Experiment IV

Drift Chamber (VDC)

Laboratory class particle physics

2018

Basic Knowledge

- Charged particle interaction with matter
- Gaseous detectors
- Scintillators
- Pulse electronics

Goals of the experiment

- Programming the readout for the drift chamber
- Evaluating the properties of the drift chamber
- Measurement of the drift velocity of electrons as a function of the drift field
- Study the relation between gas amplification and the anode voltage
- Study of the long-term reproducibility of the measurements and the impact of environmental parameters
- Comparison of different gas mixtures

Contents

A drift chamber is used to measure the spatial coordinates of traversing ionizing particles. In this experiment various properties of drift chambers have to be studied, in particular the drift velocity of electrons in the counting gas. Low energetic ($< 10\,\mathrm{eV}$) electrons (drift electrons) are produced in the drift chamber by an initial electron from a β^- decay. For this purpose two ^{90}Sr sources are used.

1 Principles of Gaseous Detectors

1.1 Electron-Matter Interaction

The main interaction for low energetic electrons ($< 10\,\mathrm{MeV}$) with matter (in this experiment: gas) is ionization. In the case of electrons the energy loss per unit length of path $\mathrm{d}E/\mathrm{d}x$ cannot be described by the *Bethe-Bloch-Formula*, however, the needed formula is closely related to it (see manual of lab experiment 7, appendix B).

1.2 Drift and Diffusion of Electrons in Gases

Secondary electrons, which are produced by the interaction of the primary charged particles (in this case the β^- radiation of the ^{90}Sr sources) with the counting gas, lose their energy rapidly by collisions with the gas molecules. Without an external electric field the energy distribution can be described by a Maxwell-Boltzmann-distribution

$$F(\varepsilon)\,\mathrm{d}\varepsilon = C\sqrt{\varepsilon}\exp\left(-\frac{\varepsilon}{k_B T}\right)\mathrm{d}\varepsilon. \tag{1}$$

The mean energy $\langle\varepsilon\rangle$ of this distribution ("thermal energy") is given by

$$\langle\varepsilon\rangle = \int_0^\infty \varepsilon \cdot F(\varepsilon)\,\mathrm{d}\varepsilon = \frac{3}{2}k_B T \approx 40\,\mathrm{meV}\ \text{(at room temperature)}.$$

While the charge center of the secondary electrons is stationary, the cloud of electrons diffuses due to the undirected movement of each of the electrons.

In order to detect the electrons an electric field is applied (drift field, see Fig. 4). Due to this electric field the electrons are accelerated between the collisions with the gas molecules. This leads to a superposition of a directed motion with the diffuse motion. The charge center of the drift cloud moves with the drift velocity v_d.

Due to their small mass, electrons can be accelerated to high energies between two collisions with gas molecules. These energies are often larger than the thermal energy, however, this depends strongly on the composition of the gas mixture. If the electric field exceeds a crital value which depends on the gases used, the energy distribution can differ from the Maxwell-Boltzmann distribution previously mentioned. The drift velocity v_d for thermal energies is given by [Blum98, p. 54]

$$v_d = \langle a \cdot t\rangle = \frac{1}{2}\,a \cdot \tau(\varepsilon(|\vec{E}|)) = \frac{1}{2}\,\frac{e}{m}|\vec{E}| \cdot \tau(\varepsilon(|\vec{E}|)) \tag{2}$$

with

$$\begin{aligned} \frac{e}{m} &= \text{specific charge of the electron} \\ \left|\vec{E}\right| &= \text{electric field} \\ \tau &= \text{mean time between collisions.} \end{aligned}$$

This equation can be derived using elementary kinematics and dynamics. The mean time τ between two successive collisions depends on the particle density $n = \frac{N}{V}$ and the scattering cross-section σ. It can be expressed by

$$\frac{1}{\tau} = n \cdot \sigma \cdot \langle v_\mathrm{e} \rangle, \tag{3}$$

where $\langle v_\mathrm{e} \rangle$ denotes the mean velocity of a single electron. Using the ideal gas law

$$p \cdot V = N \cdot k_B \cdot T \tag{4}$$

the temperature T and pressure p dependence can be determined. Substituting equations (4) and (3) in equation (2) yields:

$$v_d = \frac{1}{2} \frac{e}{m} \frac{kT}{p} \frac{1}{\langle v_\mathrm{e} \rangle} \cdot \left|\vec{E}\right| \cdot \frac{1}{\sigma\left(\varepsilon(\vec{E})\right)}. \tag{5}$$

Using $\sigma \approx$ const, which is a rough, but reasonable estimate (see Figure 1 and 2), the drift velocity v_d can be written as:

$$v_d \propto \frac{|\vec{E}| \cdot T}{p}. \tag{6}$$

The scattering cross-section σ of electrons with gas shows some energy dependencies, the cross-section is shown in Figure 1 for argon. The minimum in the scattering cross-section is caused by the Ramsauer effect[Ott98, S. 109]. The scattering cross-section also depends on various other effects, e.g. excitation level, resonances etc. Figure 2 shows an overview of the cross-section behaviour for CO_2.

Hence, in general, especially for high electric fields, the previously given formula (6) does not apply. The dependencies of the drift velocity on the electric field, the pressure, temperature and gas mixture can be calculated numerically with special programs like Magboltz [Mag02] or it can be measured experimentally. The drift velocity reaches a plateau for very high electric fields, where it only varies slightly with the electric field.

1.3 Gas Multiplication

A minimal ionizing particle traversing the drift volume of a drift chamber typically generates ten electron-ion pairs per millimeter path length. This low number of electrons would be difficult to detect. In very high electric fields the free electrons can be accelerated between two collisions to such high energies, that they are able to ionize further gas atoms. In this way the number of electrons starts to avalanche. The total number of electrons depends exponentially on the applied voltage. The gas amplification G is given by the ratio:

$$G = \frac{N_f}{N_i}$$

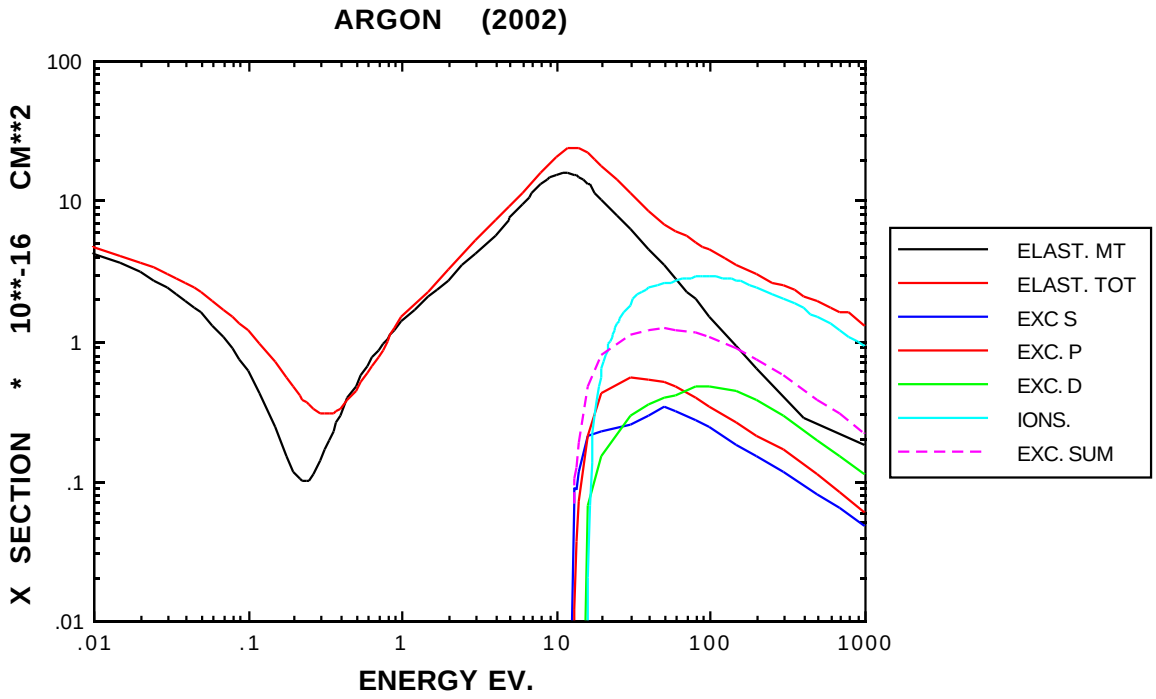

Figure 1: Cross-section for electron scattering in argon as a function of energy.[Mag].

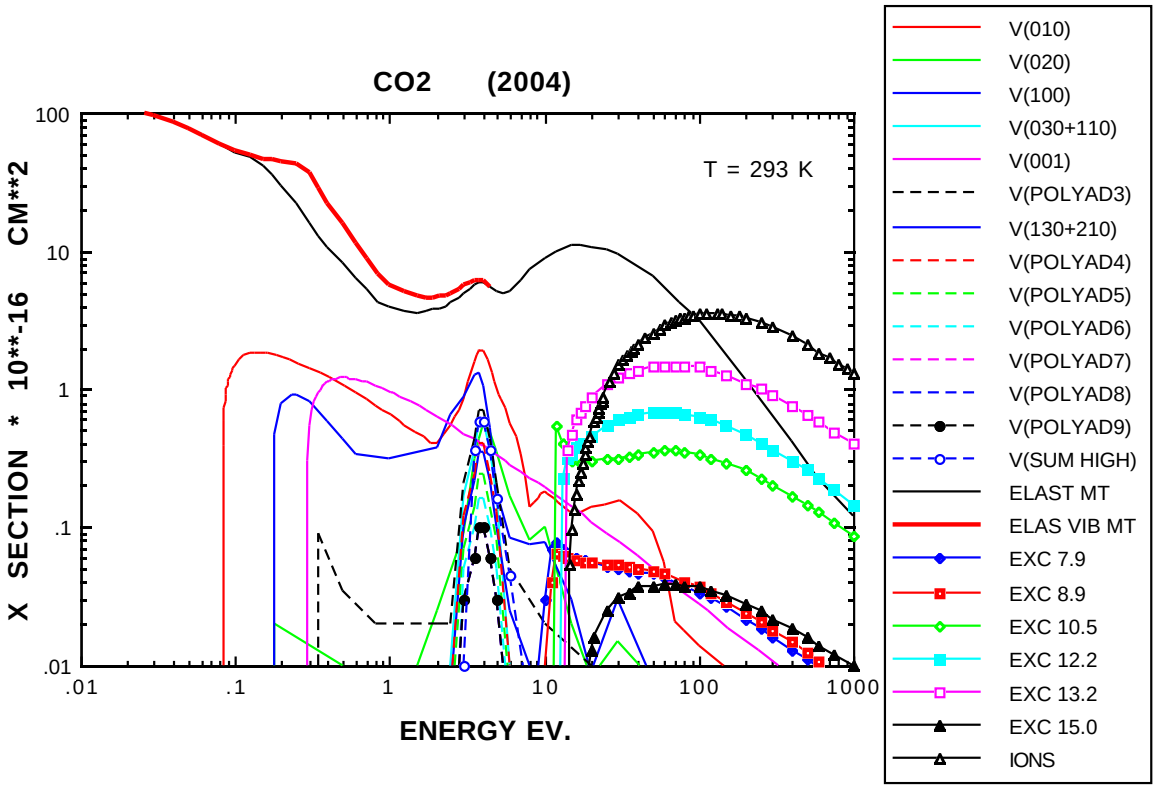

Figure 2: Cross-sections for various processes of electrons interacting with CO_2 as a function of energy. [Mag].

where

$$\begin{aligned} N_f &= \text{Total number of produced electrons} \\ N_i &= \text{Number of primary electrons.} \end{aligned}$$

With proper gas mixtures and high electric fields a gas amplification of up to 10^6 can be achieved. To reach the needed high electric field the diameter of the wire used as the anode is typically of the order of $10\,\mu$m. Drift chambers are operating in the proportional regime. It is limited by two disruptive processes:

- Excited gas molecules can emit UV-photons, which trigger new electrons at the cathode (see Figure 5) via the photoelectric effect. These electrons can cause an avalanche close to the anode wire, in an extreme case this process can lead to a permanent discharge.
- Secondary electrons can also be produced by the neutralization of positive ions at the cathode, which then can lead to an avalanche at the anode wire as well.

Both processes can be reduced by adding a quenching gas. The polyatomic organic gas molecules of the quenching gas have a multitude of rotation- and oscillation excitation modes leading to a quasi-continuous absorption spectrum. Therefore, the molecules can absorb the UV-radiation and afterwards reach their ground state by non-radiating transitions. Furthermore, in collisions the charge can be transferred from the counting gas ions to the quenching gas molecules. Instead of the light counting gas ions the heavy quenching gas ions hit the cathode, which release less secondary electrons.

1.4 Gas Mixtures

For this experiment several argon-carbon dioxide mixtures with different mixing ratios are available. In this mixtures argon (Ar) serves as counting gas while the carbon dioxide (CO_2) serves as quenching gas. The ratios vary between 20 to 80 and 10 to 90, the mixture is called SagoxXY where XY denotes the percentage of CO_2, e.g. Sagox18 is a mixture of 82 % argon and 18 % CO_2. According to the manufacturer the gas purity is at least 99.7%.

	drift velocity in μm/ns			
E field in V/cm	Sagox10	Sagox15	Sagox18	Sagox20
50	3.10	2.17	1.84	1.68
100	6.29	4.34	3.68	3.34
150	9.75	6.57	5.54	5.02
200	13.6	8.95	7.45	6.73
250	18.0	11.4	9.45	8.50
300	22.7	14.2	11.6	10.4
350	27.6	17.1	13.9	12.3
400	32.5	20.4	16.4	14.5
450	37.1	23.8	19.0	16.7
500	41.1	27.4	21.8	19.2

Table 1: Simulated data using Magboltz [Mag02] for typical Ar/CO_2 mixtures. The uncertainty on the drift velocity can be estimated with 0.5%.

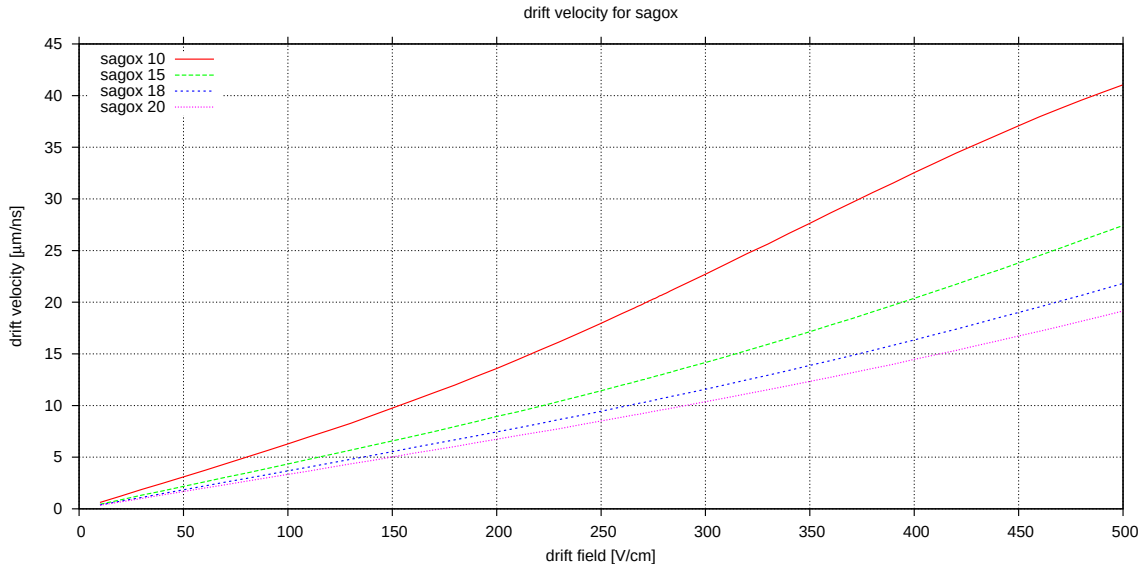

Figure 3: Drift velocity as a function of the electric drift field for four argon-carbon-dioxide mixtures. The curves were calculated with the use of the gas simulation program Magboltz [Mag02].

The plateau starts at roughly 100 V/mm which cannot be reached in this experiment. In good approximation formula (6) can be applied. Reference values for the drift velocity can be found in Table 1.4 and in Figure 3.

2 The Drift Chamber

2.1 Working Principle

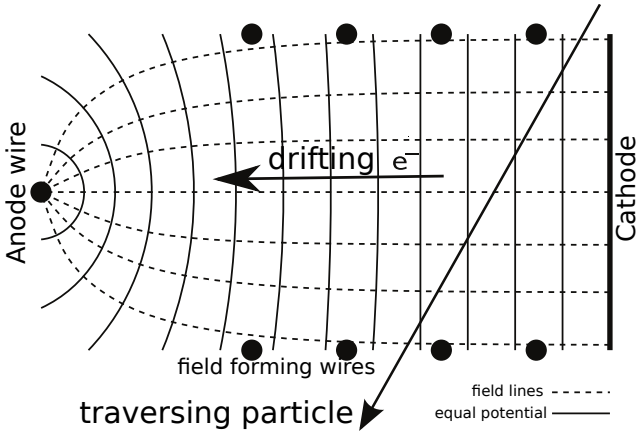

Figure 4: Electric field inside of the drift chamber.

Two electrodes are located in the gas-filled volume of a drift chamber, namely anode and cathode. By applying a voltage between them an electric drift field is created. The particles which have to be detected traverse the volume quasi-perpendicular to the electric field. On their path through the gas volume the electrons ionize the counting gas atoms. The released electrons and ions are separated due to the electric field and the electrons are accelerated towards the anode wire. In immediate vicinity of the anode wire the gas amplification sets in and generates a measurable charge pulse at the anode by induction, see figure 4.

One of the observables to measure is the time interval between the passage of the particles and the incoming voltage pulse. If the drift velocity of the electrons in the electric field is known, one can calculate the distance of the particle trajectory to the anode by using the time interval. The drift field has to be as homogeneous as possible in order to have a constant drift velocity. In the drift volume several wires are installed, which are connected by a chain of resistors to achieve consequent electrostatic potentials. These field-forming wires define electric equipotential planes and give the drift field the desired homogeneous profile.

2.2 The Drift Chamber used in the Experiment

The drift chamber used in this experiment is not used to measure the spatial coordinates of the particles; it is a so-called **V**elocity **D**rift **C**hamber which is used to monitor and measure the drift velocity in the gas under investigation. In the drift chamber in this experiment two radioactive source are installed. The ^{90}Sr sources emit β-particles on a specified path through the chamber. By knowing the position of both sources and the measured time interval of the drift one can determine the drift velocity. In this experiment, the time of the particle passage is determined by scintillation counters.

The gas volume is separated into two parts, see figure 5: In the drift volume where the cathode and the field-forming wires are installed and a nearly homogeneous electric field is generated the electrons can drift with constant velocity towards the anode. Due to the measurement of a time-difference from two points, only the drift velocity in the region of the homogeneous field is measured. The gas amplification takes place in the detection volume near the anode wire.

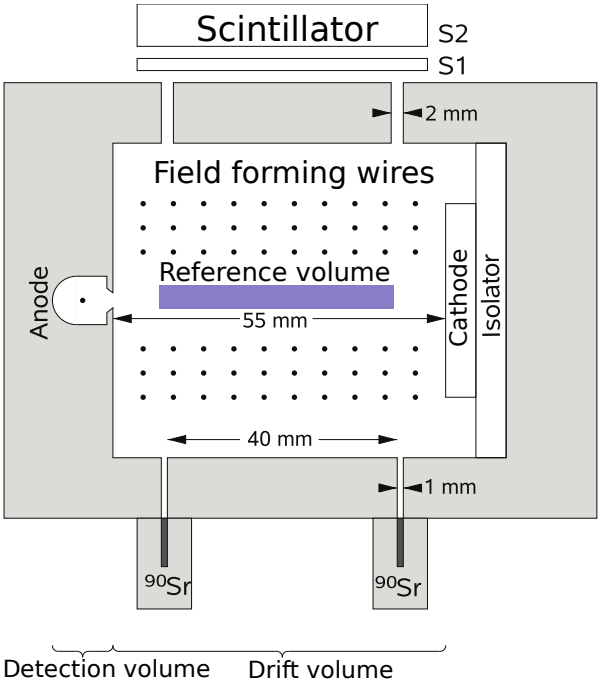

Figure 5: Schematic view of the drift chamber used in the experiment.

Scintillators are used for triggering the measurement. They detect, whether or not a particle has traversed the chamber and start the measurement of the drift time. In the experiment two scintillators are placed behind each other to make use of a coincidence to reduce the number of random triggers due to the noise of the photomultipliers. The measurement should only be started if both scintillators simultaneously detect a passing particle. Possible background radiation should be on a negligible level.

^{90}Sr decays via β^--decay into ^{90}Y. The emitted electrons have a maximal energy of 546 keV. ^{90}Y decays by emitting electrons with a maximal energy of 2.28 MeV into the ground state of ^{90}Zr. To reach the second scintillator the electrons have to traverse a mass density of about 0.5 g/cm^2 which is mostly given by the first slim scintillator.

3 Readout Electronics

3.1 Electronics

Due to the use of electronic devices in various fields of research and in industry consistent standards for measurement-, controlling- and readout electronics are mandatory. These standards apply to the dimensions of the chassis, the installation specifications as well as to the communication between the modules.

NIM-Modules (**N**uclear **I**nstrumentation **M**odule) are built in the chassis following mechanical and electrical specifications. They are easily exchangeable and can be replaced by new devices without changing the periphery of the enclosure box.

3.2 Experimental and Electronic Setup

In this section the signal paths of the chamber and scintillator signals are described. The schematic circuit diagram can be found in Figure 6. This diagram is not complete, some important parts are missing and **while preparing for this experiment** you should already make some considerations about the realization of the missing parts following the requirements given here:

Particle incident: An electron emitted by one of the two ^{90}Sr sources ionizes the gas while traversing the drift chamber and after leaving the chamber it is detected by both of the scintillators almost simultaneously.

Trigger implementation: Your measurement should be controlled by the signals of the two analog photo-detector signals, the measurement of the FADC (Flash Analog-Digital Converter, a fast-analog-to-digital-converter) should be started. Ensure, that possible noise effects are reduced as good as possible, and take into account that the signals of the two photo-detectors are subject of fluctuations. In addition the trigger pulse should be as short as possible to minimize the possible overlap with following signals.

Hint: At the beginning of the construction think about the trigger circuit, e.g. which format (analog or digital) the trigger pulse should have.

Drift chamber signal: The electrons of the ionized gas move through the drift volume towards the anode. The charge cloud enters the detection volume where in close proximity of the anode wire the gas multiplication takes place. The anode signal is amplified by a small preamplifier which is mounted directly at the chamber. Afterwards the signal should be digitized by the FADC. Taking into account the properties of the FADC think about a possible further handling of the signal.

Readout: The CAEN N6730B FADC has the following properties: Sample rate: 500 MSps, resolution 14 bit, dynamic range of 2 V and an internal memory of 5.12 MS/ch. What is the smallest measurable voltage difference of the FADC?

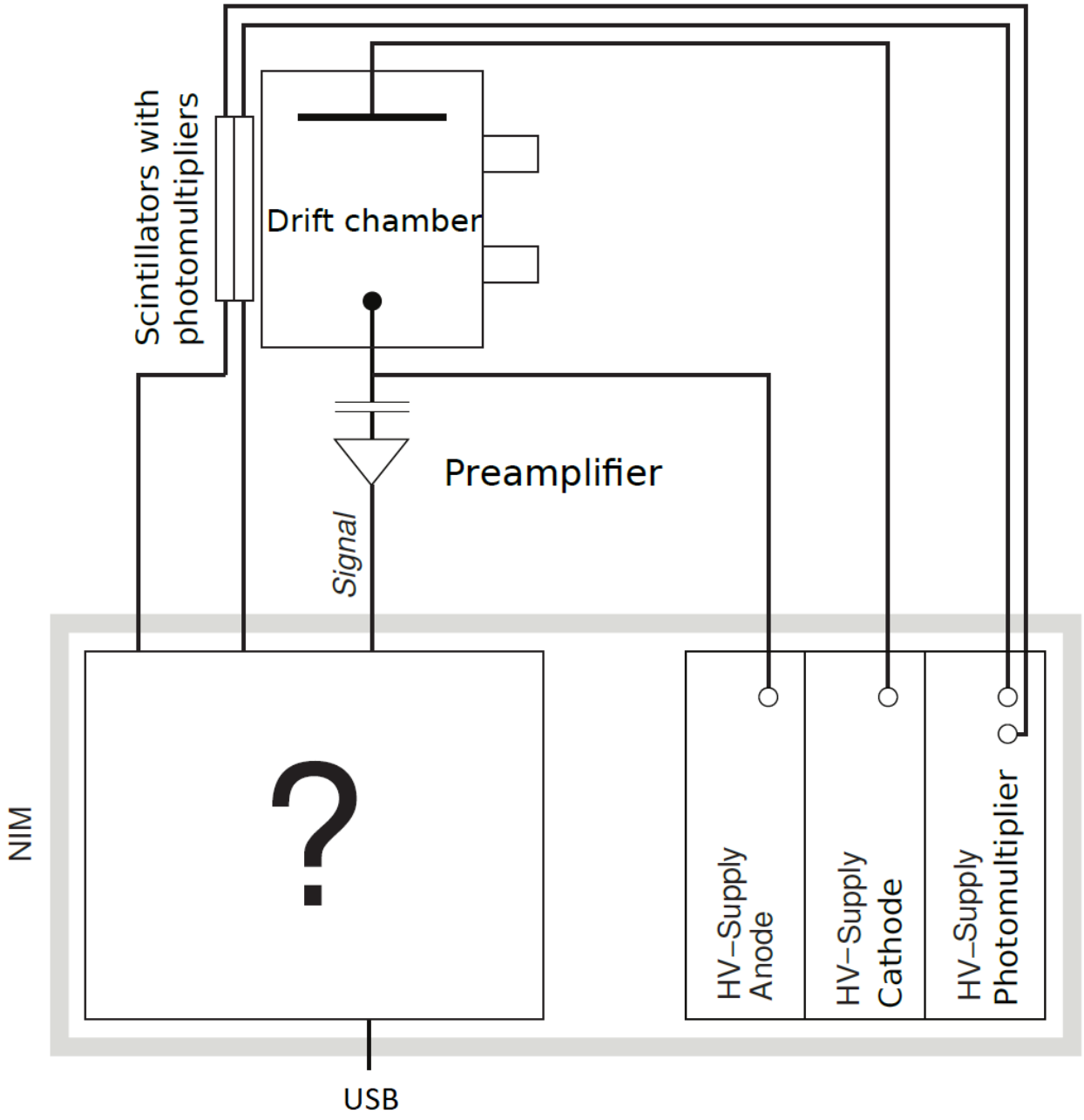

Figure 6: Electronic setup used in this experiment. Trigger and the readout have to be implemented by the students.

3.3 Data Taking and further analysis with ROOT and C++

The experiment is controlled by an application written in C++ which is able to readout the FADC and saves the readout data. Your advisor will show you the functionality of the program, which has some basic features implemented and should be extended during the experiment. The data analysis should also be performed using ROOT and C++.

4 Experimental procedure

4.1 Preparation

Before starting the experiment the two radioactive sources have to be installed in the chamber. Notice that the sources should not be put too far into the mount otherwise the removal is cumbersome. In addition the gas supply of the VDC has to be started, the VDC should be flooded sufficiently with gas before starting the experiment. Flush the chamber for roughly 30 minutes with about 8 l/h to 10 l/h. Afterwards reduce the gas flow, during the experiment there should be a flow between 1 l/h to 2 l/h through the VDC.

Hint: Each HV device has a voltage limit. In case the voltage is set higher than this value the device has to be reset before it can be used again.

4.2 Operation of the trigger

- Switch on the high voltage for the PMTs (it should be around 1950 V to 2000 V). **It must not exceed 2050 V.**
- Take a look at the two scintillator signals on the oscilloscope and figure out why the two pulse rate and shapes are so different.
- Set up the trigger circuit.
- Test whether or not the trigger starts the FADC measurement (by starting the program skeleton).

4.3 Operation of the Drift Chamber

- Switch on the voltage for the cathode. **The maximal operating voltage differs for the various gas mixtures between 2500 V up to 3500 V.**
- Set the anode voltage to 1600 V and afterwards **slowly** increase it until a signal can be seen on the oscilloscope or the computer. **The maximal voltage should not exceed 2000 V.**
- Adjust the signal in such a way, that the FADC can digitize it in an optimal way. After the preamplification the signal should have an amplitude of a few 10 mV. This setting should be the default.

Afterwards the FADC should be able to take measurements in regular intervals.

Hint: Check and measure all settings with the oscilloscope and take notes.

4.4 Drift time and properties of the drift chamber

The main goal of this experiment is to extend the program in order to evaluate the anode pulses and fill the characteristic time intervals into histograms. Think about a proper method and discuss your ideas with your advisor. If you need help you can get further literature from your advisor.

Consider sources of statistical and systematical uncertainties influencing your measurements during **and before** the experiment and on basis of this think about the optimal number of events.

- In the first part of the measurements the best anode voltage has to be determined in order to get a sufficient event rate in the following parts of the experiment. For this use a cathode voltage of approx. 1800 V. Vary the anode voltage around 1800 V and find the optimal value. If the rate is reduced due to too high pulses you can lower the amplification. **Make sure that you save all results!** Determine the dependency of the pulse height and the pulse integral on the anode voltage and check the stability of the drift velocity. It is sufficient to do this measurement for only one of the gas mixtures.
- Scan the cathode voltage starting from 1400 V **up to 3500 V** and measure the drift velocity for at least ten different electric field strengths. This measurements should be done for both gas mixtures. Since with this experimental setup the plateau mentioned in the introduction cannot be reached for Ar/CO_2 all measurements can be used. Take measurements for constant intervals of the cathode voltage.
- Set the anode voltage to the optimized value and set the cathode voltage to an arbitrary voltage and measure the drift velocity multiple times – possibly with longer time intervals between the measurements. Note the time of the measurement to estimate possible environmental influences (pressure, temperature, gravitation). Perform this measurement for both gas mixtures.

5 Data analysis

- Plot the measured mean pulse heights and pulse integrals versus the anode voltage and investigate, whether or not the dependency can be expressed by an exponential function:

$$A \propto \exp\left(U - U_0\right).$$

- Plot the drift velocity as a function of the anode voltage. Which functional relation can you observe between the two observables?
- Plot the drift velocity versus the electric field strength and compare your results to Figure 3 and Table 1.4. Estimate the mean time between two collisions τ. Try to identify and match the gas mixtures under investigation to the results shown in Figure 3.
- Compare the determined values of the reproducibility study and discuss possible deviations.

Remark: Consider all relevant uncertainties in the evaluation. Your report should clearly state which uncertainties have been considered. Besides calculating the uncertainties you should also include them in the graphical and written presentation of your results.

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