Chapter 7

Data Set, Cuts, and Efficiencies

7.1 Chronology and Raw Data Set

Run 19 took place from October, 1998, through September, 1999. A chronology is given in Tables 7.1, 7.2, and 7.3. A total of 96.4 raw live-days of data were acquired, corresponding to 63.6 raw kg d summed over BLIPs 3 through 6. Raw live-days denotes the live time of the DAQ system, before any cuts are made, excepting periods where the raw data are completely discarded due to obvious problems. Though BLIPs 1 and 2 were alive during the first half of the run, they are neglected when quoting exposures because they do not contribute to the WIMP sensitivity due to their electrodes. In Figure 7.1, the integrated real and live times for which the DAQ was on and taking dark-matter data (i.e., excluding grounding, pulser runs) is shown. For the DAQ live time alone, the largest slope observed is \( \sim 0.6 \) live-day/real day, and there are of course many periods where that number is not achieved. In Table 7.4, the expectations for data-taking efficiencies are shown. The lowest efficiency expected during stable running is 67\%, which is only about 10\% higher than is observed: most of the dead time is understood. Dead-time reductions can be made in every category except for cryogen transfers. However, it should be realized that, even with 0.95 efficiencies individually for cryogen transfers, grounding, and DAQ, and without phonon-pulser runs, one still only expects a live fraction of \( 0.95^3 \approx 0.86 \). In addition to the normal losses during running, there are significant blocks of time where the data rate drops to zero. Early in the run, the bulk of these were due to DAQ and electronics debugging and detector-operation optimization. From April onward, downtime occurred primarily because of assorted phonon-system pathologies and veto repairs and upgrades.

Pathologies in the phonon-channel behavior resulted in a nonnegligible loss of live time during Runs 19A and 19B. Such periods are easily cut out of the data set because they have obvious symptoms, such as phonon-trigger-rate excursions, obvious changes in phonon-pulse shape, or large excursions in the thermistor DC refs. The symptoms and possible explanations of this behavior are discussed in Appendix C.

Ionization- and phonon-trigger-rate distributions for the entire run for each detector are shown in Figure 7.3. The ionization trigger-rate distributions are very clean. The tails to low rate are an artifact of the way the distributions are calculated. The phonon trigger-rate distributions are not as clean, but clearly the periods with trigger-rate excursions constitute a very small part of the data set (note that both axes are logarithmic).
### Table 7.1: Run 19A Timeline

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug – Sep, 1998</td>
<td>Removal of original complement of 3 striplines, installation of full-size internal lead shield, 18 new striplines and 2 old striplines</td>
</tr>
<tr>
<td>Oct 8</td>
<td>Debugging and testing of Run 19 detectors and tower</td>
</tr>
<tr>
<td>Oct 9 – Oct 16</td>
<td>Installation of BLIP1/2 and BLIP3–6 towers</td>
</tr>
<tr>
<td>Oct 17 – Oct 21</td>
<td>Run 19A cooldown</td>
</tr>
<tr>
<td>Oct 22 – Nov 3</td>
<td>Modifications to monitoring system external wiring</td>
</tr>
<tr>
<td>Nov 3 – Nov 11</td>
<td>Ionization-bias scan: ±4 V, ±6 V, ±8 V</td>
</tr>
<tr>
<td>Nov 12 – Dec 4</td>
<td>Low-background data at 6-V ionization bias on all detectors; live fraction low due to computer crashes</td>
</tr>
<tr>
<td>Dec 4 – Dec 9</td>
<td>Crashing DAQ problem traced to bad memory chip on Pilot’s G3 upgrade card</td>
</tr>
<tr>
<td>Dec 10 – Dec 14</td>
<td>DAQ back online; “slow pulses” begin</td>
</tr>
<tr>
<td>Dec 14 – Dec 27</td>
<td>Low-background running attempted at 4-V ionization bias on all detectors, but assorted problems and repairs cause significant dead time</td>
</tr>
<tr>
<td>Dec 27</td>
<td>IVC leak during LHe transfer causes warmup; Run 19A ends</td>
</tr>
</tbody>
</table>

### Table 7.2: Run 19B Timeline

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 5 – Jan 15, 1999</td>
<td>Run 19B cooldown</td>
</tr>
<tr>
<td>Jan 17 – Jan 27</td>
<td>Modifications/repairs to front-end and RTF electronics</td>
</tr>
<tr>
<td>Jan 28 – Mar 21</td>
<td>Low-background running at 4-V ionization bias with some electronics and detector-bias optimization</td>
</tr>
<tr>
<td>Mar 22 – Mar 30</td>
<td>Stable low-background running at 6-V ionization bias</td>
</tr>
<tr>
<td>Mar 31 – Apr 5</td>
<td>Neutron calibration</td>
</tr>
<tr>
<td>Apr 3</td>
<td>Campus-wide power outage; nonlinearity appears</td>
</tr>
<tr>
<td>Apr 5 – Jun 4</td>
<td>Mostly stable running, but with phonon-trigger outbursts</td>
</tr>
<tr>
<td>May 28</td>
<td>BLIP1/2 turned off due to appearance of “slow pulses” and sufficient data acquired</td>
</tr>
<tr>
<td>Jun 4</td>
<td>Halt run to determine cause of phonon-channel problems (trigger outbursts and slow pulses)</td>
</tr>
<tr>
<td>Jun 14</td>
<td>Attempt &gt; 4 K warmup to check helium-film hypothesis; refrigerator runs away due to IVC/OVC leak; end of Run 19B</td>
</tr>
</tbody>
</table>
Table 7.3: Run 19C Timeline

<table>
<thead>
<tr>
<th>Date Range</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun 20 – Jun 30</td>
<td>Run 19C cooldown</td>
</tr>
<tr>
<td>Jul 1 – Jul 9</td>
<td>Low-background running at 1-V ionization bias for electrode study</td>
</tr>
<tr>
<td>Jul 10 – Jul 15</td>
<td>Low-background running at 6-V ionization bias</td>
</tr>
<tr>
<td>Jul 20 – Sep 14</td>
<td>Photon calibration (last day at 1-V ionization bias)</td>
</tr>
<tr>
<td>Jul 20 – Jul 30</td>
<td>5% veto hole in West counter; repaired Jul 30</td>
</tr>
<tr>
<td>Aug 3</td>
<td>Veto ADCs debugged — good veto ADC data available from here on</td>
</tr>
<tr>
<td>Aug 27 – Aug 31</td>
<td>Pot pump out of commission; circulation halted and refrigerator maintained at 4 K</td>
</tr>
<tr>
<td>Sep 15 – Sep 20</td>
<td>Low-background running at 1-V ionization bias</td>
</tr>
<tr>
<td>Sep 21 – Sep 22</td>
<td>Photon calibration at 1-V ionization bias</td>
</tr>
<tr>
<td>Sep 23</td>
<td>Neutron calibration</td>
</tr>
<tr>
<td>Sep 23 – Sep 26</td>
<td>Data taken without top polyethylene</td>
</tr>
<tr>
<td>Sep 27 – Sep 28</td>
<td>Debugging of IVC leaks while cold</td>
</tr>
<tr>
<td>Sep 28</td>
<td>Begin warmup; end of Run 19C</td>
</tr>
</tbody>
</table>

Table 7.4: Run 19 data-taking-efficiency summary. Estimated minimum and maximum expected efficiencies for those that can vary or whose exact value is not known are indicated by the “min” and “max” columns.
Figure 7.1: Cumulative data-acquisition real time and live time. The top curve indicates the actual time that the DAQ was operating; the lower curve indicates when it was “live” — i.e., waiting for a trigger. The two dashed lines correspond to slopes of 0.70 and 0.67, the expected maximum and minimum slopes from Table 7.4. The origin of the horizontal axis is Jan 1, 1999.
Figure 7.2: Cumulative live time vs. real time for BLIPs 3 through 6 and for various cuts. The data sets are, from top to bottom: all events that are not random and not detector-pulser events (same as bottom curve in Figure 7.1); and passing cGoodTime (detector is “alive”); and passing pretrigger cuts for the given detector (cPreQual for the detector); and passing pretrigger cuts for all detectors that are “alive” (cPreQual(1)). The dashed lines have slope of 0.5, which matches the lowest curves well. The origin of the horizontal axis is Jan 1, 1999. See Section 7.2 for definition of the cuts.
Figure 7.3: Histograms of the number of triggers observed per 400-s block of live time for the entire run. Note that both scales are logarithmic to clearly show the outlier behavior. The overlaid curves are Poisson fits, with the best-fit mean $\mu$ shown. Note also that an event is counted as a trigger for a given detector only if that detector was the first-triggering detector; this is why the apparent mean trigger rate is about 0.15 Hz instead of 0.33 Hz.
7.2 Data-Quality Cuts

To prepare the data for a search for WIMP-induced nuclear recoils, a number of data-quality cuts are made. The goal of these cuts is to remove pileup, periods of high noise or trace baseline wandering, and to select only those events where the pulse fits are of sufficient quality to ensure the accuracy of the energy estimate. The last point is critical: since the nuclear-recoil sensitivity of CDMS detectors is founded on high-resolution measurements of both phonon and ionization energies, degradation or blatant inaccuracy of these measurements must be avoided at all costs. Overestimation of the phonon energy is especially troublesome, as it pushes events to low ionization yield.

As Andrew Sonnenschein pointed out in his dissertation [8], cuts on the phonon- and ionization-pulse-fit $\chi^2$ can be used to eliminate many different types of problem events at once, but one is left without any understanding of the causes of the losses. To better understand such losses, cuts are defined with specific rationales in mind and the effects of the individual cuts are checked. This set of cuts relies heavily on the experience of Andrew Sonnenschein and Richard Schnee from Run 18.

All cuts are named and begin with a lower case “c” to indicate “cut.” In general, a cut on a given reduced quantity (RQ) has a name that is the RQ name prepended with a “c”; e.g., cPstd. The plots shown in this section are made for a randomly selected 10% of the data unless otherwise indicated. Also, in general, it is unnecessary to show figures for both phonon sensors of a given detector because they behave similarly.

7.2.1 Pretrigger-Trace-Quality Cuts

As mentioned in the previous chapter, a number of cuts are made on pretrigger-trace quantities. These are made to ensure the traces are free of pileup, within the digitizer window, and that the noise environment is reasonable. In this section, I describe the justifications for these cuts.

- **cP1bs, cP2bs**: These are cuts on the mean pretrigger baseline in the phonon channels, P1bs and P2bs, in units of digitizer bins. The goal of these cuts is to ensure the pretrigger trace is in a reasonable range – not so close to the bottom of the digitizer window that noise could push samples below the edge, and not so close to the top of the window that saturation occurs at an unexpectedly low energy. As mentioned in Chapter 5, either case can occur if the thermal disturbances cause the thermistor carrier amplitude to fluctuate too quickly for the DC-ref subtraction to compensate ($\tau = 66$ s). Another case is events preceded by large events, e.g., through-going muons. The event under consideration may be on the steeply falling tail of a muon event or on the recovery from undershoot due to AC coupling. The choice of the cut is made by comparing the distribution of the P1bs and P2bs parameters for unsaturated and saturated events: if the phonon baselines were absolutely stable, then there would be no correlation between whether an event is saturated (high energy) and the baseline. The distributions of P1bs are shown in Figure 7.4. As one can see, the saturated-event distribution deviates from the unsaturated-event distribution very close to the bottom of the window and above about 3000 digitizer bins. These distributions are stable over the run, so a fixed acceptance range of (15, 3000) is used for all detectors and all times. The logical AND of cP1bs and cP2bs is cPbs.
Figure 7.4: Distributions of mean phonon pretrigger-trace baseline for sensor 1, P1bs. Dark: unsaturated events for a random 10% of the data. Light: saturated events. The solid vertical lines show the cut position. The lower set of plots zooms in near 0 to show clearly the position of the lower cut. The main peak in the accepted region in the top plots corresponds to the nominal baseline position. The secondary bump corresponds to a short period when the baselines were artificially offset. Plots for P2 are not shown because they are identical.
• \textbf{cQIbs, cQObs}: These cuts are the analogues of \textit{cP1bs} and \textit{cP2bs} for the ionization channels. They reject very few events: the ionization-trace baselines are intrinsically very stable because the DC level has no dependence on the detector behavior. Also, pileup occurs far less frequently because the ionization pulses are very short, $\tau_f = 40 \mu$s. The same range, (15, 3000), is used. \textit{cQbs} is also defined analogously.

• \textbf{cP1std, cP2std}: These are cuts on the standard deviation of the pretrigger baseline, which is the standard deviation of the ADC values for the samples in the pretrigger region. These cuts remove low-level baseline wandering that increases the baseline noise, periods of high phonon-channel noise, and pretrigger pileup. Typical distributions for P1std and the effect of the cuts are shown in Figure 7.5. Only events passing \textit{cPbs} have been plotted, as \textit{cPbs} removes events with zero or anomalously low P1std and P2std due to part of the trace being below the digitizer window. The distributions have three main characteristics: a clear central peak corresponding to “normal” events, a hard lower edge, and an extended, exponentially decreasing tail. The absolute lower edge results from quantization noise. The exponential tail is due to pretrigger pileup. Events with any kind of pileup may be discarded while maintaining high efficiency because of the low trigger rate (0.33 Hz/detector).

As discussed in the previous chapter, PipeCleaner is used to determine these cuts adaptively based on the data. This is necessary due to varying noise conditions — a fixed cut would be excessively harsh during some periods and excessively loose during others. The distributions
of events passing the combined cPstd cut are also shown in Figure 7.5. The smooth upper end of the post-cut distribution reflects the variation in the adaptive cut position.

- **cQIstd, cQOstd**: These cuts on the ionization pretrigger-trace standard deviation also reject very few events because the ionization-noise environment is stable. Moreover, the pretrigger-trace standard deviation is dominated by cross-talk of the 1-kHz phonon bias and so is not very sensitive to small changes in the ionization-noise environment. The cuts do appear to eliminate some pileup, though these events could probably have been eliminated by cQPileup (see below). These cuts are determined adaptively in the same way as the cPstd cuts. The distributions of events before and after the cut are shown in Figure 7.6. The distributions for QO are wider than for QI because the 1-kHz cross-talk to QO is larger: the capacitance to the neighboring detector’s thermistors is larger for QO than QI.

- **cPdcref**: As noted earlier, there are periods during which, due to refrigerator instability, electronics anomalies, or other unknown causes, the phonon-lockin DC refs leave their normal range, indicating the detector temperatures have changed. Small variations in DC ref can be corrected by the “DC-ref correction” discussed in the previous chapter. However, large excursions leave the range where a linear correction can be done, so such times are discarded. Figure 7.7 illustrates the cut. The distributions are clearly non-Gaussian, and different ranges can be considered “normal” at different times. Too loose a cut degrades the phonon measurement resolution due to uncorrectable drifts; too tight a cut reduces the live time unnecessarily. Since neither the resolution nor the live time degrade quickly with the position of the cut, the exact position of the cut is not critical and it is determined manually.

- **cGoodTime**: This cut is used to discard periods of known low-quality data. For the early part of Run 19, its primary use is to discard a detector’s data when its electronics were in need of repair. Another use is to cut periods of DAQ or veto malfunction. The cut also includes cPdcref.

- **cErrorMask**: cErrorMask requires the ErrorMask RQ to be 0. ErrorMask is a mask with bit assignments for a number of trigger-related problems. For example, the global trigger is sent to the three independent banks of the history-buffer module to allow synchronization; ErrorMask indicates if one of these synchronization bits is not found.

- **cPreQual** cPreQual is the logical AND of the above cuts. A general cPreQual, cPreQual(1), is defined to be the logical AND of cPreQual for those detectors out of BLIPs 3 through 6 that pass their own cGoodTime cuts. The goal of cPreQual(1) is to ensure that all live detectors have clean pretrigger traces. In principle, such a harsh cut is not necessary. For example, if one detector has pretrigger pileup and the others do not, the first detector can be discarded and any possible multiple-scatter events reclassified as single scatters. The rate of such misidentification is not significant and can be estimated. The main reason for the requirement is due to nonidealities in the electronics and detectors, cross-talk, etc. For example, if one detector has a pretrigger muon, its ionization channel can electrically cross-talk to other detectors as it comes out of saturation.
Figure 7.6: Distributions of ionization pretrigger-trace standard deviation for QI (top plots) and QO (bottom plots). Light: distribution before cut. Dark: distribution after cut.
Figure 7.7: Distributions of thermistor DC-ref data. Light: before cut. Dark: after cut.
7.2.2 Posttrigger-Trace-Quality Cuts

Additional cuts are used to eliminate posttrigger pileup. In principle, the QPreTime cut should be included in the pretrigger cuts, but it is more convenient to combine it with the QPostTime cut.

- **cQPileup**: This cut checks the history buffer for pretrigger or posttrigger ionization triggers using QPreTime and QPostTime. These RQs contain the times of the last ionization trigger prior to and the first ionization trigger after the Global Trigger time. Distributions of QPreTime and QPostTime are displayed in Figure 7.8. The large peak at the origin corresponds to events coincident between detectors. For the majority of events, if there is no coincident trigger, then QPreTime and QPostTime time out — no additional triggers are found in the history buffer, which is consistent with the 20-ms width of the buffer and the typical $\sim 3$-s time between events. An acceptance window extending from $-50 \text{ µs}$ to $300 \text{ µs}$ is necessary to accept coincidences. The large posttrigger size is needed presumably because of double triggering in the electronics, not because of physical delays of this size. In the QPostTime distribution, in addition to the coincidence peak, a flat distribution of accidental triggers is observed. The distribution appears flat (instead of exponential) because the 10-ms region shown is small compared to the average time between events of $\sim 3$ s. The QPreTime distribution is more complex. The flat distribution with QPreTime $\lesssim -9$ ms arises from accidentals. The bump between $-5$ ms and $0$ ms arises from events in which the Global Trigger was enabled between the ionization and phonon pulses for an event. For such events, the system triggers on the phonon pulse and the ionization trigger appears in the pretrigger history. Such events are possible because the phonon pulse is intrinsically very slowly rising, the lockin low-pass filter introduces a time delay, and the phonon-trigger filter performs another low-pass-filtering step to optimize the energy threshold. From the distribution, it is seen that the delay can be as large as $5$ ms. These events are also rejected, though it is possible they may be usable. The fraction of events rejected is very small, $\sim (5 \text{ ms})/(3 \text{ s}) = 0.17\%$. Explicitly, the cQPileup cut is defined to retain two classes of events: first, events in which both QPreTime and QPostTime time out; and second, events in which a coincidence occurs, with QPreTime $> -50 \text{ µs}$ and QPostTime $< 300 \text{ µs}$. All other events are rejected.

- **cPst**: As described in Chapter 6, the P1st and P2st RQs indicate the time of the last sample within 5 standard deviations of the trace baseline that occurs before the largest peak in the pulse. Thus, these RQs are sensitive to posttrigger pileup where the second event is larger than the first. Surprisingly, the distributions of these RQs are quite well behaved in spite of the lack of any filtering in their determination. The behavior of these parameters is dependent on the trigger type, as is shown in Figure 7.9. Posttrigger pileup can be seen clearly in the on-detector ionization-trigger plot as a tail of events to high P1st. The sloping at very high energies occurs because the pulses are large enough that the change of slope of the pulse rise becomes apparent above the noise. The flaring of the ionization-trigger and off-detector phonon-trigger distributions at low energy follows $E^{-1}$, as expected for a time-like quantity derived from a pulse (see Appendix B for a discussion of the expected noise of time-offset estimation). The strong energy dependence in the on-detector phonon-trigger case reflects the energy-trigger-time relationship for phonon-triggered events. The cuts are defined to accept the bulk of the distributions; they are indicated in the plots.
Figure 7.8: Distributions of QPreTime and QPostTime. Dark: events passing cut. Light: events failing cut. For most events, QPreTime and QPostTime time out and so the events do not appear. The distributions are explained in the text.
Figure 7.9: Typical plots of P1st vs. phonon energy for on-detector ionization triggers, off-detector ionization triggers, on-detector phonon triggers, and off-detector phonon triggers. The cuts are indicated in the plots; events above the lines are cut.

- **cBaseQual**: This cut is the logical AND of cPreQual, cQPileup, and cPst, so named because it ensures the quality of the entire trace baseline by removing pretrigger and posttrigger pileup.

Figure 7.10 illustrates the usefulness of the pretrigger- and posttrigger-trace cuts by comparing the distribution of phonon $\chi^2$ before and after the cuts. Clearly, the cuts defined so far remove the great majority of pathological pulses.

### 7.2.3 Pulse-Quality Cuts

These cuts are intended specifically to check the pulses themselves. It is preferable to discard pathological pulses and accept the resulting efficiency loss rather than accept them with misestimated energies.

- **cpchisq, cqchisq**: Cuts on $\chi^2$ of the phonon- and ionization-pulse fits. Recall that, while called a $\chi^2$, the distribution of phonon $\chi^2$ does not match a statistical $\chi^2$ distribution. As discussed in Chapter 6, variations in $\chi^2$ appear due primarily to pulse-shape changes. Therefore, standard, statistically rigorous techniques for determining the natural cut position are not applicable, and the adaptive algorithm described in Chapter 6 is used. Given the cleanliness of the phonon-$\chi^2$ distribution after application of the previous cuts, it is questionable whether such a cut is necessary. At this point, the cut is historically embedded in the analysis. The
Figure 7.10: Typical phonon-pulse-fit $\chi^2$ vs. energy for events passing (top) and failing (bottom) cBaseQual. A detector’s hardware trigger must fire for it to pass cBaseQual; events without hardware triggers account for the band of normal events at 1–2 keV being discarded.
adaptive method for defining the cut was only developed during Run 19C and has not been applied to the Runs 19A and 19B data. The Run 19A and 19B cuts were determined by eye.

Because the ionization $\chi^2$ is well behaved, a cut on ionization $\chi^2$ is barely necessary. A very liberal cut is made, accepting all events for which an optimal-filter fit could be done. The adaptive algorithm is unable to find a reasonable cut point because the distributions are lacking in features the algorithm was designed to find.

The ionization-$\chi^2$ cut presents one problem. Due to the high interdetector capacitance in the close-packed geometry, there is significant cross-talk between detectors. No attempt is made to correct for this. It would be possible to perform a common fit, including cross-talk, as is done for the inner and outer electrodes of single detectors, but this additional complication has not been tackled yet. Because no correction is made, a significant tail to high $\chi^2$ for low-energy ionization pulses is seen when any adjacent detector exhibits saturation in the ionization channel. The ionization-$\chi^2$ cut is therefore defined using a data set in which no detectors are saturated. The cut rejects a large number of events in which there are saturated detectors. However, as mentioned earlier, all multiple scatters can be discarded without any loss of sensitivity for the WIMP-search analysis. Another data set that is important for the final analysis is the veto-anticoincident double-scatter neutrons. However, the simulations show that such neutrons are rarely accompanied by a high-energy particle since the neutron is produced outside the shield. The neutrons themselves deposit small energies (as discussed in Chapter 3). Therefore, the cut’s efficiency for these events is high. Another data set that may be biased by this effect is the veto-coincident neutrons. These neutrons are produced in the inner-lead shield and the copper of the cryostat, so accompanying high-energy photons have a better chance of interacting in the detectors simultaneously. As is discussed below, it is seen that the simulations, efficiency-corrected using the “single-scatter efficiency,” match the data well, indicating that only a small fraction of multiple-scatter veto-coincident neutrons are rejected because of a coincident high-energy detector interaction.

- **cppart**: The phonon partition quantity is \( \frac{(P_1 - P_2)}{(P_1 + P_2)} \). “Partition” is a misnomer, since the energy is not partitioned as the ionization is; the name is given because the expression is analogous to the ionization partition, \( \frac{(Q_I - Q_O)}{(Q_I + Q_O)} \). As described in Chapter 4, the ppart quantity identifies thermistor interactions, so a cut is defined to discard these events. The distributions of phonon partition and cuts are shown in Figure 7.11.

- **cQDelay**: QDelay is the time offset of the ionization pulse from the standard template position as determined by the ionization search. The distribution of QDelay vs. phonon energy for phonon triggers is shown in Figure 7.12. Recall that the delay is large and negative for such events because the phonon pulse rises so slowly, yielding a Global Trigger time late relative to the pulse. For a fixed phonon energy, the events form a band. The width of the band is determined by two effects. First, for a given phonon energy, there is some jitter in the time of the hardware phonon trigger relative to the pulse peak due to noise on the pulse. Thus, there is jitter in the position of the pulse in the digitized trace, producing noise in the calculated phonon delay and thus in the center of the ionization-search window. Second, once the search window has been established, the search can find any value in the 1.6-ms-wide window if there is no real ionization pulse present above noise. The latter effect primarily determines the band width above 10 keV. The band moves to earlier QDelay as the phonon
Figure 7.11: Histograms of phonon partition. The lines indicate the acceptance region; events failing the cut are thermistor interactions. cBaseQual and the phonon-$\chi^2$ cuts remove such events due to their unusual time structure (the thermistor with the interaction has a very fast rise time), so these cuts have not been performed before making these histograms. Recall that only 10% of the data are shown.

Energy is decreased because a constant-threshold hardware phonon trigger is used: as the phonon energy decreases, the trigger occurs later in the pulse and thus the calculated phonon delay is more negative.

For any phonon energy, events with “real charge” found are seen as an increase in the point density at the center of the band in QDelay. The underlying uniform distribution consists of “noise charge” events, where no true ionization event is found and a noise excursion is picked out by the search. A cut on QDelay is necessary for the following reason. As the phonon energy decreases, the Global Trigger time becomes later relative to the pulse, so the predicted ionization delay becomes more negative and approaches the early edge of the ionization trace for very low phonon energy. The ionization search tends to prefer to saturate at this edge, as is indicated by the collection of events at QDelay $\sim -9$ ms. The saturation produces a fitted energy that is higher than the typical noise-charge energy. These events are cut by cQDelay to prevent them from leaking through the ionization-threshold cuts (see below). A hard cut at a fixed value of QDelay is made. The length of the ionization pretrigger trace
was increased from about 6 ms to 9 ms midway through the data set when it was realized it was too short; therefore, two cut values are used, -5.5 ms for the 6 ms data and -8 ms for the 9 ms data. These two cut values are indicated in Figure 7.12.

- **cDataQual**: cDataQual is the logical AND of cBaseQual and the above three cuts, named in this way for obvious reasons.
7.3 "Physics" Cuts

In this section, I describe the cuts that help define, for physics reasons, the data set to be used for a search for WIMP-induced nuclear recoils. The previous cuts are essentially independent of the physical classification of the event — bulk electron recoil, surface electron recoil, or nuclear recoil, veto coincident or anticoincident — except indirectly through energy dependences, while the cuts discussed here select events based on “physics.”

7.3.1 Veto-Anticoincidence Cut

In the final dark-matter analysis, a cut is made to remove events coincident with activity in the veto. Because of the high trigger rate of the veto, the rate of accidental coincidences is nonnegligible. For ionization triggers, a veto-coincidence window of 25 $\mu$s is used: if there were any veto events in the 25 $\mu$s before the detector trigger, the event is considered veto-coincident. This window size was determined by choosing the point where the distribution of last veto-trigger times deviates from an accidental-trigger exponential; see Figure 7.13. The value chosen is, perhaps, too conservative.

The presence of phonon triggers modifies the above. As described in Chapter 6, a search for a pulse in the ionization trace is performed for phonon triggers. If an ionization event is found, its time can be compared to the veto-trigger history. The distribution of nearest veto-trigger times for phonon triggers with an ionization pulse found is shown in Figure 7.14. Based on the points where the distribution deviates from an exponential accidental distribution, the cut is set; a window of $\pm 25 \mu$s is used. For comparison, the distribution for phonon triggers with only “noise charge” is also shown.

For phonon triggers without ionization, the event time is established by the phonon pulse alone. Because the phonon pulse rises so slowly, the uncertainty on the event time is comparable
Figure 7.14: Distribution of nearest veto-trigger times for phonon-trigger events, relative to time of ionization pulse. Solid: with an ionization pulse above “noise charge” found. Dashed: no ionization pulse above noise charge found. The $\pm 25\,\mu s$ coincidence window is indicated. The appearance of coincident events in the noise-charge distribution reflects the conservativeness of the threshold dividing “real charge” from noise charge: some noise-charge events actually have real charge.

to the average time between veto events. Figure 7.15 shows the time of nearest veto trigger to the event time established by the phonon pulse alone. The absence of a peak at $t = 0$, even for the set of events shown in Figure 7.14 for which veto-coincidence was established, indicates essentially all phonon triggers with no ionization are accidentally coincident with veto triggers. Because veto coincidence cannot be established, all phonon triggers with only noise charge are discarded. The acceptance for WIMPs is accordingly reduced, as is discussed later.

### 7.3.2 Inner-Electrode-Containment and Nuclear-Recoil Cuts

To take advantage of the close-packed detector geometry implemented for Run 19, an inner-electrode-containment cut is defined. This consists of selecting events whose outer-electrode ionization signal is consistent with noise: the outer-electrode ionization energy is required to be within $\pm 2$ standard deviations of the noise mean, where the noise mean and standard deviation are given by the noise parameters calculated by PipeCleaner (see Chapter 6). Note that, when the detector under study was the triggering detector and phonon triggered, this requires an offset of the ionization signal from zero due to the search algorithm. This cut is named “cQinOnly.” This cut is rather extreme, accepting only about 46% of the detector volume, as was shown in Chapter 4.

An alternate definition would be to accept events that have any signal in the inner electrode under the assumption that the shared region, while less shielded than the inner-electrode-contained volume, would still be sufficiently well shielded to increase the exposure without degrading the WIMP sensitivity. Such a definition consists of accepting all events having inner-electrode signal greater than some threshold. This threshold is taken to be 4 standard deviations above the noise mean in order to be sure of having true inner-electrode signal. For purely shared events, events must exceed this inner-electrode threshold, must have signal outside the outer-electrode noise definition.
above, and must exceed a threshold on the summed-ionization signal. The latter threshold is also
defined to be 4 standard deviations above the summed-ionization noise mean. The cut defining
such shared events is “cQShare.” The logical OR of cQinOnly and cQShare is “cQinShare.” The
“cQinShare” cut accepts approximately 65% of the detector volume. The three cuts are shown
graphically in Figure 7.16.

The electron calibration discussed in Chapter 4 indicates that, for BLIP3, the electron
rejection of the portion of the detector selected by the cQShare cut is no worse than that selected
by cQinOnly. There are not enough cQShare events in BLIP4 to make a conclusion of this type.
Based on the discussion of α-Si/Al-Schottky test devices in Chapter 4, BLIP3 should exhibit worse
electron rejection than BLIP4 because BLIP3’s negatively biased face is probed by the electron
calibration. Naively, then, the cQinShare cut should be used to define the WIMP-search data set.

In practice, the cQinOnly cut is used for historical reasons — the WIMP-search analysis
was initially performed with the cQinOnly cut because it is the most conservative choice. The
possible use of the cQShare events is discussed in Chapter 8, where it is concluded that inclusion
of such events would not degrade the WIMP sensitivity. However, due to time constraints, the
analysis has not been redone with the addition of cQShare events. There is nothing, in principle,
incorrect about this choice, as long as the efficiencies are appropriately corrected.

The nuclear-recoil cut was explained in Chapter 4. Later in this chapter, I discuss checks
done to ensure the stability of the nuclear-recoil efficiency in the presence of both the ionization-
nonlinearity correction (see Chapter 6) and the nuclear-recoil band shift (Chapter 4).
7.3.3 Multiple-Scatter Tagging

A significant fraction of events involve particle interactions in more than one detector. With respect to the WIMP search, these events may be rejected outright without any loss of efficiency — the probability of a single WIMP interacting twice is vanishingly low; if it were not, this experiment would be a lot easier! However, multiple-scatter events are useful for background studies and estimation. For example, the double-scatter-neutron data set is used to estimate the neutron background for statistical subtraction in the WIMP-search analysis.

Some care must be taken in the definition of multiple scatters because there are two minor ambiguities involved. First, since all detector traces are saved, even for detectors without “hardware” triggers, it is in principle possible to obtain a lower “software” threshold for secondary detectors in a multiple-scatter event because the intrinsic noise of the offline fitting algorithms is less than that of the hardware trigger filtering. This is not done because it introduces complications while adding very little interesting data. The effective detector threshold is not set by the phonon-energy threshold, but by the “noise-charge” threshold of the ionization search. Below 10-keV recoil energy, the nuclear-recoil band merges with the noise-charge distribution. If only noise charge is found, no ionization-yield measurement can be made, so neutrons cannot be distinguished from surface events, though an upper limit on the yield can be set that may allow discrimination from bulk electron recoils. Thus, data acquired by a software trigger below 10 keV are not of much use anyways.
Second, one must decide how to classify events where more than one detector triggered but only one detector passes data-quality cuts. In a world of perfectly operating detectors, it would be reasonable to discard these events completely: they certainly should not be included in the single-scatter set, and their loss from the multiple-scatter set can be accounted for by cut efficiencies. However, there are periods during which a subset of the detectors experienced trigger-rate outbursts. The rate of accidental coincidences is greatly increased; classifying such events as multiple scatters would be incorrect and would result in a difficult-to-correct-for loss of single-scatter efficiency. Therefore, such multiple scatters are reclassified as single scatters, conservatively treating the detector failing cuts as dead.

7.4 Cut Efficiencies

In this section, I discuss the efficiencies of the above cuts and the methods used to calculate them. I remind the reader of an elementary analysis point. Any given event may be removed by more than one cut; for example, an event with pretrigger phonon pileup may be removed by both cPbs and cPstd. When calculating cut efficiencies, it is therefore important to account for such correlations. This is trivial to do. One can calculate the efficiency of a set of “overlapping” cuts in one pass, treating them as a single cut. One can also calculate cut efficiencies “relatively”: calculate the efficiency of cut A relative to the entire data set, calculate the efficiency of cut B relative to the event set that passes cut A, etc., and then multiply the efficiencies together. One or the other method is used here, depending on which is more convenient.

7.4.1 Pretrigger-Cut Efficiency

The calculation of pretrigger-cut efficiency is straightforward because the cuts have no dependence on the event characteristics. All the pretrigger cuts are grouped together in calculating this efficiency. The efficiency is calculated in four ways:

- the fraction of “real” (i.e., not random-trigger or pulser) events that pass the cut set;
- the ratio of the sum of the live time of the events passing the cut set to the sum of the live time of all events;
- the fraction of ionization-pulser (IBAPACAP, c.f. Chapter 5) events passing the cut set;
- and the ratio of the sum of the live time of the ionization-pulser events passing the cut set to the sum of the live time of all ionization-pulser events.

As was described in Chapter 5, the ionization pulser is completely asynchronous with the DAQ cycle and also appears to introduce no pretrigger noise. It thus is an excellent random-trigger source.

Calculating the efficiency in the above four different ways provides some cross-checks. There should be a difference between the fraction of events and the fraction of live time passing these cuts because the DAQ dead time is comparable to the recovery time of the phonon baseline — low live-time events should be cut preferentially. The live-time fraction is the correct efficiency to use because it represents the fraction of time the system is capable of detecting a WIMP-scattering event. The ionization-pulser data set provides an independent check.
Table 7.5 displays the efficiencies calculated in these four ways for the ensemble of cuts. The efficiencies for cGoodTime, cPreQual, and cPreQual(1) are all shown; the last cut is the one applied for the final analysis. Showing the other two indicates what fraction of the efficiency loss is due to "bad" data periods (cGoodTime) and what fraction is due to actual pretrigger-trace cuts (cPreQual). The cPreQual(1) requirement results in an additional efficiency loss of about 5% — even when a given detector has a clean pretrigger region, there is a 5% chance that another detector fails pretrigger cuts. This is small enough that is not worthwhile to try to recover such events. The systematic difference between efficiencies calculated using numbers of events and live times agrees with the expectation discussed above. There is good agreement between the data and the pulser set for each separate calculation method and cut (1% to 2% in most cases).

<table>
<thead>
<tr>
<th>Cut</th>
<th>BLIP3</th>
<th>BLIP4</th>
<th>BLIP5</th>
<th>BLIP6</th>
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<tbody>
<tr>
<td>Live time</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>(live-days)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>85.3</td>
<td>91.1</td>
<td>91.3</td>
</tr>
<tr>
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<td>78.4</td>
<td>85.6</td>
<td>85.8</td>
</tr>
<tr>
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<td>74.2</td>
<td>79.4</td>
<td>79.6</td>
</tr>
<tr>
<td>Fraction of data live time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.88</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>cPreQual</td>
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<td>0.81</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
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<td>0.77</td>
<td>0.82</td>
<td>0.83</td>
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<tr>
<td>Fraction of data events</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cGoodTime</td>
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<td>0.87</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
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<td>0.76</td>
<td>0.86</td>
<td>0.87</td>
</tr>
<tr>
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<td>0.69</td>
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<td>0.75</td>
</tr>
<tr>
<td>Fraction of pulser live time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cGoodTime</td>
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<td>0.92</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>cPreQual</td>
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<td>0.85</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>cPreQual(1)</td>
<td>0.81</td>
<td>0.81</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>Fraction of pulser events</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cGoodTime</td>
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<td>0.92</td>
<td>0.96</td>
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</tr>
<tr>
<td>cPreQual</td>
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<td>0.81</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>cPreQual(1)</td>
<td>0.74</td>
<td>0.74</td>
<td>0.77</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 7.5: Summary of live times and pretrigger-cut efficiencies. The total live time before any cuts is 96.4 live-days. “cGoodTime” denotes the live time and efficiencies of the cGoodTime cut for the given detector. “cPreQual” denotes these for the cPreQual cut for the given detector, which includes that detector’s cGoodTime cut. “cPreQual(1)” denotes the efficiency of the cPreQual(1) cut, which requires any detector passing its own cGoodTime cut to also pass its cPreQual cut. cPreQual(1) differs among detectors due to periods when not all detectors pass their own cGoodTime cuts. As noted in the text, the estimates based on numbers of events are in general lower than the estimates by live time, while the data and pulser estimates agree well within each category.
7.4.2 Posttrigger-Cut Efficiency

The efficiency of the cBaseQual cut can be calculated directly from the trigger rate. The dominant efficiency loss is from cPst because phonon pulses are much longer than ionization pulses. cPst cuts events in which a second pulse appears in the phonon trace, but only when the peak height of the second event is larger than that of the first. A lower limit on the efficiency of the cPst cut can be calculated by assuming that the occurrence of a second event of any energy causes an event to fail cPst. This is a reasonable estimate at low energies — if the first event is below 100 keV, the second event is likely to be of higher energy simply because most of the trigger rate comes from events above 100 keV. This efficiency is given by the accidental rate for a second event to appear in the 83 ms posttrigger period, which is just

\[ 1 - \epsilon_{cPst} = 0.083 \times R \]

where \( R \) is the single-detector trigger rate calculated from the data. The typical single-detector trigger rate is 0.33 Hz, so \( f \approx 0.97 \).

A small additional efficiency loss is imposed by the cQPileup cut, which discards any event for which an additional charge trigger occurs between –10 ms and 10 ms relative to the trigger time. The posttrigger portion of this dead time is already accounted for by the 83 ms dead time imposed by cPst. The pretrigger portion should be added, increasing the dead time from 83 ms to 93 ms. At the 1% precision being quoted here, this leaves \( \epsilon_{cBaseQual} \) unchanged at 0.97.

The efficiency of cBaseQual is also calculated directly from the data when calculating the multiple-scatter efficiency matrix (see Section 7.4.7) and compares well with the above result.

7.4.3 Pulse-Quality-Cut Efficiency

A nonnegligible efficiency loss is caused by the phonon-\( \chi^2 \) cut (hereafter, referred to as “the \( \chi^2 \) cut” when it causes no confusion). It is believed that the events discarded by the cut are basically reasonable but have pulse-shape variations that would lead to an energy misestimate. Therefore, the cut reduces the overall efficiency. For more detailed discussion of the \( \chi^2 \) distributions and the cut definition, refer to Chapter 6.

The efficiency of the cut is simply the fraction of events that pass it. Figure 7.10 implies this efficiency is energy dependent. To determine this efficiency function, the data are binned logarithmically in phonon energy and the fraction of events in each bin that pass the cut is calculated. This method assumes that the energy calculated for failing events is approximately correct. The efficiency is seen to be a smooth function of energy, so small errors in the fitted energy have little effect. It is important to remember that the pre-cut data set must be the one that passes all the previous cuts in order to avoid grossly underestimating the efficiency of the \( \chi^2 \) cut; this efficiency is then multiplied against the previous efficiencies to determine the overall efficiency.

The cut efficiency is certainly not independent of time. This arises mainly because the phonon-\( \chi^2 \) distributions change sufficiently that it is impossible to set a cut that has the same efficiency at all times. The algorithm used to set the cut attempts to maintain a constant efficiency, but is not very successful. However, given that the trigger rates are fairly stable, the efficiency calculated from the data set as a whole should correctly incorporate the varying efficiency. For example, a period with a low cut efficiency is weighted according to the total number of events in the set before the \( \chi^2 \) cut, which is proportional to the live time of the period, providing the correct
weighting. The prior cuts remove extraordinary periods, so this is a valid procedure. Furthermore, the assumption is conservative in that it underestimates the efficiency. For example, if a trigger outburst is left in the data set from which the efficiency is calculated, then it is overweighted because it has too many events. The efficiency for such a period is lower than is typical because of the higher noise. Thus, the mean efficiency is decreased by such a period.

The efficiency of the phonon-\(\chi^2\) cut as a function of phonon energy is shown in Figure 7.17. The efficiency has artificial structure that arises mainly from the fact that, at around 200 to 300 keV, the \(\chi^2\) distribution broadens and exhibits a tail, as seen in Figures 6.12 and 7.10. While the shape of the efficiency function may appear strange, it is correct — a more stringent cut is made at higher energy, giving a lower efficiency.

As has been mentioned before, the ionization-\(\chi^2\) cut is very loose, with essentially 100% efficiency. However, as also previously noted, its efficiency for low-energy events in which another detector had a saturating ionization pulse is significantly lower. It was argued earlier that the data sets of primary interest for this analysis — veto-coincident and veto-anticoincident single-scatter and double-scatter nuclear recoils — do not suffer because they never or rarely contain a saturated detector. It is critical to realize that other data sets — for example, multiple-scatter photons or photon-electron events — are affected by this loss, and the 100%-efficiency assumption is completely
invalid. The efficiency function must be calculated independently for such analyses.

The cppart cut on phonon partition clearly is very liberal (see Figure 7.11) and thus has essentially unity efficiency.

It is difficult to calculate the efficiency of the cQDelay cut in a rigorous manner because the true ionization energy of an event discarded by cQDelay is unknown. An event can fail cQDelay for two reasons. If the event has a large phonon energy ($\gtrsim 10$ keV), yet fails cQDelay because no “real-charge” pulse can be found, then the event is likely a dead-layer event — bulk nuclear and electron recoils at such energies produce enough ionization to be above noise charge. Because nuclear recoils are in general uniformly distributed through the detector, cutting such dead-layer events only reduces the efficiency for nuclear recoils by the ratio of the dead-layer volume to the total detector volume, which is less than 1% assuming a 30 $\mu$m dead layer. The other reason an event can fail cQDelay is that it has such low phonon energy that the ionization-search window overlaps the early edge of the ionization trace. This failure mode is independent of the event position in the detector and, in fact, is dependent mainly on the phonon energy. As is seen in Figure 7.12, the width of the QDelay band widens considerably below $\sim 5$-keV phonon energy. Since the ionization-search-window width is fixed at 1.6 ms, this additional widening is due to increased noise in the phonon-delay estimation. Figure 7.18 shows the fraction of events passing cQDelay as a function of phonon energy. These plots indicate that the latter effect is indeed the dominant loss of efficiency due to cQDelay: the efficiency above 10 keV is almost unity. Therefore, it is justified to include these efficiency functions in the overall efficiency calculation in the same way that the hardware phonon-trigger efficiency is included; this is discussed in the next section. One caveat should be made: the April, 1999, neutron-calibration data do not satisfy the above criterion that the efficiency above 10 keV be unity; thus, the inclusion of the cQDelay efficiency in the above way is invalid. This point may partially explain the worse agreement of the data and simulation for this calibration set as compared to the September, 1999, neutron calibration and the muon-coincident neutron data (see Section 7.5).

7.4.4 Trigger Efficiency

The hardware-trigger efficiency can be measured using “off-detector” triggers. An “off-detector” trigger for detector A is an event in which any of the other detectors was the first to trigger. For all events, every detector channel is digitized and trace fits done. Detector A’s trigger efficiency at energy $E$ is given by the fraction of all detector-A off-detector events having energy $E$ for which a detector-A hardware trigger is found in the posttrigger history. This is done separately for the phonon trigger as a function of phonon energy and for the ionization trigger as a function of ionization energy. This calculation is done on the event set passing all the prior cuts to ensure good energy estimates for detector A. The calculation is done for the whole data set at once — again, presumably periods of different trigger efficiency are automatically weighted by the number of events taken with a given trigger-efficiency curve. Figure 7.19 shows the ionization-trigger efficiency for all events and for inner-electrode-contained events. The horizontal axis is the summed or inner-electrode ionization energy, respectively. The trigger efficiencies are the same, as they should be because the hardware trigger cannot distinguish the two event classes (unless the pulse-height-to-energy conversions of the two channels differ appreciably; they do not). Figure 7.20 shows the phonon-trigger efficiency.
7.4.5 Veto-Anticoincidence-Cut Efficiency

The efficiency of the veto-anticoincidence cut is determined by the rate of accidental detector-veto coincidences. The total veto-trigger rate about 6 kHz. For ionization triggers, the veto-coincidence window is 25 $\mu$s. Therefore, there is a $6 \, \text{kHz} \times 25 \, \mu\text{s} = 0.15$ probability that an accidental coincidence occurs, yielding an efficiency of 0.85. For phonon triggers with ionization found, the window is $\pm 25 \, \mu\text{s}$, giving an efficiency of 0.70. For phonon triggers with only noise charge found, the efficiency vanishes because all such events are discarded.

7.4.6 Overall Nuclear-Recoil Efficiency

I discussed in detail the grid method used for calculation of the nuclear-recoil efficiency in Chapter 4. The “raw” grid, $\epsilon_{NR}^{raw}(E_R, E_Q)$, is defined as the grid including only the Gaussian distributions of nuclear recoils about the nuclear-recoil line. By definition, it satisfies the normalization condition $\int_{-\infty}^{\infty} dE_Q \epsilon_{NR}^{raw}(E_R, E_Q) = 1$ for all $E_R$. The nuclear-recoil efficiency grid, $\epsilon_{NR}(E_R, E_Q)$, incorporates the definition of the nuclear-recoil-acceptance region and the ionization-search threshold:

$$
\epsilon_{NR}(E_R, E_Q) = \epsilon_{NR}^{raw}(E_R, E_Q) \theta(E_Q - E_Q^{thr}) \theta(E_Q - E_Q^{lo}(E_R)) \theta(E_Q^{hi}(E_R) - E_Q)
$$

(7.2)
Figure 7.19: Efficiency of hardware ionization trigger vs. ionization energy. Separate plots are shown of all events and inner-electrode-contained events.
where $E_{Q}^{lo}(E_{R})$ and $E_{Q}^{hi}(E_{R})$ define the nuclear-recoil-acceptance region and $E_{Q}^{thr}$ is the ionization-search threshold (a constant). This second grid thus accounts for the efficiency lost by these two cuts. The nuclear-recoil efficiency at $E_{R}$ is given by integrating $\epsilon_{NR}(E_{R}, E_{Q})$ over $E_{Q}$.

This calculation does not include the effects of other cuts, including those with energy-dependent efficiencies, such as the phonon-$\chi^{2}$ cut. The above procedure is generalized by calculating the efficiency of each cut on the grid of $E_{Q}$ vs. $E_{R}$. For cuts that depend on phonon energy ($E_{P}$) rather than $E_{Q}$ or $E_{R}$ separately, the phonon energy at each point on the grid is calculated by inverting the Luke correction:

$$E_{P} = E_{R} + \frac{eV}{3.0 \text{eV}} E_{Q}$$

(7.3)

and the efficiency at that phonon energy applied. For example, the phonon-$\chi^{2}$-cut efficiency on the grid is calculated this way, yielding an efficiency grid $\epsilon_{\chi^{2}}^{P}(E_{R}, E_{Q})$. The trigger efficiency takes the form

$$\epsilon_{tr}(E_{R}, E_{Q}) = 1 - \left[1 - \epsilon_{tr}^{Q}(E_{Q})\right] \left[1 - \epsilon_{tr}^{P}(E_{P})\right]$$

(7.4)

$$= \epsilon_{tr}^{Q}(E_{Q}) + \epsilon_{tr}^{P}(E_{P}) - \epsilon_{tr}^{Q}(E_{Q})\epsilon_{tr}^{P}(E_{P})$$

This form may not be obvious. Consider the first line. In the second term, the first factor is the probability that the ionization trigger fails to fire and the second factor is the probability that the phonon trigger fails to fire. Both must fail in order for the event to be lost, so the second term is the combined inefficiency of the hardware triggers. As argued above, the efficiency of the cQDelay cut can be absorbed into $\epsilon_{tr}^{P}(E_{P})$. When applying a veto-anticoincidence cut, the veto-anticoincidence-cut and trigger efficiencies must be combined into one grid because of the dependence of the former.
on the latter; the resulting efficiency grid takes the form:

\[
\epsilon_{\text{anti}}(E_R, E_Q) = \epsilon_{\text{tr}}^Q(E_Q)\epsilon_{\text{anti}}^Q + \left[1 - \epsilon_{\text{tr}}^Q(E_Q)\right] \epsilon_{\text{tr}}^P(E_P)\epsilon_{\text{anti}}^P \theta(E_Q - E_{\text{thr}}^Q)
\]  (7.5)

where \(\epsilon_{\text{tr}}^Q(E_Q)\) is the ionization-trigger efficiency, \(\epsilon_{\text{tr}}^P(E_P)\) is the phonon-trigger efficiency and \(\epsilon_{\text{anti}}^Q = 0.85\) and \(\epsilon_{\text{anti}}^P = 0.70\) are the veto-anticoincidence-cut efficiencies for ionization triggers and phonon triggers with charge found, respectively. The \(\theta(E_Q - E_{\text{thr}}^Q)\) enforces the requirement that the ionization found be above the ionization-search threshold \(E_{\text{thr}}^Q\). The first term is the efficiency for ionization triggers. The second term accounts for the lost efficiency gained back by phonon triggers for which ionization is found.

The overall energy-dependent efficiency is calculated by multiplying all grids of the above form together, point-by-point, and integrating over ionization, yielding

\[
\epsilon_{\text{anti}}^{\text{tot}}(E_R) = \epsilon_{\text{pre}}\epsilon_{\text{post}}\int_{-\infty}^{\infty} dE_Q \epsilon_{\chi^2}^P(E_R, E_Q) \epsilon_{\text{anti}}(E_R, E_Q) \epsilon_{\text{NR}}(E_R, E_Q)
\]  (7.6)

where all \(E_P\) have been replaced using Equation 7.3, \(\epsilon_{\text{pre}}\) is the pretrigger-cut efficiency, \(\epsilon_{\text{post}}\) is the posttrigger-cut efficiency (both energy independent), \(\epsilon_{\chi^2}^P(E_R, E_Q)\) is the phonon-\(\chi^2\)-cut efficiency grid, \(\epsilon_{\text{NR}}(E_R, E_Q)\) is the nuclear-recoil efficiency grid, and \(\epsilon_{\text{anti}}(E_R, E_Q)\) from Equation 7.5 is the veto-anticoincidence efficiency grid.

Figure 7.21 shows the overall exposure as a function of recoil energy. The exposure is given by multiplying the overall efficiency function by the raw exposure, 96.4 live-days or 15.9 kg d. The softening of the veto-anticoincident efficiency function between 10 and 20 keV occurs because of the gradual change-over between phonon triggers, with veto efficiency 0.70, to ionization triggers, with veto efficiency 0.85. The high-energy (> 20-keV) shape is entirely due to the energy dependence of the phonon-\(\chi^2\) cut. The change in the position of the nuclear-recoil band at the April 3 power outage has been accounted for by weighting the efficiencies calculated during the two epochs by their respective livetimes. It must be emphasized that the efficiency calculated here is only valid for nuclear recoils; for example, the efficiency for bulk electron recoils is different because they lie at a different position in the \(E_Q\) vs. \(E_R\) grid.

### 7.4.7 Multiple-Scatter Efficiency

I have so far concentrated on individual detector efficiencies. However, double-scatter neutron events play an important role in the final analysis. Naively, one calculates the efficiency for detection of a multiple-scatter event simply from the product of the individual detector efficiencies. This is not accurate because it is important to take into account correlations in the data-quality-cut efficiencies for different detectors. It is only the energy-independent data-quality-cut efficiencies that need to be considered in this respect. The \(\chi^2\)-cut, cQDelay, and trigger efficiencies exhibit no correlations because their energy dependences are dominated by the individual detector noise and pulse-shape characteristics. The nuclear-recoil-cut efficiencies are also uncorrelated, aside from correlations introduced by real physics; e.g., multiple scattering of a neutron. An example case of how data-quality cuts introduce correlations is pretrigger pileup. When detector A has pretrigger pileup, its neighbor has a higher-than-random chance of also having pretrigger pileup because the neighbor may be hit by the same particle or by particles produced by the same incident muon or
Figure 7.21: Overall nuclear-recoil exposure as a function of recoil energy. Top: no inner-electrode-containment cut. Bottom: with inner-electrode-containment cut. Solid: veto-coincident. Dashed: veto-anticoincident. The raw exposure for each detector is 96.4 live-days, or 15.9 kg d. Thus, the overall veto-anticoincident cut efficiency is about 50% when no inner-electrode-containment cut is made, dropping to about 20% when this cut is applied.
high-energy photon. Therefore, it is necessary to calculate a matrix of various joint efficiencies, which, for three detectors (four would not fit on the page!), has the form:

$$M = \begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-B3 & B3 & 0 & 0 & 0 & 0 & 0 & 0 \\
-B4 & 0 & B4 & 0 & 0 & 0 & 0 & 0 \\
-B3 & B3 & -B4 & B3 & 0 & 0 & 0 & 0 \\
&-B4 & &-B4 & &B4 & &B4 & 0 & 0 & 0 \\
&-B5 & 0 & 0 & B5 & 0 & 0 & 0 \\
&-B3 & B3 & 0 & 0 & -B3 & B3 & & \\
&-B5 & &-B5 & &B5 & &B5 & 0 & 0 \\
&-B3 & B3 & -B3 & B3 & -B3 & -B3 & B3 & B3 \\
&-B4 & &-B4 & &B4 & &B4 & &B4 & &B4 & &B4 \\
&-B5 & &-B5 & &B5 & &B5 & &B5 & &B5 & &B5 & &B5
\end{pmatrix}$$

where the entries are interpreted as follows: B3&B5 implies BLIP3 and BLIP5 both pass all their cuts and -B3&B5 indicates that BLIP3 fails its cuts while BLIP5 passes its own. If a detector is not explicitly listed in an entry, then its state is not considered. The matrix is read as follows. Each row corresponds to a particular combination of detectors. Entries in that row contain all possible configurations for that combination — all detectors passing cuts, some subset passing cuts, or none passing cuts. There is therefore a unitarity condition: each row must sum to 1. The matrix must be calculated from an event set in which no detectors are saturated; cross-talk from a detector whose state is nominally irrelevant can affect the probability of the other detectors passing their cuts. As discussed earlier, a cut requiring no saturated detectors is reasonable. This matrix is used in the obvious way for correcting the simulation for the efficiency of detecting multiple-scatter neutrons; the simulated and observed multiple-scatter-neutron spectra are discussed in the next section.

### 7.5 Checks on Accuracy and Stability of Cut Efficiencies

It is critical to check that the efficiency calculated by the above method is correct and that it is stable over time. This is especially important given the change in nuclear-recoil bands at April 3.

#### 7.5.1 Accuracy

The absolute accuracy of the efficiency calculation can be checked against the simulation of the neutron calibration. The details of the simulation code are discussed in Chapter 3. A $^{252}$Cf-fission neutron source is placed roughly at the center of the top face of the veto. The spectrum of neutrons emitted by the source is shown in Figure 7.22. Because these neutrons have such low energies, the top layers of polyethylene inside the shield are removed to permit the neutrons to penetrate to the cryostat. The data rate is also higher than normal to ensure the data set is dominated by neutrons. Otherwise, the data-taking conditions are as usual. The source activity is known, so the absolute normalization of the spectrum is fully determined. The overall cut efficiency determined by the method previously discussed is applied to this spectrum. It is necessary to recalculate the efficiencies from the neutron-calibration data set because the amount of pileup is significantly increased. A veto-anticoincidence cut is not applied to the neutron-calibration data.
because a significant fraction of neutrons trigger the veto as they pass through it. So, while the efficiencies themselves differ from those of the WIMP-search data set, the method is essentially the same.

Additionally, an artificial energy window of 10 to 100 keV is imposed. It is observed in the veto-anticoincident data set that leakage of low-energy electrons into the nuclear-recoil band becomes significant below 10 keV. This observation is corroborated by data taken with the α-Si/Al-Schottky test device, Figure 4.20. The neutron-calibration multiple-scatter-neutron data set also shows an excess rate at low energies — the spectra rise too steeply at low energy. (Note that this has little effect on the empirical nuclear-recoil-efficiency estimate because multiple scatters make up a small (10-20%) fraction of the total neutron rate.) Similar effects are seen in the muon-anticoincident double-scatter-neutron data. Application of a 10-keV threshold for both detectors in multiple-scatter events yields physically reasonable spectra. As mentioned in Section 4.5.1, a 100-keV upper limit is applied because the neutron-calibration data become so sparse that the nuclear-recoil band is not accurately determined above this energy. It is straightforward to apply these energy cuts to the simulation.

The observed and simulated spectra for the two neutron-calibration data sets are shown in Figure 7.23. The cQinOnly cut has been applied. There are no free parameters in the comparison; the simulation normalization is set by the source activity and the efficiencies calculated from the data. For both calibrations, the simulated spectra match the data to about 20 to 30% accuracy. The spectral shape, while not exactly right, is fairly close. Moreover, the significant change in the observed spectra at low energies, due to changes in cut efficiencies between the two calibrations, is reproduced by the simulation after application of the cut efficiencies. The discrepancy between the simulated and observed spectra can be used to estimate a systematic error for the cut-efficiency

Figure 7.22: Energy spectrum of neutrons emitted by $^{252}$Cf calibration source. Figure taken from [8].
calculation by finding the scaling $A$ that yields the best fit of the simulated spectral shape to the data and taking $|A - 1|$ as the fractional systematic error. These numbers are listed in Table 7.6.

A second check of the accuracy of the efficiency calculation is provided by multiple-scatter neutrons. As discussed in the previous section, calculation of the efficiency for such events is nontrivial due to correlations in the cuts for detector combinations. The correlation matrix defined earlier is used in establishing this efficiency. The simulated and observed multiple-scatter-neutron spectra are shown in Figure 7.24. As noted above, all recoils of a multiple-scatter are required to be between 10 and 100 keV to appear in this histogram. The histogram is filled for each recoil of a multiple-scatter event; e.g., a double scatter adds two entries to the histogram. (It should be noted that the number of multiple scatters with more than two recoils is negligible, though nowhere in this section is it assumed that there are no triple or quadruple scatters.) Plots are shown for two ionization-partition cuts. The first set of plots requires all recoils of a multiple scatter to pass cQinOnly (“Qin/Qin”). The second set only requires one cQinOnly recoil (“Qin/Qsum”). In all cases, the agreement of the data and simulation is good. The best-fit scaling factors are shown in Table 7.6. The different levels of agreement of the all-event and multiple-scatter spectra with the simulation are indicative of the systematic error in the efficiency calculation.

The accuracy of the nuclear-recoil efficiency can also be checked by comparing the simulated and observed spectra for muon-coincident neutrons. As discussed in detail in Chapter 3, these neutrons are produced by muons passing through the veto that interact in the copper cans of the cryostat or the internal lead shield. This data set offers the advantage that it is acquired at the same time as the WIMP-search data set, and thus the efficiencies are exactly the same, with the exception that no veto-anticoincidence cut is applied. Figure 7.25 shows the simulated and observed muon-coincident-neutron spectra for the same energy cuts and event categories as shown for the neutron-calibration data. There is good agreement. Best-fit scaling factors $A$ are shown in
Figure 7.24: Observed and simulated multiple-scatter neutron-calibration spectra, coadded over all four detectors, with no free parameters. Solid: observed spectra. Dashed: simulated. Upper left: first calibration, all recoils of the multiple scatter are required to pass cQinOnly ("Qin/Qin"). Lower left: first calibration, only one recoil of the multiple scatter is required to pass cQinOnly ("Qin/Qsum"). Right: similar plots, second neutron calibration. The upper spectra in the plots are the same as were shown (with linear vertical scales) in Figure 7.23.
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### Table 7.6: Scaling factors $A$ that must be applied to the simulation to achieve agreement with the data. $|A - 1|$ is a reasonable estimate of the fractional systematic error of the efficiency calculation.

<table>
<thead>
<tr>
<th>Event Set</th>
<th>First Neutron Calibration</th>
<th>Second Neutron Calibration</th>
<th>Muon-Coincident Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>all Qin NRs</td>
<td>0.86</td>
<td>0.74</td>
<td>0.97</td>
</tr>
<tr>
<td>multiple Qin/Qin NRs</td>
<td>1.31</td>
<td>0.98</td>
<td>0.77</td>
</tr>
<tr>
<td>multiple Qin/Qsum NRs</td>
<td>1.51</td>
<td>1.18</td>
<td>1.33</td>
</tr>
</tbody>
</table>

### Table 7.7: Observed and expected dispersion of muon-coincident-neutron rates, in nuclear recoils/live-day. The excess dispersion is calculated by the quadrature difference of the observed and expected dispersions.

<table>
<thead>
<tr>
<th>Event Set</th>
<th>standard deviation, NRs/live-day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>observed</td>
</tr>
<tr>
<td>single Qin NRs</td>
<td>2.2</td>
</tr>
<tr>
<td>multiple Qin/Qin NRs</td>
<td>0.7</td>
</tr>
<tr>
<td>multiple Qin/Qsum NRs</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### 7.5.2 Stability

The stability of the nuclear-recoil acceptance over time is checked by Figure 7.26, which shows the muon-coincident-neutron rates, coadded over the four detectors, as a function of time in blocks of approximately 5 live-days. The rates of three different types of events are shown separately: cQinOnly single scatters, “Qin/Qin” multiple scatters, and “Qin/Qsum” multiple scatters. The standard 10-to-100-keV cut is made. While the stability is not as good as one would expect from random statistical fluctuations, the variations are not alarmingly large. There are two particularly critical points:, the April 3 power outage and the refrigerator warmup/cooldown cycle in June, which occurred at roughly 29 and 65 raw live-days, respectively. The rates show no statistically significant change at either of these points. Numerically, the dispersion of the data can be compared to the expected dispersion based on the data’s own error bars. Each point corresponds to about 5 live-days, so the typical number of counts $N$ yielding each point is given by the product of the mean rate and 5 live-days. The statistical uncertainty on $N$ counts is $\sqrt{N}$, so the statistical uncertainty on each point is $\sqrt{N}/(5$ live-days). This is the expected standard deviation of the data. The observed and expected standard deviations are shown in Table 7.7 and the inferred excess standard deviation is calculated. The excess dispersions indicate what is already apparent: the rates vary more than are expected, but not egregiously. Furthermore, some excess dispersion is expected because variations in noise, amplifier gain, etc. have the effect of slightly modulating the acceptance of the nuclear-recoil cut.
7.5.3 Implications for WIMP-Search Analysis

It is seen that the efficiencies are accurate and stable at the 30% level. This is not as good as one might hope for. However, it is important to realize that, because the dark-matter analysis discussed in the next chapter is severely statistics limited — only 13 single-scatter and 4 multiple-scatter nuclear-recoil candidates are seen — this level of accuracy and stability is sufficient. For future data sets, as more nuclear-recoil candidates are accumulated and the statistical uncertainty associated with the data becomes small, the accuracy of the efficiency calculation (or, possibly, the simulation) will have to be improved.
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Figure 7.26: Muon-coincident-neutron rates vs. time, coadded over detectors. Top plot: single scatters. Bottom left: Qin/Qin multiple scatters. Bottom right: Qin/Qsum multiple scatters. Each point corresponds to approximately 5 live-days. The error bars are only statistical. The mean (calculated from the data) and the $\chi^2$ of the data relative to the mean are shown.