Results concern DarkSide-50, a dark matter direct detection apparatus operating underground at Laboratori Nazionali del Gran Sasso (LNGS). This paper reports and explores an excess of events with primary scintillation energy less than 30 photoelectrons, the number of which decays over time. These events can be identified as a radioactive contamination by using Regions of Interest (ROI) to include events with such low energy that only the secondary scintillation records as a pulse. Although majority trigger 2 (mt2) and majority trigger 3 (mt3) data cannot be compared for very low energy events using trigger multiplicity recorded by hardware, multiplicity can be measured by software. This paper presents a method to do so and with the unity of the mt2 and mt3 data shows the decay as very likely Argon-37.

I. INTRODUCTION

In the past few decades, much research has been dedicated to the study of dark matter. Non-baryonic, non-luminous and non-absorbing in nature, dark matter is estimated to comprise $23\%$ of matter and energy in the universe. Dark matter has been indirectly identified through the internal motion of galaxies [1], through gravitational lensing [2], and in the cosmic microwave background [3], but characteristics of this elusive particle remains one of the foremost puzzles in physics.

A leading theory describing dark matter is Weakly Interacting Massive Particles (WIMPs). These particles have a cross section roughly equal to the weak force and thus only interact rarely with standard matter, and do not interact electromagnetically (hence dark). However, the interactions that do occur would create low energy recoils ($<100$ keV), identifiable with a sufficiently sensitive detector apparatus and proficient veto system.

One such detector and veto system, DarkSide-50 is a Liquid Argon Time Projection Chamber located nearly a mile underground at Laboratori Nazionali del Gran Sasso (LNGS) in Italy, with the goal of detecting WIMPs. This paper will outline relevant features of the apparatus, will describe the low energy peak found in the detector data, and will identify it as radioactive isotope Argon-37. Also, in the process of identifying the contaminant the PulseFinder algorithm efficiency was measured, and a new method of measuring triggers for individual was designed, allowing comparison between data from runs with differing trigger standards. These findings will also be described.

II. DARKSIDE-50 APPARATUS

The TPC and its surrounding vetoes has already described in great detail by members of the DarkSide collaboration [4]. However, a brief overview is included here.

A. Detectors and Hardware

DarkSide 50 is an assembly of three detectors. From the center outward, it is comprised of: the Liquid Argon Time Projection Chamber (LAr TPC), which detects dark matter; the Liquid Scintillator Veto (LSV), which serves as a veto for cosmogenic and radiogenic neutrons, $\gamma$-rays, and cosmic muons, as well as providing shielding from aforesaid particles; the Water Cherenkov Detector (WCD) for shielding and anti-coincidence veto for muons of cosmic origin. See Figure 1 for reference. This veto/anti-coincidence system, in addition to the detector’s location nearly a mile underground, dramatically reduces the amount of background events.

FIG. 1. DarkSide-50 Apparatus. Inside is cylindrical LAr TPC, surrounded by spherical LSV, and lastly encompassed by WCD.
The WCD is 11 meters in diameter, 10 meters high with high purity water inside. Originally from the Borexino Counting Test Facility, it makes use of Cherenkov photons produced by relativistic muons or other particles, which is detected by 80 8” PMTs mounted on the side and bottom of the tank to detect scintillation photons to provide anti-coincidence.

The LSV is 4 meters in diameter filled with 30 tons of borated liquid scintillator (equal parts pseudocumene and trimethyl borate). The neutron capture reaction $^10\text{B}(n, \alpha)^7\text{Li}$ that takes place in the liquid creates scintillation light that can be detected by an array of 80 8” PMTs along the inside of the sphere.

The TPC itself is uniquely designed to identify $\beta$ and $\gamma$ background that does manage to pass through the LSV and WCD, and discern them from WIMPS. The TPC is filled with 50 kg of highly purified liquid argon, found in underground sources to reduce amount of radioactive Ar-39 isotope. Kept at boiling temperatures, the liquid argon has a 1-cm thick layer of gaseous argon. As shown in Figure 2, there are 38 3” low-background, high-quantum-efficiency PMTs, 19 located along the top of the TPC, 19 located along the bottom. The windows separating the PMTs from the body of the detector, are coated with a wavelength shifter, tetraphenyl butadience, that absorbs the 128 nm scintillation photons emitted in the TPC and converts them to visible photons (peak wavelength 420 nm) which can be detected with high efficiency PMTs, 19 located along the top of the TPC, and 19 along the bottom. Voltage is applied across the anode (-12.7 kV) and the mesh grid (-5.6 kV), creating electric fields between the bottom and the grid, and between the grid and the top, which are kept uniform by the field cage.

The electric field is created in the TPC with an ITO cathode on the bottom of the TPC, ITO anode on the top, a mesh grid 5 mm below the liquid-gas interface and a field cage composed of copper rings surrounding the exterior of the TPC walls. Voltage is applied across the anode (-12.7 kV) and the mesh grid (-5.6 kV), creating electric fields between the bottom and the grid, and between the grid and the top, which are kept uniform by the field cage.

![DarkSide-50 liquid argon time projection chamber](image)

When a particle enters the apparatus, it recoils with the nucleus of the argon atoms (nuclear recoil) or with the electrons (electronic recoil), both of which ionize the argon atoms. This produces a primary scintillation signal that is detected by the PMTs both at the top and the bottom, referred to as “S1”. Ionization electrons then drift to the surface of the liquid argon due to the electric field between the bottom of the TPC and the mesh grid (200 V/cm). The electric field between the grid and the top extracts these electrons into the gas (2.8 kC/cm) and accelerates them through the gas (4.2 kV/cm). The motion of the electrons through the gas produces a secondary scintillation signal, or “S2” proportional to the collected ionization. Additionally, photons from the S2 can sometimes reflect off the bottom array of PMTs, causing a third scintillation signal, or “S3”. In this case, the S3 will occur 373 $\mu$s after the S2, the maximum drift time across the TPC.

Using pulse shape discrimination of primary scintillation and ratio of scintillation to ionization, the nuclear recoils expected by WIMPs can be distinguished from background. A parameter named $f_{90}$, the ratio of the first 90 ns of a pulse over the first 7 $\mu$s, takes advantage of differences in ionization density between nuclear recoils (like those created by WIMPS) from electronic recoils (as created by by $\beta$ and $\gamma$ backgrounds). As nuclear recoils have a high $f_{90}$ and electronic recoils have a low $f_{90}$, it is an excellent way to identify between the two. Also helpful is the ratio of scintillation to ionization, or the integral of the S2 pulse over that of the S1 pulse. Because electronic recoils have low density electron-ion pairs, there will be more free electrons traveling through the gaseous argon, creating a stronger S2 signal than that created by a nuclear recoil. Thus electronic recoils will have a higher S2/S1 ratio than nuclear recoils, a characteristic that can be utilized in data analysis.

![DarkSide-50 liquid argon time projection chamber](image)

**FIG. 2.** DarkSide-50 liquid argon time projection chamber.

**B. Data Acquisition and Event Reconstruction**

The data acquisition window for routine data is 440 $\mu$s with a subsequent 810 $\mu$s inhibit time, to prevent the end of S2 data or an S3 from firing as triggers. Photo-multiplier signals from the TPC and vetoes are stored when a threshold number of TPC PMT discriminators fire within a 100 ns window. Majority trigger 3 (“mt3”) data is defined as events recorded only after a threshold of three discriminators fire; likewise, two discriminators must fire for majority trigger 2 (“mt2”) data.

TPC event reconstruction software uses Fermi National Accelerator Laboratory’s *art* framework. Raw waveforms from the TPC and vetoes are used to reconstruct physical pulse for each of the three detectors. A baseline is determined and subtracted from the raw waveform in each of the 38 channels for the TPC. Each channel above a threshold of 0.1 PE/sample adds together to form a sum channel, which is then used for pulse finding. This reduces the effect of coherent noise across channels so that the PulseFinder algorithm can identify S1s and S2s using a threshold of 0.3 PE/sample. The PulseFinder
also records pulse start time and can identify overlapping pulses (most common in cases such as a multi-site deposition of an S2 signal).

When two or more pulses are found, the earlier pulse is identified as an S1, and the latter as an S2. Several cuts test the validity of this and can also identify potential S3s. A prominent cut that will be mentioned is “basic cuts,” which ensures that events have 1 or 2 pulses, a baseline is found in the waveform, and the “livetime,” or the total duration of time since the last event ended, less the inhibit time, is sufficiently long (i.e. the new data is not a remnant of the previous event).

For more detail on data acquisition and event reconstruction, refer to the DarkSide collaboration’s extended description [4].

III. IDENTIFYING THE PRESENCE OF ARGON-37

A. Low Energy Peak in S1 Data

In examining S1 pulses that pass basic cuts, a small peak is found at very low energies, specifically at less than 30 photoelectrons (PEs).

The events with S1 energies <30 PE can be normalized by the livetime of the data run (effectively converted into a rate) and graphed as a function of the time in days over which the data was taken (May 8, 2015 to June 21, 2015). Although an earlier portion of the data is mt3 data and later data is mt2 data, this was previously resolved by only graphing mt2 events in which three or more discriminators fired (i.e. a “multiplicity” of 3 or greater). The resulting graph indicates a decay of the frequency of these events over time (Figure 5), strongly suggesting a radioactive contaminant.

A $\chi^2$ best fit decay curve suggests an element with a mean lifetime of 57.62 days, as shown in Figure 5. Argon-37, the closest logical candidate for this contaminant, decays with a lifetime of 50.55 days. However, this fit assumes that all Argon-37 decay had enough energy to be detected as two-pulse events, and that mt3 data and mt2 data can be compared if the mt2 data has a multiplicity of 3 or greater. Testing the former assumption allowed an analysis of the latter.

B. One-Pulse Data

Because these Argon-37 potential events (will be referenced to as “Ar-37 events”) are very low energy, it is possible that for some events the S1 (the less energetic pulse in electronic recoils) was not regarded as a pulse by the PulseFinder algorithm. Thus some events with two pulses could be recorded as only having one pulse. This provoked an investigation into 1-pulse low-energy events. Most useful in identifying these additional events were the software tools $f_{00}$ and the ratio of secondary scintillation to primary scintillation.

1. Using Regions of Interest

Whereas 2-pulse Ar-37 events have an S1 and an S2 identified by the PulseFinder, 1-pulse low energy events...
will only record the secondary scintillation (the more energetic of the two) as a pulse, labeling it as S1. However, the primary scintillation of Ar-37 events can be reconstructed using an early window of time referred to as the Region of Interest (ROI). This ROI window has both a full 7 μs window and a 90 ns prompt window over which data is taken for all events. Because this region is where we expect primary scintillation for Ar-37 events, the ROI full window can be treated as the S1, and our S1 as secondary scintillation. In searching for 1-pulse Ar-37 events, we first require that all events pass basic cuts, have 1 pulse, and if there is an S1, it begins between 3.0 μs and 369.1 μs after the end of the ROI window. This ensures the pulse is greater than the minimum time delay between the end of primary scintillation and the beginning of secondary scintillation, but less than the minimum delay time between an S2 and an S3. These cuts isolates events in which the S1 timing is within the window of a secondary scintillation, where we expect it to be for 1-pulse Ar-37 events.

2. Using the Secondary/Primary Scintillation Ratio

The ratio of the secondary scintillation to primary scintillation (in this case S1/ROI) is helpful tool in finding 1-pulse events similar to the 2-pulse events. As shown in Figure 6, the majority of 2-pulse Ar-37 events have S2/S1 ratios spanning from ~5 to ~150, increasing in distribution height with lower energies. Comparing 1-pulse events (as shown in Figure 7), the events are characteristic of the 2-pulse Ar-37 events, except for the cluster of events with S1/ROI <7.

Events with S1/ROI ratios less than seven were individually examined and characterized by random scattering of photoelectrons, marginally containing a pulse. The requirement S1/ROI >7 was determined to be a reasonable cut for sifting through 1-pulse data.

As mentioned earlier, f₉₀ is a ratio of the integral of the first 90 ns of a pulse, divided by the first 7 μs. Electronic recoils resulting from a radioactive decay, will have a specific f₉₀ distribution. Graphing the f₉₀ of the 2-pulse Ar-37 events (Figure 8), we see that we are looking for 1-pulse events with an f₉₀ value of 0.4.

With the aforementioned start time and S1/ROI cuts on 1-pulse events, the f₉₀ distribution of the remaining events is shown in Figure 9.

This histogram shows a cluster of events like the ones we are looking for, as well as a cluster of events with an f₉₀ ~1. These events concentrated clusters of photoelectrons caused by Cherenkov light, and not a pulse that we are interested in. In 2-pulse data these are cut by requiring f₉₀ <0.85; the 1-pulse events are subjected to this cut as well. This produces the f₉₀ distribution displayed in Figure 10.

The remaining 1-pulse events, passing the basic cuts, with start time between 3 μs and 369.1 μs after the ROI window, with an S1/ROI <7 and f₉₀ >0.85. The f₉₀
4. A Word on 0-Pulse Data

Although 0-pulse data underwent much of the same analysis as 1-pulse data, search into events with such low energy and no pulse did not find any events resembling the 2-pulse Ar-37 energy events.

C. Using Distribution of Low-Energy Events to Evaluate PulseFinder Efficiency

The distribution of comparable 1-pulse and 2-pulse low-energy is an ideal resource for determining the efficiency of the PulseFinder algorithm. As shown in Figure 11, it is at energies lower than ~20 PEs that the PulseFinder begins to decrease in efficiency and ROI data begins to take precedence. (Note: As the more recent data and the future data is mt2 data, this analysis was done on mt2 data).

FIG. 9. Distribution of \( f_{90} \) as a function of number of PE in the ROI window for 1-pulse events.

FIG. 10. Distribution of \( f_{90} \) as a function of number of PE in the ROI window for 1-pulse events after all cuts.

distribution and the secondary/primary scintillation distribution for the 1-pulse events shows good agreement with their 2-pulse counterparts. We consider these 1-pulse events to be events of the same types as the 2-pulse Ar-37 events (now referred to as “1-pulse Ar-37 events”), and can be added to the decay analysis.

Since the 1-pulse events are those in which primary scintillation existed but was not found by the PulseFinder, and the 2-pulse events are those in which it was found, we can determine the PulseFinder efficiency by dividing the rate of the 1-pulse events by the two pulse events, as shown in Figure 12.

Analysis of this curve suggests that the PulseFinder finds pulses with near-100% efficiency at ~14 PE, and ~50% efficiency at ~10 PE.

D. Using Distribution of Low-Energy Events to Evaluate Mt2 and Mt3 Compatibility

The distributions of low-energy events can be compared for mt2 and mt3 data, to test whether mt3 data can
be reconstructed with mt2 data—the second assumption made in the decay analysis.

Shown in Figure 13 is comparison of the frequency of 1-pulse and 2-pulse Ar-37 events normalized by livetime; mt2 data is shown in pink and mt3 data is shown in purple. Because mt2 data was taken chronologically later than mt3 data, and the events of interest are a radioactive decay, mt2 data has a small frequency of events or peak. However, at very low energies mt2 has more events than mt3: it only requires two discriminators to fire, or a “multiplicity” of 2 or greater, therefore collecting a greater number of very low energy events than mt3, which requires a multiplicity of 3 or greater.

![Figure 13](image13.png)

**FIG. 13.** Comparison of total frequency of low-energy Ar-37-like events, normalized by livetime. Compared is mt2 data (pink) and mt3 data (purple).

As shown in Figure 14, we can require mt2 data (pink) to have a multiplicity of 3 or greater in an attempt to recreate the data that would have been received if the run had been mt3. The noticeable difference is in the very low energy region, where 1-pulse events are found. To perfectly recreate mt3 data with mt2 data, we expect the rising curves (<10 PE) to match well, just as the energies >30 PE match well, since these are both areas of background events.

![Figure 14](image14.png)

**FIG. 14.** Comparison of total frequency of Ar-37 events, normalized by livetime. Compared is mt2 data with a multiplicity of 3 or greater (pink) and mt3 data (purple).

A potential explanation of this phenomena is that not all photoelectrons in the initial 100 ns window are regarded as triggers, but rather only the first 2 or 3 photoelectrons (in mt2 or mt3 data, respectively), and those that follow closely after the initial 2 or 3. Figure 16 demonstrates two cases in which mt2 data with three triggers might display different multiplicities.

![Figure 16](image16.png)

**FIG. 16.** Model of mt2 event in which both case 1 and case 2 should be regarded as a trigger multiplicity of 3, but instead case 1 has a multiplicity of 3 and case 2 has a multiplicity of 2.

In other words, rather than the trigger window being
standard for mt2 and mt3, it depends on the majority trigger setting. Because mt2 and mt3 data will then measure multiplicity with different standards, we cannot use it to compare mt2 and mt3 data.

E. Building and Testing a Software Multiplicity

The inability of hardware multiplicity to compare mt2 and mt3 data motivates the creation of a multiplicity measure independent of majority trigger setting. This was accomplished using the ROI prompt window.

Because the ROI prompt window is the location of nearly all triggers and the integrals over each channel for individual events is available, it can be used for a software count of multiplicity. The average size of an event trigger measured by the hardware (mt2 or mt3) is 0.6 within 80% certainty (this was confirmed as ideal threshold for software, as demonstrated in the next section). Thus, multiplicity can be measured as the number of channels with an integral greater than the 0.6 PE threshold in the ROI prompt window.

To verify the results, the hardware and software multiplicities for individual events can be graphed and compared event-by-event. As shown in Figure 17, some events remain the same (seen along the diagonal, along which software multiplicity is equal to software multiplicity). There are a few events in which events had a slightly greater hardware multiplicity than software multiplicity. A sample of 10 events were manually examined and found to be caused either by triggers that fired slightly before the ROI prompt window (7 events), or with PE slightly lower than 0.6 PE (3 events).

However, the majority of events had a greater software multiplicity than hardware multiplicity. A manual examination of 50 events found nearly all (98%) to have all software triggers added came after the hardware triggers. In other words, the additional triggers found by the software algorithm were very likely triggers that were a little two late beyond required hardware multiplicity, as described in Figure 16. Because this algorithm does not depend on whether the data is mt2 or mt3, it is ideal for comparing both sets.

F. Finding the PE Threshold

0.6 PE was confirmed as the optimal threshold by examining comparison between mt2 and mt3 curves at different thresholds. After examining 0.2 PE, 0.4 PE, 0.6 PE, 0.8 PE, 1.0 PE, 1.2 PE and 1.4 PE, 0.6 PE was determined to be the best threshold. The detailed analysis for 0.6 PE is shown below, with notes regarding other thresholds. For reference to figures regarding other thresholds, see Appendix.

Distributions of events as a function of software multiplicity and ROI PE was analyzed for all thresholds, comparing mt2 and mt3. For comparable events, the distribution would look similar for mt2 and mt3 events with software multiplicity of 3 or greater. This was the case for 0.2 PE, 0.4 PE, 0.6 PE, 0.8 PE and 1.0 PE. Distributions of mt3 events (Figure 18) and mt2 events (Figure 19) with a 0.6 PE software multiplicity threshold are shown below.

FIG. 18. Histogram of mt3 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.

FIG. 19. Histogram of mt2 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.
For the 1-pulse Ar-37 events with a software multiplicity of 3 or greater, the best combination will yield comparable lines for the beginning (where events are primarily consist background events) and slightly less mt2 events towards the end, where Ar-37 events have begun to decay. This is exactly what we see in Figure 20, in which data has a threshold of 0.6 PE, but also holds true for 0.4 PE and 0.8 PE.

With the right threshold, an mt2 multiplicity of 2 or greater compared to an mt3 of 3 or greater will have an excess of background events that have only 2 triggers, but the portion with slightly fewer will remain untouched. This is exactly what we see for the threshold of 0.6 PE, as shown in Figure 21, (but also holds true for 0.4 PE and 0.8 PE.)

Lastly, if the mt2 is required to have a multiplicity of 4 or greater, we expect both the background and Ar-37 events to decrease in number, creating an mt2 curve much less than the mt3. This is what occurs with a threshold of 0.6 PE, as shown in Figure 22, (but also holds true for 0.4 PE and 0.8 PE.)

We also want to verify that the 2-pulse Ar-37 events are not significantly decreased by raising the software multiplicity from 2 to 3, just as we do not expect to see a large difference in the latter end of the 1-pulse Ar-37 events. This is tested using 2-pulse mt2 Ar-37 events, comparing software multiplicity of 3 and software multiplicity of 2. As shown in Figure 23 (in which data has a threshold of 0.6 PE, but also holds true for 0.4 PE), very few of these events are lost in increasing the multiplicity, which is expected since very few Ar-37 events will have high enough energy to have two pulse found by the PulseFinder, but only two triggers.

Both 0.4 PE and 0.6 PE show results consistent with expectations in this analysis, and thus 0.6 PE is considered to be the maximum acceptable threshold for software multiplicity.
G. Using Software Multiplicity and 1-pulse Low Energy Events to Identify Ar-37

The assumptions made to create Figure 5—that all the events are 2-pulse and mt2 and mt3 data can be compared with a hardware multiplicity of 3—have now been shown incorrect and the data can be modified to create a new decay fit. Figure 24, like Figure 5, is an exponential fit including an exponential term, a linear term, and a constant to the data. It includes 2-pulse and 1-pulse Ar-37 data, and requires both mt2 and mt3 data to have a software multiplicity of 3 or greater.

The lifetime of this decay is $52.60^{+7.75}_{-5.98}$ days, with a $\chi^2$/ndf value of 239.2/268. The linear fit, used to account for other potential decays (Phosphorus-33, Sulfur-35) which are small enough to be approximated by a linear fit. This value is $-1.466^{-11}_{+2.772} -5$, a very small contribution. Also included is the constant, used to account for systematic background events that were not successfully cut; this value is $0.003443 \pm 0.000835$.

IV. CONCLUSION

In conclusion, a search for additional low-energy events and an exploration into the use of a software multiplicity yielding a fit with a lifetime closer to that of Argon-37, increasing the probability that this radioactive decay is Argon-37. 1-pulse Ar-37 events were found in using software tools $f_{90}$ and the ratio of secondary scintillation over primary scintillation (S2/S1 or S1/ROI). The PulseFinder efficiency was evaluated and approximated at near-100% efficiency for $\sim 14$ PE, and $\sim 50\%$ efficiency at $\sim 10$ PE. Additionally, software multiplicity was defined as the number of channels with the integral over the ROI prompt window $>0.6$ PE for a given event. This allows mt3 and mt2 data to be compared, when a software multiplicity of 3 or greater is required of mt2 and mt3 data.

V. ACKNOWLEDGMENTS

Much thanks is due to Alden Fan, who oversaw each aspect of this analysis and was a ready and willing resource for endless questions. Dr. Hangou Wang was Primary Investigator for this project and was also helpful. The National Science Foundation and University of California, Los Angeles are also due credit for this program and opportunity.

VI. APPENDIX: MORE FIGURES

A. Threshold Analysis: 0.2 PE

FIG. 1. Histogram of mt3 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.

FIG. 2. Histogram of mt2 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.

FIG. 3. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.2 PE.

B. Threshold Analysis: 0.4 PE

FIG. 4. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.2 PE.

FIG. 5. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.2 PE.

FIG. 6. Histogram of mt3 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.
FIG. 7. Histogram of mt2 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.

FIG. 8. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.4 PE.

FIG. 9. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.4 PE.

FIG. 10. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.4 PE.

FIG. 11. Mt2 2-pulse Ar-37 events, comparing software multiplicity of 2 or greater (bright green) and of 3 or greater (bright green).

C. Threshold Analysis: 0.8 PE

FIG. 12. Histogram of mt3 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.
FIG. 13. Histogram of mt2 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.

FIG. 14. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.8 PE.

FIG. 15. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.8 PE.

FIG. 16. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 0.8 PE.

FIG. 17. Mt2 2-pulse Ar-37 events, comparing software multiplicity of 2 or greater (bright green) and of 3 or greater (bright green).

D. Threshold Analysis: 1.0 PE

FIG. 18. Histogram of mt3 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.
FIG. 19. Histogram of mt2 1-pulse Ar-37 events as a function of software multiplicity and ROI PE.

FIG. 20. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 1.0 PE.

FIG. 21. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 1.0 PE.
FIG. 22. Frequency of 1-pulse Ar-37 events as a function of ROI PE, normalized by livetime. Mt3 data (red) has a multiplicity of 3 or greater, mt2 data (blue) has a multiplicity of 2 or greater. Software multiplicity threshold is 1.0 PE.