Radon Background Reduction in DEAP-1 and DEAP-3600

BY

EOIN O'DWYER

A thesis submitted to the Department of Physics, Engineering Physics and Astronomy in conformity with the requirements for the degree of Master of Science

> Queens University Kingston, Ontario, Canada January 10, 2011

Copyright © Eoin O'Dwyer, 2010

Abstract

The **D**ark Matter Experiment with Liquid Argon Using Pulse Shape Discrimination (DEAP) is a dark matter experiment based in the SNOLAB facility in Sudbury, Ontario. Its aim is to detect WIMPs, Weakly Interacting Massive Particles, that may make up the missing component of the matter in our universe by the scintillation of liquid argon from nuclear recoils. A 7 kg prototype, DEAP-1, is currently in operation with work underway to scale up to a 1 tonne detector, DEAP-3600, by 2012.

Of particular concern to the DEAP experiment is ²²²Rn and its daughter products, as the alpha decays of these isotopes may create events in the detector that mimic a WIMP signature. For DEAP-3600 to be a competitive dark matter search, a limit of 0.2 fiducial surface alpha events is required in the energy region of interest for three years of run time, or 150 total surface events. The first half of this thesis concerns the testing and successful use of an activated carbon trap to eliminate ²²²Rn from the argon gas source in DEAP-1. The Carbo-Act F2/F3 grain activated carbon brand was also tested as a potential ultra-low activity candidate for a DEAP-3600 filtration system and was found to have an upper limit for its ²²²Rn emanation rate of 284 atoms/day/kg. A temperature swing system is proposed. If operated at 110 K, an upper limit of five atoms of ²²²Rn can be expected to enter the detector from the trap.

An indirect relationship between the number of low energy nuclear recoil events in the DEAP WIMP region of interest and the number of radon alpha decays was found. The ratio between the low energy events in the WIMP region of interest and the high energy alphas was found to be 0.18 ± 0.03 in the detector. From this, the upper limit of the contribution from the proposed radon trap to the WIMP background in DEAP-3600 will be be ten events for three years of run time, which is within acceptable limits.

Acknowledgements

I'd like to thank my supervisors Mark Boulay and Wolfgang Rau for their help and support in my research, without whom this thesis would not have happened. I'd also like to thank my office mates, Satoko and Erin, for their friendship; Helen O'Keefe for being British; Paradorn for being an endless source of entertainment; Victor for helping me install ROOT on my computer (a grueling process that took about a day); Bei for explaining the basics of DEAP analysis to me; Tom Sonley for rescuing my presentation at the last minute at CAP 2010; Tina for sharing the magic of her baking; Marcin for his analysis help, David Bearse and Rob Gagnon for helping me make practical things work; and Peter Skensved for his spirited defense of my desk. I'm sure I forgot many people in this list or neglected to mention them for lack of an entertaining annecdote, but the SNO collaboration has generally been amazing and helpful. I'd also like to thank my parents for continuing to believe and support my endeavors to obtain a somewhat esoteric degree.

Now I think I'll go forth from here and, to borrow the words of Tennyson, follow knowledge like a falling star, beyond the utmost bound of human thought.

Statement of Originality

The work in this thesis is my own, undertaken with the advice of the DEAP collaboration, unless otherwise stated. The testing of the DEAP-1 trap was conducted with help from Wolfgang Rau, and emanation measurements were conducted with the help of David Bearse. Work on the subsequent testing of the Carbo-Act carbon was conducted solely by myself, as was the implementation and application of the Klein-Nishina Compton fitting code, aside from advice from the collaboration.

The alpha analysis for LV consisted of replicating Kevin Olsen's method, but using my own code and own method for energy calibration. I then furthered his analysis by repeating it for the HV runs. Similar analysis for the LE and HE event rates has been conducted by Hugh Lippincott, but the code used was implemented by myself.

Contents

	Abstract	i
	Acknowledgements	iii
	Statement of Originality	iv
Chapte	er 1: Introduction	1
1.1	Evidence for Dark Matter	1
	1.1.1 Gravitational Lensing	3
	1.1.2 CMB	3
1.2	MOND	7
1.3	Dark Matter Candidates	7
	1.3.1 Relic Density	8
	1.3.2 Alternatives to the Standard Model	10
1.4	Dark Matter Experiments	12
	1.4.1 Detection	13
	1.4.2 CDMS	15
	1.4.3 XENON	17
	1.4.4 PICASSO	18

Chapter 2: DEAP

2.1	Detect	tion Using Argon	20
2.2	DEAF	2-1	24
2.3	DEAF	? 3600	26
2.4	Backg	rounds in DEAP	29
	2.4.1	³⁹ Ar backgrounds	29
	2.4.2	Neutron backgrounds	30
	2.4.3	Radon	31

 $\mathbf{20}$

34

I Radon Filtration

Chapter 3: Radon Background Reduction in DEAP 353.1The DEAP-1 Radon Spike 35Valve Leakage as a Source of ²²²Rn Contamination 3.236 3.3 Adsorption Theory 403.3.141 Temperature Dependence 3.3.2463.4493.4.1Background Subtraction 503.4.2Second Calibration of the Golightly Detector 523.4.3 55Chapter 4: Testing of DEAP-1 Radon Trap $\mathbf{59}$ 4.1624.2Distribution of Radon within Trap 63 4.3Radon Detection 65

	4.4	Result	s from the trap use	69
Cl	napte	er 5: D	Design of DEAP-3600 Radon Trap	72
	5.1	Carbo	n Testing	75
		5.1.1	Carbon Emanation	75
		5.1.2	Trap Construction	75
		5.1.3	Queen's Emanation Apparatus	76
		5.1.4	Emanation Procedure	78
		5.1.5	Emanation Results	79
		5.1.6	Pressure Testing	82
		5.1.7	Procedure for Measuring the Adsorption Constant	84
		5.1.8	Flow Rate Dependence	84
		5.1.9	Temperature Dependence	87
		5.1.10	Dimensions for the DEAP-3600 Trap	89
		5.1.11	Expected Radon Contamination	92
Π	D	ata A	nalysis	96
Cl	napte	er 6: E	nergy Calibration	97
	6.1	Compt	con Scattering	98
	6.2	Metho	d Testing	99
	6.3	Result	s of Energy Calibration	103
	6.4	Summ	ary	108
Cl	napte	er 7: A	lpha Analysis	109
	7.1	Data (Cuts	110

7.2 Low Voltage Run Analysis	.1
7.2.1 LV Alpha Energy Calibration	.4
7.3 High Voltage Run Analysis	.8
7.4 Relationship between Radon and LE Events in DEAP-1	24
7.5 Summary	26
Chapter 8: Conclusions 13	31
Bibliography 13	34
Appendix A:Light Yield Runs 14	12
Appendix B: Alpha Runs14	14
Appendix C:Data Cleaning Cuts 14	16
C.1 Light Yield Cuts	16
C.2 LV Cuts	16
C.3 HV Cuts	46

List of Figures

1.1	Rotation curve for Galaxy NGC 6503 [6]	2
1.2	The Bullet Cluster. Green contour lines show the centers of grav-	
	itation, while the intensity map shows the distribution of the hot	
	gas [3]	4
1.3	WMAP full sky map of the temperature of the cosmic microwave	
	background. [5]	5
1.4	Top: WMAP Temperature angular power spectrum. Bottom: Tem-	
	perature polarization cross-power spectrum $[5]$	6
1.5	Results from CDMS II. Detector $T1Z5(T3Z4)$ is on top (bottom) [13].	16
2.1	Examples of gamma-like (left) and nuclear recoil-like (right) PMT	
	traces from DEAP-1 [30]	23
2.2	Separation of events in DEAP-1 into nuclear recoil and gamma like	
	events [30]	23
2.3	Discrimination between gamma and nuclear recoil like events in the	
	DEAP-1 detector for the WIMP ROI [22].	24

2.4	Comparison of cross section as a function of WIMP mass for various	
	spin-independent dark matter detectors, with the old CDMS limit	
	and projected limits for proposed noble gas detectors [30]. \ldots	25
2.5	Schematic of the DEAP-1 detector.	27
2.6	Schematic of the proposed DEAP-3600 chamber. A stainless steel	
	outer chamber encloses the acrylic vessel, which is surrounded by	
	PMTs connected by acrylic light guides.	28
2.7	Muon flux as a function of depth for various underground laborato-	
	ries [27]	30
2.8	Expected background and WIMP rates in the DEAP-3600 detector	
	for a 3 year run [30]	31
2.9	Decay chain of 238 U [26]	32
2.10	Decay chain of ²³² Th [26]	33
2.11	Possible scenarios for alpha decay in the DEAP detector. Decays	
	from the TPB surface or from inside the acrylic or TPB are the	
	events of concern that may mimic a WIMP particle event [28]	33
3.1	Alpha (blue) and WIMP-like (red) event levels in DEAP-1 since	
	July 4th 2008 [29]. The initial spike in alpha activity corresponds	
	to the fill of the detector, while the large second spike corresponds	
	to a top-off of the detector after some argon was lost	36
3.2	Schematic of detector and chamber [50]	50
3.3	Sample uncalibrated detector spectrum	51
3.4	Detector background	53
3.5	Polonium spectrum after $^{222}\mathrm{Rn}$ has been flushed from detector	54

3.6	²¹⁴ Po spectrum after ²¹⁸ Po has decayed away	55
3.7	$^{214}\mathrm{Po}$ spectrum normalized to the $^{214}\mathrm{Po}$ peak in the combined spec-	
	trum	56
3.8	$^{218}\mathrm{Po}$ spectrum after the $^{214}\mathrm{Po}$ has been subtracted from the com-	
	bined spectrum	57
3.9	Conversion factors between actual $^{222}\mathrm{Rn}$ activity and measured ac-	
	tivity levels (counts/min)/(Bq(^{222}Rn)/L) as a function of the total	
	gas passed through the detector	58
3.10	Close up of ²¹⁸ Po conversion factor curve	58
4.1	Schematic of the radon trap with dimensions in inches. Gas flow is	
	from right to left through the carbon volume	60
4.2	Schematic of experimental setup.	61
4.3	Schematic of activity measurement	62
4.4	Pressure drop across DEAP-1 trap as a function of flow rate	63
4.5	Activity versus position from left of radon trap. The height of the	
	curve is normalized for the $^{222}\mathrm{Rn}$ decay between the different mea-	
	surements. Schematic of the trap is shown beneath for scale	64
4.6	Total counts versus channel number for second background test.	
	The peak is from ²¹⁰ Po	66
4.7	Total counts versus channel number for radon trap test. Peaks of	
	$^{210}\mathrm{Po},^{218}\mathrm{Po},$ and $^{214}\mathrm{Po}$ can be seen. The $^{222}\mathrm{Rn}$ distribution is hidden	
	under the $^{210}\mathrm{Po}$ peak	66
4.8	Counts per data file for 222 Rn, 214 Po, and 218 Po	67

4.9	Total number of $^{222}\mathrm{Rn}$ atoms passed through the trap as a func-	
	tion of the amount of argon gas for a $1~\mathrm{mBq/m^3}$ assumed radon	
	concentration in the argon supply	68
4.10	Alpha and WIMP rates before trap installation [29]	71
4.11	Alpha and WIMP rates after trap installation [29]	71
5.1	Proposed heating cycles for temperature swing radon filtration sys-	
	tem. Images courtesy of Wolfgang Rau	74
5.2	The Carbo-Act test trap	77
5.3	A schematic of the radon emanation apparatus. \ldots \ldots \ldots \ldots	78
5.4	Pressure drop as a function of flow rate for the Carbo-Act test trap.	83
5.5	$^{222}\mathrm{Rn}$ and $^{218}\mathrm{Po}$ count rates as a function of time using initial radon	
	injection method with lines of best fit.	85
5.6	$^{222}\mathrm{Rn}$ and $^{218}\mathrm{Po}$ count rates as a function of time using improved	
	radon injection method with lines of best fit	85
5.7	Breakthrough time for $^{222}\mathrm{Rn}$ as a function of inverse flow-rate	94
5.8	Breakthrough time for $^{218}\mathrm{Po}$ as a function of inverse flow-rate	94
5.9	Breakthrough time for $^{222}\mathrm{Rn}$ for the Carbo-Act test trap normalized	
	to a 5.3 L/min flow rate as a function of temperature	95
5.10	Breakthrough time for $^{218}\mathrm{Po}$ for the Carbo-Act test trap normalized	
	to a 5.3 L/min flow rate as a function of temperature	95
6.1	Compton edges for 1275 keV gamma	100
6.2	Fits to Monte Carlo simulated gamma rays in the DEAP-1 detector.	
	The large peak in each plot is due to the Compton edge from the	
	gamma in question, which is followed by the smaller photopeak	101

6.3	KN fit of 511 keV Compton edge and Gaussian $+$ exponential fit
	of photopeak. The photopeak with the Compton edge LY is also
	shown. Note that difference between the two light yield values can-
	not be explained by the goodness of fit
6.4	KN fit of Compton edges from 1460 keV and 2615 keV gammas
	from background run 10055 in DEAP-1
6.5	Fits of the 511 keV photopeak and the 1274 keV Compton in sodium
	run 10173 in DEAP-1. The 511 keV Compton is visible to the left of
	the photopeak and some contribution from the 1460 keV Compton
	can be seen to the right of the 1274 keV Compton
6.6	Light yield as a function of energy for the V2 of DEAP-1. The light
	yield is suppressed at high and low energies
6.7	Comparison of the LY of the V3 and V2 chambers. The 1.9 fold
	increase in LY at low energy from V2 to V3 almost disappears at
	high energy
6.8	Energy resolution as a function of energy for the V3 and V2 cham-
	bers, fitted to $1/\sqrt{E}$. Error bars represents statistical uncertainties
	only
6.9	LY in V3 for two different sets of PMT voltages
71	Dist of Edge1 Edge0 for poutron run 1877
(.1	Plot of Edgel-Edgeb for neutron run 1877
7.2	Plot of Edge0 for neutron run 1877
7.3	Neutron spectrum for run 1877 with and without edge cuts 112
7.4	Ratio between neutron spectrum with and without edge cuts. The
	ratio is essentially flat for all energies

7.5	LV alpha spectrum in terms of PE for radon spike
7.6	LV alpha energy spectrum for both the radon spike and the back-
	ground
7.7	LV pure radon energy spectrum
7.8	LV pure ²¹⁰ Po spectrum
7.9	LV rates as a function of time since first run
7.10	Energy spectrum of HV alphas before and after spike
7.11	HV pure radon spectrum
7.12	HV pure $^{210}\mathrm{Po}$ spectrum. Red line shows $^{210}\mathrm{Po}$ energy
7.13	Spike LE spectrum with background subtracted. This corresponds
	to LE events due to the leakage from the HE radon decays 123
7.14	222 Rn and 210 Po events as a function of Zfit
7.15	LE and 214 Po events as a function of Zfit
7.16	HE alpha rate from 4.5–9.0 MeV per run from September–December
	2008. A decay curve fit to the radon spike is also shown
7.17	LE nuclear recoil rate (0-1 MeV) per run from September–December
	2008
7.18	HE alpha rate from 4.5–9.0 MeV per run during spike. The data is
	fit to an exponential decay curve
7.19	LE nuclear recoil rate (0-1 MeV) per run during spike
7.20	Combined LV and HV runs for radon spike

Chapter 1

Introduction

1.1 Evidence for Dark Matter

The current scientific consensus is that the majority of the matter in the universe is dark, non-baryonic matter. The first evidence of this hidden mass was found by Fritz Zwicky in 1933, when he observed that the velocity of the galaxies in the Coma cluster was far greater than that predicted by the gravitational effect of the observed luminous matter [1]. He postulated that this was due to a large quantity of non-luminous matter in the cluster, but the result was largely forgotten until 1970 when Vera Rubin observed that the rotational speed of the Andromeda galaxy did not fall off in the manner predicted by Kepler's laws [2]. According to Newtonian dynamics, the rotational speed of a galaxy should be given by:

$$v(r) = \sqrt{\frac{GM(r)}{r}} \tag{1.1}$$

where $M(\mathbf{r})$ is the the mass of the galaxy as a function of the radius. If the luminous mass is all within a radius of r_L , then once $r \gg r_L$ the mass should be essentially constant further out in the disk, and so the velocity should fall off as:

$$v \propto \sqrt{\frac{1}{r}} \tag{1.2}$$

Instead the angular velocity of stars around the galactic center remains largely constant out to the edge of the galactic disk. Similar curves have since been found for other galaxies [6], and the effect is illustrated in Figure 1.1. Contributions from the galactic gas and postulated dark matter halo are also shown. This leads to one of two conclusions; either gravity works differently on galactic scales than for smaller length scales, or there is a large quantity of invisible matter in the galactic disk that extends out past the luminous portion.



Figure 1.1: Rotation curve for Galaxy NGC 6503 [6].

1.1.1 Gravitational Lensing

In addition to Zwicky's measurement, further evidence of dark matter has been found in galactic clusters. Gravitational lensing experiments, which use the bending of light by the clusters to measure their mass, have found large discrepancies between the luminous mass of these objects and their gravitational mass. The most interesting observations have been of the Bullet cluster [3], which consists of two galactic clusters colliding. X-ray observations of the cluster show most of the cluster's mass being comprised of superheated gas, but the gravitational centers of the cluster are displaced from these regions, as shown in Figure 1.2. This suggests that the cluster's mass consists of two components: baryonic and non-baryonic. The baryonic components from each colliding cluster interacted with one another and therefore slowed down, but the non-baryonic components were only affected by the gravitational force and sailed through, leading to the separation of dark and luminous matter. The Bullet cluster is one of the most conclusive pieces of evidence of non-baryonic dark matter, although it does not completely rule out alternative theories of gravitation.

1.1.2 CMB

Observations of the large scale structure of the universe have been instrumental in determining the overall fraction of dark matter in the universe. The cosmic microwave background, or CMB, is the leftover radiation from the big bang, at the point at which photons decoupled from normal matter. Prior to this moment, electrons and protons were too energetic to form atoms, so the mean free path of photons was extremely short. Once the universe cooled enough for atoms to form,



Figure 1.2: The Bullet Cluster. Green contour lines show the centers of gravitation, while the intensity map shows the distribution of the hot gas [3].

it became transparent to photons, leading to the creation of the CMB primordial photons. These photons redshifted as the universe expanded, cooling to a temperature of approximately 2.7 K. As the universe is assumed to be isotropic, the CMB radiation should approximate a black body curve and be essentially the same in all direction. This has been confirmed by both the COBE and Wilkinson Microwave Anisotropy Probe (WMAP) experiments to within one part in 10^5 [4][5].

However, small irregularities in density throughout the universe led to this decoupling occurring at different times for different regions, creating anisotropies in the temperature of the CMB photons. These anisotropies can be measured, allowing measurement of the large scale structure of the universe. The temperature fluctuations can be expanded using:

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l=2}^{+\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta,\phi)$$
(1.3)

where $Y_{lm}(\theta, \phi)$ are spherical harmonics [6]. The variance of a_{lm} , denoted by C_l is



Figure 1.3: WMAP full sky map of the temperature of the cosmic microwave background. [5]

given by

$$C_l = \langle |a_{lm}|^2 \rangle \equiv \frac{1}{2l+1} \sum_{m=-l}^{+l} |a_{lm}|^2$$
 (1.4)

As the temperature fluctuations appear to be Gaussian, all the information in the CMB spectrum can be compressed into this power spectrum, which give the behaviour of C_l as a function of l. This is usually plotted as $l(l+1)C_l/2\pi$ (Figure 1.4). The resulting angular power spectrum is best fitted by the Lambda Cold Dark Matter model or Λ CDM. This model describes a flat universe, with 4.4% ordinary baryonic matter, 22% dark matter, and 73% dark energy. Dark energy remains an unknown variable that serves to prevent the universe from collapsing. This result provides strong evidence that dark matter must be non-baryonic and the dominant form of matter in the universe.



Figure 1.4: Top: WMAP Temperature angular power spectrum. Bottom: Temperature polarization cross-power spectrum [5].

1.2 MOND

While the WMAP experiment and the observation of the Bullet cluster strongly suggest the existence of dark matter, the possibility that the dark matter effects are instead caused by alterations in the gravitational force at very small accelerations or very long distances has not been ruled out [8]. The most basic model suggests that the acceleration of an object goes as $a \rightarrow \mu(a/a_0)a$, where μ is a function which is equal to one when $a \gg a_0$ and $\mu \sim a/a_0$ when $a \ll a_0$. Therefore, at very large radii where a drops below a_0 , the rotational velocity goes as $v = \sqrt{GMa_0}$ which is consistent with the observed rotations.

However, with the accumulating evidence for dark matter, such as the Bullet cluster, MOND theories have to be made more and more complex to explain the phenomena. Theories that combine some form of hot neutrino dark matter and MOND have been proposed that may provide a middle ground between the two hypotheses, but these models often run into issues with relic density, which will be discussed later [9].

1.3 Dark Matter Candidates

Any potential dark matter candidate must satisfy the restrictions put on it by current observations of its effects. Massive compact halo objects (MACHOs), such as faint stars, brown dwarfs, white dwarfs, or neutron stars, have been proposed as possible baryonic sources of dark matter, but experimental searches for such objects have shown that they can only be a minor component of dark matter [12]. Given this dearth of baryonic candidates, along with the results of WMAP, dark matter must therefore be primarily non-baryonic. If the unknown mass consists of particles, they must also be cold, and therefore massive, as in order to explain galactic rotation curves the dark matter must be clumped in a halo around the galaxy. Therefore hot – that is fast moving and low mass – particles such as neutrinos are excluded. Finally, they must be "dark" and interact primarily through the weak force and gravity; otherwise they would have been previously detected by experiment. In short, the ideal candidate must be a WIMP: a Weakly Interacting Massive Particle.

1.3.1 Relic Density

During the early universe, WIMP particles (χ) would have been in thermal equilibrium with the rest of the universe as long as the average temperature was greater than their rest mass. During this stage, χ and $\bar{\chi}$ particles would annihilate and be replaced by the annihilation of other particles at an equal rate. Once the temperature of the universe fell beneath the χ mass, the abundance of χ particles would have fallen off exponentially, as there was not sufficient energy from other annihilations to replace the annihilated WIMPs, until the expansion rate of the universe, H, was greater than the reaction rate. That is, the universe was expanding fast enough that the WIMPs and anti-WIMPs could not find each other and annihilate. This would fix the abundance of the particle to its present day value, otherwise known as its relic density. A mass-independent approximation to the χ relic density[10] can be calculated to be:

$$\Omega_{\chi} h^{2} = m_{\chi} n_{\chi} / \rho_{c} \approx \frac{3 \times 10^{-27} \text{ cm}^{3} \text{s}^{-1}}{<\sigma_{A} v >}$$
(1.5)

where Ω_{χ} is the percent contribution of WIMP particles to the density of the universe, in units of the critical density, h is Hubble's constant in 100 km s⁻¹Mpc⁻¹, ρ_c is the critical mass density required for a flat universe, m_{χ} and n_{χ} are the mass and number of WIMPs respectively, and $\sigma_A v$ is the annihilation cross section of the interaction. This can be estimated to be:

$$<\sigma_A v > \approx \alpha^2 100 \text{ GeV}^{-2} \approx 10^{-25} \text{ cm}^2 \text{s}^{-1}$$
 (1.6)

where $\alpha \approx 10^{-2}$, which gives a lower limit of 0.03 as the relic density. As the weak scale interaction has no obvious connection with the closure density of the universe, this is strong evidence that if WIMP particles exist they comprise a significant portion of the dark matter in the universe. This is affectionately referred to as the "WIMP miracle" by theorists.

A more rigorous set of limits can be made by setting limits on the WIMP mass. According to dimensional arguments, the annihilation cross section of WIMPs decreases as their mass increases, so their relic density should increase. Therefore heavier WIMPs are more likely to dominate the universe's mass and so are more likely to be inconsistent with cosmological models. A model independent upper bound on the WIMP's mass is found to be:

$$\Omega_{\chi} h^2 \gtrsim \left(\frac{m_{\chi}}{300 \text{ TeV}}\right)^2 \tag{1.7}$$

The age of the universe puts an upper limit on $\Omega_{\chi}h^2$, as if the universe contains more mass, it must expand more rapidly to reach its current size in a shorter period of time. A conservative lower bound on the age of the universe is about 10 billion years, which gives a value of $\Omega h^2 \leq 1$ for $h \geq 0.4$, where Ω is the ratio between the mass-energy density of the universe and the critical density. This, of course, ensures that $\Omega_{\chi}h^2 \lesssim 1$ and so the upper limit of the WIMP mass is $m_{\chi} \lesssim 300$ TeV. If the age of the universe is older, say with a lower bound of 13 billion years, then the constraint becomes $\Omega h^2 \lesssim 0.4$. Both these upper limits are consistent with the WMAP results, but a safe constraint is that:

$$0.03 < \Omega_{\chi} h^2 < 1$$
 (1.8)

While relic density is not important for attempts to directly measure dark matter, as these are dependent on the local density within the Milky Way, it is useful for determining the viability of a WIMP candidate as the expected relic density can then be calculated and compared to these limits.

1.3.2 Alternatives to the Standard Model

The current Standard Model (SM) of particle physics does not provide any WIMP candidates. However the model is believed to be incomplete for a number of reasons. The standard model does not include neutrino oscillations, which have had to be more or less tacked on to the theoretical structure. In addition, there is the hierarchy problem as there is an enormous difference between the weak and Planck scale energy scales in the presence of a Higgs field. This has lead to the proposal that the standard model is a low energy limit of a more complete theory and numerous alternatives have been proposed, bringing with them a zoo of particle candidates. Some of the more exotic candidates include axions, sterile neutrinos, dark matter from little Higgs models, and supermassive WIMPzillas. The theories that provide the most probable WIMP candidates are extra dimension theories,

specifically Kaluza-Klein models, and supersymmetry (SUSY).

Extra Dimensions

Extra dimension theories propose that there are additional spatial dimensions which may be curled up and hence inaccessible to direct observation. This has been suggested as a possible way to solve the hierarchy problem as these curled up dimensions lower the fundamental Planck scale to an energy near the electroweak scale. Most variants of string theory appear to require additional dimensions so this is an area of much interest. Fields propagating in the curled up dimensions have quantized momentum, which give rise to Fourier modes, or Kaluza-Klein (KK) states. For Unified Extra Dimension(UED) theories, in which all particles and fields can propagate through the extra dimensions, the lightest of these KK states is a stable particle and a viable dark matter candidate. The relic density requirements for the particle places its energy at 400-1200 GeV which is within the limits of detection for upcoming or current experiments, particularly the Large Hadron Collider (LHC) and tonne scale dark matter detectors [6].

Supersymmetry

Supersymmetry theories attempt to solve the hierarchy problem by introducing a supersymmetric partner to every ordinary SM particle. These s-particles or sparticles, would differ from their SM counterparts by a difference of a spin of one half. The theories introduce a new conserved quantum property, R, which is defined as

$$R = (-1)^{3B+L+2s} \tag{1.9}$$

where B is the baryon number, L is the lepton number, and s is the particle's spin. All SM particles have R = 1, while all supersymmetry particles have R = -1. There are a number of possible dark matter particles from supersymmetry which would fit the required properties, but the most obvious choice predicted by theory is the neutralino, which may be the least massive supersymmetric particle. Neutralinos are ideal as they would be unable to decay into non-supersymmetric particles due to R conservation, and unable to decay into any supersymmetric particles, due to their mass, making them stable. Neutralinos are currently the leading candidate for WIMP particles.

1.4 Dark Matter Experiments

There are two primary modes of experiments for detecting dark matter: direct and indirect detection. Indirect detection relies on the observing the decay products produced by dark matter annihilations. The PAMELA (**P**ayload for **A**ntimatter **M**atter **E**xploration and **L**ight-nuclei **A**strophysics) cosmic ray experiment, for example, looks at the antimatter fluxes in cosmic rays for evidence of WIMP annihilation in the galactic halo [17][7]. Direct detection relies on the observation of a nuclear recoil from an elastic scattering of a WIMP off some target mass. A low background detector is necessary for these experiments to prevent confusion with more mundane standard model particle recoils, especially neutrons or alpha particles. Muon generated neutrons from cosmic rays are of particular concern, so dark matter experiments must be conducted underground to achieve shielding from this background.

There are three main detection methods being utilized for dark matter detec-

tors: solid state, liquid noble gases, and bubble detecting volumes. Some combination of heat deposition, scintillation, or ionization is used to detect the particles when they collide with the target mass. A method to discriminate between the ubiquitous beta events and nuclear recoil events, such as WIMPs or neutrons is also required and can be achieved by using two forms of detection or by some variety of pulse shape discrimination. This section will look at the differences between spin dependent and spin independent scattering and then give a brief overview of some of the leading experiments in the field of direct dark matter detection.

1.4.1 Detection

The detection of an elastic recoil of a WIMP off some nucleus is dependent on the interaction cross section. As the exact nature of WIMP particles is unknown the exact cross section and mass are unknown, so dark matter experiments attempt to explore the parameter space in which WIMP particles are expected to reside. From [10] a general formulation of the cross section can be expressed as:

$$\sigma_0 = 4G_F^2 m_r^2 C \tag{1.10}$$

$$\frac{d\sigma}{d|q|} = G_F^2 \frac{C}{v^2} F^2(|\mathbf{q}|) = \frac{\sigma_0}{4m_r^2 v^2} F^2(|\mathbf{q}|)$$
(1.11)

where G_F is the Fermi coupling constant, C is a dimensionless constant dependent on the WIMP particle, q is the momentum transfer, σ_0 is the cross section when the momentum transfer is zero, and v is the velocity of the WIMP relative to the target, that is the velocity of the dark matter halo with respect to the rest of the earth. The dark matter average velocity has been calculated to be $\bar{v} = \langle v^2 \rangle^{1/2} \cong 270$ km/s [6]. The reduced mass, m_r , is equal to:

$$\frac{m_n m_\chi}{m_n + m_\chi} \tag{1.12}$$

where m_n is the total nuclear mass and m_{χ} the WIMP mass. F is the form factor describing the spatial extension of the nucleus and is normalized so that F(0) = 1. This value changes depending on whether the WIMP particle couples to the spin of the nucleus, a spin dependent collision, or whether it couples to all the nucleons, in which case it is a spin independent collision. For spin independent collisions, the cross section is given by:

$$\frac{d\sigma}{d|\mathbf{q}|} = \frac{F^2(q)}{\pi v^2} [Zf_p + (A - Z)f_n]^2$$
(1.13)

with A being the number of nucleons, Z the number of protons, and f_p and f_n are the WIMP couplings to the neutrons and protons respectively. If $f_p \sim f_n$ then the cross section becomes dependent on the atomic mass and so more massive nuclei are preferable, such as Xe. For spin dependent interactions, C, can be defined by

$$C = \frac{8}{\pi} \Lambda^2 J(J+1)$$
 (1.14)

$$\Lambda = \frac{1}{J} [a_p \langle S_p \rangle + a_n \langle S_n \rangle] \tag{1.15}$$

where a_P and a_n are the coupling constants, $\langle S_n \rangle$ and $\langle S_p \rangle$ are the expectation values of the spin of the neutron and proton groups, and J is the total angular momentum of the atom. As the cross section depends on the form factor C, then nuclei with a high form factor must be chosen for spin dependent searches, such as fluorine.

1.4.2 CDMS

The CDMS, or Cryogenic Dark Matter Search, experiment is based in the Soudan Mine in Minnesota [13]. It utilizes Ge and Si crystal detectors, kept at milli-kelvin temperatures to observe WIMP events by measuring both the ionization charge and phonon energy of interactions with the target mass. A voltage bias is applied to the bottom of each detector to collect the ionization charge, while superconducting films detect temperature changes in the detector induced by phonons from the interaction. These two methods allow for beta discrimination in the detector, as the ionization for nuclear recoils is suppressed relative to beta events. This allows for better than 10^{-4} rejection of electron events. Since almost all misidentified events occur near the surface, and as surface events can be eliminated using a timing cut, misidentification can be reduced to 10^{-6} . Lead and polyethylene shielding reduces the background from environmental radioactivity and tagging is used to reduce backgrounds from muon generated neutrons, which are otherwise indistinguishable from WIMP events [11].

CDMS II ran from 2007–2008 and used 19 Ge detectors (~ 230 g) and 11 Si detectors (~ 100 g), running at temperatures below 50 mK. For the final phase of the experiment, 612 kg-days were achieved. After applying cuts to the data and unblinding, two events were found in the WIMP region as can be seen in Figure 1.5. Red dots indicate events that pass the timing cut, while the two bands in the left hand graphs indicate the beta (top) and neutron/WIMP (bottom) regions. Based on background estimates, the probability of these being background events is 23%. The data pushes the limit on the WIMP-nucleon spin-independent cross-section down to 7.0×10^{-44} cm² for a WIMP of mass 70 GeV/c² [13].



Figure 1.5: Results from CDMS II. Detector T1Z5(T3Z4) is on top (bottom) [13].

Super-CDMS is the latest incarnation of the CDMS experiment. It will use 10– 15 kg Ge with improved sensor technology and detectors with a mass of ~ 640 g. Plans are underway to further increase the target mass and move the experiment to SNOLAB to further reduce the muon induced neutron background, with the goal of reaching a sensitivity of 5×10^{-45} cm² [14].

1.4.3 XENON

The XENON experiment measures the scinitillation and ionization produced by recoils in pure liquid xenon to detect WIMP particles [15]. The target mass is self shielded, as gamma rays are more likely to interact near the edges of the detector so a fiducial cut reduces much of the background, as well as events from regions with weak or irregular electric fields. The detector is two-phase (liquid/gas), which allows the measurement of two signals: a prompt direct scintillation light S1, and a delayed scintillation light, S2, which is proportional to the ionization. The S2 signal is generated from drifted electrons, so by using the drift time between S1 and S2 and the drift velocity of electrons in xeon, the position of the event, Z, can be determined. This enables the discrimination of neutron events, as neutrons are likely to scatter multiple times in the detector, unlike WIMPs which have a much smaller cross section.

The XENON10 experiment was a 15 kg xenon dual phase time projection chamber experiment that ran from 2006–2007 at Gran Sasso. It was able to discriminate signal from background down to 4.5 keV nuclear recoil energy. Work is currently underway on the XENON 100 experiment, which will utilize 60 kg of liquid xenon, and the proposed 1 tonne XENON1T detector will hopefully push the limit down to 10^{-46} cm² [16].

1.4.4 PICASSO

The PICASSO, or **P**roject in **CA**nada to **S**earch for **S**upersymmetric **O**bjects, is one of the leading spin dependent dark matter experiment, and is situated in the SNOLAB facility in the Creighton Mine in Sudbury, Ontario. PICASSO consists of an array of bubble detectors, which contain superheated droplets of the fluorocarbon C_4F_{10} , which are suspended in a gel matrix. The detectors are the largest bubble detectors ever created, with a volume of 4.5 L. The gel is contained inside an acrylic vessel and sealed with a stainless steel lid that is connected to a hydraulic pressure system. There are nine piezoelectric sensors on each module, which allows for position reconstruction within the detector [18].

The basic operating principle is that a nuclear recoil event in the superheated droplets will cause them to undergo a phase transition to the gaseous phase, causing the bubble to increase in size. This creates a shock wave in the gel matrix, which can be picked up by piezoelectric sensors. Once a number of events have occurred, the bubble detector can be re-pressurized, forcing the expanded bubbles back into their previous phase. This allows for continuous use of the chambers.

By varying the running temperature of the bubble detectors, their sensitivity to different particle types and energies changes. As the chambers are essentially threshold counters, running them at a lower temperature ensures they are only sensitive to the most energetic recoils. By adjusting the temperature it is therefore possible to make the bubble chamber sensitive only to WIMP-like events, and eliminate gamma and muon backgrounds. The most serious background for PICASSO is alpha particles, to which it is sensitive for the whole temperature range. A major contribution to this was the radioactive contamination from the heavy salt used to make the gel matrix. A new generation of salt-less detectors has helped reduce this. PICASSO has also been able to discriminate between alpha particles and neutron-like events by using acoustic pulse shape analysis. The difference between the two event types is believed to be caused by differences between their energy deposition in the droplets. A neutron will elastically collide with one nucleus and transfer all its energy. The nucleus has a very small mean free path in the gel, so it is only able to create one or two nucleation points. An alpha particle, on the other hand, has a long mean free path in the gel and may interact with a string of nuclei as it loses momentum, creating a number of different nucleation points in the bubble and therefore a different signal.

Chapter 2

DEAP

The **D**ark matter **E**xperiment with liquid **A**rgon using **P**ulse shape discrimination project, otherwise known as DEAP, utilizes the scintillation light generated by the elastic collision of a WIMP with an argon nucleus to detect WIMP candidates. A prototype, DEAP-1, is currently running underground at SNOLAB in Sudbury, with plans to upgrade to the larger 1 tonne DEAP-3600 detector underway.

2.1 Detection Using Argon

Using noble liquids for WIMP dark matter detectors, such as XENON and DEAP, is attractive for a number of reasons. Many noble liquids have high photon scintillation yields, have low radioactive backgrounds, and can be scaled up to large target masses [20]. While other experiments, such as XENON, use combinations of scintillation and ionization to create their electron discrimination, the energy levels of argon allow for discrimination based on scintillation dependence on time, which differs between nuclear and gamma/beta events. In addition to this, argon boasts some advantages over xenon as a target mass given its lower cost and simpler purification requirements.

A WIMP particle, χ , can be detected by measuring the energy transferred to the target nucleus by elastic collisions:

$$\chi + N \to \chi' + N' \tag{2.1}$$

The argon atoms are then either excited or ionized and form metastable dimer states. These states then decay back into individual argon atoms, giving off scintillation light at 128 nm, which is lower in energy than the lowest excited state of the argon atom. This allows the scintillation light to escape the liquid argon without being absorbed. In noble liquids, ionizing radiation leads to the formation of dimers in the singlet or triplet states, with lifetimes of τ_1 and τ_3 respectively. These states are also produced with different amplitudes, I_1 and I_3 . These parameters depend on both the liquid and the ionizing radiation. A comparison of the values for xenon, argon, and neon is given below in Table 2.1. The ratio between I_1 and I_3 and the difference between τ_1 and τ_3 provides the discrimination factor which is highest for argon.

Table 2.1: Comparison of noble gas scintillation properties [20]

Parameter	Ne	Ar	Xe
Light Yield ($\times 10^4$ photons/MeV)	1.5	4.0	4.2
prompt time constant τ_1	2.2 ns	6 ns	2.2 ns
late time constant τ_3	$2.9 \mu s$	$1.59~\mu {\rm s}$	21 ns
I_1/I_3 for electrons		0.3	0.3
I_1/I_3 for nuclear recoils		3	1.6
$\lambda(\text{peak})(\text{nm})$	77	128	174
Rayleigh scattering length(cm)	60	90	30
The pulse shape discrimination is achieved by using the ratio between the prompt and late light from an event. For the DEAP-1 detector, the prompt light is defined as the light which occurs between $t_0 - 50$ ns and $t_0 + 150$ ns, while the total light for an event is defined as that between -50 ns and 10 μ s after the peak. The variable Fprompt is defined to be $\frac{PromptLight}{LateLight}$. Sample traces for gamma events and for nuclear recoil events can be seen in Figure 2.1. The yellow region of the plot is the prompt light window, while the blue region is the late light region. When plotted against the energy of the event, as shown in Figure 2.2, the gamma events clearly separate from the nuclear recoil events, allowing for the elimination of the former as background.

An electron recoil contamination (ERC) of 10^{-9} is required to perform a competitive WIMP search using argon, due to the presence of the isotope ³⁹Ar, which produces approximately 1 Bq per kg of atmospheric argon [21]. ERC is defined to be the probability of incorrectly classifying an electronic recoil event as a nuclear recoil event, given a particular level of nuclear recoil acceptance, and it improves exponentially with scintillation light collection efficiency. For DEAP-1, the WIMP region of interest (ROI) is between 43–86 keV_{ee}, where keV_{ee} is the electron-equivalent energy. Using a triple-coincidence tag, the ERC for DEAP-1 in the ROI was found to be less than 6×10^{-8} , and the discrimination parameter agreed with a simple analytic model [22]. The discrimination for DEAP-1 is plotted in Figure 2.3.

Projected cross-sectional limits for an argon-based experiment are compared to current limits in Figure 2.4. A 10^{-10} discrimination for β particle misidentification is achievable for an energy threshold of 20 keV_{ee}. Given this value, a 1 tonne liquid argon detector, such as DEAP-3600, should be able to push the cross-sectional limit



Figure 2.1: Examples of gamma-like (left) and nuclear recoil-like (right) PMT traces from DEAP-1 [30].



Figure 2.2: Separation of events in DEAP-1 into nuclear recoil and gamma like events [30].



Figure 2.3: Discrimination between gamma and nuclear recoil like events in the DEAP-1 detector for the WIMP ROI [22].

down to 10^{-46} cm² for a 100 GeV WIMP.

2.2 DEAP-1

DEAP-1 is the second DEAP prototype and has been in operation since 2007 at SNOLAB, in Sudbury, Ontario. It is a cylindrical 7 kg liquid argon detector with a photomultiplier tube (PMT) on either side to detect photoelectrons. The detector chamber is composed of acrylic, with an inner coating of tetraphenyl butadiene (TPB) wavelength shifter, which shifts the wavelength of the ultraviolet light from the scintillating liquid argon into the visible spectrum so it can be detected by the PMTs. The data was collected using a LeCroy oscilloscope until June 2009. After this point, the oscilloscope was replaced by CAEN digitizers controlled with



Figure 2.4: Comparison of cross section as a function of WIMP mass for various spin-independent dark matter detectors, with the old CDMS limit and projected limits for proposed noble gas detectors [30].

a VME bus and run using the MIDAS software from TRIUMF. The detector is surrounded on all sides by water shielding to eliminate neutron backgrounds from its surroundings. A diagram of the detector is shown in Figure 2.5. The position of events within the detector is given by the Zfit parameter which is defined as

$$Z_{fit} = 35.2 \ cm \times \frac{Q^A - Q^B}{Q^A + Q^B}$$
(2.2)

where the Q^A and Q^B terms are the total charges collected in PMTs A and B, and 35.2 cm is the distance from the center of the DEAP-1 detector to the faces of the PMTs. The TotalPE parameter is the total number of photoelectrons produced by each event, i.e the number collected by both PMTs.

There have been three versions of the DEAP-1 chamber that have been tested so far. Each version has seen a variety of details changed in order to reduce the background in the WIMP ROI. These changes are documented in Table 2.2.

T 7 •	\mathbf{D} + \mathbf{I} + \mathbf{I}	T	
Version	Date Installed	Improvements	Background
			Rate in WIMP
			ROI
1	August 2007	Glove box	0.4 mBq
		preparation of	
		inner chamber	
		to reduce Rn	
		adsorp-	
		tion/implantation	
		on surfaces	
2	March 2009	Sandpaper	$0.15 \mathrm{~mBq}$
		assay/selection,	
		Radon trap used	
		for fill.	
3	March 2010	Acrylic	0.13 mBq
		monomer	
		purification for	
		coating	
		chamber. TPB	
		purification.	
		Larger, high	
		quantum	
		efficiency PMTs	

Table 2.2: Versions of DEAP-1 [31]

2.3 DEAP 3600

DEAP 3600 is the planned large scale version of the DEAP detector. It will utilize 3.6 tonnes of liquid argon in a spherical acrylic vessel surrounded by PMTs, connected by light guides to the vessel, all surrounded by a stainless steel vessel. The chamber is filled through the neck and the entire apparatus is suspended



Figure 2.5: Schematic of the DEAP-1 detector.

in a water bath to shield from neutrons. The light guides are used to reduce the background from neutrons coming from the radioactive PMT glass, although this means some light loss is inevitable. A fiducial cut will leave 1 tonne for actual detection, with the remaining argon acting as shielding against background radiation and possible WIMP mimicking events from ²²²Rn chain decays, which will be discussed in the next section. A diagram of the proposed detector is shown below in Figure 2.6. Work is currently underway to have the DEAP-3600 operational by 2012.



Figure 2.6: Schematic of the proposed DEAP-3600 chamber. A stainless steel outer chamber encloses the acrylic vessel, which is surrounded by PMTs connected by acrylic light guides.

2.4 Backgrounds in DEAP

2.4.1 ³⁹Ar backgrounds

There are four main sources of background that affect the DEAP experiment: ³⁹Ar, spallation neutrons from muons, slow neutrons created by (α, n) interactions from background radioactivity, and ²²²Rn. ³⁹Ar is generated by cosmic ray collisions in the upper atmosphere and is a beta emitter with a mean energy of 220 keV. The specific activity of 39 Ar has been measured to be 0.87 ± 0.02 (stat) ± 0.08 (syst) Bq/kg of natural argon [24], which if used in the detector will result in 3.9×10^6 events/year in the ROI for DEAP-1 prior to the application of PSD [26]. This background puts a lower limit on the DEAP ROI, as can be seen for the projected rates for DEAP-3600 in Figure 2.8. While pulse shape discrimination will largely eliminate the background generated by this isotope, a reduction of this background would enable a measurement of lower energy WIMPs, as the overlap between the gamma/beta and nuclear recoil bands would be reduced and the ERC improved. As ³⁹Ar is cosmogenically produced, and has a long half life of 273 years, obtaining argon that has a low level of contamination is difficult. Such sources require shielding from cosmic rays and a long isolation from atmospheric argon. Some possibilities are deep underground wells or the US National Helium Reserve which removes both helium and argon from natural gas. Work done by the DEAP Depleted Argon group has found that argon from the former has a $\geq 95\%$ reduction in ³⁹Ar [25]. Work is underway to attain a supply of depleted argon for the DEAP-3600 detector.

2.4.2 Neutron backgrounds

Neutron backgrounds are important as they elastically recoil in the same manner as WIMPs are predicted to. Spallation neutrons come from nuclei struck by cosmic rays or high energy alphas from the ²³⁸U and ²³²Th chains. The former are easily reduced by having the detector underground in the Sudbury SNOLAB facility. Figure 2.7 shows the muon flux as a function of depth for the major underground laboratories, where the units of depth are kilometers of water equivalent shielding (km.w.e). To eliminate the neutrons from the radioactivity in the bedrock of the SNOLAB facility, the DEAP-1 detector is surrounded by a water shield of 400 twenty liter water boxes.



Figure 2.7: Muon flux as a function of depth for various underground laboratories [27].



Figure 2.8: Expected background and WIMP rates in the DEAP-3600 detector for a 3 year run [30].

2.4.3 Radon

One of the primary concerns for DEAP is how to build and fill the detector chamber without contaminating it with radon. Radon is present in almost all environments, originating from the long lived natural decay chains of ²³²Th and ²³⁸U, shown in Figures 2.9 and 2.10. Of particular concern is ²²²Rn which originates from the alpha decay of ²²⁶Ra in the uranium chain and its polonium daughter products. ²²²Rn has a half life of 3.824 days, which allows it to travel and diffuse through materials before decaying. In addition, its ²¹⁰Pb daughter product is very long lived, and so its alpha emitting daughter product, ²¹⁰Po, could provide a significant long term background for the DEAP detector. ²²⁰Rn, from the thorium chain, is a lesser concern, as its daughter products decay away quickly.

The Fprompt ratio for alpha particles is similar to that for nuclear recoils. If



Figure 2.9: Decay chain of 238 U [26].

these decays occur within the main detector volume, they can be identified by the energies of the events, which are well above the ROI for WIMPs. The main concern is the embedding of the polonium daughter products in the wall of the acrylic vessel. Two problematic scenarios can occur. If the alpha is emitted into the acrylic and the nucleus into the argon, this causes an untagged nuclear recoil which will be indistinguishable from a WIMP. If the atom is embedded in the TPB coating or the acrylic and the alpha particle is emitted into the argon, it can lose energy in the TPB and become a low energy WIMP like event. The four types of possible events are illustrated in Figure 2.11. The main focus of this thesis concerns the attempt to minimize radon contamination to the DEAP-1 and DEAP-3600 detectors during the detector fill, to assess the radon contamination of the current DEAP-1 detector, and to attempt to find the correlation between low energy WIMP-like events in the chamber and the ²²²Rn contamination.



Figure 2.10: Decay chain of 232 Th [26].



Figure 2.11: Possible scenarios for alpha decay in the DEAP detector. Decays from the TPB surface or from inside the acrylic or TPB are the events of concern that may mimic a WIMP particle event [28].

Part I

Radon Filtration

Chapter 3

Radon Background Reduction in DEAP

3.1 The DEAP-1 Radon Spike

. While most of the radon related background can be sufficiently reduced by the selection of ultra-low radon emanating materials, contamination of the chamber during the fill process is a concern, as there are opportunities for ²²²Rn to seep in and provide massive backgrounds. Despite the use of ultra-pure argon, large spikes in the nuclear recoil rate were seen during fills of the DEAP-1 chamber in 2008 (Figure 3.1). The alpha rate fell off with the lifetime of ²²²Rn, suggesting that the gas had entered by some means during the fill. Two possible issues were suggested. One was that ²²²Rn was diffusing through one of the relief valves in the fill system, while the other was that ²²²Rn contamination was being introduced to the argon gas from the container used to hold it and traveling with it into the detector chamber. Measurements of radon contamination of commercial argon

have put the expected activity of the gas at the mBq/m^3 level (STP) with large fluctuations [41]. This value is consistent with the activity of the spikes observed.



Figure 3.1: Alpha (blue) and WIMP-like (red) event levels in DEAP-1 since July 4th 2008 [29]. The initial spike in alpha activity corresponds to the fill of the detector, while the large second spike corresponds to a top-off of the detector after some argon was lost.

3.2 Valve Leakage as a Source of ²²²Rn Contamination

In order to test the level of diffusion through the relief valves, a leak test was conducted. A generic relief valve was attached to a leak tester and surrounded with a bag of helium gas at one atmosphere. The leak tester was then pumped down and the leak rate of the valve was measured. The leak rate for helium through the relief value was measured to be 5×10^{-6} std cc/sec at a pressure of

 8.3×10^{-3} mbar. In order to determine the leak rate of radon by diffusion, Fick's equation was used:

$$\vec{J} = -D\nabla c \tag{3.1}$$

where J is the flux of matter across the barrier in question, D is the diffusion constant for a given species, and c is the concentration of the species. The underlying assumption is that ²²²Rn will act like helium, with only a scaling factor given the size of the atom. If laminar flow can be assumed, then the diffusion constant can be determined to be:

$$D = \frac{k_b T}{6\pi\eta r} \tag{3.2}$$

where η is the fluid's viscosity, r is the radius of the atom, and T is the temperature. However for this assumption to hold, the Reynold's number must be sufficiently low as to permit laminar flow for both radon and helium. The Reynold's number is defined to be:

$$R = \frac{\rho \nu_s r}{\eta} \tag{3.3}$$

with ρ being the fluid density, and ν_s being the characteristic speed of the particle. The characteristic speed is found from:

$$<\nu_s>=\sqrt{\frac{k_bT}{m}}$$
(3.4)

with *m* being the mass of the atom and k_b Boltzmann's constant. At room temperature, the characteristic speeds of helium and radon atom are found to be $R_{He} = 2.34 \times 10^{-5}$ m/s and $R_{Rn} = 7.13 \times 10^{-7}$ m/s, assuming the viscosity of ²²²Rn is roughly the same as He.

As both these numbers are much less than one, laminar flow can be assumed, and so the model which gives Equation 3.1 holds. As there were no ready values for the viscosity of radon and the geometry of the relief valve was unknown, the diffusion constant, D, for helium was scaled by the square of the ratio between the atomic radii. This should give an upper limit on the diffusion as it has been found that the permeability of leak valve membranes depends on the exponential of the square of the atomic radius of the gas [33]. Taking the first equation, the flux of helium through the valve can be determined to be:

$$\vec{J}_{Rn} = D_{Rn} \nabla c = \left(\frac{r_{He}}{r_{Rn}}\right)^2 \vec{J}_{He} \tag{3.5}$$

As the leak rate, $\frac{dV}{dt}$, is measured by the volume and pressure of gas escaping, assuming both gases are ideal, this results in:

$$\left(\frac{dV}{dt}\right)_{Rn} = \left(\frac{r_{He}}{r_{Rn}}\right)^2 \left(\frac{dV}{dt}\right)_{He} = 1.2 \times 10^{-8} \text{ std cc/sec}$$
(3.6)

where the covalent radii for radon (150 pm) and helium (28 pm) are used. So the expected radon leak rate for the brass relief value would be 1.2×10^{-8} std cc/sec. If a constant flux across the value is assumed, the number of moles of radon crossing the value per unit time would be given by:

$$\frac{dn}{dt} = \frac{P\frac{dV}{dt}}{RT} = \frac{101.3 \text{ Pa} \times 1.2 \times 10^{-13} \text{m}^3/\text{sec}}{8.314 \text{ JK}^{-1} \text{mol}^{-1} 293 \text{K}} = 4.99 \times 10^{-16} \text{mols/sec}$$
(3.7)

The average activity concentration of SNOLAB air is $123.2 \pm 13.0 \text{ Bq/m}^3[32]$ so

the concentration of radon atoms in the air is obtained by:

$$\frac{N}{V_{SNOLAB}} = \frac{A}{V\lambda} = \frac{123.2 \text{Bq/m}^3}{2.0986 \times 10^{-6}} = 5.9 \times 10^7 \text{atoms/m}^3$$
(3.8)

where A/V is the activity concentration and λ is the decay constant of radon. As the testing of the relief valve occurred for a helium sample of approximately one atmosphere and at standard room temperature, it can be assumed that the leak rate for a given atom across a barrier scales linearly with the concentration. The rate of radon atoms should be related to the ratio between the atomic concentration of pure radon at STP and the radon at SNOLAB concentrations. Using the ideal gas law:

$$\left(\frac{N}{V}\right)_{STP} = \frac{P}{RT} \times 6.022 \times 10^{23} \text{ atoms/mol} = 2.5 \times 10^{22} \text{ atoms/m}^3 \tag{3.9}$$

where N/V is the atomic concentration, P is the pressure, and T is the temperature, the final result is:

$$\frac{dn}{dt}_{SNOLAB} = \frac{dn}{dt}_{STP} \frac{(N/V)_{SNOLAB}}{(N/V)_{STP}} = 1.18 \times 10^{-30} \text{ mols/sec}$$
(3.10)

which works out to approximately 20 atoms/year, or 0.06 atoms/day. While this may be significant for the long term running of the detector, the contamination is not sufficient to explain the level of contamination that was seen during the spike. Therefore the most likely explanation for the contamination was that it originated in the argon gas itself. Although the argon used is ultra-pure, the container used to store it would likely contain trace amounts of radium, allowing ²²²Rn to build up inside the gas source. The simplest way to combat this type of contamination

is by installing an activated carbon radon filter, or trap, which arrests the flow of radon into the detector chamber. Activated carbon radon traps work by the basic principle that Rn atoms will adsorb onto the surface of carbon by van-der-Waals forces at low temperatures, while lighter carrier gases, such as nitrogen or argon, will continue to flow through, essentially unabated. A more detailed discussion follows in the next section.

3.3 Adsorption Theory

Adsorption is the phenomenon that occurs when fluid particles experience a drop in potential energy due to their interactions with a solid surface, causing them to stick to said surface. This can be facilitated through a number of chemical or physical interactions, depending on the properties of the adsorbed atoms and absorbent material involved. If only weak interactions, such as Van der Waals, dipole, or quadropolar interactions are present, the process is called *physical adsorption*, which is analogous to gas condensation so the atoms of a fluid are more likely to be adsorbed onto the surface at high pressure and low temperature. The strength of these interactions and the number of sites in the material onto which atoms can adsorb are the determining factors in the efficiency of a filter based on this principle.

Radon is a non-polar atom, as is carbon, so it is the Van der Waals interaction that binds the atom to the surface in this case. The selection of radon with respect to the carrier gases is due to the following; N_2, O_2 and Ar have similar polarizabilities, so they are not separated by the carbon. Radon, on the other hand, has a much higher polarizability as so is much more likely to be trapped by the adsorbent.

Activated carbon is an ideal filtration material as it has an extremely large surface area to volume ratio, usually around 50 m²/g, but sometimes as high as $1000m^2/g$ or more [46]. It is very cost effective and is used in many commercial filters as well as in other radon filtration systems for low background experiments, such as Borexinio and CLEAN [44][45].

3.3.1 Chromatographic Plate Model

One common method for modeling adsorption columns is the chromatographic plate model. The following derivations are based on the respective derivations by A. Pocar [46]. As the radon is preferentially absorbed with respect to the carrier gas, in DEAP's case argon, the concentration of radon within the carrier gas changes as a function of time and position within the column. The column can be divided into a number of stages, n, such that equilibrium can be reached between the gas and the adsorbed material in each stage, where the stages are all of equal length h = L/n. It will transpire, however, that h is not necessarily \ll L for all real systems, so the limit of $h \to \infty$, cannot be taken in this mathematical approach.

For the case of a trace gas, such as radon, in a carrier gas, such as argon, the equilibrium condition is expressed by:

$$b_j = K \cdot y_j \quad \forall j = 1, \dots, n \tag{3.11}$$

where b_j and y_j are the concentrations of the trace gas in the adsorbed phase (molecules/area) and in the gas phase (molecules/volume) for the jth section of the column. K is a proportional constant with units of length. The gas evolves over time according to:

$$\Phi(y_j - y_{j-1}) = -a\dot{b_j}$$
(3.12)

with a being the surface area of the adsorbent in each stage and Φ the volume flow rate in the column. The dot denotes the derivative with respect to t. Equation 3.12 states that the molecules leaving the gas phase moving from one stage to the next will have to be absorbed in the latter stage. For simplicity, a steady flow rate is assumed, so Φ is constant. If σ is defined as the surface area per unit mass of absorbent:

$$\sigma = \frac{an}{m} \tag{3.13}$$

where m is the total adsorbent mass in the column, then a new constant can be introduced called the *dynamic adsorption constant*:

$$k_a \equiv \sigma K \tag{3.14}$$

with units of volume/mass. The characteristic time of the column, τ , will therefore depend on the dynamic adsorption constant, the volume flow rate, and the trapping mass m:

$$\tau \equiv \frac{k_a m}{\Phi} \tag{3.15}$$

Substituting equation 3.11 into equation 3.12 and using the above definitions gives:

$$\dot{y}_j = -\frac{n}{\tau}(y_j - y_{j-1}) \tag{3.16}$$

To go one step further, the dimensionless constant $\xi = t/\tau$ is defined and then equation 3.16 becomes

$$\frac{dy_j}{d\xi} = -n(y_j - y_{j-1}) \tag{3.17}$$

This equation can be effectively solved in Laplace space, using the definition $\tilde{y} \equiv Lap(y)$ so that equation 3.17 becomes:

$$(s+n)\tilde{y}_j - y_j(0) = n\tilde{y}_{j-1} \tag{3.18}$$

where it is now defined in terms of the variable s. The general solution for the concentration for the j-th stage is found to be:

$$\tilde{y}_j = \left(\frac{n}{s+n}\right)^j \tilde{y}_0 + \frac{1}{s+n} \sum_{k=1}^j \left(\frac{n}{s+n}\right)^{j-k} y_k(0) \equiv \tilde{y}_j^{input} + \tilde{y}_j^{ic} \tag{3.19}$$

where \tilde{y}_j^{input} describes the radon input into the column, and \tilde{y}_j^{ic} is the term which describes the initial conditions in the column. The initial conditions term, can be expressed in time space using the Laplace transform identity:

$$Lap(\xi^m e^{-n\xi}) = m! / (n+s)^{m+1}$$
(3.20)

First $\tilde{y}_j^{\ ic}$ is rearranged so that:

$$\tilde{y}_j^{\,ic} = \sum_{k=1}^j \left(\frac{n^{j-k}}{(s+n)^{j-k+1}} \right) y_k(0) \tag{3.21}$$

Then using m = j - k, this yields a new identity:

$$Lap\left(\frac{\xi^{j-k}e^{-n\xi}n^{j-k}y_k(0)}{(j-k)!}\right) = \frac{n^{j-k}y_k(0)}{(s+n)^{j-k+1}}$$
(3.22)

This identity can then be used to obtain the Laplace transform of 3.21 to obtain y_j^{ic} as a function of ξ :

$$y_j^{ic}(\xi) = \sum_{k=1}^j \frac{(n\xi)^{j-k}}{(j-k)!} e^{-n\xi} y_k(0)$$
(3.23)

The solution of the input term requires that the concentration distribution of the gas entering the column be known. The special case of the 'spike' function when the injection of radon into the column approximates a delta function is taken. This is the experimental technique utilized in this thesis for finding the characteristic time of the adsorbent. The initial concentration in each of the n stages is assumed to be zero:

$$y_j(0) = 0 \quad \forall j = 1, ..., n$$
 (3.24)

As $y_j^{ic} = 0$ for all 0 < j < n, then $\tilde{y}_j^{ic} = 0$ for all values of j and $\tilde{y}_j = \tilde{y}_j^{input}$. For the radon spike, the input is a delta function $y_o(\xi) = \alpha \delta(\xi)$ for $\xi = t = 0$, so $\tilde{y}_0 = \alpha$ and the general solution is:

$$\tilde{y}_j^{delta} = \frac{\alpha n^j}{(s+n)^j} \tag{3.25}$$

The inverse Laplace transform for Equation 3.20 yields:

$$y_j^{delta}(\xi) = \frac{\alpha n^j}{(j-1)!} \xi^{j-1} e^{-n\xi}$$
(3.26)

Then substituting in t/τ for ξ and letting j = n as the number of stages, this gives:

$$y\left(\frac{t}{\tau}\right) = \frac{\alpha n^n}{(n-1)!} \left(\frac{t}{\tau}\right)^{n-1} e^{-nt/\tau}$$
(3.27)

which is called an *elution curve*. As $n \to \infty$, the curve becomes a Gaussian peaked at τ , with a standard deviation of $\sigma = \tau/\sqrt{n}$. The maximum of the curve occurs at:

$$t_{max} = \frac{n-1}{n}\tau\tag{3.28}$$

So the higher the value of n, the narrower and more symmetric the curve becomes. The value of n can depend on a number of different factors, including the velocity of the carrier gas, the adsorption coefficient of the material, the grain size, and the packing quality.

The characteristic time is referred to in this thesis interchangeably with 'breakthrough time' as it determines how quickly the radon front breaks through the trap. It is dependent on the flow rate, Φ , and the adsorption constant, k_a , which in turn is dependent on the pressure and temperature. Higher pressure and lower temperature will result in more atoms adsorbing onto the trapping material per unit area. However increasing pressure will actually *reduce* the value of k_a and hence the characteristic time, assuming a constant flow rate. This is because k_a depends on the *volume flow rate*, rather than the *mass flow rate*. At higher pressure more radon per unit mass of carrier gas is adsorbed than at lower pressures. For the pressures used for the DEAP radon traps, which are less than 100 kPa, the k_a value is essentially constant with respect to pressure, so the pressure dependence is not of great importance [46].

3.3.2 Temperature Dependence

The temperature dependence of k_a will now be examined, following the derivation found in [40]. Taking one stage of the cylinder, let the probability of radon atoms in the gas volume adsorbing onto the carbon surface be w. The probability is proportional to the velocity of the radon atoms, the surface area of the carbon, and the concentration of radon in the gas volume. If the radon velocity is expressed in terms of the atom's kinetic energy, E_{Rn} and its mass m_{Rn} , then:

$$w \propto a \sqrt{(2E_{Rn}/m_{Rn})} y_j (V - v_c V) \tag{3.29}$$

where a is the surface area of the carbon, v_c is the fraction of the column volume occupied by the carbon, and y_j is the concentration of the radon in the j^{th} stage. The $y_j(1-v_c)V$ term represents the amount of radon in the gas phase in the stage. Using $E_{Rn} = \frac{3}{2}k_aT$ and assuming a proportionality constant, Γ , which includes a, this then becomes:

$$w = \Gamma \sqrt{(3k_a T/m_{Rn})} y_j (1 - v_c) V$$
(3.30)

As the radon atoms are in thermal equilibrium with the carbon, their energy distribution is given by the Maxwell-Boltzmann distribution:

$$N(E_{Rn}) \propto \sqrt{\frac{E_{Rn}}{\pi (k_b T)^3}} exp(-E_{Rn}/k_b T)$$
(3.31)

A radon atom can only be desorbed if its thermal energy is larger than the binding energy, E_b . In the case that $E_b \gg k_b T$, this yields:

$$N(E > E_b) = \int_{E_b}^{\infty} N(E_{Rn}) \approx \sqrt{4E_b/(\pi k_b T)} exp(-E_b/k_b T)$$
(3.32)

The probability of a radon atom desorbing from the carbon, γ , is proportional to $N(E > E_b)$ and the amount of radon adsorbed on the surface of the carbon. Assuming a proportionality constant, q, this gives:

$$\gamma = qN(E > E_b)(c_j \sigma \rho v_c V) \tag{3.33}$$

where σ is the surface area per unit mass of carbon, c_j is the number of radon atoms per unit surface area of the carbon in the j^{th} stage of the column, and ρ is the carbon density. Substituting in equation 3.32, and using the definition $c_j = Ky_j$ the equation becomes:

$$\gamma = qN\sqrt{4E_b/\pi k_b T} Ky_j \sigma \rho v_c V exp(-E_b/k_b T)$$
(3.34)

In equilibrium, the adsorption and desorption rates are identical, so $\omega = \gamma$. Combining equations 3.34 and 3.30, and defining $k_a = K\sigma$, gives:

$$\Gamma\sqrt{(3k_bT/m_{Rn})}y_j(1-v_c)V = q\sqrt{4E_b/\pi k_bT}exp(-E_b/k_bT)y_jk_a\rho v_cV$$
(3.35)

Rearranging this to solve for k_a gives the temperature dependence:

$$k_a \propto T exp(E_b/k_bT) \tag{3.36}$$

From this definition, it appears that k_a goes to infinity as $T \to 0$ and the minimum value of T is at $T = E_b/k$. However the latter of these two predictions does not hold, as when T approaches E_b/k , the approximation for Equation 3.32 does not hold, and the value of k_a goes nearly to zero.

Combining this equation with the definition for the breakthrough time (3.15):

$$\tau \propto \frac{(Texp(E_b/k_bT))m}{\Phi}$$
(3.37)

the dependence of the characteristic time on the temperature, mass, and flow rate is evident. If m and Φ are constant, this simplifies to:

$$\tau = \kappa(T)exp(\Lambda/T) \tag{3.38}$$

where κ and Λ are constants that depend on the carbon in question, and so must be found via experimentation. By determining Λ , the binding energy of the carbon can be found. This discussion is not valid, however, for a liquid carrier, so this model cannot be extrapolated below the liquefaction temperature of the gas in question.

The most important fact to note is the exponential dependence of the breakthrough time on temperature. This means that the effectiveness of any carbon trap can be easily increased by a number of orders of magnitude with the appropriate level of cooling. By heating a carbon trap up to warmer temperatures, it is also easy to purge it of radon to enable its reuse. Therefore a temperature swing system can be used to allow for continual use of the trap. Pressure swing systems are also possible, utilizing the pressure dependence of adsorption as noted earlier, but a temperature based system is preferable for DEAP as the argon gas has to be cooled before liquefaction and as a compressor cannot be used for the fill system due to cleanliness concerns, the pressure drop across the trap has to be kept to a minimum.

3.4 The Golightly Radon Detector

In order to test the effectiveness of a given trap, the easiest method is to measure the characteristic time for a pulse of radon to travel through it for a given flow rate and temperature. To do this, a radon detector must be utilized to measure the exit radon concentration as a function of time. Tests of the DEAP-1 radon trap and the DEAP-3600 Carbo-Act test trap were conducted using a radon detector devised by John Golightly [49]. The detector consists of a stainless steel cylinder, with two plates at either end, separated by plastic rods, with metal rings in between. By applying a potential across the detector, this architecture produces a homogenous electric field inside. In one of the metal plates a silicon alpha counter is inserted. For the DEAP-1 radon trap test an ORTEC BA-20-200-100 alpha counter was used. This was damaged afterwards and replaced with a ORTEC U-CAM-600 alpha counter for the DEAP-3600 test trap measurements. The schematic of the detector chamber can be seen in Figure 3.2.

The carrier gas flows through the detector and out the other side through the intake valves. While in the chamber volume the ²²²Rn atoms in the carrier gas decay, and the alphas are recorded by the silicon counter. The daughter ²¹⁸Po atoms are ionized, and due to their high mobility, are transferred to the detector plate by the electric field before they have a chance to decay. The polonium alpha emitters therefore display well defined peaks. The ²²²Rn atoms exhibit a broader



Figure 3.2: Schematic of detector and chamber [50].

energy spectrum as they decay from a wide distribution throughout the detector volume and the alpha particles from the decays lose energy as they interact with the carrier gas on the way to the counter. A sample spectrum produced by the detector can be seen in Figure 3.3. The ²¹⁰Po peak is hidden inside the broad ²²²Rn distribution on the left, while the ²¹⁸Po and ²¹⁴Po peaks are clearly visible. However if there is a polymer coating on the silicon counter, then the alphas can lose energy through interaction with the coating, leading to a large peak at low energies. This peak was present for the DEAP-3600 test measurements, but not the DEAP-1 trap measurements.

3.4.1 Background Subtraction

The method used to assess the concentration of each individual isotope in the spectrum is as follows. First a background run is performed with the detector sealed off. As ²¹⁰Pb is a long lived isotope, it builds up inside the detector after continual use and provides a long lasting ²¹⁰Po alpha background. When ²²²Rn is introduced into the chamber, the ²¹⁸Po and ²¹⁴Po peaks become visible. The spectrum can then be integrated over from zero to the maximum ²²²Rn channel



Figure 3.3: Sample uncalibrated detector spectrum.

to gain a rough value for the 222 Rn count rate if there is no polymer coating on the silicon counter, as is the case in the DEAP-1 radon trap test. If there is a polymer coating, as was the case for the testing of the carbon for the DEAP-3600 trap, then the minimum of the 222 Rn distribution is used.

Similarly, the spectrum from the ²²²Rn maximum channel up to the ²¹⁸Po maximum channel can be integrated over to obtain the ²¹⁸Po rate, and from the ²¹⁸Po maximum to the spectrum maximum to obtain the ²¹⁴Po rate. However there is a large degree of overlap between the integration windows for each isotope, as well as the large background from ²¹⁰Po. The latter can be easily managed by estimating the number of counts in the ²²²Rn integration window by obtaining the rate of ²¹⁰Po from the background run and subtracting the appropriate number of counts from the ²²²Rn rate. The overlap from ²¹⁸Po and ²¹⁴Po is more difficult and requires a calibration run. To calibrate the detector, ²²²Rn is introduced into

the chamber and counting is started. The chamber is then flushed to removed any excess 222 Rn and sealed. At this point, only polonium remains in the detector, so the shape of the 218 Po and 214 Po curves can then be observed.

3.4.2 Second Calibration of the Golightly Detector

For the testing of the DEAP-1 radon trap, the calibration created by John Golightly was used. When the detector was cleaned out in the summer of 2009, however, the silicon counter was damaged and had to be replaced. This meant a new calibration had to be conducted as outlined previously. A background run was conducted which showed that there was some ²¹⁰Po buildup in the detector as well as some residual ²¹⁴Po from the last test (Figure 3.5). The spectra from the detector for the initial data collection run (Figure 3.5) where both ²¹⁴Po and ²¹⁸Po are present, and the later run where only ²¹⁴Po is present (Figure 3.6) are shown below. For simplicity the former will be referred to as the combined spectrum and the latter as the ²¹⁴Po spectrum.

The ²¹⁴Po spectrum peak was then normalized to the ²¹⁴Po peak in the combined spectrum (Figure 3.7) and subtracted. This gave a histogram for the pure ²¹⁸Po spectrum in Figure 3.8. Even though the maximums of the combined and ²¹⁴Po spectra were aligned before scaling to account – as there was a 7 channel shift between the two runs – the combined spectrum had a broader peak, so the subtraction left a great deal of noise in the pure ²¹⁸Po spectrum, especially at the edge of the ²¹⁴Po peak region. However this averages to zero until about channel 1100, so the subtraction is effective in the region of interest.

Using the ²¹⁴Po peak at channel 1200 as an energy calibration and cutting



Figure 3.4: Detector background.

out the pile up peak at the bottom of the spectrum, the integration limits were calculated for each alpha emitter, by finding the channel for the maximum energy peak. Using these limits, the overlap of the ²¹⁴Po peak in the ²¹⁸Po and ²²²Rn peaks, and the overlap of the ²¹⁸Po peak with the ²²²Rn peak can be determined from the ²¹⁴Po and ²¹⁸Po spectra generated in the calibration run. The calculated values are given in Table 3.1. The formulas for the final rates are:

$$R_{\text{Po214}} = \left(\sum_{i=Max\ Po218\ Bin+1}^{Max\ Bin} (x(i) - b(i))\right) / F_{214}^{214}$$
(3.39)

$$R_{\text{Po218}} = \left(\sum_{i=Max \ Rn \ Bin+1}^{Max \ Po218 \ Bin} (x(i) - b(i))\right) / F_{218}^{218} - R_{\text{Po214}} F_{214}^{218}$$
(3.40)



Figure 3.5: Polonium spectrum after 222 Rn has been flushed from detector.

$$R_{\rm Rn} = \left(\sum_{i=200}^{Max \ Rn \ Bin} (x(i) - b(i))\right) - R_{\rm Po218} F_{218}^{222} - R_{\rm Po214} F_{214}^{222}$$
(3.41)

where R is the rate for each isotope, x is the number of counts in the x^{th} bin for the radon trap test spectrum, b is the expected number of counts from ²¹⁰Po for the b^{th} bin, and F_a^b is the fraction of isotope a in isotope b's integration limit.

Table 3.1: Integration Limits for $^{222}\mathrm{Rn}$ and Polonium daughter products

ſ	Isotope	Minimum Channel	Maximum Channel	²¹⁸ Po peak overlap	²¹⁴ Po peak overlap
	222 Rn	200	857	51.1%	8.5%
	218 Po	858	935	48.9%	3.2%
	214 Po	935	1200	0%	88.4%



Figure 3.6: ²¹⁴Po spectrum after ²¹⁸Po has decayed away.

3.4.3 Efficiency of the Golightly Detector

The relationship between the measured rate of ²¹⁸Po and the actual activity of radon in the detector was recalculated from a calibration run conducted in 2008 [50]. This relationship is used to extrapolate the expected ²²²Rn contamination of DEAP-1 in Section 4.3. For this run ²²²Rn from a source with a continuous availability of 66.24 Bq/min was passed into the detector at a constant flow rate with a potential bias of +2000 V across it. As the initial activity concentration of radon was much higher than the continuous availability due to buildup in the radon source, data had to be collected until equilibrium was reached. The conversion factor, C, between the measured activity of the different isotopes and the input



Figure 3.7: ²¹⁴Po spectrum normalized to the ²¹⁴Po peak in the combined spectrum.

activity of ²²²Rn was calculated using:

$$C = X/(A\phi) \tag{3.42}$$

where X is the number of counts/min of the isotope, A is the continuous availability, and ϕ is the flow rate in liters per minute. The calculated conversion factors for ²²²Rn, ²¹⁸Po, and ²¹⁴Po are plotted in Figure 3.9 as a function of time. The initial spike is due to the high initial concentration of ²²²Rn in the source at the beginning of the run.

It can be observed that the C values of 222 Rn and 218 Po reach their equilibrium values relatively quickly. However 214 Po does not reach equilibrium within the data set as it is further down on the decay chain. The 218 Po conversion factor was calculated to be 1.4 ± 0.4 (Counts/min)/(Bq(Rn)/L) by averaging from 360 L to



Figure 3.8: $^{218}\mathrm{Po}$ spectrum after the $^{214}\mathrm{Po}$ has been subtracted from the combined spectrum.

900 L as shown in Figure 3.10.


Figure 3.9: Conversion factors between actual 222 Rn activity and measured activity levels (counts/min)/(Bq(222 Rn)/L) as a function of the total gas passed through the detector.



Figure 3.10: Close up of 218 Po conversion factor curve.

Chapter 4

Testing of DEAP-1 Radon Trap

A radon trap was constructed and a test was conducted to simulate its behavior under the conditions of a fill of DEAP-1. The radon trap design can be seen in Figure 4.1. It consists of stainless steel tubing with 10 g of activated carbon spheres (CARBOXEN 528) held in place with glass wool. A stainless steel insert, colored in blue in the diagram, allowed the trap to be welded shut without burning the carbon. The stainless steel components were welded using a non-thoriated rod in order to reduce radium contamination.

The setup for the experiment can be seen in Figure 4.2. Argon gas was passed through the system at roughly 11 L/min past the pressure gauge and through the flow meter. Initially a 526 kBq 222 Rn Pylon Electronics radon source[34] was placed between the gas source and the flow meter at the beginning of the test. and half a liter of gas was passed through it. The source was then disconnected and normal argon gas flow was returned. From there, the gas flowed into the trap, which was immersed in an ethanol bath within a stainless steel dewar. The trap was kept at a temperature between -100°C and -110°C using liquid nitrogen, which



Figure 4.1: Schematic of the radon trap with dimensions in inches. Gas flow is from right to left through the carbon volume.

was added every five minutes. A thermocouple was taped to the side of the trap to monitor changes in the temperature.

After exiting the trap, the argon gas went through the detector and then through the totalizer, which recorded the total volume of gas transfered through the system and the flow rate. From there, the gas was safely vented. The detector was run with a potential bias of +2500 V across it and its signal was amplified and recorded.

Before radon was introduced to the system the flow rate was varied, and the pressure drop across the trap was measured in order to determine the relationship between the two variables. After this a background run was performed with the detector filled with argon and sealed off from the rest of the system. Data files were recorded every twenty minutes for all spectrum measurements.

With the backgrounds determined, a new data collection set was commenced after 222 Rn had been injected into the trap. 11 m³ of gas was passed through the



Figure 4.2: Schematic of experimental setup.

system to simulate the fill of the DEAP-1 chamber. The first three and a half hours were run without the +2500 V bias across the detector, as it was accidentally not switched on. However this was not important as no 222 Rn had entered the detector by that time. At the conclusion of the test, only a very small concentration of 222 Rn could be seen in the detector.

In order to verify that ²²²Rn was actually trapped without running the experiment for another two days, a measurement was conducted with a geiger counter to find the activity of the trap at various points along its length. A schematic of the measurement setup can be seen in Figure 4.3. Lead blocks were used to collimate the radiation from the trap, while the geiger counter was used to measure the activity of the gamma emitting daughter products (²¹⁴Pb and ²¹⁴Bi) from the radon



Figure 4.3: Schematic of activity measurement.

decay chain. Three measurements were taken using this setup: one immediately after the test, one the next day, and one four days after the test. This was done in order to determine if the activity peak widened upon the warming of the trap.

Finally, the trap was warmed using a heat gun for 45 minutes with a low level of argon passing through it to the outside. This purged the trap of any residual radon, making it fit for reuse. The activity was again measured using the Geiger counter. Initially the count rate remained high due to the residual daughter products, but after a day, the activity returned to background levels, indicating that the daughter products had decayed away and that the trap was essentially radon free.

4.1 Pressure Drop and Gas Flow

The relationship between the pressure drop across the trap and the flow rate in the system was found to be roughly linear, as can be seen in Figure 4.4. The slope was found to be 7.1 ± 0.3 kPa*min/Lwith an intercept of -2 ± 2 kPa which is within uncertainty of zero as expected. For the DEAP-1 fill flow rate of 11 L/min this will result in a pressure drop of 76 ± 4 kPa. This relationship can be used as a diagnostic to ensure the system is properly set up when the trap is used. It also enables the determination of the minimum pressure required for continuous flow through the trap if it is decided to recycle the argon. This would enable the purification of the argon from radon sources within the detector.



Figure 4.4: Pressure drop across DEAP-1 trap as a function of flow rate.

4.2 Distribution of Radon within Trap

The measurements of the activity of the trap at various positions along its length all returned similar results. The normalized activity plots can be seen in Figure 4.5. In the measurement conducted the day of the test, January 15th, the activity



Figure 4.5: Activity versus position from left of radon trap. The height of the curve is normalized for the ²²²Rn decay between the different measurements. Schematic of the trap is shown beneath for scale.

peak was observed to be approximately 7 cm from the input of the trap, with most of the activity trailing off by about 16 cm. The other tests on January 16th and 19th, also displayed these properties. It was therefore concluded that the peak had not moved within the sensitivity of the Geiger counter, despite warming to room temperature following the test. Therefore, as long as gas is not flowing through the system, an accidental warming of the trap should not be an issue in terms of the release of radon.

Also, in observing the level of the activity in relation to the carbon spheres that

hold the radon in the trap, it can be seen from the schematic in Figure 4.5 that, after the test, the radon had just reached the edge of the trapping material. If less volume had been required for the filling of DEAP-1, only the radon emanation of the carbon used in the trap would have contributed to radon atoms entering the detector. For the background run, only ²¹⁰Po was visible in the spectrum (Figure 4.6). For the trap test, the total spectrum for the entire run, shown in Figure 4.7, shows a small number of ²¹⁴Po and ²¹⁸Po decays, indicating the presence of radon in the detector chamber.

4.3 Radon Detection

For the background run with the argon sealed in the detector, the spectrum of which can be seen in Figure 4.6, only one event was observed above the ²¹⁰Po peak. The channel numbers are different from the previous spectra as a different alpha detector and amplifier were used. This confirms that the background of the argon gas is below the ability of the detector to accurately measure, which is not surprising given that the expected contamination is on the order of mBq/m^3 as previously reported in Section 3.1.

The number of ²²²Rn, ²¹⁴Po, and ²¹⁸Po counts per file are plotted in Figure 4.8, where each file is the data collected in a 20 minute window. Files 11 and 25 were corrupted due to interruptions in the data collection, so the rates for those files were set to zero. Radon counts in the plot before file 25 can be attributed to statistical fluctuations from the ²¹⁰Po background subtraction rather than the presence of ²²²Rn atoms, as there are no ²¹⁸Po or ²¹⁴Po counts before this point. The mean number of ²²²Rn counts between the first file and the 25th file is 2 ± 7 ,



Figure 4.6: Total counts versus channel number for second background test. The peak is from $^{210}\mathrm{Po}.$



Figure 4.7: Total counts versus channel number for radon trap test. Peaks of 210 Po, 218 Po, and 214 Po can be seen. The 222 Rn distribution is hidden under the 210 Po peak.



Figure 4.8: Counts per data file for ²²²Rn, ²¹⁴Po, and ²¹⁸Po.

which is consistent with zero. The ²¹⁸Po levels indicate that radon entered the detector around data file 26, which is corroborated by the ²¹⁴Po levels. The ²¹⁸Po levels were used to calculate the actual number of ²²²Rn atoms in the system, as the measured number of ²²²Rn counts were on the same order of magnitude as the random statistical fluctuations in the background.

As the DEAP-1 radon trap test involved a single injection of radon into the trap, a continuous concentration – such as would be expected from the argon source – was approximated by assuming that the sum of a series of identical radon injections would be equivalent. Therefore the histogram for ²¹⁸Po was added to itself shifted one bin over, which was then added to itself shifted two bins over, and so on, until the last bin was reached.

With the expected activity concentration for the argon being on the order of mBq/m^3 – as previously mentioned – this result was then scaled from 527 kBq/m³



Figure 4.9: Total number of 222 Rn atoms passed through the trap as a function of the amount of argon gas for a 1 mBq/m³ assumed radon concentration in the argon supply.

to 1 mBq/m³. Finally, the histogram was divided by the conversion factor for 218 Po, 1.4 ± 0.4 (Counts/min)/(Bq(Rn)/L), to find the activity concentration, which in turn was used to find the number of 222 Rn atoms that would have passed into the detector during the time for each bin given the flow rate used. Although the test was conducted at a potential bias of +2000 V instead of the calibration bias of +2500 V due to a large amount of electronic noise, previous work has shown that the difference in conversion factor changes by less than 1% between +2000 V and +3000 V [50]. Integrating over the total volume of argon passed through the detector gave the total number of expected radon atoms that would pass into the DEAP-1 chamber for a given volume of argon gas. The final histogram can be seen in Figure 4.9. Error bars are calculated assuming a Poisson distribution for the 218 Po counts and an estimated ± 0.25 L/min uncertainty in the flow rate. As can clearly be seen, the calculated number of 222 Rn atoms is much less than one, indicating that the trap would be highly effective at minimizing contamination from the argon.

4.4 Results from the trap use

The radon trap was used for the fill of the second version (V2) of the DEAP-1 chamber in March 2009. When the alpha rates in the background were examined, the spike in activity associated with previous fills (Figure 4.10) had disappeared, as can be seen in Figure 4.11. In combination with other improvements this led to a nearly 10 fold reduction in the WIMP background rate (the rate of events in the WIMP ROI) for the V2 chamber. Given the calculated sensitivity of the detector, these events should all be due to background events and not actual

WIMP particles. These results both confirm that the radon spike contamination was coming from the argon source and that the trap was successful at eliminating the spike.



Figure 4.10: Alpha and WIMP rates before trap installation [29].



Figure 4.11: Alpha and WIMP rates after trap installation [29].

Chapter 5

Design of DEAP-3600 Radon Trap

The radon spikes due to the argon fills in the DEAP-1 chambered highlighted the need to create a similar radon trap system for the DEAP-3600 detector. For DEAP-3600 to be a competitive dark matter search, the expected number of fiducial alpha events in the energy ROI will have to be less than 0.2 for a three year run [31]. Therefore creating a highly efficient radon filtration system is essential to the successful operation of the detector. Two important issues had to be addressed: the efficiency of the proposed carbon brand in removing radon from the argon source, and the carbon's radon emanation rate.

The DEAP-3600 chamber will be filled with 3600 kg of argon, with a planned flow rate of 100 L/min. Given the large scale of the operation, some degree of automation is desired for the running of the system. The ideal method would be a temperature swing system. This would take precooled argon gas in through one cooled trap, producing radon free argon. The filtered gas would then be used to both fill the detector and simultaneously purge the heated second trap. After the capacity for the first trap is reached, the direction of flow would be reversed. The large difference in characteristic time due to temperature between the two traps enables the purging of the heated trap with only a fraction of the purified argon. The system is illustrated in Figure 5.1.

As the breakthrough time scales with the mass of the trap and increases exponentially as temperature decreases, a larger trap than the DEAP-1 version run at a colder temperature will increase the efficiency of the filtration. Keeping the argon gaseous is ideal, as previous work has found that liquid argon has an decreased breakthrough time, likely due to increased channeling effects through the carbon [41]. As argon liquefies at -186°C, running at -160°C will maximize the breakthrough time, while keeping the argon in safely in gaseous form.

The trap will be cooled either by using a liquid nitrogen coil around the exterior of the trap or by a pressurized LN bath. The temperature will be monitored at either end of the cylinder using thermocouples, while a heating strip will warm the system during the flushing of the trap to ensure that all the radon is removed. The cooling power required can be calculated using:

$$P = F\rho \times C \times \Delta T \tag{5.1}$$

where F is the flow rate, ρ is the density of argon gas (1.784 g/L at 0°C), C is the heat capacity of argon gas (0.520 kJ/kg/K), and Δ T is the temperature drop, Assuming a 100 L/min flowrate, and a operation temperature of -160°C for the DEAP 3600 fill, this system would require 300 W of cooling power. If the cooling power of LN required is calculated:

$$P_{\rm LN} = F \rho A_r^{-1} \Delta_t H \tag{5.2}$$

where $\Delta_t H$ is the heat of vaporization (0.72 kJ/mol) and A_r is the atomic mass of argon, the LN requirement is found to be 0.4 L/min, so some variety of cryocooler would have to be used. The AL600 Cryocooler has been suggested as a suitable model [35].



Figure 5.1: Proposed heating cycles for temperature swing radon filtration system. Images courtesy of Wolfgang Rau.

5.1 Carbon Testing

5.1.1 Carbon Emanation

The filling of the DEAP-3600 chamber will require a much larger volume of gas than DEAP-1. This will result in a much longer period of operation for a radon trap, which will in turn increase the amount of radon from the carbon adsorbent that is transfered into the detector. For this reason, selecting a very low radon emanating carbon is important for ensuring minimal contamination of the detector. Based on a comparison of measurements of the radon emanation rate of a number of activated carbon brands [44], the Carbo-Act brand was selected as a potential candidate for the experiment. It has by far the lowest ²²²Rn emanation rate at $0.3 \pm 0.1 \text{ mBq/kg}$, while the other brands had measured values ranging from 100–330 mBq/kg.

5.1.2 Trap Construction

A sample of Carbo-Act F2/F3 grain activated carbon was ordered for testing. The chamber for a test radon trap was made from a 7.25 inch stainless steel tube with an inner diameter of 0.622 inches. The ends of the tube were machined to allow pipe fittings to be screwed on to either end. To reduce any background from radon emanating from the inside of the stainless steel, the trap container was first ultrasonically cleaned and then chemically etched using a 10% solution of nitric acid for approximately ten minutes, by alternating between dipping the tube in acid and then rinsing it with ultrapure water. Based on an average reported etch rate of 2.0 g/cm²hour [36], for a 14% solution of nitric acid, and a steel density of

8 g/cm³ a ten minute emersion should have removed approximately 25 μ m, which was more than sufficient for the removal of any residual radium deposited in the surface of the steel. The empty vessel was then sealed by wrapping Teflon tape around the screw fastenings and then screwing on the end pieces. The final trap can be seen in Figure 5.2. The radon emanation rate for the empty chamber was then measured using the apparatus as described in section 5.1.3.

After the emanation measurements were taken for the empty chamber, the trap was opened up and filled with the Carbo-Act sample. Ideally the carbon would have been washed with ultra-pure water to removed dust from the sample beforehand, but the carbon appeared so light that concerns were raised that it would float with the dust on the surface of the water. The carbon was therefore transfered from one glass beaker to another beaker so that the dust remained behind on the inner surface of the first beaker. However, the grains were so fine that the difference between dust and carbon was difficult to gauge, so while some dust was removed using this method, it was not as thorough as would be ideal. A more effective method must be found for building the large trap. 10.6 ± 0.1 g of carbon were added to the trap, with 0.5 inches of glass wool added to either end of the trap to hold the carbon in place.

5.1.3 Queen's Emanation Apparatus

The Queen's emanation apparatus includes a roughing pump, a cooling coil, a radon board, a Lucas cell, and a PMT dark box. The radon board consists of a large and a small stainless steel coil filled with brass wool with stainless steel Swagelok connectors and a connection to a Queen's Lucas cell [37]. A schematic of



Figure 5.2: The Carbo-Act test trap.

the setup is shown below in Figure 5.3. The freezing point of ²²²Rn is much lower than that of helium, so the three coils are all cooled with liquid nitrogen in order to trap radon atoms as the helium carrier gas passes through them. The cooling coil serves to remove any residual radon from the helium source, creating a clean carrier gas while the first large coil traps radon from the sample. As the large coil contains a greater volume than that of the Lucas cell, the radon is then transfered to the second, smaller coil by free expansion. This ensures that most of the radon is transfered to Lucas cell when the small coil is warmed [37]. After radon from the sample is collected in the Lucas cell, the cell is put in a dark box with a PMT and the alpha rate is measured.

The Queen's Lucas Cells have been designed to optimized the amount of light detected by the PMT, and to minimize the background coming from the cell. Each cell has a diameter of 2 inches, corresponding the PMT that is coupled to it. The chamber has a volume of 15.5 cm³ and is made from ultraviolet transmitting acrylic, which is one the lowest radioactive materials available. A ZnS scintillator



Figure 5.3: A schematic of the radon emanation apparatus.

coating on the inside allows for the detection of alpha decays within the scintillator volume. The choice of the coupled PMT is not critical, as the light output from ²²²Rn decays is much higher than the PMT noise level [38].

5.1.4 Emanation Procedure

After connecting the radon trap to the board, it was leak tested to ensure that no radon was coming in from the outside air. Then, before any emanation measurements were taken, the background of the Lucas cell used had to be determined as ²¹⁰Pb builds up inside the cell due to its long lifetime. The cell was pumped down using the vacuum roughing pump to remove any radon remaining from previous tests and then counted using the PMT dark box for 3.06 days. A total of 13 counts were recorded, giving a background of 4.25 counts/day.

Before each emanation measurement, any residual radon in the apparatus had to be removed. The Lucas cell was first pumped down for approximately two hours. The board was then evacuated and then purged for ten minutes with helium gas. During this process, the large and small coil on the radon board were baked using a heat gun to free any remaining trapped radon. The board was then pumped down again for thirty minutes and then flushed with helium and left slightly pressurized with the valves closed.

The radon trap was flushed with cooled helium gas for ten minutes and was then put under vacuum and left to emanate for three days. After this, it was heated using a heat gun and then immersed in a dewar of boiling water. The large and small coil on the radon board were cooled with liquid nitrogen, after which the value between the trap and the radon board was opened and the trap was flushed with cooled helium gas, which forced the emanated ²²²Rn into the large coil. The large coil was heated, after the valve back to the trap was sealed off, forcing the ²²²Rn into the small coil. Finally, the connection back to the large coil was sealed off and the small coil was heated so that the remaining ²²²Rn was forced into the Lucas cell. The Lucas cell was then removed and counting was conducted for approximately three days.

5.1.5 Emanation Results

The empty trap was emanated three times due to large uncertainties from low statistics. The values are shown below in Table 5.2. To calculate the number of decayed ²²²Rn atoms, n_{Rn} , that have emanated from the carbon trap, the expected

number of Lucas cell background counts:

$$n_{Lucas} = 4.25 \text{ counts/day} \times t_c \tag{5.3}$$

where t_c is the counting time, was subtracted from the total number of counts. As each radon atom should, on average, exhibit three alpha decays within the time span of the emanation from the ²²²Rn atom and its ²¹⁸Po and ²¹⁴Po daughter products, the actual number of radon atoms from the trap which have decayed is given by:

$$n_{Rn} = \frac{n_{counts} - n_{Lucas}}{3E_{single-alpha} \times E_{small-cell} \times E_{large-small} \times E_{trap-large}}$$
(5.4)

The E values are the efficiencies of the single-alpha detection of the Lucas cell, the small coil to Lucas cell transfer, the large coil to small coil transfer, and the trap to large coil transfer respectively. The efficiencies and their respective errors are given below in Table 5.1. Using the exponential decay equation, $N(t) = N_0 e^{-\lambda t_c}$, the number of radon atoms in the carbon trap when the counting is started, N_0 , can then be obtained by:

$$n_{Rn} = N_0 - N(t) (5.5)$$

$$= N_0 (1 - e^{-\lambda t_c}) \tag{5.6}$$

$$N_0 = \frac{n_{Rn}}{1 - e^{-\lambda t_c}}$$
(5.7)

where λ is the decay constant for ²²²Rn. The final values are shown below in Table 5.2, where the emanation rate is given in atoms/day.

Table 5.1: Radon Board Efficiencies

Lucas cell Single-Alpha Efficiency	0.74 ± 0.04
Efficiency from Small Coil to Cell	0.64 ± 0.03
Efficiency from Large Coil to Small Coil	$0.75 \pm .04$
Efficiency from Trap to Large Coil	$1.00 \pm .05$

Counts Counting Time Emanation Emanation **Emanation** Rate Time (days) (days) (Atoms/day) 3.076 2.943 6.3 ± 2.5 1 1922.9172.963 -1.6 ± 1.3 11 3 203.0003.873 2.8 ± 1.5

Table 5.2: Emanation Values for Empty Radon Trap

The emanation measurements gave an average of 3.0 ± 1.1 atoms/day from the empty chamber. With this value known, emanations could be performed on the filled chamber with 10.6 ± 0.1 g of Carbo-Act carbon. Five emanations of the filled trap were performed. Two of the emanations had to be discarded due to a leaking valve and electronic noise. In addition to these problems, as the trap was not heated and flushed before the first few tests, there was a large amount of radon trapped in the carbon from contact with room air. This lead to extremely high radon values for the first good run and so only the last two runs were used to calculate the radon emanation rate of the carbon itself. The values for the three good emanations are given below in Table 5.3. The radon emanation rate in atoms/day/kg was calculated by finding the emanation rate in atoms/day in the same manner as for the empty chamber, subtracting the emanation rate of the empty chamber, and then dividing by the total carbon mass of 10.6 ± 0.1 g.

To gain an upper limit of the expected ²²²Rn emanation rate of the Carbo-

Emanation	Counts	Emanation	Counting	Emanation Rate	Emanation Rate
		Time	Time	(Atoms/day)	(Atoms/day/kg)
		(days)	(days)		
*1	60	3.889	2.731	38.7 ± 7.4	3664 ± 702
2	21	3.950	3.710	0.6 ± 1.9	52 ± 183
3	15	3.910	2.735	-0.1 ± 1.9	-10 ± 183

Table 5.3: Emanation Values for Full Radon Trap

Act carbon, the average of the last two measurements was used. A value of 284 atoms/day/kg was obtained with a 90% confidence limit, or 3.0 mBq/kg. The value obtained by Heusser was (0.3 ± 0.1) mBq/kg[44] so the upper limit of radon emanation is an order of magnitude higher than was previously measured due to larger experimental uncertainties. However this sample still produces significantly less radon than the other samples which have been documented, so the F2/F3 grain Carbo-Act brand remains the ideal activated carbon choice for reducing radon contamination of the detector.

5.1.6 Pressure Testing

Different brands of activated carbon will have different adsorption capabilities, depending on factors such as grain size and surface area. The dynamic adsorption coefficient, k_a , also depends on the temperature and flow rate used for the trap, as noted in previous sections. Therefore, the Carbo-Act carbon was tested at different flow rates and temperatures to find the dependence of the characteristic time on these variables in order to calculate τ for the planned DEAP-3600 radon trap. Before these tests were conducted, however, the pressure drop across the full trap was examined over a range of flow rates in order to gain an idea of the approximate pressure drop across the planned DEAP-3600 radon trap. Test were conducted with the trap empty, except for the glass wool filler, and with the trap full. There was found to be a negligible contribution from the empty trap. The results for the full trap are shown in Figure 5.4. The relationship is linear as before, with $P = a\Phi + b$, where P is the pressure in kPa and Φ is the flow rate in L/min. The slope, a, was found to be 2.5 kPa/(L/min), while the intercept, b, was found to be 5 kPa. There are likely some non-linear effects at low flow rates, as the intercept is not within uncertainty of zero.



Figure 5.4: Pressure drop as a function of flow rate for the Carbo-Act test trap.

5.1.7 Procedure for Measuring the Adsorption Constant

The procedure for testing the characteristic times for the Carbo-Act trap was similar to that used to test the DEAP-1 carbon trap. However, the tests were conducted at a much higher temperature (in the -30 to $+5^{\circ}$ C range) than the DEAP-1 test, and each test was run until it was observed that the majority of the ²²²Rn injection spike had passed through the trap. The temperature bath used was also different, consisting of a 60:40 mix of antifreeze and water, which was cooled in a plastic container with styrofoam insulation, using a Neslab CC 100 Immersion cooler. This allowed for a much easier temperature maintenance than cooling manually with LN2. A copper cooling coil was also used to precool the gas before it entered the radon trap. This allowed for a more constant temperature level, which aided in the accuracy of the measurement of the binding energy of the carbon. Nitrogen gas was used as the carrier gas instead of argon. As both gases are inert and of similar mass the difference between the two is essentially negligible [47].

5.1.8 Flow Rate Dependence

Tests were conducted to verfiy the linear relationship between the characteristic time and the inverse flow rate of the carrier gas (Equation 3.15). For this, the temperature of the trials was kept constant at $-(23.5 \pm 1)^{\circ}$ C while the flow rate was varied in the range from 8 – 16 L/min. A sample curve from one of these tests is shown below in Figure 5.5. The data are fit to the theoretical breakthrough curve described by Equation 3.27, where α , n, and τ are allowed to vary.

It can be observed from the sample curve that the theoretical model does not



Figure 5.5: 222 Rn and 218 Po count rates as a function of time using initial radon injection method with lines of best fit.



Figure 5.6: ²²²Rn and ²¹⁸Po count rates as a function of time using improved radon injection method with lines of best fit.

fit the data very well for the test. This problem was not limited to this run, but to all the runs conducted for the flow rate dependence tests. The primary feature appeared to be a rapid influx of ²²²Rn at the beginning of the test, followed by a falloff in concentration that was more in line with theory. Restricting the fit to this falloff region, the breakthrough values for both the ²²²Rn and ²¹⁸Po concentrations were plotted as a function of inverse flow rate in Figures 5.7 and 5.8. ²¹⁴Po was not used as the time taken for the concentration to maximize is much longer (see Figure 3.9). The ²²²Rn breakthrough times should be linear with an intercept equal to zero, while the ²¹⁸Po breakthrough time should have a non-zero intercept due to the time taken for the ²²²Rn to decay once it has entered the detector chamber. This is indeed what is seen, with the $^{222}\mathrm{Rn}$ intercept of 3.5 ± 4.5 being within uncertainty of zero as expected and the ²¹⁸Po intercept being 17.9 ± 3.8 . The slope of both lines, 498.6 ± 58.15 and 402.4 ± 48.94 are also within error of one another as expected. Therefore, despite the difficulties in fitting the data to the theoretical function, the Carbo-Act carbon does exhibit a linear response in its breakthrough time as a function of inverse flow rate, and using the more accurate radon fit, gives a k_a value of 50 ± 8 L/g.

There were a number of possible explanations for the initial influx of ²²²Rn. The most obvious one was that some channels were created in the carbon due to poor packing of the material, which allowed some ²²²Rn through the trap almost immediately, while the rest slowly diffused in afterwards. In addition to this, because of the method by which the ²²²Rn was introduced, namely connecting and disconnecting the ²²²Rn source, a pressure wave may have being sent through the trap when the gas flow was reintroduced, which may have forced some of the radon through faster. Finally, it was postulated that this might be an effect from using a high flow rate.

5.1.9 Temperature Dependence

To address these issues for the second set of tests, the trap was reopened and the carbon inside tamped down using a stainless steel rod. It was found that the Carbo-Act carbon was highly compressible, with height of the carbon inside the column being depressed roughly 0.5". More glass wool was added to make up for this loss of space. However during this process some carbon was lost, so the mass of the carbon inside was reduced to 8.6 ± 0.1 g from 10.6 ± 0.1 g. The high degree of compressibility seemed to support the channelling hypothesis for the initial radon influx.

For subsequent measurements, the temperature instead of the flow rate was varied. The flow rate used was between 5.3–5.7 L/min in order to reduce any possible high flow effects. The way the ²²²Rn was introduced was also changed. To avoid possible pressure waves in the carbon trap, the radon source was pressurized to about 25–45 kPa above the normal run pressure in the system. The gas flow was then started, with the source connected by a t-junction to the input. Approximately five minutes was allowed to pass to ensure a stable flow rate in the system, after which the source was opened slowly while the flow rate and pressure were watched carefully to ensure there were no large jumps in either of those two values. After being left open for approximately 30 s, the source was then closed. The breakthrough time was measured from this moment onwards. Between each test the trap was heated to well above room temperature and flushed with nitrogen gas for approximately 10 minutes at a flow rate of 5 L/min to remove any

remaining ²²²Rn. Each test was conducted with 4–5 days between each other, in order to allow the ²²²Rn source to regenerate so as to maximize the radon spike used.

As can be seen in Figure 5.6, these new methods, in addition to the compression of the carbon in the tube, resulted in the elimination of the rapid influx of radon seen in the previous run, so there was a much better agreement with the theoretical model. A run at a much higher flow rate (9.9 L/min) was conducted using the new conditions, and no initial peak was observed, so the effect was not due to the flow rate.

There was however some breakdown of the model near the end of some of the runs due to an elongated tail, probably from ²²²Rn atoms in the connection between the source and the gas line slowly making their way into the trap after the initial spike. To minimize this effect, the connection between the t-junction and the source was kept as short as possible (< 5cm in length) and was massaged during the initial introduction of ²²²Rn to minimize the amount that got stuck on the inside of the plastic tubing. The fits were therefore conducted with the latter part of the tail excluded, to ensure a better fit. However the tail effect largely only affects the value of n obtained, with its effect on the τ value being much smaller. Finally, as the flow rate also affected the breakthrough time, the average flow rate for each run was used to normalize all the tests to the expected breakthrough time for a flow rate of 5.3 L/min. This vastly improved the quality of the fit.

Both the ²²²Rn and ²¹⁸Po breakthrough times exhibited the expected exponential dependence on temperature, as can be seen in Figures 5.9 and 5.10. Again, the fit to the radon breakthrough times provided a better χ^2 /ndf value than the polonium curve. The values obtained for the equation, $\tau = \kappa \times exp(\Lambda/T)$ are shown below in Table 5.4. The binding energy of the carbon is calculated using $E_b = \Lambda * k_b$ which gives a value in agreement with the value obtained by John Golightly $(0.30 \pm 0.01 \text{ eV})$ for a different variety of carbon [49]. The binding energies obtained from the two different methods do not agree, but this is likely due to the poorness of fit for ²¹⁸Po.

Table 5.4: Temperature Fits

	κ (minutes)	Λ (K)	Binding Energy (eV)	χ^2/ndf
222 Rn	$(0.5 \pm 0.2) \times 10^{-4}$	3615 ± 106	0.312 ± 0.009	8.845/6
²¹⁸ Po	$(1.4 \pm 0.5) \times 10^{-4}$	3390 ± 96	0.292 ± 0.008	34.34/6

5.1.10 Dimensions for the DEAP-3600 Trap

To find an appropriate mass for the DEAP-3600 trap, the results from the DEAP-1 trap were extrapolated to the intended operating temperature using the Carbo-Act temperature results, where it is assumed that the two carbon brands have comparable binding energies. For the DEAP-1 trap, the radon peak was halfway through the trap after approximately 10 m³ of argon had been filtered, so the runtime was half the characteristic time. Using the trapping mass of 10 g, this gave a k_a of 2 m³/g at 168 K. For the Carbo-Act test trap, the characteristic time at 168 K was found by:

$$\tau = \kappa \times exp(\Lambda/T) \tag{5.8}$$

using the values of Λ and κ obtained from the ²²²Rn breakthrough data. This gave a characteristic time of about 80 days. Then, as the trap had a carbon mass of 8.6 g and the measurements were taken for a flow rate of 5.3 L, using:

$$k_a = \frac{\Phi\tau}{m} \tag{5.9}$$

this gave a k_a value of approximately 70 m³/g which is a factor of 35 improvement on the CARBOXEN trap. However, given the exponential nature of the temperature curve, extrapolating to lower temperatures accurately is difficult so the k_a value may in fact be lower.

The first radon atoms appeared in the DEAP-1 test about halfway through the test, or after 5 m³ of gas had been filtered. This gives a loss factor, L_f , of 4 for the DEAP-1 trap, i.e. radon can be expected to begin escaping the trap after a time of $\tau/4$. However, the carbon spheres for the CARBOXEN brand are more spherical than the Carbo-Act brand, so the packing quality for the latter is worse and its loss factor may be larger. For the Carbo-Act test trap, running at a temperature of 110 K instead of 168 K should give a factor of 35000 improvement in the k_a value. If $\Delta T = 10$ K, then the uncertainty in the temperature scaling, $T_f = \Delta \alpha / \alpha = 4$. If a safety factor, S_f , of 10 is chosen, then the trapping capacity, C_a , which is the volume of gas per unit trapping mass that can be safely filtered without radon escaping, is given by:

$$C_a = 35000 \times (70 \text{ m}^3/\text{g})/L_f/T_f/S_f \approx 20000 \text{ m}^3/\text{g}$$
 (5.10)

If a 200 g trap is used for the DEAP-3600 trap, then this means 4×10^6 m³ of argon gas can be safely filtered. With the expected DEAP-3600 fill rate of 100 L/min, this would give a safe run time of approximately 76 years in which no radon from the argon source would be expected to escape the trap.

While this suggests that a 200 g trap is more than sufficient for any of the needs of DEAP-3600, there are no measurements of the adsorption coefficients of carbon traps for gaseous nitrogen or argon around the temperature being proposed. If the worst case scenario is assumed, i.e. that it is not possible to get an adsorption constant much higher than $2 \text{ m}^3/\text{g}$, then the safe run time for the proposed trap would be about 4 hours. This would still be feasible using the temperature swing system, as long as the traps were purged every few hours. Some degree of 'sneak' radon may also be expected from channeling effects in the carbon, however the likelihood of this is reduced with a larger trap size. The building and testing of a prototype trap will be required to determine if this is an issue near the operating temperature and to estimate the adsorption constant.

For the design of radon traps, there is a tradeoff between the trap diameter and its length. The longer the trap, the larger the value of n, and hence the more efficient the trap becomes [48]. At the same time, the pressure drop increases, which is problematic for the DEAP fill system. With these concerns in mind, a ratio between the length and radius of 10:1 seems appropriate. As the Carbo-Act carbon has a density of 0.32 g/mL, the proposed dimensions for the trap are a length of 30 cm with a diameter of 5 cm for the trapping mass volume.

The pressure drop across the trap will depend on the filter used to hold the carbon in place, as well as the cross-sectional area, length of the trap and the properties of the carbon. In Subsection 5.1.6 it was found that the pressure drop due to the carbon was given by $P = 2.5\Phi + 5$ for pressure in kPa and a flow rate in L/min. If run at 100 L/min, this would give a pressure drop across the trap of about 250 kPa. The pressure varies proportionally to the length and inversely to the cross section so for the actual DEAP-3600 trap:

$$P_{actual} = P_{test} \times \frac{l_{actual}}{l_{test}} \times \frac{r_{test}^2}{r_{actual}^2}$$
(5.11)

where l is the length of the trap and r is the radius. The test trap dimension are $l_{test}=18.4$ cm and $r_{test}=0.79$ cm, and the planned specifications are $l_{actual}=30$ cm and $r_{actual}=2.5$ cm. This gives an expected pressure drop of 40 kPa from the carbon, which is manageable for DEAP. This is within the same order of magnitude as a similar trap using Carbo-Act carbon (albeit of a different grain size) found by Hardy Simgen [42].

5.1.11 Expected Radon Contamination

The temperature swing system proposed in the previous sections should eliminate any radon coming from the argon source as long as it cycles between the radon traps in an appropriate amount of time. The predominant ²²²Rn contamination should therefore come from the carbon itself. The emanated radon will travel through the trap at an average speed of $v = L/\tau$ while the gas is flowing. Radon that emanates at a distance that is further from the detector end of the trap than $d = v \times t_{run}$ does not escape the trap, where $d \leq L$. Therefore the fraction of the mass in the trap that emanates radon is d/L or t_{run}/τ . After a period of time, t, has passed the fraction reduces to $(t_{run} - t)/\tau$. Therefore the total number of atoms that passes into the trap, N, is given by:

$$N = \int_0^{t_{run}} \frac{t_{run} - t}{\tau} Emdt = \frac{Emt_{run}^2}{2\tau}$$
(5.12)

where E is the emanation rate in atoms per unit mass per unit time and m is the mass of the trap. To fill the DEAP-3600 chamber with 3600 kg of argon, assuming an argon density of 1.784 g/L and a flow rate of 100 L/min, will take about 14 days. The number of emanated radon atoms from the carbon that escape the trap does not depend on the cycle time, and it is assumed that purging the trap for each cycle will remove any of the emanated radon that builds up when the trap is not being used. For a CarboAct trap of 200 g, approximately 60 atoms/day should be produced, so if the characteristic time is at least a hundred times the run time, less than five atoms should escape. Even if only a breakthrough time of $10t_{run}$ is achieved, at most 40 atoms should escape. Therefore a reasonable upper limit of radon atoms from a complete fill of the DEAP-3600 detector should be less than 40 atoms.


Figure 5.7: Breakthrough time for 222 Rn as a function of inverse flow-rate.



Figure 5.8: Breakthrough time for ²¹⁸Po as a function of inverse flow-rate.



Figure 5.9: Breakthrough time for 222 Rn for the Carbo-Act test trap normalized to a 5.3 L/min flow rate as a function of temperature.



Figure 5.10: Breakthrough time for 218 Po for the Carbo-Act test trap normalized to a 5.3 L/min flow rate as a function of temperature.

Part II

Data Analysis

Chapter 6

Energy Calibration

For the next part of this thesis, the emphasis will be on examining the ²²²Rn contamination of the DEAP-1 detector and finding the correlation between the high energy (HE) alphas in the detector and the low energy (LE) nuclear recoils. A correlation is expected as events near the inner surface of the detector may result in untagged nuclei recoiling from an alpha decay or low energy alpha particles that would be indistinguishable from a WIMP nuclear recoil (see Figure 2.11). In order to identify these backgrounds accurately, the relationship between the number of detected photoelectrons (PEs) and the particle energy must be determined. For low energies this can be accomplished with high precision by examining the spectra produced when a ²²Na gamma source or a Am-Be neutron source is placed outside the detector. A 511 keV gamma from the ²²Na and a 60 keV gamma from ²⁴¹Am can be observed in well-defined photoelectric peaks in the spectrum. Finding the location of these peaks enables the determination of the light yield (LY), which is defined as the number of PEs produced per keV or eV for each event.

A method was required, however, to extrapolate the energy calibration to

higher energies. As the light yield changed over time [53], as has been observed from the source calibrations, a method to measure the energy scale on a run-by-run basis was also desired. The most obvious way to address both of these requirements was to calibrate the detector from the know high energy backgrounds within it of which the Compton edges from the uranium and thorium chains appeared to be the best candidates.

6.1 Compton Scattering

Compton scattering occurs when high energy photons inelastically scatter off electrons. The incident photon is reduced in energy, while the rest of of its energy is transfered to the electron, which is ejected from its parent atom, becoming a beta particle. The maximum energy that can be transfered by this process is given by:

$$E_{compton} = \frac{2E^2}{m_e c^2 + 2E} \tag{6.1}$$

where E is the incident energy of the photon, m_e is the mass of the electron, and $E_{compton}$ is referred to as the Compton edge. If the photon is absorbed by the electron instead of scattering, it transfers all its energy to the ejected electron, which results in a photoelectric peak at higher energies.

In addition to the primary beta background from 39 Ar, in the DEAP-1 detector there is a significant contribution from the isotopes 40 K (a natural background in the earth's crust) and 208 Tl (from the thorium chain) which produce gammas at 1460 keV and 2615 keV respectively. The electrons which are scattered by these gammas are visible as Compton edges in the energy spectrum. These edges can be described by the Klein-Nishina (KN) cross-section:

$$\frac{d\sigma}{dT} = \frac{\pi r_e^2}{m_e c^2 \alpha^2} \times \left(2 + \frac{s^2}{\alpha^2 (1-s)^2} + \frac{s}{(1-s)} \left(s - \frac{2}{\alpha}\right)\right) \tag{6.2}$$

Equation 6.2 gives the energy distribution of inelastically scattered electrons by a gamma of energy $h\nu$, where r_e is the Bohr radius of the hydrogen atom, T is the kinetic energy of the scattered electron, $\alpha = h\nu/m_e$, and $s = T/h\nu$. The measured energy spectrum is then obtained by convolving this spectrum with a Gaussian so that:

$$Compton(X) = k \int_0^{E_{max}/E_1} \left(\frac{d\sigma}{dt}\right) exp\left(-\frac{(X-s)^2}{2\sigma_{res}^2}\right) ds$$
(6.3)

where X is the measured energy of the scattered photon/electron over $h\nu$, σ_{res} is the energy resolution, $E_{max} = h\nu$, E_1 is the energy of the Compton edge, and k is a scaling parameter. This formulation has been used in other experiments for the energy calibration of plastic scintillators [51][52].

6.2 Method Testing

After generating the code to model the Compton edges, the results were compared to the sample curves generated in [51] to ensure the veracity of the method. The modeled sample Comptons for a 1274 keV gamma with various energy resolutions are plotted in Figure 6.1. The Compton edges are scaled so that their shapes are more visible. The curves match those produced in the previously mentioned publication, and the maximum of the zero resolution curve agrees with the expected Compton energy of 1062 keV for a 1275 keV gamma.



Figure 6.1: Compton edges for 1275 keV gamma

Further testing was conducted by fitting to the output of a Monte Carlo (MC) simulation of the 2615 keV and 1460 keV gammas in the detector, using the Reactor Analysis Tool (RAT). RAT is a Monte Carlo and analysis tool developed by the Braidwood collaboration for modeling the behavior of a liquid scintillator detector surrounded by PMTs. The MC generates both the Compton edge and the expected photopeak. The photopeaks are not visible in the V2 data from DEAP-1, due to a lower energy resolution in the real detector, but they allow the comparison of the light yield and energy resolution values. The Compton edges were fitted to the Klein–Nishina formula and the photopeaks to a combination of a Gaussian and an exponential to compensate for the contribution from the Compton edges (Figure 6.2). It was found that the light yield obtained from the Compton edges did not agree within uncertainty with that found from the photopeaks. However, the light yield values were within 3–5% of the photopeak values. The values from



Figure 6.2: Fits to Monte Carlo simulated gamma rays in the DEAP-1 detector. The large peak in each plot is due to the Compton edge from the gamma in question, which is followed by the smaller photopeak.

the different Compton edges agreed with each other as expected. The values obtained are shown below in Table 6.1. Attempts to resolve this difference were unsuccessful, so to compensate for this in the analysis, the light yield values from the Compton edges were assumed to have a 5% uncertainty.

Table 6.1: Compton Edge Fit versus Photopeak

	Light Yield (PE/keV)	Energy Resolution (%)	χ^2/ndf
2615 keV Compton	$3.187 \pm .009$	$3.0 \pm .3$	207.9/182
2615 keV Photopeak	$3.078 \pm .006$	$2.8 \pm .4$	24.51/24
1460 keV Compton	$3.19 \pm .01$	$3.2 \pm .3$	142.4/131
1460 keV Photopeak	$3.056 \pm .004$	$2.9 \pm .3$	9.236/13

While the Klein Nishina formula fit well to the higher energy gammas above 1 MeV, it was not so effective at fitting the Compton edge associated with the 511 keV gamma. An attempted fit is shown in Figure 6.3. The function does not fit well to either the lower or higher energy regions of the Compton. At the lower

regions, there appears to be a deficit of events, while the energy resolution seems to decrease after the maximum of the Compton, so that the slope of the edge decreases. If the energy resolution and light yield of the Compton edge are used to determine the maximum of the Gaussian for the photopeak, the resulting function is significantly displaced from the actual peak as can also be seen in Figure 6.3. There is, therefore, some effect occurring in Compton scattering at lower energies in the detector that is not yet understood or a defect in the model. The discrepancy also seems to increase as the energy decreases. However, as the LY of this region is already accurately determined by the analysis of the photopeaks from the target sources, this is not a critical issue for the energy calibration.



Figure 6.3: KN fit of 511 keV Compton edge and Gaussian + exponential fit of photopeak. The photopeak with the Compton edge LY is also shown. Note that difference between the two light yield values cannot be explained by the goodness of fit.



Figure 6.4: KN fit of Compton edges from 1460 keV and 2615 keV gammas from background run 10055 in DEAP-1.

6.3 Results of Energy Calibration

For the second version, V2, of DEAP-1, the light yield was found for the 60 keV photopeaks from the neutron runs and the 511 keV photopeak and the 1274 keV Compton from the Na-22 source. The 1460 keV and 2615 keV Comptons from background runs were also examined. The plots for the examined runs can be seen below in Figures 6.4 and 6.5. The colored regions in the plots show the regions used for the fit, as otherwise the overlap between the different Compton edges interferes with the fit.

Plotting the LY as a function of energy (Figure 6.6) a non-linearity was found, with a reduction in the LY at high and low energies. The points with the large error bars correspond to the LY values from the Compton edges, which have an estimated 5% uncertainty, while the photopeaks' error bars are too small to be



Figure 6.5: Fits of the 511 keV photopeak and the 1274 keV Compton in sodium run 10173 in DEAP-1. The 511 keV Compton is visible to the left of the photopeak and some contribution from the 1460 keV Compton can be seen to the right of the 1274 keV Compton.

visible. While the suppression at high energy is due to the PMTs saturating in the prompt light region, the suppression at lower energies is not yet understood. This non-linearity is present in both the scope and MIDAS data, and so is not a product of run-to-run fluctuations in the LY.



Figure 6.6: Light yield as a function of energy for the V2 of DEAP-1. The light yield is suppressed at high and low energies.

In March 2010, the second version of the DEAP-1 chamber (V2) was replaced with the version three (V3) chamber. This new chamber had a more purified TPB layer, and improved acrylic coating. The PMTs in DEAP-1 were also upgraded to Hamamatsu 8" R5912 high quantum efficiency PMTs. These are the PMTs which are planned for use in the DEAP-3600 detector. The previous analysis was repeated for the new chamber and compared to the old results. (Figure 6.7) The light yield was considerably higher than in the V2 data, with a 1.9 fold increase at the 60 keV energy level. This was due to the better PMT response, rather than a change in the performance of the detector. Once again there was a non-linearity in the light yield, but this time only at higher energies, with the gains made from the change in PMTs disappearing by 2615 keV.



Figure 6.7: Comparison of the LY of the V3 and V2 chambers. The 1.9 fold increase in LY at low energy from V2 to V3 almost disappears at high energy.

Due to the higher efficiency of the PMTs, there was also an improvement of the energy resolution of the detector, as shown in Figure 6.8. The energy resolutions of both the V2 and V3 chambers are fit to $1/\sqrt{E}$, as this is the expected fall off in energy resolution due to Poisson statistics. The uncertainties shown are statistical, but the choice of fit ranges means that there is a much larger systematic uncertainties present.

The non-linearity in the light yield for the V3 data is dependent on the voltage applied to the PMTs. A higher voltage leads to more photoelectrons per event, resulting in the PMTs saturating in the prompt light region at lower energies. In



Figure 6.8: Energy resolution as a function of energy for the V3 and V2 chambers, fitted to $1/\sqrt{E}$. Error bars represents statistical uncertainties only.



Figure 6.9: LY in V3 for two different sets of PMT voltages.

Figure 6.9, the light yield for running the PMTs at two different sets of voltages are shown. Note that for the higher pair of voltages (the first voltage value is the HV applied to PMT A, the second to PMT B), the non-linearity is much greater between 60 keV and 2615 keV than for lower voltage and the two curves converge around 60 keV.

6.4 Summary

The Klein Nishina formula proved to be useful for calibrating the DEAP-1 detector over a wide range of energies in conjunction with calibrations from the neutron and sodium runs. It was found to be accurate to within 5% of the photopeak light yield value. The method is significant as it allows run-by-run calibration of the detector by using only its internal backgrounds. It also allows an energy calibration over a much wider range than previously allowed.

Chapter 7

Alpha Analysis

The energy calibration from Chapter 6 was used to evaluate the response of the detector to radon from the November 2008 spike generated by an argon top up of detector. A number of high voltage (HV) and low voltage (LV) runs were conducted during this period. The HV runs have the advantage of higher effective LY and thus better energy resolution. However the PMT signal saturates in the prompt light region for higher energies, so LV runs have the advantage of a flat nuclear recoil band, which has a roughly equivalent energy scale to the gamma band. The radon spectrum was examined in both cases to examine the behavior of the different ²²²Rn chain isotopes in the detector and to find how many low energy (LE) background events are a result of leakage from the high energy (HE) ²²²Rn chain events.

7.1 Data Cuts

An Fprompt cut was used to distinguish gamma band events from nuclear recoil events, and a Zfit cut to restrict the data to events within the detector. Additional quality cuts were placed upon the data for the nuclear recoil events. For the DEAP-1 data, Edge0 and Edge1 give the time of the leading edge of the prompt light peak in each PMT pulse. To eliminate pileup of multiple gamma events in the same pulse, events with a difference of greater than 20 ns between the leading edge times for the two PMTs were discarded, as shown in Figure 7.1. A similar cut (< 30 ns) was used for the gamma events in the light yield analysis.



Figure 7.1: Plot of Edge1-Edge0 for neutron run 1877.

In addition to this, a cut was used for the nuclear recoil events which excluded events whose leading edge time was 20 ns or more removed from the average peak value, as shown in Figure 7.2. This removed any events with late or early triggers, which would effect the calculation of the total energy of the event. Applying these cuts to the Am-Be neutron run 1877, as shown in Figure 7.3, the ratio between the cut and uncut spectra is relatively constant between 10-60 keV, with an increasing ratio at lower PE. (Figure 7.4).



Figure 7.2: Plot of Edge0 for neutron run 1877.

7.2 Low Voltage Run Analysis

For the LV analysis, the runs 1950–1954 were analyzed. As the calibrations for Na-22 and the Am-Be sources were conducted at high voltage, an alternate method was required for calibrating the LV runs. The KN formula enabled the measurement of the light yield of the LV runs from the Compton edges of the 2615 keV and the 1460 keV gammas. Previously this had been conducted by lining up the Compton edges generated in the LV data with those from the HV data, on which extensive



Figure 7.3: Neutron spectrum for run 1877 with and without edge cuts.



Figure 7.4: Ratio between neutron spectrum with and without edge cuts. The ratio is essentially flat for all energies.

work has been done by Kevin Olsen [53]. The following section is a extension of his work using the KN formula to calibrate the LY of the runs instead of the previous method.

The nuclear recoil events in DEAP come predominately from alphas in the ²²²Rn chain, but also from events in the ²²⁰Rn chain and LE events such as alphas near the surface of the detector or WIMPs. The total nuclear recoil spectrum in the chamber can therefore be described by:

$$\frac{dN_{Bg}}{dE} = \frac{dN_{Bg}^{222}}{dE} + \frac{dN_{Bg}^{218}}{dE} + \frac{dN_{Bg}^{214}}{dE} + \frac{dN_{Bg}^{210}}{dE} + \frac{dN_{other}^{210}}{dE}$$
(7.1)

where each term gives the total number of events per energy bin for the given isotope. These alphas come from radon emanation from the materials used in the detector or from contact with the mine air. The influx of ²²²Rn from the argon gas during the spike then adds an additional ²²²Rn chain contribution described by:

$$\frac{dN}{dE} = \frac{dN_{top}^{222}}{dE} + \frac{dN_{top}^{218}}{dE} + \frac{dN_{top}^{214}}{dE}$$
(7.2)

There is no immediate significant contribution to the ²¹⁰Po due to the long lifetime of ²¹⁰Pb. The total nuclear recoil spectrum after the spike is therefore given by:

$$\frac{dN_{Bg+top}}{dE} = \frac{dN_{Bg+top}^{222}}{dE} + \frac{dN_{Bg+top}^{218}}{dE} + \frac{dN_{Bg+top}^{214}}{dE} + \frac{dN_{Bg}^{210}}{dE} + \frac{dN_{other}^{210}}{dE}$$
(7.3)

If the background before the spike (Equation 7.1) is subtracted from the spectrum

during the spike (Equation 7.3), this leaves the pure radon spectrum given by Equation 7.2. This equation allows the estimation of the concentration of ²²²Rn in the detector, as it gives the relationship between the sizes of the ²²²Rn and ²¹⁸Po peaks and the ²¹⁴Po peak. The ²¹⁴Po peak is well separated from the other alphas due to its higher energy making the number of ²¹⁴Po events easy to measure. By scaling the pure radon spectrum so the size of the ²¹⁴Po peaks matches the size of the ²¹⁴Po peak in the background, the total amount of ²²²Rn and ²¹⁸Po can be estimated. Once this is known, by subtracting the scaled pure radon spectrum (Equation 7.2) from the background spectrum (Equation 7.1) the spectrum of ²¹⁰Po in the detector can also be found:

$$\frac{dN_{diff}}{dE} = \frac{dN_{Bg}^{210}}{dE} + \frac{dN_{other}}{dE}$$
(7.4)

7.2.1 LV Alpha Energy Calibration

For the energy calibration of the LV runs, there is a significant offset near zero generated by the scope. As this offset was around 10–20 PE, for the low light yield (~ 0.13 PE/keV) of the LV runs, this translated into a significant error in the energy calibration. This offset was corrected for by finding the left hand minimum of the spectrum and then shifting that minimum to zero for each run. The 1460 keV and 2615 keV gammas were then fitted using the KN formula to obtain the LY for each run. The offsets and LY for each run can be found in Table B.1 in the appendix. The 2615 keV gammas were lower on average by 6%, due to the non-linearity in the LY as previously observed.

The light yield for the scintillation produced by nuclear recoils in noble gases

is quenched relative to that for electron recoils. After taking into account the quenching factor of 0.72 ± 0.07 for liquid argon [23], it was found that there was a small discrepancy between the alpha energy spectrum and the gamma energy spectrum. The peaks were not correctly aligned with the expected energies for the ²²²Rn, ²¹⁸Po, and ²¹⁴Po peaks. To address this, the TotalPE values for each run were normalized to run 1950 using the LY from the 1460 keV gamma, as this had better statistics than the 2615 keV gamma. These values were used to generate the TotalPE spectrum as can be seen in Figure 7.5. The spectrum was then fitted to a function consisting of three Gaussians, which gave an average LY of 134 PE/eV. The average LY obtained from the KN fits was 128 PE/eV, which was a 4.5% difference.



Figure 7.5: LV alpha spectrum in terms of PE for radon spike.

Using this LY value and the normalized TotalPE values, the energy spectrum for both the spike runs and the background runs were generated. Ideally the LY would have been calculated separately for the background runs, due to possible shifts in LY from run to run, but the peaks for the ²²²Rn chain were not well defined before the spike. The background spectrum was then normalized to the runtime (46.4 hours) for the combined spike runs. The two spectra can be seen in Figure 7.6.



Figure 7.6: LV alpha energy spectrum for both the radon spike and the background.

The pure ²²²Rn spectrum was then obtained by subtracting the background spectrum from the spike spectrum, which is shown in Figure 7.7. The ratio between the combined ²²²Rn and ²¹⁸Po peaks to the ²¹⁴Po peak was found to be $4.1 \pm$ 0.3 where the uncertainty was attained by assuming $\sigma = \sqrt{n}$. This is within uncertainty of the value obtained by Kevin Olsen, which was 3.9 ± 0.5 . This value supports the hypothesis that ²²²Rn diffuses throughout the whole detector volume, while its charged decay products migrate to the sides of the detector, where they might be detected as LE events. ²¹⁸Po decays quickly with a half life of 3 minutes, so its peak is not significantly reduced with respect to the radon peak, but due to the decay process through ²¹⁴Pb (27 minutes) and ²¹⁴Bi (20 minutes) a large fraction of the ²¹⁴Po has drifted to the edges of the chamber.

The pure radon spectrum was then normalized to the background spectrum using the magnitude of the ²¹⁴Po peak. Subtracting the normalized radon spectrum from the background then revealed the residual ²¹⁰Po in the spectrum (Figure 7.8). There is a large amount of noise in the spectrum, but there is a definite peak at 5.3 MeV as expected.



Figure 7.7: LV pure radon energy spectrum.

The rate of high energy alpha events (between 4000–9000 keV) was also found for each run. (Figure 7.9). The rates were fitted to the decay function $N = N_o e^{-\lambda t}$. The resulting half life was found to be 3 ± 1 days, which agrees with the expected 3.854 days for ²²²Rn. Integrating this function over the total time yielded the expected number of decays to be 1361, which is roughly within agreement with the



Figure 7.8: LV pure 210 Po spectrum.

number found from the number of high energy alpha counts in the total spectrum (1328).

From this analysis, it can be concluded that the KN method can be used to normalize the energy scale for the LV alpha energy range effectively and that it gives equivalent results to those obtained by aligning the HV and LV Compton edges. At LV it is accurate to within 4.5% of the actual value and has the advantage over the previous method of being able to determine the run's LY without using any calibration sources other than the detector backgrounds.

7.3 High Voltage Run Analysis

The same analysis was applied to the HV runs around the time of the spike, which had not previously been attempted. As previously mentioned, for the HV runs



Figure 7.9: LV rates as a function of time since first run.

the prompt light region saturates, so the energy scale for the nuclear recoil band is not the same as for the gamma band. However the gamma band LY can be used to gauge whether there are large shifts in the energy scale between each run and normalize the TotalPE values.

The runs used are listed in Appendix Table B.2. For the spike spectrum, the runs in the range 1931–1975 were used and for the background, the runs 1567–1925 were used and normalized to run 1939. For the HV runs, the offset was small in comparison to the LY, so this was not factored into the calculation. For most of the runs the change in LY was only on the order of a few percent, so this was not a major factor in the final result. The LY for the alpha particles was found to be 0.95 PE/keV, compared to the average gamma LY of 2.1 PE/keV, or a 0.55 reduction between the two bands which is much higher than the expected quenching factor of 0.72.



Figure 7.10: Energy spectrum of HV alphas before and after spike.

The nuclear recoil spectra before and after the radon spike are plotted in Figure 7.10, where the background is normalized to the 126.8 hour run time of the radon spike data set. Due to the higher LY for the HV runs, the events below 1000 keV in the spectrum can be made out. These events were not visible in the LV regime as they were lost in the gamma band. There is clearly an increase in the number of LE events after the radon spike, indicating that at least some of the background in the WIMP ROI is due to ²²²Rn and its daughter products.

Performing the same analysis as in the previous section, the pure radon and pure ²¹⁰Po spectra were obtained. As can be seen in Figure 7.11 the radon peaks are much broader in the HV runs, while the ²¹⁰Po spectrum looks essentially the same as in the LV runs (Figure 7.12). Examining the subtracted spectrum in the LE region, Figure 7.13, there is a definite peak between 0–500 keV that corresponds to the addition of radon into the detector.

Isotope	Lower Energy	Upper Energy	LV rate	HV rate
	Limit (keV)	Limit (keV)	(events/hour)	(events/hour)
²²² Rn	5300	5800	9.1 ± 0.4	3.0 ± 0.2
²¹⁸ Po	5800	6500	8.1 ± 0.4	2.1 ± 0.1
²¹⁴ Po	6500	9000	4.5 ± 0.3	1.3 ± 0.1
²¹⁰ Po	4000	5300	0.8 ± 0.1	0.73 ± 0.08
LE	0	1000	NA	5.0 ± 0.4
ROI	43	86	NA	1.1 ± 0.2

Table 7.1: Rates of Rn chain isotopes for radon spike.

The relative rates of each isotope were found from the pure radon spectrum and pure ²¹⁰Po spectra for both the HV and LV runs and recorded in Table 7.1. The ratio between the combined ²²²Rn and ²¹⁸Po peaks to the ²¹⁴Po peak was found to be equivalent to the LV result. There did not appear to be a direct relationship between the LE events and the number of high energy alphas, as while the former increased in number after the radon spike, there were still a substantial number occurring before the spike. This suggests that either other sources are contributing to this background, or that the majority of the ²²²Rn chain events are being detected as LE events. Examining the ratio between the number of high energy alphas and the LE events in the ROI, there appeared to be 0.18 ± 0.03 ROI events per alpha particle and 0.9 ± 0.2 ROI events per ²¹⁴Po event in the subtracted spectrum.

The nature of the distribution of ²²²Rn was further investigated by plotting the distribution of the number of radon events and the number of ²¹⁰Po events as a function of their position relative to the center of the detector (the Zfit parameter). In Figure 7.14 it can be observed that the ²²²Rn events are broadly distributed

	HV ratio	LV ratio
$(^{222}\text{Rn} + ^{218}\text{Po})/^{214}\text{Po}$	4.1 ± 0.4	4.1 ± 0.3
$LE/^{214}Po$	4.0 ± 0.5	NA
$LE/(^{222}Rn + ^{218}Po + ^{214}Po))$	0.79 ± 0.07	NA
$ROI/^{214}Po$	0.9 ± 0.2	NA
$ROI/(^{222}Rn + ^{218}Po + ^{214}Po)$	0.18 ± 0.03	NA

Table 7.2: Ratios between isotope counts in pure radon spectrum.



Figure 7.11: HV pure radon spectrum.



Figure 7.12: HV pure 210 Po spectrum. Red line shows 210 Po energy.



Figure 7.13: Spike LE spectrum with background subtracted. This corresponds to LE events due to the leakage from the HE radon decays.

within the chamber volume, with slight increases near the edge of the detector around |Zfit| = 10. The events outside of the detector volume are likely due to interactions occurring in the lightguides. The ²¹⁰Po events are strongly clustered towards the ends of the detector, near the windows. This could be due to previous contamination of the windows, or from buildup from charged ²²²Rn daughters clustering towards the ends, especially to the positive Zfit side of the detector.

In addition to this, the LE events in the pure radon spectrum, were plotted as a function of Zfit, as were the ²¹⁴Po events. This can be seen in Figure 7.15. The ²¹⁴Po events follow a similar distribution to the ²²²Rn, although it appears they are more strongly clustered towards the edges. The LE events appear to favor the negative Zfit side of the detector, and are peaked in the vicinity of the ²¹⁴Po peak. Also, the LE events increase towards the window, while the ²¹⁴Po events fall off, suggesting that the ²¹⁴Po decays are being detected as these low energy events. However this is by no means conclusive.

7.4 Relationship between Radon and LE Events in DEAP-1

Given the increase in LE events with the Rn spike, it was hoped that a direct relationship between the ²²²Rn rate in the DEAP-1 detector and the LE rate could be determined. Previously, the rates in the WIMP ROI had been examined, as have been seen in previous plots shown in this thesis concerning the radon spike [29]. It was hoped that looking at all the LE events below 1000 keV would reveal a relationship between the two varieties of events.



Figure 7.14: 222 Rn and 210 Po events as a function of Zfit.



Figure 7.15: LE and 214 Po events as a function of Zfit.

Examining the HV runs 1527–1975 (Figures 7.16 and 7.17) which were taken between September 1st – December 1st, 2008, it can be seen that after the radon spike from the argon top off, the rate of high energy alpha particles per run falls off with an exponential as expected. Using the fit equation, the fit gave a half life of 3.9 ± 0.2 days which agrees with the ²²²Rn half life of 3.824 days. The LE rate appears to jump up after the spike, but remains flat afterwards, again suggesting that the correlation between the two rates is not direct. This increase in LE events had not been seen in the previous analysis of the data, but would be expected from the analysis of the HV spectra before and after the spike. A closer examination of the LE rates and radon rates after the spike can be seen in Figures 7.18 and 7.19. The combined LV and HV rates were plotted together in Figure 7.20. Here the LV rate agrees with the HV and the combined data has a half life of 3.7 ± 0.2 days.

7.5 Summary

In summary, the radon spike allowed for a better understanding of the effects of 222 Rn and its daughter products on the LE rate in the DEAP-1 detector. The ratio between the 214 Po peak and the combined 222 Rn and 218 Po peaks was found to be 4.1 ± 0.3 , averaging the results from the HV and LV runs. This indicated that there were substantially fewer 214 Po events, suggesting that these events are being detected as LE events instead. Looking at the increase in LE events after the radon spike, it was found that 0.18 ± 0.03 LE events occur in the WIMP ROI for each high energy alpha decay, or $0.9 \pm .2$ events per 214 Po decay.

However, not all the LE events can be attributed to the radon chain decays, as there were a substantial number of events below 1 MeV prior to the radon



Figure 7.16: HE alpha rate from 4.5–9.0 MeV per run from September–December 2008. A decay curve fit to the radon spike is also shown.



Figure 7.17: LE nuclear recoil rate (0-1 MeV) per run from September–December 2008.



Figure 7.18: HE alpha rate from 4.5–9.0 MeV per run during spike. The data is fit to an exponential decay curve.



Figure 7.19: LE nuclear recoil rate (0-1 MeV) per run during spike.



Figure 7.20: Combined LV and HV runs for radon spike.

spike. Examining the high energy alpha rate and the low energy nuclear recoil rate, there was no visible direct correlation between the rate of radon chain decays in the detector and the LE event rate. This suggests that while ²²²Rn contributes to the LE region, it is not the sole cause of the background.

On average each radon atom will go through the three primary alpha decays before reaching the long lived ²¹⁰Pb, so the combined number of HE and LE events will be:

$$HE + LE = R \times 3E \tag{7.5}$$

where R is the number of radon atoms in DEAP-3600 and E is the nuclear recoil detection efficiency ($\approx 50\%$) [54]. The total number of HE events is given by LE/0.18 so the total number of LE events is given by:
$$LE = \frac{R \times 3E}{1 + 1/.18}$$
(7.6)

which has be to < 150 if the 0.2 fiducial event limit is to be achieved. Rearranging to solve for the maximum R value, this gives 660 events for 3 years or a maximum 222 Rn rate of 7 μ Bq.

For a worst case scenario, where the radon trap cannot achieve much better than ten times the run time, around 40 atoms will escape into the detector. The contribution from the relief valves should be on the order of only about an atom, as they will only contribute during the fill cycle. This would result in approximately 10 events in the ROI during the three year run time. If instead the carbon performs as expected and achieves an adsorption constant of at least a factor of 100 higher, this will fall to less than one event.

Chapter 8

Conclusions

Radon backgrounds are a significant issue for the DEAP detector, given the potential of ²²²Rn and its daughter products to mimic WIMP interactions. The successful implementation of the DEAP-1 radon trap and the subsequent elimination of radon spikes during the filling of the detector showed that ²²²Rn contamination from the argon gas source was a significant, but ultimately fixable problem. No radon atoms were predicted to enter through the argon source with the trap installed and the detector data no longer shows increases in the alpha activity after argon fills.

The continuing work on the DEAP-3600 radon trap has shown that the Carbo-Act F2/F3 grain carbon has an extremely low ²²²Rn emanation rate, with an upper limit of 284 atoms/day/kg. Testing of the carbon resulted in values of $\kappa = 5 \pm 2 \times 10^{-5}$ min/K and $\Lambda = 3615 \pm 106$ K for the characteristic time equation $\tau = \kappa(T)exp(\Lambda/T)$ for a trap of mass 8.6 ± 0.1 g run at 5.3 L/min. The proposed DEAP-3600 trap should therefore exhibit a characteristic time on the order of years if it is run at 110 K, making it highly effective at arresting any ²²²Rn contamination.

To maximize the efficiency of radon filtration, a temperature swing system has been proposed as the best method for DEAP-3600. This would consist of two traps with 200 g of trapping mass and a length of 30 cm and a diameter of 5 cm to maximize the trapping efficiency while minimizing the pressure drop across the trap. Extrapolating the pressure drop for the expected flow rate and dimensions of a functioning DEAP-3600 trap, the trap should experience roughly a 40 kPa pressure drop, which is well within the manageable level for the DEAP-3600 fill. Assuming the worst case scenario in which k_a is not much greater than 2 m³/g the traps should be purged every few hours to prevent any radon from entering through the argon source. The contribution from the carbon itself should be less than 40 atoms per fill of the detector. Further work needs to be done to design the trap's cooling and heating system, construct a prototype, and test its effectiveness, especially to see if channelling effects will be a major problem for the trap design.

For the analysis of the DEAP-1 data, the Klein-Nishina formula was found to be accurate to within approximately 5% at finding the LY of the detector by using the 1460 keV and 2615 keV Compton edges in the background spectra, although further testing should probably be conducted to find the discrepancy between the photopeak values and the Compton edges. Using this method, non-linearities were found in both the V2 and V3 light yields as a function of energy which are believed to be due to light saturation or other PMT effects. This method now allows for a run-by-run measurement of the light yield and thus improved energy calibration.

Applying the Klein-Nishina method to the LV alpha events in the V2 DEAP-1 data, it was found to be accurate to within 4.5% for assessing the run-by-run energies, once the offsets for the scope runs were found. The ratio between the ²²²Rn plus the ²¹⁸Po peaks and the ²¹⁴Po peak using this method was found to be 4.1 ± 0.3 . The reduction of the ²¹⁴Po peak with respect to the ²²²Rn and ²¹⁸Po peaks, suggest that the polonium daughter products are drifting to the surfaces of the detector and maybe detected as LE events instead of HE alphas. Subtracting the normalized ²²²Rn spectrum from the background confirmed previous work demonstrating a large degree of ²¹⁰Po buildup in the V2 detector.

While the nuclear recoil energies are heavily suppressed relative to the gamma at higher voltages, the Klein-Nishina formula was used to normalize the HV runs to one another so as to have a constant energy calibration. Using this, it was found that there was no direct link between the LE events in the V2 spectrum and the high energy alphas from the ²²²Rn chain. However the ²²²Rn spike was correlated with an increase in the LE rate, so the ²²²Rn level does contribute to the events in the LE region, however it may not be the only cause of these events. In the WIMP ROI, it was found that 0.18 ± 0.03 events would occur per high energy alpha decay and 0.9 ± 0.2 events per ²¹⁴Po decay. This gives a maximum allowable ²²²Rn rate of 7 μ Bq in DEAP-3600. The expected upper limit of the contribution from the radon trap to the background in the WIMP region of interest will be ten events. If the radon trap outperforms the DEAP-1 trap as expected, this could be as low as one event.

In conclusion, it has been confirmed that the ²²²Rn chain alpha decays contribute to the LE background rate in the DEAP-1 detector, and radon filtration systems have been been found to be effective at eliminating ²²²Rn contamination from the argon source.

Bibliography

- F. Zwicky, On the Masses of Nebulae and of Clusters of Nebulae, Astrophysics Journal, 86 (1937) 217–246.
- [2] V. C. Rubin and W. Kent Jr. Ford. Rotation of Andromeda nebula from a Spectroscopic Survey of Emission regions. *Astrophysical Journal*, 159, 379 (1970).
- [3] Douglas Clowe et al., A Direct Empirical Proof of the Existence of Dark Matter, Astrophysics Journal, 648 (2006), 109–113.
- [4] D.J. Fixen et al. Cosmic Microwave Background Dipole Spectrum Measured by the COBE Firas Instrument, *The Astrophysical Journal*,420 (1994), 445– 449.
- [5] C. L. Bennett et al. First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results, Astrophys. J. Suppl., 148, 1 (2003)
- [6] G. Bertone, D. Hooper, J. Silk, Particle Dark Matter: Evidence, Candidates and Constraints, *Physics Reports*, 405 (2005) 279–390.

- [7] M. Boezio et al., PAMELA and Indirect Dark Matter Searches, New J. Phys, 11 (2009).
- [8] M. Milgrom, A Modification of the Newtonian Dynamics as a Possible Alternative to the Hidden Mass Hypothesis, Astrophys. J. 270, 365 (1983).
- [9] G. W. Angus, H. Y. Shan, H. S. Zhao, and B. Famaey, On the Proof of Dark Matter, the Law of Gravity, and the Mass of Neutrinos, *Astrophys. J.* 654, L13 (2007).
- [10] G. Jungman, M. Kamionkowski, K. Griest, Supersymmetric Dark Matter, *Physics Reports*, 267 (1996) 195–373.
- [11] Z.Ahmed et al., Status of the Cryogenic Dark Matter Search Experiment, J Low Temp Phys. 151 (2008) 800–805.
- [12] Katherine Freese, Brian Fields, and David Graff, Limits on Stellar Objects as the Dark Matter of our Halo: Nonbaronic Dark Matter Seems to be Required, arXiv:astro-ph/9904401v1
- [13] Z. Ahmed et al., Results from the Final Exposure of the CDMS II Experiment, Astrophysics (2009).
- [14] T. Bruch for the CDMS Collaboration, CDMS–II to SuperCDMS: WIMP Search at a Zeptobarn, arXiv:1001.3037v1 (2010).
- [15] J. Angle et al., First Results from the XENON10 Dark Matter Experiment, *Physics Review Letters*, 100, 021303 (2008).
- [16] E. Aprile et al., First Dark Matter Results from the XENON100 Experiment, arXiv:1005.0380v2 (2010).

- [17] N. Fornengo, Status and Perspectives of Indirect and Direct Dark Matter Searches, Advanced Space Research 4 (2008) 2010–2018.
- [18] A. Davour, Proceedings of Identification of Dark Matter 2008, Stockholm, Sweden, Aug. 2008.
- [19] S. Archambaul, Dark Matter Spin-Dependent Limits for WIMP Interactions on 19-F by PICASSO, Phys.Lett.B682: (2009) 185–192.
- [20] M.G. Boulay and A. Hime, Direct WIMP Detection using Scintillation Time Discrimination in Liquid Argon, Astroparticle Physics 25, 179 (2006).
- [21] W.H. Lippincott et al., Scintillation Time Dependence and Pulse Shape Discrimination, *Physics Review C*, 78, 035801 (2008).
- [22] M.G. Boulay et al., Measurement of the Scintillation Time Spectra and Pulse Shape Discrimination of Low-Energy β and Nuclear Recoils in Liquid Argon with DEAP-1, arXiv:0904.2930v1 (2009).
- [23] R. Brunetti et al., WARP Liquid Argon Detector for Dark Matter Survey, arXiv:astro-ph/0405342v1 (2004).
- [24] P. Benetti et al. Measurement of the Specific Activity of Ar-39 in Natural Argon, Nuclear Instruments and Methods in Physics Research, A574 (2007) 83–88.
- [25] C. Galbiati and R. Purtschert, Discovery of Underground Argon with Low Level of Radioactive ³⁹Ar and Possible Applications to WIMP Dark Matter Detectors, J. Phys. Conf. Ser. 120: 042015 (2008).

- [26] J. J. Lidgard, Pulse Shape Discrimination studies in Liquid Argon for the DEAP-1 Detector. Masters thesis, Queens University (2008).
- [27] D.M. Mei and A. Hime, Muon-Induced Background Study for Underground Laboratories, *Physical Review D*, 73, 053004 (2006).
- [28] T. Sonley, Alpha Decay Backgrounds in the DEAP-1 Detector, Canadian Physics Association Conference (2010).
- [29] Walter Hugh Lippincott, Direct detection of dark matter with liquid argon and neon, Phd. Thesis, Yale University, (2010).
- [30] M.G Boulay, DEAP-3600 Introduction, DEAP/CLEAN Collaboration Meeting (2009).
- [31] M.G Boulay, Status of DEAP-1 and DEAP-3600 at SNOLAB, DEAP Collaboration Meeting (2010).
- [32] SNOLAB Users Manual (2006).
- [33] Steven J. Schowalter, Colin B. Connolly, John M. Doyle, Permeability of noble gases through Kapton, butyl, nylon, and SilverShield, Nuclear Instruments and Methods in Physics Research A, 615 (2010) 267–271.
- [34] Model 1025 Flow-Through Radon Gas Sources, Pylon Electronics. http:// www.pylonelectronics.com/pylonpdfs/DS123R3.pdf (2010).
- [35] http://www.cryomech.com/AL600_Brocure.pdf (2010).

- [36] S.V. Gorobets et al., Effect of a Magnetic Field on the Etching of Steel in Nitric Acid Solutions, *Russian Journal of Physical Chemistry*, Vol. 80, No. 5 (2006) 791–794.
- [37] Manqing Liu, ²²²Rn Emanation into Vacuum, MSc Thesis, Queen's University (1991).
- [38] F. Dalmok, Veress, M.Sterner, H.W Lee, SNO-STR 96-052.
- [39] Bob McPhail, Hentry Lee, and Ilan Levine, Calibration of Two SNO Lucas Cells, Group Report, July 27th 2000.
- [40] Michael Bruns, Gas chromatography with radon-222, Diploma thesis, University of Heidelberg (1979).
- [41] H. Simgen , G. Zuzel, Analysis of the ²²²Rn Concentration in Argon and a Purication technique for Gaseous and Liquid Argon, *Applied Radiation and Isotopes*, 67 (2009) 922–925.
- [42] Hardy Simgen, private communication.
- [43] M. Wojcika, G. Zuzel, Low ²²²Rn Nitrogen Gas Generator for Ultra-Low Background Counting Systems, Nuclear Instruments and Methods in Physics Research A 539 (2005) 427–432.
- [44] G. Heusser et al.,²²²Rn Detection at the mBq/m3 Range in Nitrogen Gas and a New Rn Purification Technique for Liquid Nitrogen, Applied Radiation and Isotopes, 52 (2000) 691–695.

- [45] M.K. Harrison, W.H. Lippincott, D.N. McKinsey, J.A. Nikkel, Use of Activated Charcoal for the Purification of Neon in the CLEAN Experiment, Nuclear Instruments and Methods in Physics Research A, 570 (2007) 556–560.
- [46] Andrea Pocar, Low Background Techniques and Experimental Challenges for Bornexio and its Nylon Vessels, PhD Thesis Princeton University (2003).
- [47] A.B. Littlewood, Gas Chromatograph: Principles, Techniques and Applications, Academic Press, p185–186 (1962).
- [48] A.B. Littlewood, Gas Chromatograph: Principles, Techniques and Applications, Academic Press, p169, p190 (1962).
- [49] John Golightly, Characterization of a Carbon Radon Filter and Radon detection, MSc Thesis, Queen's University (2008).
- [50] H.J. Cho, G. Edge, Summer 2008: Radon Decay Experiment, Internal Report.
- [51] S. Hohara et. al, A Simple Method of Energy Calibration for Thin Plastic Scintillator, *IEEE Transactions on Nuclear Science*, vol. 48, no. 4 (2001) 1172–1176.
- [52] N. Kudomi, Energy Calibration of Plastic Scintillators for Low Energy Electrons by Using Compton Scatterings of Gamma Rays, Nuclear Instruments and Methods in Physics Research A, 430 (1999) 96–99.
- [53] Kevin Olsen, Analysis of Alpha Backgrounds in the DEAP-1 Detector, Improvements to the Resolution and Efficiency of the DEAP-3600 Dark Matter Detector and Their Effects on Background Studies, MsC Thesis, University of Alberta (2010).

- [54] Bei Cai et al., Surface background control in DEAP-3600, DEAP STR-2010-011 v5 (2010).
- [55] Tina Pollman, High Energy Alpha Background Analysis, Internal Document (2010).

Appendices

Appendix A

Light Yield Runs

Run Type	Run Number	PMT Voltage A/B	Date
Neutron	2108	1560/1610	March 26th 2009
22 Na	2210	1562/1612	May 3rd 2009
Background	2110	1560/1610	March 3rd 2009
Background	2111	1560/1610	March 3rd 2009

Table A.1: V2 Chamber Scope Runs

Table A.2: V2 Chamber MIDAS Runs

Run Type	Run	PMT Voltage A/B	Date
Neutron	10174	1562/1617	December 1st 2009
²² Na	10173	1562/1617	December 1st 2009
Background	10055	1561/1611	August 5th 2009

Table A.3: V3 Chamber MIDAS Runs

Run Type	Run Number	PMT Voltage A/B	Date
Neutron	11014	1762/1565	March 26th 2010
Neutron	11067	1662/1465	April 26 th 210
²² Na	11041	1763/1565	April 8th 2010
²² Na	11076	1662/1465	April 26th 2010
Background	11031	1762/1565	April 1st 2010
Background	11078	1662/1465	May 13th 2010

Appendix B

Alpha Runs

Run	Run time (hours)	Offset (PE)	1460 Compton	2615 Compton	Correction
			LY (PE/eV)	LY(PE/eV)	Factor
1360	17.99	11	$179.37 \pm .09$	$171.00 \pm .20$	0.95
1667	51.88	13	$173.07\pm.07$	$163.40 \pm .10$	0.98
1818	2.03	6	$174.30 \pm .40$	$166.70 \pm .60$	0.98
1871	9.17	20	$181.90\pm.10$	$170.60 \pm .20$	0.93
1950	1.24	11	$170.00 \pm .40$	161.00 ± 2.00	1.00
1951	13.23	20	$176.10\pm.10$	$165.20 \pm .20$	0.97
1952	12.02	20	$175.60\pm.10$	$164.70 \pm .20$	0.97
1953	11.98	19	$174.40\pm.10$	$164.30 \pm .20$	0.97
1954	9.17	17	$172.80 \pm .10$	$162.90 \pm .40$	0.98
		Average	175.30	165.46	

Table B.1: LV Scope runs used in Alpha Analysis

Run	Run time (hours)	LY (PE/keV)	Correction Factor
1527	20.55	2.20	0.98
1528	25.30	2.20	0.98
1568	21.40	2.04	1.06
1570	1.32	2.00	1.08
1657	0.25	2.01	1.08
1661	1.56	2.39	0.9
1684	3.31	1.97	1.10
1751	1.42	2.16	1.0
1868	9.56	2.46	0.88
1892	8.35	2.14	1.01
1895	10.77	2.11	0.98
1925	10.92	1.87	1.16
1931	7.61	2.00	1.08
1936	0.92	2.12	1.02
1939	8.50	2.16	1.0
1942	12.02	2.16	1.0
1948	10.67	2.16	1.0
1956	11.98	2.16	1.0
1957	9.81	2.16	1.0
1960	10.49	2.16	1.0
1961	12.02	2.16	1.0
1972	9.56	2.18	0.99
1973	12.02	2.18	0.99
1974	11.98	2.18	0.99
1975	11.98	2.19	0.99
	Average	2.13	0.99

Table B.2: HV Scope runs used in Alpha Analysis

Appendix C

Data Cleaning Cuts

C.1 Light Yield Cuts

- Fprompt < 0.7
- |Edge0 Edge1| < 30

C.2 LV Cuts

- Fprompt > 21.0/TotalPE + 0.38 [55]
- |Zfit 5| < 10
- |Edge0 Edge1| < 20 && |Edge0 1025| < 20 && |Edge1 1025| < 20

C.3 HV Cuts

• Fprompt > 21.0/TotalPE + 0.38 [55]

- |Zfit| < 10
- |Edge0 Edge1| < 20 && |Edge0 1025| < 20 && |Edge1 1025| < 20