NPAC Detector Physics exam
17/11/2022, 09:00–12:00

The exam is divided into 3 parts (A,B,C), which will be graded separately. Please write your answers to each part on a **separate sheet** (or sheets).

- Please write your name on each sheet (of your answers).
- The use of non-programmable ("collège"-type) calculators is allowed. All other electronic devices and documents are forbidden. Please switch off and put away any smartphones (and smartwatches etc) before the exam begins.
- Please include a brief explanation/justification with your answer, especially for numerical calculations. (It does not need to be long or detailed, but it should be clear how you reached your answer.)
- Parts A and B are worth 10 points each, and part C 12 points, for a total of 32.
- This exam paper consists of six numbered pages (including this one), printed on three sheets.
- Les étudiants francophones éprouvant des difficultés de compréhension pour certaines questions peuvent demander une traduction. Vos réponses peuvent être données en anglais ou en français.

Do not turn over this page until instructed to do so.

Ne tournez pas cette page avant le signal du surveillant.

Part A (10 points total)

Question A1 (2.5 points)

A beam of muons with momentum 400 MeV/c passes through a water tank of depth 1 m (perpendicular to the beam).

(a) Estimate the mean energy loss in MeV of each muon (within a factor of two), explaining your reasoning and noting any assumptions made. [**1.5 points**]

(b) Explain briefly and qualitatively why 400 MeV/c muons can pass through the water tank, whereas both alpha particles and electrons of similar momentum are likely to be absorbed. (Detailed calculations are not required.) [**1 point**]

Question A2 (2 points)

You are investigating whether a crystal scintillator can be used as the electromagnetic calorimeter for various different proposed e^+e^- detectors. The two use cases being considered are

(i) photons of typical energy 80 GeV from Higgs decays at a $\sqrt{s} \approx 250$ GeV collider studying electroweak physics;

(ii) photons of typical energy 800 MeV from π^0 decays at a $\sqrt{s} \approx 10$ GeV collider studying flavour physics.

Given that for this scintillator material the critical energy is $E_c = 17.4$ MeV and the radiation length is $X_0 = 2.59$ cm, how deep would the crystal calorimeter need to be to fully absorb the shower in each case? [**2 points**]

Question A3 (1 point)

A nuclear reaction generates neutrons of energy 1 MeV. Shielding is placed around the experiment to thermalise the neutrons. Suggest a suitable material for the shielding, giving a brief (physics) justification for your answer. [**1 point**]

Question A4 (4.5 points)

You are selecting a photodetector for a new experiment that will produce scintillation light. A number of different PMT-based sensor designs are available, with different quantum efficiencies.

(a) Define the term “quantum efficiency”. [**1 point**]

(b) Explain why the quantum efficiency is significantly less than 100%, and why it varies with wavelength and between different sensors. [**2 points**]

One particular photodetector would be a good match for the requirements of the experiment, except that its quantum efficiency is optimised for longer wavelengths and does not cover the range expected for the scintillation light. A colleague proposes the use of wavelength-shifting fibres.

(c) Outline the (physics) mechanism by which this solution would work. Explain whether it would still work if the situation were reversed, i.e. if the quantum efficiency were optimised for wavelengths shorter than the scintillation light. [**1.5 points**]

Part B (10 points total)

Question B1 (2 points)

Calculate the statistical limit of the energy resolution for

(i) a semiconductor (3×10^5 e^-/hole pairs per MeV, Fano-factor = 0.1, 98% collection efficiency) with a depleted zone of 300 μm, and

(ii) a 1 cm thick scintillator detector (4×10^4 photons/MeV, Light collection efficiency = 0.2, QE = 0.25, Fano-factor = 1)

for a MIP passing through with $\mathrm{d}E/\mathrm{d}x = 2$ MeV/cm. [**2 points**]

Question B2 (5 points)

A 500 MeV electron interacts in the water ($n = 1.3$) of the future Hyper-Kamiokande experiment at a distance of 5 m from the detector wall. The number of Cherenkov photons it produces per unit path (in nm) and wavelength (in nm) is

$$\frac{d^2N}{dx d\lambda} = 2\pi\,\alpha\,\sin^2\theta_C\,\frac{1}{\lambda^2}$$

where α is the fine structure constant ($\sim 7.3 \times 10^{-3}$). The range of 500 MeV electrons in water is about 1m.
Compute:

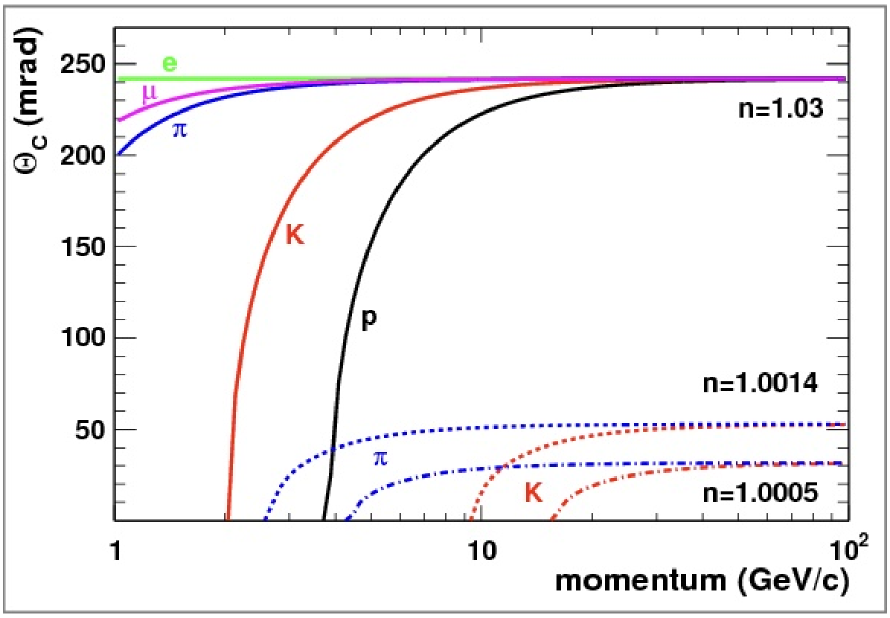
(a) The radius of the Cherenkov ring on the detector wall (neglect deformations, i.e. assume the wall to be flat and perpendicular to the electron trajectory). [**1 point**]

(b) The number of detected photons, if the PMTs detect photons of wavelengths between 300 and 500 nm with an average Quantum Efficiency of 20% and provide 40% geometrical coverage. [**2 points**]

(c) If you could change the glass of the PMTs to quartz, the minimal detectable wavelength would be 180 nm. Calculate the number of detected photons, if the PMTs detect photons of wavelengths between 180 nm and 500 nm with an average Quantum Efficiency of 20% and provide 40% geometrical coverage. Draw conclusions from the result on the statistical error. [**2 points**]

Question B3 (1.5 points)

The figure shows the Cherenkov angle as a function of momentum for different kinds of particles in media with different refraction indices: Aerogel ($n = 1.03$), C_4F_{10} gas ($n = 1.0014$) and CF_4 gas ($n = 1.0005$).



Which combination of these radiators would you choose to discriminate pions from kaons in a particle beam with a momentum of 5 GeV/c? Explain. [**1.5 points**]

Question B4 (1.5 points)

Describe in maximum 10 lines the principle of a liquid Xenon TPC for direct Dark Matter search. What signals are observed? [**1.5 points**]

Part C (12 points total)

This part contains two subsections. The first (question C1) consists of standard items from the lectures (*questions de cours*). The second (questions C2–C4) consists of a series of related questions.

First subsection of part C

Question C1 (6 points)

(a) Give the names of the two categories of gas types for gaseous detectors, and give an example of a gas for each category. Explain the role of each category of gas.

(b) What is the order of magnitude of the energy needed to creating an ionized electron-ion pair for a typical gas used in a tracking detector studied in this course?

(c) Describe **two different** possible designs that could be used for a calorimeter, explaining their differences and giving their characteristics/specifications. (These could be electromagnetic or hadronic calorimeters, but bolometers are excluded.)

Second subsection of part C

In this subsection (questions C2–C4), we consider a tracking system consisting of three independent planar detectors, arranged parallel to one another and equally spaced, as illustrated in the figures below. The three detectors are not necessarily the same. The tracking system is placed in a constant magnetic field B, perpendicular to the field of view of the figures.

For the following questions, please note:

(i) It is irrelevant to the questions below whether the particle is moving from left to right, or right to left.

(ii) Questions C3+C4 can be answered independently from C2.

(iii) Question C3 (and in particular the expression for Δs_{total}) may help you answer question C4.

Question C2 (3 points)

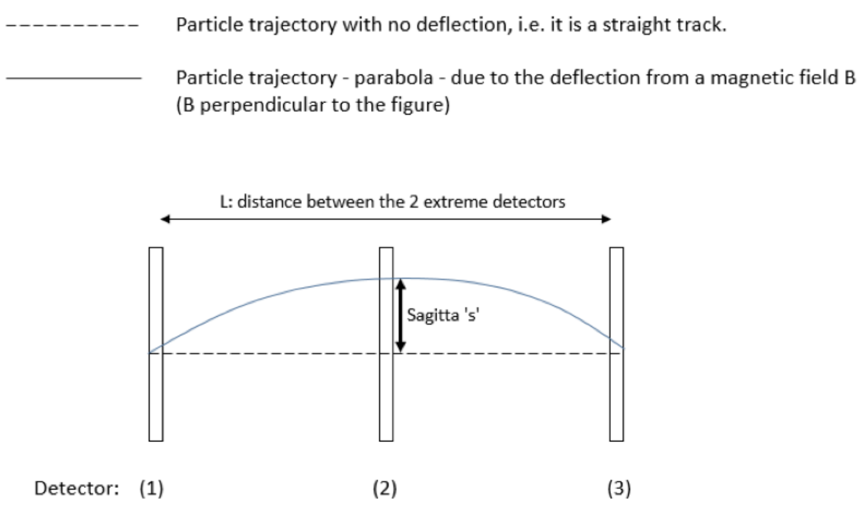
Calculate the sagitta s of a track of momentum p as a function of p, B, and L, where L is the overall distance between the first and last detectors. (The geometry is illustrated in Fig. 1.) Your expression should include any constant needed to evaluate s when

- p is expressed in units of GeV$/c$
- L is expressed in units of metres
- B is expressed in units of Tesla

and taking the speed of light to be $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$.

Remark: For this geometry, the sagitta is the perpendicular deviation with respect to a horizontal line, evaluated at the position of the middle detector.

Fig. 1: Trajectory of a particle in a magnetic field. The trajectory is a parabola.



Question C3 (1 point)

The total measurement error Δs_{total} on the sagitta is related to the individual detector position errors Δs_i as follows:

$$\Delta s_{\text{total}} \sim \sqrt{\left(\frac{\Delta s_1^2}{4} + \Delta s_2^2 + \frac{\Delta s_3^2}{4}\right)}$$

How do you interpret this uncertainty combination (and particularly the relative influence of the position uncertainties of the three detectors)?

Question C4 (2 points)

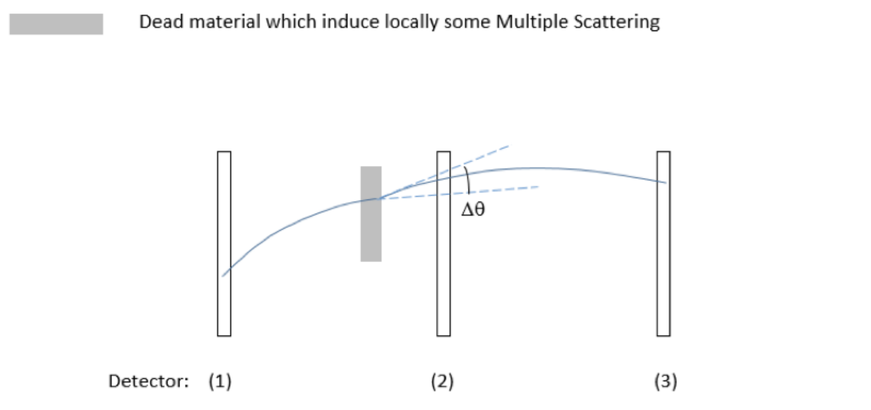
We now suppose that some dead material is present within the tracker. (The composition of this dead material is not important here: it could be cables, supports, etc.) This can deteriorate the measurement of the sagitta s via Multiple Scattering. We will attempt to understand how the *position* and arrangement of the dead material affects the sagitta measurement. We assume that this dead material is the only source of Multiple Scattering (i.e. we neglect scattering in the air, and also consider that the detectors are thin/light such that no scattering occurs in the detectors). As a result, Multiple Scattering can occur only within the dead material, and the particle trajectory can be modified (with respect to a continuous parabola) only within the dead material. We express this as a deviation angle $\Delta\theta$ at the position of this dead material, as illustrated in Fig. 2 below. (Before and after the dead material, the particle follows parabolic trajectories.)
The angular deviation $\Delta\theta$ is proportional to:

$$\Delta\theta \propto \frac{14\,\text{MeV}}{p \text{ in GeV}} \sqrt{x/X_0}$$

where x is the dead material thickness and X_0 is the effective radiation length of the dead material.

Fig. 2: Example of effect of Multiple Scattering due to some dead material on the particle trajectory. Before and after the dead material, each trajectory is a parabola.

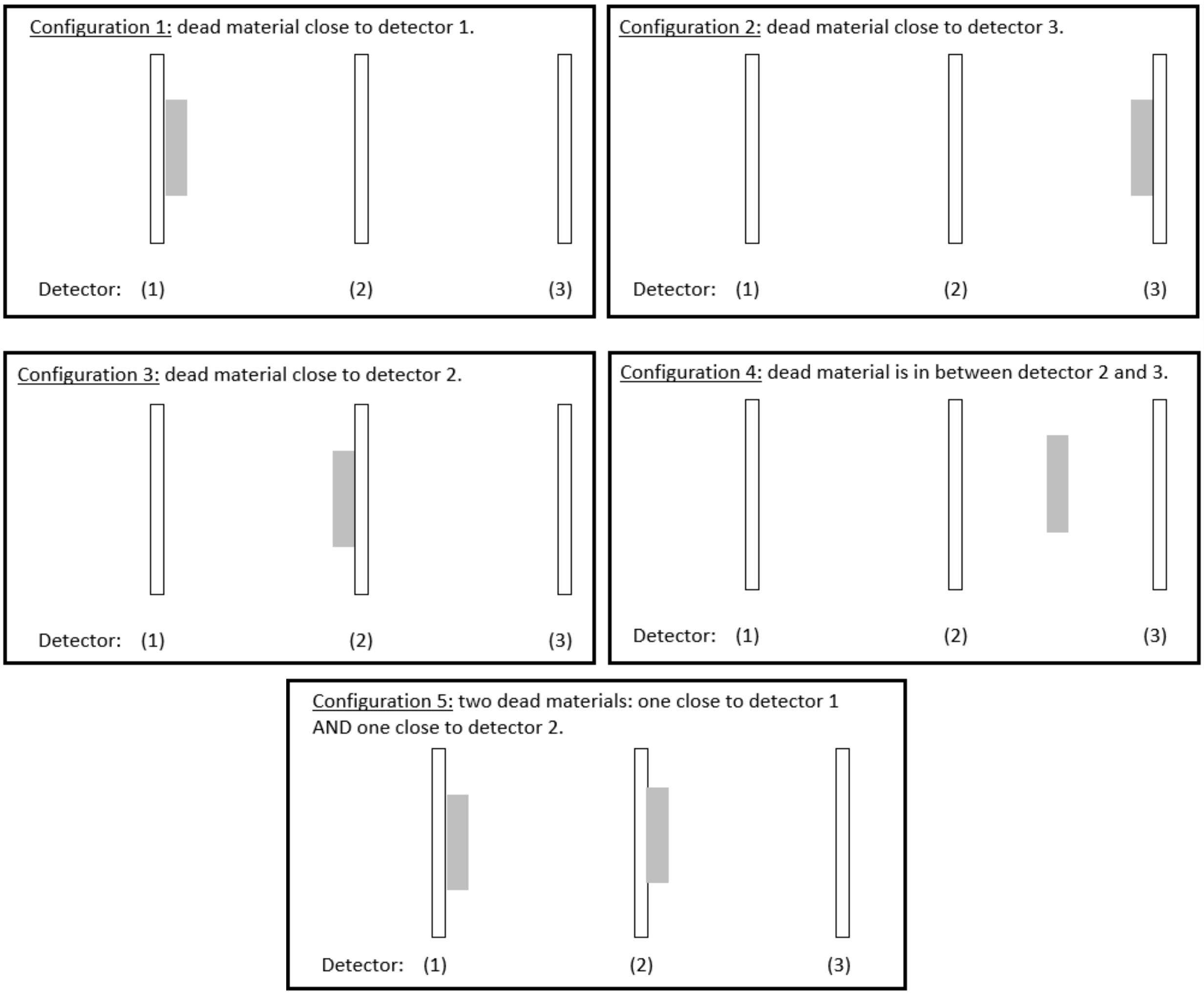
Δθ : deflection angle due to Multiple Scattering



Five different configurations are indicated in the figures below, with one unit of dead material in configurations 1–4 and two units of dead material in configuration 5. **Rank/classify the five configurations** from best to worst according to the expected effect of Multiple Scattering on the sagitta measurement

- from the worst (i.e. the largest degradation of the sagitta measurement)
- to the best (i.e. the smallest degradation of the sagitta measurement).

Justify your classification with qualitative arguements. **No calculations are required.**
Reminder: it is irrelevant whether the particle is moving from left to right, or right to left.


Configuration 1: dead material close to detector 1.
Detector: (1) (2) (3)
Configuration 2: dead material close to detector 3.
Detector: (1) (2) (3)
Configuration 3: dead material close to detector 2.
Detector: (1) (2) (3)
Configuration 4: dead material is in between detector 2 and 3.
Detector: (1) (2) (3)
Configuration 5: two dead materials: one close to detector 1 AND one close to detector 2.
Detector: (1) (2) (3)