Radiation Detector 2018/19 (SPA6309)

Ionization detectors (Leo, Chapter 6)

Ionization detectors were the first electric radiation detectors

- Ionization chamber
- proportion counter
- Geiger counter
- multi-wire chamber
- drift chamber
- time projection chamber
- liquid ionization detector
- liquid argon time projection chamber

Gaseous ionization detectors (Leo, 6.1)

The basic concept of an ionization detector is following. When a charged particle passes through a volume, it ionizes the atoms. By applying an electric field, one can collect ionized electrons or ions to detect the particle as it passes through. Because of the larger mobility of electrons and ions, gases are an ideal medium. A typical gaseous ionization detector applies a positive voltage through the wire in the centre (anode) which collect electrons as a signal. The body of this chamber acts as the ground (cathode).

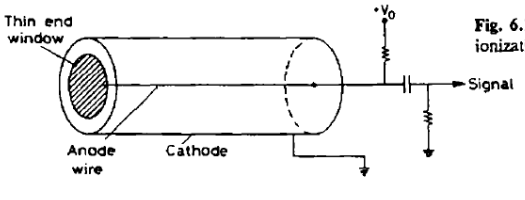


Fig. 6.1. Basic construction of a simple ionization detector

Ionization chamber

The number of electrons collected depends on how many atoms are ionized, or how much energy is deposited by a particle. Namely, when the applied voltage is low enough (<250V), the size of the signal does not depend on the voltage, but the deposited energy. This is called an **ionization chamber**. Since it collects electrons from ionization without amplification, the signal is usually very small.

The gas in the gaseous ionization detector should be easily ionized (~30 eV to create an ion). A typical gas used for these detectors have densities ~10^{-3}g/cm^3. There, the $\frac{dE}{dx}$ of a MIP particle is $\frac{dE}{dx} \sim 2000\ eV/cm \rightarrow$ ~70 electrons/cm.

The signal is an electric voltage pulse which propagates through the cable via the capacitor (typically C~100pF). What is the size of the signal by ionization when a MIP particle passes through a 10 cm ionization chamber?

$$Q = CV,\, V = \frac{Q}{C} = \frac{10 \cdot 70 \cdot 1.6 \times 10^{-19}}{100 \times 10^{-12}} = 1\mu V$$

So the expected signal is an order 1μV and so is difficult to see without amplification. (expected signal from PMT is ~10mV from single photon).

Proportion counter

If the voltage is stronger (>250V), the electric field is strong enough to accelerate electrons which bombard to a gas molecule causing secondary ionization, and this chain reaction makes a shower of electrons. Thus, in this scheme, the strength of the signal does not depend on the original energy of the charged particle, but it depends on the strength of the electric field (the voltage). This is called a **proportion counter** (because the strength of the signal is proportional to the strength of electric field).

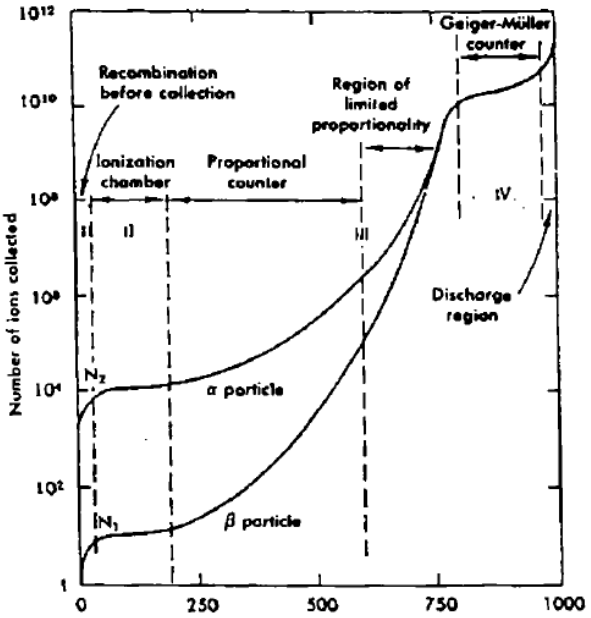


Fig. 6.2. Number of ions collected vers applied voltage in a single wire gas chamt (from *Melissinos* [6.1])

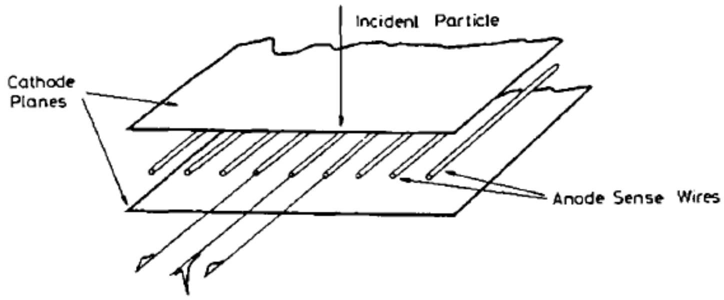
Geiger counter

However, if the field is too strong (>750V), every particle causes ionization with a large energy deposit which creates a large shower (=strong signal) in the chamber. In this way, you cannot measure the energy of the particle any more, nor the size of the signal as it isn't proportional to the field strength. However, the signal is strong and so this is the best way to "count" low energy particles. This is called a **Geiger counter**. A typical gain of a Geiger counter is ~10^7, so the expected signal is an order ~10V and this is easy to see.

Multiwire proportional chamber, MWPC (Leo, 6.6)

By making an array of anode wires in an ionization chamber, one can gain the position information by comparing signals from different wires. Here, "X-MWPC" has wires parallel to X-axis, and "Y-MWPC" has wires along the Y-axis. By alternatively placing them (X-MWPC, Y-MWPC, X-MWPC, Y-MWPC,...), tracks of charged particles can be reconstructed.

Fig. 6.7. Basic configuration of a multiwire proportional chamber. Each wire acts as an independent proportional counter. The signal on the firing wire is negative while the signals on the neighboring wires are small and positive



Drift chamber (Leo, 6.7)

Electrons are collected at an anode wire by the drift voltage. By knowing "when" a charged particle passes through, one can find the location by measuring the time it takes electrons to drift across. However, electrons become diffused when drifting, so usually, it is not easy to collect a significant number of them at long distances, say >10cm.

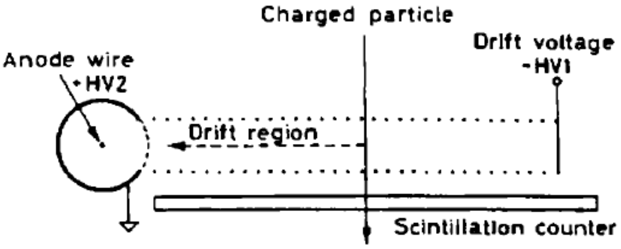
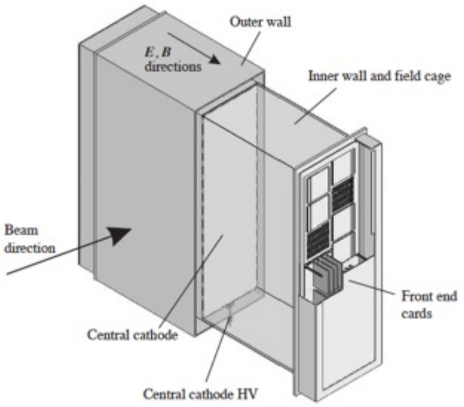


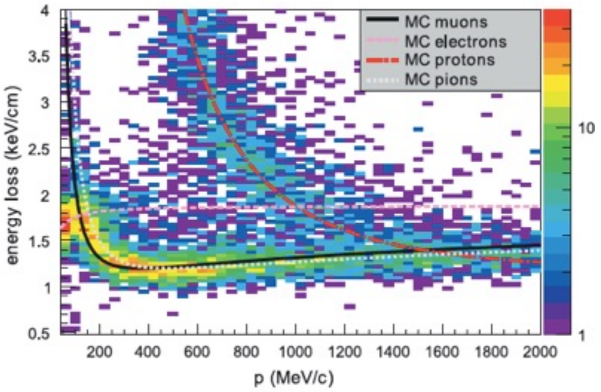
Fig. 6.15. Basic operating principle of the drift chamber (from *Sauli* [6.3])

Time projection chamber, TPC (Leo, 6.8)

Time projection chamber (TPC) is a combination of an MWPC and a drift chamber. An array of anode wires are located at the one end of the gas-filled chamber which provides the X-Y coordinate information (MWPC). At the same time, the drift times of electrons are measured to provide Z coordinate information (drift chamber), in this sense, "time" is "projected" into the Z coordinate. In the end, one can reconstruct particle tracks in 3-dimensions.

This is a drawing of an Argon gas TPC used by the T2K experiment. The data shows momentum vs energy loss. Since particle tracks are viewed in 3-dimensions, we can measure how much energy is lost in each segment for each particle, and this gives information on the particle type (**particle identification (ID)**). For example, the red curve and the black curve have different energy losses for a given momentum, and from this, we can distinguish protons and muons. Notice muons and pions are not easy to separate because their masses are very close.

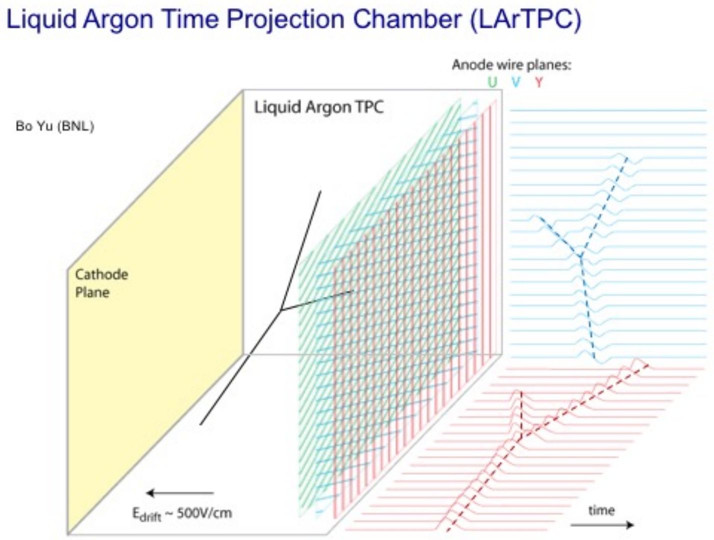




Liquid ionization detector, LID (Leo, 6.9)

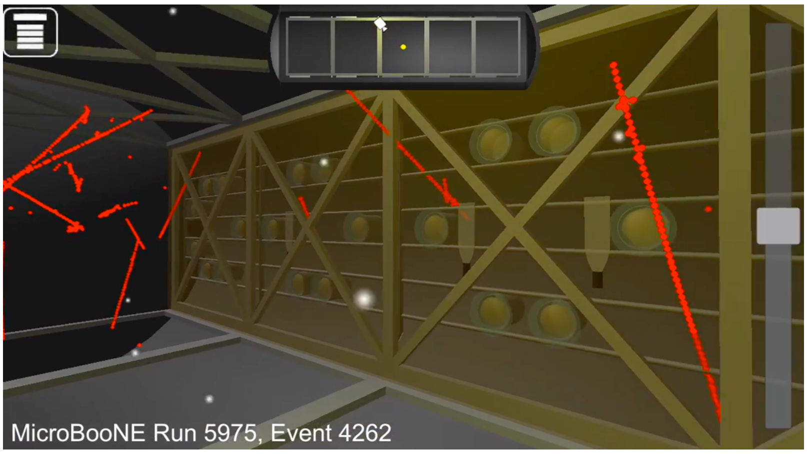
So far we have discussed ionization detectors, but all of them use gases as this makes it easy to collect ionized electrons. Liquids have the benefit of being denser and so they produce more ionization electrons. The problem lies in drifting and collecting ionized electrons as it is not easy to do in a liquid. Here, the background is all electronegative molecules, such as oxygen. By reducing the impurity to an extreme level, one could operate an ionization detector using a liquid.

Liquid argon time projection chamber, (LArTPC)

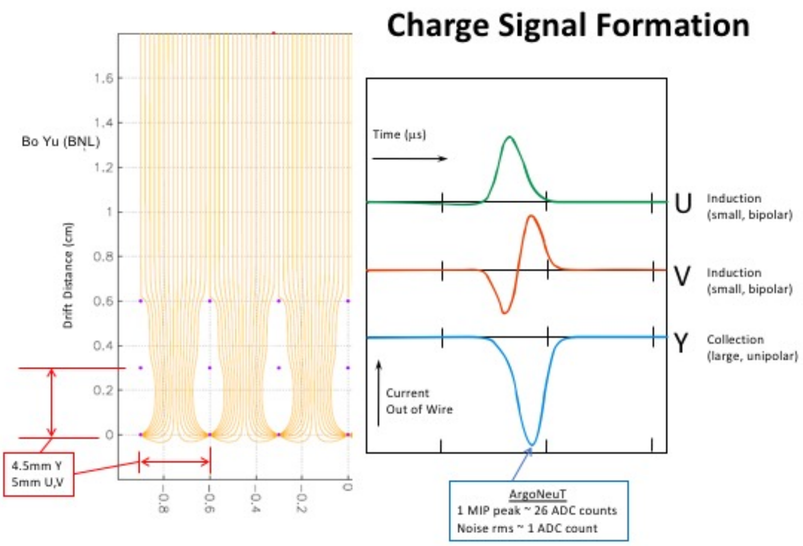


Liquid argon time projection chamber (LArTPC) are considered dream detectors of particle physics. It has features of TPCs and LIDs. The charged particle ionizes the liquid argon atoms, then the electrons drift and are collected by the array of wires. The configuration of wires (X-Y) and drift time (Z) allows reconstruction of 3-dimensional tracks, and because of this the detector is called the "modern bubble chamber". What's more, since liquid argon is very dense (1.4 g/cm^3), it has a modest interaction rate with a neutrino beam, and there are many LArTPC detectors located in the neutrino beam line.

There are many challenges for this technology. First, the temperature of liquid argon is only 87K, and so the entire detector must be cooled to this temperature. Second, liquid argon has to be extremely pure to allow the long drift times (~2m) of electrons, and typically it requires <1ppb of water and oxygen molecules. Third, drifting electrons require a very high voltage (~100kV) but sending such a high voltage into the liquid argon cryostat is not easy.



It is almost the perfect detector, but there are a few disadvantages, one of them is the lack of timing information. In order to take "pictures" of charged particles, one needs to wait for the electron to drift across. But the typical speed of drifting electrons is ~5cm/μs. This means, if you want to drift for ~2m, you need to wait ~1ms. As you have seen from the event display of the LArTPC MicroBooNE detector, it accepts many cosmic rays as background events.



Electrons drift a long path, and they are eventually collected by collection wires. But before they reach collection wires, an electric field is designed so that they pass through other wires with different orientations. Although electrons are not collected, they induce current to these wires, and by detecting them these wires can see electrons, too. These are called induction wires. Signals from induction wires are bipolar, and collection wires are unipolar.

Living legends

Time Projection Chamber
David Nygren
(Berkeley lab → U. Texas, Arlington)

Liquid Ionization Detector
Veljko Radeka
(Brookhaven national lab)

Liquid Argon Time Projection Chamber
Carlo Rubbia
(CERN → Senator of Italy)
Nobel Prize, 1984

Inventors of these detectors (TPC, LID, LArTPC) are all still alive and active. We are fortunate to live the same era with these living legends!