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Large Time Projection Chambers for Rare Event Detection

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The Time Projection Chamber (TPC) concept [**add ref to TPC section**] has been applied to many projects outside of particle physics and the accelerator based experiments where it was initially developed. TPCs in non-accelerator particle physics experiments are principally focused on rare event detection (e.g. neutrino and darkmater experiments) and the physics of these experiments can place dramatically different constraints on the TPC design (only extensions to the traditional TPCs are discussed here). The drift gas, or liquid, is usually the target or matter under observation and due to very low signal rates a TPC with the largest active mass is desired. The large mass complicates particle tracking of short and sometimes very low energy particles. Other special design issues include, efficient light collection, background rejection, internal triggering and optimal energy resolution.

Backgrounds from gamma-rays and neutrons are significant design issues in the construction of these TPCs. They are generally placed deep underground to shield from cosmogenic particles and surrounded with shielding to reduce radiation from the local surroundings. The construction materials have to be carefully screened for radiopurity as they are in close contact with the active mass and can be a signification source of background events. The TPC excels in reducing this internal background because the mass inside the fieldcage forms one monolithic volume from which fiducial cuts can be made ex post facto to isolate quiet drift mass, and can be circulated and purified to a very high level. Self shielding in these large mass systems can be significant and the effect improves with density.

The liquid phase TPC can obtain a high density at low pressure which results in very good self-shielding and compact installation with a lightweight containment. The down sides are the need for cryogenics, slower charge drift, tracks shorter than the typical electron diffusion, lower energy resolution(e.g. xenon) and limited charge readout options. Slower charge drift requires long electron lifetimes placing strict limits on the oxygen and other impurities with high electron affinity. A significant variation of the liquid phase TPC ,that improves the charge readout, is the dual-phase TPC where a gas phase layer is formed above the liquid into which the drifting electrons are extracted and amplified, typically with electroluminescence (see figure 1). The successful transfer of electrons through the phase boundary requires careful control of its position and setting up an appropriate electric field.

A high pressure gas phase TPC has no cryogenics and density is easily optimized for the signal, but a large heavy pressure vessel is required. Although shelf shielding is reduced, it can in some cases approach that of the liquid phase; in xenon at 50atm the density is about half that of water or about 1/6 of liquid xenon. A significant feature of high pressure xenon gas is the energy resolution. Below a density of about 0.5g/cc the intrinsic resolution is only a few times that of high purity germanium.[7] A neutrino-less double beta decay ($0\nu2\beta$) TPC operated below this density limit could enjoy excellent energy resolution and maintain particle tracking for background rejection.

An observable interaction with the TPC results in a charged

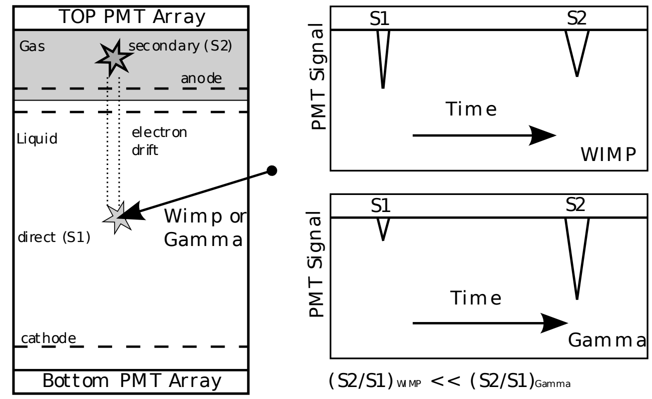

Figure 1: The configuration of a dual phase detector is shown on the left with the locations of where the primary and secondary light are generated. On the right is a schematic view of the signals of both an electron and nuclear interaction illustrating the discrimination power of this method. Figure motivated by figure in [6].

particle that travels in the drift matter exciting and ionizing the atoms until the initial energy is converted into ionization, scintillation, or heat with relatively large fluctuations around a mean distribution. Rare event TPCs can be designed to detect scintillation light as well as charge to exploit the anti-correlation to improve energy resolution and/or signal to noise.[8] An electric drift field separates the electrons and positive ions from the ionization although the separation is not complete and some electrons are captured, exciting atoms and releasing more light than the primary excitation alone. The average partition between the scintillation and ionization can be manipulated to increase the ionization (at a loss of scintillation) by a number of methods such as, increasing the strength of the electric field up to a saturation of the ionization yield , increasing the temperature to enhance the diffusion of the ionized electrons, and adding dopants such as triethylamine that can be photoionized by the scintillation photons releasing more ionization.

Scintillation light is typically collected with photomultiplier tubes (PMTs) and avalanche photo diodes (APDs) although any fast (compared to the ionization drift speed) light collector capable of detecting the typically UV photons, maintaining high radiopurity and perhaps withstanding pressure would work. (CCDs are slow and therefore only record 2 dimensions integrating over the time direction, some of which can be recovered with a few PMTs.) In most cases a wavelength shifter is required such as adding nitrogen to the drift gas, or coating the optics, although some work has been done to directly readout the 175nm light from xenon with a silicon detector. In a typical cylindrical geometry, the light detectors are placed at the ends on an equipotential of the field cage simplifying the design, but limiting the collection efficiency. The field cage can be made of UV reflective materials, such as Teflon, to increase the light collection.

Charge collection can be accomplished with proportional avalanche in the manner used in a traditional TPC (even in the liquid state) although the final signal suffers from rather

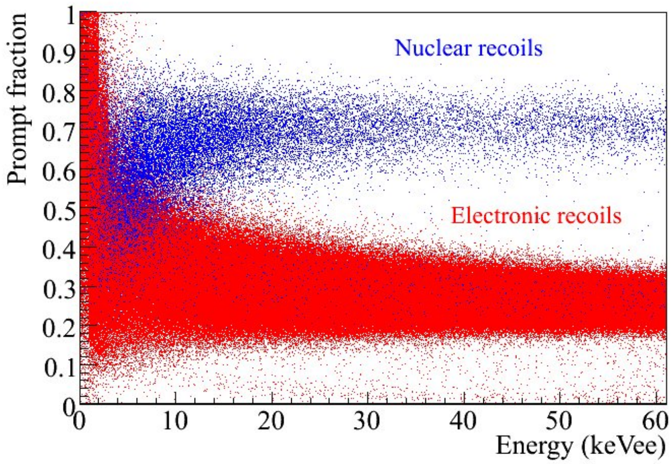

Figure 2: An example of pulse shape discrimination of nuclear recoils and electrons in argon. The prompt fraction is a measure of the pulse shape which clearly separates the two interactions down to very low energy. Figure from [4].

large fluctuations caused by small fluctuations early in the avalanche which are amplified by the process. Inductive readout of passing charges and direct collection of the unamplified charge do not rely on an avalanche and are effective methods where energy resolution is of paramount importance, but depend on low noise amplifiers and relatively large signals(e.g. $0\nu2\beta$).

Electroluminescence (i.e. secondary scintillation or proportional scintillation) can be used to proportionally amplify the the drifted ionization and it does not suffer the fluctuations of an avalanche or the small signals of direct collection. It works by setting up at the positive end of the drift volume parallel meshes or wire arrays with an electric field larger than the drift field but less than the field needed for avalanche, in xenon this is about 3-6kv/cm/bar for good energy resolution. Equation 1 shows the dependence of the yield (Y) in units of photons/electron/cm/bar as a function of pressure (p) in units of bar and electric field (E) in units of kV/cm for xenon [3]. The amplification can be adjusted with the length of the electroluminescence region, pressure and electric field.

$$Y/p = 140E/p - 116 \tag{1}$$

Differentiation of nuclear and electron recoils at low energy deposition is important as a means of background rejection. The nuclear recoil deposits a higher density of ionization than an electron recoil and this results in a higher geminate recombination resulting in a higher output of primary scintillation and lower charge. The ratio of scintillation and charge can be used to distinguish the two and in the case of an electroluminescence readout this is done simply with the ratio of primary light to secondary light. Optically transparent grids with PMT or APD readout combine to make a elegant setup wherein the same array can measure the primary scintillation (S1) and the electroluminescence (S2) eliminating the necessity of two sets of readout detectors. Figure 1 illustrates this method which works in the gas phase and in dual phase detectors. The time evolution of the primary light is also effected by the type of recoil which results from different populations of excimers in the singlet and triplet states[4] and that alone has shown excellent discrimination particularly in gasses where the decay time is significantly different (see table 1). An example of the discrimination is displayed in figure 2 where nuclear recoils and electrons can be identified down to 10's of keV_{ee}, in argon. (nuclear recoils have lower ionization for a given input energy they are typically reported in equivalent electron energy loss, keV_{ee}, when compared with electrons)

The composition of the drift matter is an important element of the TPC design, and the noble gasses are frequently selected as the bulk element in the mix (table 1). The noble gases have no electron affinity in the ground state resulting in good free electron lifetime and they produce a good amount of scintillation which is useful for particle identification and t0 determination. In the case of argon and xenon, the low average energy to produce an ion pair results in good energy resolution. The noble gases are easily purified to a high level which combined with moderate cost enables the construction of large monolithic detectors. Of the noble gasses one isotope of xenon (^{136}Xe) is a candidate for ($0\nu2\beta$).

Table 1: Properties of the noble gasses typically used in non-accelerator TPCs. [1,2] W is the average energy spent to produce one electron ion pair.

Element	W (eV)	photon yield (γ/keV)	wave length (nm)	decay time fast/slow	cost ($/kg)
Helium	46.0	50	80	10ns/1.6μs	$5
Neon	36.6	30	77	10ns/3.9μs	$60
Argon	26.4	40	128	4ns/1.6μs	$2
Xenon	21.7	42	175	4ns/22ns	$1000

The negative ion TPC [5] uses an electronegative gas (e.g CS_2) either as the drift gas or as a dopant to the drift gas that captures the primary electrons forming a negative ion which drifts in the electric field. Upon reaching the gas gain region of the TPC, the electron is stripped from the ion in the high electric field and the electron avalanches in the normal manner. The larger mass of the the negative ion keeps the kinetic energy of the ion thermal at high electric fields and therefore has far smaller diffusion. The reduction of diffusion over large distance(time) enables detail tracking of small tracks in a large volume without the benefit of a magnetic field to limit diffusion (which would be prohibitively expensive for a large volume). The trade-off is orders of magnitude slower drift placing a limit on trigger rate.

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