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**Direct Search for Dark Matter by Using
Dual-phase Liquid Xenon Detector and
Measurement of Nuclear Recoils in Liquid Argon**

A dissertation submitted in partial satisfaction
of the requirements for the degree
Doctor of Philosophy in Physics

by

Yixiong Meng

2015

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ABSTRACT OF THE DISSERTATION

Direct Search for Dark Matter by Using Dual-phase Liquid Xenon Detector and Measurement of Nuclear Recoils in Liquid Argon

by

Yixiong Meng

Doctor of Philosophy in Physics

University of California, Los Angeles, 2015

Professor Graciela Gelmini, Co-Chair

Professor Hanguo Wang, Co-Chair

Cosmological and Astrophysical observations provide compelling evidences for the existence of dark matter in the universe [41]. One class of dark matter candidates, the Weakly Interacting Massive Particles (WIMPs), has been predicted in many particle physics theories [72, 53, 49]. Direct detection experiments using dual-phase liquid noble element detectors report the best sensitivities to the detection of the dark matter particles [29, 12, 9]. The next generation direct detection experiments using the same technology, are actively been built and expected to give a factor of 100 improvement on the current best sensitivity.

This thesis discusses the measurement of nuclear recoils in a dual-phase liquid argon detector using a bunched neutron beam generated by linear accelerator facility at accelerator laboratory in Notre Dame University. Nuclear recoils of energy ranging from $10.8 \text{ keV}_{\text{nr}}$ to $49.9 \text{ keV}_{\text{nr}}$ are measured under different drift field configurations. An electric field quenching on nuclear recoils in liquid argon is discovered and quantified for the first time. This quenching effect is also found to be drift field and recoil energy dependent. By varying the drift field amplitude from 100 V/cm to 1000 V/cm for each nuclear recoil energy, the quenching effect are

measured as a function of nuclear recoil energy and drift field amplitude. Results from this measurement is used in the direct dark matter detection experiment [9] to calculate the final sensitivity of direct dark matter search.

A separate work on the optimization of detector design for the XENON1T [19] detector is also discussed in detail. Finite element simulation tool is used to design and optimize the electric field in XENON1T time projection chamber. As part of the design of XENON1T detector, electron transparency across metal grids of different geometrical configurations are also studied.

The dissertation of Yixiong Meng is approved.

William Slater

Lawrence Lyons

Jean Turner

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2015

to my family

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VITA

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CHAPTER 1

Introduction to Dark Matter

1.1 Cosmology Background

The Big Bang model was generally accepted as the standard cosmological model after the discovery of Cosmic Microwave Background and was developed with new cosmological evidences. The standard model describes the evolution of early universe from an initial singularity, followed by the Planck epoch from zero to 10^{-43} second. During this period, the universe is expected to be extremely hot and dense; and the all four kinds of fundamental forces are unified in this energy scale. The only dominant interaction is the quantum effect from the gravity. An exponentially rapid expansion of the early universe happens around 10^{-36} second, following the Planck epoch. This exponential expansion magnifies the quantum fluctuation from the Planck epoch in the cosmological scale. Without the quantum fluctuation introduced during the early stage, the early universe will be perfectly uniform from the initial singularity and will be expanding in the same pattern. However, the quantum fluctuation enhanced by inflation gives local variations which eventually lead to the formation of large scale structures. As the universe expands adiabatic-ally, it cools and the associated temperature drops with time. The symmetry-breaking occurs similar to a phase transition, when the temperature of the early universe reaches certain point.

The Λ Cold Dark Model (Λ CDM) by using six parameters, provides specific calculations on the fractions of different components of universe and associated

evolution process to the cosmological standard model.

The cosmological standard model as Mathematical described by Λ CDM model is based on the fundamental assumption that the matter in the universe is isotropic and homogeneous in the large scale, which has been proven by the various observations to an extremely high precision. The discussion in details can be found in cosmology textbook [75]. The parameterized model is derived from the Einstein field equation with a cosmological constant Λ , as shown in the equation 1.1.

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu} + \Lambda g_{\mu\nu} \quad (1.1)$$

Though there is no intrinsic mathematical motivation for this constant, this term represents a vacuum density with negative pressure, as the leading factor contributing to the expansion of the universe at current scale. Based on the assumption of homogeneous and isotropic universe, the Friedmann-Robertson-Walker metric 1.2 is used to interpret the geometrical shape of the universe, where the (r, θ, ϕ) is a co-moving spherical coordinate. The parameter k sets the curvature: $k = -1$ is open, $k = 1$ is close, $k = 0$ is flat.

$$ds^2 = dt^2 - a^2(t) \left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin\theta d\phi^2 \right) \quad (1.2)$$

$a(t)$ is the scalar factor as a function of time t . The following Friedmann equation 1.3 is derived from one component of the Einstein field equation 1.1.

$$\left(\frac{1}{a} \frac{da}{dt} \right)^2 = \frac{8}{3}\pi G\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \quad (1.3)$$

To simplify the Friedmann equation, Hubble parameter H is defined as $H(t) = \frac{1}{a(t)} \frac{da(t)}{dt}$; where H_0 is the Hubble constant for the present time. Another term critical density ρ_c is defined assuming $k = 0$ and $\Lambda = 0$ in Eq. 1.3, ρ_c is equal to $3H_0^2/8\pi G$, By using the Hubble constant $H(t)$ and critical density ρ_c , three components $\Omega_{m,0}, \Omega_{k,0}, \Omega_{\Lambda,0}$ defined as 1.4 are used in the Friedmann equation 1.3.

$$\Omega_{\rho,0} = \Omega_{m,0} + \Omega_{\gamma,0} = \frac{8\pi G}{3H_0^2} \rho_0 = \frac{\rho_0}{\rho_c} \quad (1.4)$$

$$\Omega_{k,0} = -\frac{k}{H_0^2} \quad (1.5)$$

$$\Omega_{\Lambda,0} = \frac{\Lambda}{3H_0^2} \quad (1.6)$$

The density ρ has a dependence on the volume dimension a . In the co-moving space the time dependence is folded into the dimension parameter $a(t)$. The non-relativistic component is diluted as the space expands by the factor $(a_0/a)^3$ while this factor for relativistic component such as photons and neutrinos is $(a_0/a)^4$. So to explicitly show the volume dependence for each component, the Friedmann equation with three components is written as 1.7.

$$\frac{H^2}{H_0^2} = \Omega_{\gamma,0} \left(\frac{a_0}{a}\right)^4 + \Omega_{m,0} \left(\frac{a_0}{a}\right)^3 + \Omega_k \left(\frac{a_0}{a}\right)^2 + \Omega_{\Lambda} \quad (1.7)$$

The energy budget of the universe as a function of time t is described by the function 1.7, the kinetic energy of the co-moving expansion of the universe $H^2(t)$, is from three components: the gravitational energy due to matter, the vacuum energy and the curvature. By considering the case when at the present time when $a(t = t_0) = a_0$, the equation becomes

$$1 = \Omega_{\rho} + \Omega_k + \Omega_{\Lambda} \quad (1.8)$$

The curvature parameter k related term Ω_k is equal to $1 - \Omega_{\rho} - \Omega_{\Lambda}$. So when $\Omega_{\rho} + \Omega_{\Lambda} > 1$, the universe is of close geometry while $\Omega_{rho} + \Omega_{\Lambda} < 1$ case refers to a open geometry.

Moreover, with the FRW metric the Einstein field equation also yield the acceleration equation 1.9.

$$\frac{1}{a} \frac{d^2 a}{dt^2} = -\frac{4}{3} \pi G (\rho + 3p) + \frac{\Lambda}{3} \quad (1.9)$$

To combine the equation 1.9 with the Friedmann equation 1.3, this yields the acceleration equation without curvature parameter k :

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3} (\rho + p) + \frac{\Lambda}{3} \quad (1.10)$$

To represent the density ρ with Ω_m and assume the matter dominates, the acceleration term $\ddot{a}(t)$ is

$$\frac{1}{H_0^2} \frac{\ddot{a}(t)}{a(t)} = -\frac{1}{2} \left(\frac{a_0}{a}\right)^3 \Omega_m + \Omega_\Lambda \quad (1.11)$$

The function 1.11 shows that the acceleration is dominated by the vacuum energy term Ω_Λ , which acts as of negative pressure. The matter term Ω_m contributes by gravitational force and tends to de-accelerate the expansion of the universe.

Because of the co-moving expansion of the universe, photons that travel in the universe are affected by the Doppler Effect. For example, the photons created in the early universe and travel through the expansion since then, the wavelength is shifted towards to the higher wavelength due to the expansion of universe. By using this feature of the expansion, the red-shift is sometimes used to characterize the stage of the expanding universe. The red-shift parameter is given as:

$$1 + z = \frac{a_0}{a} \quad (1.12)$$

1.2 Evidence of the Existence of Dark Matter

The first identification of missing mass problem was raised by Zwicky in the early 1930s [115]. Through dedicated examination of dynamic motion of Coma cluster, he discovered significant discrepancy between the derived mass from dynamic

equilibrium and mass-to-light ratio [92, 51]. Various cosmological and astrophysical observations since then, have provided compelling evidences for the existence of dark matter in the universe [41, 50, 54]. One class of dark matter candidates, the Weakly Interacting Massive Particles (WIMPs), has been predicted in many particle physics theories.

1.2.1 Mass-to-Light Ratio

Mass-to-light ratio was introduced into cosmology study during the 1800s. It is widely used in the astrophysics and physical cosmology as the mass a large cosmological volume (typically galaxy and cluster) divided by associated luminosity, which is usually designated with in the symbol Υ . Moreover, reported mass-to-light ratio uses the value of solar system as a baseline value. By using the sun as cosmological reference object, of which mass and luminosity are reliably estimated as $M_{\odot} = 2.0 \times 10^{30}\text{kg}$ and $L_{\odot} = 3.9 \times 10^{26}\text{W}$, the mass-to-light ratio of solar system is determined as $\Upsilon_{\odot} = M_{\odot}/L_{\odot} = 5 \times 10^3\text{kg/W}$. The luminosity basically represents the amount of light elements or baryonic matter in the cosmological system, which emit and absorb light. So the fraction of baryonic matter in the system is inversely proportional to the mass-to-light ratio.

By using the virial theorem to calculate the mass, Zwicky derived the mass-to-light ratio of the Coma cluster after careful assessment of possible uncertainties to be about 500. Comparing this value to the observation result $\Upsilon = 3$ from local Kapteyn stellar system, he suggested that there may be some invisible matter that accounts for the inter-nebular density problem. More recent study of the Coma Cluster found $\Upsilon = 182$ [114].

The mass-to-light ratio of different cosmological objects of different scales from galaxies to super-clusters have been calculated. Gravitational lensing or the dynamics of a virialized system is used to estimate the mass. Because the observation

of luminosity for certain cosmological objects is usually limited to a finite wavelength bandwidth, the extrapolation with certain assumption such as black-body or power law is implemented to infer the luminosity. The results are compared as a function of the radii R in unit of Mpc as shown in Figure 1.1 from [35]. The mass-to-light ratio difference among various systems indicates that the invisible matter is more dominate on larger scales [64].

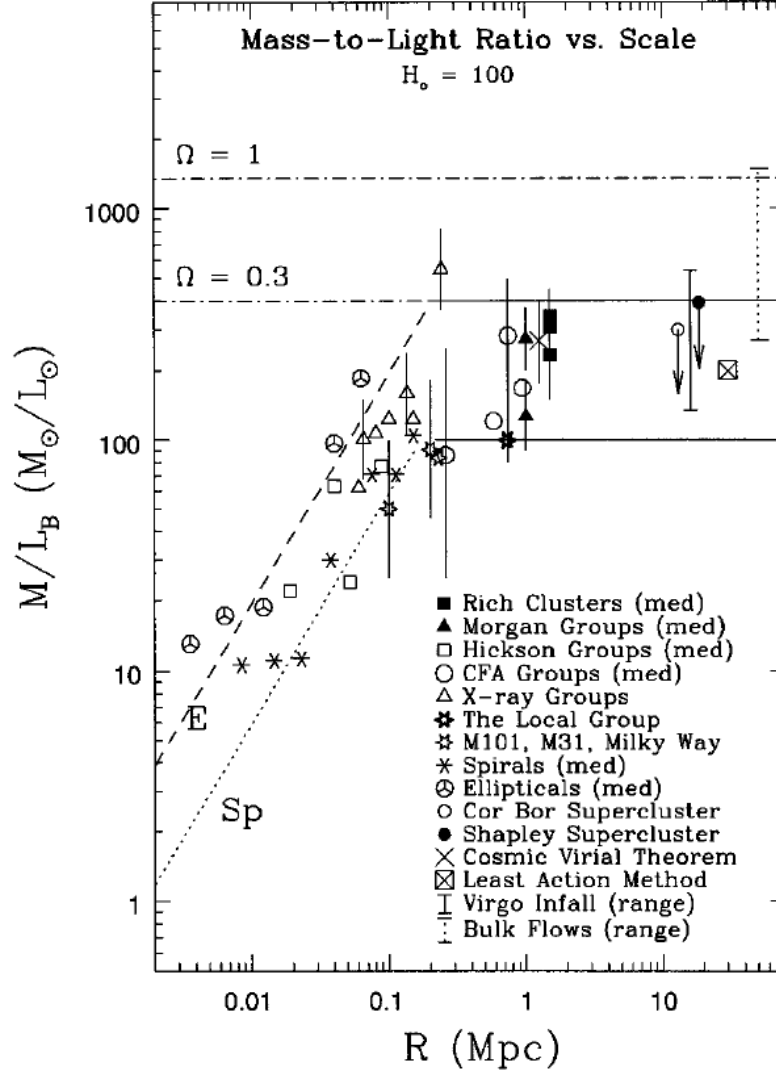


Figure 1.1: mass-to-light ratio of different systems such as galaxies, group, clusters and super-clusters, as a function of scale. In this figure Hubble constant $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is adopted in calculation, the picture is taken from [35]

As similar observation results from cluster and super-clusters are compared in Fig. 1.1, the Milky Way galaxy weights $9 \times 10^{10} M_{\odot}$ and has luminosity $1.5^{10} L_{\odot}$, its mass-to-light ratio is $6 M_{\odot}/L_{\odot}$. This ratio indicates a presence of a large amount of invisible massive component. Surveys of spiral galaxy rotation curve generally yield the mass-to-light ratio around $10 h M_{\odot}/L_{\odot}$ or larger.

The specific fractions of dark matter in different cosmological volumes are also examined by using the mass-to-light ratio [109]. The calculation is based on the known abundance of the baryonic component in the universe, mainly the light element hydrogen and helium from the Big Bang Nucleo-synthesis.

Even though the measurements of mass-to-light ratio in different cosmological systems are a compelling evidence for the existence of dark matter in the universe; limited by the large variations of the observation results in certain system, the specific fraction of dark matter is difficult to be quantitatively estimated by using the mass-to-light ratio.

1.2.2 Galactic Rotation Curve

The galactic rotation curves is a mapping of orbital velocities of visible objects such as stars or gas within a certain galaxy, versus the associated radial distances from the galaxy center. The galaxies in universe are classified into spiral galaxy and elliptical galaxy. The spiral galaxy has a dense core surrounded by a thin rotating disc where over 80% luminous components stays within a radius of approximately 10 kpc. The rotation curve of spiral galaxy is measured by red-shift due to Doppler effect of 21 cm absorption line of hydrogen atom. Due to the asymmetry of rotation curves in spiral galaxies, the averaged results of rotation curves are reported for the spiral galaxies. Contrary to the spiral galaxy, the elliptical galaxy contains little hydrogen atoms and barely emit the 21 cm radiation for detection. So the rotation curve observation of elliptical galaxy is solely based on the motion of

stars.

By using the viral theorem with the estimation of mass from visible objects, the expected orbital velocities are calculated for spiral galaxies of different sizes. When galaxy stays in a dynamic equilibrium, according to Newtonian dynamics the gravitational driving force from massive components can be derived as:

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

So the rotation curve as a function of r , the averaged distance from stars to galaxy core specially outside the disc, is expected to decrease with increasing distance since

$$v = \sqrt{\frac{GM}{r}}$$

However, the observations results comes quite contract to the expected distribution.

Vera Rubin and her collaborators first presented the rotation curve of spiral galaxy to a high degree of accuracy and demonstrated that the rotation curves keeps as a flat line well beyond the galactic bulge where most of the visible mass locates [111, 102]. This result shows that the mass distribution of spiral galaxies remains uniform even far outside the galaxy luminous disk edge. This discrepancy between visible mass distribution and gravitational mass distribution suggests the existence of an invisible component in the galaxy.

A more careful study was carried out by Persic and his collaborators on about 1000 spiral galaxies ranging over almost two orders of magnitude in luminosity [97] as shown in Figure 1.2. In this study, a optical radius R_{opt} that is the radius containing 83% of luminous components, is used to represent the distance as the variable of x-axis. The averaged rational velocity is also normalized to that at the radius R_{opt} . The gravitational contributions from luminous and invisible mass to the rotational velocity are shown separately as the dotted line and dash line; the combined fit to the observation result is the solid line. Clearly the regular

luminous matter can not account for the observed rotational velocity at large radius, especially for $R_{opt} > 1$.

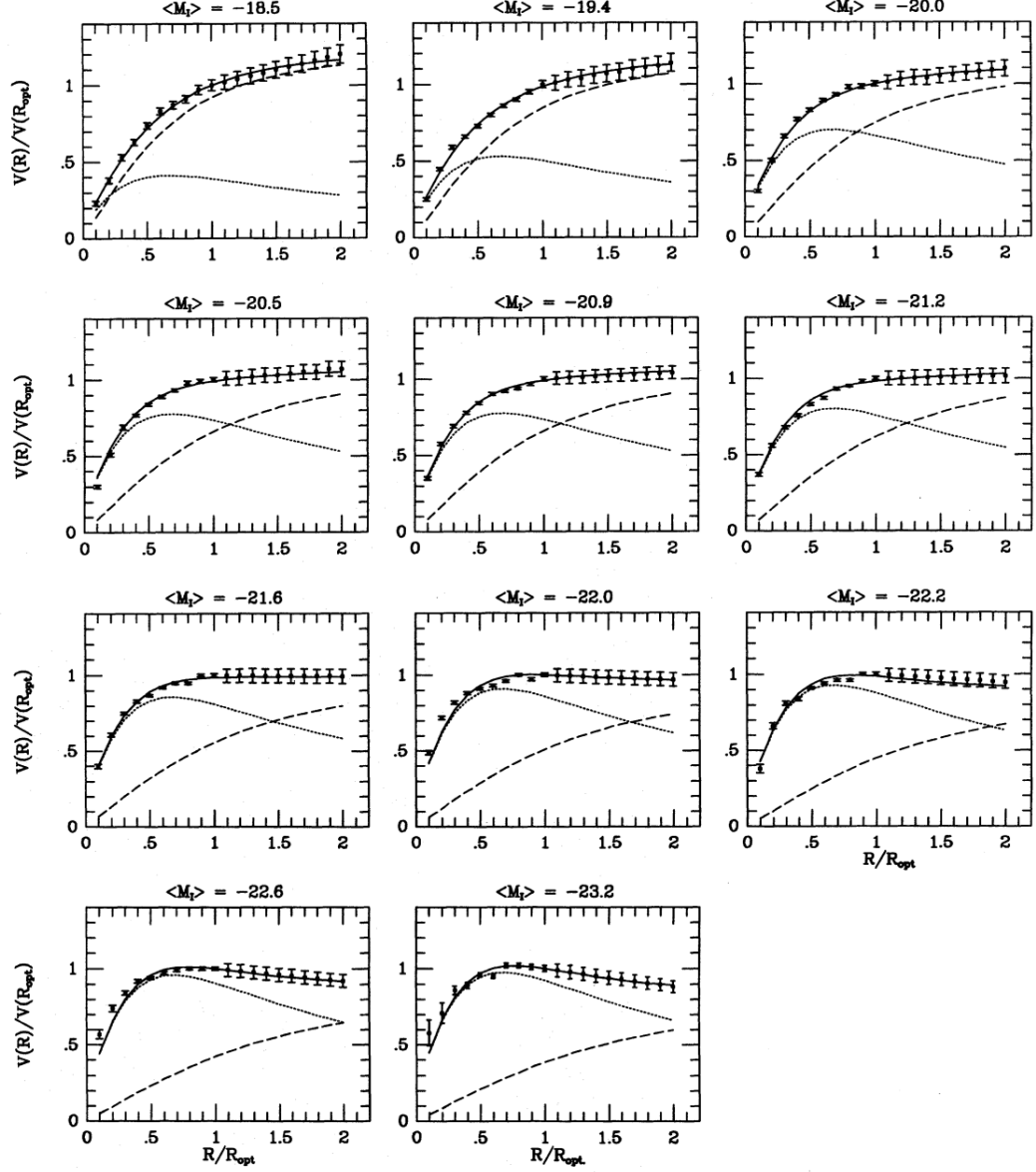


Figure 1.2: The averaged rotation curves and universal fits for different luminosity bins. All the galaxies are divided into 11 luminosity bins. The dotted line is the contribution from visible disc and dash line is the contribution from dark matter halo. Solid line is the combination of the disc and dark matter halo. Figure is taken from [97].

1.2.3 Cosmic Microwave Background

Cosmic Microwave Background (CMB) is a thermal radiation that can be received in all directions and isotropically in the large scale. Presumably it is left from the evolution of early universe. CMB was first accidentally discovered by R. Wilson and A. Penzias in 1964 [95]. Since then CMB has been precisely measured by various experiments aiming to test the standard model of cosmology. NASA Cosmic Background Explorer (COBE) found residual temperature is 2.726 K and in 1992 and first detected the anisotropy in cosmic background, at the level of one part in 10^5 [39].

NASA experiment Wilkinson Microwave Anisotropy Probe (WMAP) had achieved the full-sky map of Cosmic Microwave Background with a fine-resolution of 13 arc-minute. The full-sky map is shown in figure 1.3.

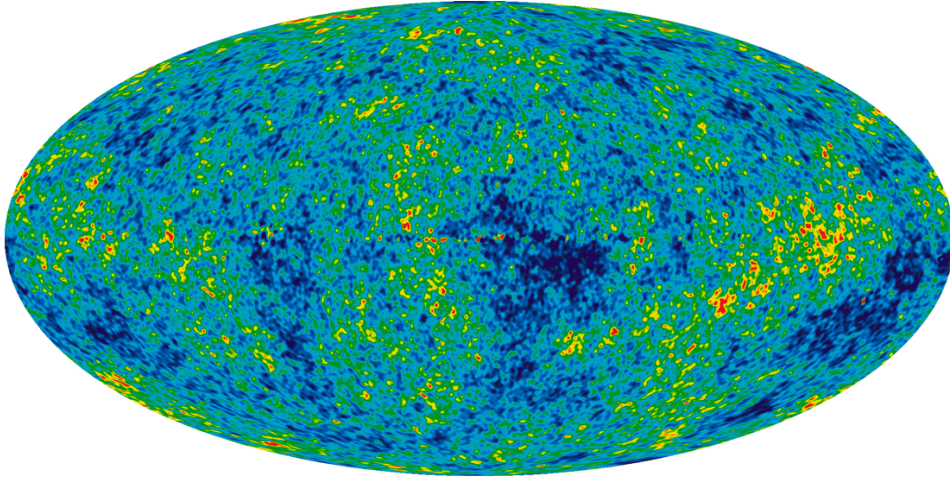


Figure 1.3: WMAP 7 years full-skyp CMB map

The temperature field result is expressed in terms of spherical harmonic function.

$$\frac{\delta T(\hat{n})}{T} = \sum_{l=0}^{\infty} \sum_{m=-\infty}^{+\infty} a_{l,m} Y_{l,m}(\hat{n})$$

Where the $\hat{n}$ is unit direction vector and $Y_{l,m}$ is associated Legendre polynomial. Therefore $a_{l,m}$ refers spherically to the temperature field. In spherical coordinate the expansion variable l , which is often called as angular momentum number in quantum mechanics, is used to describe to what extent the variation is. With an increase of variable l , the corresponding coefficient $a_{l,m}$ gives variation magnitude in smaller scale. Approximately value of variable l within few hundreds represents the variation around 1 degree while variation with l value of few thousands is in one tenth degree level. Then the variable C_l^{TT} based on coefficient $a_{l,m}$, is used in angular power spectra to fit the cosmic microwave background:

$$C_l^{TT} = \sum_{m=-l}^{m=l} \frac{1}{2l+1} a_{T,lm} a_{T,lm}^*$$

Various cosmology variables in standard model of cosmology are derived from fit result accordingly.

In figure 1.4 the $l = 0$ term gives mean temperature of cosmic microwave background and $l = 1$ term is dominated by the Doppler red-shift due the motion of solar system. The peaks indicate the anisotropy of CMB and corresponding distribution. Inferred from standard model of cosmology, During the process that photons eventually decoupled from baryon they experienced the pressure from baryons which is in-falling into the massive centers. The photon left from acoustic oscillation carried the geometry information of early universe. So first peak appearing at $l \sim 200$ is from the compressed once photons while the second peak is due to the expansion after first compression. Meanwhile, the increasing baryon density affected the height of peaks and accelerated oscillation.

According to the standard model of cosmology [81, 75, 76], the cosmic microwave background was created when the decoupling of photons from photon-

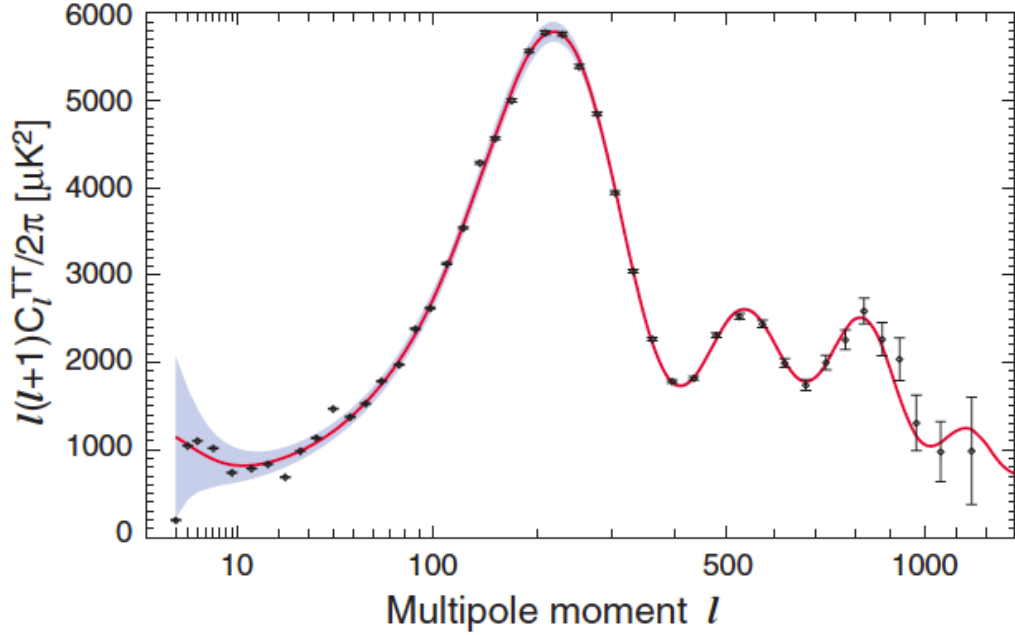


Figure 1.4: WMAP 7 years temperature field power spectra

baryon plasma happened in the early universe. Roughly around 380,000 years after the Big Bang when the red-shift $z \sim 1000$, the temperature of the universe was above 1eV and photons were still hot enough to sustain a constant ionization of hydrogen and helium atoms. The photons were bound to a plasma-like fluid of baryons and electrons through the Thomson scattering with electrons.

With the expansion of universe, temperature of the universe went down as energy-mass density decreased. Until temperature dropped below 3000 K, when the photons could no longer knock off the electrons from light element atoms, the free electrons started coupling with hydrogen and helium nucleus, neutralized the universe and released the photons that used to be bounded by the scattering with electrons in the photon-baryon plasma. The emitted photons fulfilled early universe while carrying the information of curvature and all the components in early universe. Therefore, accurate measurement of the cosmic microwave background provides detailed description of early universe. The measurement result of universe constitutes provides compelling evidence for dark matter's existence

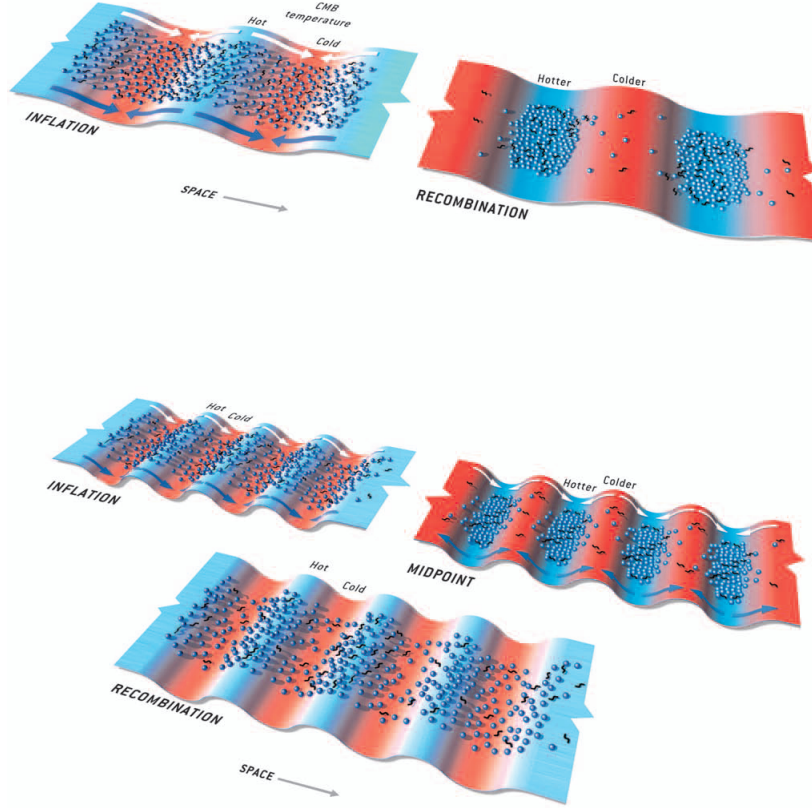


Figure 1.5: the upper figure shows the clumps of dark matter in large scale while the lower one show the dark matter clustering in small scale. This figure is from [70].

and the triumph of cosmology standard model as well.

Based on the inflation theory, the growth of early universe during inflation underwent a Gaussian-like quantum fluctuation. The quantum fluctuation created a synchronized density variation associated with all components. So the local over-density regions caused by the variation formed potential wells, which pulled the matter from the under-density regions. Moreover, the photons bounded within the plasma fluid were also affected by the gravitational potential wells. When photons were accumulated in the potential wells, a photon pressure started to

generate against collecting more photons. The gravitational force from density fluctuation and the photon pressure, together resulted in an acoustic oscillation in the photon-baryon plasma. The basic mode of acoustic oscillation is determined by the time of last scattering: $k = \pi/s$, where the s is the sound horizon at that time.

- Baryon Drag

Because of the presence of baryons in the plasma fluid, the dynamics of acoustic oscillation is changed. The baryons follow the density fluctuation and are attracted into the potential wells from local regions. So more baryons in the potential wells cause larger potential wells which lead to a greater gravitational compression of the plasma fluid. So the impact from the enhancement of gravitational force is presented as the different peak height between the first peaks (the compression and rarefaction peaks) on the variation spectrum in Figure 1.4.

- Doppler Shift

The Doppler Effect is caused by the motion of the plasma fluid. When the fluid oscillates, the CMB photons follows the motion and acquire the oscillation velocity. Because the fluid oscillation is out of phase with the temperature oscillation initialized by the quantum fluctuation from inflation, this motion shifts the frequency of CMB photons by the Doppler Effect and smooth the anisotropy. Without the baryon content in the fluid, the Doppler shift is expected to be equal in amplitude to the temperature variation. However, the existence of baryons increases the effective mass of the oscillation and lowers the frequency of the oscillation. So the prominence of acoustic peaks is increased due to the baryon limit on the Doppler shift.

The acoustic oscillation renders the anisotropy spectrum peak structure as shown in Figure 1.4. However, the spectrum at small angular scale (large l) is

suppressed by various damping:

- Diffusion Damping

The diffusion damping is caused by the transit of photons through the plasma fluid. The photon transit happened between dense and sparse regions effectively reduces the local variation therefore suppresses the anisotropy amplitude. The specific scale in which the diffusion damping becomes significant, is sensitive to the baryon density. This is because the CMB photons are confined by the Compton scattering with baryonic component, the mean-free-path of the photons in plasma fluid is limited by the baryon density.

- Damping from the Universe Expansion

The expansion of universe dilutes the baryon density of the plasma fluid. As explained in the diffusion damping, the rarefied baryon density increases mean-free-path of CMB photons.

- Damping from the Last Scattering Surface

By considering the last scattering or the recombination when the CMB photons were released from the plasma fluid: the decoupling of all the CMB photons did not happen simultaneously, the Compton scattering still affects a fraction of CMB photons after the beginning of recombination. The entire process requires an appreciable amount of time. So a finite depth of the last scattering surface is defined to address this process. Effectively, this damping from the last scattering surface increases the CMB photon mean-free-path as calculated by average.

The impact of damping can be found by the exponential damping tail on the anisotropy spectrum at the small angular scale end. Moreover, between the last scattering the receiving by earth-borne observation, the CMB photons experience other physical processes that modifies the anisotropy seen at present. There are two main effects on the CMB anisotropy.

The first effect is from the hot gas consist of ionized atoms in the intergalactic medium. The universe right after recombination was perfectly neutral and transparent to the CMB photons: there is no ionization nor associated emission of photons, which is also called Dark Ages. After the formation of first stars and quasars, the following gravitational collapses emit intense radiation that re-ionize the local universe. From that point on, the universe is composed of plasma.

The current universal plasma density is not large enough to cause any significant impact the CMB photons. However, in the relatively early universe when the free charge is much denser in some local regions, the impact on the CMB photons from that regions is still strong.

The CMB photons scatter off the high energy electrons via inverse Compton scattering and gain energy from the plasma they travel through. The low energy CMB photons receive energy via the interaction and shift the CMB spectrum. The effect is called Sunyaev Zel'dovich effect. This effect erases the anisotropy in the small scale and induces polarization anisotropy in the large scale.

The second effect is from the evolving gravitational potential that CMB photons travel through.

- CMB Polarization

The CMB is polarized at the level of μK , one order of magnitude lower than the observed temperature variation. There are two modes of CMB polarization: E-mode and B-mode. E-mode polarization is a field with vanishing curl $\nabla \times \vec{E} = 0$, analogical to the E field in electrostatics; while similarly B-mode has a vanish divergence $\nabla \cdot \vec{B} = 0$. The E-mode polarization is naturally created via the Thomson scatterings in the in-homogeneous plasma fluid. The B-mode polarization can be created via two mechanisms: the gravitational sensing of E-mode polarization and the gravitational wave arising from inflation. The measurement of B-mode polarization is extremely diffi-

cult due to the unknown foreground contamination level. (the scattering in intra-cluster dust)

- **Horizon Problem and Inflation Theory**

The full sky observation of microwave background turned out to be a almost uniform distribution with variation in small scale, in another word, in large scale the universe is isotropic. However, if based on the assumption that universe went through stable and linear expansion, when we look backwards in time to search for possible original structure or a particular physical shape, none of them can generate such isotropic microwave background. This is horizon problem.

The inflation theory gives a plausible explanation for the horizon problem. Inflation theory posits a special form of field, the inflation field in the early evolution of universe. This field leads to an extremely fast accelerating expansion of part of early universe that isolates this special part we nowadays live in from the rest of universe. Similar to the bubble formed in boiling water, due to the fluctuation within local areas, air bubble is created by phase transition and this air bubble is isolated from liquid since then.

1.3 Dark Matter Candidates

1.3.1 Weakly Interacting Massive Particles (WIMP)

The well-established model for particle physics is called the Standard Model [47, 57]. The model describes the fundamental constituents of the universe by a set of 17 elementary particles as the diagram shown in the left part of Figure 1.6. Particles can be divided by spin into two sets: 12 fermions of half-integer spin and 5 bosons of integer spin. The 12 fermions includes 6 quarks and 6 leptons; quarks are combined to make baryon such as neutron and protons while leptons

are common charged particles and neutrinos. All these fermions make up the constituents of ordinary matter. Bosons are also called force mediating gauge bosons which is responsible for four different forces between particles.

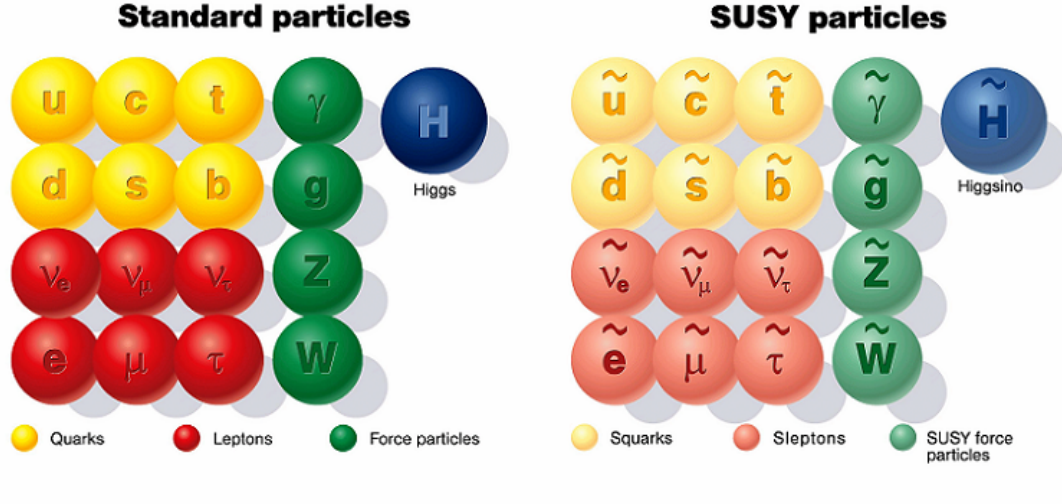


Figure 1.6: Diagram of the Standard Model on the left and the Supersymmetric extension on the right. Different types of elementary particles are color-labeled.

The standard model has predicted the existence of several elementary particles before they were experimentally discovered [66]. For example, mass of the Z boson was predicted by Standard Model at 91.1874 ± 0.0021 GeV and the experimentally measured mass was 91.1876 ± 0.0420 GeV [33]. This is a typical example of the triumph of Standard Model.

However, there are several shortcomings in the Standard Model such as the mass of neutrinos, coupling constant and hierarchy problem. All these existing issues indicate the new physics beyond standard model. One of the prominent theory to address these problems with Standard Model is Super-symmetry. Super-symmetry generally predicts a symmetry based on the spin property of elementary particles: the half-integer spin Standard Model particles such as fermions and leptons are expected to have partners of integer spin and integer spin particles such as W, Z and Higgs are expected to have half-integer spin partners. Supersymmetry proposes an other sets of elementary particles with the same properties

of the Standard Model counterparts except the spin. The diagram of predicted Supersymmetry particles are listed in the right part of Figure 1.6. The naming of Supersymmetry particles are similar to the Standard Model ones but adding an additional 's' for fermions in the front (quarks becomes squarks) and an additional 'ino' for bosons in the back (Higgs becomes Higgsino). The proposed Supersymmetry theory can solve the hierarchy and coupling constant problems in Standard Model. With the similar properties as Standard Model particles, the Supersymmetry particles should be discovered by the collider experiments. This factor is explained in Supersymmetry that this symmetry is in fact a broken symmetry and Supersymmetry particles are on the order of TeV and therefore are much heavier than the Standard Model counterparts.

Supersymmetry in the most general form contains more than a hundred free parameters and this feature make any experimental measurement or constrain to it impossible. The current popular branch of Supersymmetry theory Minimal Supersymmetry Model (MSSM) reduces the number of free down to five. The concept of R-parity is introduced in the MSSM. This R-Parity is conserved for both Standard Model and Supersymmetry particles. Using lepton number, baryon number and spin, the this quantum number is defined as $R = (-1)^{2s+3B+L}$, where the s is spin number, B is lepton number and L is baryon number [72]. So Standard Model particles have R-Parity of 1 and Supersymmetry particles have R-Parity of -1; any possible decay of Supersymmetry particles has to result in an odd number of Supersymmetry particles in order not to violate the R-Parity. Therefore, theoretically a set of lightest supersymmetrt particles (LSP) can exit and decay only via annihilation. MSSM predicts the LSP to have a mass on the electro-weak scale, around a few hundred GeV. The features of large mass of low cross-section make LSP an interesting candidate for the dark matter.

In the early universe, when the temperature of universe is high enough that it exceeds the mass of WIMPs, the WIMP particles are constantly created and

annihilated, in another word, the WIMP particles are in thermal equilibrium. With the constant comoving of the universe, the temperature of the universe continuously decreases and at certain point the thermal creation stops while the annihilation continues. The evolution of number density of WIMPs as a function of time in the early universe is shown as 1.13.

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma_A\mu\rangle[(n_\chi)^2 - (n_\chi^{eq})^2] \quad (1.13)$$

The contributions to the decreasing of WIMP number density are from two processes as the two term on the right hand side of 1.13. The first term represents the dilution effect on the WIMP number density as universe expands; the other term represents the WIMP annihilation which is proportional to the product of averaged annihilation cross-section σ_A and relative velocity μ . n_χ^{eq} is the number density of WIMPs after freeze-out occurs.

The time point that freeze-out occurs refers to the moment when the comoving expansion of the universe is so large that the diluted WIMP number density is too small for the annihilation process at any appreciable level. Since that time point on, the co-moving number density of WIMPs stays the same. This process is shown in Figure 1.7, where the horizontal axis is the time which can also be represented as the temperature of the universe. So the specific value of the annihilation cross-section along with the WIMP mass, determines the abundances of WIMPs in the universe as Figure 1.7 shows. The independent astrophysical and cosmological measurements constrains the dark matter abundance around 25%, Mass and cross-section of WIMP corresponding to this abundance, are on the same order of magnitude as LSP predicted by Supersymmetry to solve Standard Model problems. This is the reason why Supersymmetry particles LSP are strongly motivated as the candidates for the dark matter.

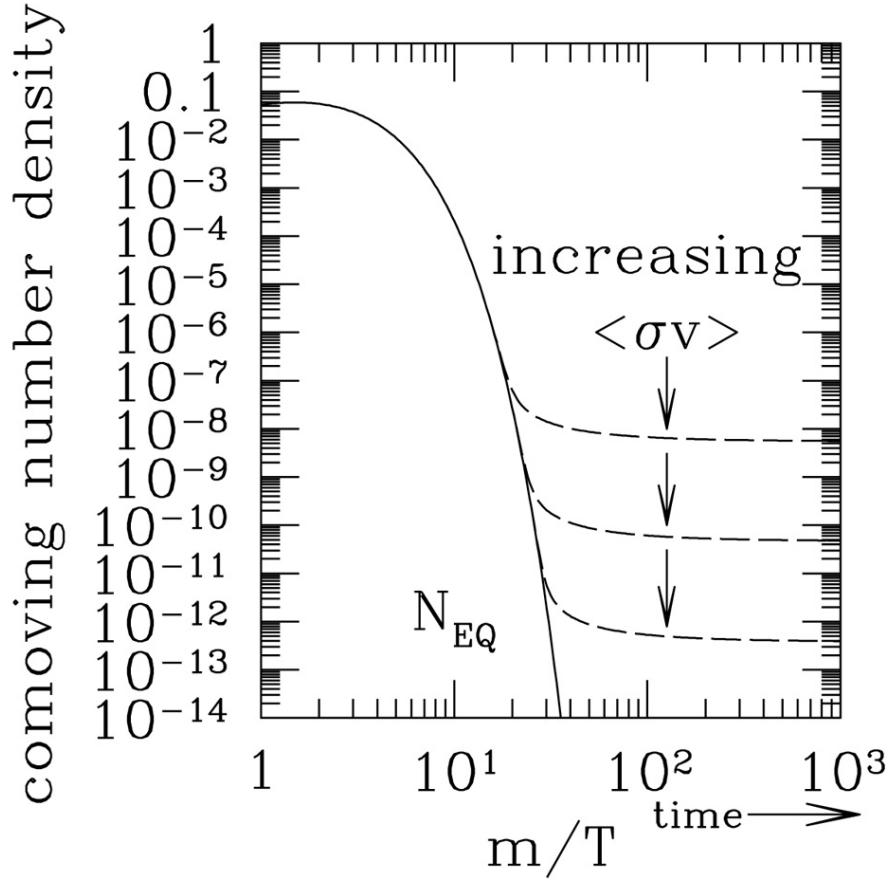


Figure 1.7: Thermal relic abundance for WIMP dark matter for different annihilation cross sections. Taken from.

1.3.2 Axion

Axion was firstly proposed in the theoretical model that Roberto Peccei and Helen Quinn discovered to solve the strong-CP problem [94, 96]. The Strong-CP problem is that in the standard model, the quantum chromo-dynamic (QCD) include a CP-violating term $\mathcal{L}_\theta = \frac{\theta g^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$ where G is the color field strength tensor and θ is the θ parameter. This term corresponds to CP violation in QCD and indicates an observable neutron electric dipole moment. However, so far no neutron dipole moment has been found in any experiment and the current best upper limit is $2.9 \times 10^{-26} e\text{cm}$. This limit implies the θ has an extremely small value: $\theta \leq 10^{-10}$. Peccei and Quinn introduced a global Peccei-Quinn symmetry $U_{PQ}(1)$ that is broken by

color anomaly and become spontaneously broken. So the term is rewritten as:

$$\left(\theta - \frac{\phi_A}{f_A}\right) \frac{g^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \quad (1.14)$$

Where the ϕ_A is the axion field and f_A is the axion decay constant. The minimum of ϕ_A is at $\phi_A = \theta f_A$, where the $\mathcal{L}_\theta$ term is canceled and CP symmetry is restored.

The connection between axion mass m_A and decay constant f_A is given based on the assumption that $m_A f_A \approx m_\pi f_\pi$ while $m_\pi = 135\text{MeV}$ and $f_\pi = 92\text{MeV}$. So the axion mass is given in term of F_A as:

$$m_A \approx 6eV \frac{10^6 \text{GeV}}{f_A} \quad (1.15)$$

The original proposed symmetry-breaking scale was about electro-weak scale $f_A \approx f_{EW}$ and corresponding axion mass was expected to be around a couple hundreds keV and coupling was strong enough to be generated in accelerator experiments. This energy scale was completely disfavored by the subsequent experimental measurements in the following years. However, the theories with new model were developed with arbitrarily large f_A , which leads to an extremely weak coupling and small axion mass. Interestingly, the extremely weak coupling renders the axion invisible feature in the detection aspect; while from the cosmological aspect, the small axion mass increases the the associated cosmological abundance. Therefore, the invisibility and large abundance make the axion-like particle a good candidate for the dark matter.

In the early universe, axion can be produced after the color confinement where the leading thermalization process is $\pi + \pi \leftrightarrow \pi + A$ [34]. But the resulting axion in this process only contributes as a hot dark matter component since the generated axion is of relativistic feature and is similar to the massive neutrinos. Another cosmological axion model is that after the Peccei-Quinn symmetry breaking at the scale f_A , the axion temperature is high compared to the effective potential so the axion field is still random until the temperature drops below the QCD scale,

when the axions fall into the wine-bottle-like potential well and acquire mass. Different mechanisms such as vacuum realignment, string decay and wall decay are suggested for the dominant mechanism to produce the non-relativistic axion and contributes as cold dark matter. In general, independent of the specific axion-generating model, the energy density of axion Σ_A is in the order of $(\frac{\mu\text{eV}}{m_A})^{\frac{7}{6}}$. So the cold dark matter fraction from the cosmological parameter $\Sigma_{\text{CDM}} \approx 0.22$, gives a rough lower limit on the axion mass on the order of $0.5 \mu\text{eV}$. The upper limit of axion mass is given by the combined results of supernova 1987a (SN 1987A) observation and accelerator research. The duration of SN 1987A is consistent with the hypothesis that the collapsed core is cooled solely by the emission of neutrinos, which rules out the axion mass from 10^{-3}eV to 2eV . The accelerator results excludes the axion mass above 2eV . So the combined upper limit for axion mass is 10^{-3}eV .

The coupling of axion to the other standard model particles are used in the direct detection experiments. For example, the axion coupling to two photons is:

$$\mathcal{L}_{A\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi} \frac{\phi_A}{f_A} \vec{E} \cdot \vec{B} \quad (1.16)$$

In the expression of coupling, $\vec{E}$ and $\vec{B}$ are the electric field and magnetic field, α is the fine structure constant. As footnote indicates, the factor g_γ is a model-dependent coefficient. Different models give the different values for g_γ : $g_\gamma = 0.36$ in DFSZ model [56] and $g_\gamma = -0.97$ in KSVZ model [73, 105]. The Lagrangian (1.16) gives a conversion from axion to two photons in external electric and magnetic field. Similarly in a Colomb field of a charged particle, the conversion is expected to happened and is usually viewed as scattering process: $\gamma + eZ \leftrightarrow eZ + A$, which is also called Primakoff effect [55].

The microwave cavity experiment for the axion detection tries to capture the microwave signals converted from the axions in a high-Q cavity permeated with an external strong magnetic field. Because the specific axion is unknown while it

corresponds to the

The Axion Dark Matter Experiment (ADMX) is an microwave cavity experiment dedicated to the detection of axions within the mass range 1-10 μeV [59]. Microwave signal is acquired by a coupled coaxial antenna on the top plate of the cavity. The entire microwave cavity is maintained at a temperature of 1.8K with a pumped liquid helium. Some significant improvements are expected to reach by using the low noise SQUID-based amplifier in the results of next generation detector.

CHAPTER 2

Dark Matter Detection

The earth-borne experiments of direct dark matter detection aim to capture the weak signals of interactions between dark matter particles and the regular matter. Current direct detection is limited by two critical factors: extremely small interaction cross-section renders the experiments ultra-low event rate; the expected signals from dark matter particles are very small and close to the detecting threshold.

In order to distinguish the dark matter signals from overwhelming background, direct dark matter detection experiments are located in the deep underground laboratories to shield the cosmic rays and induced backgrounds by the rock overburden. Other than the overburden shielding, second generation experiments of direct dark matter experiments also build veto tanks fulfilled with water or liquid scintillator to improve the detector shielding from the external background.

To enhance the detector response to the low energy signal that may be originated from dark matter particles, a large fraction of direct detection experiments simultaneously collect two different kinds of signals from a single energy deposit. By utilizing the Photo-multiplier Tube (PMT) in detecting the scintillation signal from energy deposits,

2.1 Direct Dark Matter Detection Experiments

2.1.1 Introduction to the Working Principles of Dual-phase Time Projection Chamber (TPC)

A dual-phase TPC detector as name indicates, consists of target medium in two different phases: liquid and gas. In the direct dark matter detection experiments, noble elements such as xenon and argon are employed as target medium in order to obtain a good transparency for light transmission and a high purity which makes the electrons drift in liquid possible. Since liquid volume has a much larger number density compared to the gas volume, it is used as target volume to capture the detecting particles. The detecting particles can be either charged of which the interactions will be electronic recoils or neutral of which the interactions will be nuclear recoils as Figure 2.1 shows.

The active volume of TPC is defined between cathode and anode that are made up of transparent metal grids (blue dashed lines in Figure 2.1); above anode grid and beneath cathode grid, two PMT arrays are photon sensors used to detect signals; different voltage may be applied to anode and cathode. Without an additional grid between anode the top PMT array, the voltage of anode grid has to set to be the same as the PMT bodies in order to not bring any field disturbances to PMTs.

There is another metal grid located right below the liquid-gas interface, this grid which is called extraction grid, separates the TPC active volume into two sections and electric field in each section can be adjusted by varying the relative voltage difference. Similar to the case of protecting top PMT array from any potential field disturbance, there is another metal grid beneath cathode grid and right above the bottom PMT array, the voltage on this grid is set to the same as the bottom PMT bodies in order to protect those PMTs from the strong electric field induced by high voltage on cathode.

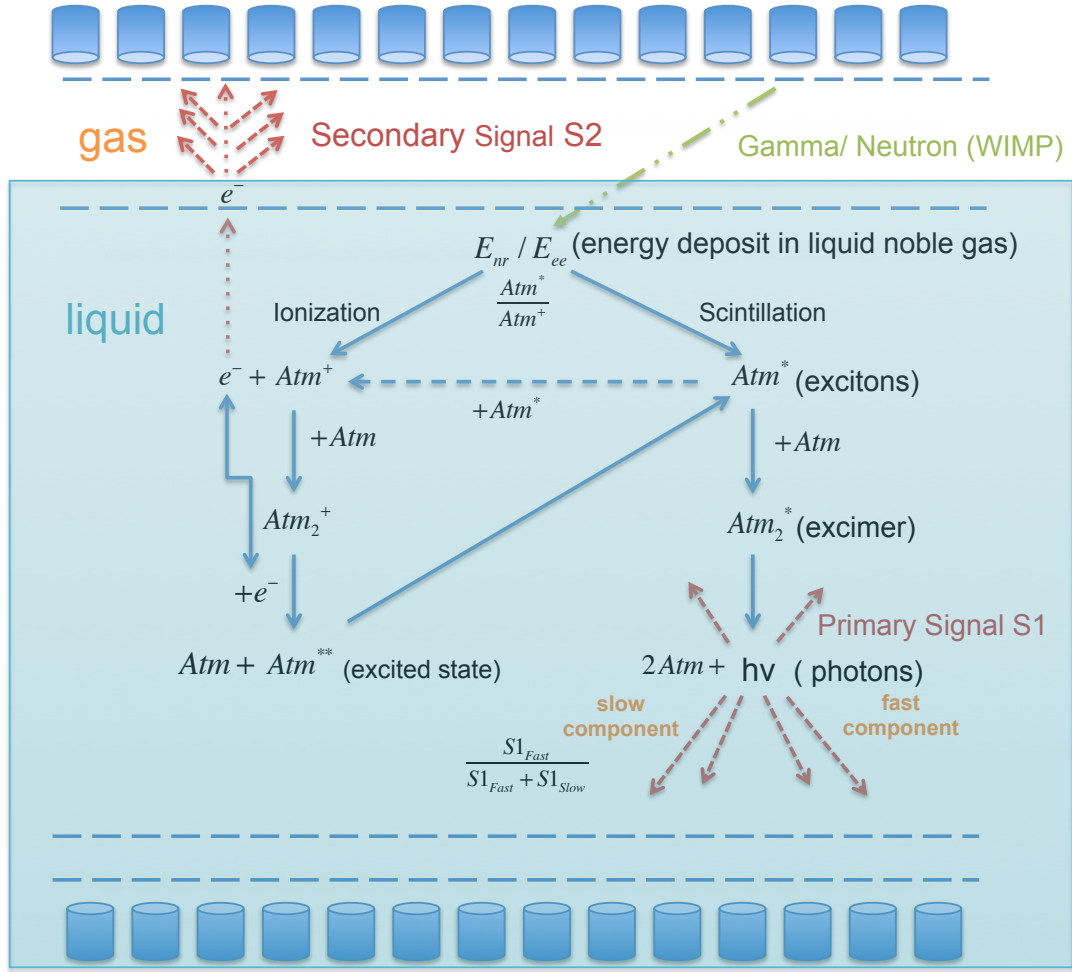


Figure 2.1: A 2D toy model to demonstrate the working principles of dual-phase TPC. Those dashed lines represent 3D grids or meshes. Photon sensors are represented by blue cylinders at top and bottom.

Once energy deposits in the active volume, a certain fraction of energy by ionization channel, ionizes medium atoms and create free electrons; while the other fraction of energy by scintillation channel, create medium atoms at excited states. Details of the following mechanism is quantitatively described in Chapter 3. When all excited atoms de-excite within a few nanoseconds, they emit photons at certain wavelength depending on the specific medium and this signal as a collection of photons is the primary signal, which is also called S1. The external electric field

between cathode grid and extraction grid drifts all the electrons escaped from recombination up all the way to the extraction grid. In the section between anode grid and extraction grid, there is another much stronger electric field. This field first extracts drift electrons through the extraction grid, a dedicated study on this process is given in Chapter 5.2. By taking the advantage of a field ratio between liquid and gas phase given by different dielectric constant, electrons are extracted into gas phase and constantly accelerating until collected at the anode grid. During this acceleration process in gas phase, another signal is emitted as a collection of photons created when electrons are accelerated. This signal created in gas phase as a secondary signal is also called S2. This signal collected by PMT arrays, has certain patterns corresponding to its geometrical positions. So by analyzing the hit pattern on PMT arrays, the location where electrons are extracted into gas phase can be determined. Moreover, using the time difference between the primary signal S1 and secondary signal S2, the position along z-axis where the interaction occurs can be determined by considering the electron drift velocity in liquid. Therefore, This process gives dual-phase TPC a unique feature of knowing 3D position where interaction occurs. Moreover, each noble element has its own additional discriminating feature originated from its physical properties. All these features are discussed in Chapter 3.

2.1.2 XENON1T Dual-phase Liquid Xenon Detector

As a part of XENON program for direct dark matter detection, XENON1T is the next-generation dual-phase liquid xenon dark matter detector [19, 31, 30]. XENON1T is currently under extensive construction in Hall B of Laboratori Nazionali del Gran Sasso (LNGS) in Italy. XENON1T is designed to be equipped with a factor of 10 larger fiducial volume and a factor of 100 reduction on background compared to XENON100 [31].

To reach the first goal, about 3.3 tons liquid xenon will be used and 2 tons will constitute the fiducial volume. For the purpose of background reduction, multiple state of the art techniques are employed. Because the radioactive contamination from PMTs has been the major background source in the current detectors, XENON1T will use new low radioactive background 3-inch PMTs R11410-21 developed by Hamamatsu to effectively reduce the PMT contribution to overall background; all 248 PMTs are expected to give background about 0.25 event per year. A larger volume of liquid xenon surrounding the active region will render fiducial volume a better self shielding; a larger fiducial volume will provide a better resolution for multiple scattering tagging. A more powerful distillation system is developed to reduce the Kr background level below $\text{Kr/Xe} < 0.1$ ppt; with Kr at this level, the intrinsic background from $^{83}\text{Kr}^m$ in liquid xenon is estimated to give background around 0.15 event per year. More systematic selection of low radioactive materials to use will render the TPC a lower level of overall background.

In addition to these improvements, TPC will be installed inside a water tank with a 4π coverage with 84 PMTs, this water tank will effectively shield the TPC from ambient background. To capture Cerenkov signals from muons, this water tank is also used as muon veto to tag and remove muon-induced backgrounds.

The water tank shown in Figure 2.3, holds 700 tons high-purity water and is



Figure 2.2: XENON1T water tank and associated facilities. The cryogenic and circulation system and connection to the TPC through water tank is on the third floor; all the electronics such as data acquisition system will be on the second floor; xenon storage is on the ground floor. This picture is taken by P. DePerio from Columbia University.

used as an active muon veto. In GEANT4 simulation, this muon veto has a 99% efficiency in tagging crossing muon a 74% efficiency in tagging showering events.



Figure 2.3: A 3D drawing of XENON1T TPC inside the water tank. The connection to the TPC through a port is from the adjacent service building, which is shown in the Figure 2.2.

With this muon veto, the total background expected from cosmic rays is around 0.01 event per year [24].

A field picture of XENON1T including the water tank and service building is shown in Figure 2.2. The TPC is located inside the water tank as Figure 2.3 indicates. A cross-section view of the TPC can be found in Figure 2.4. There are 127 3-inch PMTs on the top array and 121 PMTs on the bottom array. These newly-developed PMTs are characterized by a high quantum efficiency larger than 35% at 178 nm xenon scintillation wavelength. Detailed introduction on TPC dimensions can be found in Section 5. The active liquid xenon region is completely covered by an excellent reflector in ultra-violet wavelength Polytetrafluoroethylene

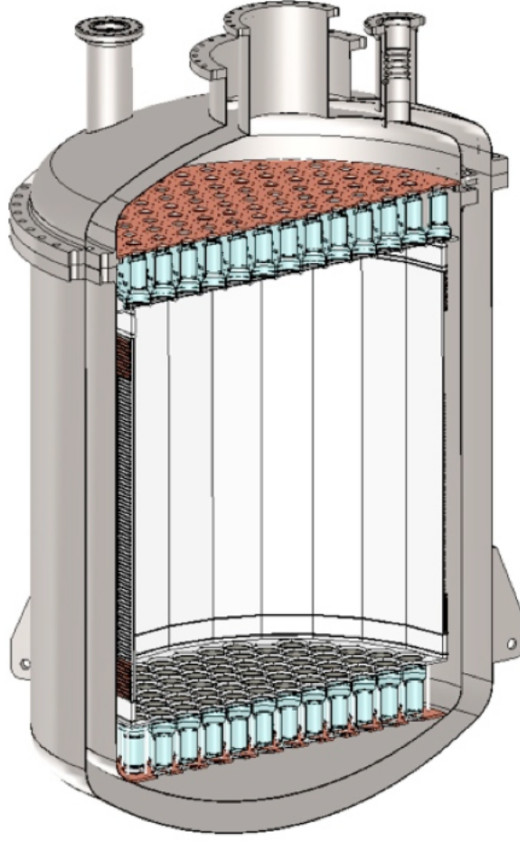


Figure 2.4: This is a cross-section view of 3D XENON1T TPC. Detailed introduction can be founded in this section. This figure is from [19].

(PTFE), of which the good connectivity has been well proven. Compared to the current running XENON100 detector, a better reflector coverage combining with a higher averaged PMT quantum efficiency is expected to render XENON1T TPC a higher light yield.

XENON1T sensitivity to electro-weak scale WIMP particles is estimated based on a few assumption: the background level is $6 \times 10^{-5} \text{event/day/kg/keV}_{ee}$; a two years live time from 2015 to 2017 is assumed as marked on Figure 2.5; a rejection power of 99.5% on electronic recoils is obtained as XENON100; a one-ton fiducial volume is used; nuclear recoil search window is set to between 5 to 50 keV_{nr} ; the acceptance of nuclear recoils in the search window is a constant value 50%.

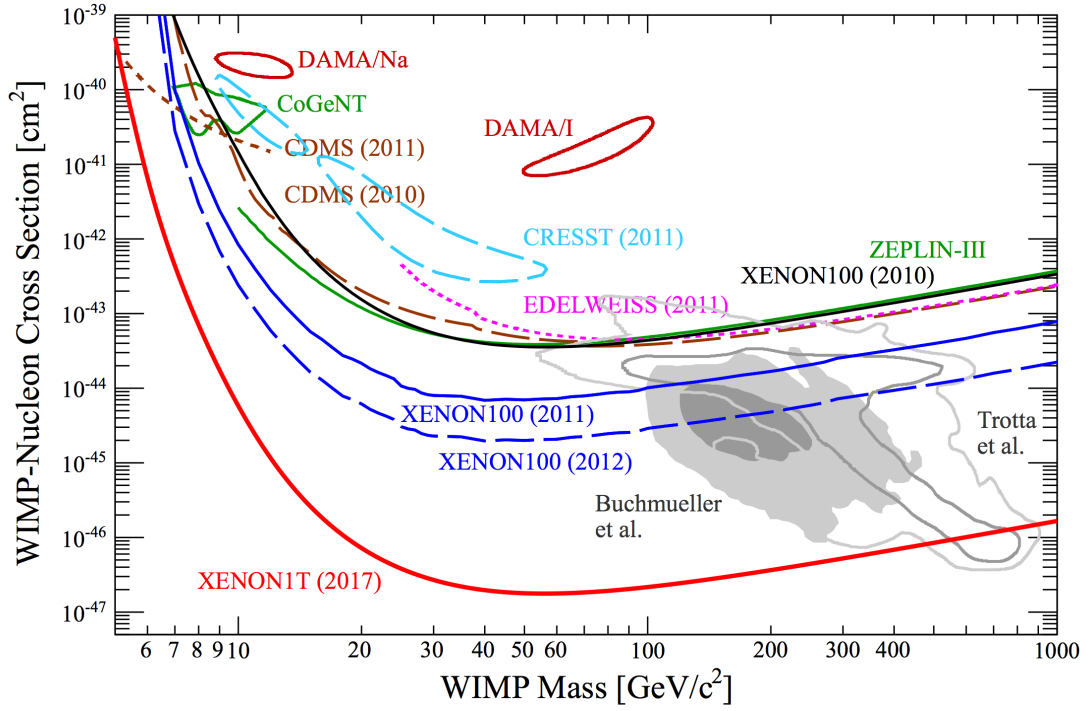


Figure 2.5: This is a projected sensitivity of XENON1T detector using 1 ton fiducial volume. The current design has upgraded the fiducial volume up to 2 tons. This figure is from [19].

The projected result is shown in Figure 2.5. So the two-years running with 5 to 50 keV_{nr} search is expected to completely exploit most of the cross-section area favored by different theoretical predictions.

2.1.3 DarkSide-50 Dual-phase Liquid Argon Detector

DarkSide-50 is a world leading direct dark matter detection experiment using dual-phase liquid argon detector. DarkSide-50 is located in the underground Laboratori Nazionali del Gran Sasso (LNGS), similar to XENON1T detector. The full DarkSide-50 detector as Figure 2.6 shows, consists of three parts: a Water Cherenkov Detector (WCD), a Liquid Scintillator Veto (LSV) and TPC [9].

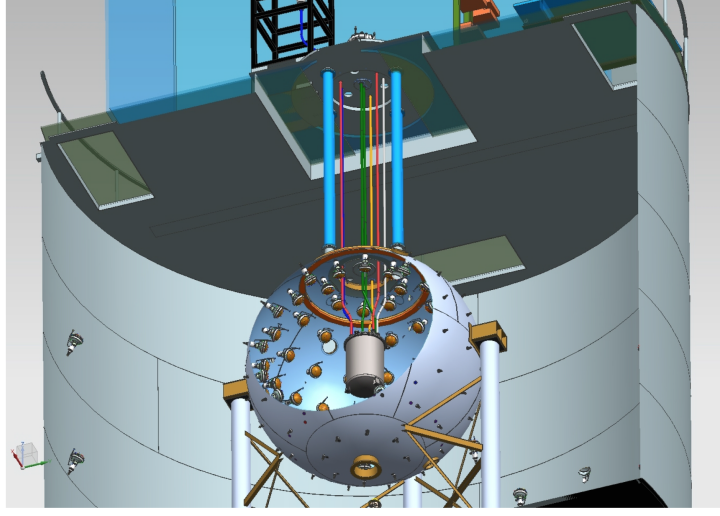


Figure 2.6: An overall view of DarkSide-50 detector. The DarkSide-50 detector includes three parts and details are given in this section. This figure is from [9].

The WCD is an 11 meter diameter by 10 meter high cylindrical tank filled with high purity water. A total of 80 ETL 9351 8-inch PMTs with an average 24 % quantum efficiency are mounted on the tank surface to form a 4π coverage. This tank was originally the Counting Test Facility used in Borexino experiment. WCD serves as a muon veto to reduce the muon-induced backgrounds by anti-coincidence; it also serves as a passive shielding for the ambient backgrounds from the rocks in LNGS, similar to the water tank used in XENON1T detector.

Inside the WCD, there is a 4 meter diameter stainless steel sphere LSV filled with 30 tons of borated liquid scintillator. Liquid scintillator is viewed by an array of

110 Hamamatsu R5912 8-inch PMTs with low radioactivity backgrounds and high quantum efficiency; all the 8-inch PMTs are pointing to the TPC in the center as what Figure 2.6 shows. The surface inside this sphere is covered by reflecting foils to enhance the light yield in liquid scintillator. By taking an advantage of a large neutron capture cross-section of ^{10}B , LSV is an active neutron veto for any potential neutron backgrounds in TPC.

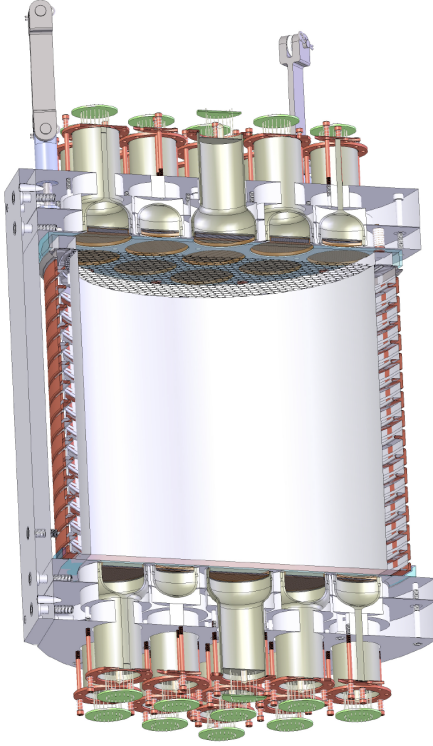


Figure 2.7: A cut-away view of DarkSide-50 TPC. The working principles are similar to the other dual-phase liquid noble detector such as XENON1T TPC show in in Figure 2.4. This figure is from [9].

The TPC stainless steel insulation dewar is in the center of LSV as shown Figure 2.6, a cross-section view of the TPC assembly can be found in Figure 2.7. An active liquid argon (LAr) cylindrical regions is surrounded by PTFE which is a good reflector over a wide range of wavelength. Two arrays of 3-inch R11065 PMTs are on the top and bottom of TPC submerged in TPC. PMT arrays are separated

from TPC active region by two fused-silica windows. The principles of dual-phase liquid noble element TPC is described in details in Section 2.1.1. But instead of using metal grids as electrodes, transparent and conductive layers of indium-tin-oxide (ITO) are coated on both sides of both fused-silica windows: ITO layer on the side facing PMT arrays are set to the same voltage as PMT bodies to protect PMT; ITO layer on the other side are used as anode and cathode respectively.

Associated properties of physical interactions are discussed in Section 3. A unique feature of scintillation signals from argon atoms is the ultra-violet wavelength at 128 nm; photons at this wavelength can not pass through the regular PMT quartz windows. So all the surface of PTFE that may reflect the photons, are coated with a wavelength shifter, tetraphenyl butadiene (TPB). TPB will absorb 128 nm photons first then re-emit them at wavelength of visible light, acting like a wavelength shifter. On the top of anode and cathode ITO layer, TPB is also coated as an additional layer.

A key feature of dual-phase liquid argon detector is the different ratios of fast and slow components between nuclear and electronic recoils in scintillation signals. This difference in scintillation signals is quantitatively described by a parameter F90; more quantitative description of this feature is given in Section 3.3. This feature plays an important role in the discrimination against backgrounds as Figure 2.8 demonstrates: a large population of backgrounds mainly constituted by various electronic recoils with F90 value centered around 0.3, are spread along a wide range of energy. They are mainly coming from the ^{39}Ar beta decay.

However, on top of the electronic recoil band, where nuclear recoil band is expected to be, it is clean and free of any event detected during the DarkSide-50 dark matter runs in [9]. The specific nuclear recoil band used in the dark matter detection campaign is indicated as the blue area in Figure 2.8. It indicates that there is no neutral neutron-like interaction found during this measurement period. To convert this measurement into scientific result as reported in Figure 2.9, a

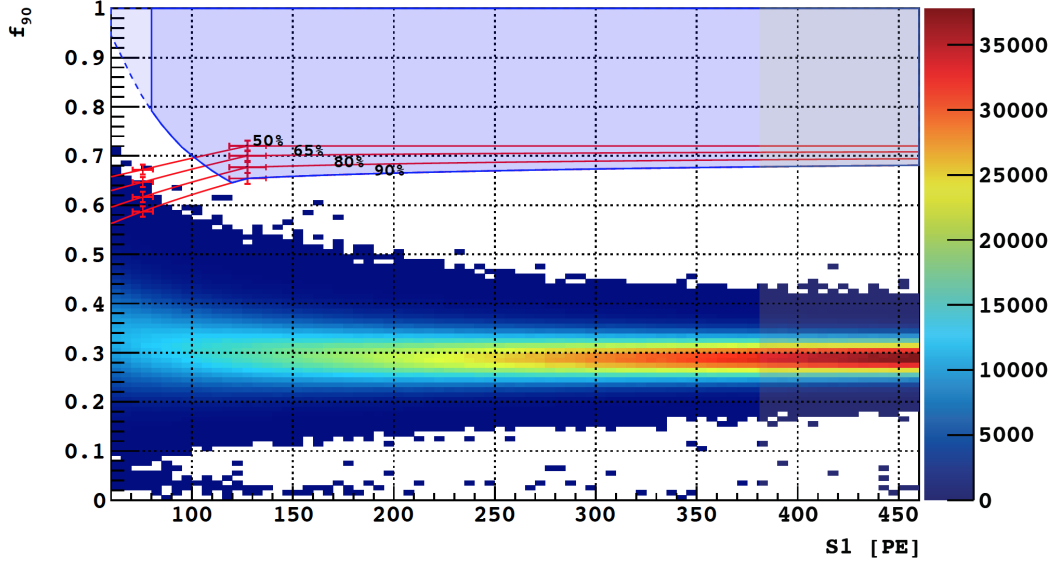


Figure 2.8: Discrimination against electronic recoil backgrounds using F90 in DarkSide-50 result. The nuclear recoil acceptance as a function of nuclear recoils is also in shown. This figure is from [9].

precise energy scale for nuclear recoils in liquid argon is needed. A comprehensive discussion regarding the energy scale in liquid noble elements including xenon and argon, can be found in Section 3.4.

An independent experiment dedicated to measure the nuclear recoils and associated properties in LAr is given in length in Section 4. The results from this measurement are used in defining the nuclear recoil energy scale and acceptance in Figure 2.8. DarkSide-50 result presented in Figure 2.9, is given based on a background null event found measurement result over 1422 ± 67 kg day exposure.

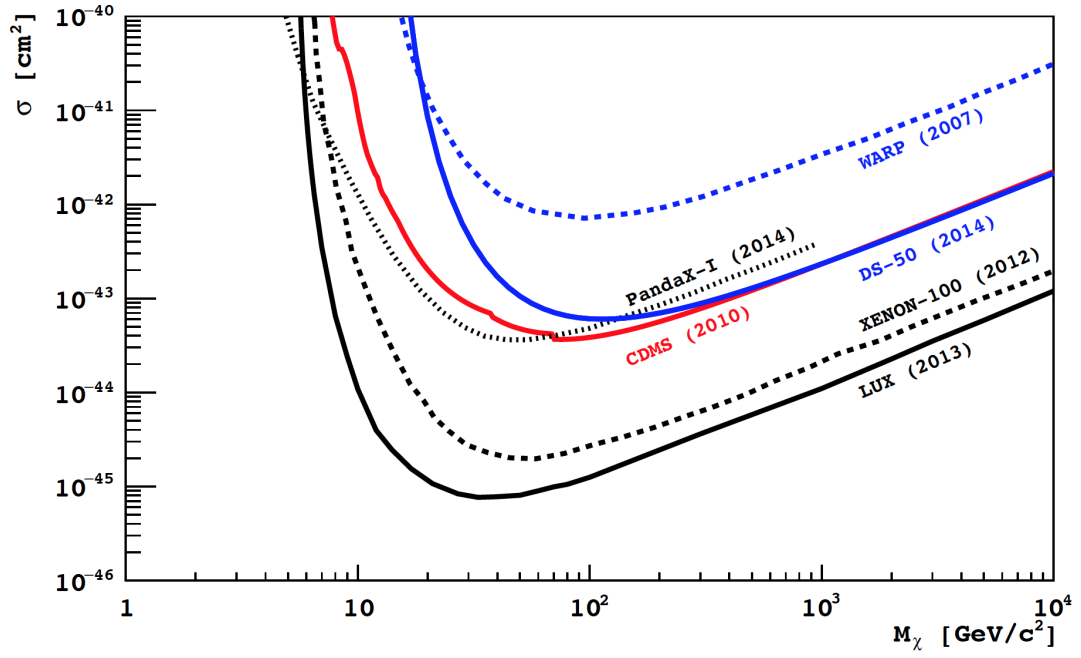


Figure 2.9: Sensitivity result from the first DarkSide-50 dark matter detection measurement in 2014. The results from other experiments are compared with it. This figure is from [9].

2.2 Dark Matter Signal from Direct Detection

All the direct dark matter detection experiments aim to explicitly identify the signals from the interaction between dark matter particles and the regular baryonic atoms. Since the information of this interaction requires the knowledge of the particles constituting dark matter, A generic elastic scattering is assumed between the detecting target nucleus and dark matter particles. A general cross-section on the weak-interaction scale is used to describe the scattering possibility. A second parameter related with dark matter particle is the mass. Other than the intrinsic properties of dark matter particles, cosmological parameters including the local dark matter density and associated velocity distribution, are also used in estimating the dark matter signal from direct detection experiments.

2.2.1 Dark Matter Event Rate Based on Local Velocity Distribution

Using the generic assumption that a nuclear recoil happens between dark matter candidate and target nucleus, The potential WIMP-nucleon cross-section is calculated. An generic cross-section expression for $\sigma_{\chi-n}$ is:

$$dR = \frac{N_0}{A} \sigma_A \nu dn \quad (2.1)$$

where N_0 is the Avogadro number ($6.02 \times 10^{26} \text{ kg}^{-1}$) and A is the target nucleus atomic number, while n is number density of dark matter as shown before. The σ_A used from this expression is cross-section per nucleus. R on the left hand side is interaction rate that dark matter particle collides with a target of 1 kg target mass, unit for this rate is $\text{kg}^{-1}\text{s}^{-1}$. To integrate event rate function over the dark matter velocity ν :

$$R = \frac{N_0}{A} \sigma_A \int \nu dn = \frac{N_0}{A} \sigma_A n_0 \langle \nu \rangle \quad (2.2)$$

The total event rate is calculated by using different various dark matter velocity

:

- Using the ideal assumption that $\nu_E = 0$ and $\nu_{esc} = +\infty$, the dark matter number density distribution is:

$$f(\nu) = e^{-\nu^2/\nu_0^2} \quad (2.3)$$

then plug this distribution function $f(\nu)$ into event rate function R is defined as:

$$R = R_0 = \frac{2}{\sqrt{\pi}} \frac{N_0}{A} n_0 \sigma_A \nu_0 \quad (2.4)$$

When R_0 adapts unit $\text{kg}^{-1}\text{day}^{-1}$, in [79] it's named as total rate unit (TRU).

Normalized to $\rho_{DM} = 0.4\text{GeVc}^2$ and $\nu_0 = 230\text{kms}^{-1}$, R_0 becomes:

$$R_0 = \frac{540}{AM_{DM}} \left(\frac{\sigma_A}{1\text{pb}} \right) \left(\frac{\rho_{DM}}{0.4\text{GeVc}^{-2}\text{cm}^{-3}} \right) \left(\frac{\nu_0}{230\text{kms}^{-1}} \right) \quad (2.5)$$

In second expression of R_0 , unit of the target nucleus A , is converted from atomic mass unit to GeVc^{-2} ($M_T = 0.932A$).

Moreover, to replace Avogadro number and cross-section σ_a with R_0 in R expression, it can be also written as:

$$\frac{R}{R_0} = \frac{\sqrt{\pi}}{2} \frac{\langle \nu \rangle}{\nu_0} \quad (2.6)$$

- if expression of dark matter particle number density $dn = \frac{n_0}{k} f(\nu, \nu_E) d^3\nu$ from last section is used, in which the expression of dn is using practical expression of ν_E and finite ν_{esc} :

$$dR = R_0 \frac{k_0}{k} \frac{1}{2\pi\nu_0^4} \nu f(\nu, \nu_E) d^3\nu \quad (2.7)$$

where $k_0 = (\pi\nu_0^2)^{3/2}$ is used. Based this expression of dark matter even rate, specific dark matter experiment can obtain the total dark matter event number within various energy rang by integrating the variable ν . Within various integration intervals, event rates are calculated as followed:

$$\frac{R(0, \nu_{esc})}{R_0} = \frac{k_0}{k_1} [1 - (1 + \frac{\nu_{esc}^2}{\nu_0^2}) e^{-\nu_{esc}^2/\nu_0^2}] \quad (2.8)$$

$$\frac{R(\nu_E, \infty)}{R_0} = \frac{1}{2} [\sqrt{\pi} (\frac{\nu_E}{\nu_0} + \frac{1}{2} \frac{\nu_0}{\nu_E}) \text{erf}(\frac{\nu_E}{\nu_0}) + e^{-\nu_E^2/\nu_0^2}] \quad (2.9)$$

$$\frac{R(\nu_E, \nu_{esc})}{R_0} = \frac{k_0}{k_1} [\frac{R(\nu_E, \infty)}{R_0} - (1 + \frac{1}{3} \frac{\nu_E^2}{\nu_0^2} + \frac{\nu_{esc}^2}{\nu_0^2}) e^{-\nu_{esc}^2/\nu_0^2}] \quad (2.10)$$

2.2.2 Nuclear Form Factor

When the nuclear recoil energy is large enough, the term $\frac{\hbar}{q}$ may be no longer large compared to the nuclear radius, where q is defined as the momentum transfer $q = 2M_T E_R^{1/2}$. In this situation there is a need for the nuclear form factor correction. This correction describes a reduction of cross-section with the increasing of q . This is because the effective nuclear structure depends on specific the momentum transfer. Even in the spin-dependent scattering (SD), where interaction only involves with dark matter particle and single nucleon, this effect is still significant to target with large atomic mass. With the correction added, cross-section is re-written separately as:

$$\sigma(qr_n) = \sigma_0 F^2(qr_n) \quad (2.11)$$

where the σ_0 is the cross-section at zero momentum transfer. σ_0 contains all the factors related to the specific interaction, while $F(qr_n)$ corresponds to momentum transfer.

In the first Born (plane wave) approximation, the form factor is the Fourier

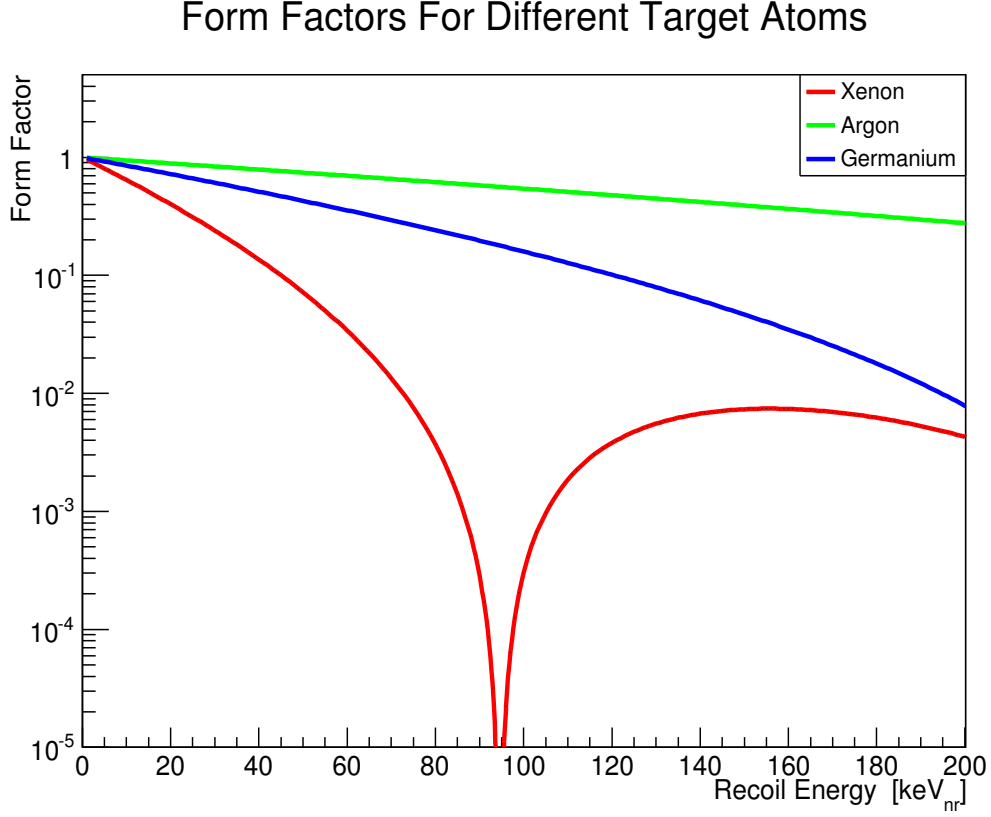


Figure 2.10: This figure shows a comparison of form factors of different target materials. Similar to the comparison of differential dark matter event rate, only three major elements Xe, Ar and Ge that have been widely employed as dark matter detection medium, are used to compare.

transform of $\rho(r)$, the density distribution of scattering centers.

$$F(q) = \int \rho(r) e^{iqr} d^3r \quad (2.12)$$

$$= \int_0^{2\pi} d\phi \int_r r^2 \rho(r) \int_{-1}^1 e^{iqr \cos \theta} d(\cos) dr \quad (2.13)$$

$$= \frac{4\pi}{q} \int_0^\infty r \sin qr \rho(r) dr \quad (2.14)$$

As for the spin-dependent interaction, the outer shell single nucleon is approximated by a thin shell.

thin shell:

$$F(qr_n) = j_0(qr_n) = \frac{\sin(qr_n)}{qr_n} \quad (2.15)$$

While the spin-independent is approximated by a solid sphere and interact with the entire nucleus. The Helm form factor is given by:

$$a = 0.52 fm \quad (2.16)$$

$$s = 0.9 fm \quad (2.17)$$

$$c = 1.23A^{1/3} - 0.6 fm \quad (2.18)$$

$$r_n^2 = c^2 + \frac{7}{3}\pi^2 a^2 - 5s^2 \quad (2.19)$$

$$F(qr_n) = 3 \frac{j_1(qr_n)}{qr_n} e^{-(qs)^2/2} \quad (2.20)$$

$$= \frac{3[\sin(qr_n) - qr_n \cos(qr_n)]}{qr_n^3} e^{-(qs)^2/2} \quad (2.21)$$

2.2.3 Event Rate as function of Nuclear Recoil Energy

The event rate calculated as function as dark matter particle velocity implicitly contains nuclear recoil as variable, since nuclear recoil energy from a dark matter particle with kinetic energy $E = \frac{1}{2}M_D\nu^2$, scattered at the angle of θ is:

$$E_R = \frac{1}{2}Er(1 - \cos\theta) \quad (2.22)$$

where

$$r = 4 \frac{M_D M_T}{(M_T + M_D)^2} \quad (2.23)$$

Assuming the scattering with target atom is isotropic so that the recoils are uniformly distributed regarding to $\cos\theta$. Therefore for a given recoil energy E_R , the kinetic energy range of colliding dark matter particle is between Er and ∞ . To explicitly write event rate as function of recoil energy, the event rate function

R is integrated over the dark matter particle kinetic energy range for a given recoil energy.

$$\frac{dR}{dE_R} = \int_{E_{min}}^{E_{max}} \frac{1}{Er} dR(E) \quad (2.24)$$

$$= \frac{1}{E_0 r} \int_{\nu_{min}}^{\nu_{max}} \frac{\nu_0^2}{\nu^2} dR(\nu) \quad (2.25)$$

Since $E_{min} = \frac{E_R}{r}$ and $E_0 = \frac{\nu_0^2}{\nu^2} E$, the integration lower limit ν_{min} is written as:

$$\nu_{min} = \left(\frac{E_R}{E_0 r} \right)^{\frac{1}{2}} \nu_0 \quad (2.26)$$

we have:

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi\nu_0^2} \int_{\nu_{min}}^{\nu_{max}} \frac{1}{\nu} f(\nu, \nu_E) d^3\nu \quad (2.27)$$

Following the same procedure, various approximation is employed and associated results are:

- using dark matter particle Boltzmann velocity distribution with assumption of $\nu_E = 0$, the integrating with ∞ as upper limit, the dark matter detecting event rate as function of nuclear recoil energy is obtained as:

$$\frac{dR(0, \infty)}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r} \quad (2.28)$$

- With finite ν_{esc} taken into consideration while ν_E is treated as zero, the event rate integration result is:

$$\frac{R(0, \nu_{esc})}{E_R} = \frac{k_0}{k_1} \frac{R_0}{E_0 r} (e^{E_R/E_0 r} - e^{-\nu_{esc}^2/\nu_0^2}) \quad (2.29)$$

$$= \frac{k_0}{k_1} \left[\frac{dR(0, \infty)}{dE_R} - \frac{R_0}{E_0 r} e^{-\nu_{esc}^2/\nu_0^2} \right] \quad (2.30)$$

$$(2.31)$$

- with non-zero nu_E and using ∞ as integration upper limit:

$$\frac{dR(\nu_E, \infty)}{dE_R} = \frac{R_0}{E_0 r} \frac{\pi^{1/2}}{4} \frac{\nu_0}{\nu_E} [erf(\frac{\nu_{min} + nu_E}{\nu_0}) - erf(\frac{\nu_{min} - nu_E}{\nu_0})] \quad (2.32)$$

- finally taking both earth velocity ν_E and Milky Way galaxy escaping velocity ν_{esc} into consideration:

$$\frac{dR(\nu_E, \nu_{esc})}{dE_R} = \frac{k_0}{k_1} [\frac{dR(\nu_E, \infty)}{dE_R} - \frac{R_0}{E_0 r} e^{-\nu_{esc}^2/\nu_0}] \quad (2.33)$$

The k_1 mentioned above is:

$$k_1 = k_0 [erf(\frac{\nu_{esc}}{\nu_0}) - \frac{2}{\pi^{1/2}} \frac{\nu_{esc}}{\nu_0} e^{-\nu_{esc}^2/\nu_0^2}] \quad (2.34)$$

In the practical situation of experimental measurements, elastic scatterings of dark matter particles in the detector generate signals within a finite energy range, or total above some minimum energy because of the background limits. In most cases, $\frac{dR(\nu_E, \infty)}{dE_R}$ is well approximated by:

$$\frac{dR(\nu_E, \infty)}{dE_R} = c_1 \frac{R_0}{E_0 r} e^{-c_2 E_R/E_0 r} \quad (2.35)$$

where c_1 and c_2 are fitting constants. Values of c_1 and c_2 are slightly different because of monthly modulation. Moreover, c_1 and c_2 are not independent and the connection can be found by the integration as followed:

$$\frac{c_1}{c_2} = \frac{R(\nu_E, \infty)}{R_0} \quad (2.36)$$

For most purposes, it is sufficient to take the fixed value for $c_1 = 0.751$ and $c_2 = 0.561$ respectively. So within the given energy range (E_1, E_2) , the integrated event rate is in the form of:

$$R(E_1, E_2) = R_0 \frac{c_1}{c_2} [e^{-c_2 E_1/E_0 r} - e^{-c_2 E_2/E_0 r}] \quad (2.37)$$

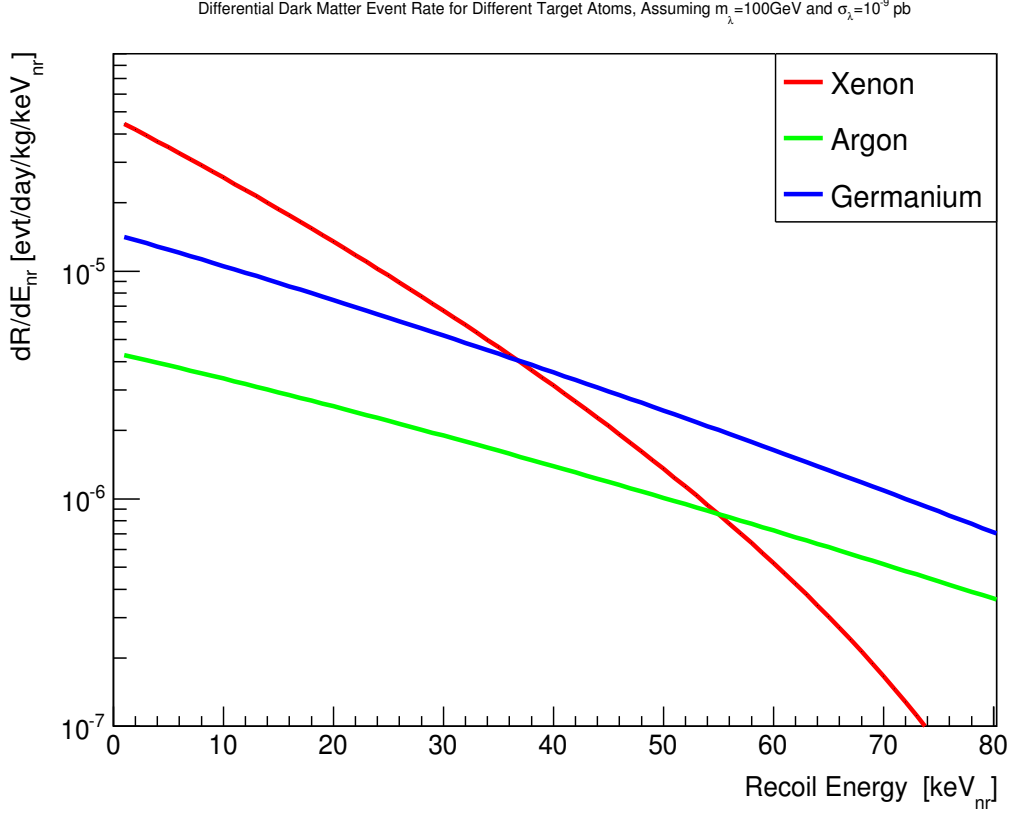


Figure 2.11: This figure shows a comparison of differential dark matter event rate on different target materials. Three major elements Xe, Ar and Ge that have been widely employed as dark matter detection medium, are used to compare. The total event rate over certain energy region determined by individual experiment, can be estimated by integrating the differential event rate function over the corresponding energy region.

2.2.4 Conversion from WIMP-Nucleus Cross-section to WIMP-Nucleon Cross-section

In the exploration of dark matter detection, various materials as the experimental targets are involved in the detection. In order to standardize the expression of dark matter detecting result and to provide the directive comparison among various experiment results, only the limits on WIMP-nucleon cross-section $\sigma_{\chi-n}$

is presented as the final results. To convert the experiment measurement WIMP-nucleus cross-section to the standard $\sigma_{\chi-n}$, there are tow factors needed to be considered in this process.

- coherent factor

During the process of nuclear recoil, the potential dark matter particle collides with a certain nucleus and this recoil deposits energy to this target nucleus. This process, the nucleus which contains A nucleons (in this step, proton and neutron are treated the same) actually has a coherent enhancement that increase the cross-section by a factor of A^2 . This enhancement applies for all types of nucleus.

- reduce mass factor

A cross-section for exchange of single particle M with vertex coupling g_1 and g_2 is given by a general expression:

$$\frac{\sigma}{\mu^2} = C\left(\frac{g_1^2 g_2^2}{M^4}\right) \quad (2.38)$$

Where $C\left(\frac{g_1^2 g_2^2}{M^4}\right)$ is used to indicate a parameter as a function of g_1, g_2 and M . When the interaction type is certain, function C can be treated as a constant in the above expression. So the conversion comes to:

$$\frac{\sigma_A}{\nu_A^2} = \frac{\sigma_1}{\nu_1^2} \quad (2.39)$$

Therefore, by combining the two factors discussed above the conversion is given as:

$$\sigma_{\chi-n} = \frac{\mu_1^2}{\mu_A^2} \frac{1}{A^2} \sigma_A \quad (2.40)$$

2.2.5 Annual Modulation

Considering the practical situation, motion of solar system through the Galaxy is at the velocity around 230 kms^{-1} , which largely determined the event rate. However, Earth is orbiting around the Sun $\pm 15 \text{ kms}^{-1}$ with respect to motion of solar system. Therefore, the fluctuation of velocity shows up as the annual modulation. So for practical purpose,

$$\nu_E = 244 + 15 \sin(2\pi y) \text{ kms}^{-1} \quad (2.41)$$

Noting that, there is a uncertainty by about 20 kms^{-1} of mean level, and the modulation amplitude has negligible uncertainty. However, inferred from above expression, the modulation about 6% gives rise to a 3% around modulation in rate.

Annual modulation contributes as another predicted evidence for existence of dark matter, if dark matter isotropically exists in the galactic halo. The event rate of dark matter is expected to fluctuate with the earth rotating in solar system, in contrast to the background events generated by the local environment, where no annual modulation seldom affects event rate.

2.2.6 Spin-dependent Cross-section

The WIMP Spin-dependent cross-section arises from the WIMP coupling to the quark axial current. The total WIMP-nucleus elastic scattering cross-section at zero-momentum transfer is described as:

$$\sigma_0 = 4G_F^2 \mu_A^2 C_A \quad (2.42)$$

where the μ_A is the WIMP-target reduced mass, given by $M_D M_A / (M_D + M_A)$ in the center-momentum frame. G_F is the Fermi coupling constant, with the value

of $G_F/(\hbar c)^3 = 1.166 \text{GeV} c^{-2}$. C_A is a dimensionless number which carries all the particle physics model related information. Spin-dependent interaction and the spin-independent one holds their own numerical expression respectively. In the spin-independent case, the C_A simply takes the form:

$$C_A = \frac{1}{\pi G_F^2} [Z f_p + (A - Z) f_n]^2 \quad (2.43)$$

in which the f_p and f_n are effective WIMP-neutron and WIMP-proton coupling constants. In most instances, $f_p \approx f_n$, so C_A has the form:

$$C_{SI} = \frac{1}{\pi G_F^2} (A f_p)^2 \quad (2.44)$$

With the usage of WIMP-proton cross-section defined in σ_p as reference, cross-section limits from practical experiment is compared with it. It can be seen that the WIMP-nucleus cross-section is proportional to the A^2 . Thus, it pays to use a high atomic mass target such as Xenon, since event rate will be enhanced by a factor of A^2 .

As for the spin-dependent cross-section, the C_A is:

$$C_A = 8/\pi \Lambda^2 J(J+1) \quad (2.45)$$

where

$$\Lambda = (1/J)[a_p \langle S_p \rangle + a_n \langle S_n \rangle] \quad (2.46)$$

a_p and a_n are the effective WIMP-proton and WIMP-neutron coupling constants, and $\langle S_p \rangle$ $\langle S_n \rangle$ are expectation value of proton and neutron spins in the nucleus. J is the total nuclear spin. So substitutes the Λ in cross-section with the expression above:

$$\sigma_A = \frac{32}{\pi} G_F^2 \mu_A^2 (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2 \frac{J+1}{J} \quad (2.47)$$

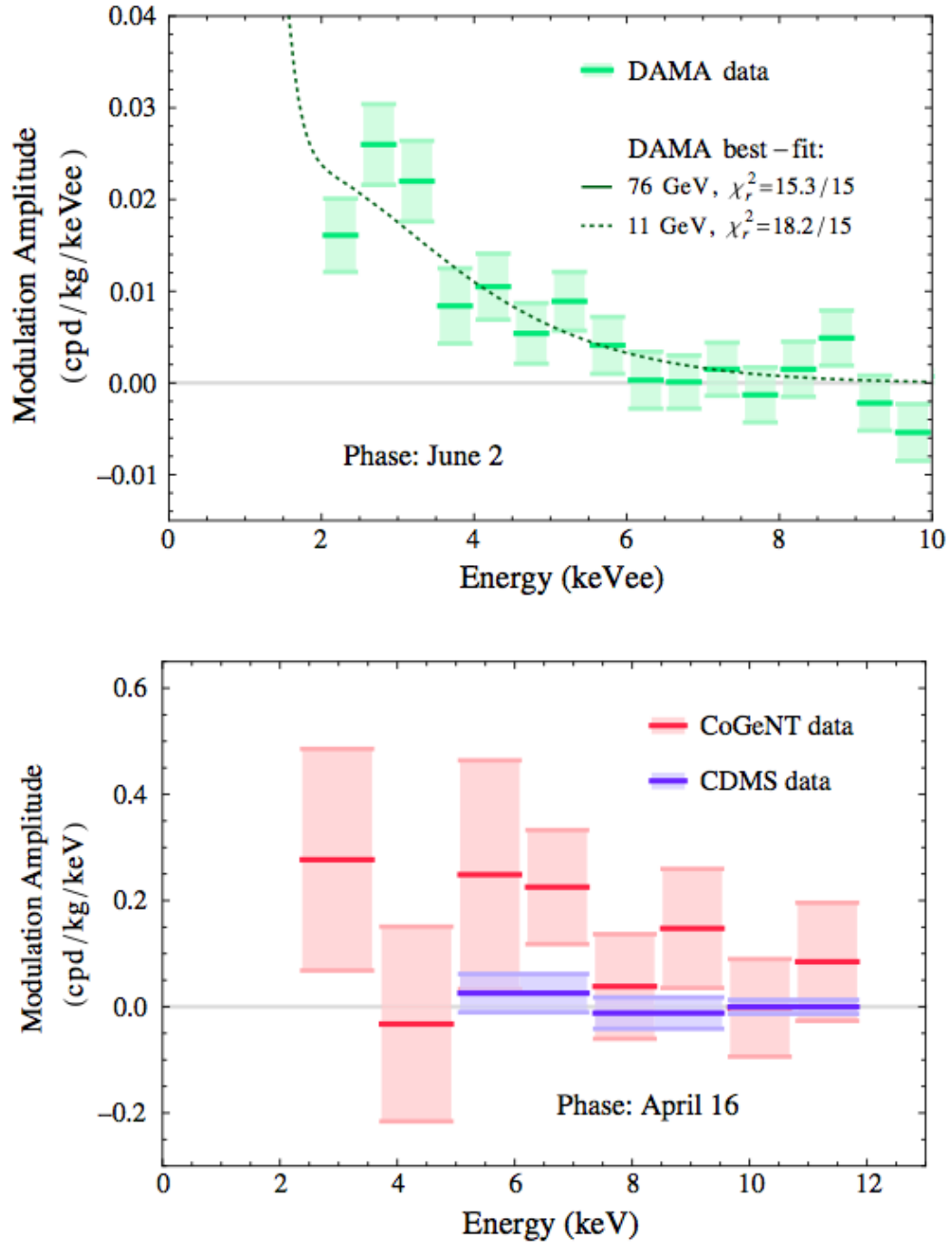


Figure 2.12: This figure is from [62]. Top figure is from DAMA data from [40]: the results from best-fit to data is shown; annual modulation phase of this fit is fixed June 2nd. The bottom figure is from [11]: The CoGeNT and CDMS data with the same binning are compared, the best-fit phase is April 16th. The color box is 1 σ uncertainty for each data point.

CHAPTER 3

Liquid Noble Element as Dark Matter Detection Medium

Noble elements are liquefied and utilized as radiation detecting medium in various applications [71, 88]. The liquid noble element has a high signal yield to the energy deposit over a large the energy range of few keV up to a few GeV. The energy deposits in liquid noble element generate two types of signal: electron from ionization and photons from scintillation. As a medium of radiation detection, both scintillation and ionization signals in the liquid noble element have good resolution [52, 25] to different kinds of particles. Basic properties of liquid noble elements and specific mechanism is introduced in the first section; relevant features of scintillation and ionization signals are described in following sections.

3.1 Liquid Noble Element Properties

Because the generic mechanism of signal generation is similar in all the liquid noble elements, One element argon is chosen to illustrate the signal generation process in liquid noble element. When energy is deposited in liquid noble element, two types of noble element atoms are directly created: argon atoms in excited state Ar^* and ionized argon atoms Ar^+ .

- The excited Argon atom Ar^*

Argon atoms in excited state Ar^* immediately forms the excited dimers:



The excited dimer has a short lifetime less than 1 nanosecond; afterwards excited dimer decays into two argon atoms at ground state and produces scintillation light simultaneously.



This process 3.2 is called direct scintillation and it gives part of the primary photon signal.

Moreover, a bi-excitonic quenching mechanism is proposed in [67]. The mechanism assumes auto-ionization of one atom in excited state Ar^* with another Ar^* as Eq.3.3

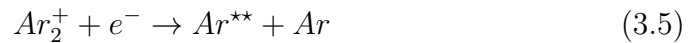


- The ionized Argon atom Ar^+

The ionized noble element atoms also form a charged dimer by combining another adjacent atoms 3.4.



The charged dimers are in the form of clouds of electron-ion pairs created by energy deposits; therefore, are mutually attracted to the nearby free electrons. A recombination process neutralizes the charge dimer into the excited state Ar^{**} as Eq. 3.5.



Because the excited state Ar^{**} is quasi-stable, those atoms de-excite to another excited state Ar^* and lose energy via emission of phonons.

$$Ar^{**} \rightarrow Ar^* + \textit{heat} \quad (3.6)$$

The excited atoms in form of Ar^* created from the recombination 3.5, will go through the same mechanism as 3.1 to form excited dimers and eventually de-excited back to the ground state while emitting photons. This process gives the other fraction of primary photon signals.

If there is an external electric field in liquid noble element, the electric field can be strong enough so that some free electrons are separated from the electron-ion cloud by the external field. Without free electrons, the recombination process Eq. 3.5 is prevented. Since the recombination process contributes to the total amount of excited state Ar^* , which eventually leads to photon signals, the presence of external electric field in liquid noble element reduces the primary photon signal.

Basic physical properties of noble elements is listed in Table 3.1. Based on the comparison among different noble elements, Xe has a relatively high boiling temperature 166.6 K, of which the liquefaction requires less cooling power; meanwhile, a high density 2.94 g/cm³ denotes a large mass within the same volume, which is important for dark matter detection experiments. These are two reasons why liquid xenon is selected as target medium in different dark matter experiments[17, 13, 31].

Table 3.1: Noble Gas Element Physical Properties

Property	He	Ne	Ar	Kr	Xe	Rn
Atomic Number Z	2	10	19	36	54	86
Mean Atomic Weight A	4.003	20.180	39.948	83.80	131.30	222
Density (Unit: g/l)	0.179	0.9	1.782	3.708	5.851	9.97
Boiling Point (Unit: K)	4.4	27.3	87.4	121.5	166.6	211.5
Melting Point (Unit: K)	0.95	24.7	83.6	115.8	161.7	202.2
Triple Point Temperature and Pressure (Unit: K and kPa)	N/A	(24.556, 43)	(83.806, 69)	(115.775, 73.2)	9161.405, 81.6)	N/A
Critical Point Temperature and Pressure (Unit: K and MPa)	(5.19, 0.227)	(44.4, 2.76)	(150.87, 4.898)	(209.41, 5.5)	(289.77, 5.841)	(377, 6.28)

3.2 Ionization in Liquid Noble Element

The liquid noble element has a distinct band structure similar to the semiconductor: a valence band is separated from a conducting band by a certain energy gap. Absorption spectroscopy result verifies this structure and the gap energy E_p is measured for different liquid noble elements: liquid xenon $E_p = 9.28$ eV and liquid argon $E_p = 14.3$ eV . Energy deposits in liquid noble element excite electrons from the valence band and become free electrons. However, the average energy required to ionize unit electron in liquid noble element is higher than the gap energy E_p . This is because the kinetic energy associated with free electrons that are below the excitation threshold. The energy deposit can be written as:

$$E_r = N_i E_i + N_{ex} E_{ex} + N_i \epsilon \quad (3.7)$$

where E_r is recoil energy; N_{ex} is the number of noble element atoms in excited state, which is also called excitons; N_i is the number of electron-ion pairs and ϵ is average kinetic energy of free electrons; E_i and E_{ex} are average energy to generate unit exciton or electron in liquid noble element.

Based on the deposit energy Eq.3.7, the average energy to create unit free electron W , which is also called work function, is written as:

$$W = \frac{E_r}{N_i} = E_i + E_{ex} \frac{N_{ex}}{N_i} + \epsilon \quad (3.8)$$

The extra energy required to ionize single free electron is a sum of averaged kinetic energy of free electrons and the excitation energy E_{ex} times the fraction of excitons to free electrons. Moreover, multiple ionization process also increases the W value since the ionization of second electron needs a higher energy.

The fraction $\frac{N_{ex}}{N_i}$ extracted from experimental data is 0.13 and 0.21 for liquid xenon and liquid argon respectively. Kinetic energy ϵ is expected to be large

than 30%. The measured W value for liquid xenon and liquid argon are 15.6 eV and 23.6 eV. However, Eq.3.7 and 3.8 only applies for electronic recoils in liquid noble elements. For nuclear recoils, the primary projectile from recoils is a noble element atom, the deposited energy is in form of kinetic energy of this atom. Deposited energy is transferred to other atoms via following secondary scatterings. In this process, a fraction of deposited energy is lost as vibration and is not converted either excitation nor ionization signals. A nuclear recoil quenching factor is introduced and tries to quantify the fraction to electronic recoils, details will be given in Chapter 3.4.

Measurements of ionization yield N_i in liquid noble detectors obtain is only a fraction of free electrons due to the recombination process Eq.3.5: assuming a fraction of electrons r recombines with local ions, actual number of electrons collected is $n_e = (1 - r)N_i$ and number of scintillation photons collected is $n_{ex} = N_{ex} + rN_i$. Without the bi-excitonic process as Eq.3.3, the conservation of sum of electrons and photons still holds as: $N_{ex} + N_i = n_{ex} + n_i$. Different recombination models are proposed to quantify this recombination process.

The fraction of electrons which escape the recombination with ions, is predicted by the Thomas-Imel model as Eq.3.9:

$$\frac{n_e}{N_i} = \frac{1}{\xi} \ln(1 + \xi), \quad \xi = \frac{N_i \alpha}{4a^2 \nu} \quad (3.9)$$

where the a is the dimension of box; N_i is the number of electrons in the box without any recombination; ν is the mean electron velocity and α is an adjustable constant. A combined parameters $\alpha/4a^2\nu$ is treated as parameter and fitted in [107]; this parameter is equal to $e^2/a\epsilon kT$, in which $\epsilon = 1.96$, $T = 165$ K and $a = 4.6$ *mum* in [108].

However, as stated in [108, 107], this Thomas-Imel model applies for low energy electronic recoils with small tracks. In [108], the small tracks are quantified by

the mean electron-ion thermalization distance $4.6 \mu\text{m}$ in liquid xenon. Birk's Law gives the light yield of scintillators as function of dE/dx with the constant k_B that varies for different types of scintillator:

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + k_b \frac{dE}{dx}} \quad (3.10)$$

Another empirical model of electron recombination for long tracks is derived based on Birk's Law is given as:

$$\frac{n_{ex} - N_{ex}}{N_i} = \frac{A \frac{dE}{dx}}{1 + B \frac{dE}{dx}} + C \quad (3.11)$$

where the stopping power dE/dx depends on the specific types of particles and interactions; A, B and C are free parameters and constrained by the experimental data. An additional constrain is that a full recombination is obtained when dE/dx goes to infinity so that $C = 1 - A/B$.

Both recombination models omit an important factor which plays an key role in the recombination, especially in the low energy electronic recoils: the external electric field. The presence of electric field is able to enhance the separation of electron-ion pairs the moment they are created. More separation of electron-ion pairs lead to a larger charge yield and a smaller light yield when both signals are measured simultaneously. But the change in charge yield may not be the same amount as the increase of light yield unless the conservation $N_{ex} + N_i = n_{ex}n_i$ holds.

However, the extent of the separation induced by electric field depends on the track shape and density, which are determined by the recoil types. The electronic recoils from α particles, of which the track density is high, the constraining effect from electric field on the recombination is significant as shown in Fig. 3.1: the charge yield increases as the electric field is raised. But even with up to 20 kV/cm drift field applied, only less than 15% of electron-ion pairs is separated

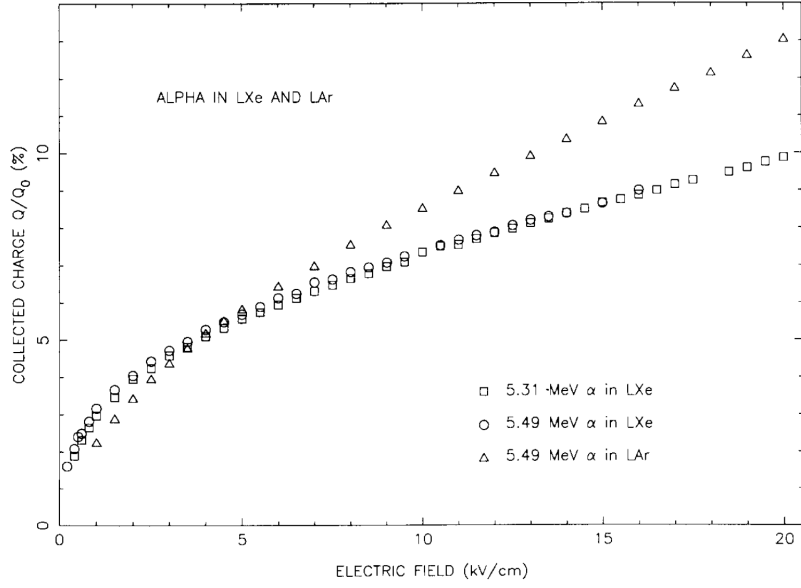


Figure 3.1: This is a measurement of electric field quenching on the ionization signals of alpha particles from ^{210}Po square dots and ^{241}Am circular dots in liquid xenon [27]. In both cases, W value 15.6 eV is used to normalize the measured ionization signals Q to a full collection efficiency Q_0 .

and contributes as charge yield.

Charge yield and light yield are measured simultaneously for various types of particles in drift fields of different amplitudes in [21] and the results are shown in Fig. 3.2. The extent of separation induced by electric field is significantly different for the electronic recoils from gamma rays or beta decay products compared to α particles in Fig. 3.1. Charge yield of electronic recoils is sharply increased when electric field of few kV/cm is applied, the effect is saturate when the electric field reaches 3 kV/cm.

By applying an external electric field, the free electrons are separated from the ion clouds and are drifted along the electric field direction. Several studies found that at low fields, the electron drift velocity is proportional to the external electric field: $\nu_e = \mu E_{drt}$. The parameter μ is called electron mobility; it is around

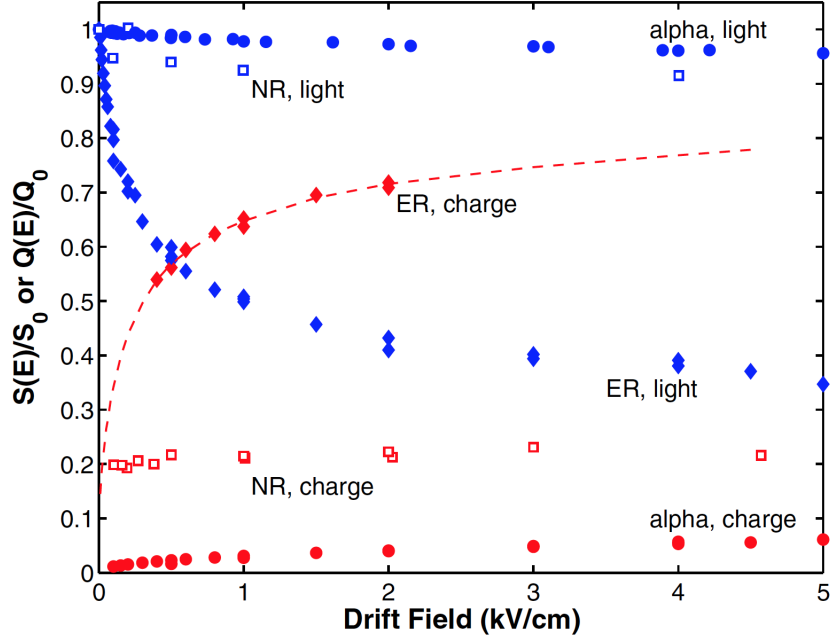


Figure 3.2: The electric field quenching on different types of recoils are shown for different recoil energies. This figure is from the the measurement [21].

2000 $\text{cm}^2/\text{V/s}$ in liquid xenon when the electric field is weak. The drift velocity ν_e saturates and stays the same when the drift field is too strong.

Other factors that affect drift velocity in liquid noble element include temperature and the concentration of impurity. A higher electron mobility μ at 4230 $\text{cm}^2/\text{V/s}$ is measured when the temperature is at 195 K [89]. In the photoionization studies where organic molecules are doped in liquid xenon, a higher electron mobility is also measured compared to the pure liquid xenon case [112].

The electron clouds are found to be spread during the drift process along the electric field direction. The spread of electron clouds are in all directions, however, the horizontal diffusion, perpendicular to the drift direction, is much larger than that in the vertical direction. Longer drift time results in a larger diffusion in all directions. The specific spread level is described by the diffusion coefficient D_T as: $\sigma_T = \sqrt{D_T T}$, where T is the drift time. Diffusion coefficient D_T has some

dependence on the drift field: in high drift field up to 10 kV/cm, the horizontal diffusion coefficient is around 50 cm²/s; in few kV/cm drift field, D_T is around 100 cm²/s. The vertical diffusion coefficient follows the similar trend but the value is about 10% of the horizontal ones. Spread of electron cloud due to horizontal diffusion can be the intrinsic limit of position reconstruction in dual-phase liquid noble element detectors, where the event position in x-y plane is reconstructed by the S2 signal pattern.

During the process of electron drift in liquid noble element, another challenge is the purity of liquid noble element. Drift electrons can be attached to the impurity atoms and form a negative ions which stop drifting and recombine eventually: $e^- + S \rightarrow S^-$. Due to the different melting point of liquid noble elements, the types of specific impurities are different [7, 8]. However, the major fraction of impurities is either components of regular air introduced during liquefaction or brought in during the massive manufacture. One of the most prominent impurities is O₂, to operate liquid noble element detectors in dual-phase mode, the concentration of O₂ has to be below 1 par per billion (ppb) level. The impact of impurities on drift electrons is proportional to the overall amount of impurity atoms and the time drift electrons stay in liquid: assuming a total number of drift electron after recombination $n_e = n_e(t_0)$ at time t_0 , the amount of electrons evolves as $dn_e(t)/dt = -kSn_e$. With impurity density S and the attachment rate k, the amount of drift electrons after drift time t, is $n_e(t) = n_e(t_0)\exp(-kSt)$. To use τ as $\tau = (kS)^{-1}$, the amount of drift electrons is $n_e(t) = n_e(t_0)\exp(-t/\tau)$. The parameter τ is also called electron lifetime in the dual-phase liquid noble element detectors. The drift electrons can be measured by exponentially fitting the profile 2D histogram of S2/S1 versus drift time.

3.3 Scintillation in Liquid Noble Element

There are two sources to create scintillation signal in the liquid noble element: direct excitation and the recombination of free electrons. The first source direct excitation refer to the process that when energy is deposited in the liquid noble element, a certain fraction of energy is employed to excite noble element atoms into the excited state; excimers which are products from process Eq.3.1, decay into ground state and produce scintillation photons Eq.3.2. The other source of scintillation is the recombination of free electrons: free electrons are created via ionization of noble element atoms; atoms in this excited states is quasi-stable, they lose energy through heat loss and become excimers Eq.3.6; these excimers are identical to those created via direct excitation Eq.3.2, which release energy by emitting photons in the decay process. Assuming a conservation of $N_i + N_{ex}$, the average energy to create unit scintillation signal W_{ph} is defined as:

$$E_r = W N_i = W_{ph}(N_i + N_{ex}) \quad W_{ph} = W \frac{1}{1 + N_{ex}/N_i} \quad (3.12)$$

W is the average energy to create single electron-ion pair as introduced in Sec.3.2. The ratio W_{ph}/W can be also used to determine the scintillation to ionization ratio N_{ex}/N_i for the interaction of different kinds of particles in liquid noble element. It is widely used that for electronic recoils, N_i/N_{ex} is 0.06; for nuclear recoils N_i/N_{ex} is around 1.

The scintillation signal is from de-excitation of excited dimer Ar_2^* as shown in Eq.3.2, this de-excitation process contains decays of excited dimers in two different states: singlet state and triplet states. Two states have different decay lifetime, specific lifetimes of each component depend on the type of liquid noble elements. The fraction of each components of scintillation signals depends on the types of interactions in liquid noble elements. For certain kind of interaction in one type of liquid noble elements, the decay curves of two excited states of distinct lifetime

is seen in average pulse shapes as shown in Fig. 3.3. Because the lifetimes of two decays are different, decay curves of scintillation signals from different excited states are well separated and lifetime of each component can be measured by fitting the decay curves. The components with short lifetime is also called fast component while those with long lifetime is called slow component.

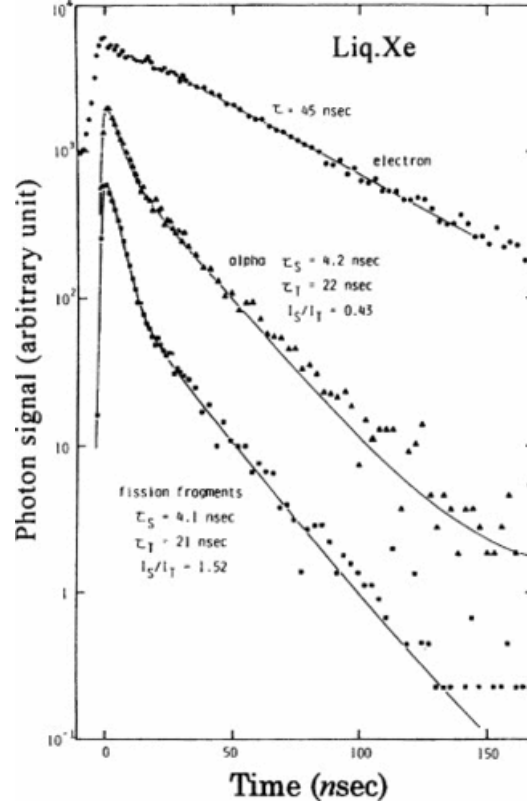


Figure 3.3: Measurements of decay lifetimes of different excited states in liquid xenon [68]. Different decay curves of scintillation signal indicate components of different lifetimes. Comparing the scintillation signals from different types of particles, the lifetimes of singlet and triplet states are different; ratio of two components also shows dependence on the types of particles.

Measurements of the ratio of decays from singlet states to those from triplet states in liquid xenon, shows a strong dependence on the types of interactions [68]. The similar trend is also found in liquid argon [82]. However, some components

lifetimes of scintillation signals from electrons in liquid xenon $\tau = 45$ nanoseconds is not consistent with those measured from fission fragments and α particles. This discrepancy is not seen in any liquid argon measurements.

When the difference between lifetimes of slow and fast components are large enough, because the fraction of each component in scintillation signal varies for different types of interactions, the induced pulse shape difference can be used as an powerful discrimination tool for different particles. The scintillation signals in liquid argon has two distinct lifetimes: $\tau_l = 1.6$ microseconds and $\tau_f = 7$ nanoseconds [69]; different lifetime $\tau_l = 1450$ nanoseconds and $\tau_f = 13$ nanoseconds are reported in [82]. So Pulse shape discrimination (PSD) parameters F90 is used to conduct the discrimination between electronic recoils and nuclear recoils. F90 is define as a pulse fraction of first 90 nanoseconds over the entire pulse area. Scintillation signals from nuclear recoils contain mainly the fast components which decay and emit photons within the tens of nanoseconds, so a large fraction of pulse areas is seen within 90 nanoseconds and associated F90 parameter is close to 1. In contrast, scintillation from electronic recoils has more slow components and associated F90 parameter is smaller than that of nuclear recoils. Fig. 3.4 shows the good separation of nuclear and electronic recoils by calculating the parameter F90. Moreover, for different types of interactions in liquid argon, specific values of F90 depends on the recoil energy.

Ionization signals are originated from free electrons; by following the Poisson statistics, the corresponding signal resolution can be predicted as $\sigma^2 = \langle (N - \bar{N})^2 \rangle = \bar{N}$. However, theoretical calculation gives the resolution as $\sigma^2 = F \times \bar{N}$, where A Fano factor F less than one is introduced [60]. The similar resolution is also expected for the scintillation signals [103]. However, the predicted signal resolution is not seen in any measurements.

The scintillation signals propagate in liquid noble elements in form of ultra-violet (UV) photons, the impurities in liquid may absorb the UV photons. An-

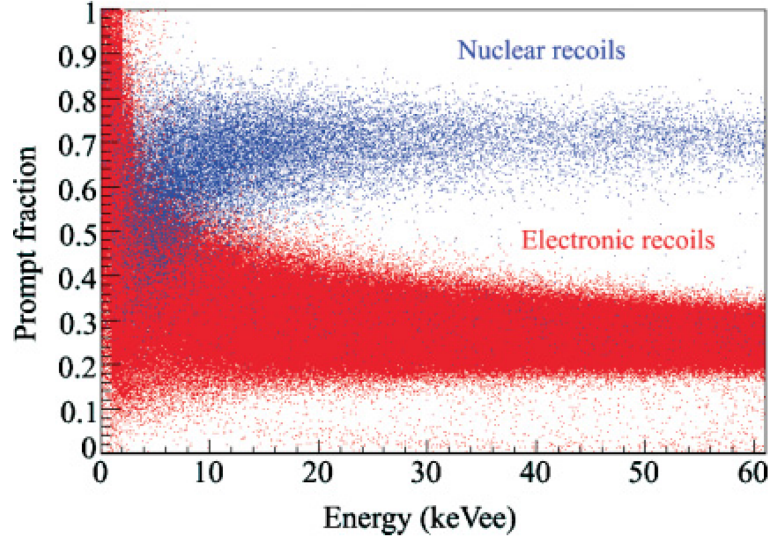


Figure 3.4: This figure from measurement [82], shows the distribution of pulse shape parameter prompt fraction for nuclear recoils and electronic recoils. At low energy region, discrimination power of PSD parameter prompt fraction is limited by the photon-electrons counting statistics.

other factor that may affect the UV photons in liquid noble elements, is Rayleigh scattering with noble element atoms. The light attenuation is described by the attenuation length λ_{att} as: $I(x) = I_0 \exp(-x/\lambda_{att})$. So the contributions from absorption and elastic scatterings are related with attenuation length as: $1/\lambda_{att} = 1/\lambda_{abs} + 1/\lambda_{sct}$. The attenuation length from Rayleigh scattering is theoretically estimated to be about 30 cm. The attenuation length due to absorption is measured indirectly by removing the contribution from Rayleigh scatterings. Electron drift in liquid noble elements has a more stringent requirement compared to that of photons absorption, the attenuation length because of absorption $1/\lambda_{abs}$ is measured to be larger than 50 cm. An absorption length more than 100 cm was achieved in [36].

3.4 Energy Scales for Different Type of Interaction

Different types of interactions in liquid noble elements such as electronic recoils and nuclear recoils, as introduced in Sections 3.3 3.2, have different track densities and fractions of energy loss to kinetic energy. Moreover, for a certain type of interactions in liquid noble elements, the specific track density also depends on the interacting particles and associated kinetic energy. Therefore, a universal energy scale which is independent of interacting particle types and associated deposited energy, is not applicable for liquid noble element detectors.

For the electronic recoils in liquid noble elements, a combined energy scale with both S1 and S2 signal has been developed and used for the dual-phase liquid xenon detectors [13, 16]. Some assumption used in this combined linear energy scale for electronic recoils:

- The bi-excitonic process as Eq.3.3 shows is negligible in the electronic recoils.
- The recombination of electrons with Ar^+ generates the same amount of atoms in excited states Ar^* as the original Ar^+ .

So assuming the parameters:

1. $\alpha(E_r)$ is the fraction of energy to create excitons, a function of recoil energy E_r
2. $\beta(E_r)$ is the fraction of energy to create free electron and ion pairs, a function of recoil energy E_r .
3. E_{ex} is the energy required to generate unit exciton.
4. E_i is the energy required to generate unit electron.
5. γ is the recombination ratio of the free electrons.

6. a is the detection efficiency of scintillation signals.

7. b is the detection efficiency of ionization signals.

The numbers of direct scintillation photons N_{ex} and free electrons prior to any recombination N_i can be written as:

$$N_{ex} = \frac{\alpha}{E_{ex}} E_r \quad N_i = \frac{\beta}{E_i} E_r \quad (3.13)$$

By considering the recombination of free electrons with ions and the detection efficiency that is associated with individual detector design, the actual scintillation and ionization signals are written as:

$$S1 = a\left(\gamma \frac{\beta}{E_i} E_r + \frac{\alpha}{E_{ex}} E_r\right) \quad (3.14)$$

$$S2 = b(1 - \gamma) \frac{\beta}{E_i} E_r \quad (3.15)$$

$S2$ is the electron signal of which the amplitude is proportional to the number of electrons N_i ; the $S2$ in used in Eq.3.14 is in unit of number of electrons. To plug Eq.3.13 into Eq.3.14, it can be re-written as:

$$S1 = a(\gamma N_i + N_{ex}) \quad (3.16)$$

$$S2 = b(1 - \gamma) N_i \quad (3.17)$$

Because the sum of excitons and free electrons is conserved as the recombination linearly converts free electrons into excitons; this conservation is expressed as:

$$N_{ex} + N_i = \frac{E_i}{W} \quad (3.18)$$

Where the W is the average energy required to create single quanta. W value is found to be 14 eV in [30] and 13.7 eV in [107]. So to plug Eq.3.16 into Eq.3.18, the combined energy scale for electronic recoils is given as:

$$\frac{S1}{a} + \frac{S2}{b} = \frac{E_i}{W} \quad (3.19)$$

Where parameters a and b are detector-dependent and can be calibrated by simultaneous measurements of $S1$ and $S2$ signals of mono-energetic calibration sources.

The similar theory for the nuclear recoils with a quenching factor is proposed in [107]. The amplitude of photons signals are proportional to the number of electrons. With number of photons and electrons simultaneous measured denoted as n_γ and n_e , the deposited energy from nuclear recoils is described as:

$$E_{nr} = \frac{1}{f_n} W(n_\gamma + n_e) \quad (3.20)$$

In which the parameter W is from the Eq.3.18, electronic recoil energy E_{er} is equal to $W(n_\gamma + n_e)$. The quenching factor f_n indicates that only a fraction of nuclear recoil energy E_{nr} is transferred to electronic excitation or scintillation.

Lindhard calculated a general expression for the fraction of nuclear recoil energy transferred to ionization. The Lindhard factor is defined as:

$$f_n = \frac{kg(\epsilon)}{1 + kg(\epsilon)} \quad (3.21)$$

In the the expression of Lindhard factor, k is a constant proportional to the ratio between electronic stopping power dE/dx and the projectile velocity, in liquid xenon $k = 0.133Z^{(2/3)}A_{-1/2}$. Parameter g does not contain any explicit physical information, is parameterized by the variable ϵ :

$$g(\epsilon) = 3\epsilon^{0.15} + 0.3\epsilon^{0.6} + \epsilon \quad (3.22)$$

ϵ depends on the nuclear recoil energy E_{nr} and is expressed as: $\epsilon = 22.5E_{nr}Z^{-7/3}$. The Lindhard factor provides an accurate prediction of the nuclear recoil quenching in semiconductors. However, the nuclear recoil quenching especially for low energy recoils in liquid xenon, can not be explained by the Lindhard factor. The value of parameter k is varied to obtain a better match with experimental measurements.

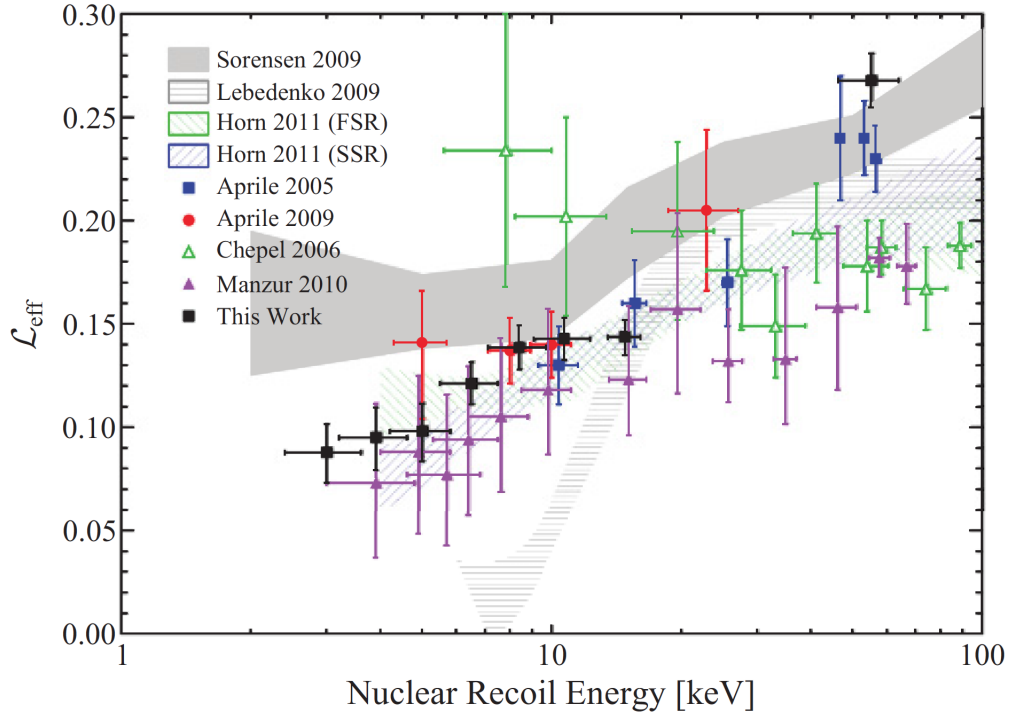


Figure 3.5: L_{eff} results from various measurements. This figure is taken from the measurement [98], where the L_{eff} is measured down to 3 keV_{nr}.

Because the primary scintillation signal S1 has less dependence on the instrumental properties compared to the proportional scintillation signal S2, another nuclear recoil energy scale used in direct dark matter detection experiments [31, 30], is solely based on the S1 signals. Using the light yield of 122 keV gamma ray from

^{57}Co as reference point, a parameter $\mathcal{L}_{\text{eff}}$ is used to calibrate nuclear recoil energy in different dual-phase liquid xenon detectors. $\mathcal{L}_{\text{eff}}$ is defined as Eq.3.23:

$$\mathcal{L}_{\text{eff}} = \frac{S1}{E_{nr}} \frac{S_{nr}}{S_{ee}} \frac{1}{L_y} \quad (3.23)$$

where the S_{nr} and S_{ee} are drift field quenching factors for nuclear recoils and electronic recoils respectively; L_y is the light yield of 122 keV gamma ray from ^{57}Co measured without any electric field applied. The parameters S_{nr} and S_{ee} are used to isolate the influence of electric field on scintillation signals, so that the measurements of $\mathcal{L}_{\text{eff}}$ and L_y without any electric field applied can be used for the dual-phase detectors. The values of S_{nr} and S_{ee} as a function of drift field amplitude, are measured independently in different small dual-phase detectors. In reported dark matter detection results [14, 28, 29], $S_{nr} = 0.95$ and $S_{ee} = 0.58$ measured from [21] are used in calculating the final results. Multiple measurements of $\mathcal{L}_{\text{eff}}$ is conducted for nuclear recoils in liquid xenon [20, 48, 22, 98] and in liquid argon [18]. All these measurements are carried out in a single-phase liquid xenon detector; neutron generators are used to provide neutron flux of fixed kinetic energy to the liquid xenon detector, mono-energetic nuclear recoils are obtained by capturing coincident scatterings at specific scattering angles. $\mathcal{L}_{\text{eff}}$ is measured as ratio of nuclear-recoil light yield and electronic-recoil light yield: $S1/E_{nr}/L_y$.

CHAPTER 4

Measurement of Nuclear Recoil in Liquid Argon

4.1 Mono-energetic Neutron Beam

The mono-energetic neutron beam used in ScENE June 2013 measurement is generated and used in the University of Notre Dame Institute for Structure and Nuclear Astrophysics. In this facility, a model FN Tandem Van de Graaff accelerator is implemented to accelerate positive ions. The positive ions are provided by a Multi-Cathode Source of Negative Ions by Cesium Sputtering (MC-SNICS) sputter ion source. The negative ions are accelerated in the FN Tandem accelerator until they reach the terminal in the middle of pressurized chamber, where a positive high voltage is applied on the terminal. When the ions of high velocity pass through the $3\text{mg}/\text{cm}^2$ thin carbon foil in the terminal section, the electrons are stripped off from the ions and ions are turned into positive ones. The positive ion beam is then accelerated in the other half of acceleration chamber and bunched by every 101.5 ns during production. The energy of proton beam can be controlled by the high voltage applied on the terminal of accelerator. Neutron generation from proton beam is carried out by interaction that:

$${}^7\text{Li} + p \rightarrow {}^7\text{Be} + n \quad (4.1)$$

The corresponding Q value of this interaction, energy difference of parent and daughter nuclides is 1.88MeV. Therefore the neutron production has an energy

threshold of proton at 1.88MeV [45, 78] as the dash line indicates in Figure 4.1. Several different proton energy is used in June 2013 beam run in order to generate neutrons of different kinetic energy. This is because during June 2013 beam run, the energy of nuclear recoil is changed by adjusting the energy of neutrons generated via the interaction represented by equation 4.1. Meanwhile the neutron detectors are mounted on the custom-designed stand with the same scattering angles. In this way the beam time is fully used and the time spent on the preparation is minimized. The specific list of neutron energy and associated nuclear recoil energy is shown in table 4.1. During the beam run at Institute for Structure and Nuclear Astrophysics, the neutron generation rate and associated background trigger rate is controlled by a selected output from the bunched proton beam current. A certain fraction of the bunched proton beam can be sent to the LiF target. Depending on the original proton beam flux, the selection of proton beam flux is made to maintain the similar level of neutron production during the entire run.

Table 4.1: Neutron Energy Used in Jun 2013 Beam Run

Proton Energy [MeV]	Neutron Energy [MeV]	Scattering Angle [deg]	Nuclear Recoil Energy [keV _{nr}]
2.376	0.604	49.9	10.8
2.930	1.168	42.2	15.2
2.930	1.168	49.9	20.8
2.930	1.168	59.9	29.0
4.093	2.327	49.9	41.5
2.930	1.168	82.2	49.9

In the preparation of neutron beam as shown in function 4.1, a thin layer of LiF of an average surface density of about 0.2mg/cm² is coated on a 1mm thick aluminum backing. The neutron production rate is proportional to the thickness of LiF target; however, too thick LiF target may introduce unnecessary

scattering of neutrons and reduce the energy resolution of neutron. The backing material is mainly used to reduce or fully absorb the protons that missed the target while holding the target material. However, it is found after the beam run that the aluminum backing of LiF gives an additional gamma background by the interaction $^{27}\text{Al}(p, \gamma)$ [93, 100].

4.1.1 Angular Distribution of Neutron Flux from $^7\text{Li}(p, n)^7\text{Be}$ Interaction

As demonstrated in Figure 4.1 from the article [45], the measurements of angular cross-section of interaction $^7\text{Li}(p, n)^7\text{Be}$ have been carried out for protons of kinetic energy from the interaction threshold up to 4.9 MeV. The similar measurement is also conducted and reported in the article [99], however the proton energy range is beyond what is used in June 2013 beam run.

The differential cross-section $\sigma(\theta)$ of neutrons from proton bombarding LiF shown in Figure 4.1 is in unit of mb/sr and the scattering angle is expressed in degree. In order to have a quantitative understanding of the angular cross-section distribution, with the fixed proton energy of 2.25 MeV, different angular cross-sections at each specific scattering angle is extracted from Figure 4.1. The associated distribution of angular cross-section for the 2.25 MeV proton is rewritten as function of $\cos(\theta)$ and the distribution is fitted with a exponential distribution. The fitting result is shown in upper figure 4.2.

Another more comprehensive approach to acquire the distribution of angular cross-section of $^7\text{Li}(p, n)^7\text{Be}$ is the numerical calculation. Basically the Legendre coefficients and zero-degree cross-section as function of proton energy are derived from various measurement results. The angular cross-section for a specific proton energy can be calculated by using the parameters extracted from previous experimental measurements. This kind of Results have been reported in arti-

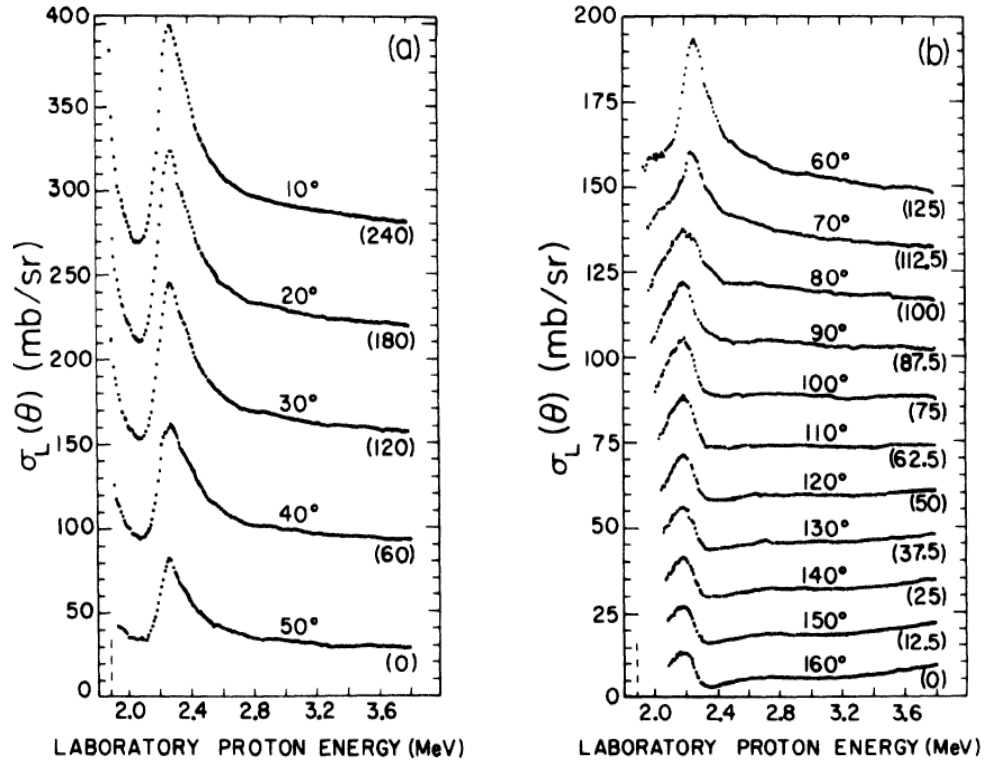


Figure 4.1: This figure is from the result [45], in which the cross-section of interaction ${}^7\text{Li}(p,n){}^7\text{Be}$ is measured at different scattering angles. The interaction energy threshold is marked by dash line in both figures.

cle [84, 78]. To compare with the other experimental measurement result, the angular cross-section of 2.25 MeV proton energy is plotted as function of $\cos(\theta)$ in lower figure 4.2, curve is also fitted by an exponential distribution as the red line indicates.

However, in the comparison of Figure 4.1, a clear discrepancy can be found between the experimental measurement [45] and the numerical calculation [84]. This is because the measurement [45] only reaches scattering angle down to ten degree and other angular cross-section below this point is extrapolated from the fitted trend. Another major difference is that the differential cross-section at zero-degree reported in this measurement is only around 90mb/sr, which is significantly smaller than other reported measurements of zero-degree differential cross-section.

Angular Cross-section Results from Phy. Rev. C, 4 (1974) 10

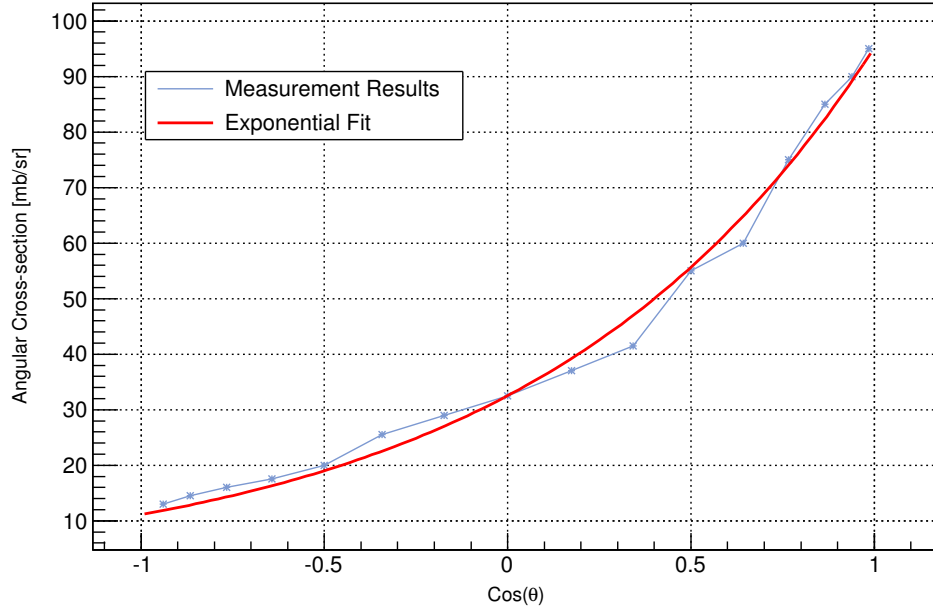


Figure 4.2: This figure shows the exponential fit result to the measurement results from [45]. The corresponding proton energy is 2.25 MeV.

4.1.2 Angular Distribution of Neutron Energy from ${}^7\text{Li}(p, n){}^7\text{Be}$ Interaction

The generation of neutron from the ${}^7\text{Li}(p, n){}^7\text{Be}$ process is a two-body nuclear interaction. The entire process can be precisely described and calculated by relativistic kinematics with known Q-values of the relevant isotopes. The website ¹ is a nuclear relativistic kinematics calculation tool. Corresponding result for neutron kinetic energy from the ${}^7\text{Li}(p, n){}^7\text{Be}$ interaction with proton energy at 2.25 MeV is calculated by using the website and the is shown in figure 4.3, where the neutron scattering angle theta is in unit of degree.

The angular neutron energy distribution is also independently measured in [84]. Result is compared with theoretical calculation in figure 4.3. The comparison between theoretical calculation and the experimental measurement gives a good

¹<http://skisickness.com/2010/04/21/>

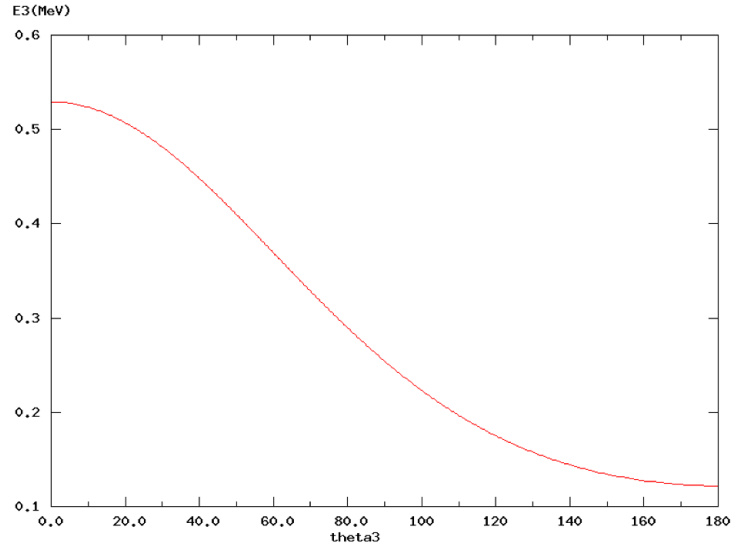


Figure 4.3: Simulated neutron energy spectrum as function of scattering angles in unit of degree. The vertical axis is the neutron energy in unit of MeV.

agreement in Figure 4.4.

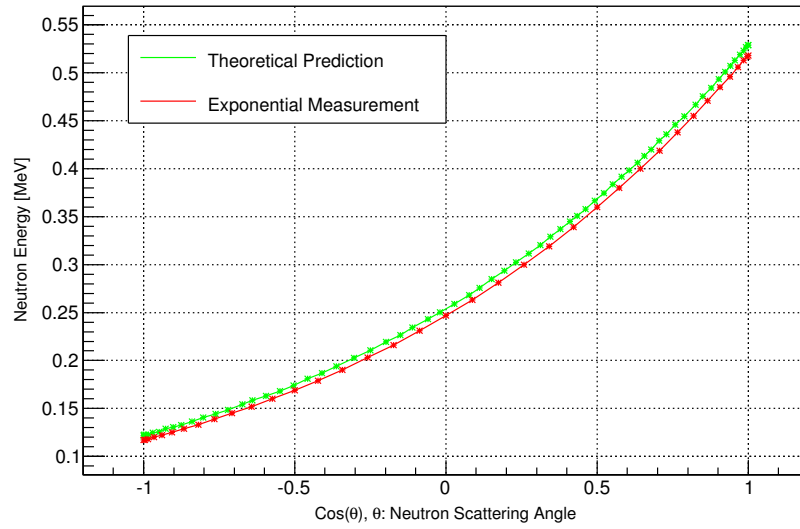


Figure 4.4: A comparison between theoretical calculation shown in upper figure and the experimental measurements. The comparison shows a good match of angular neutron energy spectra.

4.2 ScENE Detector Introduction

The June 2013 beam run of ScENE experiment is carried out at the Institute for Structure and Nuclear Astrophysics in University of Notre Dame. A picture of the experiment setup is shown in Figure 4.5. In Figure 4.5, a 6' long and 14" diameter stainless steel dewar with various cables connected on the top flange, as a part of the cryogenic system, sits in front of a costumer-designed neutron detector stand. The Time Projection Chamber (TPC) is located inside the cryogenic system. Detailed introductions of cryogenic system and TPC are in Section 4.2.1 and 4.2.2 respectively. The neutron detector stand is equipped with a horizontal arm extending to both directions and a vertical arc-shape arm. Two 5" neutron detectors are mounted on each side of the horizontal arm while a third 5" neutron detector is located on the top of the vertical arm. The bunched neutron beam, as introduced in length in section 4.1, is constantly generated in front of the TPC at a certain height. A layout of the experiment is given in Figure 4.6: neutrons of certain kinetic energy, generated from bunched proton beam on LiF target, hit argon atoms in liquid argon TPC (LAr TPC) and create nuclear recoils; only nuclear recoils of expected scattering angles are tagged by the neutron detectors. Only events with coincident signals from both LAr TPC and neutron detectors are recorded and saved for further analysis. Introduction of data acquisition system is in Section 4.2.3.

In the following parts of this chapter, symbols are assigned to the different neutron detectors; since the neutron detectors are made of the material EJ301, the neutron detectors are also called EJ301. The neutron detector on the top of vertical arm of the stand is EJ1; EJ2 is the neutron detector on the left side of the horizontal arm and EJ3 is the neutron detector on the right side. Close to the end of June 2013 beam-run, another 2" neutron detector is used to tag scattered neutron at different angle and named as EJ4. Due to some unknown

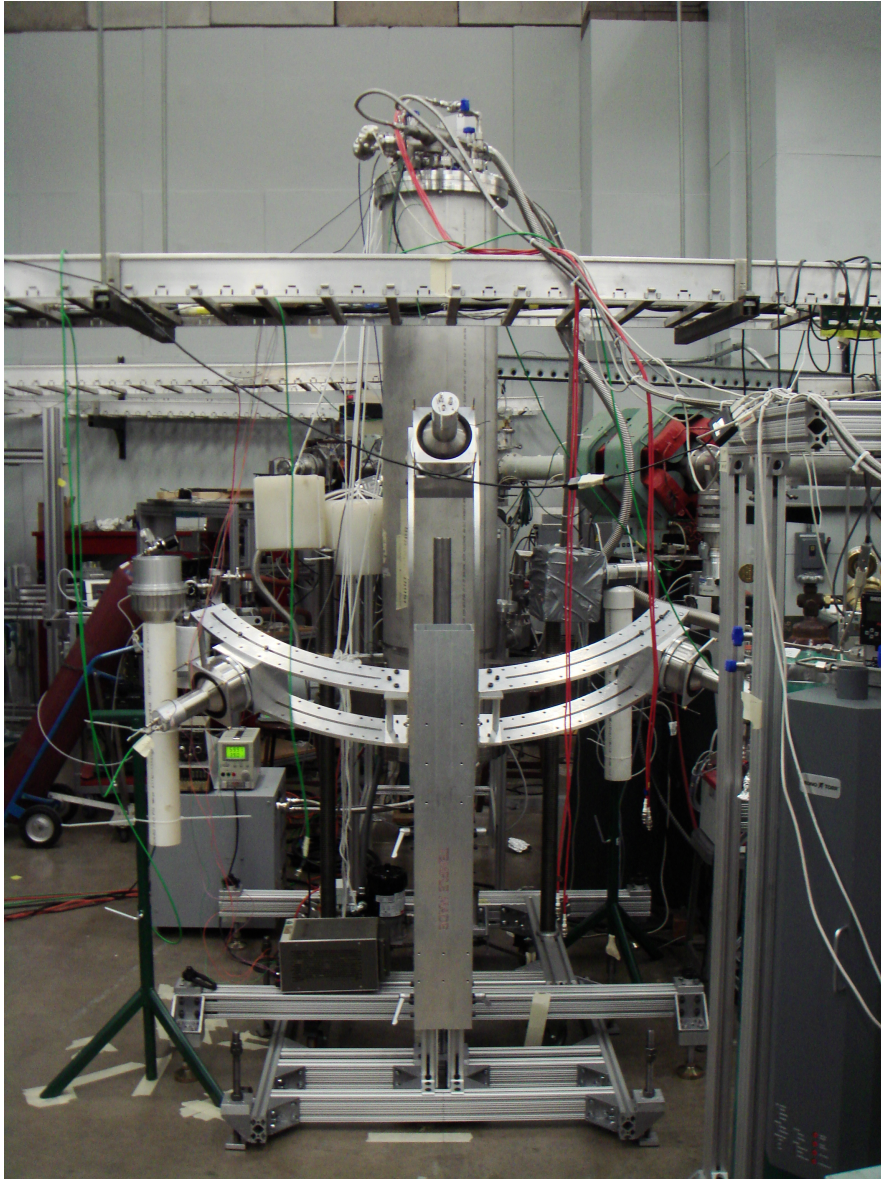


Figure 4.5: This figure is a picture of the ScENE experimental layout taken during the June 2013 beam run.

systematic uncertainties, the data collected from the neutron detector EJ1, which is facing down the LAr TPC center from the top of neutron detector stand, is not used in the measurement of nuclear recoils. After cross-checking the systematic uncertainties between the measured results of different nuclear recoils from EJ2 and EJ3, The data collected from the other two 5" neutron detector EJ2 and EJ3

is combined and used to measure the nuclear recoils in liquid argon.

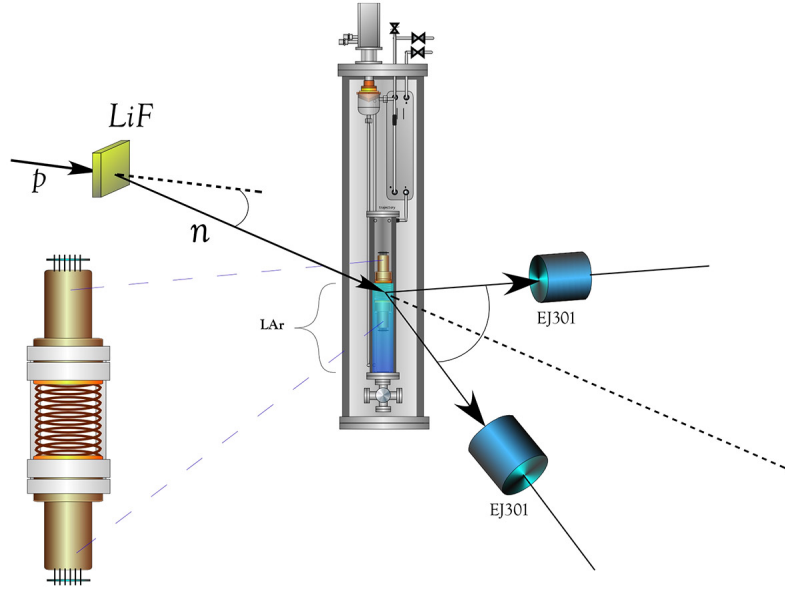


Figure 4.6: The figure is from the result of ScENE June 2013 beam run [18]. It's a schematic of the experimental setup used in June 2013 beam run. The objects in this drawing are not in the same scale.

4.2.1 Cryogenic System and Gas Circulation System

The cryogenic system is consist of an cryo-cooler: Cryomech PT60 cryogenic cooler [1], which delivers 60 Watt cooling power at 80 degree Kelvin; and a double-wall insulation system: a 6' long and 14" diameter stainless steel (SS) outer dewar is holding a 30" long and 4" diameter inner dewar inside, in between the vacuum is maintained by an external pump to be around 10^{-5} mbar throughout the entire beam run. Other than the TPC, there is also a heat exchanger inside the outer dewar. The incoming hot liquid argon after circulation and the outgoing cold argon gas go through a coiled long tube in the opposite direction inside the heat exchanger and exchange heat during this process. The outer SS dewar as shown in Figure 4.5, is concentric with the inner SS dewar and TPC. All the High-

Voltage (HV) and signal feed-throughs (FTs) of LAr TPC are located on the 16.5" diameter flange on top of the outer dewar. On the vacuum side, the PMT HV, anode HV and cathode HV are all connected to another sets of FTs at the bottom of inner SS dewar. In this way all the HV connections are submerged in liquid argon. Moreover, In order to adapt for the specific requirement of different scattering angles, the cryogenic system is mounted on a raising stand driven by a small motor, so that the system can be lifted up and down to the expected position.

During the detector operation, argon gas is constantly pulled out from TPC and fed into the gas circulation system; the argon gas is purified by going through a rare gas purifier [2]; purified argon gas is then sent to cyogenic system, where it is liquified and sent back to TPC. The circulation system is driven by a pump and the specific argon gas flow in the circulation system is controlled by a gas flow meter as indicated in Figure 4.7. Before the beam run, there is some dedicated purification period. During this period, the heater inside TPC is turned on to boil the liquid argon at the bottom of LAr TPC; at the same time, the argon gas flow is increased to 7 standard-litter-per-minute (SLM).

The $^{83}\text{Kr}^m$ injection equipment is also part of the circulation system. As shown in Figure 4.7, the injection equipment is after the purification section. To inject $^{83}\text{Kr}^m$ source into TPC, the argon gas will flow through the ^{83}Rb trap and pick up the ^{83}Rb atoms; the ^{83}Rb decay product $^{83}\text{Kr}^m$ will eventually goes into the TPC along the liquid argon flow. The application detail of $^{83}\text{Kr}^m$ in the measurements of nuclear recoil can be found in section 4.7.

4.2.2 TPC

The LAr TPC is designed as a dual-phase liquid argon detector, equipped with adjustable electron drift field in liquid phase and electroluminescence field in gas

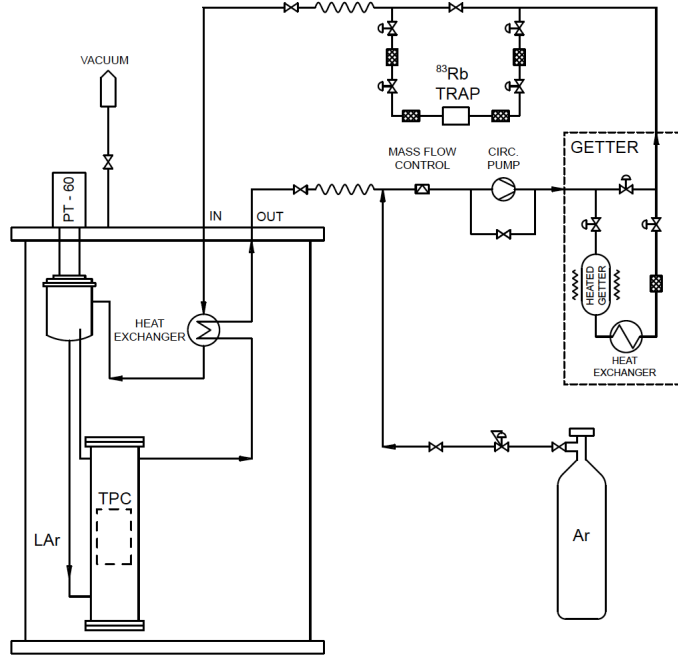


Figure 4.7: The schematics of the gas circulation system. This gas system is used to constantly purify argon during operation. Krypton injection is also conducted in system. This figure is from [46].

phase. Ultra-high purity argon gas is constantly liquified by the cryo-cooler. In order to maximize the light collection efficiency, the TPC is built with Polytetrafluoroethylene (PTFE). The designed dual-phase active volume is a cylinder of 3" diameter and 3.3" the full height. The TPC is surrounded by 13 copper rings and adjacent copper rings are connected with resistors to create the uniform drift and electro-luminescence fields in the active volume. Two Hamamatsu [3] R11410 3" photo multiplier tubes (PMTs) are employed for the signal detection: one PMT is placed on the top of the TPC in argon gas and the other is at the bottom submerged in liquid argon. A transparent quartz window is placed between the PMT photo-cathode window and the active volume for both two PMTs. The top quartz window is 0.75" thick and the bottom quartz window is 0.5" thick. The both sides of each quartz window are coated with a thin layer of Indium-Tin-Oxide (ITO) of

approximately 50 nm thick. The coated ITO layer is conductive and transparent to the visible part of the wavelength spectrum. The thin ITO layer on the side of quartz window facing active volume is connected to the top copper ring via tight contact and used as anode. The ITO layer on the other side facing PMT photocathode window is set to the same potential as the PMT body to protect the PMT from the electric field of the active volume. As it is transparent, the ITO layers do not affect the transmission of photons through the quartz windows to reach the PMTs. The electron extraction grid is 2.9" above the bottom of active volume.

However, the wavelength of photons generated from de-excitation of argon atoms is 128 nm, the photons of this ultra-violet wavelength can't transmit through the PMT's photocathode window. Therefore to use the PMTs, a proper wavelength shift (WLS) is required to convert the argon photons into detectable signals. Tetra-Phenyl-Butadiene (TPB) is a fluorescent material which is able to absorb the argon photons of 128 nm wavelength and re-emit the photons at a peak wavelength of 425 nm. In the LAr TPC, TPB as the WLS material is coated on one 3M foil [4] and the foil is placed inside the TPC and constrained by the copper rings. In order to achieve a higher photon conversion efficiency, on the side of transparent quartz windows which faces the TPC active volume, a layer of TPB is also coated on the the ITO coatings. The schematic drawing of ScENE TPC is shown in Fig 4.8.

4.2.3 Data Acquisition System

The data collected in the ScENE beam run of June 2013 are from two sources: two 3" Hamamatsu R11065 Photo-Multiplier Tubes (PMTs) in liquid argon TPC and neutron detectors made of EJ301 liquid scintillator. All the signals are digitized and recorded by two CAEN V1270B 8-channel 12-bit 250MS/s digitizers. The digitizing window of each waveform is 16 μ s, which includes a 5 μ s digitizing

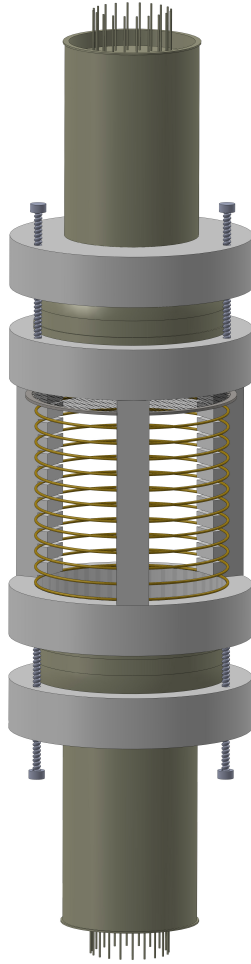


Figure 4.8: This is a schematic drawing of time projection chamber (TPC) of ScENE experiment.

window before the hardware trigger. Two low-noise amplifier which is custom-designed by LNGS, are used to amplify the analog signals from liquid argon TPC PMTs. By using the low-noise amplifier, the TPC signals are amplified by a factor of ten. On the low-noise amplifier, the amplified signal has two independent outputs. One is directly connected to the CAEN V1270B digitizer, the amplified analog signal will be digitized and recorded once the event is triggered. The other output is fed into a NIM amplifier module, which renders another amplification of factor of 10. Before sent to the NIM 612AL discriminator, the amplified signal goes

through a RC filter to reduce the noise that is picked up during the amplification. The trigger threshold of all NIM 612L segments are set to 50 mV. In cases of different recoil energy, both AND and OR logic is used for the top and bottom PMTs of the liquid argon TPC to determined the trigger at the LAr TPC part.

The high voltage to apply on Both the top and bottom PMT of LAr TPC is set to the same value 1400V. With the 1400V applied on the PMTs, the top and bottom PMT has an averaged response of 92 and 103 count-sample to single photo-electron (SPE) respectively. The full dynamic range of CAEN V1270B 12-bit digitizer is 2 V, so each count corresponds to approximately 0.49 mV; the 250 MS/s digitizing rate give a sampling rate of 4ns/sample. By considering the normal rise time and fall time of typical single photo-electron from 3" PMT, the full width of single photo-electron pulse is around 15ns. Therefore, the averaged height of SPE pulse is about 30 counts, equivalent to 14.7 mV. Both PMTs of liquid argon TPC are triggered at 0.29 photo-electron (PE).

The overall event trigger is set to be a coincidence of both LAr TPC and neutron detector. The HV applied on the 5" neutron counters are adjusted so that all the associated PMTs have the similar gain. In this case the neutron counters have the similar response to the scattered neutrons.

The trigger efficiency at LAr TPC part as a function of signal amplitude, is independently measured by the external ^{22}Na source as show in Figure 4.9. In the setup of this measurement, the ^{22}Na source is taped to the Stainless Steel front end of 5" neutron detector while facing the LAr TPC center. The ^{22}Na source constantly generates a 511 keV_{ee} back-to-back gamma ray pair via positron annihilation. The events containing signals of two PMTs from LAr TPC is triggered by the 5" neutron detector. The associated trigger at LAr PTC part is recorded simultaneously. Because the events are triggered independently by the neutron detector, the trigger efficiency at LAr TPC part can be measured as a function of signal amplitude in unit of PE. The measurement demonstrates that

the TPC has a trigger efficiency above 90% for 1 PE signal. The smallest signals of interests during the June 2013 beam run is the 10 keV nuclei recoil at 1000 V/cm drift field. For the measurement in this case with a quenched nuclear recoil light yield around 0.9 PE/keV_{nr}, the primary signal around 9 PE is not affected by any TPC trigger efficiency.

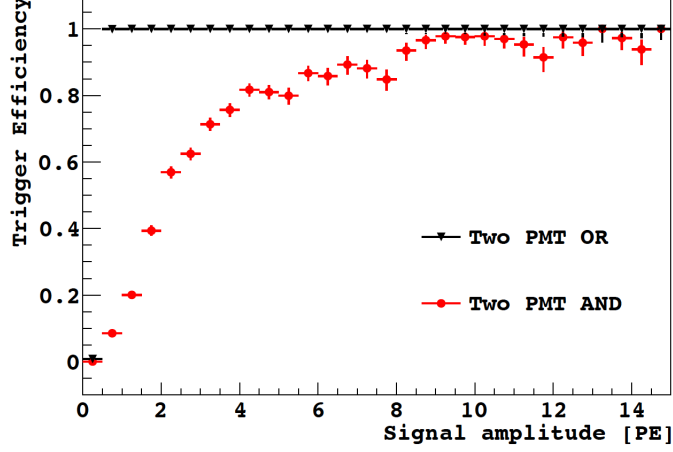


Figure 4.9: The TPC trigger efficiency of two different trigger modes: AND logic of two PMTs and OR logic of two PMTs. This figure is from [46].

Other than the coincident trigger of LAr TPC and neutron detector, there is a separate TPC-only trigger to collect the $^{83}\text{Kr}^m$ events in the active volume. The $^{83}\text{Kr}^m$ source injection system is attached to the argon gas circulation loop, the injection rate can be varied by open the passing-through valve to different extend. The intensity of $^{83}\text{Kr}^m$ within the LAr TPC is controlled by the $^{83}\text{Kr}^m$ injection system so that the $^{83}\text{Kr}^m$ decay contributes to the majority of TPC trigger. By maintaining the $^{83}\text{Kr}^m$ intensity in LAr TPC, the TPC trigger rate is stabilized around 1000 Hz. There is a 1 out 100 down-sampling selection on TPC trigger before it is fed into event trigger. Therefore, the overall contribution of TPC-only trigger to the final event trigger is around 10Hz; and the major component is the $^{83}\text{Kr}^m$ decay in LAr TPC.

4.3 Monte Carlo Simulation

4.3.1 Experimental Setups in Monte Carlo

The widely used software GEANT4 [10] is used to conduct the simulation of nuclear recoils in LAr TPC of the ScENE experiment. The three-dimensional geometry used in the GEANT4 is a precise representation of experimental setups as shown in Figure 4.10. In Figure 4.10, two different views of the GEANT4 experimental setup are shown: the left figure uses the same view point as what the Figure 4.5 shows; the right figure give a top view on the neutron detector side (the opposite side is the neutron beam). Different materials in Figure 4.10 is represented by various colors: three 5" neutron detector made of liquid scintillator EJ301 are cylinders in red on the side of TPC; the stainless steel parts of the cryogenic system are in color of deep grey; two cylinders and one block made of polyethylene, used as shielding to protect the neutron detectors from direct neutrons, are presented in white; two 3" PMTs as part of LAr TPC are in cyan; the other PTFE parts of the TPC are in purple.

The recoiled neutrons are expected to be captured by neutron detectors at certain scattering angle. Liquid scintillator material EJ301 is made of hydrogen and carbon atoms of which the neutron scattering cross-section is large. So the recoiled neutrons effectively lose the kinetic energy by cascade scatterings in EJ301 and are eventually captured. The energy deposit of recoiled neutrons in EJ301 is part of simulation results: different cases are considered and compared in Figure 4.11. In all the cases, most of recoiled neutrons are fully captured by EJ301 and deposit all the kinetic energy in EJ301. The neutron detector PMT trigger threshold is set by the NIM discriminator at 30 mV. So the trigger efficiency of recoiled neutrons in EJ301 is expected to be 100%.

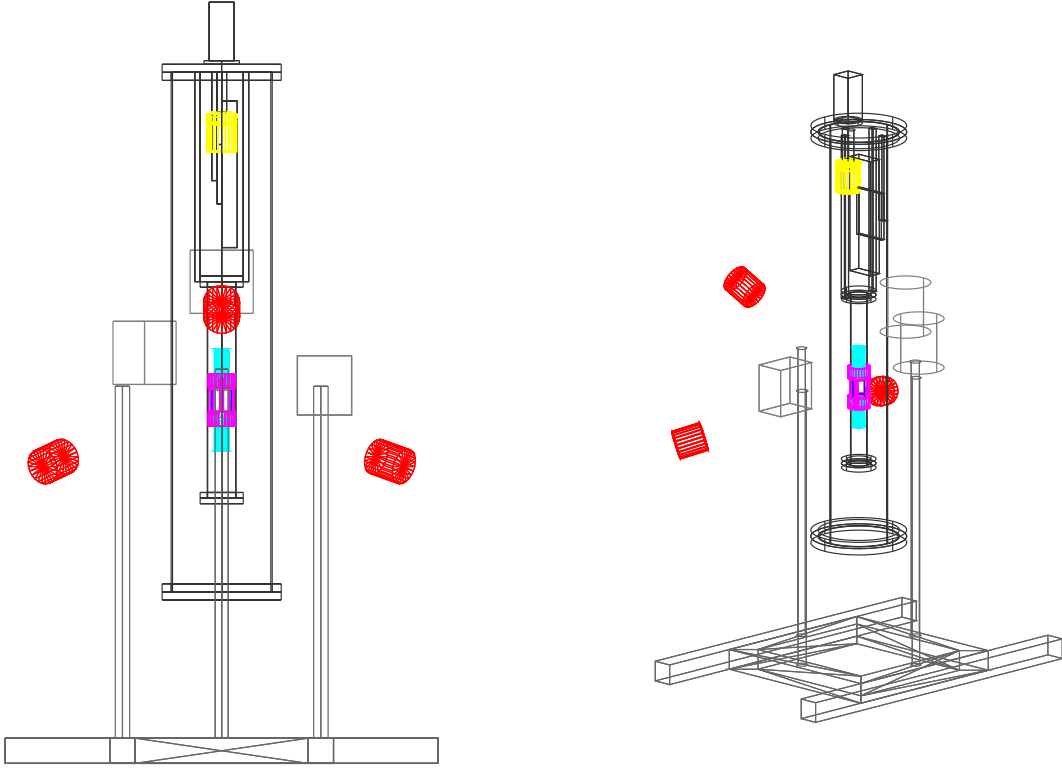


Figure 4.10: This figure shows two different view of the three-dimensional geometry used in the GEANT4 simulation of ScENE detector. In order to present a clear view of TPC geometry, liquid and gas argon is not displayed.

4.3.2 Time-Of-Flight Distribution and Event Selection

The Time-Of-Flight (TOF) parameters depict the time various particles travel between two different detector. The time resolution of detectors are limited by the data acquisition system sampling rate and are around few nano-seconds. TOF parameters are important in neutron event selection. This is because neutrons and gamma which accounts for the major backgrounds, share distinctly different traveling speed. Gamma always travels at the speed of light 3×10^8 m/s while 1 MeV neutron has a speed of 1.38×10^7 m/s. For a known distance, neutrons can be clearly identified from gamma backgrounds by using the distinct difference of

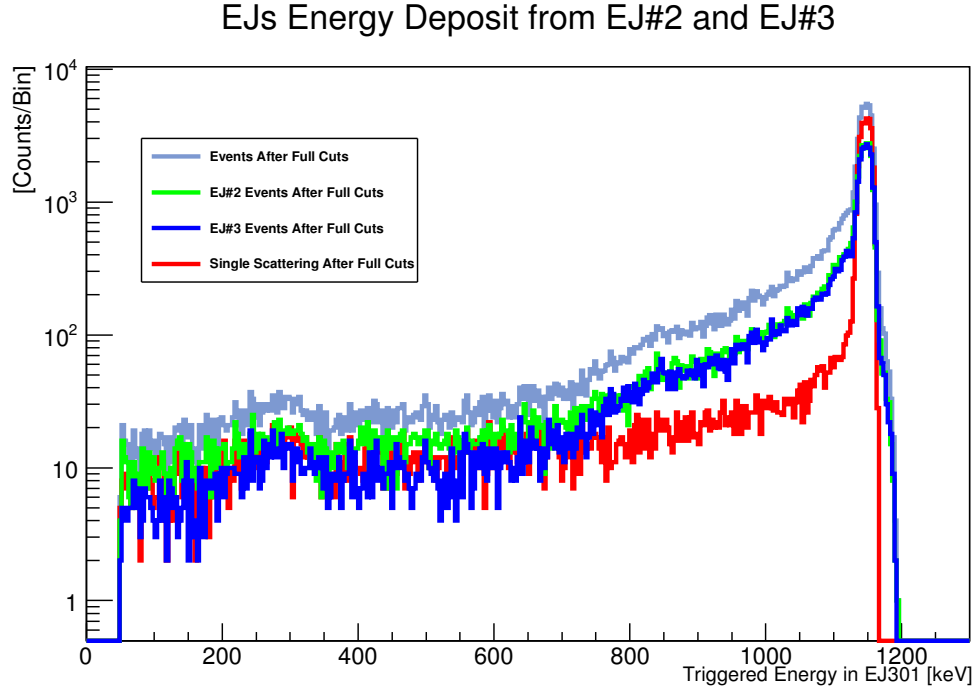


Figure 4.11: The energy deposits of recoiled neutrons in neutron counters (EJ301) are compared. This result is from 1.168 MeV neutrons case in simulation. The difference of energy deposit in EJ301 at tens of keV level introduced by different scattering angles is ignored.

traveling speed.

Equipped with the special beam feature as introduced in Section 4.1, the neutron beam is periodically generated and bunched, the associated time stamps of beam bunch are recorded as a periodic signal shown in Figure 4.13. The time stamp of particles arriving at TPC can be calculated based on the signals from two 3" PMTs. In the same manner, the time stamp that particles reach neutron detectors is estimated and given in the similar resolution. The TOF between LiF target and TPC is measured by the time difference between the beam bunch and TPC signal; this TOF is called TOF1. The other TOF between LiF target and neutron detectors is measured as the time difference between beam bunch and neutron detector time stamp; this TOF is called TOF2. The parameters TOF1

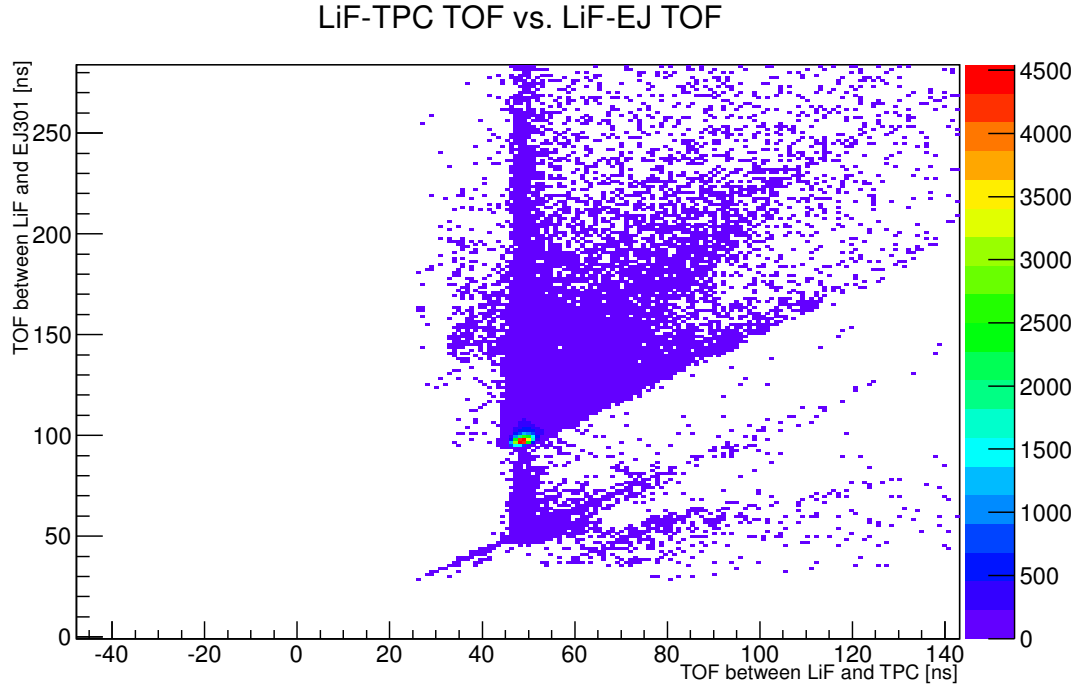


Figure 4.12: parameter TOF1 versus parameter TOF2 is shown for all events simulated with GEANT4.

and TOF2 can be calculated for all simulated events. A 2D scatter plot of simulated events in TOF1 and TOF2 parameter space is shown in Figure 4.12. In the Monte Carlo simulation, the neutrons generated from protons of known kinetic energy are directly created based on known energy and flux spectra, so the gamma background introduced during the ${}^7\text{Li} + \text{p} \rightarrow {}^7\text{Be} + \text{n}$ process is missing in the simulation. Therefore, there is no simulated events with TOF1 that match gamma TOF pattern. However, the separation between events of neutrons and gamma are clearly demonstrated in the TOF2 parameter space. One population of events share very similar values of TOF1 and TOF2: both is around 50 nanoseconds; this indicates little traveling time between the TPC and the neutron detectors, which can only be achieved by gamma. The other population of events shares a distinguishable TOF2 values, which require TOF between the TPC and the neutron detectors is similar that between LiF target and the TPC. This population

is clearly the neutron events.

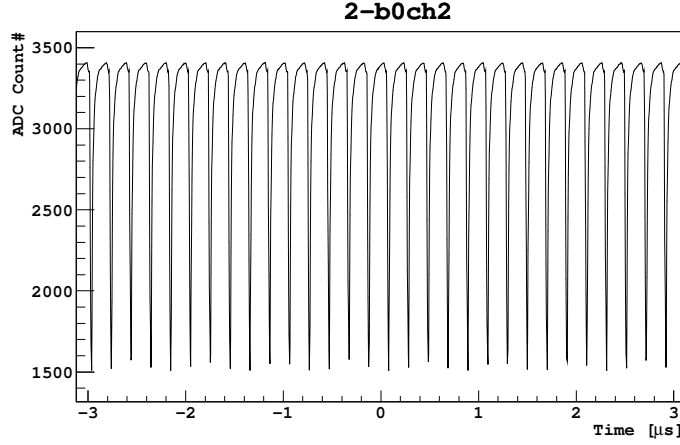


Figure 4.13: Periodic time signal of beam bunch taken during beam run. The specific period of beam bunch can be varied at steps of 100 nanoseconds; this dataset uses the period 200 nanoseconds.

However, as shown in Figure 4.12, the population of neutron events has a long tail in both parameters TOF1 and TOF2. This is because a large fraction of events randomly hit other parts of detector such as SS dewar or the heat exchanger before reaching the TPC or neutron detector, the additional interactions with other parts alter the traveling path of neutrons, as well as the direction and kinetic energy. The ideal events that are expected in this measurement, are single scatters of nuclear recoil, of which there is no other additional interactions with any other parts of the detector except single nuclear recoil in LAr TPC and captured by neutron detectors. So cuts on TOF parameters are also able to select events of single scatters of nuclear recoils. A comparison between single nuclear recoil events and all coincident events in parameters TOF1 and TOF2, is shown in Figure 4.14 and Figure 4.15 respectively. As the figures show, the single scatters of nuclear recoil have a distinct pattern in both TOF1 and TOF2 parameter spaces; by applying proper TOF cuts, the single scatters of nuclear recoil can be effectively selected and the fraction of multiple scatter background can be minimized.

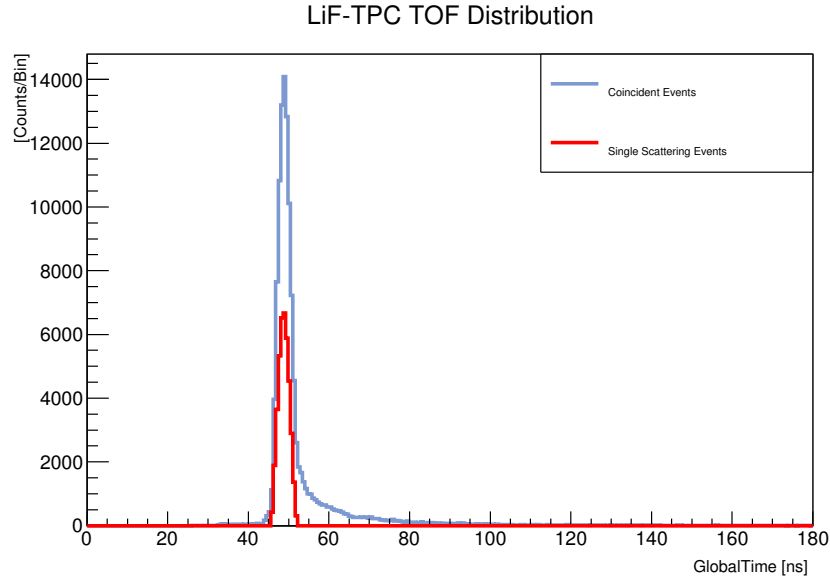


Figure 4.14: TOF1 refers to the Time-Of-Flight for particles to reach TPC from the LiF target. The distribution for observed events are shown in blue histogram while the single scattering events are in red.

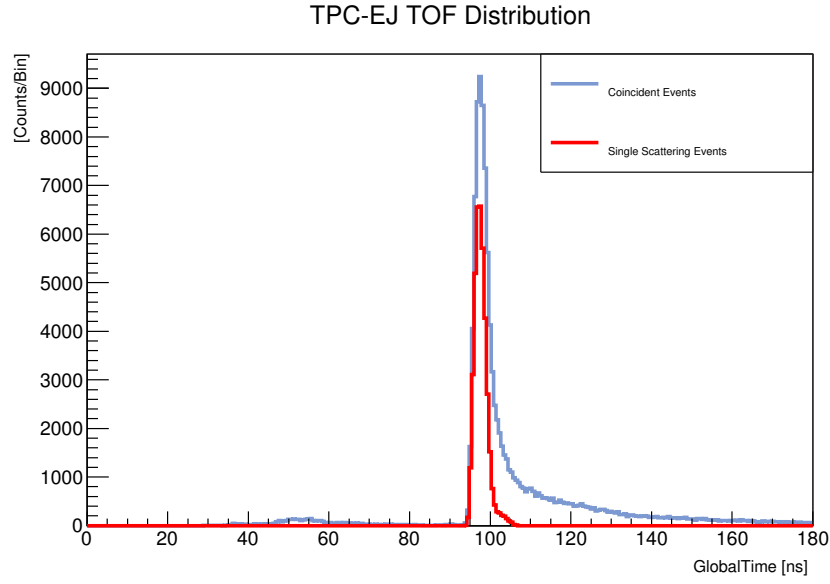


Figure 4.15: TOF2 refers to the Time-Of-Flight for particles to reach neutron counters from the LiF target. The color configuration is the same as Figure 4.14.

4.3.3 Energy Deposits of Nuclear Recoils

By tagging recoiled neutrons at certain scattering angle, the events with nuclear recoils of a certain energy in TPC are selected by the coincidence requirement. Further cuts on the TOF1 and TOF2 parameters throw away most of multiple-scattering events as shown in Figure 4.14 and 4.15. However, the final nuclear recoil energy spectrum from TPC still contains some multiple-scattering events as background after all the cuts. This contamination from multiple-scattering events is studied and result is given in Figure 4.16. In Figure 4.16, the blue histogram is the final energy spectrum in TPC after all the cuts; red histogram is the single scatter component. So the large fraction of final result is from the single scatters while the multiple-scattering background only accounts for 10% to 15% of overall events.

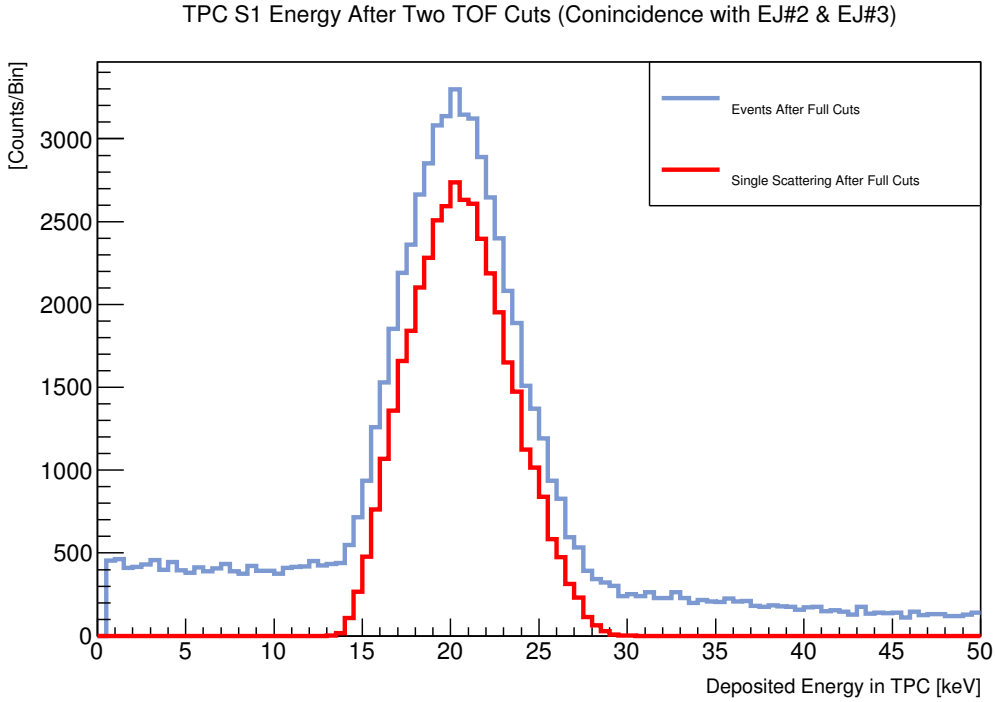


Figure 4.16: Simulated energy spectrum after all cuts. Blue histogram is all the events while the red histogram is the single scatters.

The position distribution of nuclear recoil events is also an important factor that is checked in simulation. It is known from the TPC field simulation results that the drift field near the cathode edge is not uniform as that in the other part of TPC. Therefore, it is necessary to know the position distribution of nuclear recoil events and compare it to the drift field map. The position distribution in x-y plane is shown in Figure 4.17: the nuclear recoil events are relative uniformly distributed in the TPC.

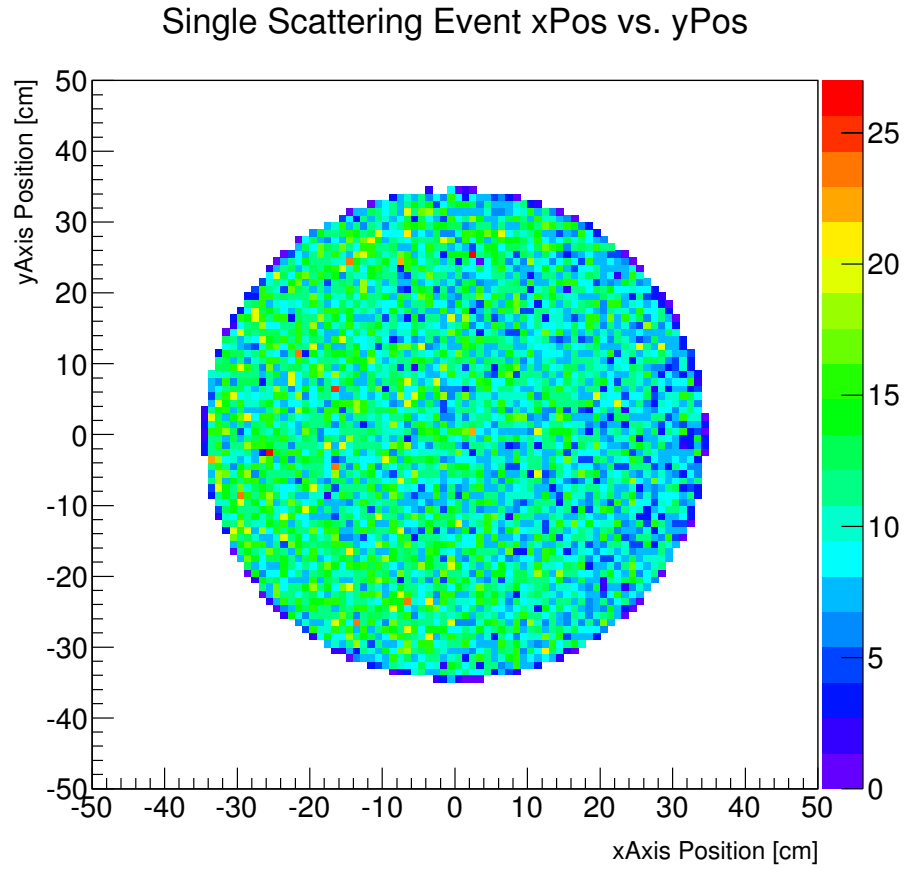


Figure 4.17: Position distribution of single scatters of nuclear recoils are shown.

4.4 PMT Single Photo-electron Calibration at Liquid Argon Temperature

ScENE TPC uses two Hamamastu R11410 3" photo-multiplier tubes (PMTs) for signal collection, one 3" PMT is on top of the TPC in argon gas and the other is at the bottom of TPC submerged in liquid argon. During the ScENE data taking, TPC was not equipped with independent single photo-electron (SPE) calibration system such as optical fiber guided laser or LED light. Therefore, by using the PMT waveform digitized during data taking, PMT SPE calibration is conducted on a basis of individual run. The advantage of this type of online SPE calibration is that the PMT SPE calibration uses digitized waveform in which the signals of scientific interests are recorded. So this kind of SPE calibration precisely characterizes the PMT responses to photo-electron. during the measurements.

The PMT SPE calibration for each data-set is important because the final measurement results are reported in unit of photo-electrons. The pulses digitized by the DAQ system are stored in unit of analog-to-digital converter (ADC) counts, the integrated areas of digitized pulses share the same unit. The PMT SPE calibration provides the conversion factor between ADC counts and photo-electron, the SPE mean discussed in this section uses the unit ADC counts per photo-electron.

4.4.1 Model of PMT SPE Response

PMT is a standard instrument widely used for photon signal detection. In the process of photon detection, two independent parts of PMT provide the full function from conversion to amplification:

1. The Photocathode for photo-electron Conversion.

Hamamastu R11410 PMT used in ScENE experiment is a head-on type PMT

as shown in Figure 4.8. The semitransparent photon-cathode window is on the top of PMT. The low noise bialkali used as photocathode is deposited on the inner side of photocathode window. The photon signal that transmits through the photocathode window, ionizes the photocathode material and generates electrons. The photon signal is converted into electron signal in this process.

- The photocathode conversion efficiency which is also called as quantum efficiency, is sensitive to the wavelength of incident photon. The quantum efficiency (QE) associated with specific photocathode of each tube is provided in the specification sheet as a function of wavelength, it is measured as

$$QE(\lambda) = \frac{N_{p.e.}}{N_{\gamma,\lambda}} \times 100\%$$

The photocathode of Hamamatsu R11410 PMT is optimized for the wavelength around 400 nm, which is the wavelength region of ScENE photon signal after wavelength shifting (WLS). The both Hamamatsu R11410 PMTs used in ScENE has QE large than 30%. This guarantees a descent photon collection efficiency.

- The photo-electron emission happened in the conversion is independent among photo-electrons. So constantly a certain fraction of incident photons are converted into electrons and picked up by first dynode. This process is statistically consistent with a Poisson process and therefore the distribution of photo-electrons from photocathode is expected to follow a Poisson distribution:

$$P(n; \mu) = \frac{\mu^n e^{-\mu}}{n!} \quad (4.2)$$

where μ is defined as $QE(\lambda) \times N_\gamma$, the expected number of photo-electrons from the photo-electron emission at photocathode. Following the Poisson distribution, the variance of photo-electrons distribution is μ at the first dynode.

2. The Multiple Dynode Stages for Amplification.

Hamamastu R11410 PMT has twelve dynode stages for the electron amplification. The amplification process at PMT proportionally increase the electron signal at photocathode at a gain of $10^6 - 10^7$. After the amplification, single photo-electron generated at photo-cathode gives a signal at the level of a few tens of mV for several nanosecond. In this way the single photo-electron signal can be digitized and properly recorded at a sampling rate of 250 Mega-Hertz.

- When high-voltage is applied onto the PMT, the voltage creates electric field between two adjacent dynodes to accelerate THE electrons flow. The accelerating electrons bombard the next dynodes and proportionally create more electrons. The newly created electrons are immediately guided by the electric field between the current and the next dynodes to accelerate and transmit the next dynode. The electron gain at each dynode is described by the secondary electron emission rate: δ . The specific expression is expected as:

$$\delta = AE^\alpha$$

where the A is constant and E is the inter-stage voltage. α is a coefficient determined by dynode geometry and material, which has a value usually between 0.7 and 0.8. Therefore the PMT gain can be written as:

$$G = \delta^n = (AE^\alpha)^n = (A(\frac{V}{n+1})^\alpha)^n = KV^{\alpha n}$$

where n is the PMT stage number and V is the total high-voltage applied on PMT. So the PMT amplification is an exponentially proportional to the applied high-voltage.

- The propagation of electron flow between adjacent dynodes are guided by local electric field. A loss of electrons during this process may be caused by the distorted electric field or the variation of dynode geometry. So the electron collection efficiency at each dynode is closed to unity. The overall SPE distribution after amplification can be approximately described by a Gaussian distribution:

$$G(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x - Q_G)^2}{2\sigma^2}\right) \quad (4.3)$$

The Q_G is in unit of photo-electron and expected to be the PMT's SPE gain. The variance σ is a SPE response property of individual PMT and can be different from tube to tube.

4.4.2 PMT SPE Calibration

The PMT photo-electronresponse is usually calibrated by a pulsed light source such as light emitting diode (LED) or laser. The pulsed light source is driven by a pulse generator at a few kilo-hertz to constantly generate regular light signals, the signals go through optical filter with $10^{-6} - 10^{-7}$ reduction factor and is dimmed to few photons. The extremely weak light signals are directly sent to the front of PMT cathodes window via optical fibers. Simultaneously, the PMTs are triggered by the same pulse generator to record the PMT responses to the light signal. The certain region of interests (ROI) of digitized waveform where the light signal is expected to be observed, is integrated and histogrammed as the SPE spectrum.

The PMT responses to the SPEs are discrete, the response for certain amount of photons, can be well described by a Gaussian distribution as introduced by Equation 4.3. Because it's assumed that the photo-electron process of photons at photocathode and the following amplification are mutually independent, The PMT responses to multiple photo-electrons can be expressed as:

$$G_n(x) = G_1(x) \otimes \cdots \otimes G_n(x) \\ = \prod_{k=1}^n \frac{1}{\sigma\sqrt{2\pi n}} \exp\left(-\frac{(x - nQ_G)^2}{2n\sigma^2}\right) \quad (4.4)$$

Moreover, the ratio between SPE and multiple photo-electrons is determined by the photo-electron conversion at photocathode as Equation 4.2 indicates. So the combined PMT responses to photo-electron spectrum is a convolution of individual photo-electron spectrum and corresponding statistical distribution as shown below:

$$S(x) = \sum_{n=0}^{\infty} P(n; \mu) \otimes G_n(x) \\ = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \frac{1}{\sigma\sqrt{2\pi n}} \exp\left(-\frac{(x - nQ_G)^2}{2n\sigma^2}\right) \quad (4.5)$$

The actual PMT photo-electron responses contain the backgrounds, which are not part of the expected signals. PMT photo-electron backgrounds can be generally divided into two types:

- Background Signals Independent of PMT photo-electron Responses

The backgrounds of which the cause is independent of PMT photo-electron responses, are internal or external radioactivity; thermal-electron emission on cathode or early dynode; the electronic noises picked up at signal transmission.

- Background Signals Associated with PMT photo-electron Responses

The background related to the photo-electron response are mainly the ion

feedback: when accelerating electrons hit helium atoms or oxygen molecules in PMT and ionize these impurity atom/molecules, the introduced ions are accelerated in the opposite direction and hit the previous dynode; this ion bombarding on dynode may generate more electrons, which will be accelerated and mixed with the regular signal.

However, due to the generation process, the second type of background signal has a distinct time delay compared to the primary signal. So the impact on the photo-electrons responses are negligible. The first type of backgrounds can be parameterized by two independent terms as:

$$B(x) = \frac{1-w}{\sqrt{2\pi}\sigma_0} \exp\left(-\frac{x^2}{2\sigma_0^2}\right) + w \theta(x) \alpha \exp(-\alpha x) \quad (4.6)$$

Where the parameter w is the fraction of the exponential background component, $\theta(x)$ is a step function that $\theta(x) = 0$ when $x \leq 0$.

As discussed in [37, 58], the actual PMT responses to multiple photo-electrons contains two components: the PMT response to photon signal 4.5 and the associated backgrounds 4.6. The observed PMT responses to multiple photo-electrons is a convolution of multiple photo-electrons and the backgrounds:

$$S_{obs}(x) = S(x) \otimes B(x) \quad (4.7)$$

The multiple photo-electron spectrum from two ScENE PMTs are drawn by histogramming the areas of small pulses in each run. The small pulses are found by a threshold lower than the regular photo-electron size. The spectra of both PMTs is shown in Figure 4.18, where the expected signal function 4.7 is used to fit the spectra. The fitted multiple photo-electron results are displayed in different colors. Because of the threshold used to find the small pulses, a large fraction of the background $\exp(-\alpha x)$ component is not included in the spectra. So in the actual fit function, the probability of second background component w is set to 0.

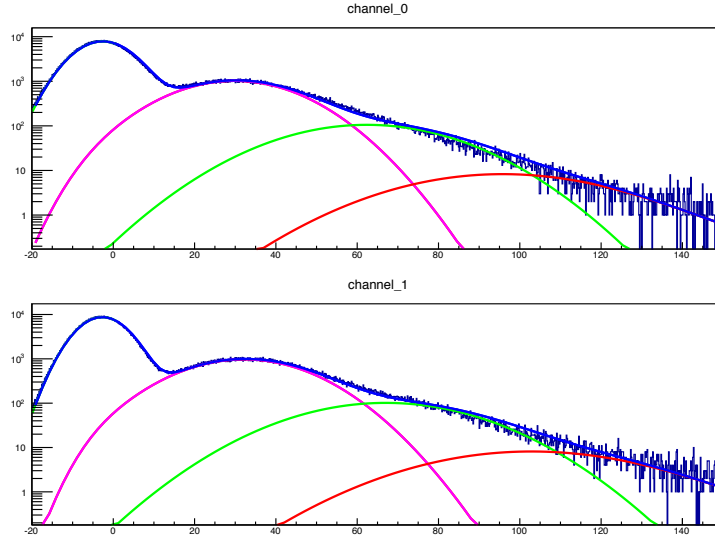


Figure 4.18: SPE spectrum fitting results of ScENE two Hamamastu R11410 3-inch PMTs are shown; top figure is the top PMT spectrum and bottom figure is the bottom PMT spectrum. The horizontal axis unit is ADC counts, vertical axis unit is event per bin. The description of fitting results is within the text content.

The first background term (which is also called pedestal) is fit to the spectra first, where the region used in fit is determined manually; corresponding amplitude and the value of σ_0 are obtained from this fit. Those numbers are implemented in the final fit function $S_{abs}(x)$. As show in the Figure 4.18, the blue lines extending all over the spectra are the final fit function; pink line is the fraction from single photo-electron; green line is two photo-electrons and red line is three photo-electrons. The probability to capture two or three photo-electrons is much smaller than that of single photo-electron.

4.5 Data Processing

Data processing is a reduction and extraction procedure, where all the useful information such as the scintillation signals from LAr TPC and values of the TOF parameters, are calculated and extracted from the digitized waveform on an event basis. The information is saved in a separate format, of which the file volume is much smaller compared to the PMT waveform data. In these useful information, the TPC scintillation signals and associated TOF parameters are of the most interests; the algorithms employed to calculate those parameters are introduced in this section. The data processing is conducted in the platform [6] which is also used in the DarkSide-10 [17] data processing and analysis.

4.5.1 Pulse Finding Algorithm

Because the scintillation signals in LAr TPC contains two components of different decay lifetimes as introduced in [82, 83], the scintillation signals include a primary large pulse and a tail of multiple small pulses at few photo-electrons level, as a typical event shown in Figure 4.19. Moreover, For the measurement of low energy nuclear recoils down to 10 keV_{nr}, scintillation signals of a few photo-electrons are expected with 6.3 PE/keV_{ee} light yield, assuming the same relative scintillation efficiency of nuclear recoils $\mathcal{L}_{\text{eff}}$ in LAr as measured in [101, 63]. Therefore, to correctly identify scintillation signals in LAr TPC, the pulse finding algorithm needs to be sensitive to small signals and able to include the entire signals spread up to a few μs .

The algorithm of pulse finding is introduced, the key parameters used in the algorithm are bold and italic. In the data processing, these parameters can be independently adjusted in a configuration file.

1. Pulse finding starts from the beginning of the sum channel, in which the PMT waveform in unit of ADC counts are converted into PE by corre-

SumChannel_AfterPulseThreshold is set to 0.1 p.e.

AfterPulseCount is 500, equivalent to 2.0 us

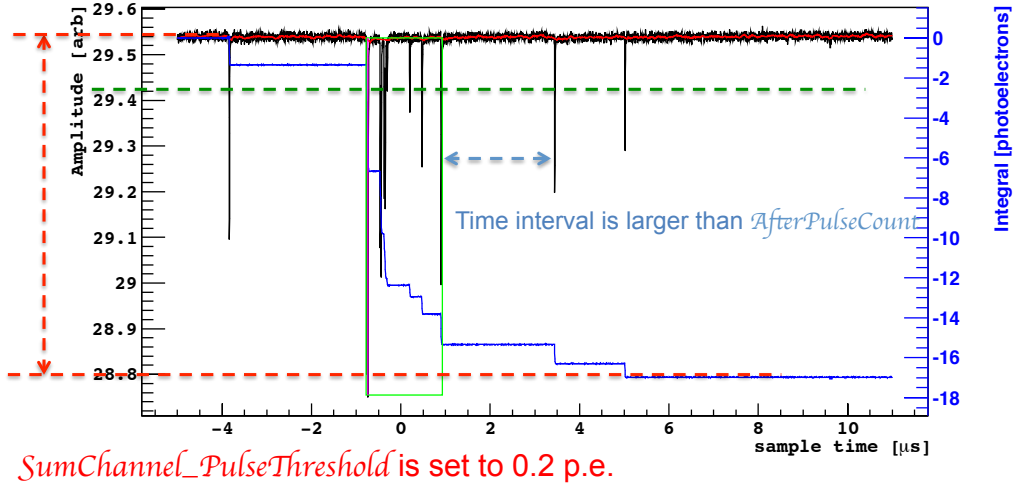


Figure 4.19: An example of the pulse finding algorithm.

sponding SPE means; sum channel is checked excursively sample by sample whether one's value exceeds the *SumChannel_PulseThreshold*; Once the value exceeds the threshold, one pulse is identified.

2. To find the start point of the pulse, each sample value is scanned backwards from the sample whose value exceeds the *SumChannel_PulseThreshold*. Starting point of the pulse is the sample of which the value is below the *SumChannel_PulseEndThreshold*. If the pulse is not the first pulse found within the waveform, the starting point of this pulse is then required not to be overlapped with the previous pulse. In case there is no sample satisfying the requirement of pulse's start point, the starting point will be set to the end point of the previous pulse.
3. To find the end point of the pulse, the samples after the one exceeding *SumChannel_PulseThreshold*, will be examined to determine the end point of the pulse. Other than to be below the threshold value *Sum-*

Channel_PulseEndThreshold, it is also required not to have any after pulse within the time window of *SumChannel_AfterPulseCount*, by the threshold *SumChannel_AfterPulseThreshold* defined for the after pulses. The time window expressed in unit of sample number, can be converted into micro-seconds by the digitizer sampling rate 4 ns sample.

Regarding the key parameters used in pulse finding algorithm: *SumChannel_PulseThreshold*, *SumChannel_PulseEndThreshold* and *SumChannel_AfterPulseCount*, several combinations of those parameters with different values are used to process one 10 keV_{nr} run, which used OR logic trigger and is expected to trigger on electronic noises. The results are shown in Table 4.2, where the numbers of events with different pulses are found are compared.

Table 4.2: Pulse Finding Algorithm Parameter Table

Pulse Threshold [PE]	PulseEnd Threshold [PE]	Afterpulse Threshold [PE]	AfterPulse Count	Good Event	NoPulse Event	SinglePulse Event	TwoPulse Event	MultiPulse Event
-0.4	-0.005	-0.1	500	824362	428325	335555	54274	6208
-0.3	-0.005	-0.1	500	824362	206748	446711	135630	35273
-0.2	-0.005	-0.1	500	824362	73859	491123	192975	66405
-0.1	-0.005	-0.1	500	824362	24628	502348	215751	81635
-0.5	-0.005	-0.1	500	824362	588265	224328	11482	287
-0.6	-0.005	-0.1	500	824362	647870	173292	3184	16
-0.5	-0.005	-0.2	500	824362	588265	223130	12598	369
-0.4	-0.005	-0.2	500	824362	428325	331405	57353	7279
-0.3	-0.005	-0.2	500	824362	206748	440039	138785	38790
-0.4	-0.005	-0.1	700	824362	428325	355287	38806	1944
-0.4	-0.005	-0.1	300	824362	428325	301954	74808	19275
-0.4	-0.005	-0.1	100	824362	428325	226488	93514	76035
-0.075	-0.001	-0.05	500	824362	15172	514808	218073	76309
-0.05	-0.001	-0.05	500	824362	2987	273871	331397	216107
-0.025	-0.001	-0.025	500	824362	1374	822966	20	2

4.5.2 TOF Finding Algorithm

There are three time points needed to be found: the reference time when the neutrons are generated from the proton beam; the time when scintillation signal is seen in TPC and the time when the neutron is captured in neutron detectors (three 5" EJ301 and one 2" EJ301 are used throughout June 2013 run). The time point when neutrons are generated is actually a reference time, this is because the neutrons are periodically generated as shown in Figure 4.13.

1. the Reference Time from the proton beam.
 - By using an arbitrary number 2800 in unit of ADC counts, the reference time from proton beam is calculated on the rising edge of the first pulse after the trigger.
 - Once the sample which exceeds 2800 ADC counts is found, the specific time point is found by interpolating the adjacent two samples at the value of 2800.
2. the Absolute Time from TPC
 - TPC time point is estimated based on the pulse finding result. The search starts from the start sample of the first pulse found in PulseFinder module.
 - The signal ratio between top and bottom PMT is used to determine which PMT waveform contributes the major part of signal and the waveform is used to find the TPC time point. Due to the different PMT quantum efficiency, current Top/Btm ratio limit is set to 1.2.
 - In the PMT waveform chosen to find the time point, when a sample is found to be above the threshold *PMT_TimeThreshold*, a linear interpolation is also used to find the absolute time at which point the ADC count is *PMT_UpperThreshold*.

- For the ADC trigger, PMT signals from two PMTs first go to LNGS $\times 10$ amplifiers; the amplified signals are fed into another $\times 10$ amplifier; the trigger is collected from a discriminator with trigger threshold set at 50 mV, which corresponds to a 5 mV waveform threshold on the PMT signals. With 12 bit CAEN 1720, $5 \text{ mV} \times 4096/2000 \text{ Count/mV} = 10.24 \text{ Count}$.

Therefore, due to the 5 mV trigger threshold on PMT level, the value of 10 ADC counts is used for the parameter *PMT_TimeThreshold*,

.

3. the time point from EJ301

- The similar method of linear interpolation is employed to calculate the time point when neutron is captured in neutron detectors. On the rising edge of signals, algorithm tries to find the first sample of which the value exceeds 3500 counts; once the first sample is found, a similar linear interpolation is conducted between this sample and the one before at the point of 3500 ADC counts.

A full list of the parameters and associated values used in the data processing is shown in Table 4.2.

Table 4.3: Parameters and Values Used in the Data Processing

Parameter Name	Value	Unit	Module	Comments
SumChannel_PulseThreshold	-0.2	PE	PulseFinder	the threshold to identify the after pulse along the tail of main pulse
SumChannel_AfterPulseThreshold	-0.1	PE	PulseFinder	the threshold for pulse finding in Sum-Channel
SumChannel_PulseEndThreshold	-0.002	PE	PulseFinder	the threshold to determine the start/end point of entire pulse
SumChannel_AfterPulseCount	500	ADC Sample	PulseFinder	time window to check small afterpulses, equivalent to 2 μ s
SumChannel_TimeOffset	-0.8	μ s	PulseFinder	Time offset for the beam reference point
EJ301_UpperThreshold	-100	ADC Count	TOF	the threshold to find pulse in EJ301 waveforms
AfterPulseCount	20	ADC Sample	TOF	time window to check small afterpulses
PMT_TimeThreshold	-100	ADC Count	TOF	the threshold to determine arriving time at TPC

4.6 Data Cut

Several cuts are developed to select events of good nuclear recoils. Two basic quality cuts used in event selection are listed below:

- **ADC Saturation Cut.** None of digitized waveforms is saturated on ADC. This requirement applies for two 3" PMT and all neutron detector channels: if any one of the ADC channels has sample reaching value 0, the event is disregarded.
- **EJ301 Single Pulse Cut.** On the trigger level, signals from any one of the neutron detectors can complement a coincidence with the signals from LAr TPC and trigger the event. This cut requires that for every event, only one pulse is found in any one of the neutron detectors; there also is no other pulses found in the triggered neutron detector.

4.6.1 LAr TPC PSD and TOF Cut

Scintillation signals in LAr TPC has a PSD feature [38, 77, 65], as introduced in Section 3.3, different types of interactions in liquid argon can be discerned by the scintillation pulse shape. The pulse shape parameter F90, defined as the ratio between the first 90 ns pulse area and the entire pulse area, is introduced to quantify the pulse shape feature. For nuclear recoils, most of the excimers is in the singlet state, which decays by a short a lifetime of tens of nanoseconds; this property gives the nuclear recoils a large F90 value. While the excimers in triplet states dominate the electronic recoils signals; this leads to a small F90 value for all the electronic recoils. Moreover, since the calculation of F90 is based on the pulse photo-electron counting, specific F90 is a function of recoil energy and drift field strength [83, 101, 63, 90]. PSD power is shown in Figure 4.20.

In the measurement of nuclear recoils in LAr TPC, the neutron generation

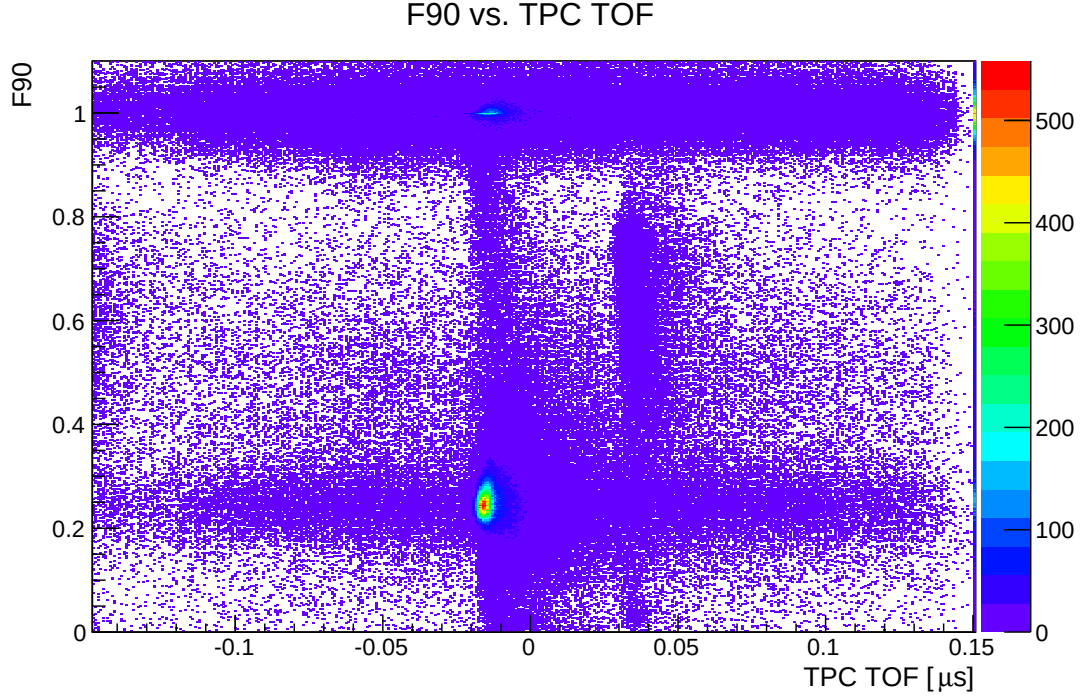


Figure 4.20: For the case of 20 keV_{nr} in LAr TPC at 0 V/cm drift-field, the distribution of events after basic quality cuts in parameter space of LAr TPC F90 versus TOF1 (TOF between LiF target and LAr TPC).

process ${}^7\text{Li}(p, n){}^7\text{Be}$ also simultaneously emits a large amount of gamma; some gamma is attributed to the interaction with target backing materials $\text{Al}(p, p')\gamma$; all of them becomes the major background for the measurement. However, because the gamma background travels at a higher speed compared to the neutrons, the TOF parameter between LiF target and LAr TPC is used as an effective background rejection parameter against the gamma flux from LiF target. Because the event F90 parameter can be also used to discriminate against the gamma background in LAr TPC, the distribution of events in a two-dimensional TPC-TOF versus F90 parameter space is shown in Figure 4.20. By F90 and TPC-TOF, the neutrons and gamma events are clustered and formed two different blobs in this parameter space. The cut on parameter TPC-TOF is based the Figure 4.20, where the separation of neutron events is shown. Because the distribution of

neutron events in TPC-TOF parameter space is not Gaussian, as predicted similarly in GEANT4 simulation in Section 4.3, an asymmetric 20 ns time window of parameter TPC-TOF is used to select neutron events

Moreover, the parameter TPC-TOF has a stronger background rejection power compared to the parameter F90. This is because the result of Figure 4.20 is from 20 keV_{nr} nuclear recoils, in which case the pulses of low energy nuclear recoils contain only around 20 photo-electrons and the therefore the discrimination power of parameter F90 is limited by the number of photo-electrons. However, the parameter TPC-TOF is dependent of the nuclear recoil energy and the background rejection power is similar over a large range of nuclear recoils.

4.6.2 Neutron Detector PSD and TOF Cut

The neutron detector PSD features are studied in [61, 80]; similar to the PSD parameter F90 used in LAr TPC, in liquid scintillator the pulses shape can also be used to discriminate different types of interactions, bascially nuclear recoils from electronic recoils. However, because of the relatively low light yield in liquid scintillator such as EJ301, for the photo-electron counting based PSD parameters, the rejection power of neutron detectors is correlated with the neutron kinetic energy. In the ScENE analysis, the neutron detector PSD parameter is calculated as the pulse area divided by the maximum pulse height.

Similar to the TPC-TOF which is TOF between LiF target and LAr TPC, the parameter EJ-TOF is defined as the TOF value between LiF target and the neutron detectors. During June 2013 measurements, all three 5" neutron detector are put exactly the same distance away from the LAr TPC so that the same EJ-TOF is expected for all the neutron detectors. Similar approach is employed to define the cut on the parameter EJ-TOF. As Figure 4.21 shows, all the events passing basic cuts are shown in the two-dimensional EJ-PSD versus EJ-TOF parameter

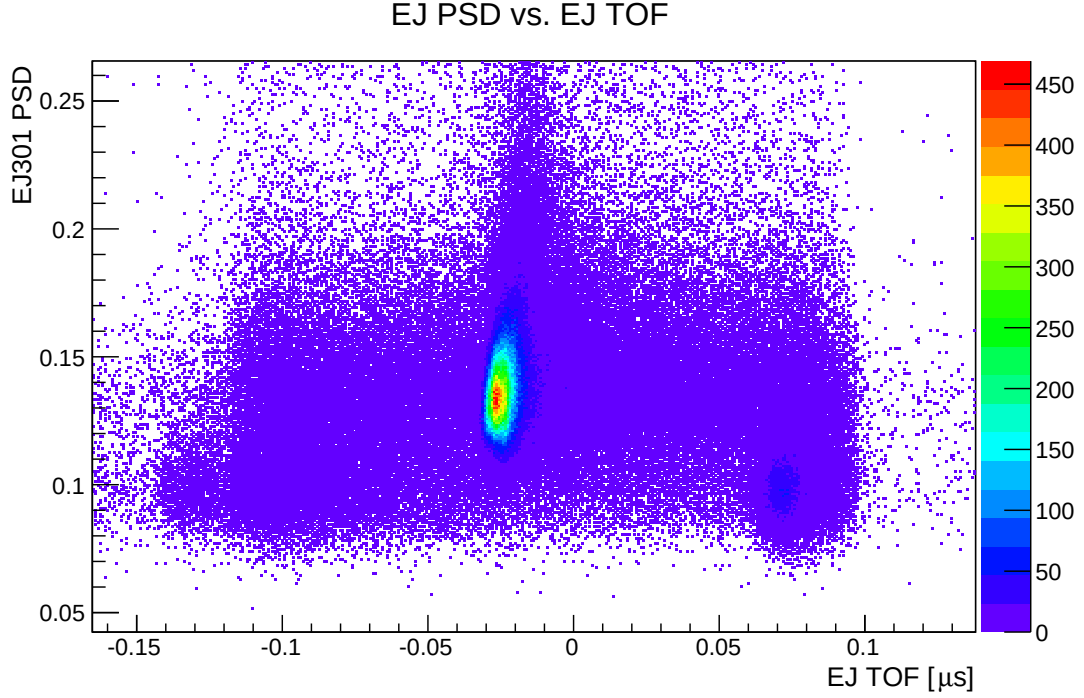


Figure 4.21: For the case of $20 \text{ keV}_{\text{nr}}$ in LAr TPC at 0 V/cm drift-field, the distribution of events after basic quality cuts in the parameter space neutron detector PSD versus TOF2 (TOF between LiF target and neutron detector).

space, the neutrons are well separated from the gamma background. A fixed asymmetric time window $[-15\text{ns}, 25\text{ns}]$ is used as the cut on parameter EJ-TOF.

However, Figure 4.21 shows that the gamma discrimination based on the neutron detector PSD is not good as the LAr TPC F90. The following study of neutron detector PSD is given in Figure 4.22 and Figure 4.23. As it is shown in Figure 4.21 that parameter EJ-TOF has a stronger rejection power against gamma background; for the 1.168 MeV neutrons captured in the neutron detectors after generating $20 \text{ keV}_{\text{nr}}$ in LAr TPC, two different time window on parameter EJ-TOF are used to mainly collect different types of events projected onto parameter EJ-PSD in Figure 4.22 and Figure 4.23 respectively.

As indicated in Figure 4.21, the TOF window (50ns, 150ns) in Figure 4.22

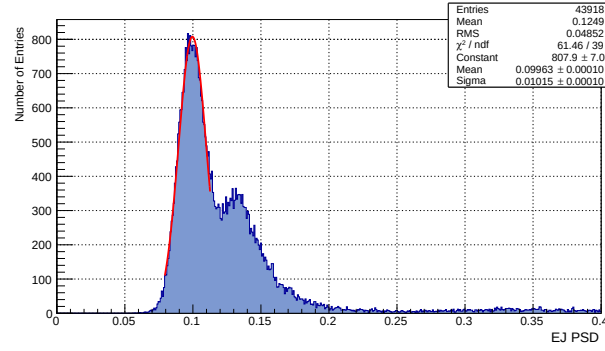


Figure 4.22: Figure shows a projected histogram of 2-dimensional scatter plot Figure 4.21 onto y-axis, with a EJ-TOF selection between 50 ns and 150 ns. This EJ-TOF time window includes mainly the neutron events.

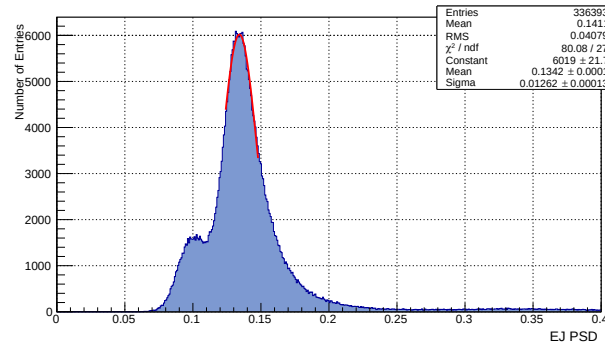


Figure 4.23: Similar to Figure 4.22, this figure shows a projected histogram of 2-dimensional scatter plot Figure 4.21 onto y-axis. But a different EJ-TOF time window between -100 ns and 100 ns is used to collect all the gamma background events.

selected mainly the neutrons events and the PSD peak of neutron events is fit with a Gaussian distribution; the associated fit parameters are also listed in the figure. Similar work is also conducted on the PSD peak from gamma events by using a different EJ-TOF time window (-100ns, 100ns). As shown in the fit parameters from Figure 4.22 and Figure 4.23, the 1.168 MeV neutron PSD peak has a mean of 0.0996 and sigma of 0.01015; while the gamma background PSD

has a mean of 0.1342 and sigma of 0.01262. So the background rejection power is not good as that from parameter F90.

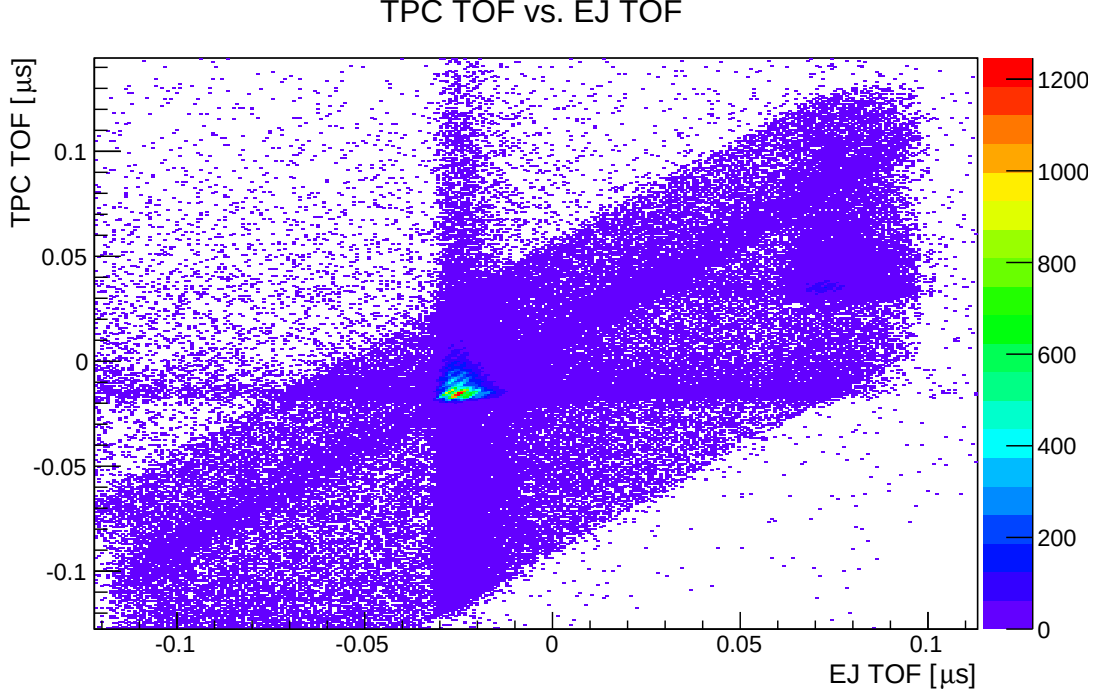


Figure 4.24: For the case of 20 keV_{nr} in LAr TPC at 0 V/cm drift-field, events after basic quality cuts are shown in the two-dimensional TOF1 (TOF between LiF target and TPC) and TOF2 (TOF between LiF target and neutron detector) parameter space.

The gamma background rejection in LAr TPC and neutron detectors based on discrimination parameters F90 and EJ-PSD are shown in Figure 4.20 and Figure 4.21 receptively. So the neutron associated values for parameters TPC-TOF and EJ-TOF can be also identified by using those two-dimensional scatter plots. However, application of event selections cuts is conducted in a different approach. The events passing basic cuts in the parameter space TPC-TOF versus EJ-TOF is shown in Figure 4.24. The neutron blob is well separated from the gamma background cluster around the center $(-0.04\mu s, -0.01\mu s)$. Figure 4.24 presents all the events in a wide TOF window, orders of magnitudes larger than

the selection TOF windows, to show the background pattern.

Beside the gamma background blob, there are three gamma bands all across the center gamma background blobs: one band where events share a similar EJ-TOF value but a random TPC-TOF value; one band all has similar TPC-TOF values while EJ-TOF is widely spread; one band has events with correlated EJ-TOF and TPC-TOF values. These three bands are created by backgrounds of different patterns. The neutron blob is centered around $(0.075\mu\text{s}, 0.03\mu\text{s})$. Since the neutron blob is well clustered, a zoomed view is shown in Figure 4.25. In the neutron blob, EJ-TOF has a larger spread compared to TPC-TOF.

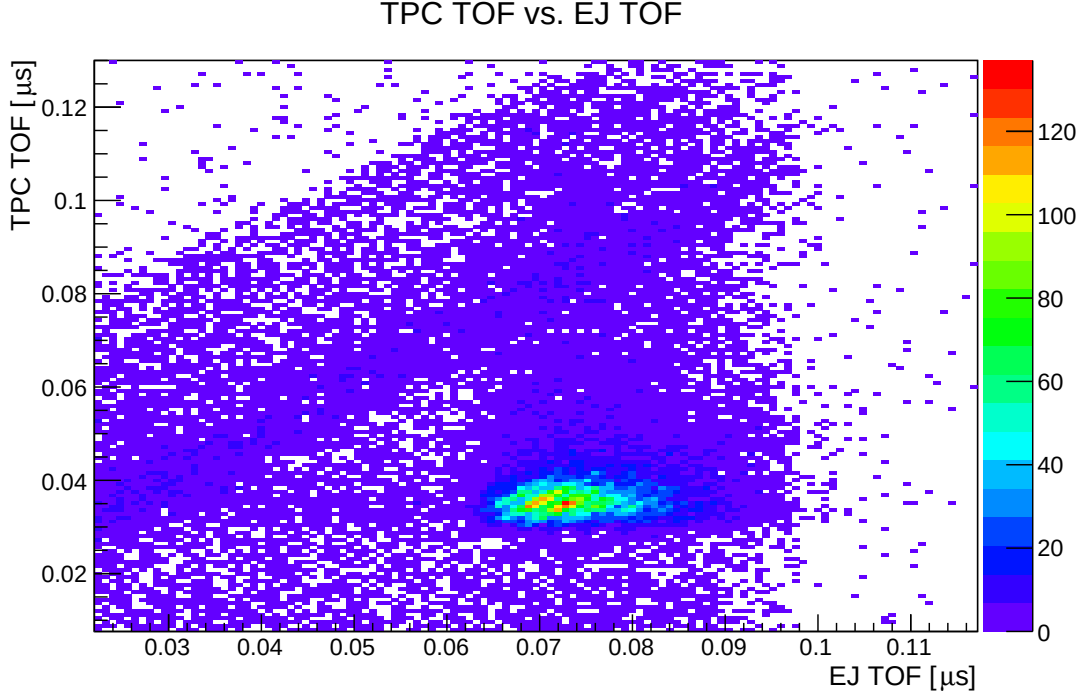


Figure 4.25: Zoomed view of neutron blob in Figure 4.24.

4.7 Nuclear Recoil Quenching on Scintillation Signal

4.7.1 Light Yield Calibration

Several radioactive sources are employed to calibrate the ScENE responses to both electronic and nuclear recoils during commissioning. For some calibration sources of strong radioactivity such as $^{83}\text{Kr}^m$, to obtain a clear electronic recoil energy spectrum from the calibration sources doesn't require the background subtraction. However, in the cases of calibration source of radioactivity similar to the ^{39}Ar beta decay such as the ^{57}Co , ^{241}Am and ^{133}Ba , the background subtraction is necessary to acquire the clean electronic recoil spectra. The specific calibration energies from each source can be found in Table 4.4. For each calibration source, the scintillation signal spectra are collected without applying any drift field. The S1 peak is fit to a Gaussian distribution and the extracted mean value is used to calculate the light yield as Equation 4.8, where the ϵ_d is the drift field value. All light yield results from different calibration sources are compared in Figure 4.26.

$$Ly(E_{ee}, \epsilon_d = 0) = S1(E, \epsilon_d = 0)/E_{ee} \quad (4.8)$$

$^{83}\text{Kr}^m$ is introduced and used as diagnostic source in the study of beta decay of tritium. $^{83}\text{Kr}^m$ has been widely in liquid noble element detector as an internal calibration source [23, 86]. $^{83}\text{Kr}^m$ is a decay product of ^{83}Rb , in which decay process the half-life time is 86.2 days [83]. Regular gamma-ray calibration sources of inter-medium energies such as ^{57}Co and ^{133}Ba , are used to externally radiates the detector with 122 keV (^{57}Co) and 356 keV (^{133}Ba) gamma rays. However, limited by the thickness of insulation walls, the associated energy deposit position is constrained to the regions closed to the detector insulation wall. Therefore the gamma-ray calibration of inter-medium energy is usually biased by the position limit. Because the krypton is a noble element of boiling point at 119.93 K and melting point at 115.79 K respectively, the corresponding radioactive isotopes can

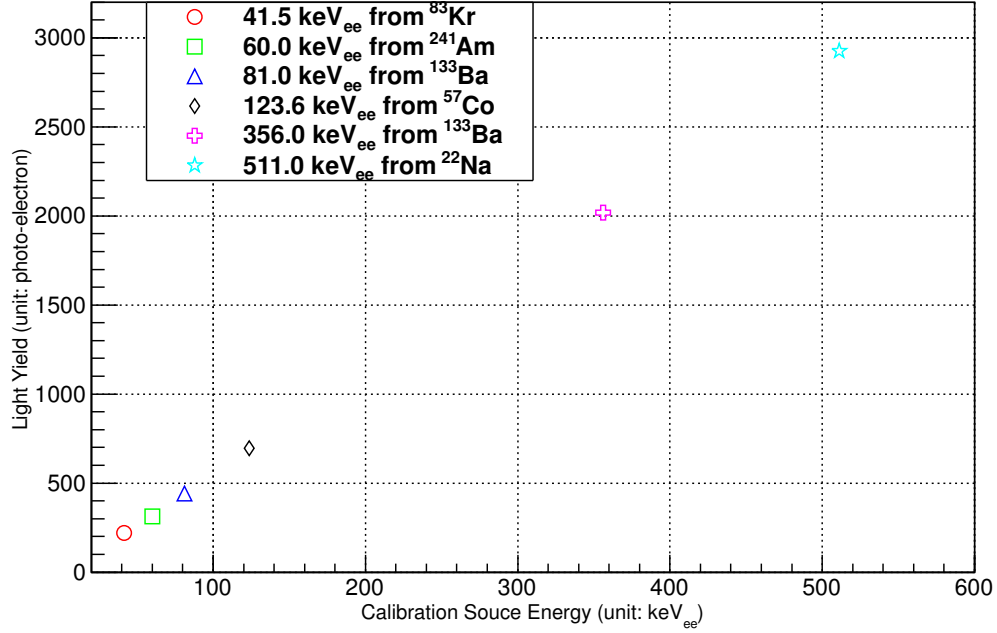


Figure 4.26: The ScENE detector light yield measurements from various electronic recoil calibration sources. The corresponding energy deposit extends from 40 keV_{ee} (⁸³Kr^m) up to 511 keV_{ee} (²²Na)

be easily solved in other noble element liquid and used as calibration sources. Therefore different from other regular electronic recoil calibration tools, ⁸³Kr^m solved in liquid noble element provides a uniform detector calibration and position-dependent bias is minimized in ⁸³Kr^m calibration. Therefore ⁸³Kr^m is used during the entire data taking process as a standard candle for light yield calibration. The light yield for ⁸³Kr^m is calculated using Equation 4.9 as below:

$$Ly(^{83m}\text{Kr}, \epsilon_d = 0) = \frac{S1_{\text{Kr}}(\epsilon_d = 0)}{E_{\text{Kr}}} \quad (4.9)$$

Where E_{Kr} is fixed to 41.5 keV_{ee}. The light yield from ⁸³Kr^m is measured to be $6.3 \pm \text{PE/keV}_{\text{ee}}$ and this number is used in the following calculation in Equation 4.10.

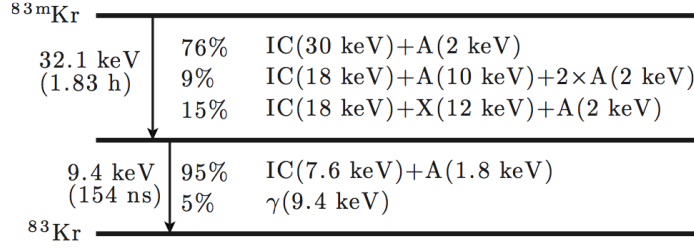


Figure 4.27: This is the decay scheme of ^{83m}Kr from [86]. The specific branching ratio in are listed in each decay. The energy emission in the two-step transition of ^{83m}Kr sends mostly internal conversion (IC) electrons and Auger (A) electrons. An x-ray (X) emission has 5% branching ratio in the second decay step.

4.7.2 Scintillation Signal Spectra

As described in details in Section 4.6, several quality cuts are carefully developed to select the nuclear recoil events in LAr TPC. After applying the two TOF cuts on TPC-TOF and EJ-TOF, the nuclear recoil events are shown using a different TOF parameter calculated between TPC and neutron counters in Figure 4.28. As shown in Figure 4.28, all the events passing the two TOF cuts, have the similar value for this TOF parameter while scintillation signal S1 amplitude are clustered into two separate blobs. This demonstrates that the cuts on two TOF parameters effectively select all the good nuclear recoil events in TPC. The two blobs with distinctly different S1 values are nuclear recoils and electronic noise.

Because the scattered neutrons are captured by three different 5" neutron counters at the same scattering angle, it is important to cross check the captured nuclear recoils by different neutron counters. The S1 spectra of nuclear recoils captured by different neutron counters are shown in Figure 4.29, where an identical set of cuts are applied to select the good nuclear recoil events. It shows a good agreement among S1 spectra from different neutron counters. In the analysis of calculating $\mathcal{L}_{\text{eff}}$, only the combined S1 spectra from EJ2 and EJ3 are used to fit

Table 4.4: Sources Used for Light Yield Calibration

Source Type	Energy (unit: keV_{ee})	Branching Ratio (unit: %)
$^{83}\text{Kr}^m$	32.1	100
$^{83}\text{Kr}^m$	9.4	100
^{241}Am	60	36
^{57}Co	14	9.16
^{57}Co	122.06	85.60
^{57}Co	136.47	10.68
^{133}Ba	81	34
^{133}Ba	356	62
^{22}Na	511	100
^{22}Na	1274	100

the Monte Carlo simulation spectra.

4.7.3 Electric Field Quenching on Scintillation Signal

The light yields from nuclear recoils of different energies is calculated using Equation 4.10, where the E_{nr} is controlled by the neutron scattering angles. There are two ways to calculate the nuclear recoil light yields as a function of nuclear recoil energies and drift field amplitude $\text{Ly}_{\text{nr}}(E_{\text{nr}}, \epsilon_d)$. In the first way, a Gaussian distribution is to directly fit the scintillation S1 spectra in unit of photo-electrons as shown in Figure 4.29, then the Gaussian mean from fit is used as $S1_{\text{nr}}(E_{\text{nr}}, \epsilon_d)$. The corresponding $\text{Ly}(E_{\text{nr}}, \epsilon_d)$ is calculated by using Equation 4.10 as shown below.

$$\text{Ly}(E_{\text{nr}}, \epsilon_d) = \frac{S1_{\text{nr}}(E_{\text{nr}}, \epsilon_d)}{E_{\text{nr}}} \quad (4.10)$$

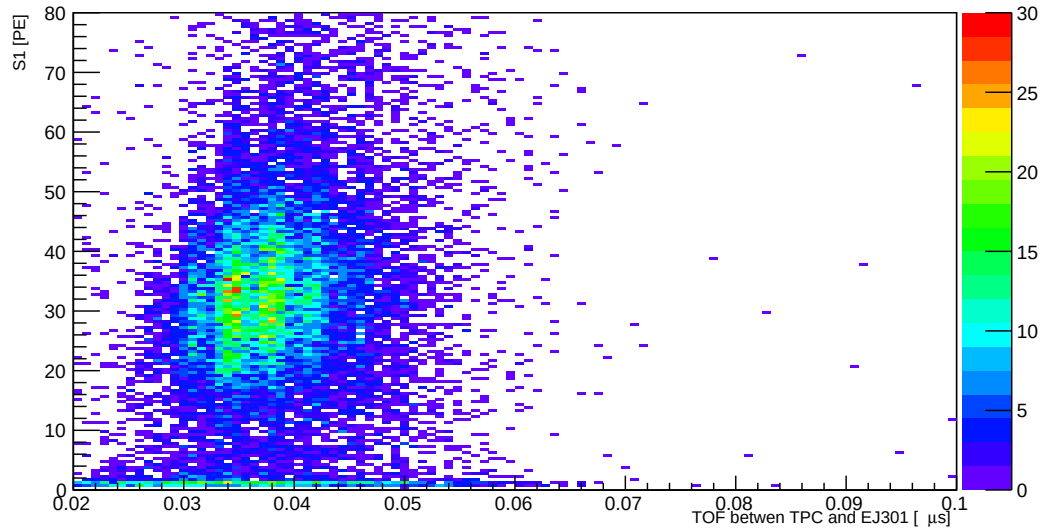


Figure 4.28: After all cuts quality cuts, 20 keV_{nr} data with 0 V/cm drift field is shown in the two-dimensional S1 and TOF (between TPC and EJ031) parameter space.

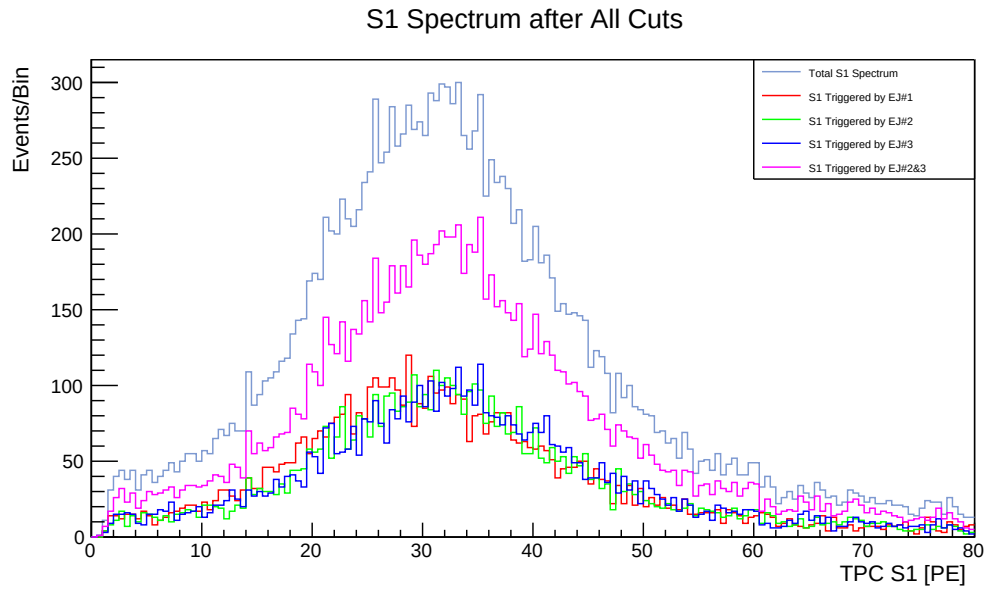


Figure 4.29: Comparison of S1 spectra from tagging of different neutron detector. All the S1 spectra are after basic quality cuts and the TOF cuts.

In the other way, the S1 spectra in unit of keV_{nr} from Monte Carlo simulation is used first to convert into corresponding observed S1 spectra in unit of photo-electrons. In this process, two parameters: detector resolution $R(E_{nr}, \epsilon_d)$ and nuclear recoil light yield $Ly(E_{nr}, \epsilon_d)$ are involved. For each simulated event from Monte Carlo spectra, the nuclear recoil energy is converted into photo-electrons by using the nuclear recoil light yield $Ly(E_{nr}, \epsilon_d)$ as $S1_{nr}(E_{nr}, \epsilon_d) = E_{nr}Ly(E_{nr}, \epsilon_d)$; then the $S1_{nr}$ is convoluted with a Gaussian distribution with variance $\sigma = \sqrt{S1_{nr}}R(E_{nr}, \epsilon_d)$, where the detector resolution R also depends on the nuclear recoil energy E_{nr} and drift field amplitude ϵ_d . In the fit step, a chi-square function calculated as Equation 4.11 is used.

$$\chi^2(\mathcal{L}_{\text{eff}}, R) = \sum_{i=1}^n \frac{(O_i - S_i)^2}{S_i} \quad (4.11)$$

Where the O_i is the number of events in bin i of observed S1 spectrum; S_i is the number of events in the corresponding bin of simulated S1 spectrum. To use Equation 4.11, it requires both observed and simulated S1 spectra have the same binning. The specific binning of each S1 case depends on the total number of events passed all quality cuts. In this fit process, two free parameters $R(E_{nr}, \epsilon_d)$ and $Ly(E_{nr}, \epsilon_d)$ are varied to minimize the χ^2 function given in Equation 4.11.

$$\mathcal{L}_{\text{eff}, {}^{83m}\text{Kr}}(E_{nr}, \epsilon_d) = \frac{Ly(E_{nr}, \epsilon_d)}{Ly({}^{83m}\text{Kr}, \epsilon_d = 0)} \quad (4.12)$$

The final results of relative nuclear recoil scintillation efficiency with respect to the ${}^{83}\text{Kr}^m$ calibration source is estimated using the Equation 4.12, where the light yield from ${}^{83}\text{Kr}^m$ is fixed to 6.3 PE/keV. As shown in the χ^2 minimization step, for each nuclear recoil light yield Ly , it depends on the nuclear recoil energy and drift field. Therefore, the relative nuclear recoil scintillation efficiency has the same dependency. The results are shown in Figure 4.30. The errors shown are a combination of statistical errors and systematic errors.

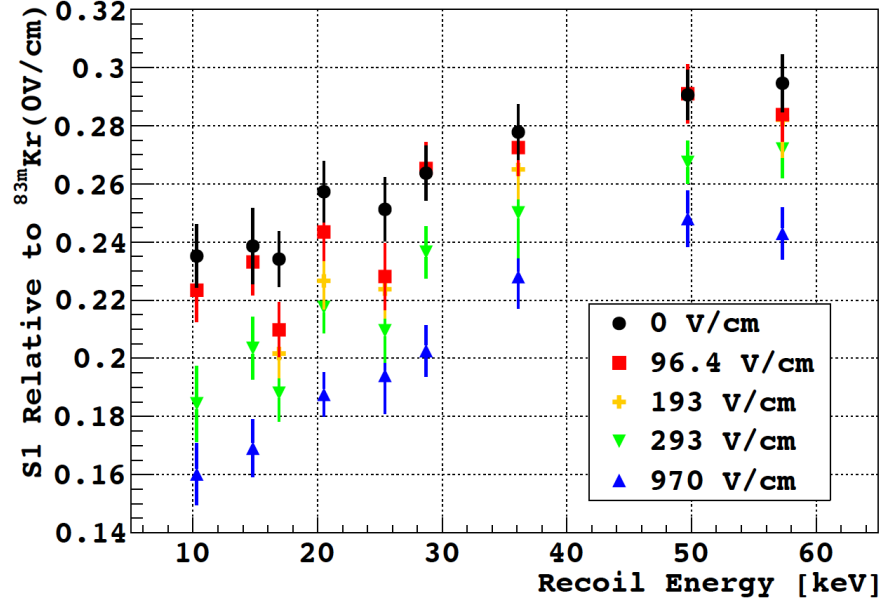


Figure 4.30: $\mathcal{L}_{\text{eff}}$ results measured relative to $^{83}\text{Kr}^m$ light yield. This figure is from [46].

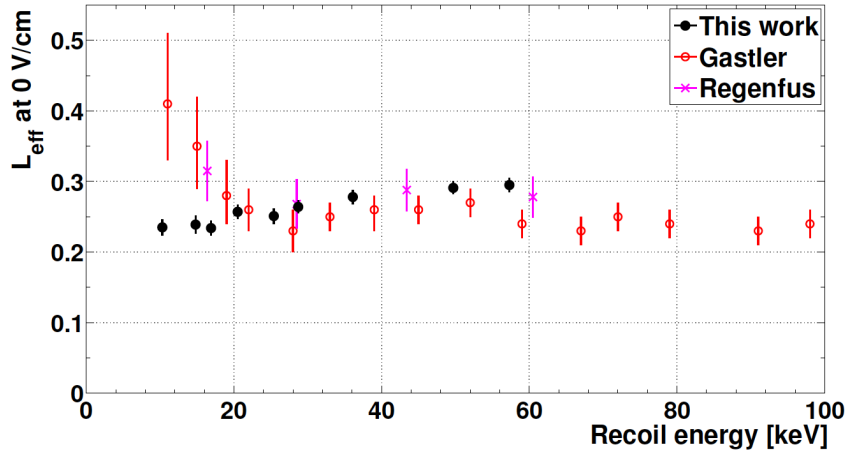


Figure 4.31: $\mathcal{L}_{\text{eff}}$ results from this measurement is compared to previous measurements [63, 101]. This figure is from [46].

CHAPTER 5

Finite Element Simulation with COMSOL

XENON1T [19] is the next-generation direct dark matter detection program for the current XENON100 detector. XENON1T program is a multi-institutes collaboration from several countries across three continents. Similar to the XENON100 time projection chamber (TPC), core XENON1T detector is also a dual-phase xenon TPC of 1-ton fiducial volume aimed to capture simultaneous scintillation and ionization signals. The electron drift in liquid xenon follow the static electric field, therefore, a good design of electric field is critical for the TPC performance. This work optimizes the TPC design to obtain a uniform electric field distribution that ultimately leads to a uniform S2 distribution.

5.1 XENON1t Prototype Electric Field Simulation

5.1.1 2D Symmetric Geometry

In order to reduce the CPU time and memory requirement from COMSOL [5] simulation, a two-dimensional symmetric geometry is used to simulate the electric field of XENON 1-ton TPC design [19]. To meet the XENON1T TPC design requirement, the TPC active volume diameter is set to 97.2 cm; the distance between cathode grid and extraction grid which sometimes calls gate grid, is 96 cm. Meanwhile, the region between extraction grid and anode grid is 1 cm while liquid-gas interface is in the middle to create a xenon gas gap of 5 mm thick.

The grid dimension used in COMSOL simulation is introduced in Figure 5.1.

For the geometry of parallel-wire grid used in COMSOL: anode grid is 0.2 mm diameter circles of 2mm spacing; all the other grid: the gate grid, cathode grid and bottom PMT screening grid are 0.2 mm diameter circle of 4 mm spacing. All of them are assumed to have revolved symmetry along z-axis feature in default implemented in COMSOL 2D symmetric simulation.

Moreover, as the zoomed view of Figure 5.1 shows, all the edges of field components such as field ring and grid ring have been smoothed to any potential high field originated from sharp edges. The parts in yellow in the Figure 5.1 indicate that they are made of metal materials.

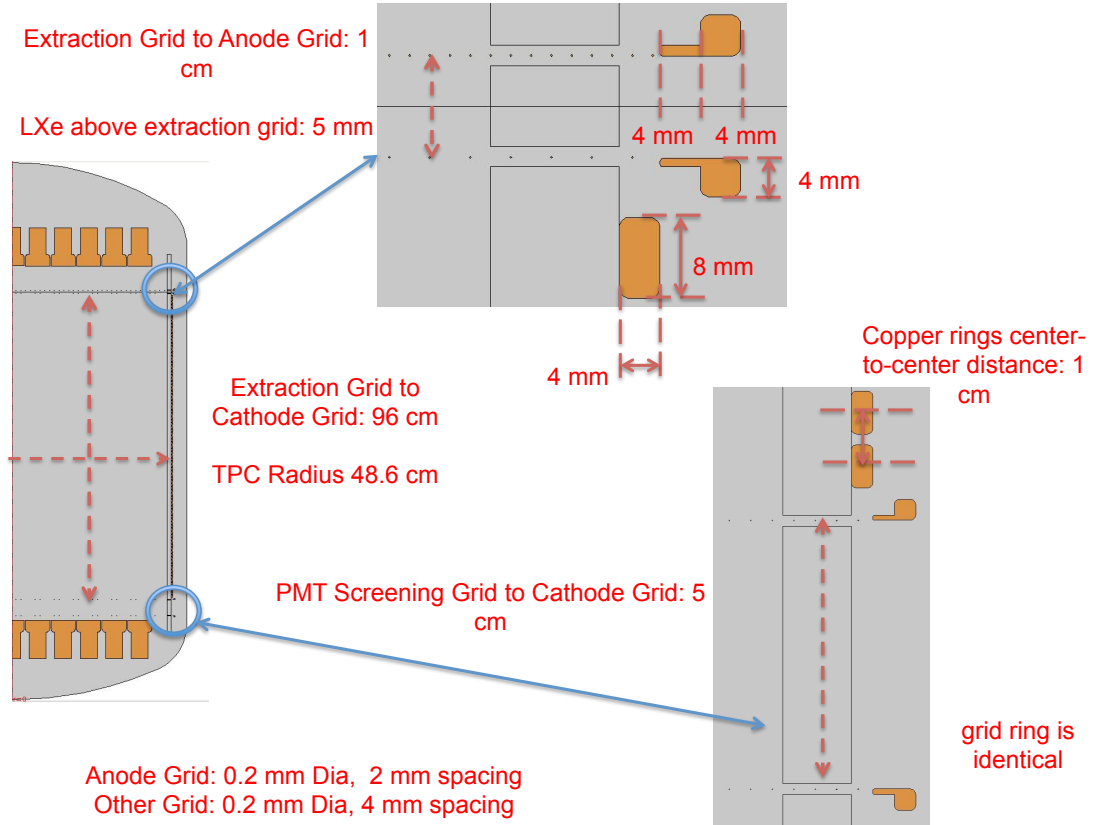


Figure 5.1: the 2D symmetric geometry of XENON1T TPC used for the field simulation. The zoomed view of anode grid corner and cathode grid corner are also shown with the specific dimension listed.

5.1.2 Configuration and Optimization of Applied Voltage

XENON1T TPC is designed to equip with a drift field of 1 kV/cm in liquid xenon and an electro-luminescence field of approximately 9.9 kV/cm in 5 mm xenon gas region. Hamamatsu ¹ 3-inch PMTs will be used on both top and bottom photon-sensor arrays. Therefore the parameters **PMT_Volt**, **ExtractionField_Volt** and **Field_Volt** are fixed to -1700V, -7500V and -1000V respectively in order to meet the TPC field requirements.

Several other voltage parameters are used in COMSOL simulation to optimize the uniformity of TPC electric field. As already being demonstrated in other TPC field simulation before [91, 85], the most non-uniform and sensitive to voltage-variation regions within TPC active volume are anode and cathode corners close to PTFE wall. Those two regions are present in zoomed view in Figure 5.1 and Figure 5.2.

Moreover, Figure 5.2 gives the anode and cathode field components where specific voltage parameters are assigned. Region not shown in Figure 5.2, between anode and cathode, is the copper rings array with a constant descending voltage -1000V every step.

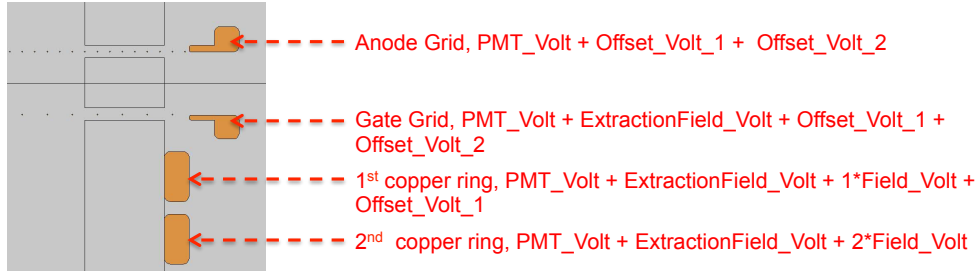
Independent optimization of electric field uniformity has been carried out in both anode and cathode regions. Three kinds of field optimization are conducted as the following shows:

1. In the anode region, two extra voltage steps are implemented by two parameters: **Offset_Volt_1** and **Offset_Volt_2**. The voltage step **Offset_Volt_1** is between first while the other voltage step **Offset_Volt_2** is between first field ring and gate grid.

The parameters **Offset_Volt_1** and **Offset_Volt_2** are optimized to optimize the field in anode region, especially the active volume close to

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Anode Voltage Settings



Cathode Voltage Settings

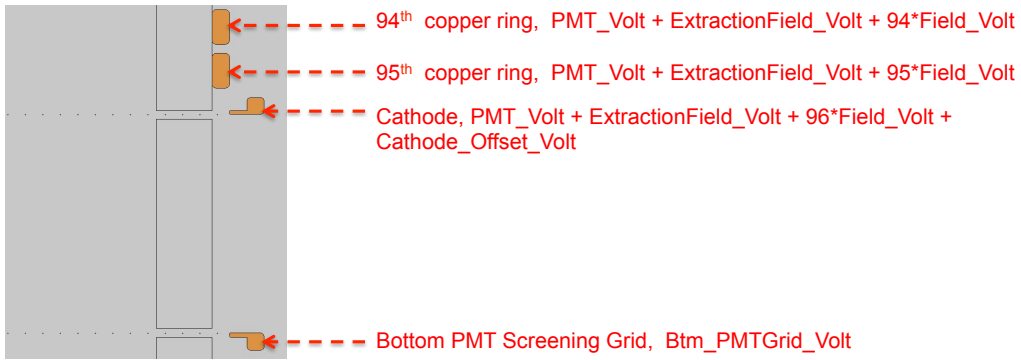


Figure 5.2: The applied voltage configuration used in 2D XENON1T TPC field simulation.

PTFE wall.

2. In the cathode region, another additional voltage difference introduced by parameter **Cathde_Offset_Volt** is applied between last field ring (the 95th field ring) and cathode. This parameter is also used to improve the field in cathode region.
3. The parameter **Btm_PMTGrid_Volt** is the voltage to apply in the bottom PMT screening grid. Instead of standard value -1700 Volt the 3-inch PMT high voltage, this parameter is optimized to reduce the field leakage from cathode into bottom PMT region.

Because of the extremely high voltage applied on cathode (-107.8kV) and the

narrow region between cathode grid and PMT screening grid (50 mm), some other voltage even positive voltage is needed to put on the PMT screening grid in order to counter-balance the field leakage from area containing extremely strong field. Specific voltage value is optimized to guarantee that region between the screening grid and PMT array is quip-potential and doesn't contain external leakage field.

Table 5.1: Parameter Value After Field Optimization of TPC

Parameter Name	Value [Volt]
hlineOffset_Volt_1	-100
Offset_Volt_2	-250
Cathde_Offset_Volt	-2600
Cathde_Offset_Volt	-250
Btm_PMTGrid_Volt	1300

By following the optimization procedure listed above, all the optimized parameter values are shown in table 5.1. The following results of electric field presented in Figure 5.4 and the electron drift path in active volume shown in Figure 5.5, are calculated based on the optimized parameter values.

5.1.3 XENON1T TPC Electric Field

Once the specific geometry (in this case, two-dimensional and symmetric) and voltage configuration are finalized, COMSOL electrostatic package is employed to conduct the simulation and to generate the full voltage map for the given geometry and voltage configurations. The voltage map from COMSOL simulation is demonstrated in Figure 5.3.

Based on simulation result of voltage map, quip-potential lines can be generated by COMSOL and drawn separately. This result is shown in Figure 5.4, where the same unit kilo-volt is in use for the legend on the right.

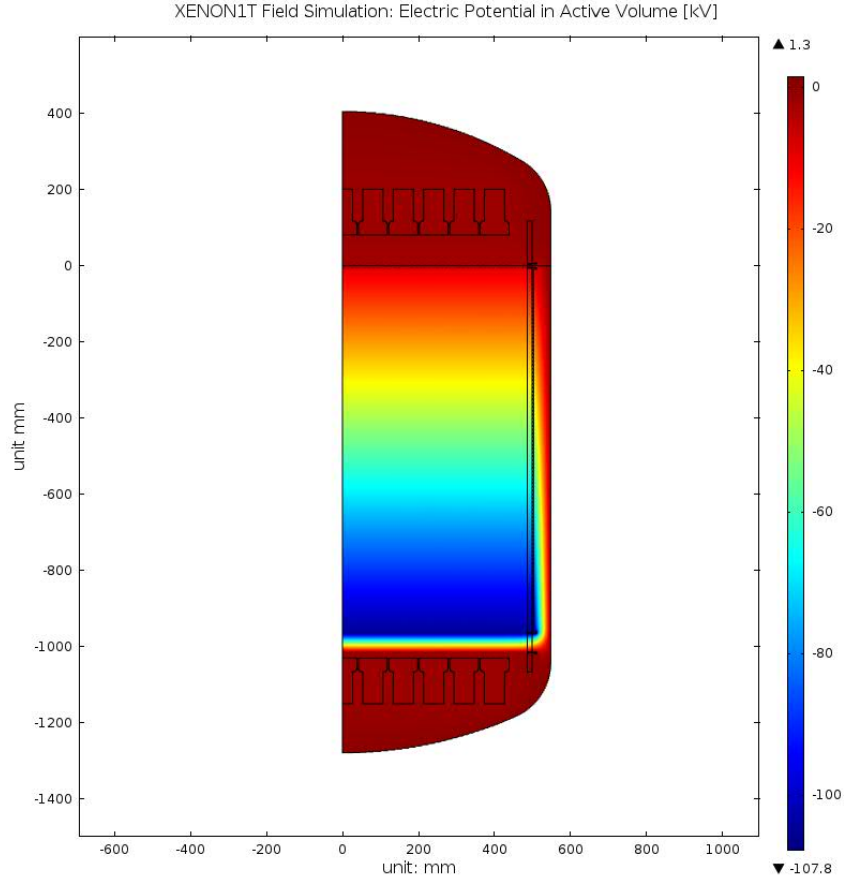


Figure 5.3: XENON1T TPC simulation result of voltage map. The voltage value is color coded as the legend on the side shows. Color legend (in unit of kilo-volt) also provides the voltage range within TPC.

Once free electrons are created by ionization inside the TPC active volume, the original random thermal motion is immediately affected by the external electric field. When the external influence becomes dominant, free electron is expected to drift upwards due to external electric field and therefore follows the electric field distribution [104, 26].

COMSOL also provides the function to show the streamlines, which is perpendicular to the equip-potential line. These streamlines as demonstrated in Figure 5.5 are expected to be the electron-drifting path inside XENON1T TPC.

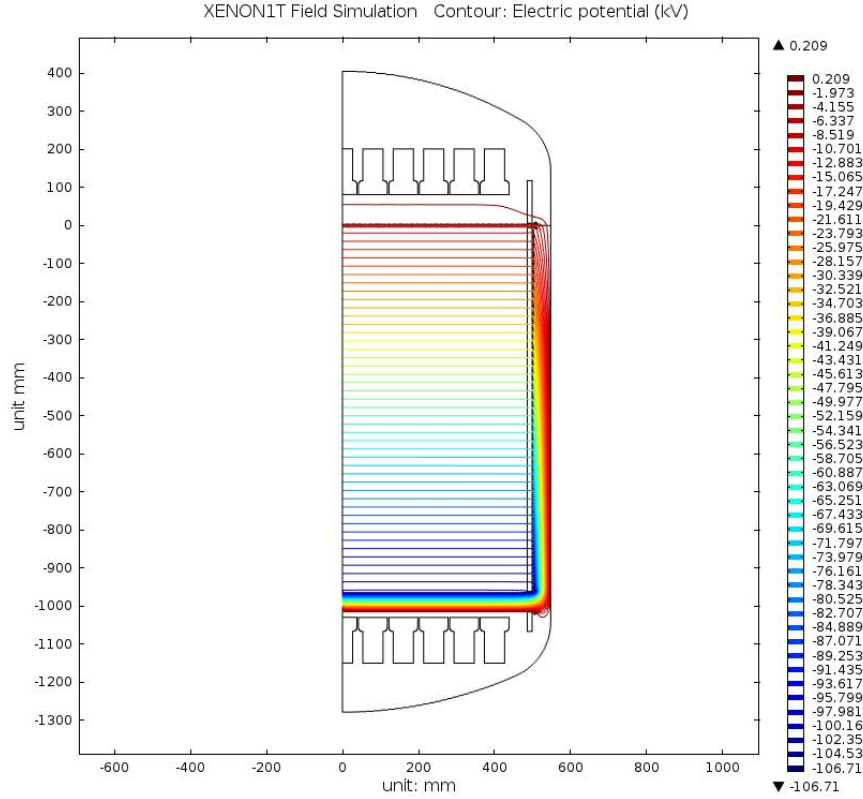


Figure 5.4: The equip-potential line distribution of XENON1T TPC. These equip-potential lines are based on voltage map Figure 5.3.

5.1.4 Electron Drift Path and Displacement

The electron drift path inside TPC is demonstrated in Figure 5.6. The electron-drift paths are expected to be uniform all over the entire XENON1T TPC. However, zoomed views of anode and cathode region provide the understandings in detail. Figure 5.6 and Figure 5.7 are zoomed views of anode and cathode respectively.

Streamlines (electron-drift paths) are produced horizontally from cathode region every 10 mm. The electron-drift path originated close to PTFE wall is visibly kinked before reaching the extraction grid in Figure 5.6 of anode region. This is due to the non-uniform field that drift path goes through.

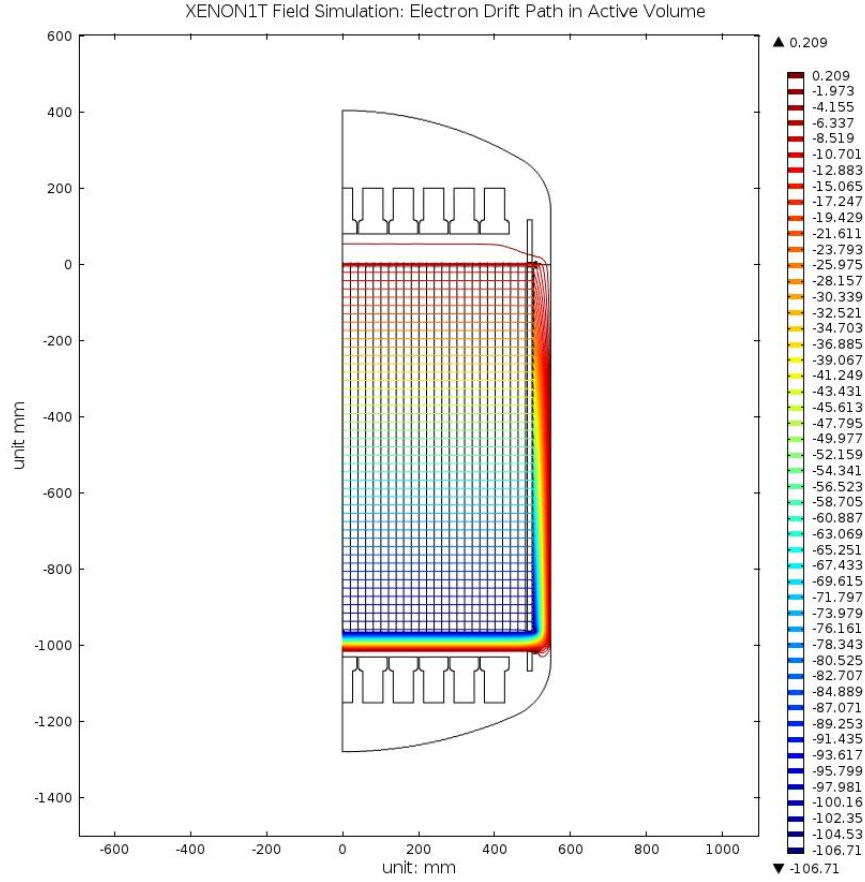


Figure 5.5: Electron drift path is demonstrated in black lines from cathode to anode inside TPC active volume. Drift path is expected to be perpendicular to the equipotential lines in Figure 5.4.

Moreover, the electron drift path is clearly distorted as Figure 5.6 and Figure 5.7 show when passing through metal grids. Two factors: non-uniform field and grid field are affecting the electron-drift path. In current field simulation result, the grid field is leading factor compared to non-uniform field.

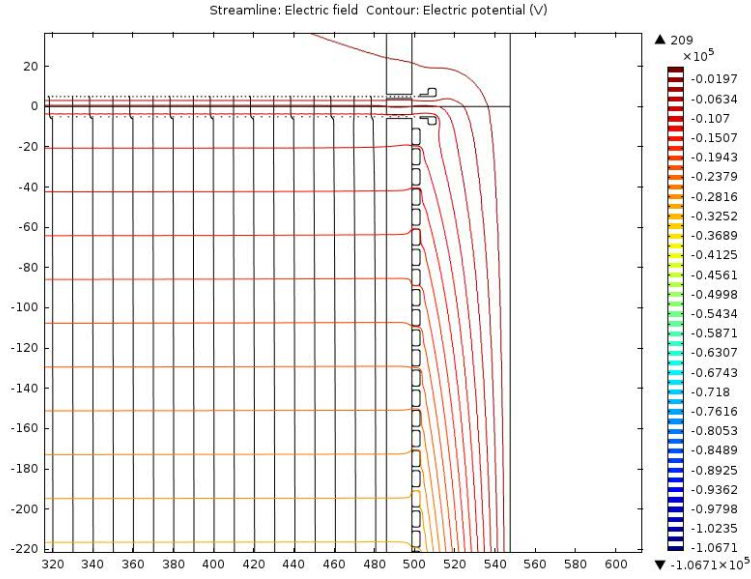


Figure 5.6: A zoomed view of anode corner, electron drift path is in black and perpendicular to the equip-potential lines. The horizontal and vertical dimensional axis is in unit of mm. The liquid-gas interface is assumed to be zero in y-Axis.

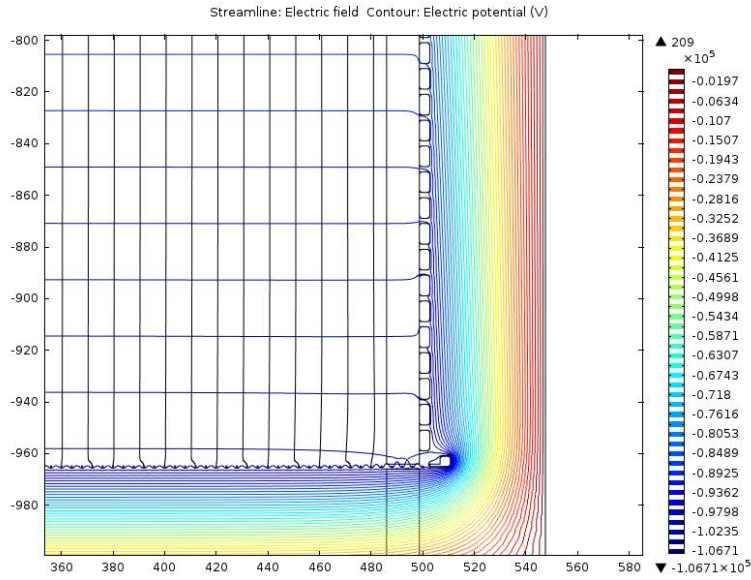


Figure 5.7: A zoomed view of cathode corner; electron drift path is in black and perpendicular to the equip-potential lines. The horizontal and vertical dimensional axis is in unit of mm. The liquid-gas interface is assumed to be zero in y-Axis.

In order to quantitatively measure and compare the distortion of electron-drift paths, 10 streamlines (the equivalent electron-drift paths) R varying from 475 mm to 485 mm are generated as Figure 5.8 show near the TPC PTFE wall (at $R=486$ mm).

The effect of grid field on electron-drift paths is present in Figure 5.8. Distortion extent depends the location of drift path with respect to the grid wire. Grid field does not affect drift paths going through the middle of grid wires while distorts the path right beneath grid wires most, approximately half of wire spacing: extraction grid uses 4 mm spacing, which corresponds to a 2 mm maximal displacement.

Meanwhile the effect due to non-uniform drift field are quantitatively measured and compared in Figure 5.8. All three drift path are plotted within $z = -960$ mm and $z = -10$ mm to separate the grid field influence. In generally, closer to the PTFE wall, larger the drift path displacement is. The $R = 485$ mm path has the largest displacement about 1.5 mm in anode region.

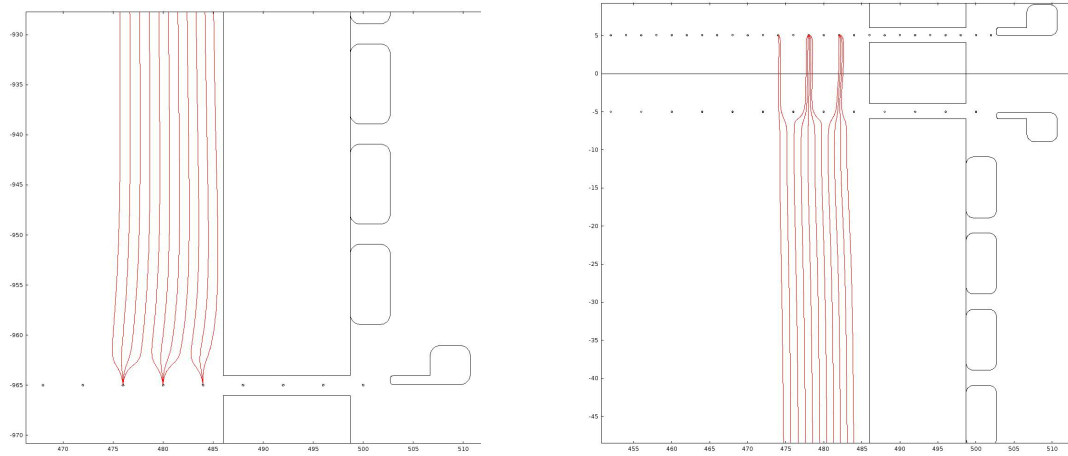


Figure 5.8: The zoomed views of ten electron drift paths at the regions of anode and cathode close to the PTFE wall.

5.2 Simulation of Drift Electron Transparency across Metal Mesh

The presence of a conductive grid in ionization detectors affects both optical and drift-electron transparency. The electric field of ionization detectors is simulated in two and three dimensions using COMSOL, a finite element analysis simulation package [5]. Drift-electron transparency across the grid is analyzed accordingly. Higher electric field ratios across the metal grid result in enhanced drift-electron transparency. Using optical transparency as a geometrical parameter, this work reports the minimal electric field ratio required to reach full drift-electron transparency for grids in various configurations. Grids consisting of parallel wires with various cross-section are studied. Hexagonal, triangular and square grids are also considered. Corresponding uncertainties originating from simulation and analysis are discussed and compared.

5.2.1 Introduction of Metal Grid Application in Ionization Detector

Many types of detectors have been developed for ionization detection. One such detector is an ionization chamber [110, 15], which consists of two parallel conductive planes as electrodes. By applying different voltages on each electrode, an electric field is created in the region between them. When ion-electron pairs are generated via ionization in this sensitive volume, the ions and electrons are immediately separated and drifted in opposite directions by the applied electric field. Signals are collected at the electrodes via an induced mirror-charge. The use of a metal grid between electrodes in ionization chambers was first introduced by O. Frisch [74] and is widely used in various ionization detectors today. This type of grid is also called a Frisch grid. The presence of a Frisch grid creates two relatively electro-insulated regions between the anode and the cathode. In this report, the region between the anode and the metal grid is called the upper active volume

while the region between the metal grid and the cathode is called the lower active volume to facilitate the description in the following sections. This metal grid provides several advantages for the ionization chambers. The Frisch grid screens the signal-collecting anode from charged particles when they are created by ionization in the lower sensitive volume. The anode does not receive any mirror-charge signal until the electrons cross the grid into the upper active volume. Therefore, the anode-collected signal is only from electrons generated by ionization in the lower active volume, and the impact from associated ions is minimized. Moreover, because electrons are visible to the anode only after crossing the Frisch grid, the induced mirror-charge signal is independent of where the ionization happens.

However, the addition of the Frisch grid limits the anode electron signal: only electrons that cross the metal grid are visible to the anode. All electrons that hit the metal surface of the grid are absorbed. In this process, the specific drift paths of electrons in an ionization chamber follow the electric field distribution. So different field distributions lead to different electron drift paths across the metal grid. Other than the grid, the concentration of electron-absorbed ions in the drift medium also affects the drift electrons in the ionization chamber. This effect is not included in the current study. In addition, as long as the drift velocity determined by the electric field is sufficiently high [104], the lateral diffusion of electron clouds [106] is a sub-dominant factor compared to the drift path.

Other than in ionization chambers, metal grids are also widely utilized in time projection chambers (TPCs) for dark matter research [17, 31, 13]. Dark matter detectors with liquid noble elements placed deep underground detect possible interactions with dark matter particles. In dual-phase dark matter detectors, both scintillation signals and ionization signals are collected by photo-multiplier tubes (PMTs) at the top and the bottom of the detectors. Specific introduction of dual-phase TPC and working principles can be found in following sections. Photons generated via scintillation are directly collected by PMTs as the primary signal,

called S1. Similar to ionization chambers, the electric field in the lower active volume separates the electrons from ion clouds and drifts them upwards until they cross the metal grid. The metal grid is used to create a stronger electric field in the region between the metal grid and the anode. After entering the upper active volume, electrons are pulled out of the liquid phase and into a gas phase pocket by a stronger extraction field. As the electrons propagate in the gas phase, they generate photons via electro-luminescence, making up the secondary signal S2. Photons associated with both S1 and S2 must propagate within the detector medium before they are collected by the PMTs. However, the metal grid used in this type of TPC may absorb the photons and cause a loss of the signal. The photon loss caused by the metal grid is treated as optical transparency in this study. In order to simplify the impact of photon loss due to the existence of a metal grid, the photons are assumed to transmit only in the longitudinal direction. The optical transparency for all metal grids studied in this report is defined as $(\text{Total Area} - \text{Metal Area})/\text{Total Area}$ in the cross-section plane.

In detectors where metal grids are placed between the cathode and the anode, with the metal grid fixed to a certain electric potential, distinct electric fields are produced in each volume by applying different voltages on the anode and the cathode. In the case where the fields in the two volumes are equal, the associated electron transparency becomes $(\text{Total Area} - \text{Metal Area})/\text{Total Area}$, the same as the optical transparency. However, when the electric field in the upper active volume is altered, the skewed electric field distribution near the metal grid is able to bring more electrons from one side of the metal grid to the other. This work focuses on the minimal electric field ratio across the metal grid that is required to reach a full drift-electron transparency.

5.2.2 Setups in Finite Element Analysis

5.2.2.1 Method and Parameters Used in Finite Element Analysis

Finite element analysis is based on the numerical technique: the finite element method (FEM) [113]. The finite element analysis software COMSOL [5] is extensively employed in this work to study the drift-electron transparency across metal grids of various geometries. In this study, the physics module AC/DC from COMSOL is used for all the simulation work. This study reports the drift-electron transparency of grids with ideally symmetric and uniform geometry, non-uniform field distribution around the grid edge and the non-smooth grid surfaces are ignored. Both two-dimensional (2D) and three-dimensional (3D) geometries are studied. Specific electromagnetic properties are defined for each elemental area in the 2D framework and for each elemental volume in the 3D framework. The voltages associated with the anode and the cathode are represented by boundary conditions in the simulation. After the geometry is created and relevant electromagnetic properties are assigned to each material, the meshing process in COMSOL divides the simulated geometry into a large number of finite elements. In all 2D geometries, the elements are triangular with maximum side length $50\text{ }\mu\text{m}$ and minimum side length $0.1\text{ }\mu\text{m}$. In 3D geometries, the elements are tetrahedral with maximum and minimum edge length of $500\text{ }\mu\text{m}$ and $0.5\text{ }\mu\text{m}$, respectively. In general, a specific element's size is determined by its local geometry; elements of smaller size are implemented in narrow or curved regions, where variation of parameters is more significant. When the geometry is completely separated into elements, each element contains all the parameters necessary to describe the local electromagnetic properties. Based on these elements and the local electromagnetic boundary conditions between adjacent elements, COMSOL generates the electric field distribution that satisfies all boundary conditions. As has been demonstrated [26, 42, 43], when the applied electric field is strong compared to the

inter-atom coulomb interaction strength, the electron drift path follows the electric field distribution, and the electric field is referred to as a drift field. From the generated electric field distribution, equipotential lines are generated by COMSOL. Figure 1 shows an example of electric field lines and equipotential lines generated by COMSOL.

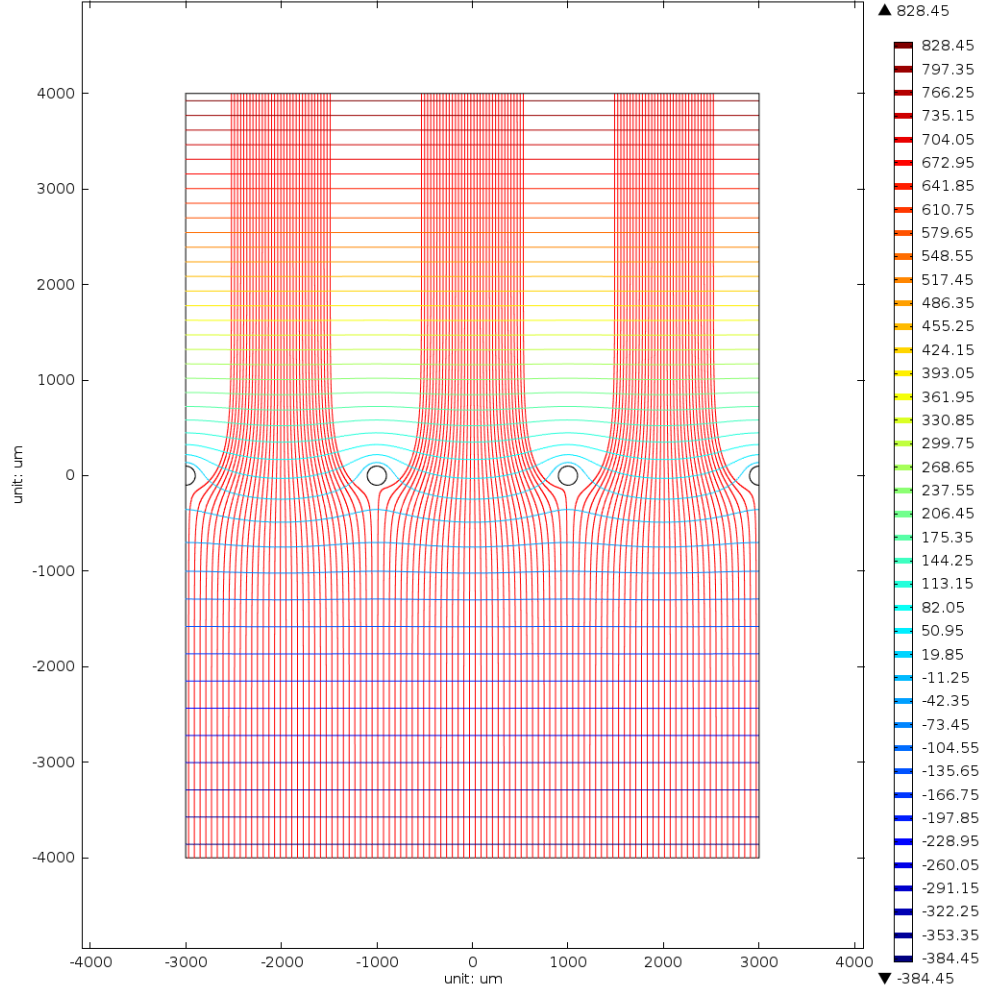


Figure 5.9: Grid made from parallel wires is shown in the 2D framework as the black circles. The wire diameter is $50 \mu\text{m}$ and the spacing between two adjacent wires is 2 mm . The COMSOL simulation result is presented with electron drift paths in red and equipotential lines in different color to indicate different voltage values. The unit of values listed in the color legend is volt.

5.2.3 Finite Element Analysis Setups in 2D System

In the 2D study limited to ideal grid geometry, a perfectly symmetric metal grid is employed to simulate the electron drift paths across the grid. The 2D geometry of a parallel-wire grid used in COMSOL simulation can be found in Figure 5.9. In this simulation setup, the horizontal lines on the top and bottom are the ideal anode and cathode. The grid, represented by circular wires in parallel (black circles in Figure 5.9), is located in the middle. The voltage associated with the grid is fixed to ground. The relevant dimensions of Figure 5.9 are as follows: the diameter of the grid's circular wire is $50\text{ }\mu\text{m}$, the pitch is 2 mm , and the distance from anode to cathode is 8 mm . These dimensions are representative of an actual TPC or ionization chamber, where the distances between the grid and electrodes are several orders of magnitude larger compared to the diameter of the grid wire. Consequently, the electric field impact from electrode geometry is negligible, so flat conductive planes are a good approximation for the electrodes in this work.

Two separate volumes are created by placing the metal grid between the anode and the cathode. Each volume acts as a Faraday cage, and near the metal grid the two regions have limited influence on each other. When the metal grid voltage is set to ground, the anode and the cathode voltages are set to different and oppositely signed values. The applied high voltages are able to generate different electron drift fields in the two volumes. In the case where the anode and the cathode voltages have the same magnitude, identical drift fields are created in each volume, and the drift-electron transparency across the metal grid is determined by the grid's geometry. In this case, like the optical transparency previously defined, the drift-electron transparency is the cross sectional area of the metal grid divided by the total cross-sectional area. However, if a higher magnitude of voltage is applied to the anode than to the cathode, the volume between the anode and metal grid will hold a stronger electric field than in the volume between the cathode and the grid. The stronger electric field can penetrate through the

Table 5.2: 3D Grid Geometrical Parameters

Cell Type	Geometry Parameters	Symmetric Geometry	Optical Transparency
Hexagonal Cell	Cell Pitch L Wire Thickness D	Fig 5.10.A	$\frac{(L-D)^2}{L^2} \times 100\%$
Square Cell	Square Side Length L Wire Thickness D	Fig 5.10.B	$\frac{(L-D)^2}{L^2} \times 100\%$
Triangular Cell	Triangle Side Length L Wire Thickness D	Fig 5.10.C	$\frac{(L-\sqrt{3}D)^2}{L^2} \times 100\%$

metal grid and leak into the lower volume, which skews the local electron drift paths across the metal grid, as shown in Figure 5.9. When the difference between the electric fields on each side of the grid is sufficiently strong, the skewed electric field (and thus also the electron drift paths) will completely bypass the metal grid and a full drift-electron transparency will be reached. Any larger electric field differences across the grid will also render a full drift-electron transparency. The minimal ratio of two different drift fields to create full drift-electron transparency is studied and compared in the following sections.

5.2.4 Finite Element Analysis Setups in 3D System

In the 3D framework, three different types of grid are simulated: hexagonal, square and triangular. All the grids have a square cross-section. Five specific cases of optical transparency are independently simulated: 97.5%, 95%, 92.5%, 90%, 87.5% and 85%. For each type of grid, some geometry parameters are adopted to describe each grid (see Table 1). Generally, the total metal area of the grid is characterized by a parameter proportional to the ratio between wire width and cell pitch.

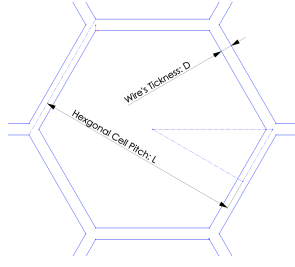


Figure 2.A

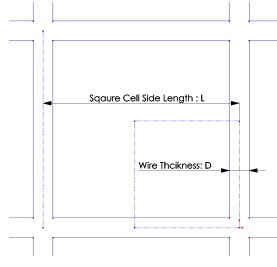


Figure 2.B

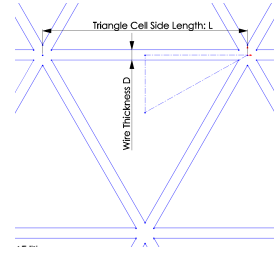


Figure 2.C

Figure 5.10: The parameters used to define the grids are presented for each geometry. The symmetric part of a single cell employed in the 3D framework to depict the grid is the region confined by the dashed lines.

Because the metal grids studied in this 3D simulation all have repeated patterns of symmetric shapes and because the horizontal size of the grid is several orders of magnitude larger than its vertical scale, the regional electric field distribution across each cell is the same over the entire grid. The symmetry of each cell can be utilized so that a single cell is represented by only a symmetric part, rather than its entirety. Hexagonal, triangular and square cell patterns are shown in Figure 5.10, with the corresponding geometrical parameters listed in the second column of Table 5.2. The symmetric part of each type of cell is depicted by the dashed lines. The symmetric part of each cell is used in COMSOL to represent the full cell, which significantly reduces the 3D geometry size and minimizes the total number of meshing elements. This approach saves considerable CPU computing time and allows more detailed studies within smaller regions of the grid.

Specific example of the 3D hexagonal grid simulation is presented on the right side of Figure 5.11. The 3D geometry of the hexagonal grid is the triangular section as shown in Figure 5.10.A confined by dashed lines. The anode and the cathode plates are 5 cm away from the metal grid so the impact of edge effects is minimized. The electron-drifting paths, shown as the red lines in Figure 5.11, are uniformly generated on the surface of the cathode right beneath the 3D metal grid.

In cases of different electric field ratios, the electron-drifting paths are simulated and the 3D metal grid drift-electron transparency is calculated accordingly.

Other than grids of hexagonal, triangular and square shapes, grids made from parallel wires are also studied in the 3D framework, as shown on the left side of Figure 5.11. The geometry in two of the dimensions is identical to that shown in Figure 5.9, with the third dimension created by a 2 mm projection of the 2D geometry into the third axis. Another difference from the 2D simulation in Figure 5.9, is that the anode and the cathode are represented by conductive planes at the top and bottom, respectively. Comparison of the calculated drift-electron transparencies in the 2D and 3D cases are presented in the analysis section, along with an analysis of the systematic errors.

5.2.5 Metal Grid Drift-Electron Transparency Calculation and Analysis

5.2.5.1 Bunemann's Approximate Calculation in 2D

Bunemann calculated the necessary ratio of electric fields across a metal grid of the parallel-wire type to obtain full drift-electron transparency [44]. In this approximate calculation, line dipoles were introduced by circular wires and terms of order r^3 and higher were neglected, to facilitate the calculation. The minimal ratio of electric fields across the metal grid to reach full drift-electron transparency is expressed as:

$$\frac{E_{\text{above}}}{E_{\text{below}}} > \frac{1 + \rho}{1 - \rho}$$

In this equation, the parameter ρ can be explicitly written as $\rho = \frac{2\pi R}{L}$, where R is the metal grid's wire radius and L is the pitch between centers of adjacent two parallel wires.

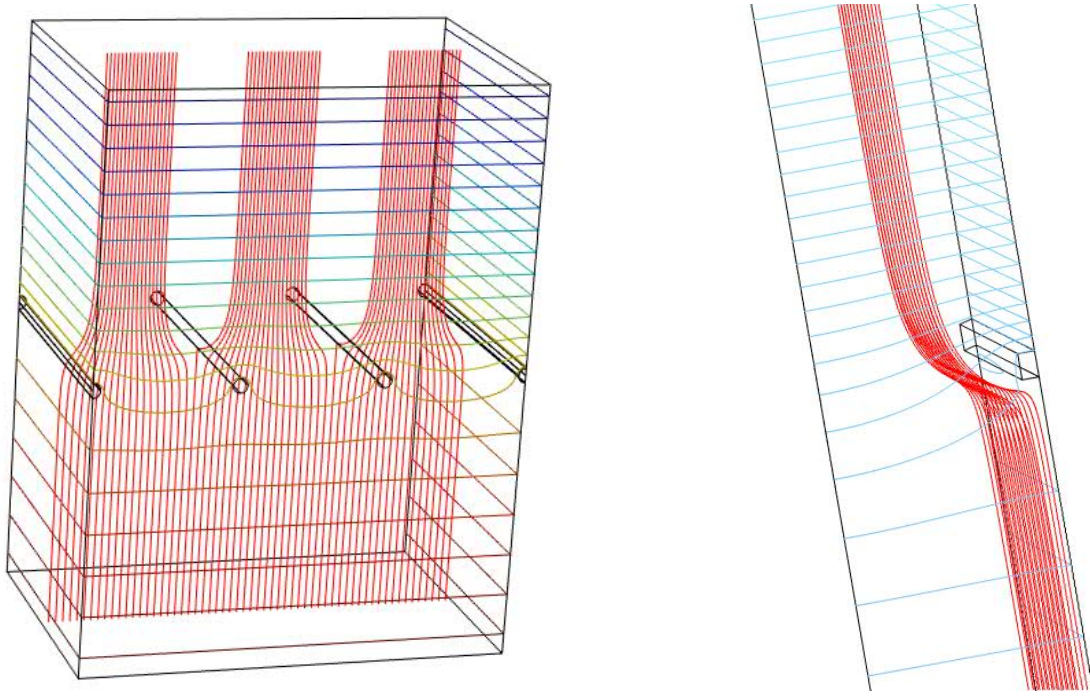


Figure 5.11: 3D geometry of a grid with circular and parallel wires is shown in the left section. The geometry of a 3D hexagonal grid simulation is shown in the right section. The equi-potential contours are shown on in different colors on the geometry's surface. Drift-electrons are created along the line at the center of the bottom surface representing the cathode, the associated drift-electron paths are the red lines passing through the grids. In order to clearly distinguish the drift paths, much fewer drift paths are intentionally shown than those used in the actual simulation process.

Based on the result from Bunemann's calculation, the minimal ratio of electric fields is a function of ρ . As described in section 5.2.1, the optical transparency of a metal grid is also considered an important characteristic. It is especially important in dual-phase TPCs, where the primary scintillation signal is critical for both energy scale and background suppression. The optical transparency of the metal grid in the active volume is maximized in order to achieve the greatest light collection. The optical transparency for this type of metal grid is generally

written as $\frac{L-2R}{L}$. The results of a minimal drift field ratio for a full drift-electron transparency is shown in Figure 5.12, where the optical transparency is used as the geometrical parameter.

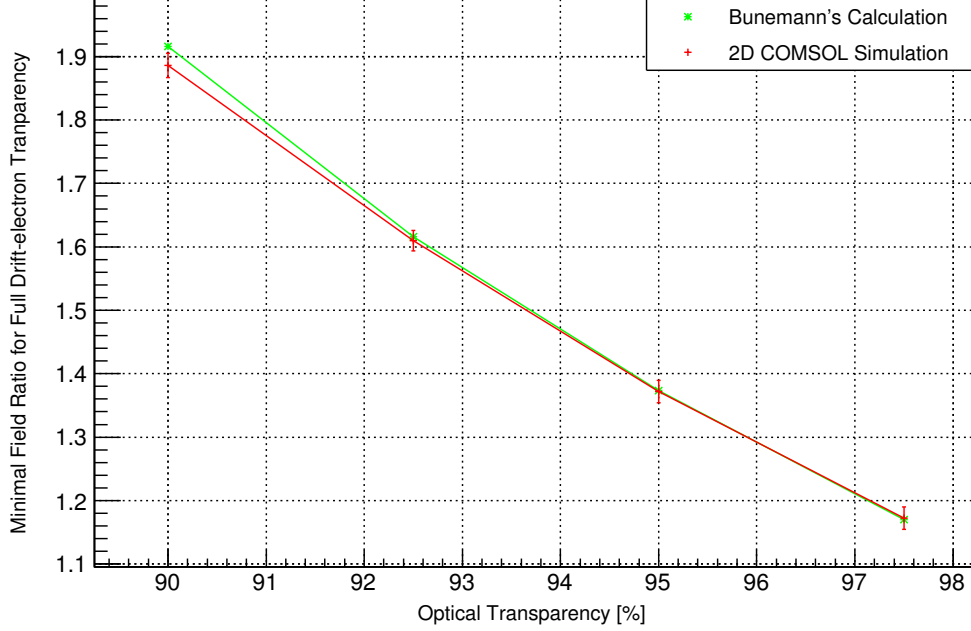


Figure 5.12: In four different cases of optical transparency, the results from the COMSOL simulation are compared with Bunemann's approximate calculation. The error bars of the simulation results are taken as systematic uncertainties.

5.2.6 Dependency of Electron-Transparency on Wire Geometry in 2D Analysis

In the 2D framework, COMSOL is used to measure the minimal drift field ratio to achieve the full drift-electron transparency across parallel-wire grids of various geometric configurations. While keeping a constant pitch of 2 mm, the wire radius varies among 25 μm , 50 μm , 75 μm and 100 μm . Similar to the geometry shown in Figure 5.9, the cathode is set to a fixed negative voltage in order to create a constant drift electric field with a magnitude of 1 kV/cm in the lower active

volume. First, an equal positive voltage is applied to the anode so that the electric field ratio is 1. Then this positive voltage on the anode is gradually increased in steps of 50 V. For every anode voltage, 2000 electron drift paths are generated uniformly at the cathode, as shown by the red lines in Figure 5.9. These red lines represent the electric field distribution which is equivalent to the electron drift paths. The positive anode voltage is raised until all the electric field lines originating from the cathode pass the parallel-wire grid, upon which the drift-electron transparency reaches 100%. The corresponding electric field amplitudes in both the upper and lower active volumes are then recorded to calculate the minimal electric field ratio required for a full drift-electron transparency, given a certain grid geometry. Moreover, the uniform electric field around the cathode and the anode is checked in every case to guarantee that the influence of electrode geometry on the electric field is negligible. Results of the comparison between the COMSOL simulation and Bunemann’s calculation are given in Figure 5.12.

As demonstrated in all reported results, the geometry of the parallel-wire grid is expressed as an optical transparency. This is accomplished by varying the pitch from 1 mm to 3 mm while changing the wire diameters accordingly. This is examined in the 2D framework, with results shown in Figure 5.13. The associated variation of the minimal field ratio caused by this geometric modification is extremely small. Quantitative analysis of this result is discussed in the systematic uncertainty analysis section.

The influence of wire cross-section geometry on the parallel-wire grid drift-electron transparency is also studied in the 2D framework. A geometry was created similar to that in Figure 5.9, but instead of wires of circular cross-section, wires of square cross-section were used. The associated optical transparency is $\frac{L-D}{L}$ where L is the pitch between two adjacent wire centers and D is the side length of the square shape wire. The same approach is followed to gradually increase the anode voltage in steps of 50 V. The minimal field ratio for full drift-

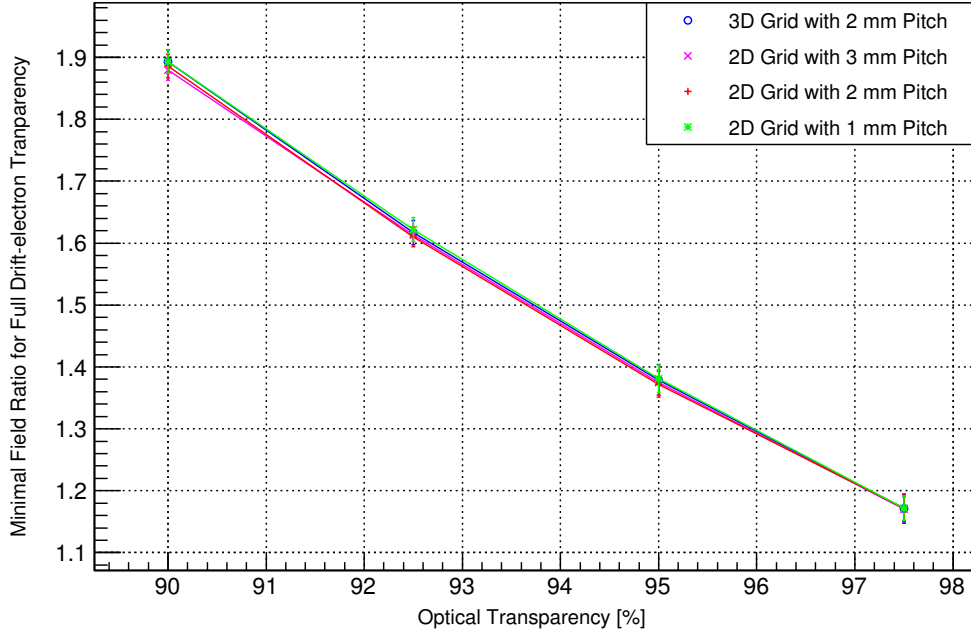


Figure 5.13: In the finite element analysis of a 2D grid made of parallel-wires, pitches of 1 mm, 2 mm and 3 mm are used for comparison. The results using the 2 mm pitch in the 3D framework is also shown. For the geometry of each analysis point shown above, the diameter of the circular wire is changed to maintain the desired optical transparency level.

electron transparency is achieved when all 2000 drift-electron paths successfully pass through the parallel-wire grid. The corresponding results are also compared with the previous results using circular wires in Figure 5.14.

5.2.7 Electric Field Ratio for Full Drift-Electron Transparency Across the Metal Grid in 3D Analysis

In the 3D framework, a similar approach to that used in the 2D framework is implemented to measure the minimal electric field ratio needed to reach full drift-electron transparency across the metal grid. The only difference is the process

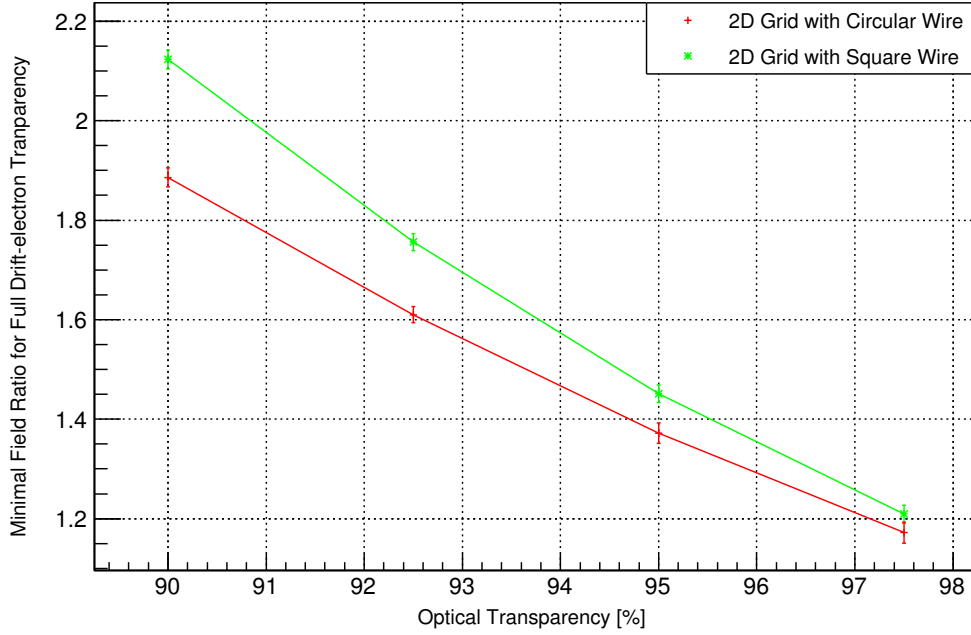


Figure 5.14: The minimal electric field ratio for 100% drift-electron transparency is simulated and compared as a function of optical transparency. Grids of square shape and circular shape wires are considered.

of drift-electron path generation. Instead of uniformly creating them on a line representing the cathode, the area from the metal grid's projection on the cathode surface is used to uniformly generate the drift paths. This is because the drift paths that are not obstructed by the metal grid, will pass through the metal grid even at an electric field ratio of one. So the method of increasing the electric field ratio across the metal grid only affects the electron drift paths that are impeded by the metal grid in the case of a field ratio equal to one. Moreover, in order to have similar coverage of electron drift paths over the region of interests, rather than 2000 drift paths as created in the 2D simulation, 20,000 drift paths are generated in the region of interest for 3D studies. Three types of commonly used metal grids, hexagonal, triangular and square shape grids, are simulated in the 3D framework. The same parameter of optical transparency is used to quantify

the specific geometry characteristics of each type of grid. Associated geometrical parameters and optical transparency calculations can be found in Table 5.2. The final results are compared among grids of different geometrical configurations in Figure 5.15.

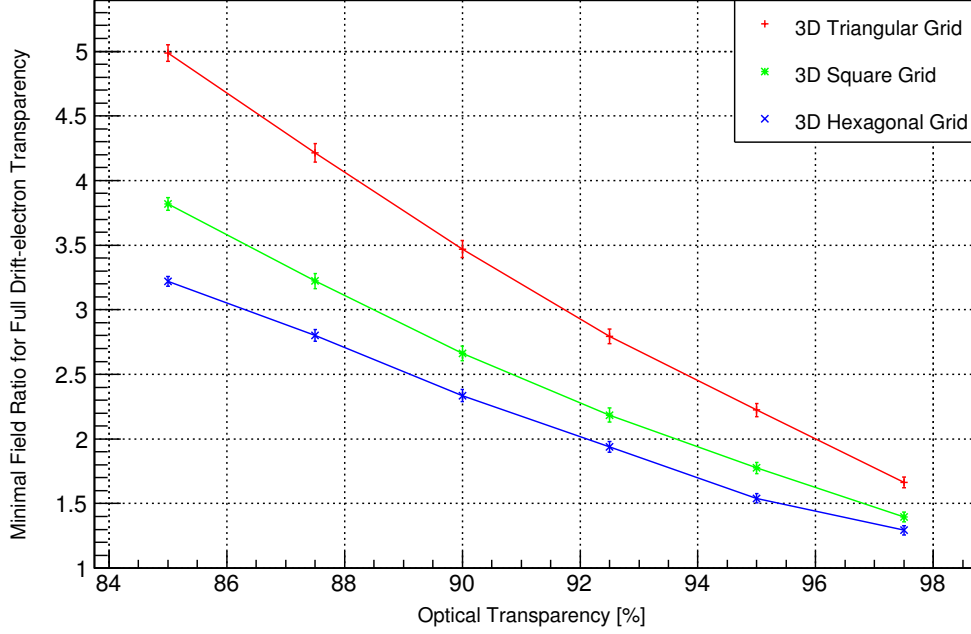


Figure 5.15: Three different 3D grids geometries are simulated. The results of the minimal electric field ratio which guarantees full drift-electron transparency across the metal grids are compared as a function of the optical transparency of the grid. The systematic uncertainties of each data point is shown as the associated error bar.

5.2.8 Systematic Uncertainties in the Finite Element Analysis

Several sources of systematic uncertainties are identified and analyzed in the process of measuring the minimal electric field ratio to achieve full drift-electron transparency across a metal grid in COMSOL. In the 2D framework, although the simplified 2D geometry is a good approximation for the symmetric metal

grids made from parallel wires, the 3D simulation is conducted for the same type of grid to verify the systematic uncertainties from the simulation framework selection. The results from the 2D simulation, of which the setup is demonstrated in Figure 5.9, is compared with those from the 3D simulation, shown in Figure 5.11. No significant variation is found, with the minimal field ratio discrepancy less than 0.5%.

The meshing element size used in FEM also contributes to the systematic uncertainty. In the 2D framework, simulations with $0.15\ \mu\text{m}$ elements are conducted to analyze the uncertainty related to the $0.3\ \mu\text{m}$ meshing element size used in this report. Moreover, larger meshing element sizes, such as $3\ \mu\text{m}$, are also used to check the impact of the FEM meshing element size on the 2D simulation results. A similar approach is adapted for the systematic uncertainty analysis in the 3D framework. The systematic uncertainty due to the meshing element size on the minimal field ratio is less than 0.5% and 1% for the 2D and 3D results, respectively.

Because the drift-electron paths are uniformly generated on the cathode surface, the total path number gives the coverage density of the area of interest. Therefore, the total number of electron drift paths generated to evaluate the grid transparency is identified as another origin of systematic uncertainty. In the 2D simulation when the number of drift-electron path is doubled, all the paths still pass through the metal grid at minimal field ratio result. In the case where the largest 3D area of interest is studied, the systematic uncertainty is studied by increasing the total drift paths from 20,000 to 22,000. With the additional 2000 drift-electron path, another seven drift-electron paths are found to be blocked by the grid. When the voltage applied to the anode is increased by 50 V, all the drift-electron paths reach the anode. So the systematic uncertainty stemming from the number of drift-electron paths is limited by the voltage increase step in this report.

The minimal field ratio study is conducted by raising the voltage applied on the anode in steps of 50 V, until all the 20000 drift paths are able to pass through the metal grid. Therefore, the finite voltage increasing step used in this work also contributes to the systematic uncertainty. This source is studied by changing the voltage increasing steps to 20 V and 10 V respectively. By comparing the results from smaller increasing steps to those with 50 V, contribution of the voltage increasing step size to the systematic uncertainty is around 1% and therefore is the leading source of the systematic uncertainties.

5.2.9 Case Study: Electron Transparency Analysis for the Grid Used in DarkSide-10 Detector

The DarkSide-10 detector [17] is a dual phase liquid argon TPC operated underground at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. The DarkSide-10 detector grid consists of hexagonal cells of 5 mm side length and 50 μm wire thickness. This grid is placed 5 mm below the argon liquid-gas interface with a corresponding electric potential fixed to ground. By applying a positive high voltage on the anode, two different but co-related electric fields are created in the liquid and gas phases between the grid and the anode. The electric fields in the two different phases constitute the extraction and electroluminescence fields. The extraction field pulls the drift-electrons across the grid while the electroluminescence field extracts the electrons from the liquid phase and accelerate the electrons in the gas phase before reaching the anode. The electron acceleration process continuously generates photons along the drift path in the gas, producing the signal S2. In the DarkSide-10 TPC, an argon gas pocket of 20 mm height is on the top of 5 mm liquid argon above the metal grid. The liquid argon below the metal grid is about 200 mm deep. In this case study of the DarkSide-10 grid's drift-electron transparency, only 40 mm of liquid argon below the grid is used in the 3D geometry. This reduced the geometry size and saves the CPU computing

time, while the uniformity of the electric field near the cathode is still guaranteed. All other geometrical parameters such as the height of liquid argon above the grid and the gas pocket height, are set to those used in the DarkSide-10 TPC.

Similar to the other 3D simulations carried out in COMSOL, only the metal grid in the ideal condition is considered in this work, the non-uniform field around the edge of the grid is ignored and the grid surface is assumed to be perfectly smooth. As pointed out in the other 3D setups, for the hexagonal grid with a symmetric pattern, only the symmetric one-twelfth piece of a single hexagonal cell is employed to simulate the electric field and the electron transparency of the DarkSide-10 grid. The details of the hexagonal cell used in the 3D simulation can be found in Figure 5.10.A.

Different from the other 3D simulations focusing on the minimal field ratio needed for 100% drift-electron transparency, this study simulates the metal grid drift-electron transparency at the different field ratios. In the entire study, a constant -4000 V is applied to the cathode to maintain a uniform 1 kV/cm electric field in the lower active volume. In every case of this study, a certain positive voltage is applied to the anode and 20,000 drift-electron paths are created uniformly across the entire cathode surface. The drift-electron paths that reach the anode surface, are counted as the drift-electron paths passing through the metal grid. The grid drift-electron transparency, as indicated along the vertical axis of Figure 5.16, is calculated as the ratio between the number of drift-electron paths passing through the metal grid and 20,000. The voltage applied to the anode is gradually increased from 0 V up to 2500 V, which corresponds to the increase of electric field ratio across the grid. As shown in the Figure 5.16, DarkSide-10 detector reaches full drift-electron transparency at an electric field ratio greater than or equal to 2.38. This result is consistent with the 3D hexagonal grid results

shown in the Section 5.2.5.

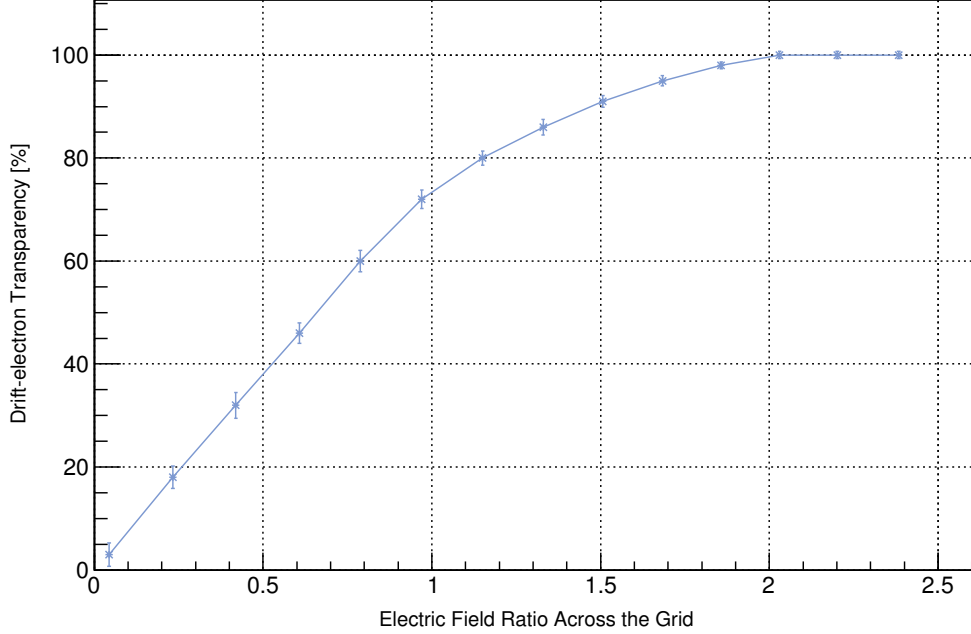


Figure 5.16: Drift-electron transparency of the grid used in the DarkSide-10 experiment is measured under different anode voltages, which is expressed as the electric field ratio (horizontal axis). The drift-electron transparency is calculated by the ratio of drift-electron paths passing through the grid to the number of total drift-electron paths generated on the cathode surface.

In the dual-phase TPC, the electroluminescence field needs to be large enough to extract electrons from liquid phase. Because electroluminescence field and the extraction field are proportional by the ratio of liquid and gas dielectric constants, the extraction field is high enough to create a field ratio that guarantee full drift-electron transparency across the grid. The DS-10 TPC operates with extraction field above 2.8 kV/cm [17], the corresponding field ratio is much larger than the minimal one to assure full drift-electron transparency. The situation is similar in the other dual-phase liquid xenon TPCs used in direct dark matter detection

experiments [31, 12], the detectors operate with extraction fields much higher than the minimal requirement for the full drift-electron transparency.

5.2.10 Discussion and Summary

The drift-electron transparency across the metal grid is studied in the case of ionization detectors, where an external electric field is employed to drift ionized electrons within the active volume. The drift-electron transparency of the metal grid is determined by the associated electric field ratio across the grid. This work reports the minimal electric field ratio across the grids to achieve full drift-electron transparency. Several types of metal grids are studied in both the 2D and 3D frameworks. All the geometries involved in this work are under the assumption of ideal conditions. This means geometry characteristics such as small sharp spikes on the electrode surface, non-symmetric patterns at the grid edges and electrode deformations caused by thermal contraction are not considered. Moreover, the electric field near the edge of the metal grids is not included.

First, the metal grid made from parallel wires was simulated in the 2D framework, the resulting minimal electric field ratio to achieve full drift-electron transparency is compared with Bunemann's calculation in Figure 5.12. This comparison shows an excellent agreement, in cases of high optical transparency. However, some discrepancy is observed in low optical transparency cases. It is believed to be caused by the fact that terms of order R^3 and higher are ignored in Bunemann's approximate calculation. Therefore, the discrepancy between the finite element analysis and Bunemann's calculation is significant only in cases of larger wires, corresponding to a lower optical transparency.

There are two reasons for the optical transparency to be selected as the geometrical parameters of the metal grids. One reason is that the drift-electron transparency across a metal grid is closely related to the associated optical trans-

parency but not the other geometrical parameters. For any grid of a certain type, the optical geometry generally gives the ratio of metal area to the total area. More metal area of the grid blocks more drift-electrons from passing through the metal grid and gives a smaller drift-electron transparency. While other individual grid geometrical parameters, such as pitch or wire diameter, can not be used to properly describe the drift-electron transparency because they do not reflect the specific metal area fraction when other parameters change at the same time. To demonstrate this, parallel-wire grids with different wire diameters are studied under the condition of identical optical transparencies shown in Figure 5.13. The results show an excellent agreement with the prediction. The other reason to use optical transparency, is that in the practical cases of grids used in dual-phase TPC, the signals are emitted in the form of photons. Therefore, the optical transparency is of great interest as it directly affects signal collection.

A detailed 2D study of parallel-wire grids also shows that the wire cross-section selection affects the drift-electron transparency. As presented in Figure 5.14, the parallel-wire grid with square cross-section demands a higher minimal field ratio for full drift-electron transparency, when compared to the circular case with the same optical transparency. This is because the shape of wires determines the amplitude of the field leakage, the influence of the higher electric field in the upper volume to the adjacent volume of lower electric field. The circular wire shape makes the field leakage stronger compared to the square case. The field leakage becomes the local field distortion right beneath the grid as introduced in Section 5.2.1, which is the driving force pulling electrons across the metal area. So grids made of circular wires need a smaller field ratio for full drift-electron transparency.

The trend that higher optical transparency requires a lower minimal field ratio for full drift-electron transparency, can be understood by extending the trend to the extreme conditions. When the optical transparency is close to 1, it refers to

the situation when the grid does not exist anymore. The photons can traverse freely without being absorbed on the grid; the field ratio will be 1 since the upper volume and the lower volume become a single volume. In the opposite scenario when the optical transparency is extremely close to 0, the grid is similar to a metal plate and no photons can penetrate through. Accordingly, the electric field ratio for full drift-electron transparency becomes infinite because the electric field from the upper volume can not leak into the lower volume anymore.

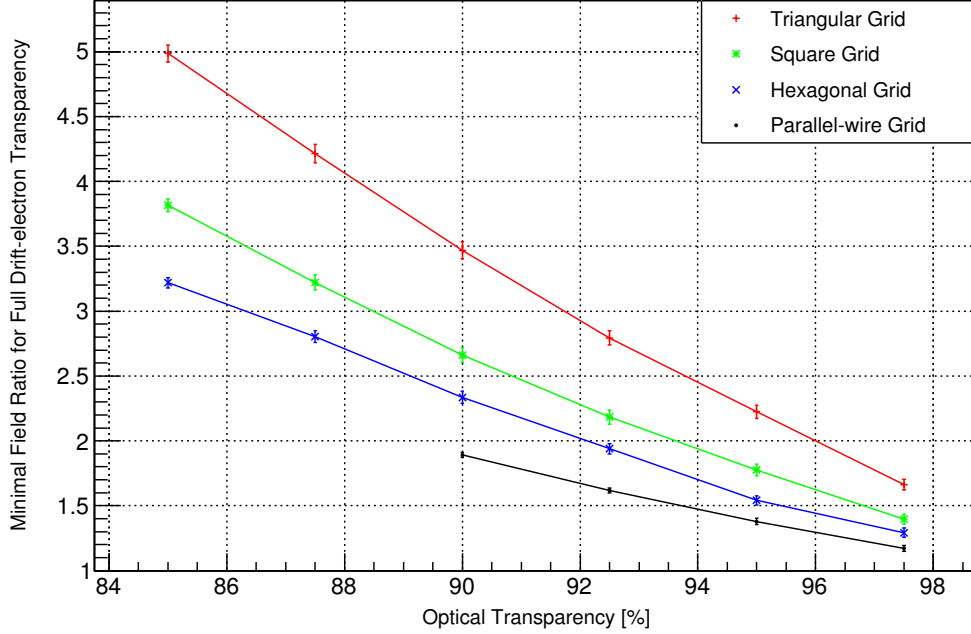


Figure 5.17: Simulation results of all the types of grids are compared. All the work is conducted in the 3D framework.

In the 3D framework, comprehensive comparisons are carried out among grids of different geometrical patterns, hexagonal, triangular and square grids with different optical transparencies as shown in Figure 5.17. Under the same optical transparency, the hexagonal grid demands the smallest electric field ratio to obtain full drift-electron transparency, while the square grid requires a higher field ratio and the triangular grid the highest one. The results can be explained by

the principle of the field leakage, which refers to the extent of field leakage from the stronger-field volume to the adjacent volume. When the hexagonal and the triangular cells are of the similar dimension, the same optical transparency can be obtained only when triangular grid uses thinner wires. The triangular grid maintains a larger number of cells over the same area. Moreover, in the aspect of the individual cells, the wires of triangular cell is closer to the center comparing to that of hexagonal grid; with similar optical transparency, triangular cells are more compacted within the surrounding wires. All these factors give rise to a smaller field leakage across the triangular grid. The improvement of drift-electron transparency is achieved by the enhancement of field leakage across the grid. Therefore, the triangular grid requires a higher minimal field ratio for full drift-electron transparency. A similar comparison can be extended to parallel-wire grids and the others. To reach a similar optical transparency with the same wires, the area between adjacent parallel wires is much larger than that of the individual cell from the other grids. Therefore, the field leakage across the grid is stronger in the case of parallel-wire grids, and this leads to a smaller minimal field ratio for full drift-electron transparency.

CHAPTER 6

Conclusion

Direct dark matter detection using dual-phase liquid noble element detectors has made significant progress in scaling up the active volume and improving the sensitivity to the spin-independent WIMP cross-sections in the past decade [9, 31]. It is expected to approach the coherent neutrino scattering background in the coming generation of direct dark matter detection experiments with multi-tons active volume.

In summary, an introduction to the cosmological evidences of dark matter and various dark matter candidates is given in Chapter 1. The following Chapter 2 introduces the principles of dual-phase time projection chamber and direct dark matter detection experiments using this technology; the expected interaction rate between atoms and dark matter particles, as a function of nuclear recoil energy and WIMP mass, is calculated for different target atoms. Associated properties of the liquid noble elements are discussed in details in Chapter 3; scintillation and ionization signals from electronic and nuclear recoils as a function of recoil energy, are quantified and compared for different noble elements.

As a key member of the ScENE collaboration, the measurement of nuclear recoils in liquid argon is present from several aspects: the bunched neutron beam generated by the linear accelerator in Chapter 4.1, the detector setup and TPC design in Chapter 4.2, the Monte Carlo simulation using GEANT4 in Chapter 4.3, 3-inch PMT gain and SPE calibration in Chapter 4.4, data processing and cut development in Chapter 4.5 and nuclear recoil results in Chapter 4.7.

As a member of XENON collaboration, I also contributed to the XENON1T TPC electric field design, optimizing the electric field uniform using the Finite Element Analysis software in Chapter 5.1. Moreover, related to the electric field configuration in TPC, the drift electron transparency quantified as a function of optical transparency for several different patterns including parallel-wire grid, hexagonal, square and triangular cells in Chapter 5.2.

I also developed a small-scale dual-phase liquid xenon TPC at UCLA. As a part of this project, I helped design and develop the cryogenic system, circulation system and slow control system associated with the TPC. Similar to the collaboration works, the PMTs are calibrated in both room and cryogenic temperatures; the TPC electric field uniform is also carefully optimized. All the corresponding details are in Chapter A.

APPENDIX A

Dual-phase Liquid Xenon Detector

Because the proper energy scale of nuclear recoil in liquid xenon is critical for the ongoing dark matter experiments in which the liquid xenon is used as the target medium [31, 13], several measurements of scintillation and ionization yield of nuclear recoils in liquid xenon have been conducted. Some measurements focus only on the scintillation yield of nuclear recoils [32, 48, 20, 22, 98]. Simultaneous measurement of scintillation and ionization signals from nuclear recoils in liquid xenon is measured and reported down to 4 keV [87].

Similar to those measurements of the nuclear recoils in liquid xenon, a dual-phase liquid xenon detector is developed and tested at UCLA dark matter laboratory to measure the scintillation and ionization signals from nuclear recoils in liquid xenon. This detector is a time projection chamber, of which the design is presented in Section A.1.1 and the electric field optimization is in Section A.2. Cryogenic system and gas handling system as parts of the detector, are also introduced in Section A.1.2 and Section A.1.3 respectively. A detailed description of PMT calibration is in Section A.3. Section A.4 shows the simulation results of nuclear recoils in this detector.

A.1 Dual-phase Time Projection Chamber Design

A.1.1 TPC Design

In the design of time projection chamber (TPC), the active volume consists of a drift volume fulfilled with liquid xenon and an electro-luminescence volume filled with xenon gas above a liquid xenon layer. The active volume is confined by a polytetrafluoroethylene (PTFE) shell of 3" inner diameter which is surrounded by 8 copper rings as shown in Figure A.1. The outer diameter of this PTFE shell surrounding the TPC active volume is 3.52". On the outer surface, circular grooves are engraved to hold 8 parallel copper rings mostly separated by equal space. Between these copper rings and stainless steel (SS) dewar inner surface, another 0.2" thick PTFE shell is used to separate them. The SS dewar is not shown in the Figure A.1, but the inner surface has diameter almost the same to that of the PTFE shell part. The inner volume of this SS dewar is vacuum insulated so that the thermal loss due to the SS surface is minimized.

There are four identical metal meshes used in the TPC active volume, from top to bottom are anode, extraction mesh, cathode and screening mesh respectively. The distance between cathode mesh and extraction mesh is 1" long while the anode is 0.35" away from the extraction mesh. The drift volume is between the extraction mesh and cathode where a drift field is built by applying a negative high voltage (HV) on the cathode. The electro-luminescence volume is between the anode the extraction mesh: a liquid xenon layout of 4.4 mm height is expected to be on top the extraction mesh while another 4.5 mm xenon gas is above the liquid xenon layer. When anode is fixed to ground and a different negative HV is applied on the extraction mesh, a strong electric field is created in the electro-luminescence volume. The electric field in liquid xenon of electro-luminescence volume is referred as extraction field; the electric field in gas xenon is called electro-luminescence field. The ratio between electro-luminescence field and extraction

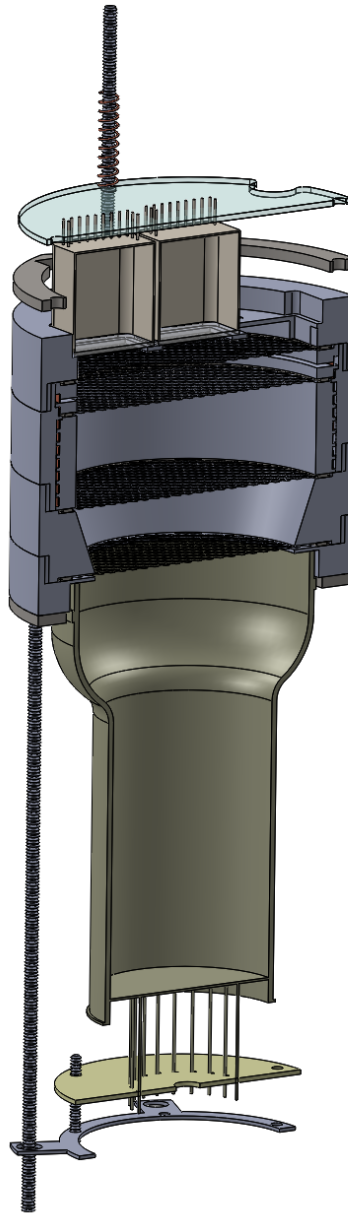


Figure A.1: This is a cross-section view of three-dimensional SolidWorks drawing of the TPC. Only two 1" PMTs are shown on the top PMT array for a better view. Some connecting rods and spring are also omitted for the same reason.

field is determined by the dielectric constant of xenon.

The screening mesh is 10 mm below cathode but right above the bottom 3" Photon Multiplier Tube (PMT). The associated potential is set to ground to protect bottom PMT from strong electric field caused by the HV applied on cathode.

The metal meshes are all 2 mm pitch hexagonal grids made by SS wire of 50 μm diameter. The copper rings used to create the field cage are of 0.1" height and made from 0.01" thick copper sheet. The pitch between two adjacent copper rings is 0.14". Moreover, for all four meshes as Figure A.1 shows, there is a 0.02" thick SS ring on top of each grid to protect them from PTFE shrinkage in low temperature.

The copper rings and anode, extraction gate and cathode, are connected all together by a resistor chain of different resistance values. When the anode mesh is set to ground while two separate negative high voltages are applied on the extraction mesh and cathode mesh, a field cage is built and equipped with the independent drift and extraction section.

The extraction field is tuned by varying the negative HV applied on the extraction mesh; the drift field is controlled by the cathode HV difference with respect to the extraction mesh voltage. Specific resistance value of resistor to connect two adjacent copper rings is determined by the COMSOL field simulation in which the field uniformity is optimized by varying those resistance values as free parameters. This work is introduced in section A.2.

Photon sensors located at top and bottom of active volume are utilized to detect both prompt signal (S1) and secondary electro-luminescence signal (S2). Seven Hamamatsu R8520 1" PMTs are placed on top as an array and one R11410 3-inch PMT is located at the bottom. Seven 1-inch PMTs array renders this dual-phase xenon detector the capability to conduct position reconstruction based on

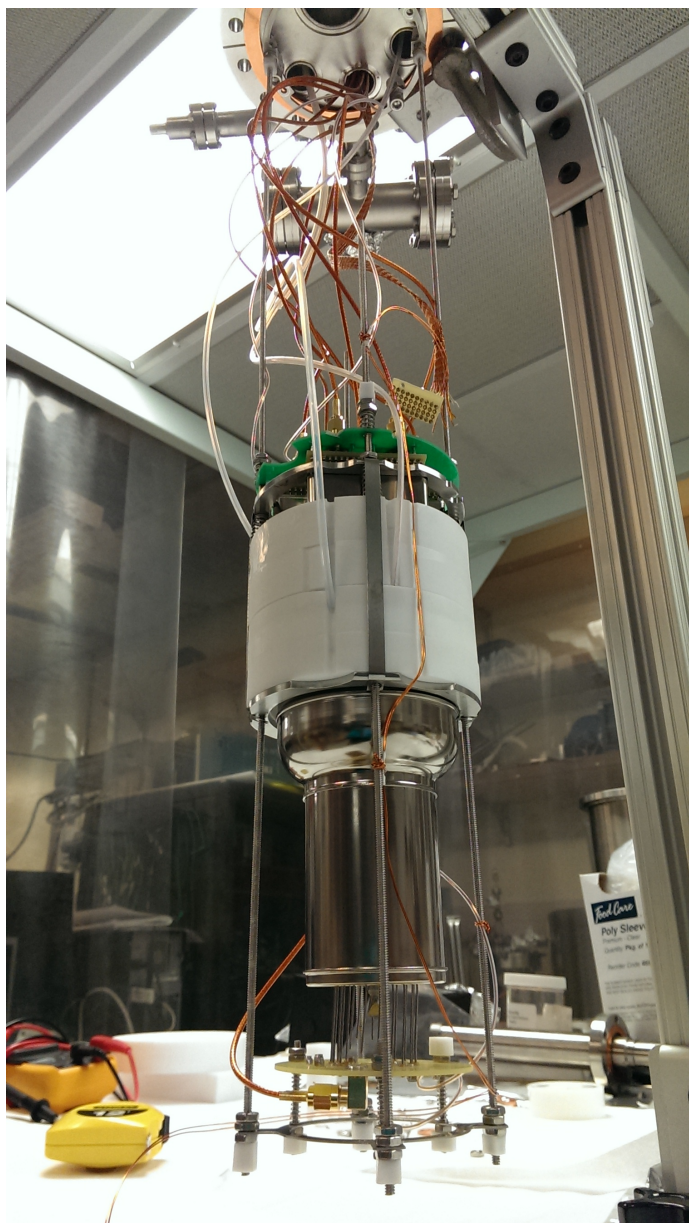


Figure A.2: This is a picture of assembled TPC hanging on the top 6" flange. The associated high voltage and signal feed-throughs are on top of this flange. The entire system is in clean room.

S2 pattern. This function can be effectively used to identify surface events.

Based on the design, xenon liquid and gas interface is expected to stay above the extraction gate grid and therefore fully cover the grid in liquid to guarantee 100% electron transparency. As demonstrated in Figure A.1, the PTFE material between this extraction gate grid and closest copper ring above it is intentionally removed. This special design is to maintain a constant contact between xenon liquid surface and the copper ring. With the help of this contact, those potential free electrons that are not fully extracted into gas phase and left floating, can be eventually absorbed by copper ring and as a result to effectively remove residual charges in gas-liquid interface.

A.1.2 Cryogenic System

The cryogenic system consists of three parts: QDrive cryo-cooler, cooling tower and transfer line, all of them is shown in the Figure A.3. A custom-made cold-head made of copper is attached to the cryo-cooler to increase the contact area of xenon gas to the cryo-cooler. A temperature sensor and a 112 ohm heater is also inserted inside the cold-head. The temperature sensor is connected to a LakeShore model 325 cryogenic temperature controller ¹ while the heater is connected to a Kepco DC power supply which is driven by the LakeShore temperature controller. The temperature at the cold-head is directly regulated by the temperature controller: a temperature set-point is given to the LakeShore controller; when the cold-head temperature read from the sensor is below the set-point, the temperature controller starts sending heating power to the heater by changing the voltage applied on the heater; the specific heating power sent to the cold-head is determined by the proportional-integral-derivative (PID) loop feedback mechanism used in the LakeShore controller.

¹<http://www.lakeshore.com/products/Cryogenic-Temperature-Controllers/Model-325/Pages/Overview.aspx>

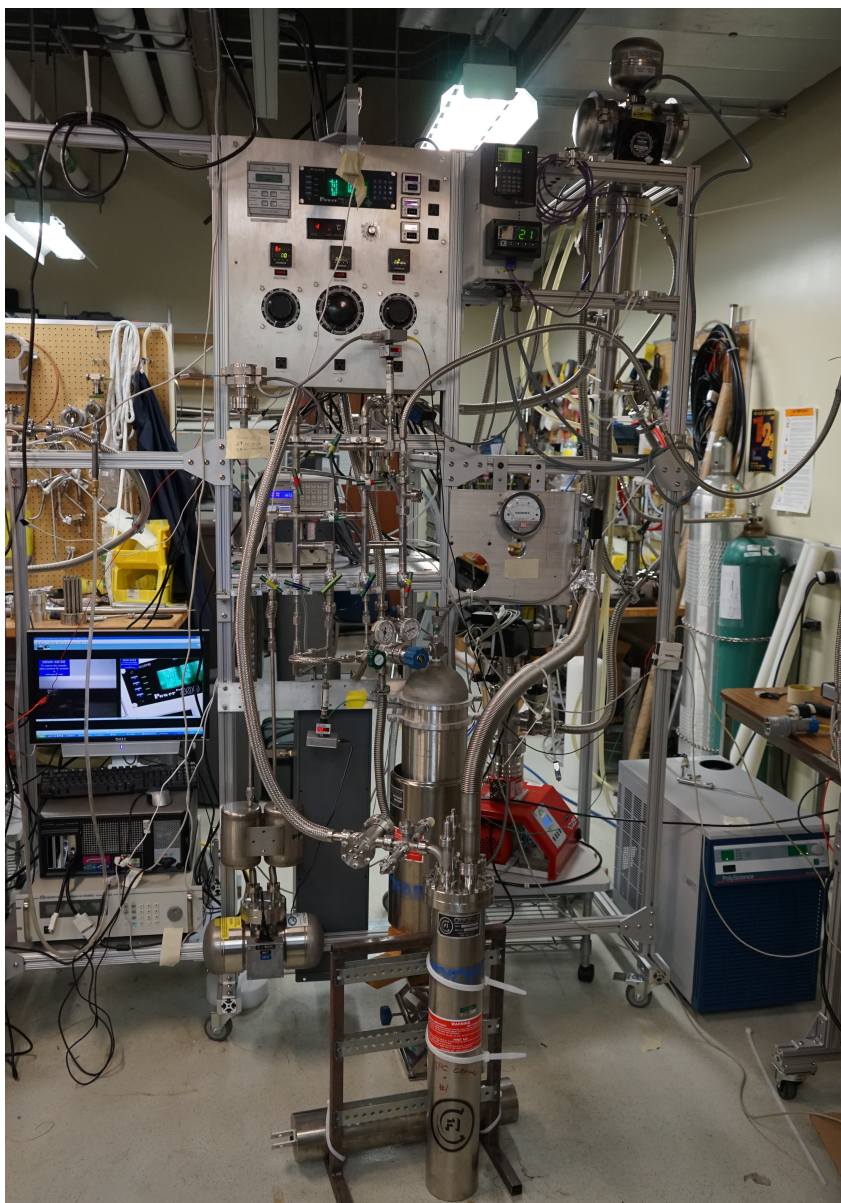


Figure A.3: This is an overall picture of the Xenon Chamber system, which includes the cryogenic system, gas handling system and the vacuum-insulated dewar where the TPC is located.

The Qdrive cryo-cooler is designed to deliver 60 Watts of cooling power at temperature 165 K. The exact cooling power delivered by the cryo-cooler is measured in vacuum to be 32 Watt with 95 V AC driven power at temperature 165 K.

The cooling tower is a vacuum-insulated SS cylinder connected right below the cryo-cooler, it is the volume where the xenon qualification takes place. The xenon gas flow is constantly pushed from the gas handling system into this volume and is liquefied on the cold-head. A good vacuum insulation minimizes the thermal loss due to the large temperature difference between the xenon melting point and room temperature.

The transfer line is a long vacuum-insulated pipe made of two concentric SS bellows. Transfer line connects the cooling tower to the SS deware where the TPC is hosted. The liquefied xenon in cooling tower streams down the transfer line by gravity and is directly delivered into the active volume of TPC. Because the Qdrive cryo-cooler vibrates constantly during operation, the use of cooling tower and transfer line separates the cryogenic system from the TPC so that the vibration impact from cryo-cooler is minimized.

A.1.3 Gas Handling System

The gas handling system as shown in middle of the Figure A.3, is made of SS tubes welded together. The basic functionality of this gas handling system is to control the xenon gas flow and associated purification process. A schematic of the gas handling system is present in Figure A.4, where the specific flow direction is indicated by those black arrows. The xenon gas is pulled out of the TPC by a circulation pump driven by a AC power supply; gas is then pushed into a rare gas purifier SAES model PS4-MT3-R-1 getter ², which effectively removes the impurities from xenon gas such as O_2 , H_2O , and CO_2 . The purified gas after

²<http://www.saespuregas.com/Products/Gas-Purifier/PS4-MT315.html>

passing through the getter is sent back into the cooling tower where it is liquefied and streams into TPC.

The gas handling system is designed that all the connections to the external equipment such as circulation pump and getter are separated by valves so that those equipment can be replaced when necessary without interrupting the entire system operation. For each individual equipment, an by-pass valves is also built in. The xenon gas is able to by-pass the getter or circulation pump in commissioning tests or other scenarios.

The xenon gas flow rate is controlled by the circulation pump as it pulls the gas out of the TPC. A higher flow rate implies more gas passing through the getter, however, the circulation flow is eventually limited by the cooling power delivered from the cryo-cooler.

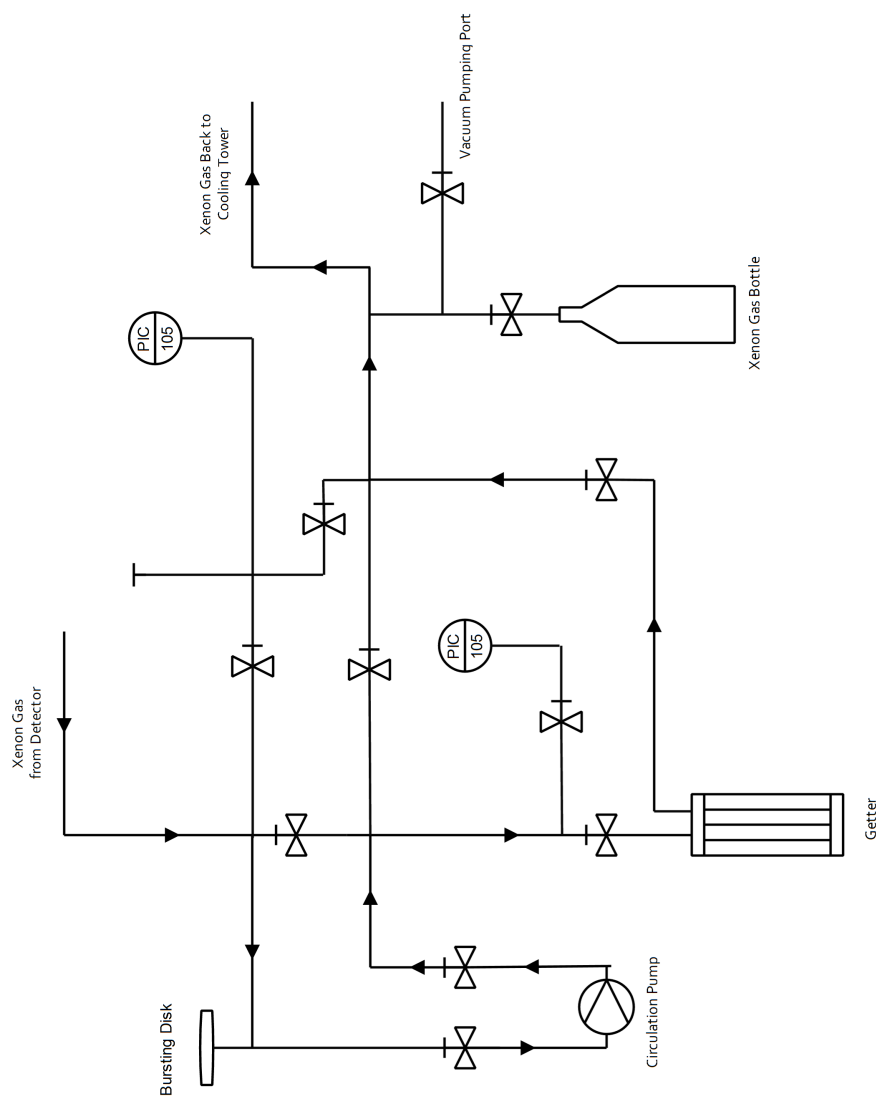


Figure A.4: This is the schematics of the gas handling system. The direction of xenon gas flow is indicated by the solid arrows. The description for the associated functions of this system can be found in this section.

A.2 TPC Electric Field Simulation and Uniform Optimization

The electric field is important for the TPC, specially for the S2 signals which are originated from free electrons. The free electrons generated via energy deposits in liquid xenon are separated from the ion-electron clouds by external electric field and are drifted up by following the drift field. After crossing the liquid-gas interface, the electrons are accelerated in the gas phase by following the electro-luminescence field; photons are constantly emitted along the electron drift path in xenon gas; the photons signal received by PMTs is the secondary signal, which is also called S2. Therefore, the distribution of drift field and the electro-luminescence field determines the shape and pattern of S2 signals.

The goal of electric field simulation is to check the field uniform of both drift field in liquid xenon and electro-luminescence field in gas phase. The electric field uniform can be modified by varying the resistance values used in the field cage. The optimized resistance chain used in field cage is shown in Figure A.5.

This electric field simulation is carried out with finite element analysis software COMSOL. A two-dimensional axial-symmetry geometry is adapted in this work. Since the main geometry of this xenon chamber is axial-symmetry, this two-dimensional geometry is a good approximation for the actual three-dimensional design. However, four hexagonal SS meshes used in the geometry, are replaced by identical parallel wires made of 50 μm diameter with 2 mm spacing in the axial-symmetry geometry, as shown in the Figure A.6.

In the field simulation result, electric field is perfectly uniform in most of active volume, which is equivalent to the straight electron-drifting paths (the straight black lines shown in Figure A.6) in liquid xenon. However, non-uniform electric field is also observed both near cathode grid edge and extraction gate grid edge. Moreover, the field distortion is more severe in cathode corner regions. This

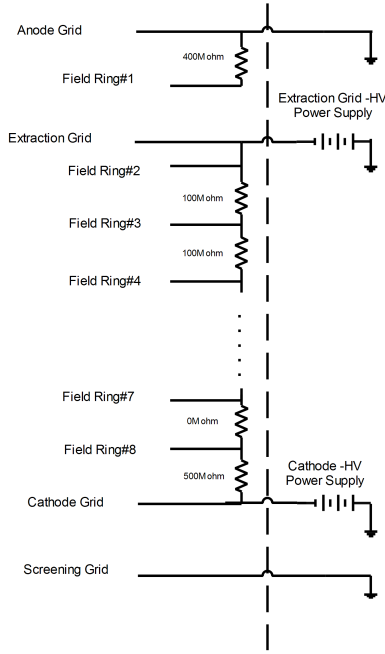


Figure A.5: The resistor chain to create the electric field configuration is shown. Two high voltage power supply as indicated in the figure, is used to control the drift field and extraction field independently.

is because the SS cathode mesh and attached SS rings have a small diameter of 3.3"; this diameter is smaller than that of other copper rings which create the field cage. Comparing to the copper rings, the cathode mesh and attached SS rings are located inside the active volume instead of the proper position and therefore leads to a distortion of drift field.

In Figure A.6 where the field simulation result is shown, color lines are equip-potential lines and various colors represent the different voltages as indicated in the legend. Black lines are drawn to be perpendicular to the equip-potential lines, which corresponds to the electron drifting paths in the active volume. The area above anode mesh is the seven PMTs array, which is introduced in section A.3. Since positive bases are used on all of them, the electric potential on the PMT bodies are at ground, the same as the anode mesh. However, there is still an equip-

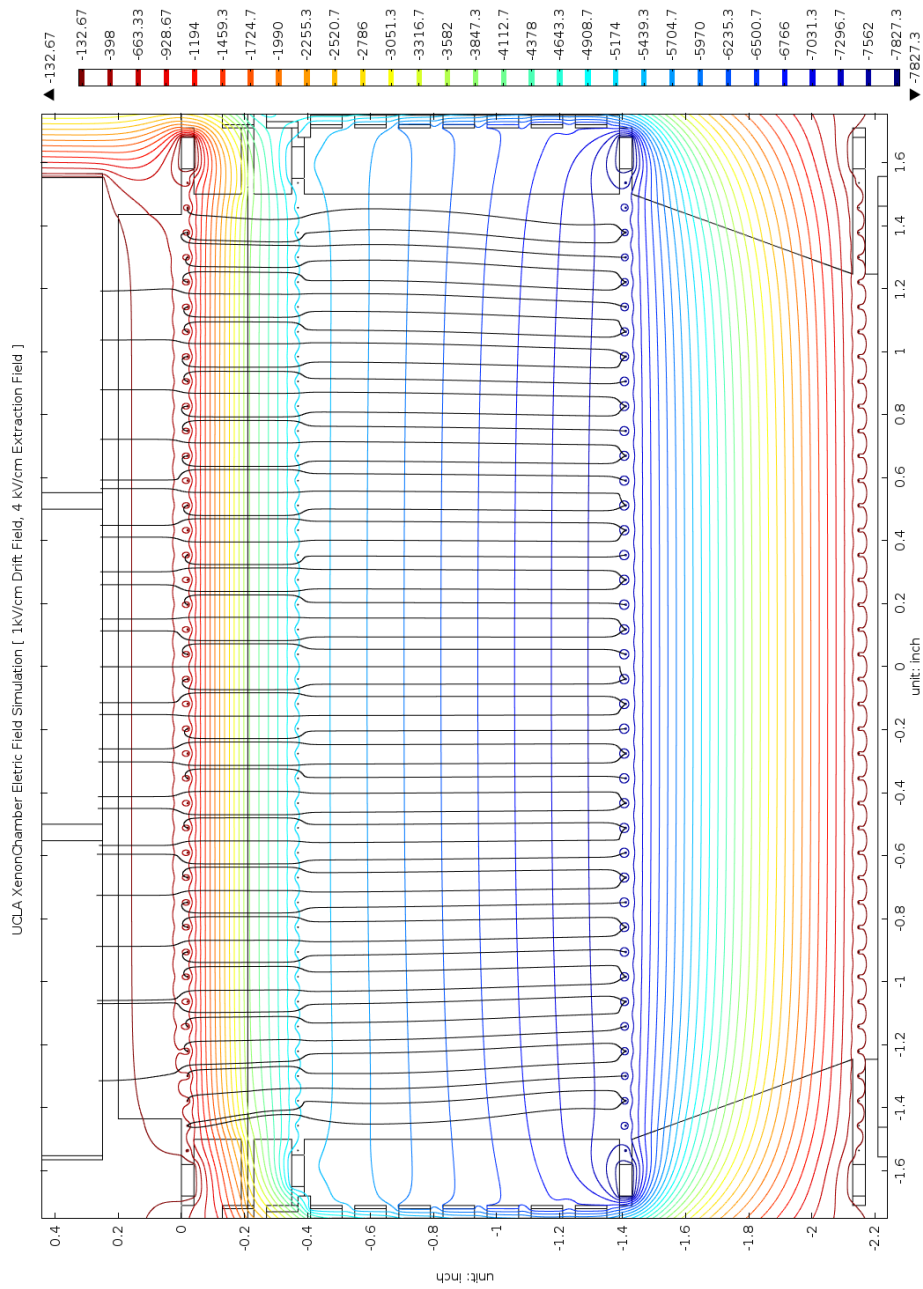


Figure A.6: This is the electric field simulation result for this xenon chamber. In this simulation, the drift field is set to 1 kV/cm and the extraction field in liquid xenon is set to 4 kV/cm. Discussion of the results is within the text content.

potential line between anode the seven PMT array in the simulation result. This is because the field leak from the area beneath the anode mesh into this area, that effectively changes the voltage in this area. The field distortion around cathode grid corner is less than 0.1" long and expected event position cut to fully exclude surface events will in principal, exclude this area of distorted electric field.

A.3 PMT Design and Calibration

A.3.1 Seven PMTs Array Design and PMT Calibration

As demonstrated in Figure A.1 and left Figure A.7, seven R8520 Hamamatsu low-temperature 1" PMTs are attached to individual PMT base. Seven 1" PMT bases are positive bases: an positive high voltage is applied on the anode to drive the PMT gain. Specific schematics of the PMT base is shown in Figure A.8. Seven 1" PMT bases are mounted on a separate motherboard as an array by four pin connection. The motherboard with seven 1" PMTs is on top of the TPC.

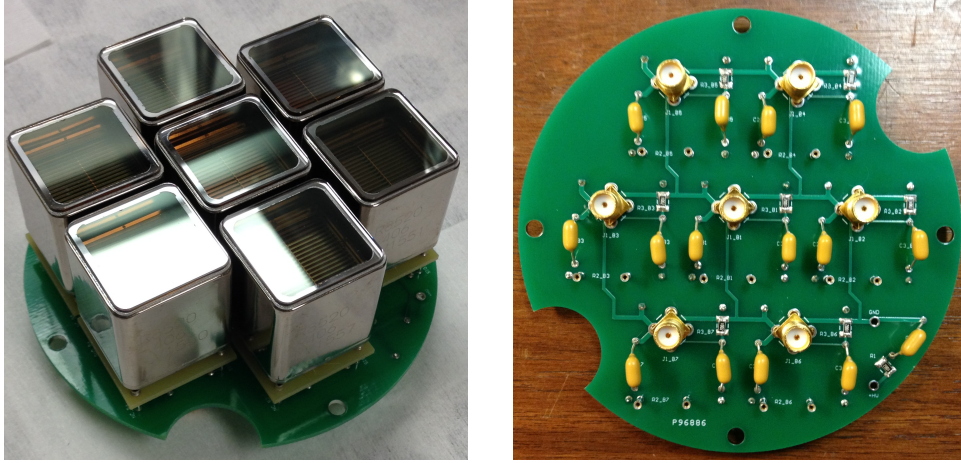


Figure A.7: The figure on the left is seven 1" PMTs mounted on the motherboard. By using different resistors on top, the motherboard delivers different HV on individual PMT. The figure on the right is a top view of the motherboard, the resistors used to control HV on individual PMT is put on the motherboard.

The use of motherboard with seven 1" PMTs array has two goals: first, motherboard is used to host all seven 1" PMTs all together on top of the TPC; the signals from seven 1" PMTs are directly collected from seven SMA connectors on the topside of motherboard. Second, by using the mother board, single high voltage source is connected to this motherboard. On the motherboard circuit, resistors of different value are utilized to deliver expected high voltage to individual

PMT from this single high-voltage source.

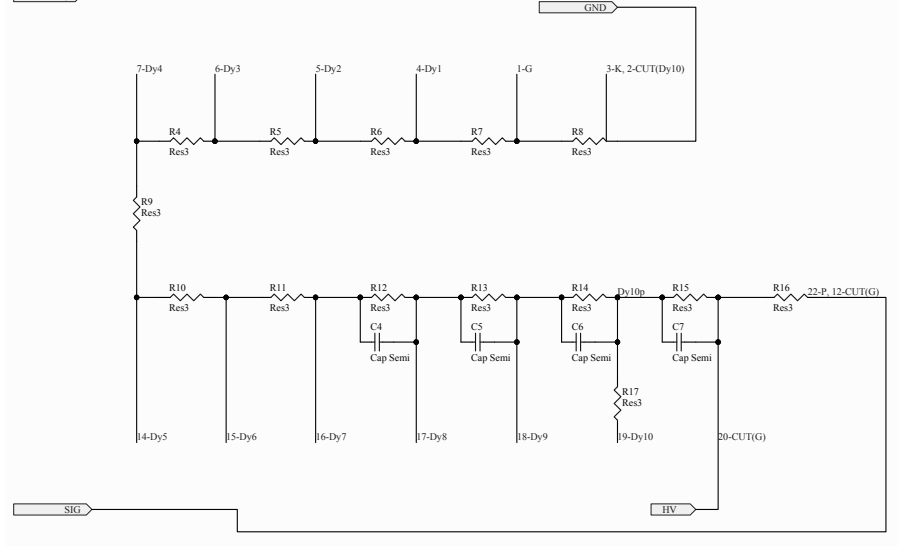


Figure A.8: The schematics of positive 1" PMT base.

All the seven 1" PMT gains are measured in a dark box at room temperature. In the dark box, an optical fiber is placed right in front of the PMT photo-cathode. A NIM gate generator is used to generate two simultaneous TTL signals: one is fed into a circuit to trigger a short LED pulse, the LED signal goes through a six order of magnitude attenuator and becomes few photons when it hits the PMT photo-cathode; the other is used to trigger the digitizer to record the PMT signal from LED pulse at the same time. The single photo-electron spectrum is created by making histogram of integrated area values over a fixed time window around the trigger for every event. Figure A.9 is the single photo-electron spectrum of PMT KA1551. The expected PMT multiple photo-electron function is fit to the spectrum and associated fit results are shown.

The integrated area are in unit of *voltage · nanosecond*, since the impedance of signal cable is 50Ω , the integrated is converted into number of electrons as horizontal axis unit indicates. The detailed introduction of the PMT multiple photo-electron function can be found in Section A.3. In generally, the pedestal

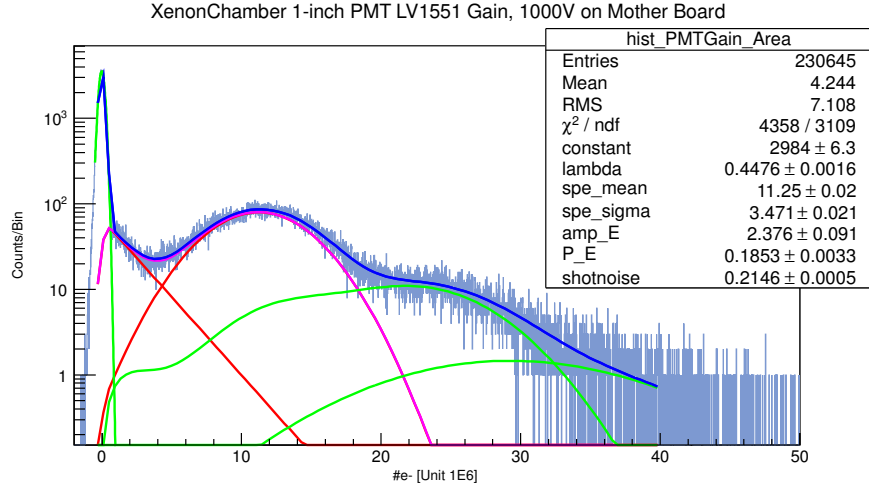


Figure A.9: The fit result of 1" PMT LV1551 single photo-electron spectrum. Applied high voltage on the motherboard is 1000 V.

is fit with a Gaussian distribution to the mean and sigma values; the parameters are fixed to those values in the second fit. In the second fit, the exponential background component is the red line; the single photo-electron response convoluted with backgrounds is shown as the pink line; two photo-electrons and three photo-electrons convoluted with backgrounds are both shown in green.

By using the similar approach, gain of all the seven 1" PMTs used on the top array is measured at room temperature with different high voltages applied on the anode. The results are shown in Figure A.10. Because the PMT gain is based on a multiple stage amplification, of which the amplitude is proportional to the field between adjacent two stages. So the gain is well described by the function $G(V) = (AV^t)^n$ where the n is dynode stage number; k is the single stage amplification parameter; parameter A is related with the charge collection efficiency to the next stage. As seen in the base schematics from Figure A.8, 1" PMT has ten stages. So the gain as a function of applied voltage for 1" PMT is re-written as $G(V) = A^{10}V^k$.

As shown in Figure A.10, for every 1" PMT, the PMT gain is measured with

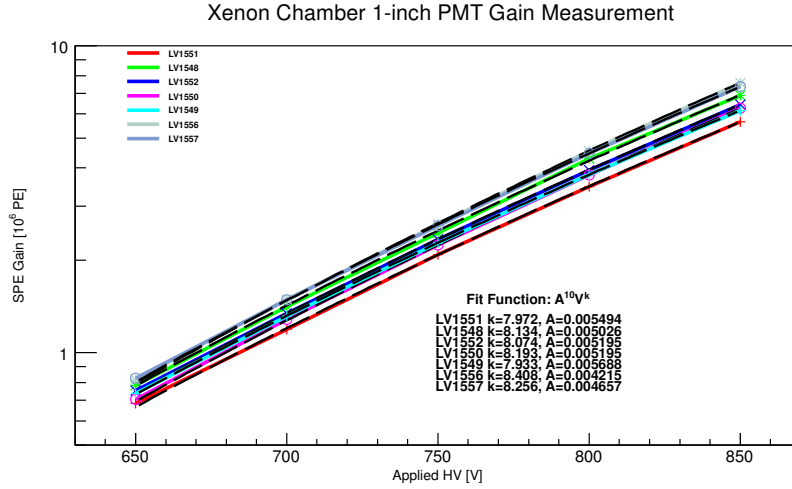


Figure A.10: Seven 1" PMT gain measurement results are shown as function of voltages applied on the anode. All the measurements are conducted in dark box at room temperature.

high voltage at anode from 650 V to 850 V at five different voltages. The PMT gain as a function of applied high voltage is fit to the measurement results of each PMT measurement. The values of two parameters for each PMT are shown in Figure A.10. Clearly, the two parameter A and k are different from one PMT to another and each PMT has its own gain feature. In order to obtain a uniform S2 response, all the 1" PMTs on the top are expected to have similar gain. The PMT gain function with two parameters are used to select the proper high voltage to use.

Assuming a 1000 V applied on the motherboard, resistance values of seven through-holes resistors are selected so that the gains of all seven 1" PMTs are about 3×10^6 . Using the gain functions $G(V)$ and the parameter values from fits, the expected PMT gain for individual PMT is calculated and listed in Table A.1. Moreover, after putting the selected resistors onto motherboard, the actual gains of seven 1" PMTs with 1000 V delivered at motherboard are measured in the dark box. The results are also listed in the Table A.1.

A.3.2 3-inch PMT Calibration

The 3" PMT is at the bottom of TPC, screened from the cathode high voltage by the screening mesh right above the PMT photo-cathode. The screening mesh potential is fixed to ground during the TPC operation. A positive base is also used for the 3" PMT. The PMT base design from FNAL is shown in Figure A.11.

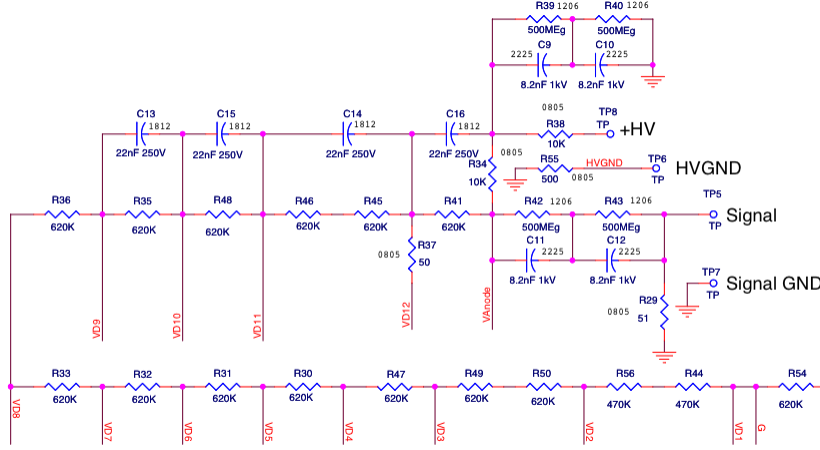


Figure A.11: The schematics of positive 3" PMT base.

Gain of three 3" PMTs at UCLA Dark Matter laboratory are measured in the dark box and results can be found in Figure A.12. Two of them use the FNAL positive base and the other one uses negative base. The procedure of 3" PMT gain measurement is identical to that of 1" PMTs. The only difference is the high voltage range: from 1200 V to 1700 V at a 50 V incremental step.

The 3" PMT has 12 dynode stages, so PMT gain function of $G(V) = A^{12}V^k$ is used to fit every PMT gain result. The values of parameter A and k for each PMT are also shown in Figure A.12. The 3" PMT KA0118 is used at the bottom of TPC.

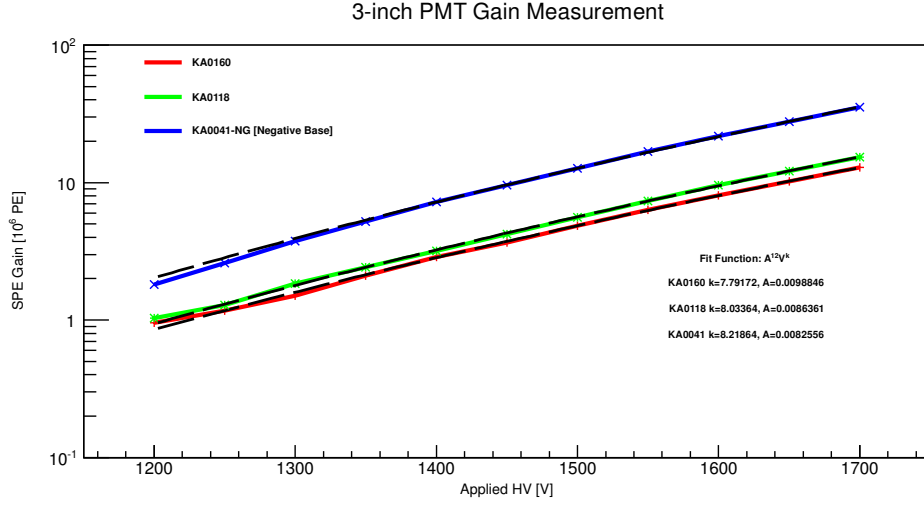


Figure A.12: Three 3" PMT gain measurement results are present. All the measurements are conducted in dark box at room temperature. 3" PMT with serial number KA0118 is used.

A.3.3 Low Temperature PMT Single Photo-electron Calibration

During the TPC operation, most of TPC parts are submerged in liquid xenon and are at the liquid xenon temperature. The rest parts in xenon gas are also at low temperature close to the liquid xenon melting point. All the PMT gains measured at room temperature may not be the same as those at low temperature. This is because resistors of different resistance values are used on the PMT bases to divide the high voltage into different stages on PMT dynodes; meanwhile, the resistors have finite and different resistance temperature coefficient. The temperature coefficient is defined as $R(T)/R(T_0) = (1 + \alpha\Delta T)$, where the T_0 is the room temperature and T is the liquid xenon temperature; α is the resistance temperature coefficient. When the α values are different from one resistor to the others due to the manufacture limit, the changes of resistance values at low temperature may lead to a PMT gain variation.

The digitizer used in data taking is CAEN V1720 8-channel 250 MS/s 12bit

module. With 4 nanosecond sampling rate, the amplitude of single photo-electron pulses is around few ADC counts, which is slightly above the electronic noise. So in order to obtain clear single photo-electronpulses, all 8-channels PMT signals are fed into a ten-times amplification NIM module. Events are triggered by individual channel, trigger channel is set to the PMT of interest. Trigger threshold is carefully tuned to be marginally above the regular electronic noise so that most of the single photo-electronpulses can be captured.

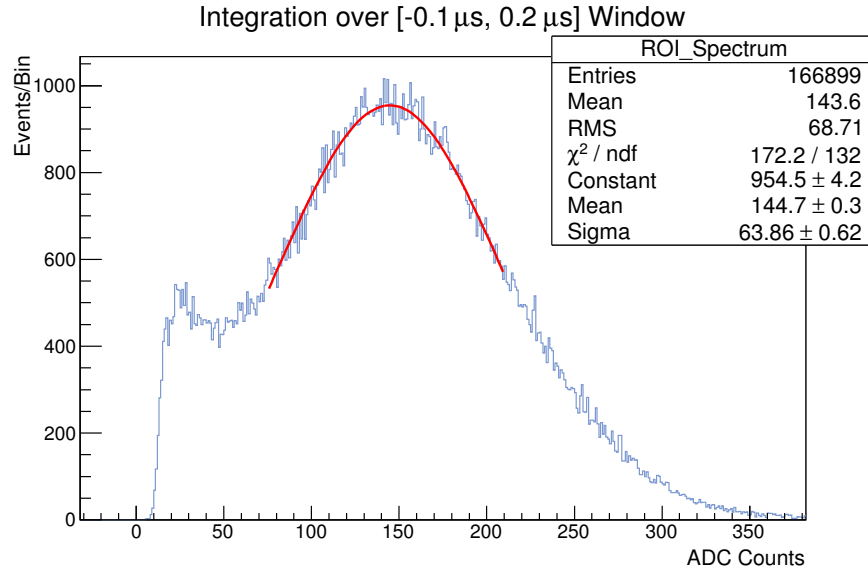


Figure A.13: This is the single photo-electronspectrum of PMT 7, area of each event is calculated by integrating over the constant time window $[-0.1 \mu s, 0.2 \mu s]$. The corresponding SPE mean $144.7 \text{ ADC/photo-electronis}$ obtained as the mean value from a Gaussian fit.

Two independent methods are employed to measure the SPE mean of each individual PMT. In the first method, pulse finding algorithm search for the suspicious single photo-electronpulses with very low threshold in the channel of interests; events of large pulses or events in which other channels also find pulses are disregarded; once small pulses are found in single channel of interests, area of the pulses including 20 samples before and after the pulses are integrated and plotted as the

single photo-electronspectrum. In the other method, without implementing pulse finding, integration over a fixed time window of 100 nanoseconds before and 200 nanoseconds after the trigger is used to create the single photo-electronspectrum. To exclude any large pulses, a similar criteria is employed to identify them: integration over the same fixed time window are also calculated for all the other channels; if any area result from other channels is larger than 500 ADC counts, this event is disregarded. A single photo-electronspectrum of PMT 7 created by using the second method is shown in Figure A.13. The SPE means of other PMTs are measured in the same approach and the results are in Table A.1, the SPE means are also converted into the corresponding PMT gains.

Table A.1: 1" PMTs Gain Measurement Results

Serial Number	k Value	A Value	Resistor [$k\Omega$]	Calculated Gain [$10^6 e^-$]	20°C Gain [$10^6 e^-$]	-110°C Gain [$10^6 e^-$]	-110°C SPE Mean [Counts]
LV1551	7.972	0.00549	348	2.81	3.72	1.555	12.76
LV1548	8.134	0.00503	357	3.25	4.21	1.996	16.37
LV1552	8.074	0.00520	357	3.03	4.33	1.764	14.47
LV1550	8.193	0.00478	357	2.92	4.10	1.608	13.19
LV1549	7.933	0.00569	348	3.07	4.36	1.798	14.75
LV1556	8.408	0.00522	374	3.17	4.12	1.818	14.91
LV1557	8.256	0.00466	374	3.13	4.11	1.920	15.75

A.4 GEANT4 Simulation of TPC Responses to Nuclear Re-coils

The plan of nuclear recoil measurement with the dual-phase xenon TPC is to use a low energy neutron beam generated via ${}^7\text{Li}(p, n)$ interaction in a Van de Graaff accelerator. When the accelerated proton beam hits the LiF target, the nuclear interaction ${}^7\text{Li} + p \rightarrow {}^7\text{Be} + n$ generates a neutron beam of which the kinetic energy is proportional to the incoming kinetic energy of proton beam. The detector responses to nuclear recoils are simulated with the simulation tool [10].

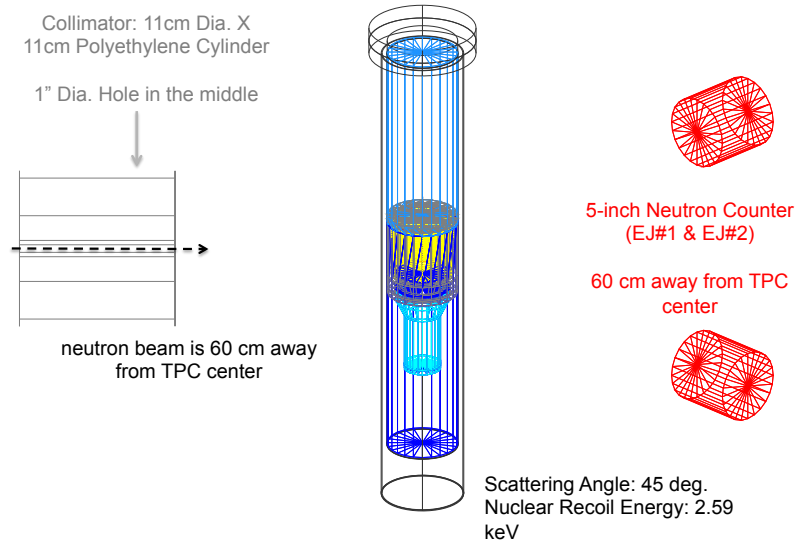


Figure A.14: Layout of the simulation geometry used in the GEANT4 simulation: dark blue region is liquid xenon while the light blue indicates xenon gas. A polyethylene cylinder is used as collimator and shielding.

Low energy nuclear recoils in liquid xenon is obtained by a coincident neutron tagging at certain scattering angles. Figure A.14 gives experimental layout of such coincident tagging: the neutron beam coming off the LiF target is in all directions, a polyethylene cylinder with a hole in the center is placed in front the target to collimate the neutron beams; only the fraction of neutron beam

with the expected kinetic energy goes through the collimator and reaches the dual-phase TPC. All the other neutrons are slowed down by multiple scatterings and eventually absorbed in the collimator. In dual-phase TPC neutrons scatter off xenon atoms and deposit energy via nuclear recoils. The specific amount of energy deposit depends on the neutron scattering angles as the Function A.4 describes. As shown in Figure A.14, neutron detectors are placed in certain location to tag the scattered neutrons of certain scattering angles, which corresponds to a specific nuclear recoil energy deposited in TPC.

$$E_r \approx E_n \frac{2m_{Xe}m_n}{m_{Xe} + m_n} (1 - \cos \theta) \quad (\text{A.1})$$

In the measurement of nuclear recoils in liquid xenon, overwhelming gamma rays from various sources such as the proton beam induced interactions and other ambient radioactivity, contributes to the signals detected in TPC as the major backgrounds. However, because of the significant difference of traveling velocities between neutrons and gamma rays, the timing information of detected signals can be used to effectively reject the gamma rays backgrounds. The gamma rays travel at the speed of light $3 \times 10^9 \text{m/sec}$; 2 MeV neutrons has a speed around 10^7m/sec . The time difference of signals between TPC and neutron detector is called time-of-flight (TOF). With a fixed distance 60 cm between TPC and neutron detector, gamma backgrounds has TOF around 1 nanosecond while neutrons has TOF around 60 nanosecond. Therefore, the time coincidence between TPC and neutron detectors is a powerful parameter to select nuclear recoil events.

Moreover, because the mean-free-path of few MeV neutrons in liquid xenon is at a few cm level, so the neutrons may scatter with xenon atom multiple times before leaving the liquid xenon active volume. Each scattering of neutrons deposits certain amount of nuclear recoils. Meanwhile, the nuclear recoils of interests is expected to be single energy deposit. So the multiple-scattering neutron events is

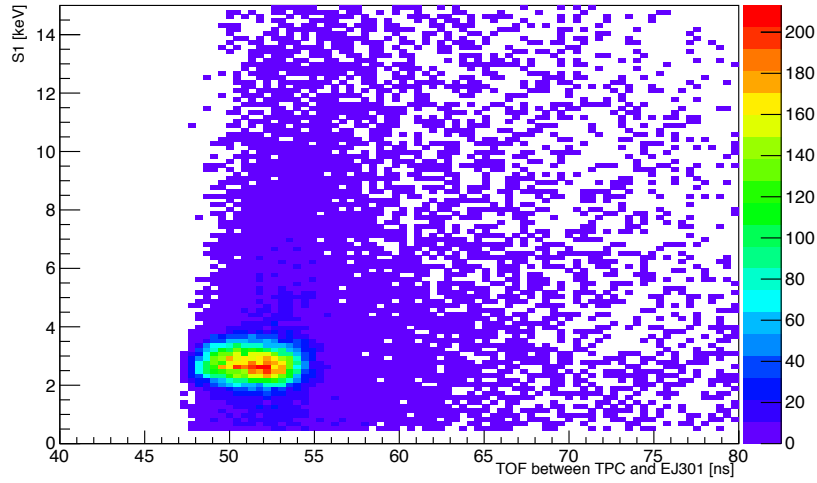


Figure A.15: Simulated S1 signals vs. Time-Of-Flight between TPC and neutron counter is shown. The TOF can effectively remove the majority of background by coincidence.

another background source. There are two methods TOF cut and reconstructed scattering position to exclude the multiple-scattering neutrons backgrounds.

In the first method, TOF values can be used to tag the multiple-scattering events. Figure A.15 is a two-dimensional scatter plot of S1 signals versus the corresponding TOF between TPC and neutron detector. Because the neutron detectors are made of the widely used materials EJ301, the neutron detectors are also called EJ301. The blob clustered around $2.6\text{keV}_{\text{nr}}$ along vertical axis in Figure A.15 is the neutron events, as expected from the nuclear recoil energy calculation of 45 degree scattering angle. The TOF values of corresponding neutron events are also well grouped around 53 nanoseconds. There is also a separate blob of gamma ray events with few nanoseconds TOF values, which is not shown in the Figure A.15. The events with largely spreaded TOF values are mainly the multiple-scattering neutron events, a cut on TOF values can exclude a large fraction of the multiple-scattering neutron events.

Figure A.16 shows the S1 spectrum of nuclear recoils with a 10 nanoseconds

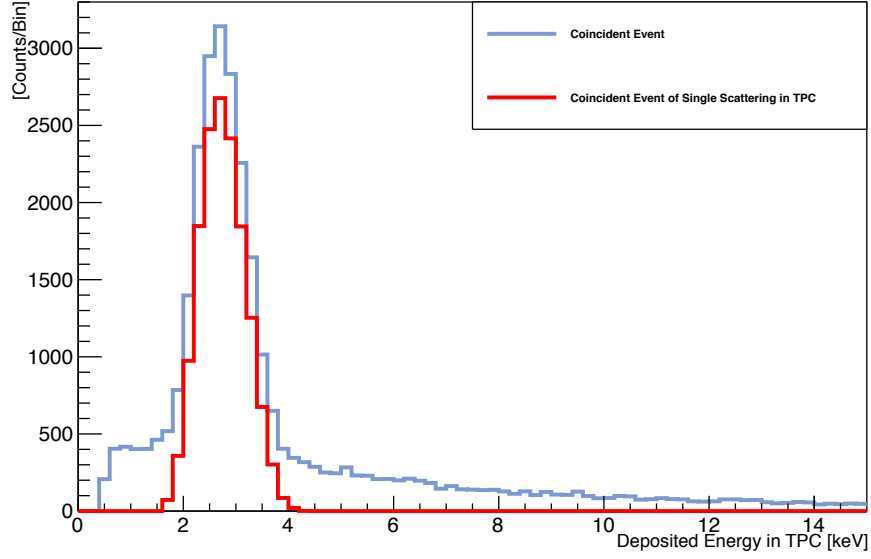


Figure A.16: The simulated S1 spectra after applying the TOF cut and other basic quality cuts: blue spectrum is the expected measurement result and red spectrum is exclusively from single nuclear recoil. The major contribution for the measured S1 spectrum is from the single scatters.

time window limits on the TOF values. The blue histogram is the spectrum expected to observe while the red histogram is the spectrum of only the single scattering nuclear recoils. So for the energy region of interests between 2 keV_{nr} and 4 keV_{nr}, the major contribution is from the single scattering nuclear recoils.

In the other method of reconstructed scattering positions, because the specific location where the scattering happens gives a certain pattern of S2 signals on the top seven PMT; for events with multiple S2s, each S2 has own position information based the pattern on top PMT array. The multiple-scattering neutrons deposit energy at several different locations; each energy deposit is expected to create a coincident signal of S1 and S2. Every S2 signals give a precise description of the interacting locations. Therefore, as long as the separating distance between multiple scatterings are large enough so that the three-dimensional position reconstruction is capable to distinguish the multiple scatterings.

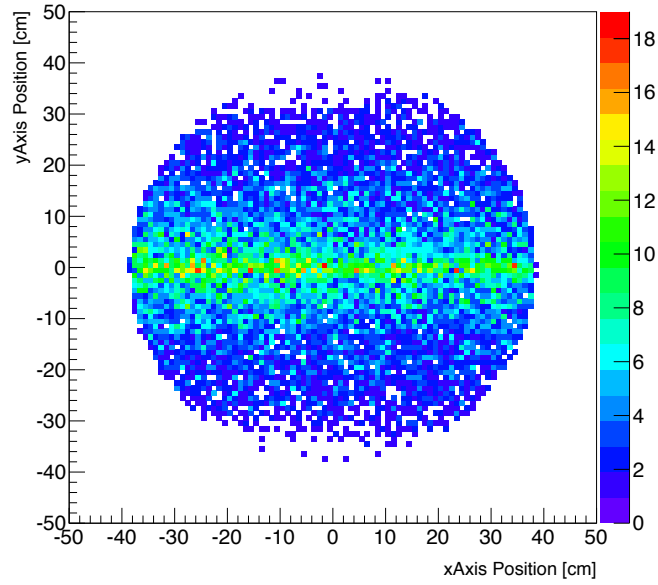


Figure A.17: Simulation results of nuclear recoil event positions in the TPC. The neutron events cover the entire active volume.

Another consideration related to the neutron event positions is the distribution of the nuclear recoil events. Figure A.17 shows the positions of all nuclear recoil events in the active volume. The figure presents a uniform distribution of nuclear recoils in the TPC. Moreover, the position reconstruction from S2 signal detected on seven PMTs also allows TPC the capability to select nuclear recoil events by interaction location.

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