# 1 Radiation and particles

**1-1** Prove that $E = mc^2$ is equivalent to $E = \sqrt{p^2c^2 + m_0^2c^4}$.

**1-2** A typical X-ray energy of medical devices is 20 keV.
a) Calculate the wave length of the radiation.
b) Which acceleration voltage is needed to produce electrons of the same wavelength?

**1-3** a) Calculate the wavelength of an electron in the H-atom ground state.
b) Assume the wave length to be equal the orbit length of electron (wrong classical picture). What is the radius of the H atom?
c) Estimate the dimension of an H atom by using the uncertainty relation $\Delta x \cdot \Delta p = \hbar$.

**1-4** Estimate by using the uncertainty relation:
a) The mass of the virtual particle mediating the nuclear force, where the average nucleon separation is 1.3 fm.
b) The life time of a strongly decaying particle, *e.g.*, the $\rho$ meson is of the order of $\Delta E = 150\,\mathrm{MeV}$.

**1-5** The radius of a hydrogen atom is of the order of 0.5 Å, the one of the proton of 0.8 fm.
Estimate the order of magnitude of the collision cross section for atomic - atomic and nucleon – nucleon collisions, respectively (1 Å$= 10^{-10}$ m).

**1-6** The electromagnetic force is mediated by virtual phontons of mass zero. Derive by using the uncertainty relation the distance law of the electric force.

# 2 Interaction of radiation with matter

**2-1** The maximum absorbance of the medium wavelength cone cells in the human eye is reached at 534 nm (green), where the maximum of the sun's emission spectrum at sea level is 550 nm.

**2-2** The linear attenuation coefficient $\mu$ of 20 keV and 50 keV X-rays is in water 0.6/cm and 0.2/cm, respectively.
a) Which fraction of the radiation is absorbed, before a 10 cm deep lying structure is reached.
b) Which thickness of a lead sheet is needed to absorb the same fraction of 20 keV radiation as a 10 cm thick water layer ($\mu_{lead} = 1015/cm$)?

**2-3** A low concentration suspension of milk in water is irradited by white light. What colour impression is observed at the wall of the glas container after transmission and at the side walls?

**2-4** Order the processes contributing to the interaction of electromagnetic radiation by their magnitude for energy 1 keV and 1 GeV.

**2-5** Is it possible to measure X-rays of 6 keV by using gaseous detectors?

# 3 Interaction of particles with matter

**3-1** In the "Bethe-Bloch" range the minimum stopping power $S_{min}$ in hydrogen ($H_2$) of 4.10 MeVg$^{-1}$cm$^2$ is reached at $\beta\gamma = 4$.
a) Calculate the corresponding kinetic energy in units of the projectile rest energy $m_0c^2$. b) What is the value of $S_{min}$ for $D_2$?

**3-2** Estimate (non relativistic) relative to the protons energy loss ($dE/dx$) and kinetic energy (assume $m_d = 2 \cdot m_p$)
a) the energy loss of deuterons (d) having the same kinetic energy than protons (p). b) the kinetic energy of deuterons experiencing the same energy loss than protons.

**3-3** An aluminum window causes angular straggling of the penetrating particles. By which factor can the angular resolution be improved by changing to a beryllium window of the same effective thickness?

**3-4** A $\Delta E - E$ arrangement has the following properties. The thickness of the $\Delta E$ (first) counter corresponds to a proton range of 10 MeV, the total thickness of $\Delta E$ and $E$ counter to 100 MeV protons.
a) In your experiment, you expect a continuum of proton energies up to 200 MeV together with a strong contribution of monoenergetic protons at 200 MeV. Sketch the plot $\Delta E$ versus $\Delta E + E$ plot including numbers of outstanding points.

# 4 Detection concepts

**4-1** What is your count rate estimate for proton - carbon collisions when using a 1 $\mu$m thick carbon foil and a beam intensity of $10^6$ protons per second?
Assume a radius - mass dependence of $r = 1.3\, fm{\cdot}A^{1/3}$ and $\rho_{carbon} = 2\, g/cm^3$.

**4-2** Neutral pions of mass 135 MeV/c$^2$ decay via $\pi^0 \rightarrow \gamma\gamma$.
a) Which kind of detector material and geometry is suitable to measure low-energy $\pi^0$?
b) How very high energetic $\pi^0$ must be detected?

**4-3** A multi wire proportional chamber (MWPC) of 1 cm thickness is filled with argon gas of 1 bar ($\rho_{NTP} = 1.6 \cdot 10^{-3}$ g/cm$^3$).
a) Estimate the theoretically achievable energy resolution of the chamber for minimum ionizing particles assuming an almost perpendicular crossing.
b) Compare with the energy resolution of to a xenon high-pressure chamber operated at 4 bar ($\rho_{NTP} = 5.6 \cdot 10^{-3}$ g/cm$^3$).
Assume the energy loss of argon behaves like helium.

**4-4** The fixed dead time of a detector element is 10 $\mu$s. What is the maximum particle rate the element can handle, if at least 99% of the particles should be registered?

**4-5** The impact point of neutrons from the reaction $\pi^{-3}He \rightarrow dn$ with stopped pions is measured in a plastic scintillator rod of 2 m length and cross section of $5 \times 5\,\mathrm{cm}^2$ from the difference of the light arrival time by using photo multiplier tubes (PMT) at each end. ($Use\ m_\pi = 140\, MeV/c^2$, $m_n = 940\, MeV/c^2$, $m_d = 1876\, MeV/c^2$, $m_{^3He} = 2808\, MeV/c^2$, and $c =$ 0.3 m/ns.)
a) Sketch the pulse height spectra measured by means of the PMTs.
b) Calculate maximum and minimum neutron time-of-flight (TOF) to the rod placed in 4 m distance perpendicular to the direction target - center of the rod.
c) Which kind of light reaches primarily the PMTs (assume an index of refraction of n=1.5 of the scintillator material)?
d) Assume a time resolution of $\Delta t \Delta = 354$ ps of each PMT. What is the position resolution $\Delta x$ achievable along the rod?