NPAC – Detector Physics
Exam 15/11/2021 9:00-12:00

Write each of the 3 parts on a separate sheet

- *Ensure your name is written on each sheet.*
- *The use of "collège"-type (non-programmable) calculators is allowed. All other devices and documents are forbidden.*
- *Les étudiants francophones éprouvant des difficultés de compréhension pour certaines questions peuvent demander une traduction. Les réponses peuvent être données en anglais ou en français.*

NPAC – Detector Physics - Part 1

Q1

LHCb has recently found 3σ evidence of tension with the Standard Model when comparing the rates of the two processes $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$.
While the underlying physics of these two channels should be very similar in the SM, the behaviour of the final-state particles in the detector differs. (The typical momentum of the B^+ mesons is 10-100 GeV.)

a) List the key detector elements/subdetectors necessary to determine the following for the final-state particles:
I. its momentum,
II. whether it is an electron, muon, or kaon.
[You do not need to propose particular technologies; it is sufficient to list subdetector/subsystem types.]

The momentum resolution of the e^+e^- system is significantly worse than that of the $\mu^+\mu^-$ system (when measuring both in the same LHCb subdetectors). This is due to the effect of an additional physical process that is negligible for muons but not for electrons.

b) Identify this process.

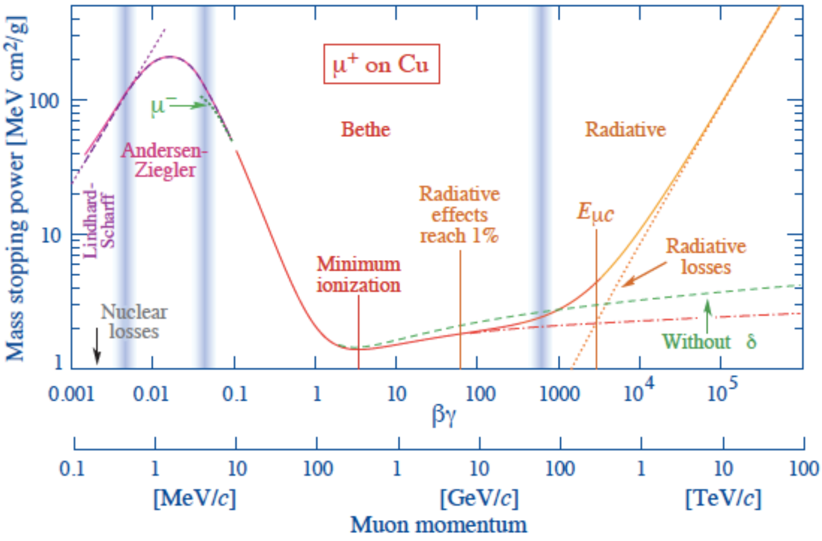
c) Suggest a way in which information from another subdetector might be used to help recover some or all of this degradation.

d) When designing a future detector, what could you change in order to reduce this effect as much as possible? (i.e. what is the key quantity/parameter that determines the magnitude of the effect?)

Q2

Consider the plot of mass stopping power below, as well as the following constants:

- Density of copper: $\rho = 8.96\ \mathrm{g\ cm^{-3}}$
- Radiation length of copper: $X_0 = 12.86\ \mathrm{g\ cm^{-2}}$
- Atomic number of copper $Z = 29$, and mean mass number $A \sim 63.5$
- Critical energy of copper: $E_c = 24.8$ MeV



a) Estimate the thickness of copper required to stop a 10 GeV beam of muons.

b) Estimate the thickness of copper required to stop a 10 GeV beam of electrons.

[Justify your answers. Approximate estimates, good to within a factor of two or so, are fine. It is enough to find the thickness that will stop the majority of the beam; you do not need to consider stragglers.]

Q3

We wish to study photons of energy E_γ between 10 eV and 10 keV. We use a thin plate of material.

a) What is the most probable way for the photons to interact with the material? Identify the process and draw a Feynman diagram (including all participating particles).

b) We have plates of various materials available (e.g. Si, Cu, Fe, Pb, ...), and plan to study how the interaction probability varies between them. What property of the material has the most infuence on the interaction probability? Roughly how does the cross-section scale with this property? (The question refers to the physical properties of the material, not the dimensions of the plate.)

c) We observe an event in which an incoming 18.0 keV photon produces a single electron of energy 9.0 keV and no other outgoing particles. What can we deduce from this? (The value of 9.0 keV represents the initial energy of the electron, ignoring any subsequent energy loss in the material.)

d) For a particular material, we measure how the cross-section varies as a function of photon energy. We notice that the variation is not smooth but has a number of ridges/peaks in the plot of cross-section vs energy. Suggest a physical origin for these ridges.

Q4

We wish to detect photons with energy $E_\gamma = 1$ MeV.

a) Suggest a suitable scintillator material, giving an approximate value for its light yield in %. Roughly how many scintillation photons will be produced? (Order-of-magnitude estimates are fine.)

b) We use a photomultiplier tube to detect the scintillation photons. Sketch a simple PMT design, noting the key physical processes that occur in the detection of a scintillation photon. Explain briefly the meaning of the terms "quantum efficiency", "collection efficiency", and "multiplication efficiency".

[$\hbar c$ = 197.3 MeV fm]

NPAC – Detector Physics - Part 2

Section 1:

(All questions are independent of each other)

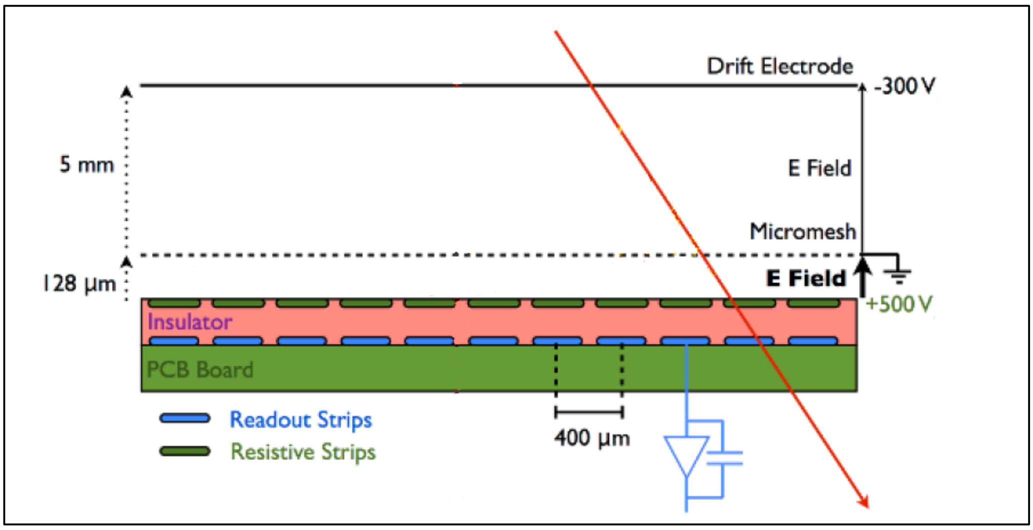
1.1) Name the two types of gas families used in gaseous detectors and explain briefly their role. Give at least one example of a gas for each family.

1.2) For each of the two gas families, give the typical energy needed to create an electron-ion pair when a minimum ionising charged particle (m.i.p.) passes through.

1.3) How many electron + ionised atom pairs do you expect for 1 cm of gas at atmospheric pressure, produced by a minimum ionising (charge) particle – m.i.p.?

1.4) Explain briefly the meaning of the terms "first Townsend coefficient" and "second Townsend coefficient".

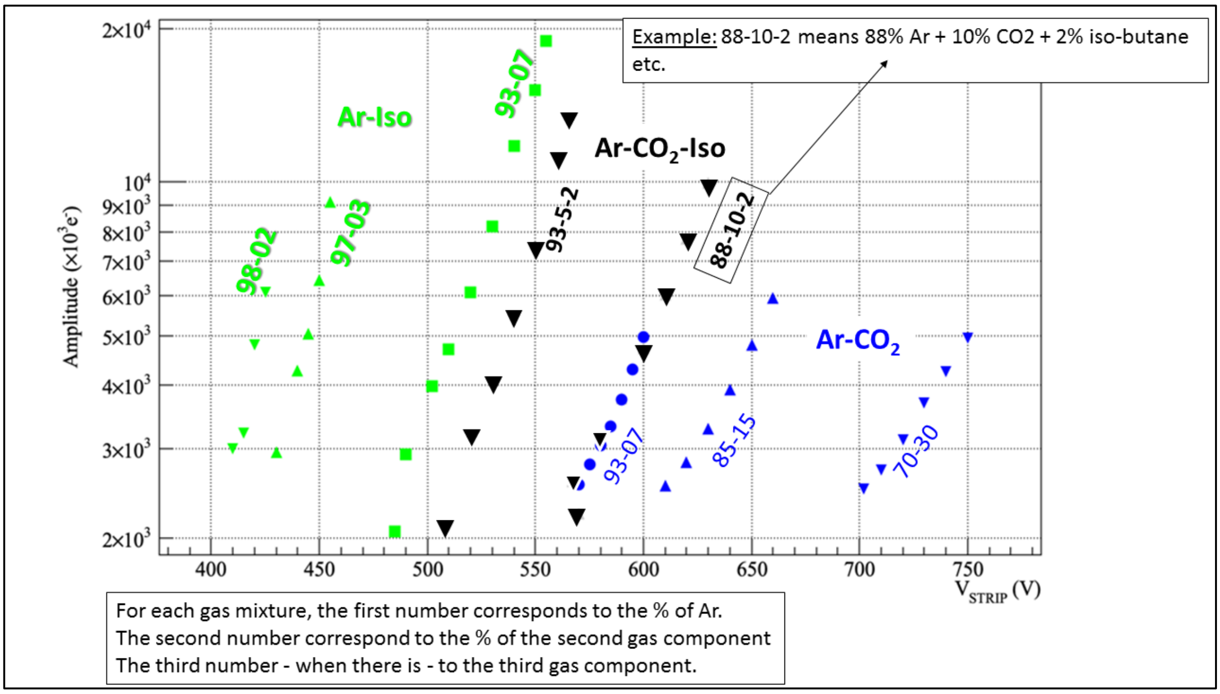
1.5) (i) In the MPGD Micromegas gaseous detector shown below, show which part is called the "drift region", and which part is called the "amplification" region.
(ii) Explain the role of each region and the phenomena which will occur after a muon passes through the detector.
(iii) Show how the different charged particles - ions and electrons - will drift in each region.
(iv) Explain why, in certain HV conditions, the mesh is almost transparent for the electrons and why the mesh could almost fully absorb the ions.



1.6) The figure below shows the typical gain (vertical axis) that could be obtained with the applied HV (horizontal axis) in a Micromegas detector, for different gas families and proportions.

Three families of gas mixtures are shown:

- (in blue) Argon + CO_2, for different CO_2 concentration of: 7 or 15 or 30%
- (in black) Argon + CO_2 + iso-butane, always for 2% iso-butane concentration, and 93 or 88% of Argon, and 5 or 10% of CO_2
- (in green) Argon + iso-butane for different iso-butane concentration of: 2 or 3 or 7%



Example: 88-10-2 means 88% Ar + 10% CO2 + 2% iso-butane etc.

For each gas mixture, the first number corresponds to the % of Ar.
The second number correspond to the % of the second gas component
The third number - when there is - to the third gas component.

As expected, for a given gas mixture, the gain increases exponentially when increasing the HV, assuming the detector runs in the same conditions for all different gas mixtures tested (at 1 atm. and 20 deg).

(i) For the Ar-CO_2 mixtures (blue curves), explain how and why its behaviour varies with CO_2 concentration. (In other words, to obtain a given gain, why does a higher CO_2 concentration require a higher voltage?)

(ii) Same question as (i) but for the Argon + iso-butane family (green curves).

(iii) How do you interpret the different slopes of the Ar-CO_2 curves (blue curves), for the different CO_2 concentration?

(iv) What physical process explains why you need a lower HV for Argon+CO_2+iso-butane family (black curves) or Argon+iso-butane family (green curve) w.r.t. Argon+CO_2 family (blue curves)?

(v) You are selecting a gas for a new detector. The options available are the two Ar-CO2-Iso mixtures (black curves) and the three Ar-CO2 mixtures (blue curves) shown in the figure. Which gas mixture would you choose, and why? Choose only one mixture and briefly explain your choice.

1.7) Assuming a mean free path of the ionizing electron in the gas of 10 microns in the amplification region, what will be the theoretical gain that could be obtained for an amplification gap of 128 micron thickness?

Definition:

By definition, the gain “g” is the ratio between the total number of ionizing electrons produced in the drift region, and the total number of electrons collected at the anode plane (i.e. after amplification occurs in the amplification region).

Section 2

(All questions are independent of each other)

2.1) Explain the two types of families of calorimeters that are possibly used in a colliding experiment. Give some advantages and disadvantages of each type.

2.2) The atmosphere is considered as a calorimeter for air-shower experiments. Remind how many radiation length – X_0 – equivalent it is from the top atmosphere to the sea level. Assuming we are at sea level, answer the following questions:

(i) What types of particles could escape for a gamma initiated shower? (i.e. an electromagnetic shower)

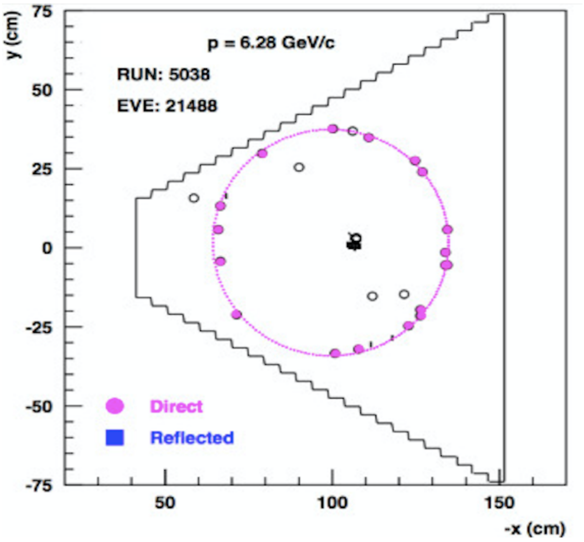
(ii) What types of particles could escape for a proton initiated shower? (i.e. a hadronic shower)

(iii) How does these depend with the energy of the incoming particle? (gamma or proton)

NPAC – Detector Physics - Part 3

Q1

The image below shows the Cherenkov ring detected in the CLAS12 detector. A charged particle with a momentum of 6.28 GeV/c crossed a thin layer of Aerogel (n = 1.05) located at a distance of (about) 1 m from the plane where the ring was measured.

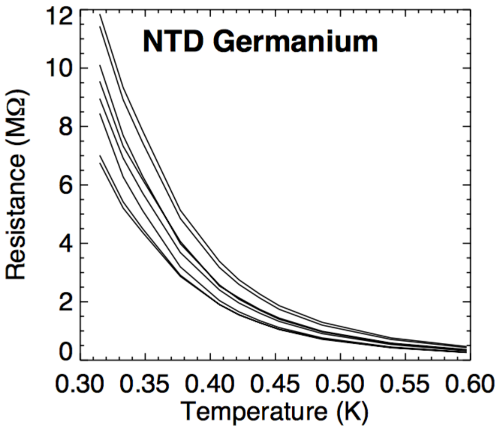


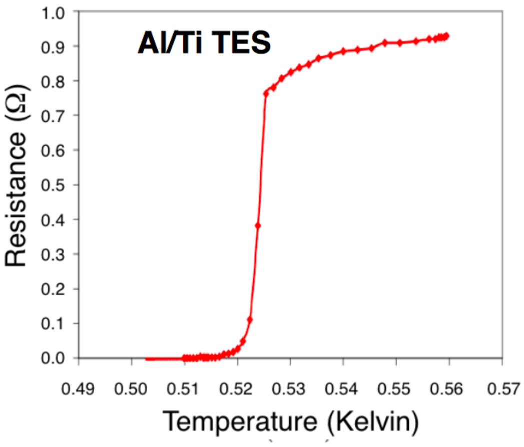
(a) Can you tell whether the particle was an electron or a proton? Justify your answer.

(b) What would you expect to see in the same detector for the other type of particle, if it had the same momentum?

Q2

The figures show the resistance as a function of temperature for two different types of materials: Neutron Transmutation Doped Germanium and an Al/Ti combination.





a. What is the relevant parameter that you can deduce from these curves, if you wish to use the material as a thermometer for a bolometer? Explain briefly its meaning.

b. At what temperature would you choose to operate each detector to achieve the best performance in terms of the parameter of question a)?

c. Are there any other advantages or disadvantages when operating the detectors at such temperatures?

Q3

A 3x3 cm^2 silicon detector has a thickness of 200 μm and is read out with microstrips of 30 μm pitch. A vertical MIP passes through the detector.

(a) Compare the charge signal of the MIP with the charge from intrinsic carriers. The energy to create a hole-ion pair in Si is 3.63 eV and the concentration of intrinsic carriers is $1.5\ 10^{10}\ cm^{-3}$. The density of silicon in $2.33\ g\ cm^{-3}$.

(b) Based on (a), explain the need to apply a bias voltage to the detector.

(c) What is the resolution on the position of the crossing particle? Assume the whole charge to be collected on one strip.