

Electron drift velocity in gases

Introduction

In most experiments concerning the interaction of very high energy particles, measurement of the momentum of the collision products is central to understanding the interaction. The most accurate measurement of charged particle momentum is made by measuring the deflection of a particle in a magnetic field. One may measure the particle's direction before entering and after leaving a region with a known magnetic field, or, alternately, directly measure the particle's coordinates along the trajectory as it travels in a magnetic field. Either technique requires that we measure spatial coordinates along the trajectory of the charged particle. We can then use the well-known relation for the force on a charged particle moving in a magnetic field, $\vec{F} = q\vec{v} \times \vec{B}$, from which we can obtain the momentum if we know the radius r of the arc the particle describes in traveling through a magnetic field via the relation governing circular motion, $mv^2/r = F$. In these equations \vec{B} is the magnetic field, and q and v are the charge and velocity of the particle.

The modern system of choice for measuring coordinates along the trajectory of charged particles is by using gas detectors such as drift cells and drift tubes. In these systems the coordinate of the charged particle is determined by measuring the *drift time* of the ionization electrons; that is, the time it takes for the ionization charge, electrons, created by the charged particle traversing the cell to drift to an anode wire where gas amplification occurs and a read-out signal is observed. In order to obtain precise spatial coordinates one needs precise time measurements and knowledge of the mean electron drift velocity as a function of electric field, $v_d(E)$, in the gas used for the detector. Knowing $v_d(E)$ we obtain the distance the electrons drifted to reach the wire, $r = v_d\Delta t$, where Δt is the time between the particle traversing the detector and the arrival of the signal from the electrons arriving at the anode wire.

Using drift chambers for precise, reliable coordinate measurements requires choosing a working gas that has a sufficiently high drift velocity to collect the charge quickly, in order to minimize "pile up" from subsequent tracks traversing the chamber or cell. In addition, the drift velocity needs to be relatively insensitive to small changes in the drift field in order to provide precise measurements. Most gas detectors used in nuclear and particle physics use mixtures of Ar and other gases. Mixtures, such as Ar-CH₄ (argon-methane), have been widely used. Other mixtures of Ar and hydrocarbons have also been used however, hydrocarbon gases such as CH₄ (methane) or C₂H₆ (ethane) are flammable and therefore present a hazard. This is particularly the case when the volume of the gas detector is very large, as it is in modern collider experiments, such as those for the Large Hadron Collider (LHC) at CERN. Because of the inherent dangers from the very large volume of gas required, these large detectors avoid, if possible, the use of flammable gases.

Non-flammable gases of choice have been mixtures of Ar-CO₂ (argon-carbon dioxide). In order to choose the appropriate Ar-CO₂ mixture, it is necessary to have a good knowledge of the drift velocity as a function of E/P , where E is the electric field and P is the pressure of the gas. Drift chamber simulation code (GARFIELD/MAGBOLTZ) developed at CERN can be used to calculate electron drift velocity in various gas mixtures. Figure 1 shows calculated electron drift velocities, as a function of E/P , for a number of gas mixtures, where Ar and CH₄ (argon and methane) are the principal ingredients. What one notices from this figure is that Ar-CH₄, in a proportion of 90/10, has a very high drift velocity at low E/P whereas for ratios of electric field to pressure, $E/P > 1$ V/cm-Torr there is very little variation. In general, most of the gas mixtures shown are

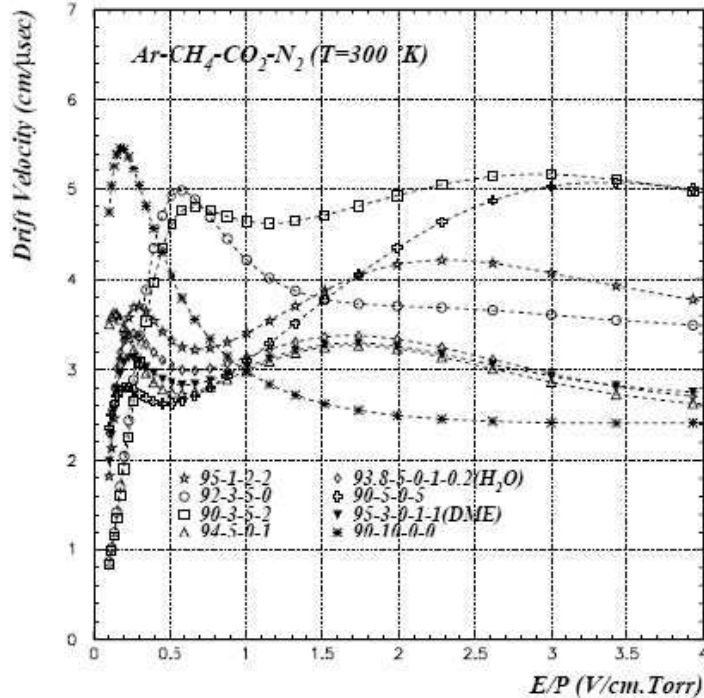


Figure 1: Simulation of drift velocity for various mixtures of argon (Ar), methane (CH₄), carbon dioxide (CO₂) and nitrogen (N₂).

rather insensitive to small changes of E/P for values above 1.5 V/cm-Torr. It is in the region where drift velocity changes very little with fluctuations in E/P that we wish to operate our chambers.

The physics of electron transport through gases is quite complex. When an electron moves through a gas, it scatters off of the gas atoms or molecules. As you may recall from the Franck-Hertz experiment, if an electron's kinetic energy is low, the collision is elastic, and because the atom or molecule is much more massive than the electron, very little energy transfer takes place; the main effect is to change the direction of the electron. But once the electron energy reaches an amount equal to a change in state in the atom or molecule, an inelastic collision can occur, and the electron loses speed. Now consider a bunch of electrons that may come from a series of ionization events triggered by an energetic particle. With gas densities typical of gas detectors, the velocity distribution of a cloud of electrons quickly reaches thermal equilibrium within a few nanometers. The cloud drifts under the influence of the applied electric field toward the anode while electrons scatter elastically or inelastically off of the atoms or molecules in the gas.

The quantity called the "drift velocity" is an average velocity over the whole electron cloud. If the angle between the electric field and the velocity of an electron is θ_e , the drift velocity w_d is given by

$$w_d = \int v_e \cos \theta_e F_e(\varepsilon_e, \theta_e) d\varepsilon_e, \quad (1)$$

where $F_e(\varepsilon_e, \theta_e)$ is the energy distribution function for the electrons. The calculation of the energy distribution function is the main challenge in the theory. The GARFIELD/MAGBOLTZ computer programs that are responsible for Fig. 1 solve the problem by numerical integration techniques and use as inputs the scattering cross sections between electrons and the constituent molecules and

atoms. An overview of this complex problem is given in reference [4], and the paper by Palladino and Sadoulet [5] presents a useful simple model of the phenomenon. Additional examples of numerical solutions of the theory are given in references [6, 7]

In this experiment, you will measure the drift velocity of electrons in mixtures of Ar-CO₂ as a function of electric field at atmospheric pressure. In order to do this, you will use apparatus that was developed by Prof. Tianchi Zhao and students to study the dependence of electron drift velocity in Ar-CO₂ and other gas mixtures. Ar-CO₂ is the gas used in the ATLAS muon spectrometer at the Large Hadron Collider (LHC) in Geneva, Switzerland and has been studied extensively.

Apparatus

The apparatus, shown schematically in Fig. 2 consists of a precisely built drift cell that has a very thin, delicate Mylar window, through which electrons from a ⁹⁰Sr source pass through the gas, ionize it and are stopped in a small scintillation counter, as they exit the drift cell. This scintillator counter signals the passage of the electron and allows one to start a clock to measure the drift of the electrons in the electric field until they reach the anode wire, where gas multiplication occurs and a signal is observed from the anode, which is used to stop the clock. The total drift time is the time it takes to drift from the source position to the anode wire. The collimator for the chamber is constructed to have two holes (Position 1 and 2 shown in Fig. 2) through which electrons can enter the chamber. The difference in the time it takes for electrons that are introduced at position 1 and 2 to reach the anode provides a measure of the drift time in a uniform electric field. From this time difference and the separation (2.54 cm) between positions 1 and 2 it is a simple operation to calculate a drift velocity. The chamber is constructed so that the electric field in the region between position 1 and position 2 is uniform. It is directly proportional to the voltage applied to the cathode.

The time between a start pulse and a stop pulse is measured by pulse-height analysis of a time-to-amplitude converter (TAC) pulse. The data are measured as a function of applied field-cage voltage for various gas mixtures.

Start pulse: From a plastic scintillator finger on the end of a PMT located under the chamber directly beneath the β source. This signal is discriminated and turned into 30 ns NIM pulse.

Stop pulse: From a proportional-wire detector anode inside the drift chamber. The signal is amplified by charge-sensitive preamp and then discriminated and turned into 30 ns NIM pulse.

Setup and check-out procedure

Unlike the experiment with proportional tubes, where you did the mixing yourself of the pure gases, the gases used in this experiment are already mixed in order to ensure that the proportion of each gas stays uniform over a long period of data collection. There are two bottles of specialty gases of high-purity mixtures of argon (Ar) and carbon dioxide (CO₂): one with 7% CO₂ and the rest Ar, which we will call the “93/7” mixture, and one with 20% CO₂ and the rest Ar, called the “80/20” mixture.

1. Turn on air handling apparatus, open the valve connected to the 93/7 mixture; its the one labeled “Ar.” Set the flow rate to 100 cc/min. Let gas flow in the chamber and look for

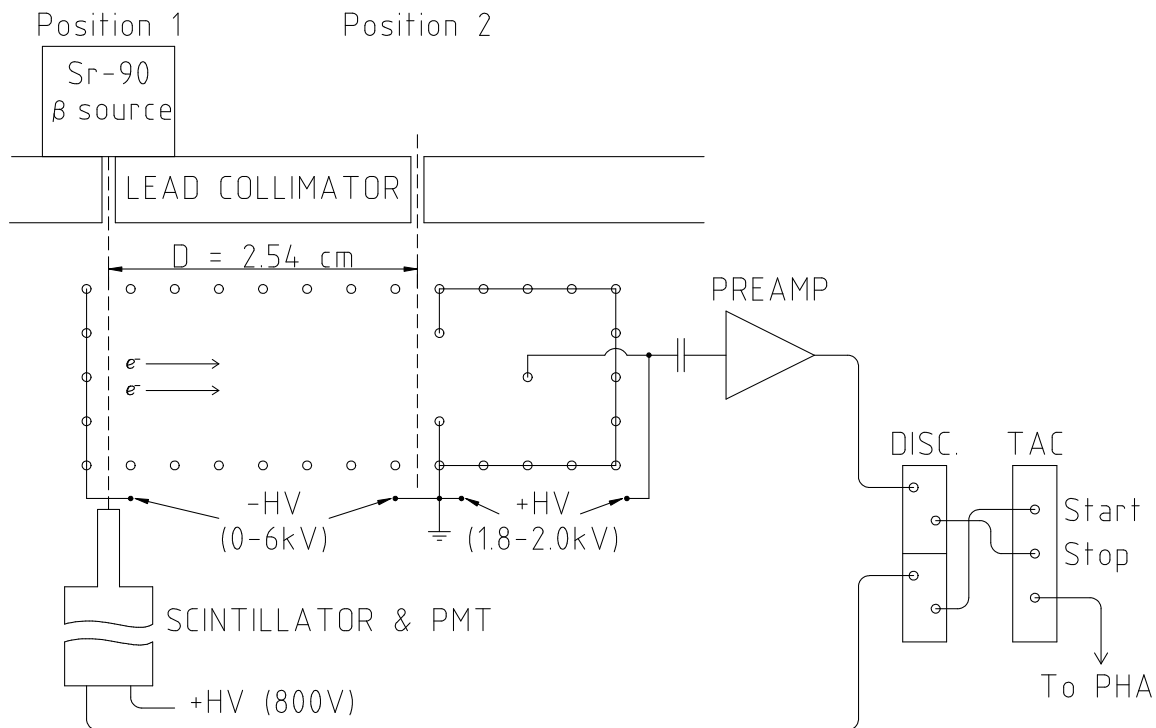


Figure 2: Schematic of the drift velocity experiment setup.

steady bubbling of the bubbler.

2. While gas is flowing, make sure chamber and lead collimator plate are aligned with the sensitive part of the scintillator finger. The alignment should be thus:
 - The *center line* of the chamber is the imaginary line that connects the two gas ports on either side. This line should be directly above the tip of the scintillator finger that lies between the lead bricks below the chamber.
 - The lead plate should be placed so that the two holes lie along the *center line*. Then the edges of the plate should be FLUSH with the outer sides of the chamber.
 - With the plate placed as described, the holes should be directly above the gap between pairs of thick wires that comprise the chambers drift cage. Look carefully to see that this is true.
3. Start with the part of the chamber that is farthest from the detector: position 1 in Fig. 2, and what we'll call the "far hole".
4. Obtain the Sr-90 source. **Caution: these sources are much more active than the gamma sources we use in other experiments. (approximately 1 mCi activity versus 0.1 mCi maximum for the gamma sources). Handle them as little as possible and point the hole at the base of the source away from yourself and other people.**
5. Place the source over the hole in the lead collimator plate, and align the score marks on the source with the score marks on the plate.

- Turn on HV supply to the PMT (750–850 V), and look for signal from the scintillator on the scope. You should see something like Fig. 3.

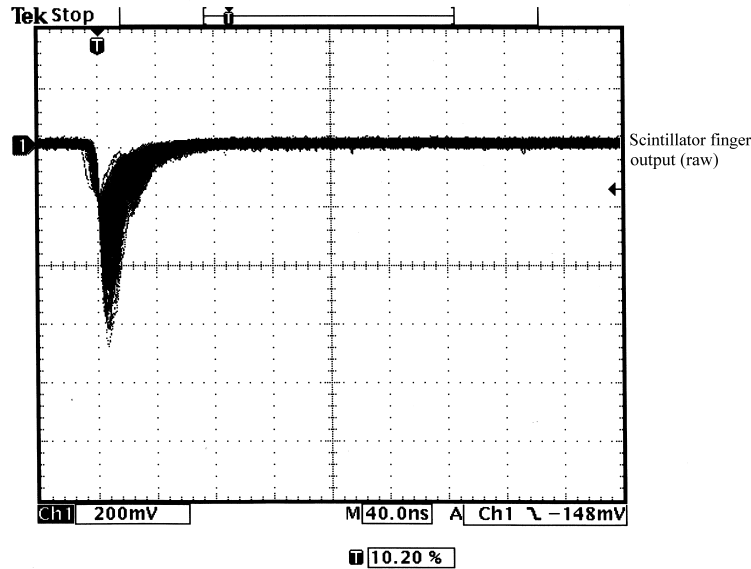


Figure 3: Typical signals from the scintillator finger PMT using the Sr-90 β source.

- Run this signal into the discriminator, and set the discriminator to give a reasonable response above noise. A typical setting would be about -70 mV (-0.70 V on the test point)
- On the bright-colored NIM-bin HV supplies, make sure all switches are down, and the multi-turn potentiometer knobs are completely counterclockwise. Turn on the digital meters (DMM), and set them to DC volts with a 10V range with three decimal digits readout. (This may be the default setting.)
- Connect the signal output from the chamber to one of the inputs of the charge-sensitive preamp, and connect the associated output of the preamp to the scope, terminated with 50 ohms. Turn the preamp power on, and set the voltage to 10 volts.
- Turn on the output (usually “A”) of the negative (bright **ORANGE**) HV supply; you should see the associated LED light. Watch the DMM and set the voltage to about -800 V (0.8 V on the DMM). The value of this voltage is not critical—you just need enough to pull electrons toward the detector.
- Turn on the output (usually “A”) of the positive (bright **RED**) HV supply. Watch the scope signal as you turn the voltage up. At about $+1.8$ to $+1.9$ kV (1.8 to 1.9 volts as measured on the DMM), you should see the negative-going signal of the wire detector.
- If you connect the discriminator from the PMT signal to channel 1 of the scope and the output of the charge-sensitive preamp to channel 2, and then trigger the scope on channel 1, you should get a display similar to Fig. 4.
- Now play with the negative HV voltage, and note how the time position of the wire-detector signal moves. You should see that the time between the “start pulse” (scintillator finger

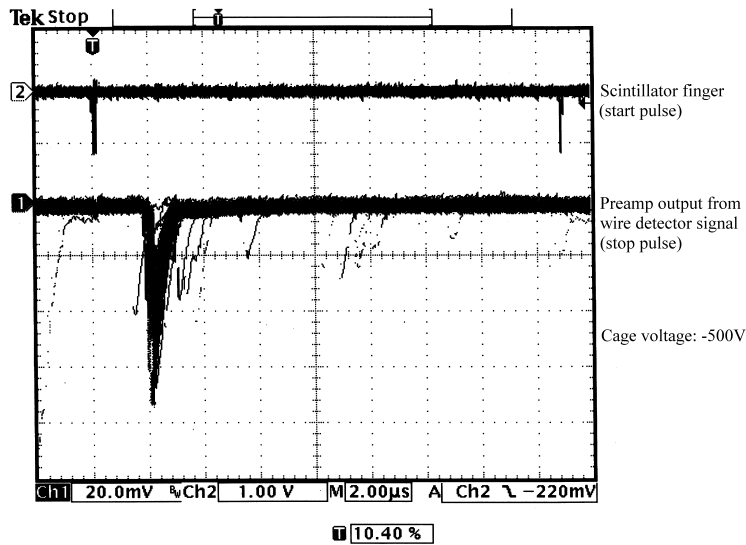


Figure 4: Signals from the PMT discriminator and the anode wire (via the preamp) for 93 cc/min Ar and 7 cc/min CO₂.

signal) and the “stop pulse” (wire-detector signal) varies as you change the negative high voltage. **If you don't see this ask for help now!** Compare Fig. 5 (−100 V) to Fig. 4 (−500 V).

14. Run the output of the preamp into another discriminator channel, and set the discriminator to a low value (typically 30–70 mV). You will need to see most of the pulses created by the detector, and these vary in height a lot, depending on the negative HV setting. Look at both discriminator outputs on the scope; you should see something like Fig. 6.

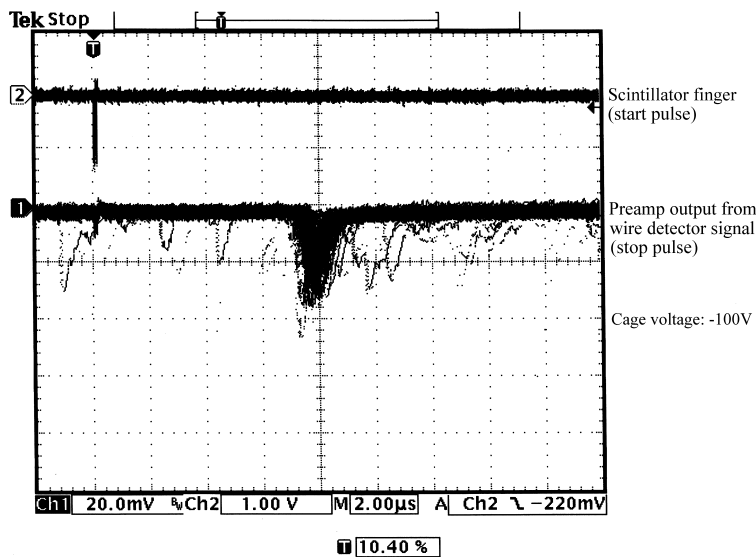


Figure 5: Same signals as in Fig. 3 but with −100 V on the cage.

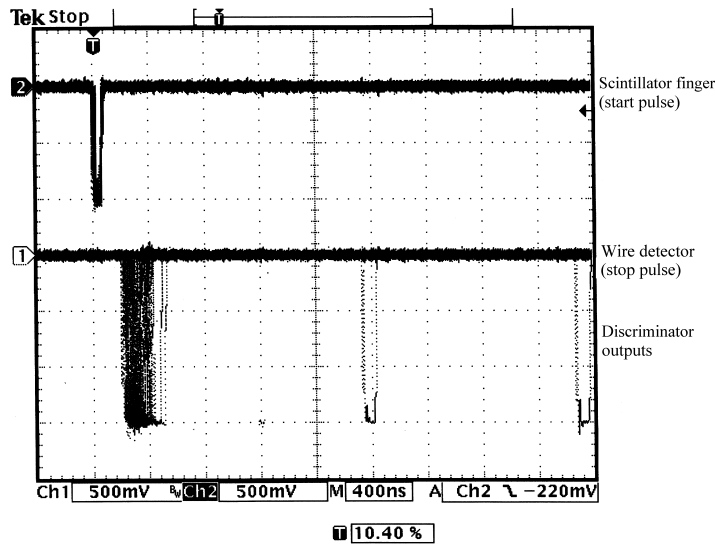


Figure 6: Discriminated signals from the PMT and anode detector. This pair of signals is fed to the start and stop inputs of the TAC.

15. Connect the discriminator outputs to the TAC inputs, and see the resulting positive TAC pulse on the scope. (You will need to set the trigger to positive-going signals, and turn the channel sensitivity down.) Note how the height varies as the TAC settings and negative HV settings vary. A good setting to start with is 100ns with x100 multiplier.
16. Finally, run the TAC output to the input of the pulse height analyzer, and take a few test runs to check count rates and TAC settings so that you can cover the widest range of useful negative HV values.

A few tips on operating the experiment

- Check the signal for the maximum and minimum negative HV settings that you plan to use. Typically, the minimum value is near -200 V and the maximum near -6 kV. You may find that the signal will decrease at the lower voltages. This can be compensated for by a small increase of the anode-wire voltage.
- Plan your voltage increments of the $-HV$ supply in a way that will allow you to map out the drift velocity curve in a sensible way: you will need more points in the range where there is a lot of change in the drift time versus voltage and fewer where the time stays more constant.
- When you run the apparatus with larger Ar/CO₂ ratios, the anode wire signal may become very noisy or show signs of overload. If this happens, reduce the anode-wire voltage. You may find that you need to adjust the power-supply voltage to the charge sensitive preamp and, possibly, the discriminator level for this signal.
- With the β source over the hole nearest the anode wire, the time intervals between the start and stop pulses are very short. You can get better resolution of these pulses by reducing the maximum voltage setting on the pulse-height analyzer program. By default, this is set to

10.0V, but the 1.00V setting, and lower-level discriminator setting (in the MCA setup) may work better.

- Also, when measuring with the “near” hole (position 2 in Fig. 2), the time will not change very much as you vary the $-HV$ supply, since most of the time is determined by the drift within the proportional-wire detector cage. Thus, you can get by with fewer measurements with the source at this position and interpolate the values you need to make the velocity calculation.
- Do not forget to use a pulser to calibrate the TAC. The pulser will produce very uniform pulse heights from the TAC. When these are measured with the pulse height analyzer, you will see at most one or two bins come up on the screen. You need only measure a few widely-spaced pulse settings to get a good calibration.

Data collection

Verify and note all of the HV and logic connections so that in your lab report you will be able to make a logic diagram and explain all of the various signals and their function. You should do this while taking data; since there will be a number runs to take, you should try to optimize your data collection time.

Data taking consists of collecting drift times as a function of applied electric field, in this case applied high voltage over a distance, d , from which you can calculate the electric field. Note that, for a given voltage, you need to measure the drift time from position 1 and position 2 in order to get the difference over a well-known distance of 2.54cm.

If time allows, you should collect data for both the 93/7 mixture and the 80/20 mixture. You will need to adjust the anode voltage and possibly the discriminator setting from the chamber detector when you change mixtures in order to see a good signal. The anode voltage may need to be changed by as much as 200–300 V.

The last thing to do is to calibrate the TAC output. To do this you need to send a start pulse and stop pulse to the TAC that gives an output voltage pulse that is proportional to $\Delta t = t_{\text{stop}} - t_{\text{start}}$. By sending this pulse to the pulse height analyzer you can relate time to peak voltage and construct a calibration curve. Take care to cover the range of channels occupied by the drift times you are measuring. Instructions will be given on how to run the pulse generator.

Analysis

In your analysis you need to plot drift velocity vs. E/P for the different gas mixtures. To do this you need to calculate the drift field from the applied voltage and drift distance. Note that the applied voltage may drop over a larger distance than 2.54 cm, depending on which chamber you are using. Do you see why? Have another look at Fig. 2, and compare it to the wiring and layout of the chamber itself.

Having obtained the E/P plots compare your results for drift velocity vs. E/P to what was measured by Prof. Zhao and his students. For the drift velocities you measured discuss the regions and identify if there are regions which would be suitable for operating a drift chamber in an experiment that one would expect to operate for several years.

In addition to the above analysis, you should discuss the following in your report:

- Explain why E/P is used as the variable in these experiments.
- Why do higher values of v_d tend to be insensitive to changes in E/P ?
- Why is there a peak in the drift velocity curves for some mixtures of gas at relatively low values of E/P ?

References

- [1] W. R. Leo, Chapter 6, especially 6.3.
- [2] G. Knoll, Chapter 5, especially II.A.
- [3] Zhao, T., Y. Chen, S. Han, and J. Hersch, “A study of electron drift velocity in Ar-CO₂ and Ar-CO₂-CF₄ gas mixtures”, *Nuclear Instruments & Methods in Physics Research A*, vol. **340**, pp. 485–490 (1994).
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