Instruments of Modern Physics
– A Primer to Lasers, Accelerators, Detectors and all that

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Contents

5 Examples of detection techniques and applications

5.1 Detectors in nuclear and elementary particle physics

While the experimental setup in nuclear physics can be quite compact, maybe only a few surface-barrier counters to detect protons and alpha particles from a nuclear reaction, detectors in elementary particle research are generally very large and consist of a multitude of components. Prominent examples are the four main experiments at the Large Hadron Collider (LHC) at CERN in Geneva/Switzerland: ALICE, ATLAS, CMS, and LHCb. A typical layout of a collider experiment comprises (from the center outward in an onion-like fashion):

- a vertex detector or "inner tracker" surrounding the storage-ring vacuum chamber,
- a tracker measuring the particle momentum by their track curvature in a magnetic field,
- an electromagnetic and a hadronic calorimeter to measure the particle energy,
- the magnet system (coils and yoke) producing a strong magnetic field,
- muon detectors,
- a trigger and readout system.

Some of the underlying concepts will be briefly described in the following.

5.1.1 Vertex detection

The purpose of vertex detection is to identify the origin of particle tracks by finding a common crossing point (vertex) of several tracks. This way, the lifetime of the original particle decaying at the vertex can be measured, and the combinatorial background from errorous track assignments can be reduced. It is already helpful to have one detector layer with very good spatial resolution close to the collision point, but most experiments comprise two or more layers forming a "tracker" which can also contribute to the momentum measurement. Relevant issues include

- spatial resolution at each layer, given by fine segmentation and low noise,
- angular resolution by combining layers and the next outer tracking device,
- proximity to the collision point,
- coverage of a large solid angle,
- minimum material at each layer and the vacuum chamber to minimize multiple scattering,
- on-chip data storage (while waiting for a trigger decision) and speed of readout,

- radiation hardness of the detector and on-chip readout electronics,
- maintenance-free operation due to its inaccessibility.

Many vertex detectors are made of typically 200 to 300 μm thick silicon strip detectors with readout chips directly bonded to the strips at the end of a detector module (as far from the collision point as possible to reduce the radiation dose). The readout chips comprise individual preamplifiers for each readout channel, parallel or sequential readout circuitry, and sometimes a "pipeline" memory to store a number of events before the trigger decides to read or overwrite the data. Other detector options are silicon pixel detectors, drift chambers with very narrow wire spacing, microstrip gas chambers or scintillating fibers.

5.1.2 Measurement of momentum and energy

The particle momentum p is generally determined by measuring the curvature radius R of tracks of charged particles (mass m and charge q) in a magnetic field B using

$$\frac{m\,v^2}{R} = q\,v\,B \quad (\vec{v} \perp \vec{B}) \qquad \rightarrow \qquad p = q\,B\,R \quad \text{or with } q = e: \quad p[\mathrm{GeV/c}] = 0.3\,B[\mathrm{T}]\,R[\mathrm{m}], \quad (1)$$

while the momentum of neutral particles is not detected directly. Many of the issues mentioned in section 5.1.1 apply as well, albeit with relaxed requirements. An additional point is the strength, homogeneity and sufficient knowledge of the magnetic field at each point in space. For this kind of tracking device, silicon detectors are too expensive and constitute too much material. The usual choice is a drift chamber with several 10000 wires or a time projection chamber.

The total energy E of neutral and charged particles is measured by stopping them in matter and observing a signal indicating the total deposition of energy. For kinetic energies of a few MeV, as in nuclear physics, a few millimeters of silicon are sufficient, while stopping multi-GeV particles requires a large amount of high-Z material such as lead, tungsten or depleted uranium. In particle physics, this type of detector is known as calorimeter or "shower counter". In most cases, the incident particle produce showers:

- Electromagnetic showers are avalanches of high-energy photons emitted as bremsstrahlung and electron-positron pairs, which again produce bremsstrahlung. The longitudinal extent of an electromagnetic shower is the shower depth $L_r \ln(E/E_c)/\ln 2$, where L_r is the radiation length (see section 4.1.1) and $E_c \approx 800$ MeV $/(Z+1.2)$ is called the critical energy. The transverse size of a shower is of the order of L_r and measured by the so-called Moliere radius M_r containing 95% of the shower particles.

- Hadronic showers are initiated by the strong interaction of a high-energy hadron with matter causing an avalanche of secondary hadrons (protons, neutrons, charged and neutral pions) as well as leptons and photons. The longitudinal extent is given by the hadronic absorption length $\lambda = M/(\sigma\rho N_A)$, where M is the molar mass, ρ is the density and N_A is Avogradro's number. An assumed cross section of $\sigma \approx 4 \cdot 10^{26} \cdot A^{2/3}$ cm^2 with atomic mass A results in $\lambda \approx (A^{1/3}/\rho) \cdot 35$ g/cm^3 for particles in the GeV regime.

Electromagnetic and hadronic calorimeters are often made of multiple layers of alternating high-Z material and scintillators. Apart from these heterogenic calorimeters, electromagnetic showers are sometimes detected using homogeneous calorimeters, in which a single material provides absorption and signal production, e.g. scintillators like NaI(Tl), BGO or lead glass.

5.1.3 Particle identification

The number of detectable particles is quite limited by their lifetime which has to be of the order of a nanosecond for a macroscopic particle track. If the sign of the charge and the momentum is observed by the curvature in a magnetic field, either the mass or the energy has to be determined. Other than that, the nature of a particle can also be guessed by the type and kinematics of other identified particles from the same decay.

If the velocity is sufficiently below $\beta \approx 1$, the mass can be measured by the time-of-flight in combination with momentum or energy, which is one of the motivations of having fast detectors like scintillation or semiconductor counters.

The energy of high-energy particles is measured with calorimeters as described above. In nuclear physics, the ΔE-E method is often used by stopping a proton, deuteron, triton, or alpha particle in a "telescope" of two or more silicon counters. The total energy E is given by the sum signal and the partial energy loss ΔE is given by one of the detectors. Plotting ΔE versus E separates different types of particles since the energy loss for a given material thickness depends on the velocity β and charge according to the Bethe formula.

Other methods of particle identification are to measure the Cherenkov angle for particles exceeding the light velocity in the respective medium, to analyze the shape of a shower in a calorimeter or a "jet" in a gas detector, or to take the penetration of a particle into a account (a non-interacting neutral particle could be a neutrino, a highly penetrating charged particle is most likely a muon).

5.2 Detectors in astroparticle physics

More than 100 years ago, it was found that a charged electrometer lost its charge faster when being closer to the ground rather than being on top of the Eiffel Tower (completed in 1889), indicating that radiation is emanated from radionuclides in the soil. However, the effect was not as strong as anticipated and when V. Hess took electrometers on balloon flights up to altitudes around 5 km between 1911 and 1913, the radiation level clearly increased. These so-called cosmic rays consist mainly of nuclei (90% protons, 9% alpha particles and 1% heavier particles) plus a small fraction of electrons, positrons and antiprotons. Most of this radiation comes from outside the solar system and the its origin and the mechanism of acceleration to the 10^{20}-eV level is an active field of research.

In addition to satellite and balloon missions, high-energy cosmic particles are studied e.g. by the Pierre Auger Observatory in the Argentinean Pampas. Scattered over an area of 3000 km^2, air shower particles are observed in 1600 water tanks in which Cherenkov radiation is detected by photomultipliers. In addition, 27 photomultiplier-array telescopes look out for fluorescence light caused by showers (which is only detectable on moonless nights).

Apart from charged particles, high-energy gamma rays of cosmic origin are of interest. Two present gamma-ray telescopes are H.E.S.S. in Namibia and MAGIC on the Canary Island of La Palma, both looking for gamma-induced air showers. MAGIC consists of two telescopes with a curved mirror (area 239 m^2) made of aluminum segments which can be pointed to any spot in the sky, focusing the light onto a photomultiplier array, H.E.S.S. comprises 5 similar telescopes (614 m^2 plus 4×108 m^2).

Neutrinos are studied to understand their own nature as well as their extraterrestrial sources (the sun and sources outside the solar system such as supernovae). It has been mentioned before that neutrino detectors have to comprise a large interaction volume and have to be well-shielded from background radiation. The common technique for extraterrestrial neutrinos is to look out for fast muons created in a weak interaction between a neutrino and a nucleon. These fast muons emit Cherenkov light when propagating in water or ice which can be detected by photomultipliers. In water, the light is less prone to scattering but there is a higher background e.g. by bioluminiscence. Examples are AMANDA and its successor IceCube at the South Pole (IceCube comprises thousands of photomultiplier-equipped modules over one cubic kilometer), the NT200 telescope in Lake Baikal/Russia and ANTARES off the Cote d'Azur/France.

5.3 Detectors for gravitational waves

Newton's law of gravitation assumes that changes in gravity effect the entire space instantaneously without delay. In Einstein's theory of relativity, no signal can propagate faster than the speed of light. A direct consequence is the prediction of gravitational waves, see e.g. [1]. The detection of these "ripples in the curvature of spacetime" has been a research topic since the 1960s. A first indirect proof for gravitational waves was presented in 1974 by R. A. Hulse and J. H. Taylor, Jr. (both awarded the 1993 Nobel Prize in physics) by observing the binary stellar system PSR1913+16, which consists of two neutron stars orbiting each other. One of them is a pulsar emitting radio-wave pulses with a very stable period of about 59 ms. over a long time. In a binary system, the observed pulse period undergoes periodic variations, allowing to deduce features of the system like the orbit period. Monitoring the system for some years, Hulse and Taylor observed that the orbit period was declining. They suggested the system is loosing energy by emitting gravitational radiation, and the experimental results were in good accordance with the prediction of gravitational waves from general relativity [2].

A direct proof of gravitational waves is much more difficult. Such a wave passing the earth induces a quadrupole-like effect perpendicular to its direction of propagation, the apparent length is stretched in one transverse direction and simultaneously compressed in the orthogonal transverse direction. The change of length is of the order of $\Delta L/L \approx 10^{-21}$ or even smaller, even if the waves are generated by extreme events like the merging of two black holes.

The first approach to detect this small effect was devised by J. Weber, who used resonant bodies, namely aluminum cylinders of 2 m length and 1 m radius. Weber predicted that gravitational waves excite the cylinders resonantly at a frequency of 1.66 kHz. Changes in the cylinders length of about 10^{-16} m could be detected by piezoelectric sensors [3]. The principle was evolved to e.g. the MiniGrail detector using a CuAl sphere as resonant body [4].

Another approach is to detect the change of length with a Michelson interferometer, see e.g. [5]. The LIGO detectors in Livingston/LA/USA comprises two interferometers, each placed in an L-shaped ultrahigh-vacuum system with an arm length of 4 km. A Fabry-Perot cavity is placed in each arm to increase the effective length by a factor of 75. The laser source is a diode-pumped Nd:YAG laser emitting 10 W of power at 1064 nm. After mode-cleaning and amplification, the beam is send into the interferometer. Any change in the interferometers arm length, for example due to gravitational waves, shifts the phase of one beam and changes the interference pattern in the detector. The targeted sensitivity is 10^{-21} resulting in a detectable arm length change of $\sim 10^{-18}$ m.

Recently, the BICEP2 experiment at the South Pole reported the observation of a signal from gravitational waves imprinted into the cosmic microwave background during the period of the exponential expansion ("inflation") of the universe [6].

5.4 The atomic force microscope

A tool to obtain information on the surface structure of a sample at a very high resolution is the atomic force microscope [7]. It extends the possibilities of its precursor, the scanning tunneling microscope, to non-conduction samples. The probe of an atomic force microscope is a very sharp tip with a radius of 5 to 20 nm at the end of a small cantilever which is placed in close proximity of the surface under study. Depending on the situation, different forces act on the tip: repulsion due to overlapping electron orbitals, van-der-Waals forces, capillary forces etc. In "contact mode" (also called static mode) the distance between tip and sample is kept constant in the range of 0.2 to 0.3 nm, where the gradient of the force is large. Assuming Hooke's law, the position of the cantilever is then proportional to the forces between tip and sample. The corresponding spring constant can be calculated with numerical methods for arbitrary tip geometries. There are severals methods to measure the cantilever position. One is to aim a laser beam at the end of the cantilever at an angle and to detect the reflected beam with a photodetector. Here, the laser acts as an optical lever arm and magnifies the tip motion. Other methods are based on interferometry, on the piezoelectric effect, or on the capacity between the cantilever and another electric contact. In a dynamic mode (”non-contact mode”) the cantilever is excited to oscillations close to its resonance frequency. Any change of external forces on the tip results in a shift of the resonance frequency and decreases the oscillation amplitude. A feedback loop keeps the oscillation amplitude constant by either shifting the frequency of the exciting force or by moving the cantilever up or down. To scan the sample surface, the cantilever is moved laterally with high precision using piezoelectric actuators. The achievable lateral resolution is of the order of a nanometer, whereas the height resolution can be below 0.1 nm.

5.5 Imaging in medical physics

Aside from basic research, detectors of different types find important applications in imaging for medical diagnostics [8, 9, 10, 11].

5.5.1 Imaging with X-rays

With the discovery of X-rays in 1895, W. C. Röntgen revolutionized medical diagnostics. The simplest method of imaging with X-rays is to irradiate the patient from one side and place a film or a photodetector on the other side. The radiation intensity behind absorbing material with an absorption coefficient μ is given by

$$I = I_0 e^{-\mu d}, \tag{2}$$

where d is the materials thickness. Thus, the film or detector shows a two-dimensional projection of the patient’s body. Taking one X-ray image delivers an effective dose[1] of 0.01 to 1 mSv to the patient. Since miscellaneous organs may overlap in the beam path adding up in their projection, it is sometimes useful to take images from different directions.

Computer tomography (CT) images the body by using X-rays in conjunction with computing algorithms. Here, the patient is placed inside a ring-shaped detector with a rotating X-ray tube. Two types of X-ray detectors are essentially used for CT: xenon high-pressure ionization chambers and scintillation crystals with photodetectors. For a given angular position Θ of the X-ray tube, the coordinate along the X-ray path is η and the orthogonal coordinate is ξ. Irradiating one ”slice” of the patient’s body, i.e. a two-dimensional distribution $g(x, y)$ of absorbing material, the detector records a line integral

$$p_\Theta(\xi) = \int_{-\infty}^{\infty} g(x, y) d\eta \tag{3}$$

for each position ξ with

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[1] The effective dose E in Sv (sievert, 1 Sv = 1 J/kg) is given by the mass-averaged absorbed dose $D_{\mathrm{T,R}}$ for tissue T and radiation type R in Gy (gray, 1 Gy = 1 J/kg) multiplied by the radiation weighting factor W_{R} (with $W_{\mathrm{R}} = 1$ for X-rays) and the tissue weighting factor W_{T} (e.g. $W_{\mathrm{lung}} = 0.12$ and $\sum_{\mathrm{T}} W_{\mathrm{T}} = 1.00$), summed over all organs.

$$x = \xi \cos\Theta - \eta \sin\Theta \qquad \text{and} \qquad y = \xi \sin\Theta + \eta \cos\Theta. \tag{4}$$

The two-dimensional Fourier transform $G(k_x, k_y)$ of $g(x, y)$ can be reconstructed from the one-dimensional Fourier transform of all projections $p_\Theta(\xi)$, and an inverse two-dimensional Fourier transform of $G(k_x, k_y)$ yields the distribution

$$g(x, y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(k_x, k_y) e^{2\pi i(k_x x + k_y y)} dk_x dk_y \tag{5}$$

of the absorption coefficient in the slice. With the patient being scanned slice by slice, a 3-dimensional image is obtained. Thus, CT involves a large number of X-ray irradiations and dramatically increases the radiation dose compared to a simple X-ray image. One CT scan of the abdomen amounts to an effective dose of about 10 mSv.

5.5.2 Positron emission tomography

In contrast to CT, where the radiation source is outside the body, positron-electron tomography (PET) uses a radiation source which is introduced into the body as biologically active molecules. The molecules are marked by a positron-emitting radionuclide (a "tracer") and gather in tissue with high metabolic activity. Among the important radionuclides in nuclear medicine are the isotopes ^{11}C, ^{13}N, ^{15}O, ^{30}P and ^{18}F. Following the decay

$$^{11}_{6}\mathrm{C} \longrightarrow {}^{11}_{5}\mathrm{B} + e^{+} + \nu, \tag{6}$$

as an example, the positron annihilates upon collision with an electron after a very short distance. Depending on the isotope and the tissue density, the maximum range of the positrons is 2 to 8 mm. Due to conservation of momentum, the annihilation results in a pair of antiparallel photons with an energy of 511 keV. The positron and electron momentum before annihilation causes an angular distribution of the photons, which is nearly Gaussian with a mean relative angle of 180° and a variation of 0.3° FWHM. An annihilation event is detected by a coincidence of two photons in opposite direction within a temporal window of 10 to 20 ns. The detector consists of a circular array of scintillators and photomultipliers, typically 600 of them on a ring with a diameter of 1 m. Similar to CT, the PET scanner records line integrals of the radionuclide activity, and the image is reconstructed in the same manner. PET scanners have a theoretical spatial resolution of 2 to 3 mm but in practice, the achievable resolution is about 5 mm. The radiation dose is of the same order of magnitude as that of CT.

5.5.3 Magnetic resonance imaging

Magnetic resonance imaging (MRI) is a technique, that uses the quantum mechanical property of ^{1}H nuclei (protons), which are very common in the human body, of having a non-zero spin and therefore a magnetic moment. In an external magnetic field B_z, the magnetic moment of the protons precesses around the field vector and can take one of the two energy eigenstates

$$E_m = -m\gamma\hbar B_z \qquad \text{with} \qquad m = \pm\frac{1}{2}, \tag{7}$$

where γ is the gyromagnetic ratio and $\hbar$ is the Planck constant. In equilibrium, the population of the eigenstates is described by the Maxwell-Boltzmann statistic. An ensemble of protons, if placed in an external magnetic field in z direction, create a macroscopic magnetization $\vec{M}_z$ directing along the magnetic field, while the individual magnetic moments are precessing. Irradiation by an RF field of the frequency $\omega = \Delta E/\hbar = \gamma B_z$, which is the Larmor frequency, allows the transition from the low-energy to the high-energy state. By using a pulsed RF field of a proper pulse length τ_{90°, the magnetization can be rotated by 90° into the x, y plane. After the RF pulse, the transverse magnetization dephases, because the individual Larmor frequency of the proton spins depends on the local magnetic field and is characteristic of the surrounding tissue. Application of another RF pulse of doubled length τ_{180° after a time $T_E/2$ rephases the spins and creates again a measurable transverse magnetization after time T_E. Up to now, all spins respond equally to this so-called spin-echo sequence and the measurement gives the magnetization of the entire body. To obtain an image of the spatial magnetization distribution, the volume is divided into voxels (3-dimensional pixels) which are encoded by adding magnetic fields with different gradients to the homogeneous magnetic field B_z, enabling the reconstruction of the image from the measured magnetization signal. Apart from the diagnostic indication, one advantage of MRI over CT or PET is that it does not involve ionizing radiation. The magnetic field, typically 1.5 T or more, is produced by a superconducting magnet and is considered to be hazard-free unless the patient carries a pacemaker or other metallic implants. For further details see e.g. [12].

5.5.4 Ultrasound imaging

A very common technique in medical diagnostics is ultrasound imaging, sending ultrasonic signals into the body and reconstructing an image from their reflection. Acoustic waves in fluids of gases are described by wave equation

$$\Delta p - \frac{\rho_0}{K} \cdot \frac{\partial^2 p}{\partial t^2} = 0 \tag{8}$$

where p is the pressure, ρ_0 is the density of the medium, and K is called the bulk modulus. The solution for spherical waves is

$$p = p_0 + p_r \frac{\exp(i(\omega t - k|\vec{r} - \vec{r'}|))}{|\vec{r} - \vec{r'}|}. \tag{9}$$

A material property relevant to acoustic waves is the so-called acoustic impedance

$$Z = \sqrt{K \cdot \rho_0}. \tag{10}$$

An acoustic wave propagating in the human body encounters several boundaries when hitting organs, bones etc. at which the acoustic impedance changes. At each boundary, the wave is partially reflected and partially transmitted as described by the reflection and transmission coefficient

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \qquad \textit{and} \qquad T = 4\frac{Z_1 \cdot Z_2}{(Z_1 + Z_2)^2}, \tag{11}$$

respectively, at the interface between tissue 1 and 2. Ultrasonic waves are generated and detected employing the piezoelectric effect. An ultrasound scanner comprises a curved array of ultrasound transducers each emitting an ultrasound wave and recording the echo. From the arrival time and strength of the reflected waves, the depth of the reflecting boundary and the reflection coefficient can be calculated, and the image can be reconstructed by combining data from all transducers.

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