**Comissioning and calibration of a small-scale modular
liquid argon detector, Argon-1, for novel studies in
background rejection techniques towards
next-generation dark matter detectors**

by

David GALLACHER

*A thesis submitted to the Faculty of Graduate and Post Doctoral Affairs in
partial fulfillment of the requirements for the degree of*

Master of Science

in

Physics - Particle Physics Stream

Carleton University

Ottawa, Ontario

© 2021

David Gallacher

Declaration of Originality

This thesis is the result of my own work, and includes nothing which is the outcome of work done in collaboration, except where indicated. This work has not been submitted to for a higher degree to any other institution.

Significant design work for the Argon-1 SiPM readout was done in collaboration with Carleton engineers; Ryan Crampton, and Rodney Schnarr, and electronics specialist James Botte. Review of boards and input into DAQ system design was done in collaboration with TRIUMF DAQ specialists; Pierre-André Amaudruz and Thomas Lidner, and electrical engineer Peter Margetak. Front-end software was built using TRIUMF supported MIDAS software with support from Pierre-André Amaudruz and Thomas Lidner, building on previous work for LolX [1]. Detailed review of readout boards was completed with experts from Université de Sherbrooke; Tommy Rossignol, Nicolas Roy, and Jean-François Pratte. The overall implementation and construction of the Argon-1 DAQ was led by myself, including the testing and preliminary design of the signal boards, and board fabrication and manufacturing was led by myself with assistance from James Botte. DAQ system design was led by myself with the goal of full waveform readout for individual photon reconstruction, this motivated the designs of the signal routing boards. The design and implementation of a full software suite for analysis and processing of the Argon-1 data was my own work, with recent additions from Michael Perry, a

new Master's student under Mark Boulay. The development of a full-scale simulation using the RAT software package used by DEAP-3600 was completed by myself, which included substantial extensions and additions to the base simulations, which is now in use for preliminary ARGO simulation studies and development of a low-background LAr detector at SNOLAB for underground argon monitoring.

In addition to the work presented in this thesis for Argon-1, significant work was carried out by myself as a member of the DEAP-3600 collaboration. My contributions to the DEAP-3600 monte-carlo simulation software are extensive and range from improvements to detector modelling and geometry, to detailed improvements of the physics model for wavelength shifting, and liquid argon scintillation. Significant work was done to improve the optical model of liquid argon by implementing an updated pulse-shape model with generalized parameters from [2] and recent work on improvements and corrections to the handling of quenching physics in simulation with data-driven validation. In addition to detector modelling contributions which has contributed to recent DEAP analysis, [3], [4], [5], [6], I have led the Cherenkov background estimations for the upcoming full data-set dark matter search paper, which is being prepared for publication at the time of writing. I have also coordinated the development of a wavelength shifting thin film that will be deployed in the DEAP-3600 detector to target a currently limiting background component by taking advantage of the long life-time of the wavelength shifter. This work includes detailed radon load calculations for new detector components, coordinating a multi-institute characterization measurement campaign between Carleton and Queens universities in Ontario, TUM in Germany, and AstroCENT in Poland, and the construction of a new detector component at Carleton University

and University of Alberta. This work will be described in detail in an upcoming publication, which at the time of writing is being reviewed for submission to NIM, of which I am the lead editor and first author.

- David GALLACHER

“Off I go, rummaging about in books for sayings which please me”

Michel de Montaigne, *The Complete Essays*

Abstract

Increasing sensitivity in next generation dark matter detectors requires the development of novel technologies, better background rejection and a greater understanding of noble liquid physics. To aid in this development, an R&D detector, "Argon-1" has been commissioned in the Carleton Noble Liquid Detector Development laboratory. Argon-1 is a modular single-phase LAr test detector that employs silicon photo-multipliers (SiPMs) for scintillation light readout. Argon-1 will be used to test SiPMs in a LAr environment, novel background rejection techniques, new wavelength shifters for LAr applications, and detailed studies of liquid noble micro-physics.

In this work, we describe the construction, commissioning and calibration of the Argon-1 detector. This includes the development and testing of SiPM signal readout infrastructure, the design and commissioning of the DAQ system, front-end software for data readout and triggering, the creation of a software infrastructure for processing and analyzing data from 65+ SiPMs channels, a GEANT4 based Monte Carlo simulation of the detector, and a slow-control system for detector stability and monitoring. One of the SiPM arrays is fully instrumented in a high-density readout, each channel only 3 mm², allowing for unique surface event tagging capabilities. Included here is a detailed study of SiPM operational parameters in-situ in a LAr environment, and calibration of detector energy response using external gamma sources.

The detector energy response of the current configuration of Argon-1 is expressed through the light-yield, defined as the number of detected photons (photoelectrons) relative to the energy deposited in the scintillator (in keV), with a

measured value of ~ 4.7 **photoelectrons/keV**, with a resolution of ~ 5 %. Total correlated SiPM noise probabilities of ~ 20 % at nominal operating voltage was measured, and separation of after-pulsing, delayed and direct optical cross-talk and their respective probabilities and timing characteristics was carried out. We outline a measurement plan for a novel background rejection technique using a layered active surface configuration, and preliminary MC studies of the technique that suggest a discrimination power of $\mathcal{O}(10^5)$ against surface-alpha backgrounds is obtainable.

Acknowledgements

Over the course of my Master's work, I have received an abundance of support and assistance. I would like to take this opportunity to thank everyone who has contributed to this work through their support; some in small, and others in very large ways.

First, I would like to thank my supervisor, Dr. Mark Boulay, who has supported me both intellectually and professionally. Your guidance and teaching has helped me to grow greatly as a physicist, and your confidence in me and support has allowed me to develop as a leader and individual.

Thank you to my colleagues and professors at Carleton University, your stimulating conversation and mentorship has inspired in me a deep and life-long love of learning and science. I must give particular thanks to those that have gone out of their way to answer my never-ending stream of questions and satisfying my nearly-insatiable curiosity; Professor Simon Viel, Dr. Marcin Kuzniak, Professor Bruce Campbell, Dr. Bei Cai, and office-mates Andrew Earlandson, and Carl Rethmeier.

Thank you to my colleagues in the technical team in the Carleton physics engineering department for your advice and sharing your expertise. Torquing down hundreds of flange bolts was nearly tolerable thanks to your enjoyable company.

Thank you to my colleagues and collaborators in the DEAP-3600 collaboration; your diligence, support and patience has given me countless examples of the type of scientist and person I would like to be.

Lastly, I must thank those closest to me. Thank you to Erica, my closest friend, roommate, and co-conspirator. Your endless patience for my physics-y rambling and your friendship has been the crutch I've leaned on so much these past years, and I don't know how I could have survived a global pandemic while completing a Master's degree without you. Thank you to my loving partner, Michelle, your support and confidence has been as unwavering as it was vital, especially when my own was lacking. Thank you for always encouraging me to be the best version of myself, and for your kindness and enthusiasm.

Contents

Declaration of Originality	iii
Abstract	ix
Acknowledgements	xi
1 Introduction	1
1.1 Dark Matter	1
1.1.1 Evidence for Dark Matter	2
Galactic Rotation Curves	3
Bullet Cluster	4
1.1.2 Dark Matter Phenomenology	5
1.2 Dark Matter Detection Techniques	9
1.2.1 Indirect Detection	9
1.2.2 Direct Detection	11
1.2.3 Direct Detection Experiments	11
DEAP-3600	12
Future Direct Detection Experiments	13
1.3 Noble Liquid Detectors	16
1.3.1 Noble Liquid Scintillation	16

1.3.2	Wavelength Shifters	21
1.4	Backgrounds In Rare Event Searches	24
1.4.1	Radiogenic Backgrounds	25
1.4.2	Environmental Backgrounds	29
1.4.3	Background Mitigation Techniques	30
	Pulse-shape Discrimination	33
2	Argon-1 at Carleton	37
2.1	Detector	38
2.1.1	Process System	39
2.1.2	Slow controller	41
2.2	Data Acquisition System	44
2.2.1	Signal Readout	46
2.2.2	Trigger Configuration	48
2.3	Silicon Photo-multipliers	49
2.3.1	Working principle	50
2.3.2	Operational Parameters	51
	Breakdown and Over-voltage	52
	Gain	53
	Photo-detection Efficiency	53
	Dark Noise	54
	Correlated Noise	55
	Temperature Dependence	58
2.4	Data Analysis	59
2.4.1	Processing and data structure	60

2.5	Monte Carlo Simulations	61
2.5.1	Simulated Argon-1 Geometry	64
2.5.2	SiPM Simulation	66
3	Argon-1 Calibration and Characterization Study	69
3.1	SiPM Mating and Feedthrough Board Design and Tests	69
3.1.1	Description	69
3.1.2	Cryogenic Cycling Test	72
3.1.3	Signal Tests	74
3.2	SiPM Characterization	77
3.2.1	Operational Parameter Measurements	79
3.2.2	Breakdown Voltage	79
3.2.3	Gain	80
3.2.4	Dark Noise & Stray Light Rate	82
3.2.5	Correlated Noise	83
	After-pulsing Probability and Timing Behaviour	83
	Optical Cross-talk Probability	84
3.3	Detector Calibration	85
3.3.1	Energy Calibration	85
3.3.2	LAr Triplet Life-time monitoring	86
3.4	Results	87
3.4.1	Operational Parameters	87
	Breakdown Voltage	87
	Gain	90
	Correlated Noise	92

3.4.2	Detector Calibration	100
	Energy Calibration	100
	Triplet life-time	103
	Additional Detector Response Parameters	109
3.5	Discussion	114
3.5.1	SiPM Characterization and Operational Parameters	115
3.5.2	Detector Calibration	117
4	Surface Background Rejection Technique with Argon-1	121
4.1	Introduction	121
4.1.1	Motivation	121
4.1.2	Layered surface technique	122
4.2	Detector Configuration	124
4.2.1	Radon Deposition Outline	126
4.3	Analysis Techniques	128
4.3.1	Pulse-shape discrimination against surface alphas	128
4.3.2	Surface-alpha tagging with high-density SiPM channelling	129
4.4	MC Simulations	131
4.4.1	MC Detector Calibration	131
4.4.2	PSD	134
4.4.3	Hit-pattern tagging	142
4.5	Measurement Plans	143
4.6	Discussion	147
5	Conclusions	151

5.1	Argon-1	151
5.2	Characterization Study	152
5.3	Surface background rejection with Argon-1	153
5.4	Outlook	155
A	SiPM Pulse-finding	159
A.1	Baseline restoration Techniques	159
A.2	Pulse-finding Technique	162
B	A1DS Overview	171
B.1	Data-structure	171

List of Tables

3.1	Results of SiPM Mating board tests with different summing configurations, uncertainties are given as standard deviations of sample measurements.	77
3.2	Summary of correlated noise parameters measured at 87K in a LAr environment with 2.5 V OV.	101
3.3	Triplet life-time fits for a subset of data from Argon-1 runs across a ~ 1 -month operation period. Fits performed from $6\mu\text{s}$ to $10\mu\text{s}$	107

List of Figures

1.1	Pie Chart illustrating the breakdown of energy density in the universe with results from [8]	2
1.2	Rotational velocity curve of spiral galaxy NGC6503, overlaid with contributions of luminous matter components, galactic disk, interstellar gas, and a dark matter halo from [10]	3
1.3	Bullet cluster X-ray (colour) and gravitational lensing (contours) data from [13]. As shown, the matter distribution, inferred by gravitational lensing, does not track the luminous matter, shown from X-ray observations, providing strong evidence for particle DM	6
1.4	Comoving number density of WIMPs in the early universe, with equilibrium curve (solid) and relic abundances for different interaction strengths (dashed) from [10] plotted as a function of time (Temperature)	8
1.5	Review of current and projected sensitivity limits for direct DM detection experiments searching for high-mass WIMPs from [15], Current best limits from xenon are from Xenon1T [16], and from argon are from DEAP-3600 [3].	9

1.6	Illustration of Indirect DM signatures from DM annihilation in the Sun, neutrinos can escape the sun and be detected by neutrino telescopes on Earth, from [18].	10
1.7	Feynman diagram showing DM and nucleon interaction, time going horizontally.	12
1.8	Cross-section of the DEAP-3600 experiment, if A WIMP DM particle interacts with the LAr target, scintillation light is produced which is transmitted to the 255 PMT's surrounding the vessel.	14
1.9	Scintillation process for noble liquids, atom 'A' can be substituted for Ar, Xe, Kr or He	17
1.10	Gaseous Argon (Red) and Liquid Argon(Black) scintillation emission wavelength spectrum from [30].	18
1.11	Quenching mechanisms in noble liquids, luminescence quenching describes quenching modes where scintillation emission is suppressed, nuclear quenching describes quenching modes where energy is lost to heat without excitation of target material.	20
1.12	Molecular structure of TPB molecule	22
1.13	Jablonski diagram for an organic WLS, illustrating the luminescence process. Inter-system crossing (ISC) and Internal Conversion(IC) are non-radiative processes that occur on O(ns) timescales, reproduced from [34]	23
1.14	Wavelength Dependence of TPB(Green) emission, PMT efficiency(Pink) and acrylic attenuation probability(Blue), The compatibility of TPB with the PMT efficiency and acrylic detector materials is clearly visible.	24

1.15	^{238}U decay chain	26
1.16	^{232}Th decay chain	27
1.17	^{222}Rn Decay chain, radon is a radioactive gas produced in the uranium decay chain, and due to its gaseous state at STP can permeate through detector materials and deposit on surfaces.	28
1.18	Muon flux as a function of water equivalent overburden for a selection of underground labs from [36]. Not shown here is the flux at surface, which is ~ 1 muon/cm ² /s, far off of the scale of the plot.	30
1.19	PMT Signals for two classes of events in DEAP-3600. Electronic recoils have longer emission times, and nuclear recoils have more prompt emission.	35
1.20	Fprompt vs reconstructed energy (PE) for a selection of DEAP-3600 data, several event populations are highlighted.	36
2.1	Argon-1 Detector diagram, composed of 2 nested stainless steel cans with multi-layer insulation, the vacuum and LAr space are kept isolated, and the inner-vessel is placed at the centre of the inner can.	39
2.2	Pictures of the Argon-1 Cryostat (left) and inner vessel (right) instrumented with 2 SiPM arrays for the most recent LAr run.	40
2.3	Argon-1 process system overview diagram, with flow paths for steady-state and filling highlighted. Optional bypasses and other important lines are shown as well. Valves, sensors and pressure safety regulators and additional components are not shown. (F.M = Flow Meter, P. Reg = Pressure Regulator)	42

2.4	Cooling curve for most recent Argon-1 Run, RTDs 1,2,3,7 & 8 are along the inner vessel, while RTDs 4-6 are on the cold-head. RTD6 is used for PID control and is attached directly on the cold-head mounting plate.	43
2.5	NI LabView Slowcontroller VI program that monitors Argon-1	44
2.6	Argon-1 DAQ Overview schematic items listed in section 2.2	46
2.7	Argon-1 Signal Readout Chain	47
2.8	V1740 Trigger Generation Example, when the signal on any channel (SiPM Pulse illustrated here), goes below the set threshold, the internal trigger signal is generated for the duration of the time-under-threshold	49
2.9	Illustration of SPAD behaviour as a function of reverse bias voltage, breakthrough voltage shown here on a log-Current vs bias voltage plot as the turning point voltage where the SPAD enters avalanche mode, and is no longer a proportional counter.	50
2.10	Illustration of SPADs modelled as a P-N junction within a SiPM array with each channel corresponding to an individual SiPM. Each SiPM is then composed of many such SPADs. Photons ionize atoms in the SPADs depletion region, creating an avalanche of charge that is then readout.	52
2.11	Illustration for different classes of correlated noise with expected measured pulse-shapes above. a) After-pulsing (AP), b) Direct Cross-talk (Di-CT), c) Delayed Cross-talk (De-CT), and d) In-direct Cross-talk (InDi-CT). Reproduced from [42].	57

2.12	SiPM Pulse-finder overview, Top: Baseline corrected (blue) and raw (red) waveforms from a single channel with many SiPM pulses, bottom: First derivative of the corrected waveform, with pulse-finding threshold shown. Pulses below threshold are flagged and pulse and sub-pulse information collected, see Appendix A for full details. . . .	60
2.13	Argon-1 Data processing schema	62
2.14	MIDAS Status and control page for Argon-1 DAQ. SiPM and DAQ settings are controlled through a web interface which interacts with the FE programs on the DAQ PC and TRIUMF Pre-amplifier boards. . . .	63
2.15	A1-DS Overview diagram, see Appendix B for full list of DS variables and information	63
2.16	RAT simulated Argon-1 detector, left: Wireframe visualization showing the nested stainless steel cans of the vessel, right: surface visualization of the Argon-1 inner vessel submerged in LAr (purple)	66
2.17	Hamamatsu H-S14161 SiPM and R5912 PMT efficiencies as a function of incident photon wavelength	68
2.18	Simulated SiPM Illustration	68
3.1	QSE SiPM Mating Boards for Argon-1, Left: Design Schematic showing channelling, Right: Picture of as-built board	71
3.2	Schematic for 64:1 Analogue Summed (ASUM) SiPM.	72
3.3	Design model for feedthrough board.	73
3.4	Schematic for Argon-1 Feedthrough Board	73
3.5	Cryogenic cycling set-up for Argon-1 SiPM mating boards	75

3.6	Cooling curve example for cryogenic cycling test for Argon-1 SiPM mating board.	76
3.7	Example scope trace for 8:1 ASUM SiPM Ganging board for Argon-1, with many SiPM pulses visible. SiPMs are dark and room temperature here.	76
3.8	Example scope trace for 1:1 ASUM SiPM Ganging board for Argon-1, SiPMs are dark and room temperature here.	77
3.9	Average SPAD decay time constant for a sample of pulses from tests of summing boards, uncertainties are given as standard deviations of the sample measurements.	78
3.10	Average SPE height for a sample of pulses from tests of summing boards, uncertainties are given as standard deviations of the sample measurements.	78
3.11	Dynamic range of Hamamatsu SiPMs, showing the number of expected SPAD firing for $PDE \sim 50\%$. Overlaid are expected thresholds for digitizer clipping based on SPE heights for PiXL and ASUM SiPM channels and digitizer range.	81
3.12	Linear fit to SPE charge (Right axis and blue) versus reverse-bias voltage, and SPE amplitude (left axis and red) versus reverse-bias voltage, where each point is the average value of all PiXL SiPM channels for a given bias voltage.	87
3.13	Example of reverse-bias versus reverse-current distribution for all 16 channels connected to pre-amplifier board #7.	89

3.14	Example fit for breakdown voltage using tangent method, using the natural logarithm of the reverse-current, the intercept of the best fit linear function in the pre-breakdown and rising edge regions is taken as the breakdown voltage. This process is repeated for every channel for all boards.	90
3.15	Rate of change of $\ln(\text{Reverse Current})$ versus reverse-bias voltage for all channels on pre-amplifier board #7. The breakdown voltage is identified as the maximum of the distribution, corresponding to the turning point voltage in linear space.	91
3.16	Breakdown voltage estimates for all channels on pre-amplifier board #7 for the 3 estimation methods described.	92
3.17	Gain of S-144160 SiPMs used in Argon-1, measured using low-intensity pulsed LED light while deployed in LAr at ~ 87 K.	93
3.18	Gain of S-144160 SiPMs from Hamamatsu [48] at room temperature, also shown is the PDE, and cross-talk probability of the SiPM.	93
3.19	Left: SPE Distribution for Argon-1 PIXL SiPM with fit to 6 Gaussians, SPE Separation is ~ 170 charge units. Right: Fit of NPE distribution to Poisson distribution ($N \cdot \frac{\lambda^k \cdot e^{-\lambda}}{k}$), PE intensities are taken from Gaussian fits for each PE peak and normalized to integral of SPE distribution. Best fit for the Poisson distribution is $\lambda = 1.21$ ($\text{Chi}^2/\text{NDF} = 21025$). The fit discrepancies are expected to come from the finite efficiency of the pulse-finder and, most importantly, the deliberate removal of 0 PE pulses, causing large discrepancies at 0 PE. A Poisson distribution with $\lambda = 1$ is overlaid for reference.	94

- 3.20 Left: Distribution of sub-peak amplitude vs delay time between sub-peaks within a given pulse, Right: Distribution of pulse charge versus time between subsequent pulses in a waveform, Only pulses with an arrival time correlated with the LED are considered here. Highlighted are the regions of interest for cross-talk and after-pulsing probabilities, as well as normalization regions. 95
- 3.21 Distribution of sub-peak amplitude vs delay time between sub-peaks within a given pulse, zooming in on the fast correlated noise region, with regions of interest for fast after-pulsing, and delayed cross-talk highlighted. 96
- 3.22 Fit to pulse separation time distribution in the fast correlated after-pulse ROI (blue) and in the late after-pulse ROI (red) with fitting functions shown, results of fits with uncertainties shown are shown in Table 3.2 97
- 3.23 Left: Distribution of sub-pulse amplitudes for pulses in the fast correlated noise region of interest, with integration windows for DiOCT shown. Right: Distribution of pulse charges for pulses in the pulse AP ROI, with integration windows for DiOCT shown. DiOCT probability is estimated as the ratio of the integral in the >1.5 PE region to the 1 PE region. 99
- 3.24 Exponential decay fit to delayed OCT sub-peak separation time, sub-peaks with $\Delta T < 40$ ns are not likely to be flagged due to the 16 ns binning, and efficiency for tagging increases with sub-peak ΔT . . 100

- 3.25 PE distribution of source data from Argon-1, both ^{137}Cs data overlaid with a background run. Each distribution is normalized to the livetime of its respective run. Full energy gamma peaks are highlighted, the Compton edge of ^{137}Cs is clearly visible at ~ 2200 PE, corresponding to ~ 470 keV, which is where we expect it to reconstruct. The 102
- 3.26 Background subtracted distributions for ^{60}Co and ^{137}Cs data. Data are first background subtracted from livetime normalized distributions, shown in Figure 3.25, then using TSpectrum to background subtract the falling Compton edge to assist in fitting. Gaussian fits are performed to each peak to estimate the mean PE and width of the distributions. 103
- 3.27 Sum of several runs of background data with identified gamma peaks, above ~ 6000 PE the non-linearity of the SiPM response due to digitizer clipping and saturation becomes significant, increasing with energy, and ^{208}Tl peak appears at ~ 2400 keV instead of 2614 keV. . . 104
- 3.28 Light yield fit for Argon-1 using external gamma sources and environmental peaks, fit to a linear function as shown in the legend, the fit only includes the external gamma source points, with environmental lines overlaid for reference. Uncertainties on the fit are taken as the relative uncertainties from the Gaussian fits to the mean PE of the external gamma source peaks, $\sim 1\%$. The fit line is extended to show the difference at high energy. 105

- 3.29 Example triplet-lifetime fit to a subset of data from background run 195, residuals shown are (Data-Model)/Model, residuals appear to be shifted down, indicating the presence of a constant shift, but appear featureless over the fit range. 106
- 3.30 Example of a full-event waveform from 'DrawEvent' in A1DS/Utils/, The top panel shows the summed baseline corrected waveforms for each SiPM, and the bottom panel shows the individual pixelated SiPM channels. In addition to baseline restoration, rudimentary zero-suppression is employed here to reduce noise, so the signal can be more clearly identified. This utility is used for individual event inspection, and is a useful tool for tuning new response parameters. . . 108
- 3.31 Fprompt vs PE distribution for ^{137}Cs source run 250, this estimator uses a full waveform integration to determine the PSD response. . . 110
- 3.32 fpromptAmp vs PE distribution for a sample of data from background run 195, we can see a separation from higher fpromptAmp events and the main band at ~ 0.25 fpromptAmp, corresponding to the ER-like background events in Argon-1. 112
- 3.33 FracASUM distribution for source run 250 and background run 259. 113
- 4.1 Illustration of Argon-1 Surface with main regions labelled. Three main classes of surface alpha decays are depicted; 1) ^{210}Po decay inside the TPB WLS layer, or at TPB-scintillator interface, 2) ^{210}Po decay inside the scintillator layer, 3) ^{210}Po decay from within the acrylic vessel, or from the acrylic-scintillator interface. 124

4.2	Argon-1 inner vessel drawing in Surface background configuration. CaF ₂ disk (Green) installed in-front of PiXL SiPM with a TPB coating on top. Full vessel drawing shown in Figure 2.1.	126
4.3	Photo of CaF ₂ disk (right) mounted on the acrylic panel after a $\sim 1 \mu\text{m}$ TPB deposition.	127
4.4	Scintillation Pulse-shape comparison for LAr NR's and CaF ₂	129
4.5	Comparison of hit pattern on PiXL SiPM for surface alpha event (left) and bulk LAr event (right), event MC truth position is shown as a gold star.	130
4.6	Surface event example with numCluster calculation highlighted, here numCluster is 8, since the 8 next-brightest channels fall in the box. . .	131
4.7	MC and Data comparison for ^{137}Cs external gamma simulation (Black) and Background subtracted ^{137}Cs source data taken during run 250 (Red). Both spectra are normalized to unit integral for comparison. Overlaid on the MC is a Gaussian fit to the full energy peak, a slight energy-dependent effect is visible for data compared to MC and the detector efficiency is apparent at lower energy.	133
4.8	$^{83}\text{Kr}^m$ MC Spectra for decays produced isotropically within the de- tector bulk inside the inner vessel. Gaussian fit is performed to the dominant peak, but 3 distributions are clearly visible, corresponding to the 2 $^{83}\text{Kr}^m$ gammas, at 9.4 and 32.1 keV, and the pileup of the two at 32.1+9.4 keV. Fit uncertainties are not representative of the true fit uncertainties due to the large (~ 18) Chi2/NDF from the fit with only statistical uncertainties.	134

4.9	LY Fit for MC using internal and external gammas, points on the plot are for internal $^{83}\text{Kr}^m$ 32 keV line, external ^{137}Cs and Tl208 gamma lines at 663 and 2614 keV respectively.	135
4.10	MC Fprompt vs PE distribution for ^{137}Cs external Gamma MC, we can see the mode of the fprompt distribution is at ~ 0.285	136
4.11	Bulk ^{40}Ar NR MC within inner vessel, for 50-250 keV recoils. 99.9% Acceptance region of interest is drawn overlaid and serves as the ROI for leakage estimation. This acceptance region approximates the WIMP region of interest for a DM search, with no detector threshold effects, and a background free assumption.	137
4.12	Fprompt vs PE distribution for Acrylic-Scintillator interface ^{210}Po Decays, Pure CaF_2 scintillation reconstructs at ~ 0.15 Fprompt	138
4.13	Fprompt vs PE distribution for Bulk Scintillator ^{210}Po Decays	139
4.14	Fprompt vs PE distribution for TPB-Scintillator interface ^{210}Po Decays, Pure LAr scintillation reconstructs at ~ 0.7 fprompt, while TPB scintillation reconstructs at ~ 0.45 fprompt. This distribution contains events with admixtures of TPB+Scintillator and TPB+LAr contributions.	140
4.15	^{40}Ar NRs with (green) and without (blue) smearing applied.	141
4.16	^{40}Ar NRs with smearing overlaid with the 99.9% acceptance ROI for non-smeared ^{40}Ar NRs, and the smeared surface ^{210}Po decays from the TPB-Scintillator interface.	141
4.17	Distributions of fmaxPE for surface and bulk LAr events, reasonable separation is obtained by placing a cut at 0.04, highlighted in red . .	143

4.18	Distributions of numCluster for surface and bulk LAr events, good separation is obtained by placing a cut at 3, highlighted in red	144
4.19	Example of DrawHitPattern Output for a detector event from a background run, left shows the PiXL SiPM channels, with PE on the Z-axis, disabled channels are crossed out for reference. Right shows the ASUM SiPM signal with PE overlaid for comparison.	145
A.1	Example of RC Circuit Diagram with expected signal output due to a square wave impulse, reproduced from [56]	162
A.2	Example fit to baseline distorted raw waveform, with corrected waveform overlaid, from 'DrawA1WF' in A1DS/Utils	163
A.3	Illustration of pulse-finding features for SiPM pulses.	166
A.4	Example of a SiPM waveform with high frequency RF noise bursts present, this noise appears intermittently and is present in-phase on all boards and channels simultaneously, insensitive of different boards and board power-supplies and V1740s, grounding and shielding were both ineffective are removing this noise. As illustrated in this example, the pulse-finder rejects the noise pulses, even though they appear under threshold.	167
A.5	Comparison of amplitude(aPE) and charge based(qPE) event PE estimators. Response is linear to several thousand PE, however the amplitude based estimator produces significantly lower estimates. .	168

A.6 Comparison of amplitude(aPE) and charge based(qPE) PE estimators for SiPM level estimates. We can see clearly here that for low photon counts in a given SiPM waveform (<10), the charge and amplitude based methods track 1:1, but the amplitude based estimator falls behind as incident flux increases.	169
--	-----

List of Abbreviations

SiPM	Silicon PhotoMultiplier
DM	Dark Matter
LAr	Liquid Argon
GAr	Gaseous Argon
NR	Nuclear Recoil
ER	Electronic Recoil
WIMP	Weakly Interacting Massive Particle
PMT	PhotoMultiplier Tube
TPB	Tetraphenyl Butadiene
WLS	Wavelength Shifter
OCT	Optical Cross Talk
DCR	Dark Count Rate
MC	Monte Carlo
PE	Photo-electron
SPE	Single Photo-electron
DAQ	Data Acquisition
SPAD	Single Photo-avalanche Diode
PCB	Printed Circuit Board
ASUM	Anologue SUMmed
OV	Over Voltage
ROI	Region of Interest
LY	Light Yield
STP	Standard Temperature and Pressure

Chapter 1

Introduction

1.1 Dark Matter

Dark matter remains one of the most compelling and challenging mysteries in modern physics. The existence of what is now known as “dark” matter was first theorized by Fritz Zwicky while studying the virialized velocity distributions in the Coma cluster in 1933 [7]. Evidence for a so-called “Gravitational Anomaly” was observed, where the measured velocity dispersion of the objects in the cluster was much larger than one inferred from luminous matter alone. This anomaly was attributed to an invisible matter present in the galaxy cluster, “Dunkle Materie”, or Dark Matter.

Based on current measurements of the energy density of the universe, there is evidence for an abundance of non-luminous matter which is not currently described by the standard model of particle physics, this “Dark” matter accounts for 27% of the total energy density [8]. This is in contrast to the total baryonic matter contribution, which accounts for only 5% of the energy density of the universe. This startling fact means that 85% of the total matter in the universe is dark, and

not currently explained by the models of modern physics.

FIGURE 1.1: Pie Chart illustrating the breakdown of energy density in the universe with results from [8]

Dark matter continues to avoid detection, both indirectly and directly. The direct detection of a dark matter and baryonic matter interaction would constitute the most unambiguous signal for the particle nature of dark matter.

1.1.1 Evidence for Dark Matter

In 2021, the growing mountain of evidence for the existence of dark matter is substantial. While Zwicky described the possibility of a substantial dark matter component in our cosmos in 1933, it took several decades and the work of many dedicated scientists to bring this idea to the fore. Now the idea that there exists a non-luminous matter in the universe, and that this matter is 5 times as abundant as the luminous matter we know so intimately, is the orthodox view in modern particle physics. The nature of dark matter continues to elude physicists, however there is

considerable motivation for a so-called "cold dark matter" composed of particles similar to, but distinct from, the baryonic matter we are so familiar with.

Galactic Rotation Curves

In the 1970s, Vera Rubin and colleagues measured the rotation curves for spiral galaxies and discovered that the velocity of stars far from the galactic centre did not decrease in velocity as the distance decreases, as expected from the Newtonian mechanics and the distribution of luminous matter [9]. This effect is illustrated in Figure 1.2 from [10]. To explain the excess in velocity for objects far from the galactic centre, the presence of a diffuse cloud, or "halo" of dark matter is hypothesized.

FIGURE 1.2: Rotational velocity curve of spiral galaxy NGC6503, overlaid with contributions of luminous matter components, galactic disk, inter-stellar gas, and a dark matter halo from [10]

Dark matter's existence in a cloud or "halo" of dark matter surrounded by the galaxy is motivated by its lack of electromagnetic interactions. Baryonic matter is able to reduce its potential energy by irradiating away photons, allowing it to collapse into a disk, while maintaining its angular momentum. Since dark matter is not capable of losing energy in this manner, but is gravitationally bound to the massive centre of the galaxy, it persists as a halo. This halo is commonly modelled using a Navarro-Frenk-White (NFW) distribution [9], which is derived from N-body simulations of dark galaxies to describe the spatial distribution of dark matter. For a NFW halo, the density of dark matter as a function of radial distance from the galactic centre is described in Equation 1.1.

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s} \left(1 + \frac{r}{R_s}\right)^2} \quad (1.1)$$

Where, ρ_0 and R_s are the local DM density, and the "scale distance" parameters respectively, and can be fit to each galaxy. More complicated density distributions exist [11] and provide better agreement to observed data. In the Milky Way, the local DM density ρ_0 is $\sim 0.3 \text{ GeV}/\text{cm}^3$, and at earth the expected mean peculiar velocity of DM assuming a Maxwell-Boltzman velocity distribution for DM is $\sim 220 \text{ km/s}$ [12]. Both of these parameters are important inputs for direct dark matter searches.

Bullet Cluster

One of the strongest pieces of evidence for particle dark matter comes from observations of colliding galaxy clusters. In the absence of dark matter, when two

clusters of galaxies collide, the expectation is that the gravitational distribution of the mass of the galaxy inferred from lensing data will track that of the radiation signature of the luminous matter in the galaxy, since all the matter is contained in the luminous component. During a collision of galaxy clusters, the hot inter-galactic gas from both clusters will interact and produce X-ray signatures that are observable from Earth, these interactions will produce a drag-like effect on the clusters, leading to the eventual formation of a larger cluster. Observations of galaxy clusters does not support this hypothesis, and the most famous example is from the Bullet cluster, shown in Figure 1.3. The Bullet Cluster, or 1E 0657-56, is composed of two colliding galaxy clusters, at a late stage in the collision process. Studies of the gravitational lensing and X-ray distributions for matter and luminous matter, provide clear evidence for the existence of dark matter [13]. In the presence of dark matter, with a relative abundance of about 5 times that of baryonic matter, the non-interacting dark matter halos of two colliding galaxy clusters are not expected to interact and slow, while the baryonic matter will interact and exchange momentum and energy, causing the inter-galactic gas to heat up and slow down. This is clearly illustrated in Figure 1.3. The Bullet cluster and other similar galaxy collision observations provide some of the strongest evidence for the cold weakly interacting particle dark matter paradigm.

1.1.2 Dark Matter Phenomenology

One of the leading particle dark matter candidates that has inspired many experimental efforts is the "Weakly Interacting Massive Particle" or WIMP, denoted as χ . The WIMP paradigm provides a DM candidate that is long-lived, and with

FIGURE 1.3: Bullet cluster X-ray (colour) and gravitational lensing (contours) data from [13]. As shown, the matter distribution, inferred by gravitational lensing, does not track the luminous matter, shown from X-ray observations, providing strong evidence for particle DM

weak-scale interaction strengths that give the particle its name. During the early stages of the universe, when temperatures were still very high ($T \gg m_\chi$), WIMPs were abundant and were in equilibrium with standard model particles through, $\chi \rightleftharpoons l\bar{l}$, where l and $\bar{l}$ are lepton and anti-lepton pairs, or quark and anti-quark pairs which are produced and annihilated in equilibrium. Over time, as T goes below the WIMP mass m_χ , the number density of WIMPs (n_χ) decreases significantly and the annihilation rate for WIMPs, $\Gamma = \langle \sigma v \rangle n_\chi$, where $\langle \sigma v \rangle$ is the product of the thermally averaged cross-section for annihilation of WIMPs into lighter particles with the WIMP velocity, goes below the expansion rate of the universe. When this occurs, the WIMPs are out-of-equilibrium and will no longer annihilate, and

all that remains is the cosmological relic abundance of WIMPs. This process follows a Boltzmann distribution for the abundance of WIMPs, and is illustrated in Figure 1.4 from [10]. Here we see that as time passes (temperature decreases) we reach the point where WIMPs are no longer produced, this process is referred to as "freezing-out" and is one model considered for the creation of the cosmological dark matter abundance. Interestingly, if the WIMP interaction strength is at the order of the weak interaction-scale ($O(\alpha^2)$), and has a mass at the Z/W boson scale ($O(100 \text{ GeV})$), the WIMP thermally averaged annihilation cross-section is such that it produces the correct observed relic abundance today ($\Omega_\chi \sim 1$). This observation is referred to as the "WIMP Miracle" or "WIMP Coincidence" for the more skeptically minded, and suggests that if an undiscovered particle exists at the electro-weak scale, it naturally provides a suitable dark-matter candidate that can explain the cosmological relic abundance. This has spurred many experimental efforts to probe for WIMP dark-matter, probing to lower and lower interaction strengths, requiring huge advances in detector technologies searching for WIMP dark matter in the GeV-TeV mass range.

There are many proposed extensions to the standard model that produce a WIMP candidate, the most popular of these being from the Minimal Supersymmetric Standard Model (MSSM), which proposes heavy super-symmetric partners for all standard model particles and contains several DM candidates [14]. After 20+ years of direct and indirect searches, the progress in exploring the available WIMP and DM parameter space has been extensive. A recent review shows the current best-limits on the standard WIMP-nucleon interaction cross-section, relevant for direct DM search experiments versus the WIMP mass, this is shown in Figure 1.5

FIGURE 1.4: Comoving number density of WIMPs in the early universe, with equilibrium curve (solid) and relic abundances for different interaction strengths (dashed) from [10] plotted as a function of time (Temperature)

from [15]. The projected sensitivity of future DM direct detection experiments will probe the remaining parameter space for high-mass WIMPs before reaching the neutrino-floor, which will be discussed in section 1.2.3.

FIGURE 1.5: Review of current and projected sensitivity limits for direct DM detection experiments searching for high-mass WIMPs from [15], Current best limits from xenon are from Xenon1T [16], and from argon are from DEAP-3600 [3].

1.2 Dark Matter Detection Techniques

The detection of dark matter is being actively pursued by many experimental efforts across the globe. These DM detection efforts can be split into two broad categories, direct search experiments and indirect search experiments.

1.2.1 Indirect Detection

Indirect detection of DM is carried out by searching for the signatures of DM present in the universe, as well as evidence of DM interactions on stellar bodies that produce unique signals that can be measured on Earth. This includes gravitational lensing of stellar objects, and detailed measurements of cosmic-microwave

background (CMBR) radiation to gain an understanding of the distribution and nature of DM. This is often done by comparing simulations of early universe evolution to measurements of CMBR and 21-cm radio-astronomy observations, and inferring as much information as possible about DM from these comparisons [17].

Another example of indirect detection search experiments are cosmic ray and neutrino telescopes that are sensitive to particles from the sun and other stellar objects. These particles may originate from DM annihilations in the sun, or galactic centre. In these models of DM, DM can interact with baryonic matter and produce high energy neutrinos and gamma rays or both, depending on the class of DM mediator particle. This is illustrated in Figure 1.6 from [18].

FIGURE 1.6: Illustration of Indirect DM signatures from DM annihilation in the Sun, neutrinos can escape the sun and be detected by neutrino telescopes on Earth, from [18].

No indirect DM signal has been observed, while an excess of high energy neutrinos remains unexplained [19], and could point towards a potential DM source. These searches remain highly motivated, and upgrades to existing neutrino telescopes and Gamma-ray observatories are underway. An additional indirect detection of a DM signal can be obtained by producing DM at a particle collider, such as

the LHC, and measuring the resulting baryonic products, or lack-there-of [20].

1.2.2 Direct Detection

The direct detection of DM would provide the most unambiguous evidence for the particle nature of DM. Direct detection requires DM to directly interact, or interact through a dark mediator, with a target inside a detector on Earth. This is achieved using ultra-sensitive detectors looking for the cosmic DM present in our galactic halo.

1.2.3 Direct Detection Experiments

Passive direct detection experiments such as DEAP-3600, Darkside, Xenon1T, LUX, and PANDA-X[16], [21]–[23], use noble liquid calorimeters, often as time-projection chambers to detect the ionization and excitation signals produced by a DM interaction. These experiments use either liquid argon, or liquid xenon as both the target and detection medium. These experiments are targeting the "high mass" WIMP-like DM signal, however other experimental efforts are directed to different classes of DM. Experiments such as NEWS-G, and SuperCDMS target low mass regions of the DM parameter space[24], [25], in NEWS-G's case, using a gas target to detect single electron scatter events.

These experiments are looking to observe the scattering of the DM particle off of a nucleon in their target material, this scattering would deposit a small amount of energy in the detector which could be detected through ionization, scintillation light, or heat signals, depending on the detector. This interaction is shown in Figure 1.7, where the interaction itself is left empty. While many models exist

to describe the nature of the interaction, without any positive signal of direct DM detection so far to constrain this, it is left empty to remain agnostic to the type of interaction.

FIGURE 1.7: Feynman diagram showing DM and nucleon interaction, time going horizontally.

DEAP-3600

The DEAP-3600 experiment, or "**D**ark matter **E**xperiment using **L**iquid **A**rgon **P**ulse-shape discrimination", is a direct detection DM experiment located at SNOLAB, in Sudbury ON, Canada [21]. DEAP uses a liquid argon target in a single-phase configuration, where only the scintillation light signal is used. DEAP's first physics run took place from 2016-2020, ending due to the COVID-19 pandemic, which required boiling off the argon.

The detector itself is composed of an acrylic cryostat that contains the ~ 3300 kg liquid argon target and detector medium. If a DM particle scatters off of an argon nucleus, it would result in a low energy nuclear recoil event, producing scintillation light. This scintillation light is produced in the vacuum ultra-violet

at ~ 128 nm, the LAr scintillation light is then shifted to the visible by a wavelength shifter (WLS) coating on the acrylic, which shifts the LAr light to visible at ~ 420 nm. After being shifted by the coating, the light is emitted isotopically and propagates through the acrylic vessel and light-guides to one of the 255 photomultiplier tubes (PMTs) that view the inner detector. The detector cross-section is shown in Figure 1.8. PMTs are photo-detectors capable of single-photon counting and produce charge signals proportional to the number of photons incident on the sensor surface, with considerable gains ($O(10^5)$) and excellent timing resolution ($O(\text{ns})$).

Future Direct Detection Experiments

The current generation of noble liquid direct detection experiments at the tonne-scale is transitioning towards next generation experiments at the ten and hundred-tonne scale. Scaling up these detectors will require significant advances in detection technologies and background reduction techniques in order to reach their sensitivity targets. One major improvement being employed by major experiments such as Darkside-20K [26], and DARWIN [27], is the transition from PMTs to Silicon photo-multipliers (SiPMs) for light detection. SiPMs offer several advantages over PMTs, such as faster timing resolution ($O(\text{ps})$), and most importantly, the ability to be made radio-pure. PMT photo-cathode glass represents a major background component for rare event search experiments that employ them, and since SiPMs are made almost entirely of silicon, they can be made extremely low in radio-impurities. These impurities, such as naturally occurring uranium and

FIGURE 1.8: Cross-section of the DEAP-3600 experiment, if A WIMP DM particle interacts with the LAr target, scintillation light is produced which is transmitted to the 255 PMT's surrounding the vessel.

thorium isotopes and their progeny are present in all materials in varying concentrations, the decay products from these radioisotopes constitute a major source of background in rare event search experiments.

Researchers from DEAP, Darkside, ArDM, CLEAN and others have come together to form the global argon dark matter collaboration or GADMC [28]. The objective of this collaboration is to combine efforts on the global argon dark matter program and coordinate the development of Darkside-20k, and ultimately a

next-generation multi-hundred tonne liquid argon detector, "ARGO". ARGO will be the ultimate high-mass WIMP search liquid argon detector, with sensitivity to the so-called "neutrino floor", the level at which the coherent scattering of solar and atmospheric neutrinos off of argon becomes the limiting background for DM searches. Since coherent scattering of neutrinos or " $\text{CE}\nu\text{NS}$ " [29], is impossible to distinguish from a WIMP DM interaction in the singular, only aggregate analysis of the rate of such events will allow for DM to be differentiated from neutrino events. One possible handle on the neutrino induced background is the directionality of the events, which requires reconstruction of the momentum of the recoiling particles, not possible in current generation detectors but obtainable in noble gas TPCs. In addition to advances in detector technologies like SiPMs, a detector at ARGO's scale will require advanced data-handling and processing techniques, and aims to take advantage of advances in smart data-processing and triggering developed by accelerator experiments. Reducing the level of backgrounds in ARGO requires the use of underground argon, which has much lower concentrations of radioisotope ^{39}Ar , present in small quantities in atmospheric argon used in current generation experiments. ^{39}Ar in atmospheric argon has a specific activity of $\sim 1 \text{ Bq/kg}$ of liquid argon, and is the dominant background in liquid argon detectors. The mechanics of ^{39}Ar separation from DM-like signals will be discussed in the following sections.

1.3 Noble Liquid Detectors

1.3.1 Noble Liquid Scintillation

"Noble liquids" refer to condensed noble gasses such as xenon, argon, krypton and helium, in their liquid state. Argon is a liquid at 87 K and STP, while xenon is liquid at 165 K. Noble liquids exhibit the property known as "scintillation", where energy deposited is converted into a proportional amount of light. The proportionality factor between the energy deposited into a scintillator, and its light output, is known as the "scintillation light yield" (SLY). The SLY is given in units of number of photons/keV, and for liquid argon this value is ~ 40 ph/keV, and for liquid Xenon ~ 50 ph/keV [30].

The scintillation process for noble liquids is shown in Figure 1.9. When an incident particle interacts with an atom in the material, energy is transferred to the atom which is either put into an excited state, ionized, or the energy is lost to heat. Ionized atoms quickly ($O(fs)$) form ionized molecules with neighbouring atoms afterwards will recombine with a nearby electron to form an excited molecule or excimer. Primary excited atoms will combine with a nearby atom and form an excimer. During initial excitation, either primary excitation from incident particle interactions, or after recombination, the excimer will be in a highly excited state that decays to a metastable state very quickly through internal conversion, the resulting metastable state will be in either a singlet or triplet configuration. This metastable state will then decay back to the ground state of the atom with a characteristic decay time, in liquid argon, singlet states decay very quickly ($O(ns)$) while the spin-forbidden triplet state decays with a longer characteristic time ($O(us)$). The

decay to the ground state is accompanied by the emission of a scintillation photon, with a wavelength typically in the vacuum ultra-violet. This is highlighted in Figure 1.9, with decay times for singlet and triplet states, and mean emission wavelength shown for LAr and LXe. By measuring the quantity of scintillation light, ionization electrons, or both, one performs an analogous measurement of the energy deposited in the detector material by the incident particle, this energy is referred to as the "reconstructed" energy and is strongly dependent on the detector performance parameters.

FIGURE 1.9: Scintillation process for noble liquids, atom 'A' can be substituted for Ar, Xe, Kr or He

The emission wavelength spectra for liquid and gaseous argon scintillation are shown in Figure 1.10 from [30]. LAr scintillation peaks in the vacuum ultra-violet

at ~ 128 nm, far below the optimal sensitivity of modern photo-detectors. This necessitates the use of a wavelength shifting material to enable light detection. This is explained in detail in the following subsection.

FIGURE 1.10: Gaseous Argon (Red) and Liquid Argon(Black) scintillation emission wavelength spectrum from [30].

Particle identification (PID) in noble liquids takes advantage of different linear energy transfers (LET) for different incident particles. For DM searches in LAr detectors, the primary incident particle is a recoiling argon nucleus which has been transferred energy by the DM particle interaction, called a nuclear recoil (NR). Other incident particles include, beta particles, alphas, gammas, muons, and neutrinos. The LET for NRs differ significantly from ionizing radiation such as betas, gammas and muons, which produce primarily electronic recoils (ER) signals. High LET incident particles such as ^{40}Ar -NRs and alphas produce primarily excitations, and lower LET incident particles such as betas and gammas produce primarily ionization signals. This is the basis for pulse-shape discrimination (PSD), which is discussed in detail later in this section. PSD Takes advantage of the very long

triplet lifetime in argon, which allows for excellent separation of DM signal from ER backgrounds, with separation of $O(10^9)$ obtainable [4]. This level of separation is not obtainable in a xenon-based detector due to the much shorter xenon triplet time.

Not all the energy of the incident particle is capable of being reconstructed, and some is lost through a variety of processes, known as "quenching". Quenching in noble liquids takes two main forms, luminescence quenching and nuclear quenching, these two categories are shown in Figure 1.11. Nuclear quenching, also known as "Lindhard" style quenching, is energy loss due to collisions that do not produce excitations or ionization, and the energy transfer results in heat in the material instead. Nuclear quenching is proportional to the nuclear stopping power for the incident particle in the material and has been described in detail by Lindhard [31]. Luminescence quenching occurs when excited atoms are prevented from producing scintillation light. The first main contributor to luminescent quenching in liquid argon is due to bi-excitonic collisions, where two excited atoms collide and produce an argon ion + ground state atom and ionization electron. The ion produced can in turn recombine and produce a single scintillation photon instead of two. The second main contributor to luminescent quenching is due to the so-called "Penning Process", where an excited argon atom collides with either a ground state argon atom, or impurity in the bulk material, and produces an argon ion and ionization electron which may or may not recombine and produce scintillation light. Luminescent quenching is proportional to the ion density in the core of the incident particle track, and therefore proportional to the electronic LET. This is often modelled using a Birks-style saturation law, which has been successfully applied

to describe liquid argon quenching [32].

FIGURE 1.11: Quenching mechanisms in noble liquids, luminescence quenching describes quenching modes where scintillation emission is suppressed, nuclear quenching describes quenching modes where energy is lost to heat without excitation of target material.

Birk's saturation law, which produces a "Birks-style" quenching factor, is described by Equation 1.2 [33]. Where ' q_l ' is the luminescence quenching factor, ' k_B ' is the Birk's constant, and ' dE/dx ' is the electronic stopping power for the incident particle in the material.

$$q_l = \frac{1}{1 + k_B \frac{dE}{dx}} \quad (1.2)$$

The total energy available to be reconstructed by the detector can be described as:

$$E_{quenched} = \Delta E_{step} \cdot q_l \cdot q_n \quad (1.3)$$

Where, ' ΔE_{step} ' is the energy deposited in a particular step, ' q_l ' is the luminescence quenching factor and ' q_n ' is the nuclear quenching factor, derived from Lindhard theory. In particle transportation simulation packages such as GEANT4, transportation occurs in finite small steps, and in this case the effective quenching factor can be found at each step in a semicontinuous approximation, provided the step size is sufficiently small.

1.3.2 Wavelength Shifters

Wavelength shifters(WLS) are fluorescent materials that convert light from one wavelength to another. These are also known as Up/Down converting materials, and can be organic or in-organic. The most common WLS for LAr applications 1,1,4,4-tetraphenyl-1,3-butadiene (TPB) which is an organic wavelength shifter. TPB has a high conversion efficiency and is stable in LAr environments. Other examples of organic WLS include pyrene, p-Tetryphenyl and polyethylene naphthalate. Organic WLS materials are composed of conjugated aromatic hydrocarbon rings and strongly absorb UV radiation, the molecular structure of TPB is shown in Figure 1.12 for reference. The luminescence mechanism for organic WLS materials is represented in Figure 1.13, as a Jablonski diagram. When an incident UV photon is absorbed by the WLS layer, the molecule is excited from the ground state ' S_0 ' to an excited state. Molecular vibrational levels are present for all states, and transitions from a vibrational level to a meta-stable excited state occur rapidly through non-radiative mechanisms. Conversions to a triplet state can occur, although this is suppressed due to the spin-forbidden nature of the triplet state. Transitions from singlet excited states $S_1 \rightarrow S_0$ occur on O(ns) timescales and produce fluorescence,

while transitions from $T_1 \rightarrow S_0$ occur on longer timescales, $O(\mu s)$, due to the spin-flip suppression, and produce phosphorescence. Energy loss from the initial excitation in the form of vibrational transitions and internal conversion leads to a net shift from low wavelength absorption to higher wavelength emission. The gap between the absorption spectra for a WLS material and its emission spectra, is also called the Stokes shift.

FIGURE 1.12: Molecular structure of TPB molecule

In LAr experiments such as DEAP, and others, where the VUV emission of argon at ~ 128 nm is below the peak sensitivities of modern photo-detectors, TPB is employed to rapidly convert LAr scintillation light to visible. This conversion allows the light to transit the acrylic of the vessel, and to be detected optimally by the PMTs. This does come with costs however, TPB is known to have a significant very-late component due to phosphorescence and this contribution can degrade pulse-shape discrimination performance, since initially prompt photons will be detected much later. Another consideration is the isotropic emission of the WLS luminescence, this has the effect of degrading position reconstruction performance. There

are a number of parameters of interest when selecting a WLS material.

- Peak Emission Wavelength, $\lambda_{E,max}$
- Photo-luminescent quantum yield (PLQY), The ratio of emitted photons/absorbed photons
- Re-emission decay constant, τ_i , 'i' being distinct for singlet/triplet emission.
- Stokes Shift, or self-absorption probability

FIGURE 1.13: Jablonski diagram for an organic WLS, illustrating the luminescence process. Inter-system crossing (ISC) and Internal Conversion(IC) are non-radiative processes that occur on O(ns) timescales, reproduced from [34]

Shown in Figure 1.14, is the wavelength emission spectra of TPB, alongside 2 other critical wavelength dependent features for the scintillation light detection, PMT efficiency, and acrylic attenuation. PMT efficiency is shown for Hamamatsu R5912-HQE PMTs used by DEAP, and acrylic attenuation is given as the mean

survival probability of a photon of a given wavelength while traversing 1 m of acrylic (While in the light guides) according to the Beer-Lambert Law.

Wavelength Dependence for critical components

FIGURE 1.14: Wavelength Dependence of TPB(Green) emission, PMT efficiency(Pink) and acrylic attenuation probability(Blue), The compatibility of TPB with the PMT efficiency and acrylic detector materials is clearly visible.

1.4 Backgrounds In Rare Event Searches

"Rare event search experiments" describe a broad category of physics goals, from direct DM detection, to neutrino-less double-beta decay observation. While the physics goals differ, the challenges for signal detection are shared between these experiments. Experiments looking for never before seen signals, must measure all signals and come up with ways of separating "signal", the physics signal they're

looking for, from "background", all other ways of producing responses in the detector. The techniques for discrimination of background from signal, and methods of reducing background levels, are of critical importance for rare event search experiments.

In the context of a single-phase LAr direct DM detection experiment like DEAP-3600, where the WIMP signal expectation is < 1 event/yr, background reduction and separation are of critical importance.

1.4.1 Radiogenic Backgrounds

Radiogenic backgrounds are events that generate physical signals in the detector, caused by trace amounts of radioactive elements within the detector materials. For LAr detectors, the most significant radiogenic background is ^{39}Ar , a radioisotope of argon that is found in trace amounts in atmospheric argon. ^{39}Ar is produced naturally in the atmosphere due to cosmic ray collisions on stable ^{40}Ar , it has a specific activity of ~ 1 Bq/kg of LAr, for a large LAr detector such as DEAP, this constitutes an operational background rate of ~ 3300 Hz.

Naturally occurring uranium and thorium, ^{238}U , ^{235}U , and ^{232}Th , and their progeny are the most common source of radiogenic backgrounds. Trace amounts of uranium and thorium are present in all materials, and will be present in all detector materials unless special care is taken with material screening and selection. The decay of these radioactive materials produce incident radiation that can mimic signal events. For LAr detectors, alpha decays are of particular importance, this is because alphas preferentially excite LAr into a singlet state, the same as ^{40}Ar NRs. The decay chains for ^{238}U and ^{232}Th are shown in Figure 1.15 and Figure 1.16

for reference. Due to the long lifetime of ^{238}U and ^{232}Th ($\text{O}(\text{Gy})$), the progeny decays are often considered to be produced "in equilibrium" where they are being produced and decaying in a steady-state.

FIGURE 1.15: ^{238}U decay chain

Radon is a radioactive noble gas produced in the ^{238}U and ^{232}Th decay chains, and is a particularly troublesome material for rare event search experiments. Radon

FIGURE 1.16: ^{232}Th decay chain

is a gas at STP and will emanate from detector materials into the sensitive region of the detector, producing signals due to its decay products. Additionally, since radon is present in small amounts in air, during construction of detector components radon will deposit onto the surface of the materials and result in a build-up of long-lived ^{210}Pb on surfaces. Since ^{210}Pb has a half-life of 22.3 years [35], it is effectively a constant source of backgrounds once deposited. In LAr detectors, ^{210}Pb deposition from radon during construction is particularly troublesome for two reasons: The decay of ^{210}Po will produce alpha radiation, as well as a recoiling ^{206}Pb

nuclei. Decays of ^{210}Pb that are embedded a small distance into detector materials will result in an alpha that has been degraded in energy, and for sufficiently low energy alphas will reconstruct similar to the expected DM signal. Recoiling ^{206}Pb nuclei present a similar difficulty, for ^{210}Pb present on the surface.

FIGURE 1.17: ^{222}Rn Decay chain, radon is a radioactive gas produced in the uranium decay chain, and due to its gaseous state at STP can permeate through detector materials and deposit on surfaces.

1.4.2 Environmental Backgrounds

Environmental backgrounds are a class of background events that are always present in the environment of the detector. This includes, cosmic rays, cosmic muons, neutrinos and cosmogenic activation neutrons and spallation showers. In order to shield from muons and cosmic rays, rare event search detectors are placed in underground labs, or labs located under mountain ranges. This choice of location shields the detector from cosmic rays and decreases substantially the expected cosmogenic backgrounds. DEAP-3600 is located at SNOLAB, which is located at the Creighton mine in Sudbury, Ontario, Canada, and is 2 km underground, providing 6 km of water equivalent depth. The flux of muons as a function of depth for a selection of underground labs is shown in Figure 1.18, highlighting the importance of going to these extreme lengths. Neutrinos are a form of irreducible backgrounds for direct DM search experiments, but for neutrino detectors they are the signal of interest, and going deep underground shields the majority of cosmic muons that can mimic neutrino signals for neutrino detectors. Other forms of environmental backgrounds such as cosmogenic activation and spallation showers are caused by activation of detector materials, or materials nearby detectors from cosmic rays, which in turn decay to stable states, often releasing neutrons. These neutrons are of particular importance for direct DM detection experiments because a single-scatter neutron interaction inside the detector bulk will look identical to a potential DM interaction. Mitigation of these types of backgrounds is typically done by including some form of active veto, which detects muons and allows for a veto-period afterwards, which suppresses the cosmic ray background greatly. This will not prevent

neutrons from materials surrounding the detector, such as the cavern walls. In order to reduce this component of backgrounds self-shielding is often employed, or an active-veto which can detect neutrons as employed in Darkside [22].

FIGURE 1.18: Muon flux as a function of water equivalent overburden for a selection of underground labs from [36]. Not shown here is the flux at surface, which is ~ 1 muon/cm²/s, far off of the scale of the plot.

1.4.3 Background Mitigation Techniques

To mitigate the sometimes abundant sources of backgrounds in rare event search experiments, a number of technical methods are employed. As mentioned in the

previous subsection, moving to an underground site can greatly reduce the backgrounds due to cosmic rays, and is an essential step for reducing environmental backgrounds. In addition, material screening and selection employed in reducing background levels in sensitive detectors, this process typically includes radioassays of potential detector materials to ensure they are sufficiently low in activity for use in a sensitive detector. Assays of detector components can be carried out underground as well, to reach even higher sensitivities for measurements, and SNOLAB has a suite of high purity germanium detectors that are used to screen materials for experiments use. The careful selection of detector materials makes a big impact on the expected background rates due to radiogenic components. As previously mentioned, radon is a particularly troublesome source of background events in rare-search experiments. Since radon is a gas, it will permeate through detector components and can be deposited onto detector surfaces in large quantities during construction stages. Special care for handling sensitive detector components to reduce radon loading is taken, by constructing sensitive components in a nitrogen purged glovebox, and ensuring the components remain sealed during transportation and installation, much of the radon load can be mitigated. For components where this is not possible, such as the DEAP-3600 Acrylic vessel, active radon removal is employed by resurfacing the component, either through sanding or chemical etching, to remove radon and radon daughters deposited onto the surface.

Not all background contributions will be removed with stringent material screening protocols, and therefore active background discrimination is employed to distinguish signal from backgrounds. A common example of active background mitigation is through position reconstruction, where the expected position of the event source is determined using reconstruction algorithms. By reconstructing the expected position of all events occurring, events from detector surfaces, which are expected to have much higher rates of background events but constant rates of signal events, can be removed from consideration, this process is known as "fiducialization" and monolithic detectors such as DEAP-3600, will fiducialize their detector volumes and only consider events occurring within some smaller inner volume. Particle identification (PID) is another powerful tool for background mitigation, for direct DM search experiments, where the expected signal is a low energy nuclear recoil, all events that reconstruct as electronic recoils, or beta/gamma interactions can be removed from consideration. In a single-phase LAr detector such as DEAP-3600, the main tool for particle identification is pulse-shape discrimination, which will be discussed in detail in the following subsection. In dual-phase detectors or noble liquid time projection chambers (TPC's) an electric field is applied to drift ionization electrons away from the interaction site, which is then amplified and detected as a charge signal (S2), and the scintillation photons from the excitation channel are detected separately as light (S1). By comparing the proportion of charge to light signal, particle identification is performed, where beta/gamma events have high ratios of charge/light and nuclear recoils & alphas produce lower ratios of charge/light. Many other forms of PID exist to exploit differences between signal and background for other detector technologies, and is a primary consideration

during the design stages of particle detectors.

Pulse-shape Discrimination

Pulse-shape discrimination (PSD), is an active background mitigation technique applied to differentiate signal events from background. PSD takes advantage of the difference in the shape of signal arrival, due to differences in the nature of interactions. In LAr detectors, PSD uses the arrival time of photons at the photodetectors, taking advantage of the large difference between the LAr singlet decay time of ~ 6 ns and the triplet decay time of ~ 1600 ns. This works because the proportion of excited/ionized argon atoms is not constant under different ionizing radiation, moreover the ratio of singlet states is higher for the excitation channel, while the proportion of triplet states is higher for the ionization channel, referring to Figure 1.9. Nuclear recoils, have high proportion of excited argon atoms, while electronic recoils have a higher proportion of ionized atoms, this leads to much faster emission times for nuclear recoil signals and longer emission times for electronic recoils, on average. This is highlighted in Figure 1.19, PSD is quantified in LAr detectors using a parameter known as "Fprompt" which is outlined in Equation 1.4, Fprompt measures the fraction of total light that occurs within a so-called "prompt window", $[-28 \text{ ns}, 150 \text{ ns}]$, surrounding the triggered event time, relative to the total light measured in the event. Since nuclear recoil signals produce more prompt light due to the higher fraction of excited argon atoms, they reconstruct high in Fprompt, and conversely, electronic recoil events, mostly beta/gammas,

reconstruct lower in F_{prompt} .

$$F_{prompt} = \frac{\sum_{-28}^{150}{}_{ns} PE}{\sum_{-28}^{10}{}_{us} PE} \quad (1.4)$$

The effect of this is highlighted in Figure 1.20, showing a 2D plot of the reconstructed energy of the event (in PE) versus F_{prompt} for a selection of DEAP-3600 data. Clear separation between Signal-like nuclear recoils from background-like electronic recoils is shown. The discrimination power for PSD in LAr detectors has been shown to be $O(10^8)$ [4], providing excellent separation from the dominant ^{39}Ar background.

FIGURE 1.19: PMT Signals for two classes of events in DEAP-3600. Electronic recoils have longer emission times, and nuclear recoils have more prompt emission.

FIGURE 1.20: F_{prompt} vs reconstructed energy (PE) for a selection of DEAP-3600 data, several event populations are highlighted.

Chapter 2

Argon-1 at Carleton

Argon-1 is a 35 kg LAr cryostat located in the COLD Lab at Carleton University in Ottawa, ON, Canada. The inner detector is a 26-sided irregular polyhedron with square and triangular faces which is designed to approximate a spherical symmetry for photo-detector placement while remaining modular and simple to construct and deconstruct. The inner detector is a single phase LAr detector outfitted with Silicon photo-multipliers (SiPMs) which detects the LAr scintillation light.

The primary research aims for the Argon-1 detector are targeted towards gaining understanding of LAr detector backgrounds as well as performing critical testing of new photodetector technologies for next generation experiments such as ARGO. This includes the testing of a novel surface background rejection technique which will be discussed in detail in chapter 4, measurements of LAr scintillation parameters and quenching for alpha radiation, down to low energies, and studies of new WLS materials for use in LAr detectors.

2.1 Detector

The Argon-1 vessel is a 26-sided polyhedron, which features flat faced sides that allow for full contact of SiPM windows to the acrylic of the vessel. In the current configuration two 64 channel Hamamatsu MPPC (Hamamatsu S14161-3050HS-8) are installed with one having all channels read out individually (PIXL SiPM) and one SiPM with all 64 channels summed passively (ASUM SiPM). Using the full pixelated readout, it will be possible to tag events originating from the surface of the vessel, taking advantage of their unique light distribution pattern, to distinguish them from inner vessel events. The inner vessel is composed of acrylic panels that are coated with 1 μm of TPB which was vacuum evaporated onto each piece individually at Carleton University. The vessel is surrounded by 3M ESR specular reflective foil and then wrapped with strips of polyethylene wrap and heat-sealed to secure the reflective foil. The detector is described in the diagram in Figure 2.1 with vessel and outer can are shown in Figure 2.2.

The detector itself is held inside an inner stainless steel vessel or "can" that contains the sensitive components, this is nested inside a larger stainless steel vessel that is exposed to the clean-room environment. The space between the two vessels is pumped to a vacuum level of $< 10^{-6}$ mbar which provides insulation to the inner can and LAr space. Additionally, the entire inner can assembly, including the inlet from the cold-head, is covered in 20 layers of multi-layer insulation that helps maintain the inner vessel at a constant temperature for the LAr.

FIGURE 2.1: Argon-1 Detector diagram, composed of 2 nested stainless steel cans with multi-layer insulation, the vacuum and LAr space are kept isolated, and the inner-vessel is placed at the centre of the inner can.

2.1.1 Process System

The process system for Argon-1 handles the flow, purifying and condensation of clean gaseous argon (GAr) into LAr which meets the purity requirements for scintillation. In order to meet the requirements for PSD, argon must have fewer than 1 parts per billion (ppb) of electronegative contaminants, such as O_2 and N_2 , which, if not removed, will cause excess quenching of the ionized electrons leading to a decreased population of triplet states that provides the discrimination power separating ER-like signals from NR-like signals in LAr.

FIGURE 2.2: Pictures of the Argon-1 Cryostat (left) and inner vessel (right) instrumented with 2 SiPM arrays for the most recent LAr run.

A drawing of the current process-system is shown in Figure 2.3, with key components high-lighted, and optional bypasses shown for additional components included for reference. Flow paths for filling and steady-state operation are high-lighted as well. Gas from 99.999% purity argon bottles enters the system and pumped with a diaphragm pump into the SAES getter purifier which uses a hot zirconium material to create irreversible chemical bonds to impurities such as oxygen and nitrogen, and effectively traps other impurities such as hydrogen and tritium. Before purifying, the gas is sampled using a vacuum RGA to ensure that the system is leak-free and that the gas meets the inlet requirements for the SAES getter, with O_2 and N_2 below 1 ppm [37].

After purification the gas flows through a helium-condensed cold head assembly, the gas remains inside a stainless-steel coil which is thermally coupled to the cold head through a copper mount and copper gauze that wraps around the coil. The cold head provides 90 W of cooling power to the system. During cool-down, GAr will flow repeatedly through the purifier, cold-head and into the inner can, which holds the detector, the cold gas from the cold-head assembly will cool the inner detector until the entire system is cold enough to condense GAr into LAr, typically at 85K. This process occurs gradually over several days and when the pressure of the system drops, additional gas is fed in from the supply bottle controlled by a pressure regulator. Since cooling occurs gradually, the argon is condensed slowly at first, providing more and more cooling to the inner vessel as the inlet pipe is cooled, and proceeds rapidly when argon droplets begin to fall into the inner vessel. Once this point is reached, filling the detector takes another 7 days and ~ 2.5 bottles of GAr.

An example of the cooling curve from Argon-1 is shown in Figure 2.4 from a recent run. Once the inner-can is cool enough to hold LAr without boiling, the temperature of the inner can drops rapidly due to LAr droplets falling and pooling inside. Afterwards, the fill proceeds over ~ 7 days.

2.1.2 Slow controller

To monitor the stability of the system and to control the cold-head assembly, a slow control program was developed using National Instruments LabView software. The VI for the slow controller is shown in Figure 2.5 for reference. All temperature

FIGURE 2.3: Argon-1 process system overview diagram, with flow paths for steady-state and filling highlighted. Optional bypasses and other important lines are shown as well. Valves, sensors and pressure safety regulators and additional components are not shown. (F.M = Flow Meter, P. Reg = Pressure Regulator)

and pressure monitors of the system are read-out every 1 ms, and logged at a controllable rate, which allows data to be logged more frequently during critical times of detector operation, but less frequently during steady-state operation. The cold-head assembly temperature is kept constant with 3 cartridge heaters through relays connected to the slow control program. When the temperature of the cold-head assembly measures below a set-point temperature, the heater relays are switched open activating the heaters, since the heaters provide constant power and are not current-controlled, once the temperature rises above the set-point, the relays are closed and the heaters turned off. During steady-state operation these cycles occur

FIGURE 2.4: Cooling curve for most recent Argon-1 Run, RTDs 1,2,3,7 & 8 are along the inner vessel, while RTDs 4-6 are on the cold-head. RTD6 is used for PID control and is attached directly on the cold-head mounting plate.

once every 3-5 minutes and last for ~ 3 seconds. This cycling is to prevent freezing of argon in the cooling-coils, which would slow down the cool-down procedure and cause a build-up of pressure in the process system that can lead to argon being vented into the room. During the next reconfiguration the cold-head assembly will be controlled with an external PID controller that monitors the pressure in the cold-head rather than the temperature to provide more immediate response and prevent the cold-head control from being crashed due to computer issues, as this has happened in the past runs due to forced Windows updates and other unexpected events. The liquid level is monitored with a level sensor and read out through the slow control program.

FIGURE 2.5: NI LabVIEW Slowcontroller VI program that monitors Argon-1

2.2 Data Acquisition System

The data acquisition system (DAQ) for Argon-1 is composed of 4 main components; SiPMs for light readout, Pre-amplifier boards that amplify the weak SiPM signals and provide bias voltage to the devices, digitizers housed in a VME crate located next to the detector, and the DAQ computer which hosts the front-end software. The front-end software uses the Maximum Integrated Data Acquisition System (MIDAS) software package[38], supported by TRIUMF. In collaboration with our colleagues at TRIUMF, the Argon-1 Front-end software was written using MIDAS with a CAEN VME Library interface.

An outline of the DAQ is shown in Figure 2.6. The central components of the DAQ are listed below:

1. 2x 64 Channel Hamamatsu MPPC (S14161-3050HS-0)
2. 160 channel vacuum micro-coax feed-through PCB board
3. Low-noise Keithley Power supply
4. TRIUMF Pre-amplifier boards and bias voltage supply
5. 1 GHz LeCroy Wave-surfer 510
6. CAEN VME Crate with:
 - C – Crate controller board (CAEN V3718)
 - 1/2 – Digitizers + Adapters (CAEN V1740 + A746B)
7. NIM Crate with:
 - Quad fold logic board for coincidence trigger generation
 - Discriminators and fan-outs
 - Pulse pattern generator
8. Optical link adapter board (CAEN A3818) on PCIe
9. DAQ PC (Asus ROG STRIX B550-E + AMD Ryzen 7 4.4 GHz)
10. MIDAS Front-end software and ROOT data-structure & analysis software

FIGURE 2.6: Argon-1 DAQ Overview schematic items listed in section 2.2

2.2.1 Signal Readout

The signal readout system designed for Argon-1 works in 3 main stages; Physical signal transmission, Analogue signal transmission, then digital signal transmission. These stages are outlined in Figure 2.7. Photons incident on the SiPMs produce signals that are transmitted out of the detector on a custom feedthrough board that allows for 160 micro-coax channels through Samtec QSE connectors.

The raw signal is transmitted through $50\ \Omega$ impedance coaxial cables into pre-amplifiers that amplify the SiPM signals and perform charge to voltage conversion in a trans-impedance configuration. Amplified analogue signals are converted to digital waveforms by two CAEN V1740 digitizers, and then transmitted as digital data over an optical fibre to an optical bridge installed in the DAQ PC. Event read-out, triggering and construction is handled by the MIDAS front-end software that ultimately writes out the waveform data for all channels into compressed binary files. The V1740s each have 64 channels and the Argon-1 DAQ can support expansion to 135 channels in the future, while at time of writing, uses 65 total channels for 1 fully instrumented Hamamtsu array (All 64 channels read out individually) and one summed together.

FIGURE 2.7: Argon-1 Signal Readout Chain

2.2.2 Trigger Configuration

To ensure event synchronization between the two V1740 boards, the clock of the main V1740 (Board 1) is propagated to the second V1740 and synchronized using the CAEN SyncTest software following [39]. The clock of the secondary V1740 (Board 2) is then overruled by the clock of Board 1. To verify the synchronization of the two boards, both clock and trigger signals are propagated to an oscilloscope and where the delay was found and applied to Board 2 to ensure O(ps) synchronization.

The V1740 digitizers allow for internal threshold triggering, this occurs in groups of 8 channels, where each group of 8 channels has a threshold set by an internal register configured in the DAQ front-end software. The polarity of the signal is switched to negative, and the time under threshold is used to generate a NIM trigger for each group. This is illustrated in figure Figure 2.8. Both boards are read-out simultaneously in a daisy-chain configuration, connected by optical fibre to the A3818 PCIe bridge on the DAQ PC. To ensure event synchronization between the two boards, the internal trigger signals for the active groups of both boards are propagated to the TRIGOUT port of each board. These signals are passed into a NIM Quad-fold logic module, which can be operated in either AND or OR configuration. For nominal running, the trigger uses a “global OR” configuration, that is, if any channel in any group on either board goes under threshold, a trigger is generated by the NIM module. Once a trigger is generated by the NIM module it is sent back to the two V1740 boards into the TRIGIN port, and the V1740 front-end program is configured to acquire data for both boards when a trigger is generated on the external TRIGIN.

FIGURE 2.8: V1740 Trigger Generation Example, when the signal on any channel (SiPM Pulse illustrated here), goes below the set threshold, the internal trigger signal is generated for the duration of the time-under-threshold

2.3 Silicon Photo-multipliers

Silicon photo-multipliers (SiPMs) are the photodetectors used in Argon-1 to detect LAr scintillation light. A SiPM is a solid-state photodetector composed of an array of single photon avalanche diodes (SPADs) operated in so-called "Geiger-mode" with a reverse bias voltage of $O(10\text{ V})$. These devices are sensitive to single photons and are used for photon counting applications. The reverse bias voltage required to enter into Geiger-mode is called the breakdown voltage, and is illustrated in Figure 2.9. When a photon interacts with a SPAD in the SiPM, it produces a cascade of charge referred to as an "avalanche" that amplifies the initial photo-electron with a gain of $O(10^5 - 10^6)$. Each individual SPAD within the SiPM is connected in series to a high impedance quenching resistor, typically of $O(100\text{ k}\Omega)$, after a photon produces a Geiger-avalanche in the SPAD, this resistor resets the SPAD, which can be modelled as a simple RC circuit with a characteristic decay time proportional

to the capacitance of the SPAD and the resistance of the quenching resistor. The details of SiPM operation and parameters of interest are outlined in the subsequent sub-sections.

FIGURE 2.9: Illustration of SPAD behaviour as a function of reverse bias voltage, breakthrough voltage shown here on a log-Current vs bias voltage plot as the turning point voltage where the SPAD enters avalanche mode, and is no longer a proportional counter.

2.3.1 Working principle

The SPADs within each SiPM channel are composed of layers of silicon with different levels of positive or negative doping, as such the SPAD can be modelled as a P-N junction. An illustration depicting the SiPM and SPAD structure is shown in Figure 2.10. During SiPM operation, a large reverse bias voltage is applied across the SPAD, setting up a depletion region in Geiger-mode. A photon interacts within the depletion region at the P-N junction of the SPAD, ionizing a silicon atom. The charge carrier is ejected from the silicon atom and accelerated across the region,

liberating more charge, creating an avalanche. The width of the depletion region increases as the field strength increases with the magnitude of the reverse bias voltage, a larger depletion region results in a larger sensitive region for photon interaction, increasing the efficiency of the device as well as the number of subsequent charges produced in the avalanche due to the increased acceleration of the primary charge carrier. This also leads to a higher overall gain of the device. Each SPAD is individually capable of producing an avalanche due to incident photons, and the resulting current is summed together into an analogue signal which is read-out. Each SPAD works individually and by counting the total number of fired SPADs, which can be done by measuring the integrated charge for the SiPM pulses, an analogous measurement of the total number of impeding photons is made since they are directly proportional. After each SPAD fires there is a characteristic reset time that is proportional to the resistance of the quenching resistor, and the capacitance of the cell, this is called the "SPAD reset time" and is modelled by Equation 2.1.

$$\tau_{reset} = R_q \cdot C_J \quad (2.1)$$

2.3.2 Operational Parameters

There are many parameters of interest concerning the operation of SiPMs and the understanding of their output signals. Understanding of these characteristics is of critical importance for the use of SiPMs in LAr based dark matter detectors. These parameters are also correlated with one another and depend strongly on temperature.

FIGURE 2.10: Illustration of SPADs modelled as a P-N junction within a SiPM array with each channel corresponding to an individual SiPM. Each SiPM is then composed of many such SPADs. Photons ionize atoms in the SPADs depletion region, creating an avalanche of charge that is then readout.

Breakdown and Over-voltage

The break-down voltage of the SiPM is defined as the reverse bias voltage that causes the device to enter Geiger-mode. This is defined as the voltage required to create an electric field with a strength sufficient to produce a charge avalanche. By applying a bias voltage greater than the breakdown voltage, a larger depletion region is created, increasing the sensitive area for photon interaction and the total number of charge carriers produced by an avalanche. The difference between the applied reverse bias voltage and the breakdown voltage is called the "over-voltage" and is described by Equation 2.2. Nominal operation occurs with over-voltages of 10 - 25% of the breakdown voltage.

$$V_{ov} = V_{bias} - V_{bd} \quad (2.2)$$

The breakdown voltage of a SiPM is typically measured by fitting out the turning point voltage of a reverse-IV curve. This is demonstrated in chapter 3.

Gain

Gain is defined as the increase in total signal of the device relative to the input. In the case of a SiPM the gain represents the overall increase in charge due to the avalanche process from the original single ionized charge carrier due to the photo-ionization inside the depletion region of the device. The gain of the SiPM is a function of the internal capacitance of the SPADs, determined by manufacturing, as well as the overvoltage. This can be represented by Equation 2.3.

$$G = \frac{C_j V_{ov}}{q_e} \quad (2.3)$$

Where, ' C_j ' is the junction capacitance of each SPAD, and ' q_e ' is the elementary charge.

Photo-detection Efficiency

The photo-detection efficiency (PDE) of the device is the probability for an incident photon to trigger an avalanche. This is often parameterized as a function of the wavelength of the incident photon, and is a combination of a number of different parameters. This includes the quantum efficiency of the photosensitive region, the geometric fill-factor of the device, and the avalanche initiation probability. The geometric fill-factor, or, ϵ_{ego} is the fraction of the total surface area of the device that is photo-sensitive. For our SiPMs this number is roughly 0.77. The fill-factor is determined by manufacturing and depends strongly on the SPAD packing efficiency. The avalanche initiation probability is the probability that an ejected electron in the sensitive region will initiate an avalanche, which is a function of the applied

field strength. The quantum efficiency is the probability that a given photon of a particular wavelength will ionize an atom inside the device, and depends strongly on the substrate composition. PDE is summarized by Equation 2.4.

$$PDE(\lambda, T, V) = \epsilon_{geo} * QE(\lambda) * \epsilon_{avalanche}(T, V) [\%] \quad (2.4)$$

The avalanche initiation probability may also depend on temperature, this could occur due to the reduced temperature of the silicon crystal lattice which in turn reduces the expected energy loss for the ionization electrons from phonons in the lattice during the initial stages of the avalanche. This allows for a higher avalanche initiation probability for a constant field strength.

Dark Noise

Dark noise is intrinsic noise to the SiPM which looks identical to single-photon signals and occurs over random time intervals. The source of this noise at room temperature is primarily thermally generated charge carriers, which create avalanches in the depletion region of the SPAD. These pulses occur without photoionization and are often quantified as a rate, dark count rate (DCR), or current depending on the application. The DCR of a SiPM is dependent on a number of characteristics, most significantly on the pixel density (the number of SPADs per unit area), the temperature, and the overvoltage. The pixel density is determined during manufacturing and can be selected for the desired application. DCR has been shown to have an exponential dependence on temperature, which is expected from a Boltzmann distribution of thermally generated charge carriers. At room temperature

DCR's of $O(10)$ kHz/mm of SiPM area are expected, however this drops significantly at cryogenic temperatures as demonstrated in [40], down to $O(1)$ Hz. At cryogenic temperatures such as LAr operation temperature at 87 K, dark noise becomes dominated by Shockley-Reed-Hall (SRH) and other quantum mechanical sources.

In order to characterize the dark noise or DCR, the SiPM is typically enclosed in a dark environment sealed from light, then the rate of triggers above the 0.5 photon threshold is measured. This can be repeated for different overvoltages in order to determine the ideal operating condition.

Correlated Noise

Correlated noise in SiPMs refers to subsequent pulses that are generated by a primary SiPM avalanche. These correlated noise pulses have two primary sources, after-pulsing and optical crosstalk. After-pulsing occurs when a photon or electron created during the primary avalanche is trapped by an impurity in the lattice inside the depletion region. This excited impurity atom will decay back down to the ground state, triggering a subsequent avalanche and occurring with a characteristic lifetime which depends on the impurity and state, in practice there will be many such states and impurities present and these will mix together to give a few dominant modes of average decay. These lifetimes can be $O(\text{ns}) - O(\mu\text{s})$ [41]. Since after-pulses always occur in the same SPAD as the primary avalanche, if they occur during the reset time of the SPAD they will trigger an avalanche without the full gain, and these appear as pulses shortly after the primary pulse, with a smaller

amplitude. Typical after-pulsing probabilities are between 1-3% for SiPMs, and is strongly correlated with temperature [41].

The second type of correlated noise is optical-cross talk (OCT). OCT is the most prominent source of correlated noise in SiPMs, and occurs when a photon that is produced in a primary avalanche exits the pixel where the primary avalanche occurs and enters a neighbouring pixel, introducing a secondary avalanche. This occurs on $O(\text{ps})$ timescales, much faster than the timing resolution of a typical SiPM setup, and appears as a 2-photon signal at the output. There are a variety of classes of OCT which reconstruct in different ways, this is illustrated in Figure 2.11 alongside after-pulsing. Direct cross-talk (Di-CT) occurs when a photon transits into a neighbouring SPAD and triggers a secondary avalanche, this can occur directly as illustrated, and by reflecting off of the window surface. Delayed cross-talk (De-CT) occurs when a photon produced in the primary avalanche photoionizes an atom in the silicon substrate of the SiPM ejecting an electron that random-walks its way into a neighbouring SPAD and triggers a secondary avalanche with full amplitude, this can occur on timescales of $O(\text{ns})$ to $O(\mu\text{s})$ and is indistinguishable from very late after-pulsing if the after-pulse occurs after the SPAD has reset. The last form of cross-talk described here is referred to as "in-direct" cross-talk (InDi-CT) and occurs when a photon from the primary avalanche leaves the SiPM it occurs in, and transits into a neighbouring SiPM. For a detector with a large surface area of instrumentation, these photons could transit the entire detector and register a hit on the adjacent surface. In a liquid argon detector, this would contribute to the stray light rate and would be indistinguishable from dark noise or phosphorescence of TPB.

FIGURE 2.11: Illustration for different classes of correlated noise with expected measured pulse-shapes above. a) After-pulsing (AP), b) Direct Cross-talk (Di-CT), c) Delayed Cross-talk (De-CT), and d) In-direct Cross-talk (InDi-CT). Reproduced from [42].

OCT is often characterized as a probability, which is calculated as shown in Equation 2.5. Where ' $R_{0.5PE}$ ' is the rate of pulses at a 0.5 PE threshold, ' $R_{1.5PE}$ ' the rate at a 1.5 PE threshold. This measurement must occur in a dark environment. Since OCT occurs due to photon transmission to a neighbouring cell, this rate is not expected to be homogenous across the SiPM, as cells in the centre have more surrounding SPADs.

$$R_{OCT} = \frac{R_{1.5PE}}{R_{0.5PE}} \quad (2.5)$$

In order to measure the AP rate or probability, time-resolved measurements of the SiPM signals must be made in order to separate the correlated noise from primary pulses, this is demonstrated in [41].

Temperature Dependence

Understanding of the temperature dependence of SiPM characteristics is critical for the operation of SiPMs in a LAr environment. There are several and correlated ways in which temperature plays a role in the performance of the device, and characterization of these interrelated effects is required for the understanding of detector signals which employ SiPMs. The breakdown voltage has been shown to vary strongly with temperature [41]. This occurs due to the decrease in thermal vibrations of the silicon lattice and therefore lower amounts of phonon scattering off the primary charge carrier during the initial stages of the avalanche, which allows for avalanches to be initiated with a lower field strength. Since the break-down voltage will decrease as a function of temperature, if the applied bias voltage is not corrected to account for this effect, it can cause a significant change in the PDE and noise rates for the device, due to the increased effective over-voltage. A second temperature dependent effect occurs for the reset time of the SPAD. Typically, SiPMs are manufactured with polysilicon quenching resistors, which increase in resistance significantly as you approach cryogenic temperatures [41]. The SPAD reset time is directly proportional to the quenching resistance as an effective 'RC' time-constant, and will increase significantly at LAr operation temperature relative to room temperature. This introduces additional difficulties in signal reconstruction; since the gain of the signal is not effected as long as the over-voltage is kept constant, but is now spread over a longer period. For noisy electronic set-ups this can significantly effect signal-to-noise. In addition to the increased SPAD reset time, the characteristic lifetime for after-pulsing also increases as you decrease in

temperature due to "freezing-in" of the meta-stable states. This effect can cause significant difficulties for removing after-pulsing contributions from the signal, since a larger proportion of the AP avalanches can fall outside the SPAD reset time and reconstruct indistinguishably from true single-photon events.

2.4 Data Analysis

Data analysis for Argon-1 occurs in several stages. The primary stage converts raw compressed MIDAS files into the raw branch of the custom ROOT format for Argon-1, A1DS. The second stage performs a custom baseline correction algorithm to restore the distorted raw waveforms, and then performs the pulse-finding and pulse-level variable aggregation. After pulse-finding, for each SiPM the pulse-level variables are summed over to extract SiPM-level information, which is summed over to extract event-level information, this includes the estimated signal intensity, photo-electron (PE) signal, the fraction of prompt signal and pulse arrival times. The next stage takes in the input from pulse and SiPM level information and extracts high-level information such as a basic position fitting result, the number of early pulses, and the expected number of sub-events. This branch will be expanded upon in the future to include any additional high-level event variables that are constructed. Subsequent analysis occurs with stand-alone ROOT macros, which perform dedicated analysis tasks.

An example of the pulse-finding for a SiPM waveform is shown in Figure 2.12.

FIGURE 2.12: SiPM Pulse-finder overview, Top: Baseline corrected (blue) and raw (red) waveforms from a single channel with many SiPM pulses, bottom: First derivative of the corrected waveform, with pulse-finding threshold shown. Pulses below threshold are flagged and pulse and sub-pulse information collected, see Appendix A for full details.

2.4.1 Processing and data structure

The data from Argon-1 is initially written out in a compressed binary format by the MIDAS front-end. This compressed binary data is passed through a series of processing stages outlined in Figure 2.13.

These stages are as follows:

1. MIDAS FE: The front-end software interfaces with the CAEN digitizer boards through the optical link using CAEN API protocols and MIDAS infrastructure for monitoring and running the DAQ. See Figure 2.14 for control page.

2. Midas2Root: Custom program that converts compressed .mid files into the A1-DS Raw (A1WF) format. Reads MIDAS event header information for timestamp, event ID, and other parameters of interest. Run-level information is read from the online database and saved to the .root file.
3. A1-DS RAW: A1-DS Raw branch is a vector of A1WF classes, which each hold 2 vectors, containing the sample times and ADC value at each sample for each SiPM waveform, as well as some generic information about the SiPM.
4. A1Calibrate: Custom program that fills the A1CAL branch, this stage involves SiPM pulse-finding and event and SiPM level information extraction. See Appendix A for details of SiPM pulse-finding procedure. See Appendix B for data-structure overview. At this stage we prune all raw waveforms after processing to reduce file size for calibrated files.
5. A1Evaluate: Custom program that fills the A1EV branch, this stage takes in the output of A1Calibrate in the A1CAL branch and performs high-level analysis and construction of higher-level parameters. After this stage the full TTree for A1DS is completed.
6. A1MakeNtuple: Program to flatten the full A1-DS TTree into a flat Ntuple for quicker analysis, also sums over some variables.

2.5 Monte Carlo Simulations

A detailed Monte-Carlo (MC) simulation was written to simulate events in Argon-

1. MC simulations are an essential tool for understanding detector response, and

FIGURE 2.13: Argon-1 Data processing schema

are employed universally in experimental particle physics [43]. MC Simulations use pseudo-random number sampling from known probability distributions to perform tasks such as multi-dimensional integration, optimization, and more. GEANT4 [44] is a widely used simulation software for simulating the passage of particles through matter. Detailed physical detectors simulated, and a priori knowledge of the detector materials and properties are used in combination with a desired set of physical interactions with incident particles in order to simulate the response of the detector to physical signals in a controlled way.

FIGURE 2.14: MIDAS Status and control page for Argon-1 DAQ. SiPM and DAQ settings are controlled through a web interface which interacts with the FE programs on the DAQ PC and TRIUMF Pre-amplifier boards.

FIGURE 2.15: A1-DS Overview diagram, see Appendix B for full list of DS variables and information

RAT (RAT is analysis toolkit) is an analysis and simulation framework that

combines GEANT4 simulation with event-loop processing that allows for modular event-level analysis and processing, which produces output in a ROOT file format [45]. RAT offers easy to use GEANT4-style syntax for so-called "macro" files, text files with lists of special commands for instructing the RAT software, expandable and customisable data-bases for physical properties of detector materials, and modular detector design. RAT follows the "AMARA" principle, as micro-physical as possible, and allows for the simulation and tracking of individual optical photons with dedicated classes for Cherenkov radiation, Scintillation, Wavelength shifting, and optical boundary surface and transportation processes. The MC simulation for Argon-1 was constructed using the RAT software package forked off of the main DEAP-3600 RAT development, which includes substantial changes to physical processes related to Liquid argon and wavelength shifting.

2.5.1 Simulated Argon-1 Geometry

The MC simulation for Argon-1 is stored on the DEAP-3600 Gitlab and is regularly re-linked with the DEAP-3600 RAT code to maintain code quality and remain up-to-date on the active development of the DEAP-3600 codebase.

The detector geometry was developed as part of this work and required the creation of several additional custom geometry classes to realistically produce the Argon-1 geometry. GEANT4 geometries use a tree-style configuration, where each branch on the upper part of the tree, called "daughter" geometries, must be placed entirely within "mother" geometries, which are located at a lower level of the tree, and must not overlap with other daughters. Each detector component is defined in a series of stages listed below. Special considerations must be taken with respect to

coordinate transformations for rotations and placement of detector components, as each daughter volume has an inherent coordinate system that must be transformed with respect to its mother's coordinate system in order to ensure proper placement and orientation, this is done by employing Euler rotations on the desired object.

1. `G4VSolid`: A geometric object that defines the physical extension of an object, several generic objects such as spheres, cylinders, and boxes are implemented as subclasses.
2. `G4LogicalVolume`: Takes in a `G4VSolid` object and imparts material properties, sensitivity and user parameters.
3. `G4VPhysicalVolume`: Places a `G4LogicalVolume` in a mother geometry with a defined position and orientation.

The simulated Argon-1 detector is shown in Figure 2.16 below. To accurately model the Argon-1 inner vessel, a dedicated class was written to handle the construction, rotation, and placement of all inner vessel components. This includes a WLS layer covering the inner surface of all acrylic panels, the option to place a scintillator, and the ability to change the WLS and acrylic material and properties for future detector configurations.

The Argon-1 simulation will be used to develop a detailed understanding of the physical detector response, and MC simulation results for detector calibration will be compared against data. Development is in progress for a real-time deployable source for measuring properties of LAr scintillation under different sources of radiation, and in parallel the ability to simulate this source is also in progress.

FIGURE 2.16: RAT simulated Argon-1 detector, left: Wireframe visualization showing the nested stainless steel cans of the vessel, right: surface visualization of the Argon-1 inner vessel submerged in LAr (purple)

2.5.2 SiPM Simulation

In order to accurately model the detector response for Argon-1, a new photo-detector class for SiPMs was created and implemented into RAT as part of the "rat-argon1" branch. Simulated SiPMs are composite box geometries with a main "sensitive" detector composed of silicon, and a window material, composed of silicone. Three additional detector geometry classes were written to implement this, and to remain general for future use by other experiments, the SiPM material properties and optical response parameters are read-in through data-base entries that are easily modified and interchangeable. The implemented classes and short descriptions of their purpose are listed below. The option to place a SiPM mounting board is included as well for realistic simulation of the Argon-1 geometry which includes such boards.

- `SiPMSD.cc/hh`: Sensitive detector class for the SiPM geometries, this class reads in properties from the `OPTICS.ratdb` database for efficiency and correlated noise parameters of the SiPM, records all photon "hits" to the MC data-structure using the same simulated PMT methods. A hit has a chance of being registered when a photon interacts within the top 0.7 mm of the surface to avoid registering hits from photons absorbed on the side or back of the SiPM.
- `GeoSiPMFactory.cc/hh`: `G4VPhysicalVolume` construction factory for building and placing an array of SiPMs within a mother geometry. 3 options for SiPM alignment are implemented. "Point"; where all SiPMs automatically orient themselves towards a point, "Manual"; where each SiPM gets a manual orientation read in by a database table, and "Axial" where all SiPMs are oriented along an axis selected by the user defined along a unit vector input.
- `GeoSiPMArrayFactory.cc/hh`: Helper class to build an array of SiPM geometries.
- `SiPM.ratdb`: Database file used by `GeoSiPMFactory` which contains SiPM material and physical size parameters, can be expanded upon and multiple entries included for other SiPM types which is passed as a command in detector construction.

Shown below is an illustration of the Simulated SiPM in Figure 2.18 and a comparison of the H-S14161 efficiencies versus high efficiency PMT R5912 in Figure 2.17.

FIGURE 2.17: Hamamatsu H-S14161 SiPM and R5912 PMT efficiencies as a function of incident photon wavelength

FIGURE 2.18: Simulated SiPM Illustration

Chapter 3

Argon-1 Calibration and Characterization Study

3.1 SiPM Mating and Feedthrough Board Design and Tests

3.1.1 Description

During the course of this work, 7 custom PCBs were designed, including a feedthrough PCB for taking out the SiPM signals from inside the cryostat, and 2 classes of so-called "mating" boards for connecting to the SiPMs. The SiPMs used in Argon-1 are S-14160-08-H Hamamatsu MPPCs with 64 individual SiPM channels, where each channel is 3 mm^2 in size. The SiPMs have a proprietary PWB material backing, and in order to read out the high density SiPM with individual channels, a "mating" PCB was designed to be re-flow soldered directly to the SiPM.

Considerable effort was taken to ensure material compatibility between the chosen PCB material and the PWB material of the SiPM to avoid excessive stress at low

temperatures. The mating boards were fabricated with a version of FR4 composite material with a coefficient of thermal expansion (CTE) of ~ 15 ppm/K at room temperature, compared to a CTE of ~ 10 ppm/K at room temperature for the PWB of the S1416 series SiPMs from Hamamatsu, revealed in private communication with Hamamatsu. The solder paste was also selected to have the highest strength obtainable, and the quantity and solder-paste configuration was chosen to have the highest possible surface area in order to reduce the effect of thermal strain between the two materials when cooling to 87 K. This work was completed in cooperation with the manufacturing house, DICA Electronics, and their engineering specialists, the Carleton Physics electronics specialist James Botte, who created the PCB design files, the Carleton Physics Engineering department engineers, Ryan Crampton and Rodney Schnarr who created the design for the physical layout of the mating boards, and performed detailed FEA thermal strain analysis for the boards. Detailed review of electrical designs were carried out with colleagues at TRIUMF national lab and U. de Sherbrooke.

4 versions of a SiPM mating board with RF-style MCX connectors were designed, as well as one version of a micro-coax Samtec QSE-style with additional RF-connectors for signal routing (QSE board hereafter). The QSE board schematic and picture are shown in Figure 3.1, each connector is capable of reading out 40 individual SiPM channels, the design goal here was to allow for high-density signal cables to be used on the SiPMs which would simplify feedthrough board design and installation considerably, since only 2 cables are required to take out 80 SiPM channels. The 4 different RF-Style boards were configured with different number of passively-ganged channels, where SiPM channels were added in parallel to form

an analogue sum signal to allow for fewer readout channels. The boards had the following number of total channels, 64 (No ganging), 8 (8:1 ganging), 4 (16:1 ganging), and 1 (64:1 ganging). The 64:1 analogue summed SiPM was chosen as the candidate for the current iteration for Argon-1, and the schematic for this board is shown in Figure 3.2 for reference.

Each QSE board can route 16 additional SiPM signals out of the detector on the Samtec EQCD cables used inside Argon-1.

FIGURE 3.1: QSE SiPM Mating Boards for Argon-1, Left: Design Schematic showing channelling, Right: Picture of as-built board

The feedthrough was designed to allow for maximum signal routing while remaining vacuum leak-tight to prevent argon contamination from external air. The feedthrough contains 2 feedthrough boards, as shown in Figure 3.3, with schematic shown in Figure 3.4 for reference. The feedthrough boards each have 2 40-channel QSE connectors on either side, allowing for 80-channels per board and 160 channels overall. The feedthrough boards are fixed in a delrin block fixture, designed

FIGURE 3.2: Schematic for 64:1 Analogue Summed (ASUM) SiPM.

to have no direct line of sight through the feedthrough, and were first sealed with quick-setting epoxy to prevent leaks, then vacuum sealed with slow-setting low viscosity epoxy. Exposed copper along the middle of the boards allow for grounding to the feedthrough flange, and allow for good contact with the epoxy filling.

3.1.2 Cryogenic Cycling Test

To ensure the cryogenic stability of the boards once deployed inside Argon-1, cryogenic cycling tests were carried out using liquid nitrogen as the coolant. This was done using a LN2 dewar in a semi-closed environment sealed with a nylon bag, this set-up is shown in Figure 3.5. GN2 from the LN2 supply boil-off was purged through the environment constantly to prevent moisture from condensing on the boards during the cooldown. Cooldown was carried out in finite steps by lowering

FIGURE 3.3: Design model for feedthrough board.

FIGURE 3.4: Schematic for Argon-1 Feedthrough Board

the boards with a lab stand through the boil-off gas until eventually submerging in the LN₂. The cooling curve for this test is shown in Figure 3.6. X-rays were taken by the fabrication shop of the board before and after submerging, and continuity tests were performed on every channel before and after as well. No channels presented any issues with broken solder-joints from the X-ray scans, and all channels maintained continuity before and after cryogenic cycling, visual inspection of the boards after cycling showed some small crazing was seen around the standoffs,

and slight discoloration of the board in general. The cryogenic cycling tests was repeated once more for the QSE board and again for the RF-style boards, no issues were observed.

3.1.3 Signal Tests

Bench top room temperature tests were carried out to inspect the signal quality for the prototype SiPM mating boards. This analysis was completed using a LeCroy Wavesurfer 1 GHz oscilloscope, as the full DAQ was not yet commissioned.

3 key parameters were evaluated; signal-to-noise ratio, SPAD decay constant, and charge linearity. The signal-to-noise ratio was evaluated qualitatively at this preliminary stage, but is defined roughly as the ratio of the single photo-electron (SPE) peak for the SiPM signal relative to the baseline electronic noise RMS.

An example scope trace for the 8:1 ASUM board is shown in Figure 3.7, and a similar trace for the 1:1 RF board is shown in Figure 3.8.

The results of the SiPM summing board tests are shown in Table 3.1, and plotted in Figure 3.10 and Figure 3.9. These tests were carried out using a H-13360 series SiPM from Hamamatsu with a custom adapter board that was used for testing. SiPM signals from the fully summed 64:1 SiPM were too saturated with an SPE height that was below the noise floor, resulting in an effectively DC signal, where single photons were not able to be resolved. Measured values here are from room temperature data, not included is the integral of each SiPM pulse for charge linearity, which approximately constant for each board. Dark noise rates for the single channel SiPMs were ~ 500 kHz at room temperature, given the expected 64x dark count rate on the fully summed SiPM, at ~ 3.2 MHz, with the expected increase

FIGURE 3.5: Cryogenic cycling set-up for Argon-1 SiPM mating boards

FIGURE 3.6: Cooling curve example for cryogenic cycling test for Argon-1 SiPM mating board.

FIGURE 3.7: Example scope trace for 8:1 ASUM SiPM Ganging board for Argon-1, with many SiPM pulses visible. SiPMs are dark and room temperature here.

in decay time constant out to several hundred ns, with an expected time between dark counts of ~ 30 ns, resolving individual photons with this device at room temperature is not feasible. The linearity in charge response and expected decrease in DCR at LAr temperatures motivated the choice of the fully summed ASUM SiPM, which was deployed in Argon-1 in addition to the QSE-style pixelated SiPM.

FIGURE 3.8: Example scope trace for 1:1 ASUM SiPM Ganging board for Argon-1, SiPMs are dark and room temperature here.

SiPM Type	Board	Number of Summed Channels	Avg. Decay Constant [ns]	Avg. Height [mV]	SPE
64:1		64	N/A		Below noise floor
8:1		8	104.1 ± 6.5	7.8 ± 0.7	
4:1		4	87.2 ± 10.9	11.5 ± 0.5	
1:1		1	46.4 ± 13.9	27.8 ± 0.5	
QSE		1	37.9 ± 2.0	29.5 ± 1.3	

TABLE 3.1: Results of SiPM Mating board tests with different summing configurations, uncertainties are given as standard deviations of sample measurements.

3.2 SiPM Characterization

The understanding of SiPM operation in a LAr environment is critical for next generation noble liquid experiments which will employ them as the principal light detection technology, replacing PMTs. In order to better understand these operational parameters and their impact on the detector response, a SiPM characterization study was carried out while the detector was filled with LAr using an external

FIGURE 3.9: Average SPAD decay time constant for a sample of pulses from tests of summing boards, uncertainties are given as standard deviations of the sample measurements.

FIGURE 3.10: Average SPE height for a sample of pulses from tests of summing boards, uncertainties are given as standard deviations of the sample measurements.

LED with 400 nm emission and 8 ns pulse-width. Understanding of the SiPM device performance is critical for accurate modelling of detector response, especially

considering the expected temperature dependent changes in SiPM operational parameters.

3.2.1 Operational Parameter Measurements

3.2.2 Breakdown Voltage

The breakdown voltage was measured using 2 methods while the SiPMs were deployed, using a gain estimation and by taking IV curves. The reverse bias measurement from gain estimation is described in [46], and is performed by measuring the integral of SPE pulses, as well as the SPE height, as an estimate of the gain, and extrapolating backwards to the x-intercept. This provides a slightly biased estimate of the breakdown voltage, since there will still be a small amount of gain while operating in the linear regime of the SPAD. The second method is the conventional method of taking reverse-IV curves for the SiPMs and estimating the turning-point voltage corresponding to when the device enters Geiger-mode.

After measuring the reverse-IV curve for each SiPM channel, the breakdown voltage can be fit out in several ways. The turning point voltage can be found by fitting out the intercept of two linear tangents for the natural logarithm of the reverse current vs reverse bias voltage and finding their intercept. Another method for fitting the turning point voltage is by finding the maximum of the derivative of the natural logarithm of the reverse current vs reverse bias voltage, which corresponds to the inflection point in reverse current vs reverse bias voltage [42]. All 3 methods are compared here.

3.2.3 Gain

The SiPM gain is measured by measuring the integrated charge for a single photon peak. This is expressed by Equation 3.1.

$$G = \frac{\text{Integrated charge}}{q_e} = \frac{\Delta V_{ov} \cdot (C_j + C_e)}{q_e} \quad (3.1)$$

Where, ' q_e ' is the elementary charge, ' C_j ' and ' C_e ' are the junction or intrinsic SPAD capacitance, and the equivalent circuit capacitance respectively. The circuit capacitance is a function of all the electrical components in contact with the SPAD, including parasitic effects from other SPADs, and is difficult to measure. Since we do not measure the integrated charge directly, but the integral of the ADC converted charge from the digitizer, there is an additional formulation that is used Equation 3.2.

$$G = \frac{\Delta_{PP} \cdot ADC_f}{q_e} \quad (3.2)$$

$$\begin{aligned} ADC_f &= \frac{V_{pp}}{R_{in}} \cdot \frac{1}{2^{Nbit}} \cdot \Delta t \cdot \frac{1}{G_{pre}} \\ &= \frac{2 \text{ V}}{50 \text{ } \Omega} \cdot \frac{1}{2^{12}} \cdot 16 \text{ ns} \cdot \frac{1}{1000} \\ &= 1.5625 \cdot 10^{-16} \text{ [C / ADC]} \end{aligned}$$

Where, ' Δ_{PP} ' is the separation between NPE in integrated ADC, and ' ADC_f ' is the ADC conversion factor, where ' V_{pp} ' is the peak-to-peak voltage of the digitizer, ' R_{in} ' is the input impedance, 'Nbit' is the number of bits available in the digitizer,

' Δt ' is the time separation between bins for the digitizer, or $1/\text{Frequency}$, and ' G_{pre} ' is the gain of the pre-amplifier unit [47]. The ADC conversion factor for Argon-1 is $1.5625 \cdot 10^{-16}$ [C/ADC] in units of Coulombs per ADC count.

Another important variable to consider is the dynamic range of the SiPM. The dynamic range can be expressed with Equation 3.3 from [46]. The expected dynamic range for the Hamamatsu SiPMs used in Argon-1 is shown in Figure 3.11 with the expected thresholds for digitizer clipping given the SPE amplitudes for the PiXL and ASUM SiPMs.

$$N_{Fired} = N_{pixls} \cdot (1 - e^{(-N_{Photons} \cdot PDE / N_{pixls})}) \quad (3.3)$$

FIGURE 3.11: Dynamic range of Hamamatsu SiPMs, showing the number of expected SPAD firing for $PDE \sim 50\%$. Overlaid are expected thresholds for digitizer clipping based on SPE heights for PiXL and ASUM SiPM channels and digitizer range.

3.2.4 Dark Noise & Stray Light Rate

Thermally generated avalanches, and other forms of "dark" counts, referred to as the dark noise, are due to sources of uncorrelated avalanches in SiPMs. The dark count rate, or DCR, can be measured by counting the rate of events above the 0.5 SPE threshold while the SiPMs are fully dark. However, while the detector is fully submerged in LAr and while filling with GAr, the presence of scintillation light limits the ability to perform a measurement of the dark count rate of the SiPMs at LAr temperatures. An analogous measurement of the so-called "stray light" and combined DCR rate can be performed by measuring the rate of uncorrelated photons using the pre-trigger window in the waveforms for a selection of physics data. The rate of photons in the pre-trigger window will have contributions from stray light, late TPB phosphorescence from previous events and dark counts from the SiPMs.

Before deployment inside Argon-1 the SiPM dark count rate at room temperature was measured inside a dark box with a NIM scaler. This was done by setting the threshold of the NIM scaler to be approximately $\sim 1/2$ of the SPE height at nominal gain and measuring the rate of events. This value was ~ 500 kHz for individual channels on the pixelated SiPM, at an V_{ov} of 3 V.

Another parameter of interest for SiPM operation is the signal-to-noise ratio (SNR), which we define as the mean SPE amplitude of the SiPM signals to the average baseline RMS value for waveforms from the full signal chain. Typically, SNR is defined using the ratio of signal power to noise power, however in single photon counting applications as in our case, this is not a particularly useful definition. Photon counting is done using a pulse-finding algorithm, and the fast electronic

baseline noise can produce false-triggers if the amplitude is sufficiently high and the SPE signal is low, because of this the useful measure of SNR for our application is the ratio of signal amplitude to baseline RMS.

$$SNR = \frac{\text{Mean SPE Amp.}}{\text{Baseline RMS}} \quad (3.4)$$

For the mean SPE amplitude of ~ 13 ADC units at nominal gain (34 V), and our average baseline RMS of ~ 0.75 ADC units, we have an estimate for the SNR for our setup of ~ 17 .

3.2.5 Correlated Noise

Understanding the correlated noise from the SiPMs is critical for understanding the detector performance. To measure correlated noise, we follow a modified version of the method outlined in [39]. Using the LED pulser, triggering on the LED external trigger, we produce low-intensity diffuse light with an average of ~ 5 pulses per event, and measure the height and integral of the mostly SPE pulses for all SiPM channels, by plotting the distribution of pulse height/charge vs the time between subsequent pulses or sub-peaks. The distribution in delta-t between sub-peaks and pulses can be used to separate the distinct populations of correlated noise. This is highlighted in Figure 3 in [41].

After-pulsing Probability and Timing Behaviour

The after-pulsing probability and timing signature is calculated by isolating the after-pulsing populations on a 2D distribution of sub-peak separation time versus

sub-peak height, and on the 2D distribution of pulse integral versus time between subsequent pulses. The motivation for the two separated components is to isolate the fast after-pulses which are separable within a given pulse using sub-peak timing, and the contribution from late AP which occurs after the end of the initial pulse. Doing this allows for the isolation of two main after-pulsing components, which exhibit different timing signatures. The timing signature of the after-pulses was calculated using an exponential fit to the delta-T timing distribution for events in the AP ROI.

$$P_{AP} = \frac{N_{ap}}{N_{Primary}} \quad (3.5)$$

Where ' N_{ap} ' is the number of pulses in the after-pulsing ROI, and ' $N_{primary}$ ' is the total number of primary pulses.

Optical Cross-talk Probability

The direct optical-cross talk probability is typically measured as the ratio of 0.5 PE events to 1.5 PE events when the SiPM is dark. With a detector full of scintillating material, the SiPMs are never truly dark, and so quantifying the OCT probability is more difficult. We estimate the diOCT probability in two ways, through the ratio of >1 PE primary pulses to 1 PE primary pulses as identified in PE vs delta-T space, and by estimating the ratio of >1 PE events to 1 PE events from after-pulses and delayed cross-talks. The motivation for this is because there will be a contamination of true >1 photon events in the primary pulse phase space, and since any avalanche has a probability of producing a diOCT avalanche, by isolating

>1 PE after-pulses from 1 PE after-pulses we get a second estimate of the diOCT probability.

$$P_{diOCT} = \frac{N_{diOCT}}{N_{1\ PE}} \quad (3.6)$$

Where ' N_{diOCT} ' is the number of pulses in the direct OCT ROI, and ' $N_{1\ PE}$ ' is the number of primary single PE pulses.

3.3 Detector Calibration

3.3.1 Energy Calibration

The energy response of Argon-1 was calibrated using external gamma sources of ^{137}Cs and ^{60}Co placed outside the outer vessel. By fitting the observed peaks in the PE distribution of Argon-1 data, we can calculate the light yield for a given energy scale as shown in Equation 3.7.

$$LY_{\gamma} = \frac{\mu_{\gamma}}{E_{\gamma}} [PE/keV] \quad (3.7)$$

Where ' μ_{γ} ' is the mean of a Gaussian distribution fit to the background subtracted full energy deposition peak of the gamma spectrum for a given calibration source, and ' E_{γ} ' is the energy of the external gamma line. We can also investigate the resolution of the detector, and we define this as shown in Equation 3.8, for a resolution measured for a specific gamma energy.

$$R_{\gamma} = \frac{FWHM_{\gamma}}{\mu_{\gamma}} [\%] \quad (3.8)$$

Where ' $FWHM_\gamma$ ', is the full-width-half-max of the Gaussian fit to the full energy gamma peak, defined as ' $\sqrt{2 \ln 2} \cdot \sigma_\gamma$ ', with the standard deviation of the fitted Gaussian ' σ_γ '.

In order to better estimate the light yield of the detector, we can fit out the light yield as the slope of a linear fit to the distribution of observed PE for the full energy peak, versus the gamma energy.

3.3.2 LAr Triplet Life-time monitoring

The purity of LAr is measured using the triplet life-time of the average pulse-shape of events from the detector. This is done using a simple one exponential fit, performed in a late window in the average pulse-shape waveform, $[6 \mu s, 10 \mu s]$ with fit function shown in Equation 3.9.

$$A(t) = N \cdot e^{-t/\tau_t} \quad (3.9)$$

Where, $A(t)$ is the amplitude of the average pulse-shape as a function of time, and ' N ' is a simple normalization parameter, and ' τ_t ' is the LAr triplet life-time. This fit is performed on the summed baseline corrected raw waveforms of the SiPM data for all Pixelated SiPM channels, the ASUM SiPM trace is not included due to enhanced distortion from parasitic effects, as well as increased distortion from the pre-amplifier that effect the pulse-shape.

3.4 Results

3.4.1 Operational Parameters

Breakdown Voltage

The breakdown voltage of the SiPMs in LAr conditions were found using the two methods outlined above. The first method uses a linear fit to the average SPE charge and amplitude of pulses from the pixelated SiPM. The data for SPE data was taken from a run of low-intensity LED light, triggering on the pulser.

FIGURE 3.12: Linear fit to SPE charge (Right axis and blue) versus reverse-bias voltage, and SPE amplitude (left axis and red) versus reverse-bias voltage, where each point is the average value of all PIXL SiPM channels for a given bias voltage.

Using the linear fit to the SPE amplitude as a gain estimator, we can determine the X-intercept corresponding to the linear fit displayed in Figure 3.12. The best fit value for the breakdown voltage for this method is 31.36 ± 1.0 V.

We repeat the above procedure for the SPE integrated charge for the gain estimator in Figure 3.12, and the resulting X-intercept give a value for the average breakdown voltage of 31.83 ± 1.0 V. The uncertainty on the x-intercept was found by varying the best fit value for slope and y-intercept of the least squares fit from excel by 3% each.

The second method for estimating the breakdown voltage comes from reverse-IV curves taken using the program 'iv_cmd.py' provided with the front-end pre-amplifier by TRIUMF. This python script measures the voltage and current using embedded sensors on the pre-amplifier board and scans over a range of reverse bias voltages. An example of a set of reverse-current versus reverse-bias voltage is shown in Figure 3.13.

To find the breakdown voltage for the SiPM channels connected to the board, we use two different techniques for determining the turning point voltage corresponding to the breakdown voltage. The first method is the 'Tangent' method, which defines the breakdown voltage as the intercept point between two lines fit to the rising edge and the pre-breakdown region, an example of one fit for this method is shown in Figure 3.14. The second method for fitting the turning point voltage uses the rate of change of $\ln(\text{Reverse Current})$, where the maximum of the derivative corresponds to the turning point voltage, identified as the breakdown voltage, example distributions are shown in Figure 3.15. The maximum of this distribution is then found by using a simple look-up for the maximum point, and also as the analytic maximum of a spline interpolation function fit around the maximum. The results of these 3 methods are compared in Figure 3.16.

FIGURE 3.13: Example of reverse-bias versus reverse-current distribution for all 16 channels connected to pre-amplifier board #7.

The results from reverse-IV data are significantly deviant from the values measured using the gain estimation method, and don't align with observations from operation of the SiPMs. This difference will be discussed in detail in section 3.5.

Another parameter of interest is the SPAD reset time when operating at LAr temperatures, which we fit with a single-exponential decay function to a profile histogram of SPE pulses. Fits to the average SPE pulse-shape at LAr temperatures, from the full-signal chain, gives a time constant for the SPAD resetting, of ~ 200 ns. Inspection of larger pulses from high-flux runs of using the LED, shows hints of a longer SPAD reset time component with $O(\mu s)$ reset time constant.

FIGURE 3.14: Example fit for breakdown voltage using tangent method, using the natural logarithm of the reverse-current, the intercept of the best fit linear function in the pre-breakdown and rising edge regions is taken as the breakdown voltage. This process is repeated for every channel for all boards.

Gain

The gain of the SiPMs was measured using the method described above and is shown in Figure 3.17 as a function of bias voltage.

Hamamatsu provides data on gain for the S-144160 series SiPMs used here, and is shown in Figure 3.18 from [48]. There is a slight decrease in gain, this is likely due to the pulse-finder integration clipping the end of pulses and slight parasitic effects of the pre-amplifier circuit which are fixed using the baseline restoration algorithm. Keeping in mind the breakdown voltage of ~ 31.5 V, results at nominal

FIGURE 3.15: Rate of change of $\ln(\text{Reverse Current})$ versus reverse-bias voltage for all channels on pre-amplifier board #7. The breakdown voltage is identified as the maximum of the distribution, corresponding to the turning point voltage in linear space.

operating voltage (2.5 V OV or 34 V bias voltage)

We also inspect the SPE distribution of the PIXL SiPM. Using an LED run (Run #234) the SPE distribution averaged over all channels is shown in Figure 3.19. The SPE distribution is fit with a sum of 6 Gaussian functions, and the intensities from the Gaussian fits are used to estimate the probability for NPE distribution. The NPE distribution is fit to a Poisson distribution, with moderate success, resulting in a very high Chi squared/NDF of ~ 21025 , this is due to limitations of the pulse-finder efficiency and deliberate removal of 0 PE pulses. These pulses are not counted in the pedestal and resulting in a lower than expected 0 PE peak in the

FIGURE 3.16: Breakdown voltage estimates for all channels on pre-amplifier board #7 for the 3 estimation methods described.

NPE distribution and Poisson fit.

Correlated Noise

The correlated noise analysis, for after-pulsing and optical cross-talk, was performed using a low-intensity LED trigger run at the nominal operating voltage of 2.5 V OV. The correlated noise probabilities are found by calculating the ratio of pulses using pulse and sub-pulse information that reconstruct in their respective region of interests. This distribution is shown in Figure 3.20, with the region of interest for direct cross talk, and normalization regions shown. Primary peaks

FIGURE 3.17: Gain of S-144160 SiPMs used in Argon-1, measured using low-intensity pulsed LED light while deployed in LAr at ~ 87 K.

< S14160 series >

FIGURE 3.18: Gain of S-144160 SiPMs from Hamamatsu [48] at room temperature, also shown is the PDE, and cross-talk probability of the SiPM.

FIGURE 3.19: Left: SPE Distribution for Argon-1 PIXL SiPM with fit to 6 Gaussians, SPE Separation is ~ 170 charge units. Right: Fit of NPE distribution to Poisson distribution ($N \cdot \frac{\lambda^k \cdot e^{-\lambda}}{k!}$), PE intensities are taken from Gaussian fits for each PE peak and normalized to integral of SPE distribution. Best fit for the Poisson distribution is $\lambda = 1.21$ ($\text{Chi}^2/\text{NDF} = 21025$). The fit discrepancies are expected to come from the finite efficiency of the pulse-finder and, most importantly, the deliberate removal of 0 PE pulses, causing large discrepancies at 0 PE. A Poisson distribution with $\lambda = 1$ is overlaid for reference.

(sub-peak zero) and pulses with only one sub-peak, reconstruct from ~ 4000 onward, while sub-peaks within a pulse appear from 0 ns out to ~ 1000 ns. The floor of pulses and sub-peaks at the bottom of the distribution are noise triggers and not from physical photons. Subsequent avalanches that occur within the same SiPM channel before the initial avalanche reaches baseline will be registered as sub-peaks, while avalanches that occur after an initial avalanche will be considered separate pulses, for more details of pulse-finding and the data-structure see

Appendix A. Zooming in on the fast correlated noise region, only visible when considering sub-peaks, in Figure 3.21. We can see clearly the distributions of after-pulses, characterized by an exponential distribution of arrival times, and with amplitude increasing with time. This is explained by the SPAD recharge time, the longer the delay between pulse and after-pulse, the more charge available for the after-pulse avalanche, eventually reaching ~ 1 PE.

FIGURE 3.20: Left: Distribution of sub-peak amplitude vs delay time between sub-peaks within a given pulse, Right: Distribution of pulse charge versus time between subsequent pulses in a waveform, Only pulses with an arrival time correlated with the LED are considered here. Highlighted are the regions of interest for cross-talk and after-pulsing probabilities, as well as normalization regions.

Inspecting the timing structure for the fast correlated after-pulses in the region outlined in Figure 3.21, and the late after-pulsing region in pulse time distribution, we can identify two different populations of after-pulses. Best fits to the pulse time

FIGURE 3.21: Distribution of sub-peak amplitude vs delay time between sub-peaks within a given pulse, zooming in on the fast correlated noise region, with regions of interest for fast after-pulsing, and delayed cross-talk highlighted.

distributions in this region are shown in Figure 3.22. The data in the fast after-pulse ROI is best described by a single decaying exponential, while the data in the late after-pulse ROI is best described by an exponential term + constant background term. The constant term will capture the rate of uncorrelated photons that arrive after a primary pulse in the same waveform, but are uncorrelated with the previous pulse. Since these after-pulses occur so late, the SPAD is fully recharged after the initial avalanche and these late after-pulses all reconstruct as SPE pulses.

FIGURE 3.22: Fit to pulse separation time distribution in the fast correlated after-pulse ROI (blue) and in the late after-pulse ROI (red) with fitting functions shown, results of fits with uncertainties shown are shown in Table 3.2

The fast after-pulsing probability was calculated by taking the integral of sub-peaks in the fast AP ROI shown in Figure 3.21, to the integral of sub-peaks in the primary avalanche region, from [4000,8000] ns and above the noise floor. Since

both SPE pulses and SPE+DiOCT pulses can trigger after-pulses, we integrate all primary pulses. Uncertainties were propagated using Poisson errors on the integrated counts in each region, and evaluated for the ratio. The results are shown in Table 3.2. The late after-pulsing probability was calculated by taking the ratio of the integral in the AP ROI shown in Figure 3.20, to the integral of all primary pulses (SPE+DiOCT), scaled by the contribution to the total signal in the AP window determined by the fitted parameters in Figure 3.22.

$$P_{lateAP} = \frac{\int_{800\text{ ns}}^{4000\text{ ns}} f_{ap}(\Delta t) d\Delta t}{\int_{800\text{ ns}}^{4000\text{ ns}} f_{ap+const}(\Delta t) d\Delta t} \cdot \frac{N_{diOCT}}{N_{SPE}} \quad (3.10)$$

Where, $f_{ap}(\Delta t)$ is the single-exponential function contribution to the total fit function, and $f_{ap+const}(\Delta t)$ is the total fit function with the constant contribution. The fractional contribution of the exponential term in the late after-pulsing window is ~ 0.622 .

In order to estimate the DiOCT probability with light leaking into the nominal region of interest, we can suppress the contribution of uncorrelated light in the >1.5 PE region by looking at the ratio of 1 PE to >1.5 PE events in the after-pulse ROI. By measuring the ratio of after-pulses to after-pulses + DiOCT we can get a better estimate of the DiOCT ratio inside a non-dark detector. The integration windows for this ratio is shown in Figure 3.23. The pulse-integral estimation for P_{DiOCT} is 16.81 ± 1.06 %. Using the ratio of after-pulses to after-pulses + DiOCT from sub-peak amplitudes, we can perform an analogous measurement of the direct optical cross-talk probability, this gives a value for P_{DiOCT} of 11.70 ± 0.57 %.

The delayed OCT pulse separation time is shown in Figure 3.24. The delayed arrival time was fit to a simple exponential function with a decay constant of

FIGURE 3.23: Left: Distribution of sub-pulse amplitudes for pulses in the fast correlated noise region of interest, with integration windows for DiOCT shown. Right: Distribution of pulse charges for pulses in the pulse AP ROI, with integration windows for DiOCT shown. DiOCT probability is estimated as the ratio of the integral in the >1.5 PE region to the 1 PE region.

$\tau = 38 \pm 1$ [ns]. The delayed OCT signal is due to the diffusion of charge carriers generated by avalanche photon emission, that then drift into the bulk of a neighbouring SPAD and generate a secondary avalanche. This process can happen very quickly, from ns- μ s, and the exponential decay describes the diffusion of the generated charge carrier. Due to the 16 ns binning of the waveform, and insensitivity to sub-peaks at times shorter than ~ 30 ns, the distribution of the delayed OCT

appears clipped, pulses with diffusion times shorter than ~ 30 ns will reconstruct as direct OCT.

FIGURE 3.24: Exponential decay fit to delayed OCT sub-peak separation time, sub-peaks with $\delta T < 40$ ns are not likely to be flagged due to the 16 ns binning, and efficiency for tagging increases with sub-peak δT .

3.4.2 Detector Calibration

Energy Calibration

The energy calibration of Argon-1 was performed using external gamma sources of ^{60}Co , and ^{137}Cs . We also look at the background source of radiation and extract information. ^{137}Cs has a single gamma line at 662 keV, while ^{60}Co has two gammas at $\sim 98\%$ branching each, at 1173 keV and 1334 keV respectively [35]. These sources were placed outside the detector, in the case of the ^{137}Cs source, it was low enough activity that it could be placed right outside the detector, while the ^{60}Co

TABLE 3.2: Summary of correlated noise parameters measured at 87K in a LAr environment with 2.5 V OV.

Property	Fast after-pulse	Late after-pulse	Direct OCT	Delayed OCT
Probability	$4.7 \pm 0.2\%$	$1.1 \pm 0.1\%$	$11.7 < P < 16.8 [\%]$	$2.2 \pm 0.2 \%$
Timing Signature	$\exp(-t/\tau_{apF})$	$\exp(-t/\tau_{apL})$	Immediate	$\exp(-t/\tau_{deCT})$
Decay Constant (τ)	$165 \pm 2 [\text{ns}]$	$922 \pm 63 [\text{ns}]$	N/A	$38 \pm 1 [\text{ns}]$

source had to be located ~ 1.5 m away to reduce the event rates to levels the DAQ could handle. The DAQ maxes out at ~ 700 Hz, and the background radiation contributes ~ 130 Hz of activity.

The source spectra for ^{137}Cs and ^{60}Co are overlaid with data and shown in Figure 3.25, data are normalized to the livetime of the runs. Background subtraction is done in two stages; in the first stage the expected background from data is subtracted from the live-time normalized distributions as shown in Figure 3.25, and in the second stage a TSpectrum background subtraction is performed to extract the peak information of the source peaks. The fully background subtracted distributions are shown in Figure 3.26 with Gaussian fits to find the mean PE, and width of each peak.

Using a preliminary LY scaling from the source data, the background data was also inspected. Two additional peaks were identified, corresponding to the ^{40}K electron capture gamma line at 1461 keV and the ^{208}Tl 2614 keV gamma line from the ^{232}U chain. This distribution is shown in Figure 3.27. The mean PE are read off of this distribution, and correspond to ~ 6800 PE and ~ 11600 PE for the ^{40}K and ^{208}Tl peaks respectively.

Using the mean PE from the 5 identified gamma lines, we perform a linear

FIGURE 3.25: PE distribution of source data from Argon-1, both ^{137}Cs data overlaid with a background run. Each distribution is normalized to the livetime of its respective run. Full energy gamma peaks are highlighted, the Compton edge of ^{137}Cs is clearly visible at ~ 2200 PE, corresponding to ~ 470 keV, which is where we expect it to reconstruct. The

fit of PE vs Gamma energy to estimate the light yield of the detector. The linear fit is forced through zero and the uncertainties on the mean PE are taken as the relative uncertainty of the Gaussian fit uncertainties for the Cobalt fits at $\sim 1\%$. The resolution of the gamma sources found from source data to be $\sim 5\%$. We define resolution as shown in Equation 3.8. We measure a light yield for Argon-1 of ~ 4.7 PE/keV, uncertainties are not fully evaluated, so this number is taken as approximate. The ^{40}K and ^{208}Tl higher energy peaks fall slightly below the linear trend, this is likely due to non-linearity in the charge response from clipping of the

FIGURE 3.26: Background subtracted distributions for ^{60}Co and ^{137}Cs data. Data are first background subtracted from livetime normalized distributions, shown in Figure 3.25, then using TSppectrum to background subtract the falling Compton edge to assist in fitting. Gaussian fits are performed to each peak to estimate the mean PE and width of the distributions.

digitizers, and slight saturation of the ASUM SiPM.

Triplet life-time

To determine the detector stability over the course of data taking, we monitor the triplet life-time for LAr scintillation. The triplet-lifetime is measured by performing a fit to the average pulse-shape of a subset of data for each run. The average pulse-shape is created by performing the baseline-correction to the raw waveforms, then summed and flipped in polarity. We then perform a fit to a window, in the late

FIGURE 3.27: Sum of several runs of background data with identified gamma peaks, above ~ 6000 PE the non-linearity of the SiPM response due to digitizer clipping and saturation becomes significant, increasing with energy, and ^{208}Tl peak appears at ~ 2400 keV instead of 2614 keV.

time, using a simple exponential fit. The time window is from $6\mu\text{s}$ to $10\mu\text{s}$, and the fitting function is shown in Equation 3.11.

$$f(t) = N \cdot e^{-t/\tau_t} \quad (3.11)$$

An example of the triplet-lifetime fit is shown in Figure 3.29. Systematic uncertainties on the SiPM response and baseline correction are not included here, but

FIGURE 3.28: Light yield fit for Argon-1 using external gamma sources and environmental peaks, fit to a linear function as shown in the legend, the fit only includes the external gamma source points, with environmental lines overlaid for reference. Uncertainties on the fit are taken as the relative uncertainties from the Gaussian fits to the mean PE of the external gamma source peaks, $\sim 1\%$. The fit line is extended to show the difference at high energy.

are expected to contribute significantly. Late after-pulsing is also expected to contribute in the intermediate (between prompt and late LAr) window, due to its long decay constant of ~ 920 ns, and a small feature is visible at ~ 5500 ns, approximately $1\ \mu\text{s}$ after the peak, which we attribute to this after-pulsing component. Due to this contribution, we select a fit window beyond this and extend until $10\ \mu\text{s}$ to capture as much of the triplet light as possible.

FIGURE 3.29: Example triplet-lifetime fit to a subset of data from background run 195, residuals shown are (Data-Model)/Model, residuals appear to be shifted down, indicating the presence of a constant shift, but appear featureless over the fit range.

There is significant correlation between the baseline correction tuning parameters and the fitted triplet time, given the large baseline distortion due to the pre-amplifier circuit (shown in Figure 2.12, and explained in detail in Appendix A), the absolute value of the triplet-lifetime is slightly higher than reported in literature for LAr, which varies significantly between 1300-1600 ns [2], a more robust consideration of late after-pulsing, baseline correction effects and systematic uncertainties would likely make us consistent. Since LAr light is typically wavelength shifted by TPB, there are significant correlations between the TPB late luminescence, PMT after-pulsing and the triplet life-time, the measured value will differ by experiment,

and also depends strongly on LAr purity level. We monitor the triplet life-time to ensure the system is leak-tight and no impurities have been introduced. These electronegative impurities, often N₂ and O₂, will absorb ionization electrons from the incident particle track, preventing recombination and decreasing the effective triplet contribution to the overall pulse-shape, this leads to a lower than expected triplet life-time. Fitted values of the triplet life-time for subsets of data from runs over a 1-month period are shown in Table 3.3, since we are monitoring for stability, we care mostly about the relative change in measured life-time and less about the absolute value which is heavily correlated with the measurement as mentioned. Given this, the triplet life-time was stable over the data taking period and no substantial quantities of impurities are suspected. Varying the start and end window of the fit by ± 500 ns varied the fitted lifetime by up to 50 ns, so we take this as the uncertainty on the best fit values, indicating that the fitted values are stable over the data taking period.

TABLE 3.3: Triplet life-time fits for a subset of data from Argon-1 runs across a ~ 1 -month operation period. Fits performed from $6\mu\text{s}$ to $10\mu\text{s}$.

Run Number	Run Type	Date	Fitted triplet life-time [ns]
195	Background	May 5th 2021	1667
199	¹³⁷ Cs	May 14th 2021	1679
207	Background	May 18th 2021	1671
250	Background	June 3rd 2021	1650
257	⁶⁰ Co	June 3rd 2021	1662
259	Background	June 4th 2021	1644

An example physics event from background run 207 is shown in Figure 3.30, which plots the summed baseline-restored raw waveforms for the pixelated SiPM

channels(Top blue) and ASUM SiPM for comparison, and the non-summed individual waveforms for the pixelated SiPM (bottom). Here we see the stark difference between ASUM SiPM response (top red) and the pixelated SiPM response (top blue), and we can more clearly distinguish the presence of the triplet light in the bottom panel where individual SiPM channels are overlaid.

FIGURE 3.30: Example of a full-event waveform from 'DrawEvent' in A1DS/Utils/. The top panel shows the summed baseline corrected waveforms for each SiPM, and the bottom panel shows the individual pixelated SiPM channels. In addition to baseline restoration, rudimentary zero-suppression is employed here to reduce noise, so the signal can be more clearly identified. This utility is used for individual event inspection, and is a useful tool for tuning new response parameters.

Additional Detector Response Parameters

Several other parameters of interest for detector operation are considered here. The first parameter of interest is the so-called "stray light rate", this rate is defined as the number of dark counts + stray photons + light from previous events that are detected in the pre-trigger window. Since the pre-trigger window is uncorrelated with the main events, we can measure the total pulses in this region and scale by the livetime for this region to find the rate of uncorrelated pulses. The window considered for this is from 0 ns, to 4000 ns. The stray light rate is expressed in Equation 3.12, and was estimated to be ~ 3 kHz/SiPM Channel, this was measured using pulses from the PiXL SiPM channels, as the ASUM SiPM has no SPE sensitivity, the expected rate for the ASUM SiPM is 64x the PiXL rate at ~ 192 kHz.

$$\text{Stray Light Rate} = \frac{\sum^{N_{events}} \int_0^{4\mu s} N_i dt}{N_{events} \cdot 4 \mu s} \quad (3.12)$$

Where, ' N_i ' is the number of 1-3 PE pulses found in the pre-trigger window.

Particle identification in LAr is done using PSD variable 'fprompt', which describes the fraction of total light that falls in a 'prompt' window around the trigger time. The prompt window used in Argon-1 is [-50ns,250ns] about the trigger time, this window is longer than typical, due to the slow charge response of the SiPMs at LAr temps. This window was chosen by optimizing for maximum prompt charge in the window, with the smallest amount of triplet light possible. First order PSD estimates were determined by convolving the slow SiPM response with the pulse-shapes of LAr for NR and ER events, and finding the crossing points of the CDF of the convolved PDF to maximize separation. The fprompt vs PE distribution for a

^{137}Cs source run is shown in Figure 3.31. The ER band appears at ~ 0.1 f_{prompt} , instead of ~ 0.3 as expected, due to the slow SiPM response. This version of ' f_{prompt} ' is estimated using the integral of the corrected waveforms in the prompt window relative to the signal window.

FIGURE 3.31: f_{prompt} vs PE distribution for ^{137}Cs source run 250, this estimator uses a full waveform integration to determine the PSD response.

We can do better than the waveform integral approach for PSD estimation. A second PSD estimator, ' $f_{\text{promptAmp}}$ ' is being developed that takes into account the sub-peak timing and height distribution when determining how to distribute the pulse-charge. This calculation is shown in Equation 3.13. This works by taking the given charge for an ' i -th' pulse, and distributing the integrated pulse charge across the sub-peaks that make up the pulse by their weighted contribution to the sum of all sub peak amplitudes, $A_{\text{total},i}$ for the i -th pulse, if the sub-peak time falls in the $f_{\text{promptAmp}}$ window, $[-50 \text{ ns}, 250 \text{ ns}]$ about the trigger time, $\sim 4550 \text{ ns}$, we

add it to the numerator. We repeat this for all pulses in all channels for each event. The denominator is simply the sum of all PE in all pulses in the event window, [-50 ns, 17040 ns]. The result of this estimator is shown in Figure 3.32, where we can see it much more faithfully reproduces the expected PSD distribution for ER events, at $\sim 0.25-0.3$, and we also see evidence for higher f_{prompt} events, with good separation. Both estimators use a longer window of 250 ns, to account for the timing delay and timing response of the SiPMs at cryogenic temperatures. Some features are apparent at lower $f_{promptAmp}$, including bands that are also present in the waveform integration estimator ' f_{prompt} ', but are not as well separated. This estimator is still in development and the origin of the band structure is not certain, but could originate from pile-up contributions, or from trigger timestamp delays leading to drift in the trigger time. For the runs shown here, the trigger timestamp was not saved with nano-second precision due to a bug in the MIDAS front-end code, so no ' t_0 ' calibration is possible, this will be corrected for the next physics run.

$$f_{promptAmp} = \frac{\sum_{j,i}^{N_p, N_{sp}} \int_{-50 \text{ ns}}^{250 \text{ ns}} qPE_i \times A_{SP,j} / A_{total,i}}{\int_{-50 \text{ ns}}^{12500 \text{ ns}} qPE_i} \quad (3.13)$$

Where, we sum the fractional qPE contribution of the j -th subpeak to the total amplitude sum of sub-peaks, for the i -th pulse, summed over all pulses in all channels for each event.

In the current detector configuration, there are 2 SiPM arrays on opposite faces of the vessel. Taking advantage of this symmetry, we can estimate a rough position along the X-axis of the detector by measuring the fraction of total light detected in either SiPM. This is highlighted in the variable ' $fracASUM$ ' which is defined in

FIGURE 3.32: $f_{promptAmp}$ vs PE distribution for a sample of data from background run 195, we can see a separation from higher $f_{promptAmp}$ events and the main band at ~ 0.25 $f_{promptAmp}$, corresponding to the ER-like background events in Argon-1.

Equation 3.14, where ' PE_{ASUM} ' is the total PE measured in the ASUM SiPM and ' PE_{P_i} ' is the PE measured in the 'i-th' PiXL SiPM channel, and summed. Events at the origin of the detector should reconstruct at ~ 1 $\frac{PE_{ASUM}}{PE_{P_i}}$, corresponding to equal light measured in both detectors, the distribution for a background and source run are shown in Figure 3.33. There is bias towards lower $\frac{PE_{ASUM}}{PE_{P_i}}$, this is potentially due to an underestimation of the gain for the ASUM SiPM. There is also an asymmetric tail towards higher $\frac{PE_{ASUM}}{PE_{P_i}}$, this is possibly due to the 3 SiPM channels on the PiXL SiPM that are not working as of writing, this decreases

the effective surface area of the PiXL SiPM by $\sim 5\%$.

$$fracASUM = \frac{PE_{ASUM}}{\sum_i^{64} PE_{P_i}} \quad (3.14)$$

A slight shift for events towards lower fracASUM is visible for source events; since the source is physically located in line with the SiPMs, but directly behind the PiXL SiPM it would be expected for more events to reconstruct with higher charge in the PiXL SiPM. The resolution here is not large, however, and the differences could also be due to other systematic effects not considered here.

FIGURE 3.33: FracASUM distribution for source run 250 and back-ground run 259.

3.5 Discussion

Considerable effort was taken to design and qualify a SiPM mounting board that was suitable for use inside a LAr environment. Two board designs, pixelated and fully analogue summed, were chosen for deployment during the most recent characterization run of Argon-1. Before deployment, the boards were characterized through a series of signal fidelity and cryogenic cycling tests, and no significant issues were observed. In addition to the candidate boards, several other designs were considered and tested. To interface between the ultra-pure LAr environment and the atmospheric environment outside the detector, a leak-tight and clean feedthrough is required. Additionally, since the SiPM signals are amplified and current-to-voltage conversion is carried out external to the detector, it's critical that the signal is not distorted or effected by the feedthrough or cabling between the sensor and the amplifier. To ensure signal fidelity and prevent reflections, 50 Ω impedance micro-coaxial cabling is used everywhere in the setup, both inside LAr and from feedthrough to pre-amplifiers, and along the feedthrough board itself, coaxial cable provides shielding from external RF interference along the signal route. During operation, the SiPM and boards performed as expected, as of writing 3 channels on the pixelated SiPM are malfunctioning, however the issue has been isolated to a poor connection between the feedthrough board and the EQRF cable assembly connector, and they have been operational intermittently. During regular operation, the ASUM SiPM signal has been observed to become fully saturated from events that produce much more light than typical events, potentially due to atmospheric muons, when this occurs the SiPM signal linearity is broken down and charge reconstruction is not reliable, additionally these events completely clip

the digitizers and the following 2-3 events have completely distorted baselines due to the previous high signal event, these events are flagged during processing and not included in analysis. Due to the very long SPAD reset time of the ASUM SiPM, PSD is not reliable, as individual photons are not resolvable. To circumvent this, PSD estimators are calculated with pixelated SiPM channels only.

3.5.1 SiPM Characterization and Operational Parameters

A full suite of SiPM characterization measurements were carried out as part of this work to gain a more detailed understanding of the detector response, and to build an understanding of SiPM behaviour in a LAr environment. The breakdown voltage was measured using 2 different techniques, gain estimation and by reverse IV. These two results are in tension with one another, and is currently under investigation. Two effects are believed to be at play here, a possible DC offset in the boards which will impact the measured voltage and current signal from the reverse IV curves, and the effect of low noise. For the first effect, since the pre-amplifier boards have a floating voltage supply and given an observed baseline shift on the output signals from the pre-amplifier boards, it seems likely that there is a net shift applied, which could bias the IV measurements forward. The second effect is due to the very low DCR at LAr temperatures, since the rate of dark photons, and stray light is very low for each channel, for a small sampling window over which the IV measurement is performed, it is possible we do not have enough signal to produce avalanches within the integration, which would bias the measurement to a higher field strength, where lower energy charge carriers would have sufficient acceleration to trigger an avalanche. Both effects are under investigation as of writing, and

the reverse IV curve will be measured independent of the DAQ signal chain using a separate voltage supply and pico-ammeter in the coming weeks. In the meantime we rely on the gain based estimation which gives a breakdown voltage estimate of 31.6 ± 1.4 V, averaging the two gain estimates. One additional consideration is from the manufacturers specs for the SiPMs. The room temperature breakdown voltage for the S1461 series SiPMs is given as ~ 38 V, with a temperature dependent coefficient of 34 mV/K, considering the ~ 210 K delta-T between operating temperatures, the expected breakdown voltage by extrapolation is ~ 31 V, which is reasonably close to our gain estimation. Considering the likely large uncertainty associated with the room temperature data extrapolation and the bias from the gain estimation due to non-zero gain in the linear regime of the SPAD, these values are fairly consistent, and inconsistent with the current status of the reverse-IV values.

Several other parameters for SiPM operation were measured as part of this work. The gain of the SiPMs were measured to be $O(10^5)$, with linear response as a function of bias voltage. The correlated noise characteristics of the SiPMs were measured in detail, including the direct and delayed optical cross-talk probabilities, fast and late after-pulsing probabilities and their timing distributions. These results are summarized in Table 3.2, the total contribution of all correlated noise considered here is $\sim 20\%$, with direct optical cross-talk being the dominant component at $\sim 11\text{-}16\%$. A follow-up study comparing the correlated noise characteristics at room and LAr temperatures with varied operating voltages is planned, but beyond the scope of this work. We identified two major after-pulsing contributions with different characteristic decay times, likely due to different classes of impurities in the silicon crystal lattice, one with a decay time constant which is less than

the SPAD reset time at LAr temperatures, and the second with a $O(\mu s)$ decay time, and lower probability. Understanding the correlated noise behaviour of SiPMs is critical for using the devices in high-precision measurement apparatus as well as ultrasensitive detectors such as next-generation DM detectors. Due to the very late phosphorescence of TPB and stray light in the detector, it is not possible to measure the true DCR in-situ, however the stray-light rate is an important characteristic for understanding the detector signals and was measured to be ~ 3 kHz/SiPM Channel on the pixelated SiPM, and assumed to be 64x this value for the ASUM SiPM, due to the increased photo-sensitive area.

3.5.2 Detector Calibration

Energy calibration for Argon-1 was performed using external ^{137}Cs and ^{60}Co gamma sources, as well as environmental radiation and using the dominant peaks from ^{40}K and ^{208}Tl . Using this data, the light-yield of the detector was found to be ~ 4.7 PE/keV, comparing this to other single-phase LAr detectors such as DEAP-3600, which reports a LY of ~ 6.1 PE/keV [3] for an after-pulsing corrected energy estimator. Preliminary simulations of a fully instrumented Argon-1 with $\sim 4\pi$ SiPM coverage indicates light-yields of ~ 7.5 PE/keV are achievable. If we consider that $\sim 20\%$ of all detected PE are correlated noise pulses, the detected photons/keV is closer to 3.8 PE/keV, however since we are not able to distinctly identify whether a given pulse is from a true incident photon or from cross-talk or late after-pulsing, we model the after-pulsing and cross-talk contributions in MC to gain better agreement. With faster electronics it may be possible to reliably flag fast after-pulsing, that is, after-pulses that occur on the tail of the primary pulse and have $< 1\text{PE}$ in

pulse-height. This is possible for waveforms with few total pulses, which was true for the low-intensity LED runs used to quantify the after-pulsing and OCT probabilities as described above, but for physics runs the total photon flux is too large to reliably flag after-pulses with the digitizers in use. The energy response is fairly linear up to the ^{40}K EC peak, however afterwards it begins to diverge slightly. This is attributed to digitizer clipping of the ASUM SiPM waveforms, which, due to their much larger photo-sensitive area, see much more light than the other channels but are restricted to the same dynamic range. Saturation effects are also possible for the SiPMs at very high photon fluxes as well. In preparation for the next detector run, the ASUM SiPM will have its dynamic range optimized for higher energy events by adding a baseline offset to the waveform to take advantage of the full dynamic range, and by reducing the gain for this channel, this is at the expense of single photon counting capabilities.

The PSD estimation using the ASUM SiPM waveforms is significantly degraded due to lack of single-photon resolution. An example of the ASUM SiPM waveform compared to the summed pixelated SiPM waveform is shown in Figure 3.30. Updated PSD estimators are in development that will only use the pixelated SiPM pulses, and an example of one 'fpromptAmp', is shown in Figure 3.32. These PSD estimators perform better than the currently implemented waveform integral version, 'fprompt', and are required for future studies that require pulse-shape discrimination. Due to the long SPAD reset time ($\tau_{SPAD} \gg \tau_s$), which is much longer than the argon singlet time, it is difficult to resolve subsequent individual photons on the falling edge of a large prompt-pulse, this is circumvented by using 3 separate estimators for PE, one based on pulse charge, one based on the sum of the

sub-peak amplitudes and the third which is a raw integral of the entire baseline restored waveform, details of these estimators are available in Appendix B. Future studies of alphas in LAr, and of a surface rejection technique as described in the following chapter chapter 4, will require a reliable PSD estimator. The fprompt of electronic recoils in Argon-1 reconstructs at ~ 0.1 , while the expectation is ~ 0.3 [4], the fpromptAmp PSD estimator reconstructs closer at ~ 0.25 . The triplet decay time of LAr was monitored for runs over the data-taking period and was stable within measurement uncertainties, indicating that the detector maintained its pure state over a period of 6 months from initial fill to data-taking with no complications. The triplet lifetime fit value of ~ 1650 ns is slightly higher than the expected value of LAr triplet time of 1400-1600 ns [2], however this simple fit does not consider the SiPM properties, the late after-pulsing contributions and only uses a simple event selection.

This work provides the foundation for future detailed science studies with Argon-1, and we demonstrated here the reliable operation of a single-phase LAr detector using SiPMs, with considerable light-yield given the $< 10\%$ photo-sensitive surface area coverage. Future sensitive detectors employing SiPMs will require detailed analysis of operational parameters to accurately model detector response and expected signals in order to reach the sensitivities needed for future rare-event search experiments. In the following section, exploratory MC-based studies are performed of the capabilities of Argon-1 to measure a novel background rejection technique for LAr detectors, and we compare the real detector and MC detector response.

Chapter 4

Surface Background Rejection Technique with Argon-1

4.1 Introduction

4.1.1 Motivation

One of the initial objectives for Argon-1 will be the testing of a novel background rejection technique using a layered active surface coating [49], [50]. Alpha decays from radiogenic isotopes embedded into detector surfaces will lose energy before entering into the active volume, if these alphas lose sufficient energy they can appear as a low energy, NR-like event that can mimic a WIMP signal. In addition to the radiogenic alphas, decays from long-lived radio-isotope ^{210}Pb that is embedded on detector surfaces from exposure to ^{222}Rn during detector construction will continuously produce ^{210}Po . ^{210}Po decays through alpha emission with an alpha energy of ~ 5.3 MeV [35], these alphas can be degraded and reconstruct at low energy (50-250 keV), in the WIMP-search region of interest, and the recoiling ^{206}Pb

nuclei may be ejected into the active detector region, producing a true low-energy nuclear recoil event. These backgrounds are categorized as "surface backgrounds" and are a major component in dark-matter search experiments, an example of this can be seen in Figure 1.20, where alphas with high f_{prompt} , are degraded in energy and show up as a tail reaching down into the WIMP DM search region of interest. The common technique for surface background rejection is through "fiducialization", where for a monolithic detector like DEAP-3600, event reconstruction is employed to identify the interaction site for each event, and events near detector surfaces are not considered in analysis. This effectively reduces the detector volume to a smaller "fiducial" volume, which will reduce backgrounds from surface components, at the expense of reducing exposure and potential search sensitivity. Event reconstruction is not perfect, and events that mis-reconstruct due to less than 100% photosensitive surface coverage can be a major background component for DM search experiments. An effective surface background rejection technique will loosen the requirements for fiducialization, increasing fiducial volumes, and decrease background contributions, thus increasing sensitivity of future detectors.

4.1.2 Layered surface technique

To combat surface backgrounds, a layered active surface can be employed as shown in Figure 4.1 reproduced from [49]. This technique works by introducing an active layer between the TPB WLS coating and the non-active detector medium, which for Argon-1 is acrylic or PMMA. By selecting an active layer with a decay-time constant much longer than the LAr singlet time, decays from the surface will be shifted away from the region of interest for a WIMP search. Three classes of decays

are depicted, constituting the main classes of backgrounds from the surface. These classes and their potential impact are outlined here:

1. ^{210}Po decays on or in the TPB wavelength shifting layer at the surface.
 - Without surface layer: Recoiling Pb206 nuclei scintillates in LAr producing a high prompt low-energy event that can fall into the WIMP ROI, alpha scintillates in TPB before being stopped in acrylic, TPB scintillation is slower than LAr, but not enough light is produced to shift away from ROI.
 - With surface layer: Recoiling Pb206 still enters LAr, but the alpha enters the scintillator layer, producing mostly late light and increasing the reconstructed energy of the event, moving it away from the ROI.
2. ^{210}Po decays inside the scintillator or at the TPB-Scintillator interface.
 - Without surface layer: TPB is directly deposited onto acrylic and alphas from the TPB-acrylic interface will be slowed in the TPB and produce events with admixtures of TPB and LAr light, typically outside the ROI.
 - With surface layer: Alphas can scintillate inside the slow layer, TPB and LAr, producing admixtures of prompt and late light, and having energies typically higher than the ROI, not a concern for WIMP-searches.
3. ^{210}Po decays inside the acrylic or at the acrylic-scintillator interface
 - Without surface layer: Alphas from several micrometers inside acrylic will be degraded sufficiently to reconstruct in the ROI, TPB scintillation

will shift some of these alphas outside the ROI, but not all, this is the most significant event topology.

- With surface layer: Alphas must scintillate inside the slow scintillator directly, if the layer is thicker than the range of O(MeV) alphas, all alphas will be stopped producing only late light from the scintillation in the introduced layer. All events from this topology are shifted effectively away from the ROI for a sufficiently slow scintillating layer.

FIGURE 4.1: Illustration of Argon-1 Surface with main regions labelled. Three main classes of surface alpha decays are depicted; 1) ^{210}Po decay inside the TPB WLS layer, or at TPB-scintillator interface, 2) ^{210}Po decay inside the scintillator layer, 3) ^{210}Po decay from within the acrylic vessel, or from the acrylic-scintillator interface.

4.2 Detector Configuration

To perform a measurement of the efficacy of the surface background rejection technique described here, we will install a TPB coated CaF_2 disk inside Argon-1 in

front of the high-channel density Pixelated SiPM. Before installation, the acrylic panel that the disk is mounted on will be doped with Radon, as described in the next subsection. A drawing showing the inner vessel with CaF_2 disk installed is shown in Figure 4.2. The CaF_2 disk is doped with Europium sourced from Saint Gobain Crystals [51], it has a decay constant at room temperature of ~ 940 ns, which is expected to increase at LAr temps, CaF_2 is a high light yield scintillator at $\sim 19 \text{ ph/keV}_\gamma$, about half the intensity of LAr. Alphas are expected to be quenched to $\sim 20\%$ of the gamma-equivalent yield. The scintillation emission peaks at ~ 435 nm, well-matched with TPB and the SiPM efficiency. By placing the CaF_2 disk in front of the PiXL SiPM we will be able to tag events by hit-pattern in order to validate the PSD efficiency. The tagging technique will be discussed in subsection 4.4.3.

Before installation the CaF_2 disk must be coated with TPB, to ensure that the underlying surface has no TPB we mount the CaF_2 Disk and coat both the CaF_2 and surrounding area, the result of a TPB deposition on the disk is shown in Figure 4.3. During the initial installation of the CaF_2 during our previous run tests, the CaF_2 disk fractured into 2 large pieces. The supporting pins shown in Figure 4.3 were installed too tightly, and the strain during the assembly caused the disk to fracture. The upcoming runs with the disk installed will have a different support structure to reduce strain and to secure the disk in its two pieces, the break of the disk was clean and should function as expected once installed.

FIGURE 4.2: Argon-1 inner vessel drawing in Surface background configuration. CaF_2 disk (Green) installed in-front of PiXL SiPM with a TPB coating on top. Full vessel drawing shown in Figure 2.1.

4.2.1 Radon Deposition Outline

To increase the statistics for the surface alpha measurement, the acrylic panel that the CaF_2 disk is mounted on will be doped with ^{222}Rn . The panel will be exposed to a high concentration radon atmosphere by placing it in an enclosed volume with a known radon emitter. During the course of characterization measurements of materials for the DEAP-3600 hardware upgrades, many materials were assayed in the

FIGURE 4.3: Photo of CaF_2 disk (right) mounted on the acrylic panel after a $\sim 1 \mu\text{m}$ TPB deposition.

COLD lab at Carleton. One sample of Buna-N had exceptionally high radon emanation rates, at $\sim 32\text{k}$ Radon atoms/ m^2/hour . We only want to dope the surface of the acrylic under the CaF_2 disk so, we will cover the remaining surfaces with Kapton tape during the initial deposition then sand the taped surfaces after deposition to remove any residue and most surface activity. Afterwards, the CaF_2 disk will be installed and the entire disk and panel assembly will be coated with $1 \mu\text{m}$ of TPB. We can approximate the amount of radon activity expected on the sample surface based on the exposure time and surface area. Using a 700 cm^2 sample of Buna-N, placed inside an 0.1 m^3 volume for 48 hours, we expect the activity to be $\sim 1 \text{ kBq}/\text{m}^3$ within the chamber. The sample will be placed within this high radon concentration environment for 24 hours. Assuming that 10% of the radon in the

chamber deposits on the surface of the sample, gives an expected ^{222}Rn surface activity for the sample of $\sim 10 \text{ Bq/cm}^2$. Assuming half of all the ^{222}Rn are ejected due to the high energy recoil of the $^{222}\text{Rn} \rightarrow \text{Pb218}$ transition, and also that all the radon decays quickly down to long-lived Pb210. The expected activity of ^{210}Po decays, which are supported by the Pb210 concentration, is then $\sim 2.5 \text{ mBq/cm}^2$. In order to get $O(10^3)$ decays with an assumed 50% tagging efficiency, we will need to run Argon-1 for ~ 12 hours (With 19 cm^2 of sensitive surface area).

4.3 Analysis Techniques

4.3.1 Pulse-shape discrimination against surface alphas

The relatively long time decay time constant of CaF_2 ($\sim 940 \text{ ns}$) will produce scintillation events very low in f_{prompt} . The higher fraction of total energy deposited in CaF_2 , the greater the shift in f_{prompt} . As mentioned previously, the active surface layer will effectively shift all events away from the WIMP ROI, this is done in 2-dimensions, increasing the reconstructed energy for some events, and decreasing the "promptness" of the events due to the contribution of late light from CaF_2 . The expected pulse-shapes for NR-like LAr and CaF_2 scintillation are overlaid in Figure 4.4 for reference, this highlights the unique differences between the pulse-shape of surface events, which must deposit a fraction of their energy in CaF_2 and true bulk argon NR events, which is the expected WIMP DM signal.

FIGURE 4.4: Scintillation Pulse-shape comparison for LAr NR's and CaF_2 .

4.3.2 Surface-alpha tagging with high-density SiPM channelling

We can independently flag surface-alphas using the hit-pattern of the light collected by the PiXL SiPM. Events originating from the surface, primarily surface alphas, will have a distinct hit pattern that can be identified in analysis that will serve as an independent test for the surface alpha discrimination using PSD. This difference is highlighted in Figure 4.5 where the hit pattern for a surface alpha event is compared to a bulk ^{40}Ar NR event in MC. Several preliminary figures of merit are considered here.

The first parameter created for identifying surface events is called 'fmaxPE', and is defined as the fraction of light in the brightest PiXL channel, and given in Equation 4.1. Where, PE_{max} is the PE detected in the brightest PiXL channel and

FIGURE 4.5: Comparison of hit pattern on PiXL SiPM for surface alpha event (left) and bulk LAr event (right), event MC truth position is shown as a gold star.

'N', is the number of hit SiPM channels in an event.

$$f_{maxPE} = \frac{PE_{max}}{\sum_i^N PE_i} \quad (4.1)$$

The second parameter created for identifying surface events is called 'numCluster' and is defined as the number of the 8 next-brightest channels that are within one channel in Z or Y of the brightest channel. This is illustrated in Figure 4.6. For events with large amounts of clustering, most of the brightest channels will be congregated together, where for diffuse events, they are randomly distributed, which is illustrated clearly in Figure 4.5. These two simple parameters, 'numCluster' and 'fmaxPE' are used to isolate a sample of surface alphas independent of the event energy or timing information.

High Density SiPM Hit Pattern

FIGURE 4.6: Surface event example with numCluster calculation highlighted, here numCluster is 8, since the 8 next-brightest channels fall in the box.

4.4 MC Simulations

To prepare for detector measurements of the surface alpha background rejection technique, and to better understand the detector response, MC simulations of the detector for calibration sources and expected surface alpha signals were produced.

4.4.1 MC Detector Calibration

To compare the detector response in MC to the measured detector response, we simulate external gammas at (177.0 mm, 0,0), located in line with the centre of the

inner vessel, but outside the outer can. This location is approximately the same as where the source was positioned during data runs. External gammas are simulated at 2 energies for comparison, 661 keV for ^{137}Cs comparison and 2614 keV for ^{208}Tl comparison. For ^{137}Cs , the detector and MC comparison is shown in Figure 4.7, with both spectra normalized to unit integral. We see good agreement between data and MC for the fitted location of the full energy peak for the ^{137}Cs 661 keV gamma line. The mean of a Gaussian fit to the full energy peak for the MC spectra is ~ 3136 PE, which is in good agreement with the measured value from ^{137}Cs calibration runs of ~ 3154 qPE. Comparing the full spectra in Figure 4.7, we can see that the low-energy behaviour deviates, likely due to DAQ and trigger threshold effects which are not included in the pure MC-truth, as well as differences in the detector model which are more apparent with low photon numbers. We can also see evidence for an energy dependent efficiency in the data spectrum, not present in the MC. As event energy increases, the rate of data events tends to decrease instead of remaining flat as shown in MC, this effect could be due to the event selection cuts, which includes a cut requiring on fracASUM, requiring that the events don't have too much charge ($>75\%$) in either SiPM.

In preparation of the deployment of an internal $^{83}\text{Kr}^m$ calibration source, we can also simulate $^{83}\text{Kr}^m$ internal gammas isotropically inside the inner vessel. The results of this simulation are shown in Figure 4.8, where the 3 distributions are visible, corresponding to the 2 $^{83}\text{Kr}^m$ gammas, at 9.4 and 32.1 keV, and the pileup of the two at 32.1+9.4 keV [35]. The decays were simulated using the $^{83}\text{Kr}^m$ generator developed for DEAP-3600, and part of the rat-deap software, which includes the relevant branching fractions and probabilities for each decay including the decay

Cs137 Spectra

FIGURE 4.7: MC and Data comparison for ^{137}Cs external gamma simulation (Black) and Background subtracted ^{137}Cs source data taken during run 250 (Red). Both spectra are normalized to unit integral for comparison. Overlaid on the MC is a Gaussian fit to the full energy peak, a slight energy-dependent effect is visible for data compared to MC and the detector efficiency is apparent at lower energy.

time for the metastable first excited state.

We can fit out the LY of the detector response in MC to compare to data, this is shown in Figure 4.9. The fitted MC LY is ~ 4.78 , which, compared to the data LY of ~ 4.71 , is in good agreement. LY fits for data are weighed down at high energies by saturation effects and clipping of the ASUM SiPM pulses, leading to charge loss.

For comparison to Figure 3.31, we can plot the MC Fprompt vs PE distribution for ^{137}Cs data, this is shown in Figure 4.10.

Kr83m Spectra

FIGURE 4.8: $^{83}\text{Kr}^m$ MC Spectra for decays produced isotropically within the detector bulk inside the inner vessel. Gaussian fit is performed to the dominant peak, but 3 distributions are clearly visible, corresponding to the 2 $^{83}\text{Kr}^m$ gammas, at 9.4 and 32.1 keV, and the pileup of the two at 32.1+9.4 keV. Fit uncertainties are not representative of the true fit uncertainties due to the large (~ 18) Chi2/NDF from the fit with only statistical uncertainties.

4.4.2 PSD

To estimate the surface background rejection efficiency, we simulate ^{210}Po at 3 locations on the detector surface:

- Acrylic-Scintillator Interface
- Within the Scintillator Bulk
- Scintillator-TPB Interface

For comparison to the expected WIMP signal for future DM detectors, we compare the PSD vs Energy distributions for surface alphas in this configuration to

LY Fit for Argon-1 MC

FIGURE 4.9: LY Fit for MC using internal and external gammas, points on the plot are for internal $^{83}\text{Kr}^m$ 32 keV line, external ^{137}Cs and Tl208 gamma lines at 663 and 2614 keV respectively.

^{40}Ar NRs simulated isotropically inside the vessel from 50-250 keV. We isolate these events with minimal cuts, only requiring that the events have more than 5 hit SiPM channels. The leakage fraction of the surface alpha background into the ^{40}Ar NR region of interest is defined in Equation 4.2. We define the ^{40}Ar NR region of interest using a graphical cut for events falling within a box in F_{prompt} vs PE space, this is done to maximize the acceptance of ^{40}Ar NRs. The graphical cut used is shown overlaid with ^{40}Ar NR's in Figure 4.11. The acceptance of ^{40}Ar NRs in this region is $99.86 \pm 0.19 \%$.

$$LF = \frac{N_{ROI}}{N_{events}} \quad (4.2)$$

The distributions for surface alphas from each of the 3 listed regions are shown in Figure 4.12, Figure 4.13, and Figure 4.14, with ^{40}Ar NR ROI highlighted in red.

External Cs137 MC Simulations

FIGURE 4.10: MC Fprompt vs PE distribution for ^{137}Cs external Gamma MC, we can see the mode of the fprompt distribution is at ~ 0.285 .

None of the event topologies produce any events in the ^{40}Ar NR ROI, so we set a limit on the leakage fraction using the Feldman-Cousins method, assuming zero background contributions into the ROI. This is done using the ROOT Cern TFeldman Cousins implementation [45]. The 90% U.L on zero events in the ROI is 2.44, which for the $\mathcal{O}(100\text{ K})$ events simulated here gives a 90% U.L on the LF for all 3 regions of $< 2 \times 10^{-5}$.

We can see the impact of this technique by looking at the expected surface activity of ^{210}Po decays from the DEAP-3600 experiment of 0.26 mBq/m^2 [3], by employing the technique described here with a scintillator such as CaF_2 we can calculate the expected leakage into the WIMP ROI, with no fiducial cuts. Given the detector surface area of $\sim 0.9\text{ m}^2$, and a 3 year live-time, the expected leakage for

PSD Comparison for Surface alphas and Bulk NR signals

FIGURE 4.11: Bulk ^{40}Ar NR MC within inner vessel, for 50-250 keV recoils. 99.9% Acceptance region of interest is drawn overlaid and serves as the ROI for leakage estimation. This acceptance region approximates the WIMP region of interest for a DM search, with no detector threshold effects, and a background free assumption.

surface alphas after employing this technique is < 0.5 events, with no other cuts applied. Utilizing this technique would significantly reduce the requirement for fiducialization from surface alphas, however a fiducial cut is still useful for neutron rejection.

We have shown that the energy scale in MC is a reasonable approximation of the energy scale in data through external gamma source calibration comparisons, however there is a persisting difference in the PSD estimator 'fprompt'. PSD is

PSD Comparison for Surface alphas and Bulk NR signals

FIGURE 4.12: Fprompt vs PE distribution for Acrylic-Scintillator interface ^{210}Po Decays, Pure CaF_2 scintillation reconstructs at ~ 0.15 Fprompt

critical for LAr applications, so to investigate the effect of a systematically different PSD in MC, which uses MC-truth information for determining f_{prompt} , and the data, which must reconstruct the detected photons and their hit times, we can smear the MC and see the effect on our measurement sensitivity. We smear the MC f_{prompt} by applying a Gaussian with a mean of 1.0, and a standard deviation equal to the relative difference between the modes of the MC f_{prompt} , and data $f_{\text{promptAmp}}$ distributions for Cs137 external gammas. The mode for MC is at ~ 0.285 , and in data, assuming the lower bands are due to trigger offset effects that will be corrected in hardware, is at ~ 0.25 . This is a relative offset of 14 %. We sample a random number from the Gaussian distribution described and apply it to

PSD Comparison for Surface alphas and Bulk NR signals

FIGURE 4.13: f_{prompt} vs PE distribution for Bulk Scintillator ^{210}Po Decays

the f_{prompt} for each event from ^{40}Ar NRs, and the surface event topology closest to the ROI, the TPB-Scintillator interface. The effect of this smearing is shown in Figure 4.15, for ^{40}Ar NRs.

Repeating this procedure for surface alphas from the TPB-scintillator interface, we can see the impact of this effect in Figure 4.16, where we compare the distributions of the smeared ^{40}Ar NRs and ^{210}Po from the TPB-Scintillator surface. This can be compared to Figure 4.14, without smearing. The fraction of ^{40}Ar NRs in the nominal ROI is 88.8%, with a large fraction reconstructing at high f_{prompt} . We use the nominal ROI to determine the leakage fraction, since including the high f_{prompt} window would include leakage from Cherenkov events.

PSD Comparison for Surface alphas and Bulk NR signals

FIGURE 4.14: f_{prompt} vs PE distribution for TPB-Scintillator interface ^{210}Po Decays, Pure LAr scintillation reconstructs at ~ 0.7 f_{prompt} , while TPB scintillation reconstructs at ~ 0.45 f_{prompt} . This distribution contains events with admixtures of TPB+Scintillator and TPB+LAr contributions.

Re-evaluating the leakage fraction for this scenario gives a leakage of surface events into the NR ROI of $< 1.3 \times 10^{-4}$, with 9 events falling into the nominal ROI at the edge. Restricting the acceptance slightly at high PE would bring the leakage back down to 0 events, at a minimal acceptance cost.

Ar40 NR Fprompt

FIGURE 4.15: ^{40}Ar NRs with (green) and without (blue) smearing applied.

Surface TPB Fprompt

FIGURE 4.16: ^{40}Ar NRs with smearing overlaid with the 99.9% acceptance ROI for non-smeared ^{40}Ar NRs, and the smeared surface ^{210}Po decays from the TPB-Scintillator interface.

4.4.3 Hit-pattern tagging

Taking advantage of the high-density SiPM channelling in front of the scintillator, we can attempt to identify surface alpha candidates independent of PSD and energy estimators by looking at the unique signal characteristics. We compare the distributions of 'fmaxPE' and 'numCluster' defined previously for a sample of surface ^{210}Po decays (Acrylic-Scint interface) and bulk ^{40}Ar NR signals, representative of diffuse inner detector events. The fmaxPE distributions are shown in Figure 4.17, with a potential selection cut identified at $\text{fmaxPE} = 0.04$. The acceptance of ^{40}Ar NRs passing this cut, with no other cuts applied is $\sim 61\%$, while the leakage of Surface events is $\sim 19\%$, for events falling below the cut threshold. The separation for 'numCluster' does better than the simple fmaxPE identifier, and is shown in Figure 4.18, where the proposed cut is at $\text{numCluster} = 3$. The acceptance of ^{40}Ar NR's below this cut threshold is $\sim 92\%$, while the leakage of surface alphas into the low numCluster region is $\sim 20\%$.

Additional surface event tagging parameters considered did not have as much power as the two presented here. By using a hit-pattern based analytic approach to flagging potential surface events, we will be able to identify a sample of potential surface event candidates from measurement data that is insensitive to the event energy or PSD estimators. This is useful for quantifying the technique's discrimination power, and for providing an additional handle on surface events using SiPM signals. In anticipation of the data from the surface alpha measurements, a utility tool was created as part of the Argon-1 DS called "DrawHitPattern" which maps the real SiPM channels to their respective binning on the actual device to allow for event-by-event inspection of potential surface candidates. This is incredibly useful

FIGURE 4.17: Distributions of $f_{\max PE}$ for surface and bulk LAr events, reasonable separation is obtained by placing a cut at 0.04, highlighted in red

for inspecting candidate events and comparing potential new discriminators. In addition to this, all parameters described here for MC have been implemented in the data analysis as well. An example of "DrawHitPattern" output for a random inner vessel event from a background run is shown in Figure 4.19 for reference.

4.5 Measurement Plans

Due to COVID-19 related delays, we were not able to perform the measurement of the surface background rejection technique, so we outline here the steps and plans for a future measurement.

The detector should be reconfigured to include the CaF_2 scintillator disk held

FIGURE 4.18: Distributions of numCluster for surface and bulk LAr events, good separation is obtained by placing a cut at 3, highlighted in red

in place in front of the PiXL SiPM. The side panel holding the CaF_2 disk will be re-coated with TPB, sanding off the TPB already present and while re-coating a blank will be put in place on the surface to ensure no TPB is deposited where the disk will be held, as the disk is already coated with TPB and will not be re-coated. Before TPB coating on the panel, the surface will be doped with ^{222}Rn as described in the previous sub-section, longer doping times could be used to increase the expected signal rate.

After reconfiguration and assembly is completed, the vessel will be mounted inside the cryostat and SiPMs connected. After mounting, the SiPMs should be powered on and signals inspected using dark noise as well as LED pulses to confirm all channels are properly connected and working. The detector should then be filled with pure LAr following the standard procedure.

FIGURE 4.19: Example of DrawHitPattern Output for a detector event from a background run, left shows the PiXL SiPM channels, with PE on the Z-axis, disabled channels are crossed out for reference. Right shows the ASUM SiPM signal with PE overlaid for comparison.

In order to measure the surface background while suppressing external gammas, the trigger settings will be set to trigger on events that produce light in more than one group of 8 on the PiXL SiPM, and the ASUM SiPM will not participate in the trigger. This will reduce the rate of low-energy diffuse backgrounds that are predominantly triggered on the ASUM SiPM due to its much larger photo-sensitive area. The detector should be re-calibrated with ^{137}Cs and $^{83}\text{Kr}^m$, gamma sources. Should the alpha source deployment system be installed, full energy alphas from Am-241 should be inserted into the vessel using the source deployment tube to measure the detector response to full energy alphas. In order to better measure the full energy alphas, a lower gain is recommended for the pre-amplifiers, since

V1740 digitizer clipping will become a serious issue.

Once sufficient quantities of data have been collected, data should be skimmed using surface event hit-pattern based cuts to identify potential surface candidates. These candidates should be inspected with 'DrawHitPattern' for comparison. Using the surface event selection, including reconstructed position estimation using fracASUM, the PSD and energy distributions of surface event candidates should be compared to simulations. It is expected that the scintillation decay time constant and light yield of CaF_2 will change at cryogenic temperatures [52], so the location of the surface event candidates could be significantly different from the simulation expectation. The expected leakage from surface events is not expected to increase due to this temperature dependent effect, as the time constant tends to increase with lower temperatures, and yields increase, both effects will improve discrimination power for surface alphas in this configuration.

Once the candidate event population has been identified in PSD and energy space, the MC should be updated to faithfully reproduce the data. Afterwards, the acceptance of the event selection for data should be estimated using MC, and used to determine the discrimination power of the technique described in this chapter, with uncertainties on detector response and MC accuracy considered.

In addition to the measures listed, the NR response of Argon-1 will need to be calibrated. This could be done with an americium-beryllium neutron source (AmBe) which is available in the department. Collimated neutrons from the AmBe source would be directed towards Argon-1 and correlated with a signal tag from the source to suppress non-neutron backgrounds from the source (gammas and

neutron-induced environmental radiation). Once the NR signal is calibrated, a detailed study of potential backgrounds in the signal region should be carried out. Potential backgrounds in the signal region include degraded surface alphas from panels without the CaF_2 disk, and surface-alphas from the side panel with the CaF_2 disk, but from the corners where the surface has no disk layer. These backgrounds will be heavily suppressed by hit pattern based tagging cuts. Another source of environmental low-energy NR signals include low energy neutron scattering from fissions in materials surrounding and making up the detector. This will be suppressed by the self-shielding of the LAr surrounding the inner vessel, as well as planned water shielding which will be implemented in the future. Muon spallation products and muon shower induced neutrons will also be a source of low-energy NR backgrounds, these will be suppressed by muon-veto panels which will be installed above the detector.

4.6 Discussion

Surface-alpha backgrounds are a significant source of background for WIMP search DM detectors. We described here a hardware oriented background rejection technique using a layered scintillating surface with a decay time constant much longer than the LAr singlet time. By introducing this active layer at the surface, radioactive and long-lived radio-isotopes found in higher quantity at detector surfaces can be effectively moved away from the region of interest for WIMP DM search experiments using LAr. The discrimination power of this technique depends on

the time-constant of the chosen active layer, and using a CaF_2 layer as a demonstrator with Argon-1, $\mathcal{O}(10^5)$ are expected, and corrections for PSD efficiency show similar rejection efficiencies can be obtained at a small signal acceptance cost. Using this technique, future large-scale detectors could significantly reduce the fiducialization requirements, increasing sensitivity and extending the physics reach of the experiment, for example the DEAP-3600 example could completely eliminate its currently limiting surface alpha backgrounds by employing a similar technique. In addition to its utility for large scale detectors, the technique offers significant advantages for small-scale detectors where fiducialization is not possible, an example being the COHERENT experiment using LAr [53]. COHERENT uses a single-phase LAr detector at the Oak Ridge National Laboratory Spallation Neutron Source, and recently reported the first measurement of coherent elastic neutrino-nucleus scattering (CEvNS) on a liquid Argon target [53]. This is a particularly important for measurement for future DM detectors which will reach the so-called 'neutrino-floor', the point where NRs due to CEvNS with solar and atmospheric neutrinos becomes a limiting background. Currently, COHERENT is limited by beam-related neutron backgrounds, however in the future if beam-related neutrons are reduced, the significant source of backgrounds in their signal region may be due to degraded alphas from the surface of the detector. This would be more critical for future CEvNS detectors located next to continuous neutrino sources such as reactors, where time-correlation for beam neutrino events can't be employed to reduce backgrounds. By employing a similar technique described here, these surface backgrounds can be effectively removed using standard PSD and energy selection cuts.

Using high-density SiPMs surrounding the surface of detectors offers an additional handle on surface alpha backgrounds. As shown in Figure 4.5, the expected hit-pattern for surface events and diffuse inner vessel events are substantially different. Utilizing these differences, several simple parameters were created to differentiate between bulk and surface events, and can reject $\sim 90\%$ of bulk events with $\sim 80\%$ "signal" acceptance. More sophisticated image reconstruction and machine learning techniques are well suited to this task and could be employed to increase the separation power of the technique.

In addition to Monte-Carlo driven studies of this technique, we have outlined plans and instructions for a future measurement of the technique using Argon-1 using a CaF_2 disk.

Chapter 5

Conclusions

5.1 Argon-1

Argon-1 is a modular R&D single-phase LAr detector which will be used for studies of novel background rejection techniques and technologies for future large-scale LAr DM detectors such as ARGO. The current configuration of the inner-vessel includes 2x1" Hamamatsu S14161 SiPM arrays, covering $< 10\%$ of the total inner vessel surface area. The detector is controlled with a NI Labview based slow-control program, which monitors and logs pressure and temperature data for the detector and process system. The detector data is readout with 2 V1740s using a MIDAS front-end which controls the SiPM power-supply and pre-amplifier boards, as well as the data-taking and internal trigger. Raw compressed MIDAS data containing V1740 waveforms is converted into a custom data-structure using the Argon-1 DS software infrastructure. Raw waveforms undergo baseline restoration to correct for amplifier circuit distortions, and pulse-finding is employed to identify individual SiPM pulses in the waveform and produce pulse and sub-pulse level information for each of the 65 channels. The software infrastructure developed as part of this

work is written in C++ with ROOT and MIDAS libraries, using a ROOT TTree as the core of the data structure. Branches for calibrated detector data and high-level event variables are included and can be easily expanded upon for future studies. The detector is now fully commissioned, and this work lays the groundwork for future science studies using Argon-1.

5.2 Characterization Study

To better understand the detector response and SiPM behaviour in LAr conditions, we have carried out a characterization study of the detector and SiPM response. A full suite of SiPM operational parameters were measured, including; break-down voltage, after-pulsing probabilities and timing response, optical cross-talk probabilities and response times, SPAD reset times, dark count rate, and signal-to-noise ratio. Understanding of the SiPM response is critical for accurate event reconstruction, and critical for future DM detectors, which will employ many metres squared of SiPM coverage. The energy response of Argon-1 was calibrated using external ^{137}Cs and ^{60}Co gamma sources, as well as environmental radiation with dominant lines from ^{40}K and ^{208}Tl . Using these sources, the light-yield of the detector was fit out by a linear function to the mean reconstructed energy of the gamma peaks, giving a light yield of $\sim 4.7 \text{ PE/keV}$. The energy resolution of the full energy gamma peaks was found to be approximately $\sim 5\%$. PSD estimation with the SiPM waveforms is a challenge due to the long SPAD reset times at LAr temperatures, however PSD estimators using waveform integration instead of pulse-level

reconstruction behave reasonably well, and improved versions are in being developed, including a version which utilizes both pulse-charge and sub-peak timing information, 'fpromptAmp' which is a significant improvement over the raw integration technique. These two differ by $\sim 14\%$ at the peak, with a longer prompt window used by 'fpromptAmp'.

Energy reconstruction deviates from a perfectly linear response after ~ 6000 PE due to clipping of the digitizer for the ASUM SiPM channel, and saturation effects of the SiPMs. In preparation for the next major run, the dynamic range will be optimized by introducing a baseline shift to the ASUM channel, and by optimizing the pre-amplifier gain for this channel to reduce clipping, without the expense of decreased PDE which would be introduced by naively changing the bias voltage to lower the gain.

5.3 Surface background rejection with Argon-1

We have discussed in detail a proposed novel surface background rejection technique for LAr detectors using an active surface layer with a decay time constant much longer than the LAr singlet time. This technique takes advantage of the fact that radiogenic alpha's from detector surfaces will deposit some or all of their energy in the slow scintillating layer, forcing these events away from the WIMP DM region of interest. A full-scale MC was developed using the GEANT4 based software package, RAT, which is used by DEAP-3600, SNO+ and several other experiments. MC and Data comparison for detector energy response shows good agreement, with an MC LY of ~ 4.8 PE/keV, compared to the ~ 4.7 PE/keV from

data. Exploratory studies of the proposed surface alpha background rejection technique were performed and shows significant promise for rejection of surface alphas through PSD with $O(10^5)$ discrimination power, and 99.9% NR acceptance, which is a significant increase over traditional fiducialization techniques. When we account for systematic differences in the PSD capabilities between MC and data, the discrimination power drops to $O(10^4)$, however a more restrictive signal region would result in $O(10^5)$ rejection. In addition to the PSD method outlined here and in [49] and [50], we also outline an independent method for quantifying the surface-alpha background using the hit-pattern of a pixelated SiPM array. By taking advantage of the differences between the diffuse hit pattern of inner-vessel events and the concentrated hit pattern of surface events, we can build analytical discriminators to separate the two populations of events. Two examples of separators are presented here, one 'fmaxPE' which measures the fraction of total light in the brightest pixelated channel, and 'numCluster' which is a count of the number of next-brightest channels surrounding the brightest channel. The latter discriminant allows for 90% NR signal acceptance, with 80% rejection of surface events, without taking into account any energy or timing characteristics. These techniques will be developed as part of the next major run which will test the surface background rejection technique outlined here, and we provide detailed plans outlining that future measurement.

5.4 Outlook

Dark matter remains one of the most compelling and sought after problems in modern particle physics, and the positive detection of particle dark matter has evaded experimental efforts for the past 20+ years. To reach the ultimate sensitivity in next generation liquid argon direct dark matter detectors, larger target masses, advanced technologies, more advanced background rejection and better understanding of noble liquid micro-physics is required. High mass WIMP DM searches remain highly motivated and the remaining free parameter space will be probed by the next generation of DM search experiments, ARGO and DARWIN (Figure 1.5). To aid in the development and understanding required for ARGO, and other large scale noble liquid detector programs, the Carleton Noble Liquid Detector (COLD) lab, located at Carleton University in Ottawa, Ontario, Canada, was constructed. The COLD lab is a class 10,000 clean room with plans for 4 KW of cooling available through a liquid nitrogen plant, to provide for fast R&D prototyping. Argon-1 is a modular small-scale R&D LAr cryostat with ~ 35 kg of LAr, it contains an inner-vessel that contains ~ 3 kg of LAr, outfitted with analogue SiPMs for scintillation light readout. In this work, we outlined the development and commissioning of the Argon-1 detector and performed detector calibration and studies of SiPM behaviour in an active LAr environment. A data acquisition system was designed and commissioned, capable of reading out the current iteration of 65 SiPM channels, and expandable up to 135 channels in the future. We outlined the plans for a powerful surface-alpha background rejection technique, which, if employed in future detectors with a suitable surface scintillating layer, could lead to $O(10^5)$ surface alpha rejection without the use of fiducialization, allowing an

experiment to regain significant sensitivity.

In addition to the studies described here, there are several other studies that are planned for Argon-1. The development of a slow wavelength shifting material using pyrene, a WLS material with a long fluorescence decay time, embedded within a polystyrene film is being characterized and deployed in DEAP-3600 as part of a suite of hardware upgrades targeting specific limiting backgrounds, a full suite of measurements has been carried out at several facilities across Canada and Europe, but the last piece of information required is the characterization of its performance inside a live LAr environment. By coating a version of Argon-1 with the candidate film, we will be able to provide valuable input for understanding background events from DEAP-3600 after the deployment of this film, including its alpha scintillation properties which are currently unknown. Low energy degraded alphas present in the bulk of the detector due to dust particulates can be a limiting background for a LAr based experiment such as DEAP-3600, and an advanced modelling scheme has been developed for DEAP-3600 to understand this background contribution, however there is little information available about low-energy alpha quenching available and significant uncertainty on the validity of the Birk's saturation model when applied to noble liquid scintillation. To better understand this background contribution, and the quenching of low-energy alphas in LAr, a deployable alpha-source will be installed onto Argon-1 in the coming months, this will allow for deployment of alpha sources with varying energies into Argon-1 while the detector is in operation. These are ^{241}Am sources that have been coated with varying thicknesses of silver to degrade the energy of the alphas before entering the LAr, and have had their energies quantified in an Ortec alpha

counter that is present inside the COLD lab. Sources of various energies will be deployed into Argon-1 and their scintillation and quenching properties will be studied in detail. Analogue SiPMs are the dominant solid-state photodetector available, however development of a true digital photodetector or "dSiPM" is under development in collaboration with our colleagues at U de. Sherbrooke [54], this digital SiPM technology will be a massive leap forward for photo-sensors employed by particle physics and other sensitive detectors such as PET scanners. We are in collaboration with U de. Sherbrooke and, as of writing, coordinating the deployment of prototype dSiPMs into Argon-1 for an in-situ test of the technology next to an analogue SiPM setup in a live LAr environment, a critical milestone for the technology. The prototypes to be deployed use a modified version of the QSE-style boards developed as part of this work, and will be able to interface through the custom feedthrough employed by Argon-1. In addition to these planned studies, there are a number of other potential studies possible with a fully-instrumented Argon-1. One interesting study would be the deployment of small concentrations of Xenon gas into the LAr, which has been shown to act as a fast, and efficient wavelength shifter of the LAr scintillation light [55]. Xenon fluoresces at ~ 175 nm and is more accessible to VUV sensitive SiPMs than the ~ 128 nm LAr scintillation light, if Xenon was deployed in Argon-1 to investigate its WLS characteristics, the TPB acrylic panels would need to be replaced with a support grid for the SiPMs instead, this could be 3D printed from PTFE, as done for LoLX [1]. Xenon WLS provides significant advantages over TPB for event reconstruction, as the loss of position information due to the isotropic TPB emission at detector surfaces is removed. The use of xenon as a WLSer for LAr comes at the cost of the powerful

PSD capabilities of LAr due to the observed decrease in triplet and singlet separation for Xe-doped LAr [55], however there are many applications where the PSD requirements are not so strict as in a single-phase LAr detector. Another potential study could be the cosmogenic activation of ^{40}Ar into ^{39}Ar . As ^{40}Ar is exposed to cosmic rays it becomes activated to beta-decaying isotope ^{39}Ar , and the use of atmospheric argon, with abundance of ~ 1 Bq/kg is the dominant background in current generation LAr DM search experiments [4]. One way to circumvent this is to extract argon from deep underground wells where the ^{39}Ar has decayed away significantly, with reductions of a factor of 1000 in activity, however the extraction and transportation on, surface leads to potential re-activation of the pure ^{40}Ar into ^{39}Ar . By filling Argon-1 with low-activity underground argon and monitoring the ^{39}Ar decay rate over a long period of time, we could study the cosmogenic activation of the argon and provide important insight for ARGO, where several hundred tons of underground argon are required. In the current experimental configuration this will be a challenge due to the large environmental background rate, however lead, copper and water shielding are being developed to surround Argon-1 to reduce this background contribution.

There are a myriad of interesting studies that can be carried out with a quick-turnaround modular detector like Argon-1, and future direct DM search experiments, such as ARGO, will benefit significantly from this.

Appendix A

SiPM Pulse-finding

This appendix describes heuristically and technically the pulse-finding algorithm for Argon-1 and the baseline restoration methodology. Full details can be found by reading the source code.

A.1 Baseline restoration Techniques

The baseline restoration technique used for Argon-1 is a modified version of the technique described in [56]. The principle behind the correction is based on understanding the RC differentiation circuit within the pre-amplifier board. An example RC circuit is shown in Figure A.1. When a long impulse is injected into the RC circuit, a fraction of the total charge is held in the circuit and released with an exponential time signature with a characteristic decay time proportional to the effective capacitance of the circuit, ' C_{eff} ', including the SiPMs. This is expressed as Equation A.1. This leads to a baseline distortion, as shown in Figure A.2 and Figure 2.12, and this effect becomes very significant for large SiPM signals. Without a

baseline restoration, photon counting is incredibly challenging, since the distortion is signal dependent.

$$\tau_{readout} = R_{load} \times C_{eff} \quad (\text{A.1})$$

To correct for the distortion, we de-convolve the distortion out of the signal by taking advantage of our a priori knowledge of the distortion. The first stage is to fit out the $\tau_{readout}$ for our full DAQ signal chain. This is done by fitting an exponential decay function to a sample of low PE signals from different channels. The example fit shown has a $\tau_{readout}$ of ~ 2800 ns, other fit values vary between 2500-3500 ns, with fits from the ASUM SiPM channel preferring lower times and fits to individual SiPM channels preferring longer times. The $\tau_{readout}$ is proportional to the amount of restoration required, and a value of **2750 ns** was chosen for the analysis in this work. This choice was motivated by the fits as shown, and also qualitative inspection of restored waveforms. This time constant is applied to all SiPM channels, however the ASUM SiPM tends to be slightly under-corrected and has a small overshoot remaining after correction, it is possible that the ASUM SiPM has additional parasitic effects due to the large number of SPADs connected in parallel, and evidence for this is seen in saturated pulses, previous analysis runs with differing readout correction factors led to significant gain asymmetries between the two SiPMs, however this could be corrected for by fine-tuning.

The restoration technique can be described heuristically as:

- Before beginning restoration, we perform a baseline shift to the entire waveform using the average of the first 20 bins in the waveform. If a pulse-candidate is found in this region, we skip ahead 20 bins and perform our

correction using the 20-40th bins in the waveform, this check is repeated until a stable region is found.

- Using the derivative of the raw WF find the t_0 of the first SiPM pulse around the trigger-time.
- Every bin after the t_0 of the waveform can be represented as a sum by $V_{raw}(n) = V_{input}(n) + V_{shift}(n)$, where 'n' is the n-th bin in the digitized waveform.
- In order to determine $V_{input}(n)$ at each point, we subtract off the expectation for $V_{shift}(n)$
- $V_{shift}(n)$ is defined recursively considering all impulses from 0 to n, and is proportional to $\exp(-\Delta t / \tau_{readout})$, where Δt is the bin width.
- Recursively determine $V_{shift}(n)$ and subtract off from $V_{raw}(n)$.
- After this process is complete, there will be a DC offset from the true baseline from t_0 to the end of the waveform. We estimate the DC offset for each pulse individually by averaging the last 5 bins of the waveform and applying a shift from t_0 to N.
- Once this procedure is complete the restored waveform as shown in Figure A.2 (blue) can be used to perform pulse-finding.

Full details of the technique can be found in [56] and by reading the source code in 'A1DS/ds/A1PulseUtil.cc/hh'. The implemented version differs from the version presented in [56], by considering only the region of the pulse after ' t_0 ' and applying only a constant DC shift rather than a linear shift, which was shown to work better.

FIGURE A.1: Example of RC Circuit Diagram with expected signal output due to a square wave impulse, reproduced from [56]

A.2 Pulse-finding Technique

After baseline restoration is complete, the corrected waveform is passed to the pulse-finder utility function. This takes in a corrected waveform, and returns a vector of A1Pulse objects with pulse and sub-pulse level information contained. The pulse-finder is described heuristically below. Pulse candidates are determined by the 1st order derivative of the waveform, searching for bins under threshold.

- Find the 1st derivative of the corrected waveform, this is done using the Richardson Derivator function within ROOT Cern's software libraries [45]. This returns the 1st derivative of the waveform at each bin as a TGraph, which we convert to a TH1.
- Find the RMS of the derivative baseline using the first 20 bins in the derivative waveform. The pulse-candidate threshold is a scalar multiple of the derivative baseline RMS. The threshold parameter σ was found by trial and

FIGURE A.2: Example fit to baseline distorted raw waveform, with corrected waveform overlaid, from 'DrawA1WF' in A1DS/Utils

error during tuning, a higher threshold removes more false noise triggers, but misses sub-peaks.

- When a bin under threshold is found, we look for the zero-crossing time of the derivative corresponding to the minimum of the waveform. This point is then passed to a false-minimum inspector, which does a scan of nearby bins in the corrected waveform to look for the true minimum. The bin before the first bin under threshold is taken as the pulse-start time.
- The true minimum is then saved as the primary peak time.

- Next, the pulse-end is found by looking for the bin where the waveform is within a scalar multiple of the corrected waveform baseline RMS, and which also has a region of stable baseline derivative. This is saved as the pulse end time and the difference between start and finish are the pulse width.
- Looping over bins within the pulse window, we look for sub-peak candidates which meet the pulse-finding threshold of 70% of the primary peak threshold. The motivation here is that after-pulses often do not have full-amplitudes and thus lower derivatives.
- If sub-peaks are found, the peak time is found using a true-minimum scan as before and recorded along with their estimated sub-peak height.
- The sub-peak height is the difference between the corrected waveform value in the peak bin and the last stable bin on the falling edge before the sub-peak is identified, defined in derivative space.
- All pulses have at least one sub-peak (the primary peak) and all sub-peak information is saved to vectors of peak times and peak heights recorded in the A1Pulse object for this pulse.
- The integral of the pulse is calculated between the start and end times of the pulse on the corrected waveform, and is used to determine the charge-based PE estimator
- The primary peak height is recorded separately as the pulse amplitude based PE estimator.

An illustration outlining the various components of a "pulse" is shown in Figure A.3, and an example of the pulse-finding is shown in Figure A.2 where the peak and sub-peak times, as well as the pulse start and end time are shown on the top figure. The bottom half of the figure shows the derivative of the corrected waveform, with full and 70% sub-peak threshold overlaid for reference. This is the output from the utility function "DrawA1WF" which is a program developed to inspect individual SiPM waveforms and the expected results of pulse-finding and baseline correction, this tool is invaluable for tuning of parameter settings. Various parameters are controlled and fine-tuned for pulse-finding, including the primary pulse threshold σ , the sub-peak reduction factor for the threshold, currently 70%, the number of bins used for baseline RMS calculations, the threshold for finding the end of the pulse, and the noise-discard thresholds. To suppress fast external RF electronic noise pulses, an example of which is shown in Figure A.4, pulses that integrate below a set value, and which have a pulse-width below 150 ns, are discarded and considered noise due to their nonphysical characteristics. SiPM SPE pulses at LAr temps have a pulse-width on average of ~ 500 ns. These parameters were tuned manually, and re-tuning is required for different operational configurations. For full details of the pulse-finder logic, the source code must be read.

Several examples of pulse-finding results are shown in Figure 2.12, Figure A.2 and Figure A.4, with SiPM pulses found clearly highlighted. We can also inspect the linearity of the amplitude and charge based PE estimators, 'aPE' and 'qPE' respectively. As shown in Figure A.6, the PE estimators are linear for low-intensity signals, however for higher intensity signals, the effect of the long SPAD reset time becomes apparent. Due to the $O(100 \text{ ns})$ decay time constant at LAr temps, for

FIGURE A.3: Illustration of pulse-finding features for SiPM pulses.

large pulses the SiPM does not reset for several μs , which leads to non-correlated pulses piling up on the falling edge of a previous pulse, which get flagged as sub-peaks, since we do not perfectly flag all sub-peaks, and finding sub-peak heights for high PE events is difficult, we end up with lower than expected PE estimates for the amplitude based method.

FIGURE A.4: Example of a SiPM waveform with high frequency RF noise bursts present, this noise appears intermittently and is present in-phase on all boards and channels simultaneously, insensitive of different boards and board power-supplies and V1740s, grounding and shielding were both ineffective at removing this noise. As illustrated in this example, the pulse-finder rejects the noise pulses, even though they appear under threshold.

FIGURE A.5: Comparison of amplitude(aPE) and charge based(qPE) event PE estimators. Response is linear to several thousand PE, however the amplitude based estimator produces significantly lower estimates.

FIGURE A.6: Comparison of amplitude(aPE) and charge based(qPE) PE estimators for SiPM level estimates. We can see clearly here that for low photon counts in a given SiPM waveform (<10), the charge and amplitude based methods track 1:1, but the amplitude based estimator falls behind as incident flux increases.

Appendix B

A1DS Overview

B.1 Data-structure

As part of this work, a full ROOT TTree based data-structure was written in C++/ROOT which contains all relevant information analysis of the SiPM data. This is outlined at a high-level in Figure 2.15, and here we go into detail. We outline below all variables in the Argon-1 data structure with brief descriptions, for full details see the Gitlab source code, or the doxygenated source code available on the Argon-1 DAQ PC. If you have any questions, email dgallacher@snolab.ca.

- **A1Event** - Highest level of the DS
 - ★ run - Run Number from MIDAS
 - ★ subRun - Subrun number from MIDAS
 - ★ seqNum - MIDAS Sequence number, not used
 - ★ trigID - MIDAS Trigger mask, see CAEN V1740 manual for details
 - ★ evID - MIDAS run event number, not sub-run dependent
 - ★ evTime - MIDAS subrun event time in seconds

- ★ gtID - MIDAS Global trigger ID
- ★ timeStamp - ROOT TTimestamp of event time
- ★ fRunStartTime - ROOT TTimestamp of run start time
- ★ midas2rootVersion - Which version of midas2root was used to process this run
- ★ NHit - Number of channels read out by MIDAS
- ★ <A1WF> - List of A1WF Objects, one for each SiPM Channel
 - ☐ type - What SiPM type is this, QSE or ASUM
 - ☐ sipmID - Global SiPM ID (Unique identifier)
 - ☐ <aV> - Vector of voltages/ADC values for the raw digitized waveform
 - ☐ <aT> - Vector of time values for the raw digitized waveform (Bin centres)
- ★ A1CAL - Calibrated SiPM information branch
 - ☐ NSiPMs - Number of SiPMs in this event with at least 1 pulse
 - ☐ qPE - Pulse-charge estimate of event energy, sum of all qPE on all hit SiPMs
 - ☐ aPE - Pulse-amplitude estimate of event energy, sum of all aPE on all hit SiPMs
 - ☐ adcl - Pulse-integral estimate of event energy, sum of integral of all corrected waveforms for all hit SiPMs
 - ☐ fprompt - Pulse-charge based PSD estimator, uses pulse-start time and qPE for each pulse to build

- fpromptAmp - Pulse-charge and sub-peak time PSD estimator, uses pulse-charge and sub-peak timing to build
- fpADC - Pulse-integral PSD estimator, uses integral of corrected waveforms in a prompt window and full integral.
- **<SiPMs>** - List of A1SiPM objects, containing SiPM level information
 - type - Type of SiPM, QSE or ASUM
 - sipmID - Global SiPM ID, unique to this SiPM
 - channelID - V1740 Channel this SiPM was read-out on
 - boardID - Which V1740 Board this SiPM was read-out on
 - NPulses - Number of pulses found in this SiPM for this event
 - totalQ - Total integrated charge in ADC*ns units for all pulses in this SiPM
 - promptQ - Total integrated charge in ADC*ns units for pulses in the prompt window in this SiPM
 - qPE - Total charge-based PE in this SiPM for this event, calibrated with SPE charge
 - qPE_prompt - Total charge based PE estimate for pulses in the prompt window in this SiPM
 - aPE - Total amplitude-based PE in this SiPM for this event, calibrated with SPE height
 - aPE_prompt - Total amplitude based PE estimate for pulses in the prompt window in this SiPM

- `adcI` - Integral of the corrected waveform of this SiPM for this event
- **<Pulses>** - List of `A1Pulse` objects for all pulses found in this SiPM, see following list.

★ **A1EV** - High level event summary variables

- ☐ `numEarlyPulses` - Number of pulses found in the pre-trigger window
- ☐ `subEventN` - Estimated number of physics events inside this triggered event
- ☐ `deltaT` - Time in ns from the last triggered event
- ☐ `centroidFitPos` - `TVector3` of the centroid fitted position for this event.
- ☐ `fmaxPE` - Fraction of total light in the brightest PIXL SiPM channel for this event
- ☐ `id_fmaxPE` - ID of the `fmaxPE` channel
- ☐ `numCluster` - Number of next-brightest channels in the box surrounding the brightest PIXL SiPM channel, see Figure 4.6
- ☐ `fracASUM` - Fraction of PE in the ASUM SiPM relative to the PE in the PIXL SiPM (Summed over all PIXL channels)
- ☐ `vCOM_PIXL` - Centre of charge position for the hit-pattern on the PIXL SiPM
- ☐ `skewness` - Skewness of the distribution of charge in channels on the PIXL SiPM

A1Pulse:

- totalQ - Total integrated charge in ADC*ns units for this pulse
- qPE - Charge-based PE for this pulse, totalQ/SPE_Charge
- aPE - Amplitude-based PE for this pulse, totalQ/SPE_height
- pulseStart - Time of the start of this pulse, bin-centre of preceding bin before triggered time
- pulseEnd - Time of the end of this pulse, bin-centre of the end of the pulse found in A1PulseUtil::FindPulses2()
- pulseWidth - Difference between pulseStart and pulseEnd
- peakTime - Time of the triggered peak for this pulse, as bin-centre.
- peakHeight - Height of the triggered peak for this pulse, in ADC units
- baselineMethod - Which method was used to correct this baseline, 0 == David's algorithm, 1 == TSpectrum Correction
- baselineV - ADC value of the baseline before the pulse, should be ~ 0
- baselineRMS - RMS in ADC of the baseline before the pulse
- nSubPeaks - Number of sub-peaks found in this pulse, default =1
- <subPeakTimes> - List of sub-peak times, as bin-centre at peak bin.
- <subPeakHeights> - List of sub-peak amplitudes, taken as the difference between the sub-peak time waveform value and the last stable bin before the triggered condition, see Appendix A.

Bibliography

- [1] A. de St Croix, “The light only liquid xenon experiment: Signal production, data acquisition and commissioning”, PhD thesis, University of British Columbia, 2020. DOI: <http://dx.doi.org/10.14288/1.0394278>. [Online]. Available: <https://open.library.ubc.ca/collections/ubctheses/24/items/1.0394278>.
- [2] P Adhikari, R Ajaj, G. R. Araujo, M Batygov, B Beltran, C. E. Bina, M. G. Boulay, B Broerman, J. F. Bueno, A Butcher, B Cai, M Cárdenas-Montes, S Cavioti, Y Chen, B. T. Cleveland, J. M. Corning, S. J. Daugherty, P. di Stefano, K Dering, L Doria, F. A. Duncan, M Dunford, A Erlandson, N Fatemighomi, G Fiorillo, A Flower, R. J. Ford, R Gagnon, D Gallacher, and et al., “The liquid-argon scintillation pulseshape in DEAP-3600”, *EPJ C*, vol. 80, no. 4, p. 506, Apr. 2020. DOI: 10.1140/epjc/s10052-020-7789-x. eprint: 2001.09855v2.
- [3] R Ajaj, P. A. Amaudruz, G. R. Araujo, M Baldwin, M Batygov, B Beltran, C. E. Bina, J Bonatt, M. G. Boulay, B Broerman, J. F. Bueno, P. M. Burghardt, A Butcher, B Cai, S Cavioti, M Chen, Y Chen, B. T. Cleveland, D Cranshaw, K Dering, J DiGiuseffo, L Doria, F. A. Duncan, M Dunford, A Erlandson, N

- Fatemighomi, G Fiorillo, S Florian, A Flower, R. J. Ford, R Gagnon, D Gallacher, and et al., "Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB", *PRD*, vol. 100, p. 022 004, 2019. DOI: 10.1103/PhysRevD.100.022004. eprint: 1902.04048.
- [4] T. D. Collaboration, P. Adhikari, R. Ajaj, M. Alpízar-Venegas, P. A. Amaudruz, D. J. Auty, M. Batygov, B. Beltran, H. Benmansour, C. E. Bina, J. Bonatt, W. Bonivento, M. G. Boulay, B. Broerman, J. F. Bueno, P. M. Burghardt, A. Butcher, M. Cadeddu, B. Cai, M. Cárdenas-Montes, S. Cavuoti, M. Chen, Y. Chen, B. T. Cleveland, J. M. Corning, D. Cranshaw, S. Daugherty, P. DelGobbo, K. Dering, J. DiGiuseffo, P. D. Stefano, L. Doria, F. A. Duncan, M. Dunford, E. Ellingwood, A. Erlandson, S. S. Farahani, N. Fatemighomi, G. Fiorillo, S. Florian, T. Flower, R. J. Ford, R. Gagnon, D. Gallacher, and et al., *Pulseshape discrimination against low-energy ar-39 beta decays in liquid argon with 4.5 tonne-years of deap-3600 data*, 2021. arXiv: 2103.12202 [physics.ins-det].
- [5] R. Ajaj, G. Araujo, M. Batygov, B. Beltran, C. Bina, M. Boulay, B. Broerman, J. Bueno, P. Burghardt, D. Gallacher, B. A., and et al., "Electromagnetic backgrounds and potassium-42 activity in the deap-3600 dark matter detector", *Physical Review D*, vol. 100, no. 7, 2019, ISSN: 2470-0029. DOI: 10.1103/physrevd.100.072009. [Online]. Available: <http://dx.doi.org/10.1103/PhysRevD.100.072009>.
- [6] P. Adhikari, R. Ajaj, D. Auty, C. Bina, W. Bonivento, M. Boulay, M. Cadeddu, B. Cai, M. Cárdenas-Montes, S. Cavuoti, D. Gallacher, and et al., "Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the deap-3600 detector", *Physical Review D*,

- vol. 102, no. 8, 2020, ISSN: 2470-0029. DOI: 10.1103/physrevd.102.082001. [Online]. Available: <http://dx.doi.org/10.1103/PhysRevD.102.082001>.
- [7] F. Zwicky, "Republication of: The redshift of extragalactic nebulae", *General Relativity and Gravitation*, vol. 41, no. 1, pp. 207–224, Jan. 2009. DOI: 10.1007/s10714-008-0707-4.
- [8] P. Collaboration, N Aghanim, Y Akrami, M. Ashdown, J Aumont, C Baccigalupi, M Ballardini, A. Banday, R. Barreiro, N Bartolo, *et al.*, "Planck 2018 results. vi. cosmological parameters", 2020.
- [9] J. F. Navarro, C. S. Frenk, and S. D. M. White, "The structure of cold dark matter halos", *The Astrophysical Journal*, vol. 462, p. 563, 1996, ISSN: 1538-4357. DOI: 10.1086/177173. [Online]. Available: <http://dx.doi.org/10.1086/177173>.
- [10] M. Kamionkowski, "Wimp and axion dark matter", 1997. DOI: arXiv:hep-ph/9710467.
- [11] C. Okoli, "Dark matter halo concentrations: A short review", Nov. 2017.
- [12] P. de Salas, K. Malhan, K. Freese, K. Hattori, and M. Valluri, "On the estimation of the local dark matter density using the rotation curve of the milky way", *Journal of Cosmology and Astroparticle Physics*, vol. 2019, no. 10, pp. 037–037, 2019. DOI: 10.1088/1475-7516/2019/10/037. [Online]. Available: <https://doi.org/10.1088/1475-7516/2019/10/037>.
- [13] D. Clowe, M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, and D. Zaritsky, "A direct empirical proof of the existence of dark matter",

- The Astrophysical Journal*, vol. 648, no. 2, pp. L109–L113, 2006. DOI: 10.1086/508162. [Online]. Available: <https://doi.org/10.1086/508162>.
- [14] G. Jungman, M. Kamionkowski, and K. Griest, “Supersymmetric dark matter”, *Physics Reports*, vol. 267, no. 5, pp. 195–373, 1996, ISSN: 0370-1573. DOI: [https://doi.org/10.1016/0370-1573\(95\)00058-5](https://doi.org/10.1016/0370-1573(95)00058-5). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/0370157395000585>.
- [15] J. Billard *et al.*, “Direct Detection of Dark Matter – APPEC Committee Report”, Apr. 2021. arXiv: 2104.07634 [hep-ex].
- [16] E. Aprile, J. Aalbers, F. Agostini, M. Alfonsi, L. Althueser, F. Amaro, M. Anthony, F. Arneodo, L. Baudis, B. Bauermeister, and et al., “Dark matter search results from a one ton-year exposure of xenon1t”, *Physical Review Letters*, vol. 121, no. 11, 2018, ISSN: 1079-7114. DOI: 10.1103/physrevlett.121.111302. [Online]. Available: <http://dx.doi.org/10.1103/PhysRevLett.121.111302>.
- [17] V. Gluscevic, Y. Ali-Haïmoud, K. Bechtol, K. K. Boddy, C. Boehm, J. Chluba, F.-Y. Cyr-Racine, C. Dvorkin, D. Grin, J. Lesgourgues, M. S. Madhavacheril, S. D. McDermott, J. B. Muñoz, E. O. Nadler, V. Poulin, S. Shandera, K. Schutz, T. R. Slatyer, and B. Wallisch, *Cosmological probes of dark matter interactions: The next decade*, 2019. arXiv: 1903.05140 [astro-ph.CO].
- [18] R. K. Leane, *Indirect detection of dark matter in the galaxy*, 2020. arXiv: 2006.00513 [hep-ph].
- [19] M. Aartsen, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, M. Ahrens, C. Alispach, K. Andeen, T. Anderson, I. Ansseau, and et al., “Characteristics

- of the diffuse astrophysical electron and tau neutrino flux with six years of icecube high energy cascade data", *Physical Review Letters*, vol. 125, no. 12, 2020, ISSN: 1079-7114. DOI: 10.1103/physrevlett.125.121104. [Online]. Available: <http://dx.doi.org/10.1103/PhysRevLett.125.121104>.
- [20] S. Giagu, "Wimp dark matter searches with the atlas detector at the lh", *Frontiers in Physics*, vol. 7, p. 75, 2019, ISSN: 2296-424X. DOI: 10.3389/fphy.2019.00075. [Online]. Available: <https://www.frontiersin.org/article/10.3389/fphy.2019.00075>.
- [21] P. A. Amaudruz, M Baldwin, Batygov, and et al., "Design and construction of the DEAP-3600 dark matter detector", *Astroparticle Physics*, vol. 108, pp. 1–23, 2019. DOI: 10.1016/j.astropartphys.2018.09.006. eprint: 1712.01982. [Online]. Available: <https://linkinghub.elsevier.com/retrieve/pii/S0927650518300914>.
- [22] P. Agnes, I. Albuquerque, T. Alexander, A. Alton, G. Araujo, M. Ave, H. Back, B. Baldin, G. Batignani, K. Biery, and et al., "Darkside-50 532-day dark matter search with low-radioactivity argon", *Physical Review D*, vol. 98, no. 10, 2018, ISSN: 2470-0029. DOI: 10.1103/physrevd.98.102006. [Online]. Available: <http://dx.doi.org/10.1103/PhysRevD.98.102006>.
- [23] X. Cui, A. Abdukerim, W. Chen, X. Chen, Y. Chen, B. Dong, D. Fang, C. Fu, K. Giboni, F. Giuliani, and et al., "Dark matter results from 54-ton-day exposure of pandax-ii experiment", *Physical Review Letters*, vol. 119, no. 18, 2017, ISSN: 1079-7114. DOI: 10.1103/physrevlett.119.181302. [Online]. Available: <http://dx.doi.org/10.1103/PhysRevLett.119.181302>.

- [24] Q. Arnaud, D. Asner, J.-P. Bard, A. Brossard, B. Cai, M. Chapellier, M. Clark, E. Corcoran, T. Dandl, A. Dastgheibi-Fard, and et al., “First results from the news-g direct dark matter search experiment at the lsm”, *Astroparticle Physics*, vol. 97, 54–62, 2018, ISSN: 0927-6505. DOI: 10.1016/j.astropartphys.2017.10.009. [Online]. Available: <http://dx.doi.org/10.1016/j.astropartphys.2017.10.009>.
- [25] R. Agnese, A. Anderson, M. Asai, D. Balakishiyeva, R. Basu Thakur, D. Bauer, J. Beaty, J. Billard, A. Borgland, M. Bowles, and et al., “Search for low-mass weakly interacting massive particles with supercdms”, *Physical Review Letters*, vol. 112, no. 24, 2014, ISSN: 1079-7114. DOI: 10.1103/physrevlett.112.241302. [Online]. Available: <http://dx.doi.org/10.1103/PhysRevLett.112.241302>.
- [26] C. E. Aalseth, F. Acerbi, P. Agnes, I. F. M. Albuquerque, T. Alexander, A. Alici, A. K. Alton, P. Antonioli, S. Arcelli, R. Ardito, and et al., “Darksided-20k: A 20 tonne two-phase lar tpc for direct dark matter detection at lngs”, *The European Physical Journal Plus*, vol. 133, no. 3, 2018, ISSN: 2190-5444. DOI: 10.1140/epjp/i2018-11973-4. [Online]. Available: <http://dx.doi.org/10.1140/epjp/i2018-11973-4>.
- [27] J. Aalbers, F. Agostini, M. Alfonsi, F. Amaro, C. AMSler, E. Aprile, L. Arazi, F. Arneodo, P. Barrow, L. Baudis, and et al., “Darwin: Towards the ultimate dark matter detector”, *Journal of Cosmology and Astroparticle Physics*, vol. 2016, no. 11, 017–017, 2016, ISSN: 1475-7516. DOI: 10.1088/1475-7516/2016/11/017. [Online]. Available: <http://dx.doi.org/10.1088/1475-7516/2016/11/017>.

-
- [28] *Future dark matter searches with low-radioactivity argon*, <https://indico.cern.ch/event/765096/contributions/3295671/>, Accessed: 2021-07-06.
- [29] J. Billard, E. Figueroa-Feliciano, and L. Strigari, "Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments", *Physical Review D*, vol. 89, no. 2, 2014, ISSN: 1550-2368. DOI: 10.1103/PhysRevD.89.023524. [Online]. Available: <http://dx.doi.org/10.1103/PhysRevD.89.023524>.
- [30] T. Heindl, T. Dandl, M. Hofmann, R. Krücken, L. Oberauer, W. Potzel, J. Wieser, and A. Ulrich, "The scintillation of liquid argon", *EPL (Europhysics Letters)*, vol. 91, no. 6, p. 62002, 2010, ISSN: 1286-4854. DOI: 10.1209/0295-5075/91/62002. [Online]. Available: <http://dx.doi.org/10.1209/0295-5075/91/62002>.
- [31] J. Lindhard and M. Scharff, "Energy dissipation by ions in the kev region", *Phys. Rev.*, vol. 124, pp. 128–130, 1 1961. DOI: 10.1103/PhysRev.124.128. [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRev.124.128>.
- [32] D.-M. Mei, Z.-B. Yin, L. Stonehill, and A. Hime, "A model of nuclear recoil scintillation efficiency in noble liquids", *Astroparticle Physics*, vol. 30, no. 1, 12–17, 2008, ISSN: 0927-6505. DOI: 10.1016/j.astropartphys.2008.06.001. [Online]. Available: <http://dx.doi.org/10.1016/j.astropartphys.2008.06.001>.

- [33] J. B. Birks, "Scintillations from organic crystals: Specific fluorescence and relative response to different radiations", *Proceedings of the Physical Society. Section A*, vol. 64, no. 10, pp. 874–877, 1951. DOI: 10.1088/0370-1298/64/10/303. [Online]. Available: <https://doi.org/10.1088/0370-1298/64/10/303>.
- [34] "Characteristics of fluorescence emission", in *Molecular Fluorescence*. John Wiley & Sons, Ltd, 2012, ch. 3, pp. 53–74, ISBN: 9783527650002. DOI: <https://doi.org/10.1002/9783527650002.ch3>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/9783527650002.ch3>. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527650002.ch3>.
- [35] D. Brown, M. Chadwick, R. Capote, and et al., "Endf/b-viii.0: The 8th major release of the nuclear reaction data library with cielo-project cross sections, new standards and thermal scattering data", *Nuclear Data Sheets*, vol. 148, pp. 1–142, 2018, Special Issue on Nuclear Reaction Data, ISSN: 0090-3752. DOI: <https://doi.org/10.1016/j.nds.2018.02.001>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0090375218300206>.
- [36] J. J. Gómez-Cadenas, J. Martin-Albo, M. Mezzetto, and M. S. F. Monrabal, "The search for neutrinoless double beta decay", *La Rivista del Nuovo Cimento*, vol. 2, 2012. DOI: 10.1393/ncr/i2012-10074-9. [Online]. Available: <https://www.sif.it/riviste/sif/ncr/econtents/2012/035/02/article/0>.
- [37] *SAES Getter Manual*. [Online]. Available: <https://www.entegris.com/shop/en/USD/products/gas-filtration-and-purification/gas-purifiers/GateKeeper-HGU-Heated-Getter-Gas-Purifiers/p/GateKeeperHGUHeatedGetterGasPurifiers>

-
- [38] *Midas*, https://midas.triumf.ca/MidasWiki/index.php/Main_Page, Accessed: 2021-07-06.
- [39] CAEN, *AN2086 - Synchronization of CAEN Digitizers in Multiple Board Acquisition Systems*. [Online]. Available: {<https://www.caen.it/?downloadfile=4235>}.
- [40] P. K. L. et al., “Characterisation of a silicon photomultiplier device for applications in liquid argon based neutrino physics and dark matter searches”, *JINST*, 208. DOI: <https://arxiv.org/abs/0807.3220>.
- [41] F. Acerbi, S. Davini, A. Ferri, C. Galbiati, G. Giovanetti, A. Gola, G. Korga, A. Mandarano, M. Marcante, G. Paternoster, C. Piemonte, A. Razeto, V. Regazzoni, D. Sablone, C. Savarese, G. Zappalá, and N. Zorzi, “Cryogenic characterization of fbk hd near-uv sensitive sipms”, *IEEE Transactions on Electron Devices*, vol. 64, no. 2, pp. 521–526, 2017. DOI: 10.1109/TED.2016.2641586.
- [42] S. Gundacker and A. Heering, “The silicon photomultiplier: Fundamentals and applications of a modern solid-state photon detector”, *Physics in Medicine & Biology*, vol. 65, no. 17, 17TR01, 2020. DOI: 10.1088/1361-6560/ab7b2d. [Online]. Available: <https://doi.org/10.1088/1361-6560/ab7b2d>.
- [43] J. Qiang, *Monte carlo simulation techniques*, 2020. arXiv: 2006.10506 [physics.comp-ph].
- [44] S. Agostinelli, J. Allison, K. Amako, and et al., “Geant4—a simulation toolkit”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250–303, 2003, ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(03\)](https://doi.org/10.1016/S0168-9002(03))

- 01368-8. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- [45] R. Brun and F. Rademakers, "Root — an object oriented data analysis framework", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 389, no. 1, pp. 81–86, 1997, New Computing Techniques in Physics Research V, ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(97\)00048-X](https://doi.org/10.1016/S0168-9002(97)00048-X). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S016890029700048X>.
- [46] F. Acerbi and S. Gundacker, "Understanding and simulating sipms", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 926, pp. 16–35, 2019, Silicon Photomultipliers: Technology, Characterisation and Applications, ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2018.11.118>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168900218317704>.
- [47] V. et al., "Caen application note an2502", 2011. [Online]. Available: http://www1.caen.it/xtra/newsletter/2011_04_04/AN2502_SiPM_Characterization.pdf.
- [48] Hamamatsu, *Hamamatsu Datasheet - S14160/S14161 series*. [Online]. Available: https://www.hamamatsu.com/resources/pdf/ssd/s14160_s14161_series_kapd1064e.pdf.

-
- [49] M. G. Boulay and M Kuźniak, “Technique for surface background rejection in liquid argon dark matter detectors using layered wavelength-shifting and scintillating thin films”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 968, p. 163 631, 2020.
- [50] D. Gallacher and M. Boulay, “Surface background rejection technique for liquid argon dark matter detectors using a thin scintillating layer”, *Journal of Instrumentation*, vol. 15, no. 03, pp. C03016–C03016, 2020.
- [51] *Calcium fluoride data-sheet*, https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/calcium-fluoride-data-sheet_69768.pdf, Accessed: 2021-06-29.
- [52] V. B. Mikhailik and H. Kraus, “Performance of scintillation materials at cryogenic temperatures”, *physica status solidi (b)*, vol. 247, no. 7, pp. 1583–1599, 2010. DOI: <https://doi.org/10.1002/pssb.200945500>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/pssb.200945500>. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/pssb.200945500>.
- [53] D. Akimov, J. B. Albert, P. An, and et al., “First measurement of coherent elastic neutrino-nucleus scattering on argon”, *Phys. Rev. Lett.*, vol. 126, p. 012 002, 1 2021. DOI: [10.1103/PhysRevLett.126.012002](https://doi.org/10.1103/PhysRevLett.126.012002). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.126.012002>.
- [54] J.-F. Pratte, F. Nolet, S. Parent, F. Vachon, N. Roy, T. Rossignol, K. Deslandes, H. Dautet, R. Fontaine, and S. A. Charlebois, “3d photon-to-digital converter

- for radiation instrumentation: Motivation and future works”, *Sensors*, vol. 21, no. 2, 2021, ISSN: 1424-8220. DOI: 10.3390/s21020598. [Online]. Available: <https://www.mdpi.com/1424-8220/21/2/598>.
- [55] D. Akimov, V. Belov, A. Konovalov, A. Kumpan, O. Razuvaeva, D. Rudik, and G. Simakov, “Fast component re-emission in xe-doped liquid argon”, *Journal of Instrumentation*, vol. 14, no. 09, P09022–P09022, 2019. DOI: 10.1088/1748-0221/14/09/p09022. [Online]. Available: <https://doi.org/10.1088/1748-0221/14/09/p09022>.
- [56] A. Nagai, “Investigation of SiPM physics parameters down to cryogenic temperatures and for a bio-medical application”, Theses, Université Paris Saclay (COMUE), Sep. 2016. [Online]. Available: <https://tel.archives-ouvertes.fr/tel-02345743>.