STUDY OF ARGON ELECTROLUMINESCENCE
LIGHT YIELD USING DATA FROM
DARKSIDE-50

CHENGLIANG ZHU

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Abstract

Since the secondary scintillation signals of dual phase Time Projection Chamber (TPC) detectors are produced through noble gas electroluminescence, a comprehensive understanding of electroluminescence is essential for the design and simulation of a future detector.

In this dissertation, I determine a fundamental property, the field dependence of light yield, of argon electroluminescence, using data from DarkSide-50 (DS-50), a detector designed for direct detection of dark matter.

The analysis requires a good understanding of the detector geometry in the secondary scintillation region of DS-50. However, deformations of the detector components are implied by the data, and they cannot be directly measured. I thus determine the field dependence under two hypotheses for the deformations. The results obtained by applying the different hypotheses have systematic differences, but are close to each other and agree with the results from other studies.

The results from this study are applied to predict the secondary scintillation light yield and its stability for different design schemes for DarkSide-20k (DS-20k), the next generation of DarkSide detector.
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Chapter 1

Introduction to Dark Matter and the WIMP Model

In the past century, with the development of technologies and fundamental theories, people started observing the universe with a larger scope in both space and time. In spite of the rapid growth of our knowledge about the universe, a self consistent model of it cannot be built with all the luminous matter, which has been well understood. More and more theories, built on experimental observations, call for the existence of non-luminous matter, often referred as dark matter. In the current chapter, we will list the evidence that supports the existence of dark matter. Then, the discussion will be focused on a particular dark matter candidate, Weakly Interacting Massive Particles (WIMPs). Different approaches for the detection of WIMPs will be introduced at the end of the chapter.

1.1 Evidence for the Existence of Dark Matter

Although dark matter has not been directly detected, its existence is supported by much of the macroscopic evidence from its gravitational influence on luminous astrophysical matter. The variety of the evidence has convinced most contemporary
physicists and astronomers of the existence of dark matter. The evidence can be categorized into three different classes:

- **The Motions of Galaxies and Clusters:** The earliest and most well known evidence is given by the motions of galaxies in clusters [37] and stars in galaxies [29]. Early study of the Coma Cluster indicated that the mass of the cluster needs to be much larger than the luminous mass, measured through the brightness, to provide enough force to "glue" the galaxies in the cluster together. More recent studies calculated rotation curves of spiral galaxies with the red shift of the light from their stars. As most of the visible mass in a galaxy concentrates near its center, the velocities of the stars near the edge are expected to decrease as $r^{-1/2}$, based on Newtonian gravity. However, the velocities stay nearly constant instead of decreasing. Additional source of centripetal force, required to keep the edge stars of a galaxy orbiting at high speed, can be provided by the gravity of a dark matter halo [26].

- **Gravitational Lensing:** As photon trajectories can be affected by gravity, a massive astronomical object between the background and the observer can cause a lensing effect concentrating the light from background galaxies and clusters. By this effect, some of the telescope images contain distorted and replicated galaxies and clusters. Those images can be used for the calculation of the distribution of foreground mass. Based on the calculation, the luminous matter at foreground is often found to be insufficient [22]. Gravitational lensing is also used to calculate the mass distribution of two merging clusters (the Bullet Cluster). As the two clusters run into each other, intergalactic baryonic matter particles interact with each other, emit electromagnetic radiation, and slow down. However, the separation of the two clusters’ centers of mass calculated with gravitational lensing is significantly larger than the separation measured using optical techniques. This observation supports the existence of weakly
interacting dark matter, which can pass through the clusters without being slowed down as much as luminous baryonic matter.

- **Cosmic Microwave Background:** Based on the Big Bang theory, currently the most accepted universe evolution theory, our universe was a fast-inflating uniform quark soup within a millisecond after the big bang. Then, nucleons formed and helium started to appear in a few minutes. In the next hundreds of thousands of years, the universe was a expanding and cooling plasma. Small temperature and density fluctuations in this early universe were caused by quantum perturbations. Since baryonic particles are coupled with photons more strongly than dark matter, they were smoothed by photons more effectively. In this case, the smoothness of the early universe was determined by the ratio between baryonic matter and dark matter. As the universe continue cooling, the energy density became too low to break hydrogen atoms and produce free charged particles, which have large scattering cross section with photons. From then on, the photons are free to travel in the universe.

Those relic photons, which are still wandering in the universe today, form a Cosmic Microwave Background (CMB). Since the early universe was in thermal contact, in general, the uniformity of its temperature was high. Therefore the relic photons from different directions have nearly the same spectrum, which is similar to the spectrum of 3 K blackbody radiation. However, a small anisotropy of CMB contains information about the density and temperature fluctuations of the early universe determined by the composition of mass energy. The latest CMB space telescope, Planck, has a sensitivity high enough to plot a high resolution temperature map, whose residual with respect to the mean temperature is decomposed with spherical harmonics to get a power spectrum. By fitting a lambda cold dark matter ($\Lambda$CDM) model (a standard parametrization of Big

\(^{1}\)A stands for the cosmological constant, which represents the vacuum energy density in space.
Bang cosmology) to the power spectrum, Planck data indicates that the universe is composed of 4.9% baryonic matter, 26.8% dark matter, and 68.3% dark energy \[2\].

Except for being non-luminous, several other properties of dark matter are inferred from the evidence discussed above. Most of the dark matter has to be cold (non-relativistic), so that the mass in the early universe can condense to form the structure that we observe today. Considering its abundance, dark matter has to be stable, so that it can keep its proportion after the universe became dispersive and the chance of annihilation became low. Based on the analysis of the small anisotropy of the CMB, dark matter should also be non-baryonic. Otherwise, the strong coupling between baryons would make the early universe more smooth.

## 1.2 Weakly Interacting Massive Particles

With the constraints inferred from the evidence, many candidate models of dark matter can be built, such as axions derived from the CP problem in quantum chromodynamics (QCD), asymmetric dark matter models inspired by the particle anti-particle asymmetry of baryons, and sterile neutrino based on the hypothesis of the existence of the forth neutrino flavor in addition to $\nu_e$, $\nu_\mu$, and $\nu_\tau$. In this section I will focus the discussion on the Weakly Interacting Massive Particle (WIMP), a generic model that requires dark matter to have a relatively high mass (in the GeV to TeV range) and weak coupling with ordinary matter in addition to gravitational interaction. Due to the generality of the WIMP model, it has a large group of sub-species such as neutralino, heavy sterile neutrino, and a few models of asymmetric dark matter.
1.2.1 The WIMP Miracle

The search of WIMP dark matter is strongly motivated by the "WIMP miracle". In the dense early universe, as the particles were actively produced and destroyed, the proportion of a specific type of particle could quickly reach an equilibrium, where the production rate and reduction rate were equal. With the expansion and dispersion of the universe, the interaction rate between particles became too low to maintain the equilibrium. Because dark matter is stable, the relic proportion of dark matter gets preserved. The equilibrium between dark matter and baryonic matter was determined by the mass of dark matter and its coupling cross section with baryonic matter. Based on the observed dark matter to luminous matter ratio, the coupling cross section of dark matter particles with mass in GeV and TeV range should be in the weak scale. Miraculously, this result matches with the requirement for WIMP dark matter. This coincidence is often referred as the "WIMP miracle". It strongly motivates the search of WIMP dark matter.

1.3 Detection of WIMPs

Although their non-luminous nature makes WIMPs difficult to study, the weak coupling between WIMPs and ordinary particles provides possible approaches to detect it. Based on the mechanism of the interaction, the detection of dark matter can be categorized in to three different classes.

WIMP-WIMP annihilation emits radiation, which can be used to study the fundamental properties of WIMPs. Therefore, several Earth-based and space-based high sensitivity telescopes are looking at massive celestial bodies, where dark matter density is supposed to be relatively high, to look for photons and neutrinos originating from WIMP annihilation.
WIMPs can be emitted from the collision of standard model particles. Such processes can be triggered in accelerators like Large Hadron Collider (LHC). Since WIMPs will most likely pass through the detector without interacting, they will account for the missing energy and momentum of the events. If such missing energy and momentum, which can not be explained by standard model particles, occurs statistically significant, then it indicates the detection of dark matter.

A WIMP particle can scatter off a standard model particle through the weak interaction and transfer energy and momentum to it. This process provides us with the third approach of WIMP detection - direct detection. Since the data, that will be used in this dissertation, are from DarkSide-50 (DS-50) designed for direct detection of WIMPs, this approach will be introduced in detail in the rest of the chapter.

1.3.1 Direct Detection

Direct detection is an active field of dark matter search, which aims for the detection of scattering between standard model particles and dark matter particles. In a detector designed for direct detection, high energy particles can scatter off the particles in the target material and cause the target particles to recoil. Consequently, the photons and phonons produced by the recoiling particles can be observed by the sensors around it to produce signals.

Light particles will interact with orbital electrons of the atoms in the target material, while heavy particles such as WIMPs, whose de Broglie wavelength is comparable with the radius of nuclei, will scatter coherently with the nuclei. The interaction between WIMPs and target nuclei can be described explicitly by the differential recoil rate

\[
\frac{dR}{dE_R} = N_N \frac{\rho_0}{M_\chi} \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{d\bar{v}f(\bar{v})\nu}{dE_R} \frac{d\sigma}{dE_R},
\]

(1.1)
where $M_{\chi}$ is the mass of WIMPs, $N_N$ is the total number of target nuclei, $\rho_0$ is the density of WIMP halo at Earth, $\vec{v}$ is the WIMP velocity with respect to the Earth, $f(\vec{v})$ is the distribution of WIMP velocity, $\frac{d\sigma}{dE_R}$ is the differential cross section of the scattering, $v_{\text{max}}$ is the maximum velocity bounded by the escape velocity of the Milky Way, and $v_{\text{min}}$ is the minimum velocity. The minimum velocity required to cause a recoil with energy $E_R$ corresponds to the head-on collision, in which situation the velocity can be calculated by [36]

$$v_{\text{min}} = \sqrt{\frac{E_R(M_T + m_{\chi})^2}{2M_TM_{\chi}^2}}, \quad (1.2)$$

where $M_T$ is the mass of the target nucleus. The scattering cross section, $\sigma$, can be obtained with

$$\sigma = \sigma_{\chi}[A\frac{\mu}{\mu_n}F(q)]^2, \quad (1.3)$$

where $\mu$ is the WIMP-nucleus reduced mass, $\mu_n$ is the WIMP-nucleon reduced mass, $\sigma_{\chi}$ is the WIMP cross section, $A$ is the atomic number of the target, $F(q)$ is the nuclear form factor, and $q = \sqrt{2M_TE_R}$ is the momentum transfer.

Most of the parameters in the previous equations, such as the escape velocity of the local galaxy and the atomic number of the target material, can be calculated or measured. By applying the dark matter halo model to the local galaxy, we can obtain the WIMP mass density, $0.3 \text{ GeV}c^{-2}\text{cm}^{-3}$ [31], and the velocity distribution of WIMPs with respect to the earth [32].

The equations shown above leave us with three unspecified variables, $M_{\chi}$, $\sigma_{\chi}$, and $E_R$. Therefore, by fixing $M_{\chi}$ and $\sigma_{\chi}$, we can obtain a spectrum of WIMP-nucleus interaction rate. To display how the choice of target material can affect the interaction rate, $M_{\chi}$ is fixed to 100 GeV and $\sigma_{\chi}$ is fixed to $10^{-45}\text{cm}^2$. After that, the spectra of the interaction rate for different target atomic numbers are plotted and shown in the left plot of Figure [1.1]. At low energy, the rate with xenon is higher than the rate with
Figure 1.1: Left: the expected nuclear recoil spectra induced by 100 GeV WIMPs through spin-independent interactions with different target materials. Right: the argon nuclear recoil spectra induced by WIMPs of different masses. The WIMP nucleon interaction cross section is assumed to be $10^{-45}\text{cm}^2$ in both plots. These plots are made by J. Xu [36].

argon and germanium, because $\sigma$ is proportional to $A^2$. As the energy gets higher the nuclear form factor significantly suppress the $\sigma$ for heavy target atoms. Therefore, the rate of WIMP-nucleus interaction with xenon can be lower than that with argon and germanium.

To show how the WIMP-nucleus interaction rate depends on the WIMP mass, $\sigma_\chi$ is fixed to $10^{-45}\text{cm}^2$ and the spectra of the rate in argon with 5 different values of WIMP mass are plotted and shown in the right plot of Figure 1.1. As a result, small WIMP mass corresponds to low recoil energy. The efficiency of detecting the recoil events is referred as the acceptance of the detector. The acceptance diminishes with the decrease of the recoil energy, since low energy events will produce small signals, which are hard to discriminate from backgrounds and noise.

With the acceptance of the detector being well understood, we can predict the WIMP detection rate for a given WIMP mass and cross section. By comparing the predicted rate and the detected rate, the direct detection experiments set limits on the parameter space as shown in Figure 1.2. Each curve in the figure represents a 90% upper exclusion limit for WIMP cross section with the corresponding WIMP mass.
Currently, since a large proportion of the WIMP mass - cross section parameter space has been ruled out by different experiments searching for dark matter, the "WIMP miracle" described in Section 1.2.1 is not as popular as before. However, the remaining parameter space can still be explained by many WIMP candidates. So a great number of experiments are still trying to increase their sensitivity for the search of WIMPs.

Detectors built for direct detection of WIMPs can be categorized as crystal-based detectors (SABRE [34], DAMA/LIBRA [12], SuperCDMS [8]), liquid xenon-based detectors (LUX [9], XENON [11], PandaX [19]), and liquid argon-based detectors (DarkSide [4], DEAP [10]). As mentioned previously, the target material is carefully chosen to have high WIMP sensitivity. However, since the rate of WIMP events is low, the radiopurity and background discrimination are also important for controlling the background level. Besides, as larger target volume leads to larger WIMP event rate, the scalability of target material should be considered as well.

Depending on the design, the liquid based detectors can be sub-divided into single phase detectors, which have only scintillation signals from the liquid, and dual phase detectors, which have two types of signals (one from liquid and one from gas). Dual phase detectors will be introduced more detailed in the next chapter, when we focus our discussion on DS-50.

Currently, as shown by the limit curves the lowest limit is set by xenon based detectors (LUX, XENON1T, PandaX-II). DS-50 provides the best limit from argon based experiments. Considering the mass of active volume of DS-50, 50 kg, which is much smaller than that of the ton scale detectors, DS-50 has proved the potential of liquid argon-based detectors. A much lower limit can be expected from the next generation of DarkSide detector, DarkSide-20k (DS-20k) [1].
Figure 1.2: Limit on the spin-independent WIMP-nucleon scattering cross-section for various WIMP masses, based on the background- and signal-free result observed in the 530d UAr analysis. Selected results are also plotted for comparison. [6]
Chapter 2

DarkSide-50

DarkSide-50 (DS-50) is a detector designed for direct detection of WIMPs, located in Hall C at Laboratori Nazionali del Gran Sasso (LNGS) in Italy, 1.4 km underground. 50 kg of active liquid argon is used in the central Time Projection Chamber (TPC) to await WIMPs. Two outer detectors (ODs) nested outside of TPC are designed for both active and passive shielding of cosmic radiation and decay products from radioactivity on Earth.

The detector has been running for more than 4 years, since Nov 2013. The dark matter search of DS-50 can be separated into two phases. During first phase, the detector was filled with atmospheric argon (AAr) refined form the air, which has high rate of $\beta$ activity caused by a radiogenic isotope, $^{39}$Ar. The second phase started in Apr 2015, with the AAr replaced by underground argon (UAr) refined from underground gas, which has not been exposed to cosmic radiation.

In this chapter, various components of the detector will be introduced and signal production and data acquisition (DAQ) will be discussed.
2.1 Outer Detectors

Since the scattering cross section between WIMPs and argon nuclei is small, background reduction is very important for DS-50. In addition to the shielding provided by the rock above the underground lab, two ODs are nested around the TPC, to suppress the background. The outermost detector is the water Cherenkov veto (WCV), which is a 10 m tall, 11 m diameter water tank, with 1 kt of radio-purified water inside. Besides the passive shielding provided by water, the Cherenkov radiation from muons passing through the WCV is viewed by 80 ETL 9351 8” photomultiplier tubes (PMTs). With the help of the muon signals from the WCV, TPC events triggered by muons and particles produced by muons as they travel through the rock and lab can be vetoed.

![Figure 2.1: DarkSide-50 assembly.](image)

Since the nuclear recoils initiated by neutrons can not be easily discriminated from nuclear recoils initiated by WIMPs, neutron vetoing is essential for the detector.
The neutron vetoing detector, also referred as the Liquid Scintillator Veto (LSV), is a 4 m diameter sphere located at the center of the WCV, filled with a cocktail composed of 5% trimethyl borate (TMB), 95% pseudocumene (PC), and 1.4 g/l 2,5-diphenyloxazole (PPO). The boron in TMB can efficiently capture thermal neutrons. PC has good scintillation efficiency. PPO is a good wavelength shifter, which converts scintillation UV photons to visible photons. After being wavelength shifted, the scintillation photons originating from neutron scattering and capture are detected by 110 Hamamatsu R5912 LRI 8” PMTs mounted on inner surface of the LSV. Nearly all of neutrons that scatter inside the TPC will also produce signals in the LSV before they get in or after they leave the TPC. The veto efficiency for neutrons giving WIMP-like signals in the TPC is estimated to be 99.66 ± 0.01%.

2.1.1 Data Acquisition and Pulse Reconstruction

Each PMT of the ODs is read out and digitized in 16 bits with a 1.25 GHz frequency over a 200 µs acquisition window, (-10.5, 189.5) µs with respect to TPC trigger time. Before summing the digitized waveforms from different channels and searching for signals by a cluster finder in the summed waveform, a few corrections are applied on the waveform of each channel: [5]

- **Saturation Correction:** When the waveform saturates the analog to digital converter (ADC), the waveform in the saturated region is estimated by extending the waveforms before and after the saturation to form a triangular peak.

- **Overshoot Correction:** The baseline is supposed to be close to zero and any meaningful signal should be negative. This correction removes the positive voltage caused by electronics overshoot.

- **SPE Calibration:** Since different PMT channels have different gains, the channel waveforms should be normalized by single photoelectron (SPE) mean.
The SPE mean of each PMT channel is calibrated by shooting sparse photons to the PMT window through an optical fiber.

- **Baseline Subtraction and Suppression:** The original baseline offset of each channel is found and subtracted from the waveform. To avoid recording noise between pulses, after the baseline subtraction, waveforms below a $\sim 0.25$ PE threshold are not recorded for clustering.

After applying the pre-clustering corrections on each channel, a summed waveform for the LSV or the WCV can be constructed by summing the corresponding channels in the detector. A "Top-Down Cluster Finder" algorithm is applied to identify scintillation signal pulses which are represented by clusters formed by adjacent high amplitude samples in the summed waveform. The algorithm first finds the peak of the whole waveform and terminates the process if its height is below 2PE. If the peak height is larger than the 2PE threshold, the algorithm will look for the start time of the cluster by searching for the nearest 20 ns empty window before the peak. A cluster end time is established similarly by searching for the first empty 20 ns window after the peak. In this way, one cluster is found with its start, end, and peak position. The previous steps will be repeated on the remaining waveform in the data acquisition (DAQ) window until no peak above the 2PE threshold can be found.

With the clusters found, the cluster-level parameters, the integral, time, and shape of the clusters, can be constructed. More sophisticated analysis can be done with these parameters to study the activity inside the ODs.

### 2.2 Time Projection Chamber

The TPC of DS-50 is a cylindrical teflon chamber with a $36.5 \text{ cm tall} \times 36.5 \text{ cm diameter}$ (measured at room temperature) active argon cavity inside. The whole chamber
is submerged into 150 kg of liquid argon, contained by a stainless steel cryostat constructed with two nested walled vessels with thermo-resistive materials in between. The \(~ 50 \text{ kg} \) active liquid argon inside the chamber is watched by 38 Hamamatsu R11065 3” PMTs, with 19 at the top of the TPC and 19 at the bottom. In front of top and bottom PMT arrays, there are two fused silica windows referred as the anode (top) window and the cathode (bottom) window. With 15 nm indium-tin-oxide (ITO) coating, the surfaces of the fused silica windows are conductive. The edge of the anode window extends down to form a diving bell shape, which creates a gaseous argon reservoir. With gaseous argon fed in, a layer of gaseous argon, referred as the gas pocket, is formed below the anode window. The thickness of the gaseous argon layer, referred as the gas pocket height, is controlled by a bubbler welded on the anode window, which will be introduced in detail in Section 5.1. A stainless steel mesh is located about 0.5 cm below the liquid surface, which can establish a high electric field in the gas pocket together with the ITO layer on the anode window. For standard dark matter search running, \(-5.6 \text{ kV} \) is applied to the grid, while the lower surface of the anode window is grounded. With these settings, there is a 2.8 kV/cm extraction field between the grid and the liquid surface and a 4.2 kV/cm multiplication field in the gas pocket, if the grid mesh and anode window have no deformation. The strength of the standard drift field (field between the grid and the cathode window) is set to 200 V/cm by applying \(-12.7 \text{ kV} \) on the cathode window. The uniformity of the drift field is preserved by copper rings mounted on the outer surface of the TPC wall and the resistors between them. The inner surfaces of the teflon TPC wall and the fused silica windows are coated with a wavelength shifter, tetraphenyl butadiene (TPB), which efficiently converts argon scintillation UV photons to visible photons with wavelengths around 420 nm.

A high energy particle can scatter off an electron or a nucleus of an argon atom to trigger an electronic recoil (ER) or a nuclear recoil (NR), and subsequently cause
Figure 2.2: The cross section of the TPC and cryostat.

A sequence of interactions between argon atoms. Except for the energy lost in thermalization, the rest of the energy deposited from the initial scattering will excites or ionizes argon atoms. A part of the ions and free electrons created with ionization will recombine and become excitons. By the de-excitation of the excitons, scintillation UV photons will be emitted. UV photons from scintillation will be wavelength shifted to visible photons and get detected by the PMTs to form a scintillation signal, S1. The electrons escape recombination will drift to the gas pocket guided by the drift field in the TPC. Under the high multiplication field in the gas pocket, the electrons will produce scintillation photons through electroluminescence. Photons generated in the gas pocket will also be wavelength shifted and detected to form an ionization signal,
S2. The scintillation process in liquid argon and gaseous argon will be discussed in more detail in later sections of this chapter.

2.2.1 Data Acquisition and Pulse Reconstruction

The TPC signals from 38 PMT channels are responsible for event triggering. For the standard dark matter search, the trigger requires the output of at least two channels to be larger than a $\sim 0.6$ PE threshold simultaneously. This sensitive trigger should be activated by the first signal, S1, of an event. In a 440 $\mu$s data acquisition window, (-5, 435)$\mu$s with respect to the trigger time, the waveform of each channel is digitized with a 250 MHz rate and saved.

The SPE mean for each channel is calibrated about two times a day, with sparse photons transmitted into the TPC by a laser fiber connected to the bottom PMT holder. Thus, the waveform of each channel can be normalized by the SPE mean to remove the bias caused by gain difference.

Baseline Finder

Because of the DC offset applied on the digitizer, a baseline subtraction is necessary for the waveform from each channel. Since small baseline fluctuations can be caused by electronic noise, a baseline finding algorithm is designed to depict a moving baseline for each channel. First of all, in the pre-trigger region of the DAQ window, the algorithm finds the highest amplitude, which should correspond to the maximum positive noise fluctuation, because signals only create negative pulses. Then, the region from the highest amplitude to two $A_{\text{max}}$ below is defined as the search region. ($A_{\text{max}}$ is the maximum noise amplitude, different from channel to channel.) After that, a 80 ns baseline-finding window is moved chronologically from the start time of the DAQ window. If the amplitude of the waveform in the baseline finding window are all inside the search region, then we set the baseline of the middle point of the window to
the average amplitude in that window. If no baseline is found in the pre-trigger region, the process will be terminated and we fail baseline finding for that channel. Once the baseline is found, the search region will be redefined as the moving average $\pm A_{\text{max}}$, and the process will be continued to the end of the DAQ window. The potential signal positions, where the amplitude in the 80\,ns baseline-finding windows are not all in the search region, will be skipped. Their baseline will be linearly interpolated by the baseline level before and after them. With this algorithm, the moving baseline of all the channels can be found and subtracted, before summing up the waveforms for pulse finding.

**Pulse-finding**

After the summed waveform is built, a pulse-finding algorithm is performed on it to identify signals and construct signal parameters. The waveform is down sampled by a factor of 250. To search for a pulse, the algorithm scan through the coarse bins chronologically from the start of the DAQ window. At each bin, the slope of the waveform is calculated using the bins before and after it. Once the slope shows a more than 3\,PE increase in amplitude between adjacent coarse bins, a pulse is found. The fine samples inside and after the current coarse bin are searched chronologically until a sample with amplitude larger than 0.3\,PE is found. The start time of the pulse is defined to be two fine bins prior the bin above the threshold. The end time is found by moving a 3.2\,\mu s window from the start time until the integral in the window gets lower than 2\,PE or another pulse is found (In this case, another pulse is piled up with the current one.). The previous steps are performed until the end of the DAQ window. Once the start times and the end times of the pulses are found, event and pulse parameters can be constructed for analysis.
Essential Parameters

A few essential parameters used in the current study are:

- **S1**: Integral of the first pulse in an event, if there is at least one pulse.
- **S2**: Integral of the second pulse in an event, if at least two pulses are found.
- **t_{drift}**: If the number of pulses is larger than or equal to two, \( t_{drift} \) is the time between the start times of the first two pulses.
- **F90**: The fraction of the first pulse within 88 ns after its start time. This parameter represents the fraction of fast scintillation in a signal.

### 2.2.2 Scintillation Process in Liquid Argon

As mentioned previously, TPC events can be classified into two categories, ERs and NRs. An ER is initiated by a scattering event between a light particle and an argon electron. As the recoiling electron is moving in liquid argon, it can excite argon atoms, create argon ions, and cause other electrons to recoil. Because of the huge mass difference between electrons and argon nuclei, nearly all the energy of the recoiling electron will be dissipated to other electrons. On the other hand, a NR is initiated by a scattering event between a heavy particle and an argon nucleus. A portion of a recoiling nucleus’ energy will be transferred to electrons to create argon excitons and ions, while the rest of the energy will be transferred to other nuclei. If the energy transferred to a nucleus is too small to excite and ionize an argon atom, it will be lost to heat. As a result, both ERs and NRs generate argon excitons and ions, which have potential to emit scintillation photons.

The excitons can emit scintillation photons with the process

\[
\text{Ar}^* + \text{Ar} \rightarrow \text{Ar}_2^*
\]

\[
\text{Ar}_2^* \rightarrow 2\text{Ar} + h\nu.
\]
With an electron in the excited state, the exciton can create a valence bond and dimerize with a ground-state argon atom to form an excimer. This process is known as self-trapping. Then, the excimer will break apart to two ground state atoms and emits a 128 nm scintillation photon.

An argon ion can also dimerized with a ground state argon atom through self-trapping. The charged dimer has chance to recapture its lost electron or capture an electron from a nearby ionization. With a free electron captured, the charged dimer will break apart into one ground state argon atom and one doubly excited argon atom. The doubly excited argon will quickly lose its vibrational energy to heat and become a normal exciton. As described before, a scintillation photon can be emitted from the exciton by self-trapping and de-excitation. The whole scintillation process of ions can be described by:

\[
\begin{align*}
\text{Ar}^+ + \text{Ar} & \rightarrow \text{Ar}_2^+ \\
\text{Ar}_2^+ + e^- & \rightarrow \text{Ar}^{**} + \text{Ar} \\
\text{Ar}^{**} & \rightarrow \text{Ar}^* + \text{heat} \\
\text{Ar}^* + \text{Ar} & \rightarrow \text{Ar}_2^* \\
\text{Ar}_2^* & \rightarrow 2\text{Ar} + h\nu
\end{align*}
\]

**Pulse Shape Discrimination**

As the WIMP events cannot be ERs, the background can be significantly suppressed, if ERs and NRs can be discriminated. In this section, we will focus on the primary method used to distinguish ER and NR - pulse shape discrimination. An auxiliary discrimination method using the ratio between S1 and S2 will be introduced briefly.

An argon excimer is composed of a charged dimer, \( \text{Ar}_2^+ \), and an orbital electron. Both of them have a total spin of \( \frac{1}{2} \). As a result, the excimer can have either a singlet
state with spin 0 or one of the triplet states with spin 1,

\[
\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \quad \text{singlet},
\]
\[
\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \quad \text{triplet}.
\]

Since a singlet state excimer has the same total spin as the total spin of two ground state argon atoms, it can de-excite to ground state atoms quickly with a 7 ns lifetime. However, the de-excitation of a triplet state excimer is less straightforward, because of the involvement of angular momentum transfer. This situation makes the lifetime of triplet state excimers as long as 1.6 μs. Because of the lifetime difference between singlet state excimers and triplet state excimers, a scintillation signal has a fast component and a slow component. Therefore, the singlet-to-triplet ratio can determine the pulse shape of an event.

Compared to the excimers created by ERs, the excimers created by NRs have a larger singlet-to-triplet ratio. Therefore, the S1 waveform of a NR have a larger fast component to slow component ratio than that of an ER. The reason for the difference in singlet-to-triplet ratio between ERs and NRs are not thoroughly understood. A few hypotheses are listed as following.

- When an exciton is created from the excitation of a ground state atom, the electron at the excited state tends to have its original spin. In this case, the excimer formed with such an exciton can have either the singlet state or the second state of the triplet states. Therefore, the singlet-to-triplet ratio should be 1. However, the spin of an exciton created by the recombination of an ion and an extraneous electron is random. Consequently, the excimer can randomly
have one of the four spin states. Therefore, the singlet-to-triplet ratio should be 1/3. For this reason, the exciton-to-ion ratio of an event can determine its singlet-to-triplet ratio and consequently determine its waveform.

The exciton-to-ion ratio of nuclear recoils is measured to be $\sim 1$, while the ratio for electronic recoils is $\sim 0.21$. Following the logic built previously, nuclear recoils have more fast component in their waveform than electronic recoils.

- Angular momentum can be exchanged among the excimers to randomly change their spin states. If the time scale of such exchange is larger than the lifetime of singlet state excimers and smaller than that of triplet state excimers, then the triplet state excimers can be converted to singlet state excimers, which quickly de-excite.

The recoiling electrons can travel longer and dissipate their energy to a larger region compared to recoiling nuclei. Consequently, NRs will have larger excimer density than ERs. In this case, the change of the spin states described previously happens more frequently for NRs and makes their scintillation faster.

As introduced in the previous section, F90 measures the fast component to slow component ratio of the S1 of an event. The average F90 is $\sim 0.7$ for NRs, and $\sim 0.3$ for ERs. By applying a lower F90 boundary for dark matter search, we can remove nearly all the ERs.

The ratio between S2 and S1 also has some separation power for discriminating ERs and NRs. Since NRs have larger exciton-to-ion ratio, they have fewer free electrons produced through ionization. Besides that, the high recombination probability caused by high ionization density makes the electron number surviving from recombination even smaller. Therefore, if the same amount of energy is transferred to the recoiling particles, NRs should have significantly smaller S2s. Thus, NRs should have smaller S2/S1 than ERs. S2/S1 is widely used in xenon based experiments for dis-
criminating ERs and NRs. However, since pulse shape has much higher separation power than S2/S1 for argon based experiments, S2/S1 is used as a minor ER cut or a crosscheck for pulse shape discrimination.

2.2.3 Scintillation Process in Gaseous Argon

Because of the high electric field in the gas pocket, free electrons can quickly acquire energy from the electric field as they move towards the anode. Besides that, the rarity of argon atoms in gaseous argon leaves the free electrons space to accelerate before impacting with orbital electrons. When the electrons acquire enough energy from the electric field, they will be able to create excitons along their way to the anode. As with the scintillation of excitons in liquid argon, the excitons in gaseous argon can emit scintillation UV photons by dimerization and de-excitation.

S2 signals, also referred as secondary scintillation signals or ionization signals, are produced by this scintillation process in gaseous argon. Other than constructing S2/S1, which has separation power for discriminating ERs and NRs, S2s are used for position reconstruction. The vertical position of an event is represented by $t_{\text{drift}}$, which is acquired from the start time difference between S1 and S2. The information about the horizontal position of an event can be achieved by the $xy$ reconstruction algorithm, which uses the S2 channel fraction$^1$ of each PMT channel $^{[15]}$.

Electroluminescence

The scintillation process in the gas pocket is also known as electroluminescence. Since the energy of the scintillation photons is completely provided by electric field, the field dependence of the scintillation light yield represents the fundamental property of electroluminescence. Studies of argon electroluminescence can be beneficial to the

---

$^1$For an event with an S2, the channel S2s correspond to the numbers of S2 photoelectron integrated from the channel waveforms, while the total S2 corresponds to the number of S2 photoelectron integrated from the summed waveform. The S2 channel fractions are the ratios between the channel S2s and the total S2.
design and Monte Carlo simulation of a detector whose signal production involves scintillation in gaseous argon.

Figure 2.3: Results of recent studies on argon electroluminescence. The light yield and field are normalized by the number density of argon atoms. Data from recent measurements [13] are shown with the red squares, while the result from a simulation program [27] is shown by the black solid curve.

The results of two recent studies on argon electroluminescence light yield are shown in Figure 2.3. The solid line represents the result of a Monte Carlo simulation using Garfield, a program widely used for gas detector simulation [27]. The red squares represent the result of a recent measurement done by Bondar [13], which agrees well with the simulation. Results from the analysis of DS-50 data will be added to the figure at the end of this dissertation.
Chapter 3

Data Selection Criteria

In the current chapter, the datasets used in this study will be introduced at first, followed by the discussion about the corrections on energy dependent parameters, S1 and S2. The last section of the chapter will includes the major cuts applied to our data.

3.1 Datasets

The data acquired under different detector settings with different calibration sources have different properties and uses. The primary datasets used in this study are listed as follows.

• 1. 50 Days Data: This dataset is from DS-50’s first phase of data taking. It includes data collected within a 50 days detector livetime, which was used for the first paper of analysis results [3]. The settings of the electric fields are the settings for standard data taking, with a drift field of 200 V/cm, and an extraction field of 2.8 kV/cm. During the first phase, the TPC was filled with atmospheric argon, which contains 1 Bq beta decay caused by a radiogenic isotope $^{39}$Ar. Since other backgrounds are controlled at extremely low levels,
nearly all the events in this dataset are ERs caused by the decay of \(^{39}\text{Ar}\). Therefore, this dataset is useful when a large sample of uniformly distributed ERs is needed for calibration.

- **2. Krypton Dataset:** A krypton isotope \(^{83m}\text{Kr}\) created by the decay of \(^{83}\text{Rb}\) was added to active liquid argon through argon circulation, when taking this data sample. The settings of the electric fields are the same as the settings used for 50 days dataset. The decay of \(^{83m}\text{Kr}\) has two steps and emits two X-rays correspondingly (32.1 keV and 9.4 keV). Because of the short lifetime, \(\sim 222\) ns, of the intermediate state, the decay of a \(^{83m}\text{Kr}\) atom only produce a single event, with identical energy 41.5 keV. Because of the high decay rate of \(^{83m}\text{Kr}\) during the calibration, we can get a clean ER sample with identical recoil energy. This dataset will be used for energy calibration in this study.

- **3. Data with Different Voltages:** These are the primary data for our study of the field dependence of light yield in the process of argon electroluminescence inside the gas pocket of DS-50. It includes nine atmospheric argon runs. Most of the settings are standard data taking settings. However, the voltages between the grid and the anode window of the 9 runs in this dataset vary run by run from 4.59 kV to 6.38 kV. Therefore, these runs should have the same S1 spectrum, but different S2 spectra. The differences in the S2 spectra contain information about the field dependence of argon electroluminescence light yield.

### 3.2 Correction of S1 and S2 by Position

As introduced in Chapter 2, the most significant parameters in this analysis are S1 and S2, which depend on the recoil energy. In addition, S2 is also proportional to the electroluminescence light yield in the gas pocket. These dependences will be analyzed
in detail in the following chapters. Before that, we need to make preliminary position dependent corrections for $S_1$ and $S_2$.

### 3.2.1 Position Correction of $S_1$

Because of the geometry of the detector, $S_1$ photons from events close to the anode of the TPC are likely to be reflected from the liquid gas interface. For these photons, relatively longer paths towards the PMTs result in larger probabilities of being absorbed by the detector material. Such effect causes the $S_1$ light yield to have a vertical position dependance. The light yield near the cathode window is $\sim 17\%$ larger than the light yield near the grid mesh.

The horizontal position dependance of $S_1$ is caused primarily by the absorption of UV photon in liquid argon. Because of the high purity of our liquid argon, 128 nm UV photons from argon scintillation were measured to have an absorption length equal to $3.75 \pm 1.15 \text{ m}$ (introduced in Appendix A.1), which is large compared to the size of the TPC. Therefore, $S_1$ signals have a weak dependence on radius. According to the study of mono-energetic electronic recoils form the Krypton dataset, at half height of the TPC, the $S_1$ light yield at the center can be $2\%$ lower than the edge.

Figure 3.1 shows the normalized $S_1$ light yield at different vertical and radial positions. For each event, a position corrected $S_1$, $S_{1\text{corr}}$, can be obtained by dividing the raw $S_1$ by the normalized $S_1$ light yield read from the bin with the corresponding position in Figure 3.1.

### 3.2.2 Vertical Position Correction of $S_2$

The vertical dependance of $S_2$ signals are caused by the loss of electrons while drifting up. This makes the light yield of $S_2$ proportional to $e^{-\frac{t_{\text{drift}}}{\tau}}$, where $\tau$ is drift lifetime of electrons. The measurement of drift lifetime is done by fitting an exponential function to the distribution of $S_2/S_1$ vs. $t_{\text{drift}}$. The vertical position corrected $S_2$ signal, $S_{2\text{corr}}$,
Figure 3.1: Normalized S1 light yield vs. $t_{\text{drift}}$ obtained with $^{83}$Kr data. Different colors are corresponding to different $r^2$. Y axis is normalized to have the average light yield at half of maximum $t_{\text{drift}}$ equal to 1.

of an event can be obtained by dividing the raw S2 by $e^{-\frac{t_{\text{drift}}}{\tau}}$. Due to the high purity of the liquid argon, most of the datasets used in this study have their drift lifetime larger than 5000 µs, except for 3 of the old runs in the data with different voltages, whose drift lifetime is 915 µs. The contamination, which is responsible for the short drift lifetime, is caused by active changing of the detector settings (including settings for argon recirculation system), before those 3 runs are taken.

The horizontal dependence of S2 signal will be displayed and analyzed in the next two chapters.
3.3 Cuts

In this section, I list all the cuts designed to exclude the events which are not suitable to the electroluminescence study. Some additional cuts will be designed to fulfill specific purposes in the latter analysis, I will mention them in the corresponding sections.

1. Number of Channels Cut: There are 19 PMTs in both of the top and bottom PMT arrays. This cut ensures that the DAQ system properly stores the data from each of the 38 channels for an event. Nearly all the events pass this cut.

2. Baseline Cut: As introduced in Section 2.2.1, a moving baseline is required for baseline subtraction before summing over the channels and integrating for the size of signals. This cut assures that our algorithm successfully finds a baseline for each channel of the event. Usually, it fails when one or several channels are noisy.

3. Livetime & Inhibit Time Cut: After a triggered event, there is a 800 µs inhibit window. Because of the blindness of the detector in an inhibit window, it may miss an S1 signal, but trigger on the S2 of that event. To leave enough time between events so that signals in the new event have no correlation with possible signals in the previous inhibit window, we require inhibit time + livetime after it to be larger than 1.35 ms. To prevent unexpected low event rate caused by trigger malfunction, the livetime is also required to be less than 1 s.

4. Trigger Time Cut: Because of the design of the TPC trigger, it is supposed to trigger on the first pulse in a DAQ window. This cut requires that the start time of the first reconstructed pulse is located inside the trigger window, a 100 ns time window around the trigger time. In this way, we assure that the event is triggered on the first reconstructable signal. Consequently, events
triggered on tiny after pulses or noise, which cannot be reconstructed can be
removed. Nearly 95% of the events pass this cut.

5. **Single-Hit Cut:** This cut assures that there is only one recoil recorded in
each event. Which means only one S1 and one S2 are detected. Sometimes the
photons from a ionization signal can kick out several electrons from the cathode
due to photoelectric effect, so a small signal at one maximum drift time after
the S2 is acceptable.

6. **S1 Max Fraction Cut:** This cut rejects events with much of their S1 signals
concentrated in one of the PMTs. It has potential to remove the Cherenkov
events and surface alphas occur inside or on the surface of the fused silica
windows located at the top and bottom of the TPC.

7. **S1 Saturation Cut:** This cut assures that the S1 signal of an event does not
saturate the analog to digital convertor (ADC).

8. **S2 Saturation Cut:** This cut assures that the S2 signal of an event does not
saturate the ADC.

9. **F90 Cut:** A lower limit of F90 set to be 0.1. Since S2 signals have much
smaller F90 than S1 signals, this limit can remove the events with S1s and S2s
overlapped and events triggered on S2s. Besides, an 0.55 upper limit is set to
F90 in order to exclude NRs, whose typical F90 is around 0.7, and further purify
the ERs.

10. **Drift Time Cut:** The vertical position, $z$, of an event is determined by $t_{\text{drift}}$, the
difference between the start times of the S1 and S2. This cut removes all the
events whose $t_{\text{drift}}$s are smaller than 40 $\mu$s or larger than 334.6 $\mu$s, namely it rejects
the events near the top and the bottom, which may contain contamination from
the surface background or Cherenkov background.
Figure 3.2: $S_{1_{\text{corr}}}$ spectra. Figure (a) shows the spectrum of all the events in the 50 days dataset, whose $S_1$ signal saturates ADC. Figure (b) shows the spectrum of all the events, whose $S_2$ signal saturates ADC. The dataset corresponding to a grid-to-anode voltage of 6.38 kV is used, because it is the dataset with the largest $S_2$ light yield in this study.

11. **$S_{1_{\text{corr}}}$ Range Cut:** Due to the large statistical error on signal size and the frequent $xy$-reconstruction failure for low energy events, we only choose events with $S_{1_{\text{corr}}}$ larger than 100 PE.

On the other hand, high energy events tend to saturate the ADCs in our DAQ system, as shown by Figure 3.2a and Figure 3.2b. Using these saturated events can cause systematic error of signal size. However, removing these saturated events, by the saturation cuts introduced previously, can cause higher order systematic error, when we average the size of signals, because the larger signals have larger probabilities to saturate. Therefore, I only use the events, whose $S_{1_{\text{corr}}}$ is lower than 650 PE, where the saturations happen seldom.

12. **Uncorrected $S_2$ Cut:** Our study of electroluminescence require successful and accurate $xy$-reconstruction. However failures and malfunctions of the reconstruction algorithm are observed with events, whose uncorrected $S_2$s are low. In addition, events close to the TPC wall can have their drift electrons absorbed by the TPB and teflon. Such events can have unexpectedly low $S_2$
and induce bias to the current study, which highly depends on its precision. For these reasons, we cut all events with uncorrected S2 lower than 200 PE. No bias will be caused by this cut, because after the S1 Range Cut no normal event should have uncorrected S2 as low as 200 PE.

13. **Radius Cut:** This is a loose cut, that removes all the events with reconstructed radii larger than the radius of the TPC. After the $S_{1_{\text{corr}}}$ Range Cut and Uncorrected S2 Cut, most of the events can be reconstructed properly inside the TPC. Only a tiny fraction of events are removed, so we assume no bias will be caused by the loss of these events.

14. **Defect Reduction Cut:** Some areas on the top anode window are under suspicion of TPB defect\(^1\). The events whose horizontal positions overlap with these areas are excluded by this cut, since the size of the S2 signals, which is essential in this study, will be affected by the TPB defect. This cut is only applied for the data with different voltages.

The statistics of each dataset after applying the first 13 cuts consecutively are presented in Table 3.1. For most of the datasets, more than 40% of the events survived all the cuts. However, the last three datasets are cut heavily by the $S_{1_{\text{corr}}}$ range cut, because these three relatively old datasets were collected when we didn’t have a G2 trigger\(^2\) to reduce the less useful high energy events by a factor of 10.

---

\(^1\)Fused silica windows can contain regions, where the TPB layer gets removed or degraded. UV photons can not be wavelength shifted efficiently in these regions.

\(^2\)G2 trigger is designed to save storage space by skipping a fraction of high energy events.
Table 3.1: Number of events surviving the cuts.

<table>
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<th>Cut 4</th>
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Chapter 4

Electroluminescence Light Yield

As introduced in Chapter 2, the ionization signal, S2, is produced through electroluminescence in the gas pocket. In Chapter 3, S2 gets $z$ corrected to $S_{2\text{corr}}$. This chapter will focus on the process of converting $S_{2\text{corr}}$, in number of photoelectron, to the product of two variables, $Yh_g$, which more fundamentally represents the electroluminescence light yield as the number of UV photons produced by a single electron while traveling through the gas pocket with height $h_g$. In the expression, $Y$ is the number of UV photons produced by a single electron in unit scintillation path length.

In the first section of this chapter, I will obtain the average $S_{2\text{corr}}$ for events with the reference $S_{1\text{corr}}$, 200 PE, for different horizontal positions in DS-50. In the second section, the average number of drift electrons produced by events with the reference energy will be determined. Consequently, average $S_{2\text{corr}}$ produced by a single drift electron can be calculated. In the last section, I will describe the process of converting single electron $S_{2\text{corr}}$ to single electron UV light yield.

In the process described above, we observe a radial dependence of the electroluminescence light yield in DS-50. The light yield at the center is $\sim 4$ times higher than at the edge. The reason for this radial dependence will be studied in Chapter 5.
4.1 Scale by S1

From Chapter 3.2, we have gotten position corrected parameters $S_{1\text{corr}}$ and $S_{2\text{corr}}$ ($S_{2\text{corr}}$ is only corrected vertically). To prepare for the study of electroluminescence light yield in the following sections, we need to obtain an $S_{2\text{corr}}$ map for different $xy$ positions in DS-50. However, as the first scintillation signal size and the number of drift electrons, which produce the second scintillation, are proportional to the energy of the recoil, $S_{1\text{corr}}$ and $S_{2\text{corr}}$ are both energy dependent. Since $S_{1\text{corr}}$ is fully position corrected and proportional to energy, we can simply eliminate the energy dependence of $S_{2\text{corr}}$ by choosing events in a narrow $S_{1\text{corr}}$ range. Unfortunately, according to Table 3.1, the statistics in the data with different voltages are too small to allow us to do that simple operation. In this section, I scale $S_{2\text{corr}}$ by $S_{1\text{corr}}$ to make it approximately energy independent, so that more events can be used for making the $S_{2\text{corr}}$ map.

Figure 4.1 contains the events in the 50 days dataset. The $S_{1\text{corr}}$ range cut is not applied to show $S_{2\text{corr}}/S_{1\text{corr}}$ in a larger energy range. To reduce the smearing caused by radial dependance, a new cut is applied to only select the events with maximum S2 channel to be the central channel in the top PMT array. With these electronic recoil events, I made the 2D scatter plot to show the relation between $S_{2\text{corr}}/S_{1\text{corr}}$ and $S_{1\text{corr}}$. The mean values of $S_{2\text{corr}}/S_{1\text{corr}}$ are calculated for the $S_{1\text{corr}}$ bins and fitted with a function, which contains a polynomial component and an exponential component. The result of the fitting is displayed as

$$f(x) = 21.68 + 5.136 \times 10^{-2} x + 4.959 \times 10^{-6} x^2 + e^{4.421 - 3.590 \times 10^{-2} x}.$$  \hspace{1cm} (4.1)

The next step is using the fitting result we got to scale the value of $S_{2\text{corr}}$. We choose $S_{1\text{corr}} = 200 \text{ PE}$ as a reference ($S_{1\text{ref}}$), and scale the events with different $S_{1\text{corr}}$.
Figure 4.1: A $S_{2\text{corr}}/S_{1\text{corr}}$ vs. $S_{1\text{corr}}$ plot with events selected to have maximum S2 channel to be the central channel in the top PMT array. A polynomial + exponential function, shown as the red curve, is fitted on the means in each $S_{1\text{corr}}$ bin. The $S_{1\text{corr}}$ range cut is not applied to show the correlation in a larger energy range.

to have the same $S_{2\text{corr}}$ size as events with $S_{1\text{ref}}$. As shown by

$$S_{2\text{scale}} = \frac{S_{2\text{corr}}}{S_{1\text{corr}}} \frac{f(S_{1\text{ref}})}{f(S_{1\text{corr}})} S_{1\text{ref}},$$  \hspace{1cm} (4.2)$$

I divide $S_{2\text{corr}}/S_{1\text{corr}}$ of each event by the fitted value at the corresponding energy, $f(S_{1\text{corr}})$, and then multiply the result by the fitted value at the reference energy, $f(S_{1\text{ref}})$, to scale $S_{2\text{corr}}/S_{1\text{corr}}$ to $S_{2\text{scale}}/S_{1\text{ref}}$. After that, I multiply the result by $S_{1\text{ref}}$, to get $S_{2\text{scale}}$. The result after scaling is shown by Figure 4.2 which presents a flat distribution. In this way, I get a parameter, $S_{2\text{scale}}$, which has similar distribution over different energies, so that I can use data from a larger energy range without worrying about the smearing caused by energy dependence.
Figure 4.2: $S_2^{\text{scale}}$ vs. $S_1^{\text{corr}}$. The plot is made with the 50 days data. Only the events with maximum $S_2$ channel to be the central channel among the top PMT array are selected. An $S_1^{\text{corr}}$ range cut is applied to remove the low energy events with large statistical error and high energy events with bias caused by ADC saturation.

4.2 Ionization Signal of a Single Drift Electron

In the previous section, we choose the events whose maximum $S_2$ channel is the central channel in the top PMT array to reduce the $S_2$ smearing caused by radial dependance and focus on the energy dependance. After successfully scaling the $S_2^{\text{corr}}$ by energy, it is time to take a look at the radial dependance. Figure 4.3 shows the average $S_2^{\text{scale}}$ at different locations.

The events in Figure 4.3 are scaled to have the same energy, $S_1^{\text{ref}}$. To take a step closer to the electroluminescence light yield of argon, we need to obtain a map of the average $S_2^{\text{corr}}$ originated by a signal drift electron. In the rest of this section, I will introduce two studies of the single drift electron ionization signal done by my colleagues.
4.2.1 Study of Single Drift Electron Ionization Signals Using S2 Echo

Most single-scatter events include only two types of signals, S1 and S2. However some events will have very small S2 echo signals, S3s, located one maximum drift time after S2 signals. These S3s are produced by the photoelectric effect by shining S2 photons on the cathode. Since the cathode is at the bottom of the TPC, electrons from it need to spend the maximum drift time to drift all the way up. Just as S2s, S3s are ionization signals. However, because of the weakness of the photoelectric effect, a
significant number of S3s correspond to one drift electron. Therefore, it is a great data sample for the study of the single electron ionization signal.

The trigger of the detector is adjusted to make the events being triggered on S2 signals for this particular study, so that we can search for S3s at the same position in the DAQ window, one maximum drift time after the position of S2s. Figure 4.4 shows the waveform of a typical event triggered on S2 with an S3 at one maximum drift time.

![Figure 4.4: DAQ window of a typical event with an S3. The S3 is located in the green shaded area. The blue line shows the integration of the signals.](image)

As ionization signals, single electron S3 signals have the same radial dependance as S2s. A radial correction designed for S2s is applied to the S3s to correct their size at different horizontal positions to the size at center. The spectra of S3s are shown by Figure 4.5. In the figure, events are grouped by their maximum S3 channels. As the S3s are radially corrected, those spectra should give single drift electron peaks at the same position. However, as the size of S3s are very small and even smaller for the events near the edge, so the $xy$ position reconstruction algorithm have large uncertainty for the outer events. Such effect causes a large smearing of the radially corrected S3 signals. Furthermore, the pulse finder may miss some of the smaller
events and introduce a bias on the average signal size. For these reasons, we only use the black histogram, which corresponds to the events with maximum S3 channel being the top central channel and generally have their positions close to the central axis of the TPC.

Figure 4.5: Spectrum of S3. The events are grouped with the position of their maximum S3 channel.

From the radially corrected S3 spectrum with maximum channel being the central channel, we successfully obtain the average size of central single drift electron ionization signal, $25.8 \pm 0.3 \text{ PE}$ [28]. This result is confirmed by another study introduced below.
4.2.2 Study of Single Drift Electron Ionization Signals Using Getter-off Data

This study is done with the data taken during the replacement of a getter, which purifies the recirculating argon for DS-50. When the getter was off for replacement, the level of contamination in the liquid argon rose. Contamination such as oxygen atoms can capture drift electrons to form ions with a $\sim 12\text{ ms}$ lifetime\textsuperscript{1}, then release them. By searching for small S2-like signals after a normal S1 + S2 single scatter event, we found a large sample of single drift electron ionization signals. As the captured period is short, a captured electron will be released at nearly the same position as where it got captured, so we can use the position of the previous normal event as the position of the single drift electron ionization signal, instead of applying the $xy$ position reconstruction algorithm on the small ionization signal itself. This advantage reduced the uncertainty of the reconstruction, so that single electron ionization signals can have more accurate radial correction.

Figure 4.6 shows the correlation between single drift electron ionization signals and the square of radius. The data creates a band with negative slope in the scatter plot, which shows the relation between ionization signal and radius. From the intersection between the band and the Y axis, we obtain the size of single drift electron ionization signal at the center, $25.09 \pm 0.21\text{ PE}$\textsuperscript{2}.

The results from the two previous studies are very close to each other. The weighted arithmetic mean\textsuperscript{3} of the ionization signals generated by single drift electrons

\textsuperscript{1}The lifetime is measured with the distribution of the time differences between the single electron signals and the previous S2s

\textsuperscript{2}The mean weighted by uncertainty is calculated by

$$\bar{x} = \sigma_x^2 \sum_{i=1}^{n} x_i / \sigma_i^2,$$

where $\sigma_x$ can be obtained with

$$\sigma_x = \sqrt{\frac{1}{\sum_{i=1}^{n} \sigma_i^{-2}}}.$$
Figure 4.6: Single electron ionization signal vs. $r^2$. The green shaded area shows the region, where the pulse finder fails to find the ionization signals effectively.

at the center is calculated to be $25.33 \pm 0.17$ PE. Figure 4.7 shows the relation between $S_{2_{\text{scale}}}$ and the radius with the same events used to plot Figure 4.3. The average size of $S_{2_{\text{scale}}}$ at the center is obtained to be $6643 \pm 8$ PE. By dividing this value by the size of single electron ionization signal at the center, we get the average number of drift electron to be $262.25 \pm 1.76$ for events at the center with $S_{1_{\text{corr}}} = 200$ PE.

### 4.2.3 Trapping Time of Free Electrons at Liquid-gas Interface

We found the number of drift electrons that reach the gas pocket for events with the same energy, $S_{1_{\text{ref}}} = 200$ PE, and same position (center). In this section, I will
introduce the loss of drift electrons before they arrive at the gas pocket and explain why the radial dependence of $S_2$ light yield is not caused by losing drift electrons. In fact, events with the same $S_1_{\text{corr}}$ should have the same number of drift electrons that arrive at the gas pocket.

Since $S_1_{\text{corr}}$ is position corrected, we can assume the events with $S_1_{\text{corr}}$ equal to $S_1_{\text{ref}}$ have the same initial energy. Therefore, same number of drift electrons should be produced from the positions of the recoils. The loss of drift electrons on their way up to the liquid surface is compensated by the $z$ correction of $S_2$, as introduced in Section 3.2.2. However, the extraction field between the grid and the gas pocket may be non-uniform, caused by the deformation of the detector components, which will be introduced in detail in the next chapter. We need to know if non-uniform loss of drift electrons at the liquid-gas interface can be caused by non-uniform extraction field.
As a result of the high mobility of the free electrons in pure liquid argon, the minimum energy of the conduction band, $V_0$ is negative. So a potential barrier exists for the electrons to move from liquid to gas. A free electron can be trapped at this potential barrier for microseconds before getting passed by semiclassical diffusion or quantum tunnelling. According to the study done by A.F. Borghesani and his colleagues, the trapped time at gas-liquid interface follows

$$\tau \propto \frac{\lambda_1}{\mu E} \exp \left( \frac{V_0 - 2eA_l^{1/2}[1 + (A_v/A_l)^{1/2}E^{1/2}]}{k_B T} \right),$$  

(4.3)

where $\lambda_1$ is the momentum transfer mean free path, $\mu$ is the electron mobility, $E$ is the field strength, $k_B$ is the Boltzmann constant, $T$ is the temperature, and $A_v$ and $A_l$ can be calculated from

$$A_v = \frac{e^2}{16\pi \epsilon_0 \epsilon_v \epsilon_l} \frac{\epsilon_l - \epsilon_v}{\epsilon_l + \epsilon_v},$$  

(4.4)

$$A_l = A_v \epsilon_v / \epsilon_l,$$  

(4.5)

where $\epsilon_0$ is the vacuum permittivity, $\epsilon_v$ and $\epsilon_l$ are the dielectric constant of vapor and liquid.

This equation predicts a linear relation between $\ln(\tau E)$ and $E^{1/2}$. By applying a linear fit to their data, they model the relation between trapping time and field strength. With this linear model, we can predict the trapping time of electrons at the liquid-gas interface close to the wall to be 1.72 $\mu$s for our standard operating environment with a 2.8 kV/cm extraction field, and 2.84 $\mu$s for the dataset with the lowest extraction field, 2.3 kV/cm, in this study. The radial dependence of S2 can be caused by an anode window sag or an upward deflection of the grid mesh (Possible deformations of the detector components will be discussed in detail in Chapter 5).

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3The minimum kinetic energy free electrons need to acquire, to be able to get into a material from vacuum.

4Momentum transfer mean free path, is the mean free path of the free electrons trapped at the barrier under random walk.
In both situations, the extraction field at the edge should be the same as designed, because the distance from the grid to the liquid surface and the distance from the liquid surface to the anode window will be the same as designed. In both of the situations, since the distance between the grid and the anode gets smaller near the center, while the voltage stay unchanged, the extraction field near the center will be larger than that of the edge, so the trapping time at a smaller radius can only be smaller. From these results, the trapping time at the interface is too small compared to electron drift lifetime to cause any significant loss of free electrons. So we can assume all the electrons that reach the liquid surface can make their way to the gas pocket.

To sum up the analysis in this section, we can assume events with same $S_{1\text{corr}}$ but different horizontal positions will have the same average number of drift electrons that reach the gas pocket. Previously, we found the average number of drift electrons that reach the gas pocket, $262.25 \pm 1.76$, for central events with $S_{1\text{corr}} = 200 \text{ PE}$. Now, we can generalize that number of drift electrons to different $xy$ positions. Therefore, we can obtain single drift electron ionization signals at different horizontal positions by dividing the values on the $z$ axis in Figure 4.3 by $262.25 \pm 1.76$ or scaling values on the $z$ axis to make the center equal to $25.33 \pm 0.17 \text{ PE}$\footnote{Size of single drift electrons signal at the center obtained in the last section.}. The results are shown by Figure 4.8.

4.3 Correction by Single UV Photon Detection Efficiency

We have successfully obtained the average number of photoelectrons detected for the scintillation of a single drift electron in the gas pocket. However, for more general study of electroluminescence of argon, we need to convert the number of photoelectron
Figure 4.8: Map of single drift electron ionization signal [PE]. Achieved by normalize Figure 4.3 to make the value at center equal to the measured average single drift electron ionization signal.

to the number of UV photons generated during the electroluminescence process. To make that correction, we need to study the detection efficiency of a single UV photon.

It is difficult to generate UV photons at known locations inside the gas pocket of DS-50, so we need a lot input from a sophisticated Monte Carlo simulation program. Our Monte Carlo simulation, called g4ds, is coded with Geant4 [7], a scientific toolkit for high energy physics simulation. The program has all the geometry information of DS-50 and has libraries to simulate particle interactions in different materials. For this study, the optics simulation in g4ds is of most interest. The most of optical parameters used in g4ds are measured or calculated, while a few parameters are hard
to be accurately measured. These parameters with large uncertainties are tuned carefully. Please reference to Appendix A for more detailed information about the optics tuning for g4ds.

![TPB emission spectrum](image)

**Figure 4.9: TPB emission spectrum.**

Using g4ds, 128 nm UV photons are generated at different positions in the gas pocket. To be detected, a UV photon needs to reach a TPB layer first and get its wavelength shifted to a visible photon with wavelength around 420 nm. The emission spectrum of TPB is shown in Figure 4.9. Then the visible photon from the TPB will pass through a few transparent materials to get to the photocathode of one of the PMTs. Via the photoelectric effect, the photon can eject one photoelectron. The probability of ejecting a photoelectron is a wavelength dependent value known as the quantum efficiency. Relative efficiencies for different wavelength are shown in Figure 4.10 provided by the PMT manufacture, Hamamatsu. This quantum efficiency spectrum is normalized to have its maximum to be one. The actual quantum effi-
ciency is significantly lower than that, but in g4ds this normalized quantum efficiency spectrum is used to increase running efficiency. A correction will be applied to the results to correct the bias caused by this optimization.

Figure 4.10: Relative quantum efficiency. The quantum efficiencies for the UV photons with wavelength below 200 nm are not plotted, since the PMTs will only detect visible photons, whose wavelengths are between 400 nm and 600 nm, as shown in Figure 4.9.

By generating UV photons as just described, I am able to get a map for the detection efficiency as shown in Figure 4.11. It shows that when a UV photon is generated in the gas pocket in our simulation, the probability of a corresponding photoelectron being detected is around 50%. Half of the photons either get absorbed by the detector materials or fail to eject an electron from the photocathode. The map also clearly shows the pattern of the top PMT Array, because the UV photons generated under PMTs have higher probability to generate photoelectrons in the PMTs above them.
A few corrections need to be made to the detection efficiency map to remove the biases introduced by the Monte Carlo simulation. First of all, according to a measurement of the fluorescence efficiency of the wavelength shifter, TPB, $1.2 \pm 0.1$ visible photons will be created on average for every 128 nm UV photon, as shown in Figure 4.12 [20]. However, in Monte Carlo we generate only one visible photon for each UV photon to simplify the code. So the detection efficiency should be increased by a factor of $1.2 \pm 0.1$ to compensate.

Figure 4.11: Average detection probability of UV photons generated in different horizontal positions inside the gas pocket in the Monte Carlo simulation. To get the detection probability of the actual detector, additional corrections need to be made to compensate the inaccurate QE, collection efficiency, and TPB fluorescence efficiency.
Secondly, according to Hamamatsu [21], with 824 V applied on a PMT, the collection efficiency between the photocathode and the first dynode of the PMT is measured to be 85%. Since no uncertainty is given by Hamamatsu and the quality of the PMTs can vary between tubes, we assign a 5% error to the collection efficiency. In the Monte Carlo, collection efficiency is set to 100% for the consideration of running efficiency. For this reason, a 85 ± 5% correction should be applied to the Monte Carlo results to get the actual detection efficiency.

Finally, we need to make a PMT quantum efficiency correction, because the quantum efficiency used in g4ds is set to be higher than the actual value to get higher computation efficiency. At room temperature for 420 nm photons the average quantum efficiency of the 38 PMTs in the DS-50 TPC is 34.2 ± 0.23%, measured by the manufacture Hamamatsu [21]. According to a study [24] done on Hamamatsu phototubes, the quantum efficiency for detecting 400 nm photons linearly increases as the temperature goes down at a rate of 0.0246 %QE/°C, shown by Figure 4.13. Extrap-
olerating with this rate, the actual quantum efficiency at liquid argon temperature is 39.27 ± 5%. However, the photons we are actually detecting have average wavelength slightly longer than 400 nm and the model of PMTs used in DS-50 is different from the model used for the study of temperature dependence. Therefore, we set a 5% uncertainty on this quantum efficiency. The value used in Monte Carlo for 420 nm photons is 94.9% as shown in Figure 4.10. So the detection efficiency from Monte Carlo should be decreased by a factor of 2.42 ± 0.31.

![Figure 4.13: QE growth rate with temperature as a function of wavelength or the QE derivative with respect to temperature measured with five Hamamatsu phototubes.](image)

Dividing the values on the z axis of Figure 4.8 by the corresponding detection efficiencies, we can get a map for \( Yh_g \), the number of UV photons produced by a single electron while traveling through the gas pocket with height \( h_g \). Figure 4.14 shows the results achieved using this method.
Figure 4.14: Map of $Y_{h_g}$, path length unnormalized single drift electron UV light yield, [electron$^{-1}$].
Chapter 5

Field Dependence of Electroluminescence Light Yield

In the previous chapter, we obtained a map for $Yh_g$, the number of UV photons produced by a single electron while traveling through the gas pocket with height $h_g$, shown in Figure 4.14. From the map, we observed a strong radial dependence of the UV light yield. In the first two sections of the current chapter, we are going to discuss two hypotheses about the deformations of detector components, which can cause the radial dependence UV light yield. Then, we will introduce an optimization algorithm, which can correct the light yield and electric field strength at different radii, based on the hypotheses of deformations. Subsequently, we can get the relation between the light yield, $Y$, and the field strength, $E$. In the last two sections, the results obtained with the optimization algorithm will be presented and compared with the results from other studies.

5.1 Geometry at the Edge

The design of the detector between the grid and the anode window is shown in Figure 5.1. By design, gas pocket height $H_g$ should be constant at different horizontal
positions, \( h_g = H_g \). So the average UV light yield per drift electron per unit path length, \( Y \), can be simply calculated by dividing \( Y_h \) by \( H_g \). The multiplication field, \( E_{\text{mult}} \), can be calculated by

\[
E_{\text{mult}} = \frac{V}{H_g + H_l \epsilon_g / \epsilon_l},
\]

(5.1)

where \( V \) is the voltage between the anode window and the grid, \( H_l \) is the distance from the grid to the liquid surface, \( \epsilon_g \) is the dielectric constant of gaseous argon, and \( \epsilon_l \) is the dielectric constant of liquid argon.

![Figure 5.1: Components between the grid and anode window.](image)

If the actual geometry is the same as designed, the field strength and the scintillation path length should be the same for all events. Consequently, \( Y h_g \) should be the same at different positions. However, according to the Figure 4.14, the light yield has strong dependence on radius. This contradiction implies deformations of the detector material. Therefore, we need to do more complicated analysis to study the actual geometry of the detector.

In spite of the confusion about the geometry near the center, we can assume that the structure and field at the edge match with the design with the following reasons.
At the edge, the grid mesh to the anode window distance, $H_g + H_l$, is determined by a carefully machined teflon holder in between. The liquid level, is determined by a bubbler located close to the edge of the anode window. In this case, Equation 5.1 should still be valid for the data close to the edge of the detector. For the rest of this section, I will describe how the geometrical constants in Equation 5.1 are measured.

As mentioned previously, the edge grid to anode window distance, $H_g + H_l$, is determined by the teflon support between them, which is accurately machined to have a 1.5 cm thickness at room temperature. However, the thermal contraction of teflon, when cooled from room temperature to liquid argon temperature, is significant and its uncertainty dominates the uncertainty of $H_g + H_l$.

Measurements of the thermal contraction of different teflon samples, when cooled to liquid nitrogen temperature\footnote{Liquid nitrogen temperature is $\sim 10$ degrees lower than liquid argon temperature. Bias caused by using liquid nitrogen instead of liquid argon should be small compared with the uncertainty of the measurements.} were done by my colleagues. The results vary significantly around a central value of about 2%. The variation can be explained by a study done by Kirby \cite{Kirby}. As described in the literature he found a steep change in the thermal contraction rate at 20 °C, which may be caused by the change of rotation of molecules about their axis \cite{Kirby}. For this reason, we set a relatively large uncertainty, 0.5%, to the thermal contraction to make it $(2 \pm 0.5)\%$. With this amount of thermal contraction, the grid to anode distance becomes $14.70 \pm 0.07$ mm.

The anode window is part of a diving bell, which works as a gaseous argon reservoir. The edge gas pocket height, $H_g$, is determined by the bubbler mounted on the diving bell. As shown in Figure 5.2, the vertical distance from the bottom of the anode window to the bottom of the bubbler is 10.16 mm, and the bottom of the two holes on the bubbler are 1.9 mm above the bottom of the bubbler. This makes the distance between the bottom of the bubbler holes and the bottom of the anode window 8.26 mm. Based on the observation, we assume the bubbles can overcome the liquid
hydrostatic pressure at the bottom of the holes and form a spherical surface before being blown out. Because of the surface tension on the bubble, there is a pressure difference between the inside and outside of it, which can be calculated from

\[ P_g - P_l = \frac{2\gamma}{r}, \]

(5.2)

where \( \gamma \) is the surface tension of liquid argon and \( r \) is the radius of the bubble. This equation is derived from Young-Laplace Equation with the bubbles assumed to be spherical. The height difference between the TPC liquid surface and the bottom of the holes, 1.3 mm, is calculated from

\[ \Delta h = \frac{2\gamma}{r\rho g}, \]

(5.3)

where \( \rho \) is the density of liquid argon. By adding this distance to the distance between the bottom of anode window and the bottom of the bubbler holes, we get \( H_g = 9.56 \pm 1.45 \) mm. The uncertainty is set to the radius of the bubbler holes because of
the assumption of spherical bubble shape and the possible fluctuation of the pressure during the formation of the bubbles.

The grid to liquid surface distance, $H_l$, is simply the difference between the grid to anode distance and the gas pocket height. With the errors added up in quadrature, the value of $H_l$ is $5.14 \pm 1.45$ mm.

### 5.2 Geometry Models for the Detector between the Grid and the Anode Window

The local light yield in the gas pocket can be expressed as the product of the path length normalized light yield, $Y$, and the path length, which is equal to the height of the gas pocket, $h_g$. Therefore, the change of path length unnormalized light yield, $Y h_g$, can be caused by the change of one or both of the multipliers, $Y$ and $h_g$.

As discussed previously in Chapter 2, the energy of the scintillation photons produced through electroluminescence is provided by the strong electric field in the gas. Therefore, the path length normalized light yield, $Y$, should depend on the strength of the multiplication field in gaseous argon, $E_{\text{mult}}$. Since, the electric potentials at the grid mesh and the ITO layer under the anode window are held constant, the potential difference between the grid and the anode window will not change with radius. To change the field over different radii, one needs to change either the distance or the material between the anode window and the grid mesh, which can be caused by deformations of the anode window and grid mesh. Therefore, the deformations of the grid and anode window can make $Y$ radially dependent.

The path length unnormalized light yield, $Y h_g$, is linearly dependent on the gas pocket height, $h_g$, which is the distance between the liquid surface and the anode window. Deformation of the anode window can make $h_g$ radially dependent and subsequently make $Y h_g$ radially dependent.
To sum up, the radial dependences of both $Y$ and $h_g$, which determine the path length unnormalized light yield in the gas pocket, can be caused by the deformation of one or both of the grid mesh and the anode window. In the rest of this section, two hypotheses about the deformations are introduced.

### 5.2.1 Sag Hypothesis for the Anode Window

The first hypothesis for the radial dependance of the S2 light yield is the sag of the anode window, shown in Figure 5.3. This hypothesis is supported by several pieces of evidence. First, when we removed the gas pocket by stopping feeding gaseous argon into the TPC and letting the gas in the gas pocket liquify, the central events lost their S2s earlier than the events close to the edge. This phenomenon indicates that the height of the anode window is lower at the center. Second, the peaks of S2s for central events tend to be sharper, which indicates a shorter scintillation time. This can be the result of a shorter scintillation path length or a stronger field. Both can be caused by the sag of anode window.

![Figure 5.3: Geometry around the gas pocket with an anode window sag.](image)

$E_{mult}$ at $h_g$ and $H_g$

$E_{ext}$ at $h_g$ and $H_l$
With this hypothesis, although the scintillation path length, $h_g$, of the free electrons will get smaller near center, the strength of the multiplication field will get larger. A stronger field can avoid the energy loss in thermalization and increase the scintillation efficiency, because it can provide the free electrons enough energy between collisions to more efficiently create excitons, which can emit photons and produce scintillation signals. Therefore, an anode window sag is a possible reason for a higher light yield near the center.

From previous chapters, we found the UV light yield per electron in the gas pocket, $Y h_g$. By dividing this variable by the scintillation path length, $h_g$, we can obtain the path length normalized light yield $Y$. The local multiplication field, $E_{\text{mult}}|@h_g$, can be represented by

$$E_{\text{mult}}|@h_g = \frac{V}{h_g + H_l \epsilon_g/\epsilon_l} = \frac{H_g + H_l \epsilon_g/\epsilon_l}{h_g + H_l \epsilon_g/\epsilon_l} E_{\text{mult}}|@H_g,$$

(5.4)

where $H_g$ is the gas pocket height at the edge, $H_l$ is the liquid height between the grid and the liquid surface, $E_{\text{mult}}|@H_g$ is the multiplication field at the edge, $\epsilon_g$ and $\epsilon_l$ are the dielectric constants of gas and liquid.

To sum up, both the multiplication field, $E_{\text{mult}}|@h_g$, and the path length normalized light yield, $Y$, can be expressed as functions of gas pocket height, $h_g$. At the edge $h_g$ is equal to $H_g$, while the gas pocket height of the region with smaller radius remains unknown.

### 5.2.2 Deflection Hypothesis for the Grid

Another hypothesis for the radial dependence of S2 light yield is the deflection of the grid. If the grid mesh humps slightly to form a dome\(^2\), the field between the grid and the anode window will be stronger towards the center. As discussed previously,

\(^2\)The deformation of the grid may be caused by the electrostatic force on the grid.
a stronger field will result in a larger path length normalized light yield, $Y$. In the meanwhile, the scintillation path length, $h_g$, remains the same. Therefore, the light yield in the gas pocket, $Y_{h_g}$, should be increased towards the center. Although no evidence has been found to support the deflection of the grid mesh, it is possible that the radial dependence is caused by a combination of the anode window sag and the grid deflection. Therefore, it is worth to study the effect of the grid deflection and compare with that of the anode window sag.

Figure 5.4: Geometry around the gas pocket with grid deflection.

With this hypothesis, the gas pocket heights at different radii are assumed to be the same as the gas pocket height at the edge, $h_g = H_g$, as shown in Figure 5.4. In this case, the path length normalized light yield, $Y$, can be directly obtained by dividing the light yield, $Y_{h_g}$, that we found in the last chapter, by the edge gas pocket height, $H_g$. The strength of the local multiplication field, $E_{\text{mult}} |_{@h_l}$, can be expressed as

$$E_{\text{mult}} |_{@h_l} = \frac{V}{H_g + h_l \epsilon_g / \epsilon_l} = \frac{H_g + h_l \epsilon_g / \epsilon_l}{H_g + h_l \epsilon_g / \epsilon_l} E_{\text{mult}} |_{@H_l}, \quad (5.5)$$

where $h_l$ is the local grid to liquid surface distance, and $E_{\text{mult}} |_{@H_g}$ is the multiplication field at the edge. To sum up, with this deflection hypothesis for the grid, the path
length normalized light yield, $Y$, can be directly calculated, however the multiplication field, $E_{\text{mult}}|_{@h_l}$, depends on the local grid to liquid surface distance, $h_l$, which remains unknown except the edge.

5.3 Correction of $Y$ and $E_{\text{mult}}$ with Optimization

In this section, we use six runs with six different voltages between the grid and the anode window. The data in each dataset are binned in radius. For the events in each bin, the process described in Chapter 4 is applied to get the path length unnormalized UV light yield, $Y h_g$.

Figure 5.5: $Y$ vs. $E_{\text{mult}}$ assuming no deformation. The data are binned by radius and multiplication field at the edge. Lines with different colors stand for different radii from the center.

Before applying the hypotheses about the deformations of the detector components introduced in the previous sections, we assume that both the anode window and the
grid mesh are perfectly flat as designed \((h_g = H_g\) and \(h_l = H_l\)). In this case, path length normalized light yield, \(Y\), can be obtained by dividing \(Y_{hg}\) by \(H_g\), while the multiplication field can be obtained with Equation \[5.1\]. The data points are plotted in Figure \[5.5\] where the \(x\) axis corresponds to the multiplication field, \(E_{\text{mult}}\), the \(y\) axis corresponds to the path length normalized light yield, \(Y\), and different colors stand for different radii from the center.

As shown in the figure, the data points do not line up and show the field dependence of electroluminescence light yield, because the grid mesh and the anode window are not both perfectly flat as we assumed. We need to consider the hypotheses about the deformations of detector components introduced previously and make corrections for the \(Y\) and \(E_{\text{mult}}\) of the data.

The bottom curve in Figure \[5.5\] corresponds to the events close to the edge of the detector. We assume they have the same gas pocket height and grid to liquid surface distance as the edge. The uncertainty caused by that assumption will be discussed in the next section. In this case, the data points on the bottom curve have their actual field and light yield equal to the values on the axises.

However, the data points above the bottom curve need to be corrected by an optimization algorithm with the previously introduced hypotheses. We will start with the sag hypothesis for the anode window.

### 5.3.1 Correction Based on the Sag Hypothesis for the Anode Window

As discussed in Section \[5.2.1\], both \(Y\) and \(E_{\text{mult}}\) depend on local gas pocket height, \(h_g\). If we know the correction value for \(h_g\), \(Y\) can be corrected as

\[
Y_{\text{corr}} = \frac{H_g}{h_g} Y_{\text{uncorr}},
\]

(5.6)
(a) Correct the bins with $r \in (14, 16)\text{cm}$.

(b) Correct the bins with $r \in (12, 14)\text{cm}$.

(c) Correct the bins with $r \in (10, 12)\text{cm}$.

(d) Correct the bins with $r \in (8, 10)\text{cm}$.

Figure 5.6: Step by step correction for $Y$ and $E_{\text{mult}}$ based on the sag hypothesis for the anode window. The first four steps are shown in the figures above, while the final result will be given in the next section.

and $E_{\text{mult}}$ can be corrected as

$$E_{\text{corr}} = \frac{H_g + H_l \epsilon_g / \epsilon_l}{h_g + H_l \epsilon_g / \epsilon_l} E_{\text{uncorr}}. \quad (5.7)$$

At this stage, we need to use the bottom curve, which corresponds to the data collected at the edge, as a boundary condition to help us determining the correct values of $h_g$ for the positions with smaller radii. As we have data collected with different voltages applied between the grid and the anode window, the field at a position with a smaller radius and a smaller voltage can be the same as the field at a position with a larger radius and a larger voltage. For this reason, when the correct
$h_g$ is used to for the correction of the data points in an upper curve, we can expect the upper curve to overlap with the bottom curve. Thus, by tuning the $h_g$ to make an upper curve overlap with the bottom curve, we can obtain the correct $h_g$ for the upper curve and correct $Y$ and $E_{\text{mult}}$ for its data points.

With the general idea introduced above, I can correct the top curves one by one to make them overlap with the bottom curve by optimization. The first four steps of this process are shown in Figure 5.6.

When correcting the data points in an upper curve to find their positions in the bottom curve, a 3rd order polynomial fit is done on the existing points on the bottom curve. The residuals between the fit line and the points in the upper curve that we are trying to correct, are measured to calculate the $\chi^2$. The positions of the points being corrected are adjusted, by tuning $h_g$, to minimize the $\chi^2$. With this optimization method, we can get the relation between path length normalized light yield, $Y$, and the strength of the multiplication field, $E_{\text{mult}}$, in a larger field range.

5.3.2 Correction Based on the Deflection Hypothesis for the Grid

Since we assume the radial dependence of S2 is completely caused by the deflection of the grid, the anode window should be flat and the gas pocket height should be a constant, $H_g$, at different horizontal positions. Therefore, the values of $Y$ in Figure 5.5 are normalized with path length $H_g$ correctly, and no further correction is needed for the vertical positions of the data points. As introduced in Section 5.2.2, the $E_{\text{mult}}$ is determined by the distance between the grid and the liquid surface, $h_l$. Assume we know the correct value of $h_l$ for a certain radius, the $E_{\text{mult}}$ can by corrected by

$$E_{\text{corr}} = \frac{H_g + H_l \epsilon_g / \epsilon_l}{H_g + h_l \epsilon_g / \epsilon_l} E_{\text{uncorr}}. \quad (5.8)$$
(a) Correct the bins with $r \in (14, 16)\text{cm}$.

(b) Correct the bins with $r \in (12, 14)\text{cm}$.

(c) Correct the bins with $r \in (10, 12)\text{cm}$.

(d) Correct the bins with $r \in (8, 10)\text{cm}$.

Figure 5.7: Step by step correction for $Y$ and $E_{\text{mult}}$ based on the deflection hypothesis for the grid. The first four steps are shown in the figures above, while the final result will be given in the next section.

Similar to the correction process introduced for the sag hypothesis for the anode window, the bottom curve is used as a boundary condition when correcting the upper curves. Instead of tuning $h_g$, I tune $h_l$ to make the upper curves overlap with the bottom curve. The final corrected positions for the data points from the upper curves are determined by minimizing $\chi^2$ as introduced in the last section. The first a few steps of the correction are shown by Figure 5.7, while the final result will be shown in the next section.
5.4 Results with the Sag Hypothesis for the Anode Window

The result, after applying the optimization algorithm based on the sag hypothesis for the anode window, is shown in Figure 5.8. The data from three old runs, which are not used for getting $h_g$ for different radial bins in the optimization process, are also plotted and corrected.\(^3\)

![Figure 5.8: Optimization results with the sag hypothesis for the anode window.](image)

5.4.1 Errors

The errors in Figure 5.8 are the statistical errors of this study. Each error bar represents the standard error of the mean light yield calculated for the data in each bin.

\(^3\)The corrections for the old runs are done with the $h_g$ obtained with 6 newer runs as described in Section 5.3.1
Systematic Errors in the Light Yield

The systematic errors of light yield come from a few different sources. The first is the error from the single drift electron ionization signal $25.8 \pm 0.17$ PE ($25.8 \text{ PE} \pm 0.66\%$), introduced in Section 4.2. It is a factor in the sequence of light yield calculation, so the fractional error should be added with errors from other sources.

The quantum efficiency used in the study is $(39.3 \pm 5.0)\%$ as introduced in Section 4.3. A fractional error of 12.7% on the light yield of all datasets and all radial bins is caused by the quantum efficiency.

In Section 4.3 I assigned 5% error to the 85% PMT charge collection efficiency. This will result in a 5.9% fractional error of the light yield.

In this study, we assumed the events in the bin corresponding to the largest radius has the same light yield as that of the events at the edge, so that it can be used as a boundary condition for the optimization algorithm. We need to estimate the error from that assumption. Figure 5.13 shows the relation between UV light yield per electron and radius of the 50 days dataset. The black histogram has the same binning as the binning of the data with different voltages. Since the 50 days dataset has much higher statistics, we also make a red plot with much finer binning. By comparing the edge bins of the two plots, we observe a 9.6% difference. Based on this observation, we add a 10% systematic error to light yield of the edge bins of the data with different voltages.

Systematic Error in the Multiplication Field

According to Equation 5.4, the sources of systematic error of the field can come from, $H_{lg} (14.7 \pm 0.07 \text{ mm})$, $H_g (9.56 \pm 1.45 \text{ mm})$, $V$, and $\epsilon_l (1.53 \pm 2\% \text{ [25]})$. In order to get different multiplication fields, the voltages of the different runs are different. Within a run, the stability is measured by a voltmeter accurate to 1 V. Since the readout only varies between two adjacent integers, we set the uncertainty of Voltage to 2 V.
The dielectric constant of gaseous argon, $\varepsilon_g$, is 1.000574 at room temperature under one standard atmospheric pressure. Although under different temperature and pressure, $\varepsilon_g$ in TPC is believed to still be extremely close to one. So we will use the value provided by Bryan and assume no error.

**Error Propagation and Integration**

The error of the optimization process itself is negligibly small, since the $\chi^2$ varies a lot with a tiny change in the local gas pocket height, $h_g$. However, the result of optimization is strongly dependent on the values of both the light yield and the field strength. For this reason, redoing the optimization process is necessary to get the upper and low boundaries of the region corresponding to a one-$\sigma$ error.
Upper Boundary

Since the light yield should increase as we increase the multiplication field, to get an upper boundary for the region corresponding to one $\sigma$ error, we need to apply the optimization algorithm to the upper one-$\sigma$ limit of the light yield and the lower one-$\sigma$ limit of the multiplication field of each data point.

Figure 5.10: Upper one $\sigma$ boundary of the electroluminescence. The result with minimum $H_g$ is shown in red, while the result with maximum $H_g$ is shown in blue. A 3rd order polynomial fit is done on each of the results. The fit lines are shown by solid lines with corresponding colors.

To get the total systematic errors of light yield, we simply sum up the systematic errors in percentage. Then the total error can be obtained by adding the total systematic error with the statistical error in quadrature.

As introduced in Section 5.2.1, the multiplication field can be expressed as

$$E_{\text{mult}} = \frac{V}{h_g + H_l\epsilon_g/\epsilon_l}, \quad (5.9)$$
For the one-\(\sigma\) lower limit of the multiplication field, it is clear that a smaller voltage, \(V\), a smaller dielectric constant of liquid argon, \(\epsilon_l\), and a larger grid to liquid surface distance, \(H_l\), lead to a smaller field. So the lower limit of \(V\), the lower limit of \(\epsilon_l\), and the upper limit of the grid to anode distance are used. However effect of variation of the edge gas pocket height, \(H_g\), is more complicated.

A larger \(H_g\) will in general lead to a smaller field. However, with the same amount of sag, \(\Delta h\), it can lead to a smaller corrected light yield according to

\[
Y_{corr} = \frac{H_g Y_{uncorr}}{h_g} = \frac{H_g}{H_g - \Delta h} Y_{uncorr}. \tag{5.10}
\]

So it is not clear how changing of \(H_g\) can affect the result. To figure that out, we tried both the upper limit of \(H_g\) and the lower limit of \(H_g\), with the other variables set for getting the upper boundary. As Figure 5.10 shows, the change of the field is more significant with smaller field, while the change in light yield is dominant with larger field. The two fit curves cross each other at 5.11 kV/cm. The points plotted with the upper limit of \(H_g\) are used for multiplication field below 5.11 kV/cm and the points plotted with the lower limit of \(H_g\) are used for multiplication field above 5.11 kV/cm.

**Lower Boundary**

For the lower boundary of the region corresponding to one \(\sigma\) error, the lower limit of light yield and the upper limit of field of each data point is needed before applying the optimization algorithm. The lower limit of light yield of each data point is simply obtained by subtracting the total error from the mean light yield. Upper limit of \(V\) and lower limit of \(H_l\) are applied for larger fields. Just like what we did for the upper boundary, both the upper limit and the lower limit of \(H_g\) are tried. After applying

\(^4\)A larger grid to anode distance, \(H_g + H_l\), results in a larger \(H_l\), because \(H_g\) is independently determined by the bubbler.
Figure 5.11: Lower one \( \sigma \) boundary of the electroluminescence. The result plotted with the lower limit of \( H_g \) is shown in red, while the result plotted with the upper limit of \( H_g \) is shown in blue. A 3rd order polynomial fit is done on each of the results. The fit lines are shown by solid lines with the corresponding colors.

The optimization algorithm and the fit, the results cross each other at 5.53 kV/cm, as shown by Figure 5.11. For multiplication fields below that, the points plotted with the lower limit of \( H_g \) are used, while the points plotted with the upper limit of \( H_g \) are used for multiplication fields above 5.53 kV/cm.

Together with the boundaries, the final result is shown in Figure 5.12.
Figure 5.12: $Y$ vs. $E_{\text{mult}}$ with the upper and lower one $\sigma$ boundaries (sag hypothesis for the anode window).

### 5.4.2 Standard Units

Fundamentally, the electroluminescence efficiency depends on the average amount of energy acquired by the free electron between two scatters. Therefore, it depends on not only the strength of the electric field, but also the average distance between two scatters. For this reason, the units used in Figure 5.12 are not general enough to be compared with the results from other experiments, because other detectors may have different pressures, which results in a different average distances between two scatters.

---

5. Electroluminescence efficiency is the efficiency of converting electric potential energy to scintillation photons.

6. If the amount of energy acquired by the free electron is too small, a large proportion of energy will be lost in thermalization, which does not produce scintillation photons. On the other hand, if the amount of energy is large enough, the free electron can efficiently excite the atoms.
To generalize the units, both the light yield, $Y$, and the field, $E_{\text{mult}}$, need to be normalized by the number density of argon atoms, $N$, which is proportional to the inverse of the average distance between scatters. After the normalization, the $y$ axis is $Y/N$, which is proportional to the light yield between two scatters, while the $x$ axis is $E/N$, which is proportional to the energy acquired by the free electron between two scatters.

From the pressure at the top of the cryostat, 1050 mbar, and the depth of the bottom of the gas pocket, 18.5 cm, the pressure of the gaseous argon is 1105 mbar. The boiling temperature of argon at that pressure is 88.13 K. With these conditions, we get the number density of gaseous argon, $9.423 \times 10^{19} \text{cm}^{-3}$.

Figure 5.13: $Y/N$ vs. $E/N$ (sag hypothesis for the anode window). The data from A. Bondar's study [13] and the Monte Carlo result presented by C.A.B.Oliveira [27] are plotted for comparison.

After converting to standard units, the result is shown in Figure 5.13, where $Y/N$ is the number of UV photons produced per drifting electron per unit path length divided...
by the number density of the argon atoms in gaseous argon, and \( E/N \) is the electric field in the gaseous argon divided by the same number density. Although with large uncertainty, data of this study match with the results from other experiments very well. The data shows a smaller slope for smaller field, because the energy acquired from the electric field by the free electron between two scatters is not high enough to excite argon atoms and produce scintillation photons efficiently. At higher field, the scintillation process is more efficient and a smaller proportion of the electron’s energy is lost in thermalization, which does not produce scintillation photons, so the relation between light yield and field becomes more linear.

5.5 Results with the Deflection Hypothesis for the Grid

As introduced in Section 5.3.2, if the radial dependence of S2 is caused by grid deflection, the values of light yield, \( Y \), shown in Figure 5.5 do not need to be corrected. In this case, the optimization process will get the \( E_{\text{mult}} \) corrected by adjusting \( h_l \) and moving the data points in the upper curves rightwards to overlap with the bottom curve.

The sources of errors in the light yield, \( Y \), are the same as what we used in the last section. To draw the upper boundary, the upper limit of light yield is used. To get the lower limit of field, the upper limit of grid to anode distance, the lower limit of \( \epsilon_l \), and the lower limit of \( V \) are used. With the increase of \( H_g \), the light yield \( Y \), obtained by \( Yh_g/H_g \), and the field, obtained by

\[
E_{\text{mult}} = \frac{V}{H_g + h_l\epsilon_g/\epsilon_l},
\]

(5.11)
Figure 5.14: $Y$ vs. $E_{\text{mult}}$ with upper and lower boundaries (deflection hypothesis for the grid).

will both decrease. However, the change in field is always more significant. In this case, we don’t have to obtain the boundary by joint two pieces of data like what we did in the previous section with the sag hypothesis for the anode window. The upper limit of $H_g$ can be simply used for the upper boundary of the one $\sigma$ region. On the other hand, lower limit of $Y$, lower limit of grid to anode distance, upper limit of $V$, upper limit of $\epsilon_l$, and lower limit of $H_g$ are used for the lower boundary.

Together with the two boundaries of error, the optimization result is shown in Figure 5.14. The units used in this figure are transferred to the standard units as introduced in Section 5.4.2. The final result is shown in Figure 5.15 together with the result obtained with the sag hypothesis for the anode window, the Monte Carlo result presented by C.A.B.Oliveira [27], and the data measured by A. Bondar’s [13].

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for comparison. Compared with the result obtained with the sag hypothesis for the anode window, the result we got in this section has slightly lower light yield, but it is still very close to the results from other studies.

Figure 5.15: $Y/N$ vs. $E/N$. The both results obtained based on the sag hypothesis for the anode window and the deflection hypothesis for the grid are plotted. The data from A. Bondar’s study [13] and the theoretical model presented by C.A.B.Oliveira [27] are plotted for comparison.
Chapter 6

Application of Electroluminescence

In the last chapter, we obtained the field dependence of argon electroluminescence, a fundamental property of electroluminescence in argon, based on several hypothesis. This dependence will be applied in this chapter to help us to better understand our detector and give us guidance in the design of new detectors.

The first section of this chapter will focus on quantitative estimations of the deformations of the anode window and the grid mesh. In the second section, we will discuss how electroluminescence light yield is used to guide us in the design of DS-20k.

6.1 Quantitative Estimates of Detector Component Deformations

As introduced in Section 5.2, the strong radial dependance of S2 light yield could be caused by the deformation of one or more detector components. In the current section, quantitative estimates of these detector component deformations will be made.
6.1.1 Estimation of the Anode Window Sag

If we assume an anode window sag is responsible for the S2 radial dependence, the relation between the local multiplication field and the local gas pocket height is given by Equation 5.4. More explicitly, the strength of $E_{\text{mult}}$ with different values of $h_g$ is

\[ E_{\text{mult}} = \frac{V}{h_g + Hc_g/\epsilon_i} \]
shown in Figure 6.1. The relation between $Y$ and $E_{\text{mult}}$ is found in the last chapter, shown in Figure 5.12. The same plot is shown in Figure 6.2 with a third order polynomial fit to model it. We can get the $h_g$ dependence of $Y$, by combining the function shown in Figure 6.1 and the fit function shown in Figure 6.2. Subsequently, the $h_g$ dependence of path length unnormalized light yield, $Yh_g$, can be obtained. Figure 6.3 shows the path length unnormalized light yields with different $h_g$.

![Figure 6.4: Map of $h_g$ [cm].](image)

With the relationship between $Yh_g$ and $h_g$, we can convert the $Yh_g$ shown in Figure 4.14 to $h_g$. The result is shown in Figure 6.4. In general it shows a lower gas pocket height towards center caused by the sag of anode window. The amount
of sag is about 4 mm. The top and right area, where $h_g$ has abnormal height and fluctuation, may be an area with TPB defect. The low light yield caused by inefficient wavelength shift leads to an unrealistically high $h_g$. In other positions near the edge, $h_g$s are observed to be a little higher than $H_g$, 0.956 cm. One possible source of this bias is the overestimation of the light yield at the edge by using events in the largest radial bin as events right at the edge, in the study of electroluminescence light yield. Therefore, the actual light yield at the edge is lower than the value predicted with the result from the last chapter. Consequently, the low light yield lead to an high $h_g$ as I just described.

Inspired by small deflection theory [35], which quantifies the amount of deflection caused by uniform normal forces exerted on a disk, we model the shape of the $h_g$ distribution using

$$h_g = p_{offset} + p_{mag}((p_{scale} R_{TPC})^2 - (x^2 + y^2))^2 + p_x x + p_y y$$  \hspace{1cm} (6.1)$$

where $R_{TPC}$ is the radius of the TPC, $p_{offset}$ determines the overall height of the function, $p_{mag}$ controls the amount of the sag, $p_{scale}$ scales the radius of the sagged area (The anode window may not be supported right at the edge.), $p_x$ and $p_y$ are slopes used to model a small tilt of the detector. In this function, 5 parameters ($p_{offset}$, $p_{mag}$, $p_{scale}$, $p_x$, and $p_y$) are adjusted to perform the fit.

The result of fitting Function 6.1 to $h_g$ map is displayed in Figure 6.5. A cross section of Figure 6.5 at $x = 0.4$ cm (the center of an $x$ bin) is shown in Figure 6.6. According to the fit function, the gas pocket height at the middle is 5.54 mm. Compared with the edge gas pocket height, the anode window is sagged by 4.02 mm.

Starting from the smooth $h_g$ distribution modeled by the fit function, we can get a smooth light yield, $Y h_g$, based on the relation between $Y h_g$ and $h_g$ presented in Figure 6.3. To get the residual between this modeled smooth light yield distribution
and the light yield directly from data, we subtract the modeled light yield from the data light yield shown in Figure 4.14. The result is shown in Figure 6.7. From the residual map, we observe fluctuations around 0, which can be caused by the bias from the position reconstruction algorithm, the uncertainty from the fit, and the difference in quantum efficiency and collection efficiency among the PMTs. The area where the residual gets lower than $-10$ UV photons show local positions with unexpectedly low light yield. This gives us a clue about where TPB defects can be located on the surface of the anode window.
6.1.2 Estimation of the Deflection of the Grid

If the radial dependance of light yield is caused by the deflection of the grid, the geometric variable changing along the radius is the grid to liquid surface distance, \( h_l \).

The relation between local multiplication field, \( E_{\text{mult}} \), and \( h_l \) is shown in Figure 6.8. Furthermore, with the study of the deflection hypothesis for the grid in last chapter, we got the relation between light yield, \( Y \), and \( E_{\text{mult}} \), as shown in Figure 5.14. The same plot is made in Figure 6.9 with a 3rd order polynomial fit. Combining function shown in Figure 6.8 and the fit function in Figure 6.9, we can obtain the value of \( Y h_g \) for any given \( h_l \), shown in Figure 6.10. Remember that the light yield, \( Y \), in Figure 6.9 is normalized to a unit scintillation path length, so it should be multiplied by the gas pocket height, \( H_g \)\(^2\) to get the path length unnormalized light yield, \( Y h_g \), in Darkside-50 detector.

With the relation between \( Y h_g \) and \( h_l \) obtained above, we can convert the \( Y h_g \) map, shown in Figure 4.14 to a map of \( h_l \). The amount of grid deflection can be obtained by subtracting \( h_l \) from the edge grid to liquid surface distance, \( H_l \). The result is shown in Figure 6.11. In general, it shows a convex shape as expected.

\(^2\)With the deflection hypothesis for the grid, \( h_g \) should be equal to \( H_g \).
Figure 6.7: Light yield residual map [UVphotons/electron]. This map is obtained by subtracting the $Y_{h_g}$ map acquired from data by the modeled $Y_{h_g}$.

However, as the map of gas pocket height we get for the sag hypothesis for the anode window, the map of deflection has unexpected fluctuation at the top and right, which can be explained by local TPB defects.

Equation 6.1 is also applied as fit function to the 2D deflection map, shown in Figure 6.11 Since the tilt of the detector should change the liquid level, it is not reasonable to model the tilt by adding a slope to the grid. Beside, no strong tilt has been observed from the result of the previous section. For these reasons, the slope parameters $p_x$ and $p_y$ are forced to be zero. As shown in Figure 6.12, the 2D
function displayed by the smooth green mesh models the shape well. A cross section of Figure 6.12 at $x = 0.4\text{ cm}$ (the center of an $x$ bin) is shown in Figure 6.13. The center value of the fit function is 4.58 mm, which is more than the amount of anode window sag needed to get the same central light yield. Even though decreasing the gas pocket height will sacrifice scintillation path length, it increases electric field more
efficiently. Therefore, less deflection is needed for the anode window to get the same central light yield.

6.2 Use of the Electroluminescence in the Design of DarkSide-20k

One of the most important purpose of studying the electroluminescence is providing guidance in design of new detectors, whose signal formation include the electroluminescence process in argon. In this section, we will discuss the secondary scintillation
light yield and its stability of the next generation of DarkSide detector, DS-20k, using our knowledge of argon electroluminescence acquired from the previous chapters. A stable secondary scintillation light yield in a dual phase TPC detector can be beneficial to position reconstruction and the discrimination between ERs and NRs.

In the first subsection, the $E_{\text{mult}}$ dependence of $Y$ will be derived for the operation environment of DS-20k\textsuperscript{3}. Then, I will use this dependence to study the stability of

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\textsuperscript{3}The $E_{\text{mult}}$ dependence of $Y$ will be affected by the pressure in the gaseous argon, as described in Section 5.4.2. Since the gaseous argon pressure in DS-20k is different from the pressure in DS-50, we cannot directly use this dependence in DS-50. Therefore, it should be derived from the $E/N$ dependence of $Y/N$, which is more generalized.
the secondary scintillation light yield in DS-20k, under liquid level fluctuation, anode window sag, and grid mesh deflection. With the study introduced in this section, we should be able to optimize the design of DS-20k to make its secondary scintillation light yield more resistant to small deformations of detector components.

6.2.1 Field Dependence of the Electroluminescence Light Yield in DS-20k

Since the gaseous argon pressure in DS-20k’s gas pocket is different from that in DS-50’s gas pocket, we should start the study by using electroluminescence light yield with the standard units as shown in Figure 5.13. According to current design, the pressure in the gas pocket will be 1.39 bar. Under this pressure, the phase transition temperature of argon will be 90.41 K. According to the ideal gas law, the density of argon should be 193.7 mol/m$^3$. Multiplying the both axis in Figure 5.13 with the number density of gaseous argon, we can get the relation between light yield and multiplication field suitable to DS-20k. The result is shown in Figure 6.14 with a 3rd order polynomial fit to model the relation between light yield, $Y$, and multiplication field, $E_{\text{mult}}$. For this study, we use the electroluminescence light yield obtained with
the sag hypothesis for the anode window, because we have evidence about the sag of the anode window. If the radial dependence of $S_2$ is caused by the deflection of grid mesh, the light yield will be only a little lower, as shown in Figure 5.15.

6.2.2 S2 Light Yield Stability under Fluctuation of Liquid Level

In this section we will discuss the light yield and its stability under liquid level fluctuation, which can be caused by small pressure variation, in the process of bubble formation in the bubbler holes. The change of liquid level results in changes of the gas pocket height $h_g$ and the distance between the grid and the liquid surface, $h_l$. 

Figure 6.14: Light yield vs. multiplication field (DS-20k). The light yield in this plot is the number of UV photons generated per electron per centimeter in DS-20k. A 3rd order polynomial fit is performed on the plot to model the relation.
Figure 6.15: The plots are made by fixing $h_g + h_l$ to 1.5 cm. (a) shows multiplication field with different $h_g$ and $V$. (b) shows the light yield with different $h_g$ and $V$. The cutoff at upper left and lower right is caused by the lack of understanding of electroluminescence for multiplication field lower than 4.4 kV/cm and above 8.1 kV/cm.

However, the distance between the grid and the anode window, $h_g + h_l$, should stay constant.

To study the liquid level fluctuation, I fix the distance between the grid mesh and the anode window to 1.5 cm, so that the change of $h_g$ corresponds to the change of liquid level. However, this preliminary value can be changed to improve the performance of the detector. The multiplication fields with different values of $h_g$ and $V$ are calculated, according to Equation 5.1, and shown in Figure 6.15a. Figure 6.15b is a map of light yield, which is obtained by using the dependence shown in Figure 6.14 with the corresponding multiplication field. Since this dependence does not extend below 4.4 kV/cm or above 8.1 kV/cm, the values at upper left and lower right corners of the plot are not calculable. To make the cutoff clear, I suppressed the light yield at those area to zero. The light yield, $Yh_g$, is positively correlated with $V$, because a larger voltage will lead to a stronger field in the gas pocket, which corresponds to a larger $Y$. Its correlation with $h_g$ at relatively large $h_g$ is negative, because a larger $h_g$
Figure 6.16: The plots are made by fixing $h_g + h_l$ to 1.5 cm. (a) shows the absolute value of partial derivative of light yield with respect to $h_g$. The cutoffs are caused by the same reason as the cutoffs in the light yield plot. (b) shows the fractional change of light yield with respect to $h_g$.

will cause a weaker field. However, at smaller $h_g$, the correlation is positive, because, in this case, change in scintillation path length, $h_g$, dominates the change of light yield, $Y h_g$.

To quantify the stability of light yield under change of the liquid level, the partial derivative of light yield with respect to $h_g$ is shown in Figure 6.16a. The diagonal valley in the middle of the plot corresponds to the situation that the effect of field strength and the effect of scintillation path length cancel each other. The fractional change of the light yield is shown by Figure 6.16b, obtained by dividing the partial derivative by the corresponding light yield shown in Figure 6.15b. If the gas pocket height and the voltage of DS-20k are set to the values corresponding to a point in the valley, then we can expect the secondary scintillation light yield is resistive to small liquid level fluctuations.
Figure 6.17: The plots are made by fixing $h_l$ to 1 cm. (a) shows multiplication field with different $h_g$ and $V$. (b) shows the light yield with different $h_g$ and $V$. The cutoff at upper left and lower right is caused by the lack of understanding of electroluminescence for multiplication field lower than 4.4 kV/cm and above 8.1 kV/cm.

6.2.3 S2 Light Yield Stability under Anode Window Sag

As described in the previous chapters, we believe in the sag of anode window in DS-50. The radial dependence of S2 is at least partially depend on the sag. Therefore, to get a stable secondary scintillation light yield in DS-20k, we need to study the stability of the light yield with the variation of the height of the anode window. The sag of the anode window should result in the change of $h_g$. However, the distance between the grid mesh and the liquid surface should stay unchanged.

To study the sag of the anode window, I fix the distance between the grid mesh and the liquid surface, $h_l$, to 1 cm, so that the change of $h_g$ corresponds to the change of anode window height. Just as what I did in the last section, the multiplication fields with different values of $h_g$ and $V$ are calculated, according to Equation 5.1 and shown in Figure 6.17a. Figure 6.17b is a map of light yield, which is obtained with the field dependence of light yield shown in Figure 6.14. The light yield, $Y h_g$, is positively correlated with $V$ as described in the previous section. Similar to the
situation shown in Figure 6.15b, the correlation between $Yh_g$ and $h_g$ at relatively large $h_g$ is negative, because a larger $h_g$ will cause a weaker field, which corresponds to a smaller $Y$. However, at smaller $h_g$, the correlation is positive, because, in this case, change in scintillation path length, $h_g$, dominates the change of light yield, $Yh_g$.

To quantify the stability of light yield under change of the anode window height, the partial derivative of light yield with respect to $h_g$ is shown in Figure 6.18a. The valley at upper left corresponds to the situation that the effect of field strength and the effect of scintillation path length cancel each other. The fractional change of the light yield is shown by Figure 6.18b, obtained by dividing the partial derivative by the corresponding light yield shown in Figure 6.17b. If the gas pocket height and the voltage of DS-20k are set to the values corresponding to a point in the valley, then we can expect the secondary scintillation light yield is resistive to a small anode window sag.
6.2.4 S2 Light Yield Stability under Grid Deflection

As discussed in Section 5.2.2, the deflection of the grid mesh can cause a non-uniform S2 light yield. Therefore, the secondary scintillation light yield stability, with variation of the grid height, need to be studied. The deflection of the grid should affect the distance between the grid and the liquid surface, $h_l$, but not the height of the gas pocket, $h_g$.

To study the effect of grid deflection, I will fix the gas pocket height, $h_g$, to 0.7 cm, so that the change of $h_l$ corresponds to the change of grid height. Similar to what I did in the previous two sections, the multiplication fields with different values of $h_l$ and $V$ are calculated, according to Equation 5.1, and shown in Figure 6.19a. Figure 6.19b is a map of light yield, which is obtained with the field dependence of light yield shown in Figure 6.14. The light yield, $Yh_g$, is positively correlated with $V$ as described in the previous sections. Its correlation with $h_l$ is always negative, because a larger $h_l$ will result in a smaller $E_{\text{mult}}$, which corresponds to a smaller $Y$. 

Figure 6.19: The plots are made by fixing $h_g$ to 0.7 cm. (a) shows multiplication field with different $h_g$ and $V$. (b) shows the light yield with different $h_g$ and $V$. The cutoff at upper left and lower right is caused by the lack of understanding of electroluminescence for multiplication field lower than 4.4 kV/cm and above 8.1 kV/cm.
Figure 6.20: The plots are made by fixing $h_g$ to 0.7 cm. (a) shows the absolute value of partial derivative of light yield with respect to $h_g$. The cutoffs are caused by the same reason as the cutoffs in the light yield plot. (b) shows the fractional change of light yield with respect to $h_g$.

To quantify the stability of light yield under change of the height of the grid, the partial derivative of light yield with respect to $h_l$ is shown in Figure 6.20a. As $h_l$ is always negatively correlated with the light yield, the partial derivative is never 0. The fractional change of the light yield is shown in Figure 6.20b, obtained by dividing the partial derivative by the corresponding light yield shown in Figure 6.19b. Based on the fractional change, the secondary scintillation is more resistive to grid deflection with a high voltage and a small $h_l$. 
Chapter 7

Conclusion

DS-50 is a dual phase TPC detector, whose secondary scintillation signals are produced through electroluminescence in gaseous argon. Therefore, it provides us important data for the study of the field dependence of argon electroluminescence light yield.

With the elaborate study of the process of secondary scintillation in Chapter 4, I successfully obtained the values of single drift electron UV light yield, $Y_{h_g}$, in different horizontal positions of DS-50 gas pocket. A radial dependence of S2 light yield is explicit shown in this result.

As discussed in Chapter 5, the radial dependence can be caused by the sag of the anode window and the deflection of the grid mesh. Based on these two hypotheses, optimization algorithms were applied to the data to obtain the field dependence of electroluminescence light yield. As shown in Figure 5.15, the two results based on the two hypotheses are close to each other. The results from a Monte Carlo simulation done by C.A.B.Oliveira [27] and a measurement done by A. Bondar [13] lie within the uncertainties of this work.

With the field dependence of electroluminescence light yield, quantitative estimations of anode window sag and grid mesh deflection were displayed in Chapter 6. A
3.67 mm sag at the center of the anode window can explain the S2 radial dependence in DS-50. On the other hand, the radial dependence can be explained by a 4.12 mm deflection at the center of the grid mesh. Furthermore, the electroluminescence light yield was also used to predict the stability of the S2 light yield for different design schemes of DS-20k. Thereby, the design can be improved to make the S2 light yield more resistive to liquid level fluctuation, anode window sag, and grid deformation.
Appendix A

Optical Tuning of Darkside-50

Figure A.1: View from the Inside of the TPC.

A MonteCarlo simulation program plays a very important role in the understanding of a sophisticated detector. For Darkside-50, the simulation guides the design of the detector and helps us predict the background for the blind analysis [6]. The simulation program, g4ds, is written with the GEANT4 toolkit [7], which is able to simulate the particle interactions in different materials. Figure A.1 shows a photon traveling inside the simulated TPC. Most of the optical parameters in g4ds are either calculated from physical models or measured in laboratories. However, there are still
some parameters that have only rough measurements. In this chapter, I will discuss
the tuning\footnote{The tuning of the optics parameters are done by adjusting the parameters in their uncertainty
ranges to make certain features of data and Monte Carlo match.} of these optical parameters in the DS-50 TPC, and show the result of
this tuning.

\section{A.1 The Absorption Length of UV Photon in UAr}

The absorption length of 128\,nm scintillation UV photons highly depends on the
purity of the liquid argon, which makes it very hard to predict. However, it is an

- Figure A.2: (a) and (c) show the original positions of the simulated scintillation
  photons. (b) and (d) show the distribution of distances the photons travel before
  hitting any TPB. The black distribution corresponds to an infinite absorption length,
  while the red distribution corresponds to a 1.6\,m absorption length. As only the
  photons, that reach the TPB layer, are plotted, the difference of the black and red
distributions shows the loss due to absorption.

- Figure A.2: (a) and (c) show the original positions of the simulated scintillation
  photons. (b) and (d) show the distribution of distances the photons travel before
  hitting any TPB. The black distribution corresponds to an infinite absorption length,
  while the red distribution corresponds to a 1.6\,m absorption length. As only the
  photons, that reach the TPB layer, are plotted, the difference of the black and red
distributions shows the loss due to absorption.
essential parameter in our simulation, as it affects the position dependence of the S1 light yield. The scintillation photons originating from different positions need to travel different distances before hitting the TPB. Their survival probabilities in this process depend highly on the absorption length and their original positions. As you can see in Figure A.2b and Figure A.2d when we set the absorption length to 1.6 m, 13.4% of scintillation photons are absorbed for events at the center of the TPC, while only 7.7% of them are absorbed for events near the side wall. Our study will use the \(xy\) position dependence of scintillation signals to get the absorption length specifically for DS-50.

Figure A.3: S1 light yield vs. \(t_{\text{drift}}\). The events are from krypton dataset. Different colors are corresponding to different distances from the central axis of the TPC. The average S1 light yield at the half of the TPC height is normalized to 1.

Figure A.3 shows the position dependence of S1 obtained with the krypton dataset introduced in Section 3.1. Since the initial energy of the electron recoils are the same, 41.5 keV, the sharp peak in the S1 spectrum, made with the events

2\text{This figure is the same as Figure 3.1 which was used for the position correction of S1.}
from a certain position, can represent relative S1 light yield for events in that position inside the TPC. The $z$ dependance of the light yield is caused mainly by the difference of the distances the wavelength shifted photons need to travel before reaching PMTs, while the $xy$ dependance of the light yield is highly correlated with UV absorption. Since the $xy$ dependance is strongest at the half of the TPC height, we choose the bins correspond to the events at the half of the TPC height for our analysis. However, another parameter, the Rayleigh scattering length of UV photons, is also highly correlated with the $xy$ dependance of S1 light yield. The theoretical value of the Rayleigh scattering length is 90 cm, while a measured value is 66 cm [30]. We will try both of them in our Monte Carlo simulation.

![Figure A.4: $\chi^2$ vs. UV absorption length. The red plot corresponds to the theoretical Rayleigh scattering length, while the blue plot corresponds to the measured one.](image)

Similar to what we do for data, we also get the position dependance of $^{83}$Kr with Monte Carlo simulation. But for Monte Carlo, we can adjust the UV absorption length in liquid Argon. The data light yield at half $z$ is compared with Monte Carlo light yields, with the UV absorption length in Monte Carlo being set to different values. To quantify the comparison, $\chi^2$’s are calculated and presented in Figure A.5.
Figure A.5: Probability vs. UV absorption length. The red plot corresponds to the theoretical Rayleigh scattering length, while the blue plot corresponds to the measured one.

The red data points correspond to theoretical Rayleigh scattering length, while the blue ones correspond to the measured Rayleigh scattering length.

Figure A.5 shows the $\chi^2$ probability for modeling the data with Monte Carlo models with different UV absorption lengths. By choosing the $p$ value to be $> 0.1$, we obtain the value of UV absorption length $3.425 \pm 0.743$ m for the theoretical Rayleigh scattering length. On the other hand, if the Rayleigh scattering length is equal to the measured value, then the UV absorption length is $3.874 \pm 1.038$ m. Although, the uncertainty of our measurement is large, the effect on the light yield of our detector is small, because of the small scale of the detector. One can expect a much more accurate measurement by applying the same method on a larger scale detector such as DS-20k.
A.2 General Tuning of Optics

Besides UV absorption length, there are a few other parameters with relatively large uncertainties. So I perform a fine tuning of these parameters to make sure the Monte Carlo accurately and efficiently simulate the signal production process of DS-50. The tuned parameters are listed in Table A.1, with descriptions of their physical meanings. For data and Monte Carlo we make diagnostic plots for comparison. The typical diagnostic plots for S1 are light yield vs. $z$ and S1 top bottom asymmetry (TBA) vs. $z$, as shown in Figure A.6. The TBA is calculated with

$$TBA = \frac{\text{Top} - \text{Bottom}}{\text{Top} + \text{Bottom}}.$$  \hspace{1cm} (A.1)

Table A.1: Tuned parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tuned Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ArTPBVIsTran</td>
<td>0.675</td>
<td>Transmittance of the surface between argon and TPB for visible photons</td>
</tr>
<tr>
<td>TeflonTPBVisRef</td>
<td>0.975</td>
<td>1-absorption of the surface between teflon and TPB for visible photons</td>
</tr>
<tr>
<td>LArGridVisRef</td>
<td>0.525</td>
<td>1-absorption of the surface between argon and grid for visible photons</td>
</tr>
<tr>
<td>LArGridUVRef</td>
<td>0.15</td>
<td>1-absorption of the surface between argon and grid for UV photons</td>
</tr>
<tr>
<td>PhotoCathodeAbs</td>
<td>0.9</td>
<td>absorption of PMT photocathode</td>
</tr>
<tr>
<td>PArRind</td>
<td>1.325</td>
<td>Pseudo LAr index of refraction</td>
</tr>
<tr>
<td>TPBVIsRind</td>
<td>1.5</td>
<td>TPB index of refraction</td>
</tr>
</tbody>
</table>

The diagnostic parameters for S2 are S2 maximum channel fraction and S2 TBA. S2 maximum channel is the PMT channel that collects the highest number of photo-

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3Pseudo LAr is a thin layer of liquid below the anode window. It compensates the optical property difference between the TPB - gas interface and the TPB - liquid interface, which is not well modeled in Monte Carlo.
Figure A.6: S1 diagnostic plots. The left plot shows the $z$ dependence of S1 light yield. The right plot shows the $z$ dependence of S1 top bottom asymmetry. The Monte Carlo plots (red) are tuned to match with the data (blue).

Figure A.7: S2 diagnostic plots. The Monte Carlo plots (red) are tuned to match with the data (blue).

electrons for the corresponding S2 signal. Thus, S2 max channel fraction is fraction of S2 photoelectrons collected by S2 maximum channel in an event. The S2 TBA is defined by Equation A.1. To better show the feature of the diagnostic parameters, I only use events occur in a 2 mm wide slice along the $x$ axis. The results are presented in Figure A.7.

After fine tuning of the parameters, I made a few more plots to check my work. Figure A.9 shows the channel occupancies of both S1 and S2. Channel occupancy
of a PMT channel is defined as the fraction of photoelectrons detected by the PMT in a large atmospheric argon dataset with $^{39}$Ar events uniformly distributed in the TPC. In general, the data and Monte Carlo match well. In Monte Carlo the PMT channels with the same type (with same distance to the central axis) have very close occupancies, while the channels in the data with the same type can be different by a little. The reasons behind that are the non-uniform TPB defect on the anode window and the difference in quantum efficiencies and collection efficiencies among the real PMTs.

Figure A.8: PMT deployment. The PMTs are categorized with their distance to the central axis. Different types of PMTs are shown in different colors.

Figure A.9: Channel occupancy plots. The PMTs are categorized with their distance to the central axis. The positions of the PMTs are displayed in Figure A.8.
S2 signals are essential for the study introduced in this dissertation, so I include S2 channel fraction distributions, Figure A.10 to compare the distributions of S2 channel fraction\(^4\) between data and Monte Carlo. The four different plots correspond to four different types of PMT channels, with their positions shown in Figure A.8. The red distributions show the fraction distributions of S2 in the corresponding channels for all the events in a uniformly distributed \(^{39}\)Ar data sample, while the blue distributions correspond to Monte Carlo results. The data and Monte Carlo present similar patterns of S2 fraction. In each distribution, the data with small channel fractions correspond to the events far from the PMT, while the data with large channel fractions correspond to the events whose \(xy\) positions are close to the position of the PMT.

\(^4\)The channel fraction of a PMT channel is the parameter corresponding to the fraction of photoelectron detected in that PMT.
Figure A.10: The S2 fraction distribution of the PMTs in the top array. The red distributions correspond to the results from data, while the blue distributions correspond to the results from Monte Carlo. Only one blue distribution is plotted for each type of PMT, because the tubes with the same type are identical in Monte Carlo.
Bibliography


