1.4 *Particle accelerators*

The study of atomic nuclei and of their constituents and the search for small or point-like building blocks of these constituents has required the study of scattering and annihilation processes at ever larger centre-of-mass energies. This has been achieved by constructing particle accelerators. For protons the electrostatic van-de-Graaf accelerator, the weakly focussing cyclotron and the synchrocyclotron have given accelerated particles up to 15 MeV, 20 MeV and 500 MeV energy in the laboratory system, respectively. In 1956, E. D. Courant and H. A. Snyder invented the principle of strong focussing by alternating magnetic field gradients along the circular orbit. This breakthrough enabled the construction of the proton synchrotron at the European Laboratory for Particle Physics, CERN, at Geneva and of the alternating gradient synchrotron (AGS) at the Brookhaven National Laboratory near Upton, New York. Both accelerators achieved proton energies around 30 GeV. An extension of this principle led to the construction of the proton synchrotron at the Serpukhov Laboratory in the USSR, with a peak energy of 76 GeV. Energies of 450 GeV were reached with two large proton synchrotrons in the 1970s, one at the Fermi National Laboratory (Fermilab) near Batavia (Illinois) and the other at CERN: the super proton synchrotron (SPS). At Fermilab, the development of superconducting pulsed dipole magnets with a peak magnetic field of 4.5 T was the basis for the tevatron machine in the ring of the existing proton synchrotron. The peak energy of protons of mass m_p in the tevatron is now $E = 1000\,\text{GeV}$, corresponding to a centre-of-mass energy $\sqrt{s} = \sqrt{2m_\text{p}E} = 45\,\text{GeV}$.

At CERN, another line of development was followed in order to increase the centre-of-mass energy in hadron collisions: the SPS was used as a storage ring for protons and antiprotons. However, the collision rate in this storage ring is limited by the flux of stored antiprotons. The invention and implementation of the stochastic cooling of antiprotons beams by S. van der Meer solved this problem and enabled the discovery of the production of the intermediate bosons $\text{W}^\pm$ and Z^0. The centre-of-mass energy of 630 GeV reached in this machine was surpassed in 1987 at Fermilab, where the tevatron was also converted to an antiproton–proton storage ring, with a maximum centre-of-mass energy of 1800 GeV. Even higher energies will be reached around the year 2005 by the large hadron collider (LHC), a proton–proton storage ring with

14 TeV centre-of-mass energy, to be installed in the 27 km circumference tunnel of the LEP machine at CERN.

The development of electron accelerators started with the betatron, where electrons reach energies up to 45 MeV in the secondary circuit of a ‘transformer’. The principle of strong focussing also here led to the synchrotron; examples of such machines are the electron synchrotrons at Bonn (2 GeV), Cornell (10 GeV) and DESY (7.4 GeV). Since the energy lost by the circulating electrons by synchrotron radiation increases as a function of the energy E and the radius R that is proportional to E^4/R, linear accelerators are more economical for very high electron energies. The highest laboratory energy for such linear accelerators (50 GeV) is obtained at the Stanford Linear Accelerator Centre, SLAC.

Also for electron accelerators, the principle of colliding beams is the appropriate method for studying collisons at higher centre-of-mass energies. The technique of electron–positron storage rings was developed at Novosibirsk, Frascati and Cambridge MA with ‘small’ machines. The first great success came with the storage ring SPEAR at Stanford. With this ring, at centre-of-mass energies up to 4 GeV, bound charmonium states and charmed mesons were discovered. The second machine in this energy domain was the DORIS ring at DESY in Hamburg, followed by the CESR ring at Cornell. A tenfold increase in centre-of-mass energy was achieved by the two machines PETRA at DESY and PEP at SLAC: PETRA reached $\sqrt{s} = 46$ GeV in 1986 and the TRISTAN storage ring at KEK near Tsukuba reached 60 GeV in 1987. In order to study directly the properties of the Z^0 boson and the electroweak interaction, two machines reaching a centre-of-mass energy of 90 GeV were constructed: the single-pass linear collider (SLC) at SLAC and the large electron–positron collider (LEP) at CERN. SLC is based on the Stanford linear accelerator, while LEP is a circular storage ring with circumference 27 km. Both came into operation in 1989 but, owing to its superior luminosity, LEP has since accumulated several million Z^0 decay events in each of its four detectors, while SLC contributes by doing scattering experiments with polarized electrons. After six years of experiments at the Z^0 peak, LEP has now entered a new energy domain above the Z^0 mass, searching for the Higgs scalar and for supersymmetric partners of the known elementary particles. In 1996, a centre-of-mass energy of 172 GeV was reached.

While the electron–positron collider is the ideal tool for studying the structure of the electroweak interaction in detail, the structure of the nucleon and of the forces between its quark and gluon constituents can be studied by inelastic lepton–nucleon scattering. Fixed-target lepton–nucleon experiments have explored the range of momentum transfers up

Table 3. *Large particle accelerators*

Machine	Laboratory	Maximum beam energy (GeV, unless otherwise indicated)	Start of operations
Proton synchrotrons			
PS	CERN, Geneva, Switzerland	28	1960
AGS	Brookhaven, Upton, USA	33	1960
PS	Serpukhov, Protvino, USSR	76	1967
SPS	CERN, Geneva, Switzerland	450	1976
Tevatron	Fermilab, Chicago, USA	1000	1985
PS	KEK, Tsukuba, Japan	8	1976
Electron accelerators			
Electron synchrotron	DESY, Hamburg, Germany	7.4	1964
Linear accelerator	SLAC, Stanford, USA	32	1966
Microtron	MAMI, Mainz, Germany	0.85	1991
Synchrotron	ELSA, Bonn, Germany	3.5	1991
Proton–(anti)proton storage rings			
SPPS	CERN, Geneva, Switzerland	450	1981
Collider	Fermilab, Chicago, USA	1000	1987
LHC	CERN, Geneva, Switzerland	7000	2005
Electron–positron storage rings			
ADONE	Frascati, Italy	1.5	1969
DAPHNE	Frascati, Italy	1.5	1998
DCI	LAL, Orsay, France	1.8	1976
BEPC	Beijing, China	2.8	1989
SPEAR	SLAC, Stanford, USA	4	1972
DORIS	DESY, Hamburg, Germany	5.6	1973
VEPP IV-M	Novosibirsk, USSR	6	1990
CESR	Cornell, USA	6	1979
PETRA	DESY, Hamburg, Germany	22	1978
PEP	SLAC, Stanford, USA	15	1980
Tristan	KEK, Tsukuba, Japan	32	1987
SLC	SLAC, Stanford, USA	50	1989
LEP	CERN, Geneva, Switzerland	60	1989
LEP 200	CERN, Geneva, Switzerland	95	1996
Electron–proton storage ring			
HERA	DESY, Hamburg, Germany	30(e) + 820(p)	1991
Heavy ion accelerators			
UNILAC	GSI, Darmstadt, Germany	20 MeV/nucleon (U)	1976
SIS	GSI, Darmstadt, Germany	1 GeV/nucleon (U)	1990
ESR	GSI, Darmstadt, Germany	storage ring, 200 MeV/nucleon (Ar)	1990
GANIL	Caen, France	95 MeV/nucleon (O)	1983
		60 MeV/nucleon (Ca)	1983
		35 MeV/nucleon (Kr)	1983
Super-HILAC	LBL, Berkeley, USA	9.5 MeV/nucleon (all nuclei)	1970

Table 3. *(cont.)*

Machine	Laboratory	Maximum beam energy (GeV, unless otherwise indicated)	Start of operations
SPS	CERN, Geneva, Switzerland	200 GeV/nucleon (O) 160 GeV/nucleon (Pb)	1986 1995
Medium-energy proton accelerators			
LAMPF	LANL, Los Alamos, USA	800 MeV	1973
SIN	PSI, Villigen, Switzerland	590 MeV	1974
TRIUMF	TRIUMF, Vancouver, Canada	520 MeV	1974
COSY	KFA, Jülich, Germany	2500 MeV (cooled)	1993

to a Q^2 value of $200\,(\mathrm{GeV}/c)^2$. A big step towards higher momentum transfers was made with the electron–proton collider HERA at DESY, completed in 1990. A superconducting ring for protons of 820 GeV and another ring for electrons of 30 GeV enable the observation of collisions at $Q^2 = 10^4\,(\mathrm{GeV}/c)^2$. Two experiments started data-taking in 1992. A list of accelerators in operation at this time is given in table 3.

1.2 Interactions of particles and γ-radiation with matter

The physical processes which enable us to detect particles are different for neutral and charged particles. Photons can interact by the photoelectric or Compton effects or by creation of an electron–positron pair; the latter process dominates at energies above 5 MeV. The electrons or positrons resulting from these interactions can be detected in the same way as other charged particles. Neutrons interact strongly with nuclei, and in doing so they produce charged secondary particles. Neutrinos can only be detected by their weak interaction with nuclei or with electrons: lepton number conservation requires the emission of a charged or neutral lepton in these processes, and in addition hadrons are created in inelastic reactions.

Charged particles can be detected directly through their electromagnetic interactions with the atomic electrons of the detector material. This is treated in section 1.2.1, and the interactions of γ-rays are described in section 1.2.2.

1.2.1 *Detection of charged particles*

For the detection of charged particles, use is made of their electromagnetic interaction. If a charged particle traverses a layer of material, three processes can occur: atoms can be ionized, the particle can emit Cherenkov radiation or the particle can cause the emission of transition

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radiation. A unified deduction of the energy loss by ionization and of the intensity of the radiation emitted can be found in the work of Allison, Wright and Cobb [AL 83, AL 80]. Consider the electromagnetic interaction of a charged particle of mass M and velocity $\mathbf{v} = \beta c$ in a material of refractive index n and with dielectric constant $\varepsilon = \varepsilon_1 + i\varepsilon_2$ such that $\varepsilon_1 = n^2$. In the interaction, a photon of energy $\hbar\omega$ and momentum $\hbar k$ is created. Energy–momentum conservation gives a relation between the four-momenta of the incoming particle (P), the outgoing particle (P') and the photon (P_γ): $P' = P - P_\gamma$. For small photon energies ($\hbar\omega \ll \gamma M c^2$) this gives

$$\omega = \mathbf{v} \cdot \mathbf{k} = vk \cos\theta_c \tag{1.14}$$

where θ_c is the angle between the directions of the emitted photon and the incoming particle. In a material the photon energy and momentum are related by the dispersion relation

$$\omega^2 = \frac{k^2 c^2}{\varepsilon} \tag{1.15}$$

Eqs. (1.14) and (1.15) yield

$$\sqrt{\varepsilon}\frac{v}{c}\cos\theta_c = 1 \tag{1.16}$$

At photon energies below the excitation energies of the material (the 'optical region') ε is real and $\varepsilon > 1$ such that θ_c is real for $v > c/\sqrt{\varepsilon}$. The emission of real photons is then possible (the 'Cherenkov effect') if the velocity of the particle is larger than the phase velocity $c/\sqrt{\varepsilon}$ of light in the material (the 'Cherenkov threshold'). At photon energies in the range from 2 eV through 5 keV, $\varepsilon = \varepsilon_1 + i\varepsilon_2$ is a complex number with $\varepsilon_2 > 0$ and $\varepsilon_1 < 1$. In this case, only virtual photons are exchanged between the particle and the atoms of the material, resulting in excitation or ionization of the atoms and a corresponding energy loss of the particle. Finally, in the X-ray domain, i.e. at photon energies above 5 keV, the absorption coefficient becomes small ($\varepsilon_2 \ll 1$), and still $\varepsilon_1 < 1$. The threshold velocity for the Cherenkov effect is then larger than the light velocity *in vacuo*. In spite of this, radiation is emitted below this threshold if there are discontinuities in the material traversed by the particle. This is called transition radiation.

In a simplified two-dimensional model [AL 83], some properties of these processes can be considered. Let the particle move along the z-axis of the coordinate system, i.e. $\mathbf{v} = (0, 0, v)$, and the observer be situated at the point $(0, y, z)$. Then from eq. (1.14) $vk_z = \omega$ and, from eq. (1.15),