Chapter 8

Background-Particle Rates and Constraints on the WIMP-Nucleon Cross Section

8.1 Introduction

In this chapter, I finally cut to the chase — the veto-anticoincident nuclear-recoil data set and its implications for the WIMP-nucleon cross section. Rates for photons, electrons, and nuclear-recoil candidates are presented. Using the double-scatter data set and data from CDMS Run 18, it is argued that the observed single-scatter nuclear recoils are due to scattering of “external” neutrons, neutrons produced by muon interactions outside the shield (see Chapter 3). The double-scatter neutron and Run 18 data sets are used to estimate the external-neutron background, which is then statistically subtracted from the single scatters to determine an exclusion limit on the spin-independent WIMP-nucleon elastic-scattering cross section. Rates of noise-charge events and of thermistor interactions due to tritium beta decay are also presented. Finally, some conclusions regarding residual photon and electron sources are made.

Recall the three ionization-partition cuts defined in Chapters 4 and 7: cQinOnly (inner-electrode-contained), cQShare (inner-outer-shared), and cQoutOnly (outer-electrode-contained). These cut names are used throughout this chapter for brevity.

8.2 Veto-Anticoincident Nuclear-Recoil Data Set

The veto-anticoincident nuclear-recoil data set is defined by the cuts presented in the previous chapter. This set is divided into single-scatter events, which are used to search for WIMP-induced nuclear recoils, and double-scatter events, which measure the external-neutron background.

8.2.1 Single-Scatter Data Set

Figures 8.1, 8.2, and 8.3 show plots of ionization energy vs. recoil energy for cQinOnly, cQShare, and cQoutOnly veto-anticoincident single-scatter events. Figures 8.4, 8.5, 8.6, 8.7, 8.8, and 8.9 show ionization yield vs. recoil energy plots for the same data. The ionization-yield plots are
split into two sets, before and after the April 3 change in the nuclear-recoil bands. The appropriate nuclear-recoil-acceptance regions are shown in the ionization-yield plots.

A number of features are clear:

- For all four detectors, the number of low-yield events (inside, above, and below the nuclear-recoil-acceptance regions) is significantly higher in the cQoutOnly data. This is expected, given the degraded photon rejection in the outer electrode observed in the photon-calibration data. It is likely that self-shielding also plays a role.

- The rate of low-ionization-yield events in BLIP3 is significantly higher than in the other detectors, even for the cQinOnly data set. As discussed in Section 4.3, BLIP3 suffered repeated processing steps during development of the new electrode-fabrication method, so its electrodes may have been contaminated or damaged during processing. These possibilities are discussed in Section 8.5.

- BLIP4 also shows an elevated low-yield event rate in its cQinOnly data in the form of a band in $Y_R$. As is discussed later, there is good evidence that these events are due to electrons emitted by the contaminant on BLIP3. There is good separation between this low-yield band and the nuclear-recoil-acceptance region.

- Most importantly, in both the cQinOnly and cQShare data sets, there appear to be populations of true nuclear-recoil events in BLIPs 4, 5, and 6.

The structure at about 10 keV is the 10.4-keV gallium line; the conversion from phonon energy and ionization energy to recoil energy and ionization yield makes it tilt. Barely visible are lines at 46 keV and 67 keV; the sources and implications of these lines are discussed in Section 8.5.

**Photon and Electron Rates, Choice of Ionization-Partition Cut**

Prior to performing the WIMP-search analysis, it is necessary to assess the bulk electron-recoil and surface-event rates, outside the nuclear-recoil band, to determine expected rates of misidentified particles. The primary goal is to determine whether an ionization-partition cut should be made to optimize the WIMP sensitivity. It is, of course, necessary that this decision be made on the basis of these data alone and not with any consideration of how many nuclear-recoil candidates are actually observed!

To assess the rates of bulk electron recoils and surface events, three “particle types” are defined: photons ($Y_R \sim 1$), nuclear recoils (anything in the nuclear-recoil-acceptance region), and electrons (all events between the photons and nuclear recoils). Figures 8.10, 8.11, and 8.12 show recoil-energy spectra for photons and electrons. Note that, because of the clear leakage of events into the nuclear-recoil band for cQoutOnly events, the cQoutOnly “electron” spectra underestimate the true rate of electron interactions; this is corrected in the discussion of residual background sources, Section 8.5. The average rates of photons and electrons between 10 and 100 keV are shown in Table 8.1. These rates are normalized using the volume fractions determined from the neutron-calibration data and simulation, as discussed in Section 4.5.1. It would be more physically reasonable to normalize the electron rates by surface area, rather than mass ($\sim$volume). However, volume-normalized rates indicate the impact of the electron rates on WIMP sensitivity. Electron
Figure 8.1: Ionization energy vs. recoil energy for veto-anticoincident cQinOnly single-scatter events. Nuclear-recoil candidates are circled. Note that, because the pre- and post-April 3 data sets are combined in these plots and the nuclear-recoil bands are different for the two data sets, uncircled events that appear to lie in the nuclear-recoil-acceptance region in fact do not. Dashed: ionization-search threshold.
Figure 8.2: Ionization energy vs. recoil energy for veto-anticoincident cQShare single-scatter events. Legend as in Figure 8.1.
Figure 8.3: Ionization energy vs. recoil energy for veto-anticoincident cQoutOnly single-scatter events. Legend as in Figure 8.1.
Figure 8.4: Ionization yield vs. recoil energy for veto-anticoincident cQinOnly single-scatter events in the pre-April 3 data set. Nuclear-recoil candidates are circled. Light line: center of nuclear-recoil band. Dark lines: nuclear-recoil acceptance region. Recall that the acceptance region is defined asymmetrically in $Y_R$. Dashed: ionization-search threshold.
Figure 8.5: Ionization yield vs. recoil energy for veto-anticoincident cQinOnly single-scatter events in the post-April 3 data set. Legend as in Figure 8.4.
Figure 8.6: Ionization yield vs. recoil energy for veto-anticoincident cQShare single-scatter events in the pre-April 3 data set. Legend as in Figure 8.4.
Figure 8.7: Ionization yield vs. recoil energy for veto-anticoincident cQShare single-scatter events in the post-April 3 data set. Legend as in Figure 8.4.
Figure 8.8: Ionization yield vs. recoil energy for veto-anticoincident cQoutOnly single-scatter events in the pre-April 3 data set. Legend as in Figure 8.4.
Figure 8.9: Ionization yield vs. recoil energy for veto-anticoincident cQoutOnly single-scatter events in the post-April 3 data set. Legend as in Figure 8.4.
CHAPTER 8. BACKGROUND-PARTICLE RATES AND CONSTRAINTS ON THE WIMP-NUCLEON CROSS SECTION

### Table 8.1: Veto-anticoincident single-scatter-photon and -electron rates, averaged between 10 and 100 keV, in keV$^{-1}$ kg$^{-1}$ d$^{-1}$. The detector volume ratios used for the exposure normalization are 0.46:0.19:0.35, as calculated in Section 4.5.1. Uncertainties are statistical only; cut efficiencies add a systematic normalization error of about 10%, but the normalization scaling should be very similar for all the rates.

<table>
<thead>
<tr>
<th>Event set</th>
<th>BLIP3</th>
<th>BLIP4</th>
<th>BLIP5</th>
<th>BLIP6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qin</td>
<td>1.287±0.055</td>
<td>0.825±0.044</td>
<td>0.667±0.039</td>
<td>0.793±0.042</td>
</tr>
<tr>
<td>QShare</td>
<td>1.570±0.094</td>
<td>1.280±0.086</td>
<td>1.394±0.087</td>
<td>1.915±0.101</td>
</tr>
<tr>
<td>Qout</td>
<td>2.011±0.079</td>
<td>1.311±0.064</td>
<td>1.205±0.059</td>
<td>1.580±0.068</td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qin</td>
<td>2.006±0.068</td>
<td>0.462±0.033</td>
<td>0.054±0.011</td>
<td>0.140±0.018</td>
</tr>
<tr>
<td>QShare</td>
<td>1.366±0.088</td>
<td>0.203±0.034</td>
<td>0.146±0.028</td>
<td>0.409±0.047</td>
</tr>
<tr>
<td>Qout</td>
<td>2.532±0.088</td>
<td>0.969±0.055</td>
<td>0.636±0.043</td>
<td>0.727±0.046</td>
</tr>
</tbody>
</table>

A number of features are apparent in these rates. First, the cQinOnly photon rates among BLIPs 4, 5, and 6 are uniform at the 10% to 15% level. There is less uniformity among the cQShare event rates. There is also less uniformity among the cQoutOnly event rates. In the limit that photon events are dominated by Compton scattering of high-energy photons, the photon rates (in keV$^{-1}$ kg$^{-1}$ d$^{-1}$) should be the same for all ionization-partition cuts and detectors because the mean free path of high-energy photons is large compared to the detector thickness. (Note that the gallium-X-ray rates should also be proportional to volume.) The lack of uniformity among the detectors for the cQShare and cQoutOnly cuts may be due to varying exposures to 46-keV photons emitted by $^{210}$Pb (presumably situated on the detector housing); these photons are apparent in the spectra. The implications of the variations in photon rates, and especially the differing intensities of the photon lines, are explored in Section 8.5. Second, though the electron rates observed for the cQoutOnly cut are similar to those observed for the cQinOnly or cQShare cuts, it is apparent from the ionization-yield plots that the cQoutOnly events appear to be distributed more uniformly in $Y_R$, while the cQinOnly and cQShare events form a band at relatively high $Y_R$ with a tail. This is corroborated by the histograms of ionization yield, Figures 8.13, 8.14, and 8.15, which even indicate a peak in the $Y_R$ distribution at fairly low $Y_R$ for the cQoutOnly data. Finally, the cQinOnly and cQShare electron rates and $Y_R$ histograms are quite similar. For a flux of electrons emitted by an external source (the detector package, for example), the inner-electrode regions are more shielded than the shared regions, so one would expect the latter to have significantly higher electron rates. However, if the residual electron source is surface contamination, which is likely to be uniformly
distributed over a detector’s surface, it is reasonable that similar rates are observed. Implications for the residual electron-source location are discussed in Section 8.5.

Based on the ionization-yield plots and these rates, the following decisions can be made regarding definition of the WIMP-search data set. First, cQoutOnly events should be discarded, for a number of reasons. Though the cQoutOnly photon rates are not significantly higher than the cQinOnly or cQShare rates, the photon calibration indicates that the photon-misidentification parameter is 2 to 10 times higher for cQoutOnly than for cQinOnly or cQShare. This alone is good reason to discard the cQoutOnly data. Beyond this, the much flatter $Y_R$ distributions seen for the cQoutOnly data indicate that, though the cQoutOnly electron rate is not significantly different from the rates seen for the cQinOnly and cQShare cuts, the electron-misidentification parameter is likely to be much worse. It would be preferable to use a separate electron calibration to demonstrate conclusively that the outer-electrode electron-misidentification parameter is higher. Unfortunately, the electron calibration presented in Section 4.5.3 does not probe the top-bottom break. However, physically, it is clear that if photon misidentification is worse in the outer electrode by a factor of 2 to 10, electron misidentification is likely to be drastically worse.

Second, there appears to be no reason to discard the cQShare data set. The electron and photon rates (modulo the overestimation issue discussed above) are not significantly higher than for the cQinOnly data set. The calibration data sets indicate that both the photon- and electron-misidentification parameters for the shared region appear to be no worse than for the inner-electrode region. The $Y_R$ histograms for the background data corroborate this point. Thus, the expected rate of misidentified photons and electrons in the two regions should be about the same. It should be stressed that two pieces of data play roles in this decision: first, the observed similar rates; and second, the observed similar misidentification parameters $\beta_\gamma$ and $\beta_\beta$. A counterexample would be a case in which, though the misidentification parameters were the same, the cQShare photon and electron rates were, for example, 10 times higher than the cQinOnly rates. The larger rates would yield 10 times larger expected rates of misidentified events, obviously indicating that the cQShare data set should be discarded in such a case.

When the WIMP-search analysis was initially performed, only cQinOnly events were used. This choice was based on an earlier analysis comparing the veto-coincident-electron rates for the cQinOnly and cQShare sets, which saw a significantly higher cQShare electron rate (of order 30 times) [141]. This was interpreted as evidence that the electron misidentification for shared events is higher, and thus the cQShare data set was discarded. However, the more recent analysis presented in Section 4.5.3 shows that, at the available statistical precision, the electron misidentification for cQShare events is no worse than for cQinOnly events. This latter result suggests that the higher veto-coincident cQShare electron rate is due primarily to a higher incident flux on the shared region, relative to the inner-electrode region, because the shared region is not as well shielded. Since the veto-anticoincident-electron event rates do not reflect such a difference, there is no reason to distinguish the cQinOnly and cQShare data sets.

Having said this, the cQShare data set is discarded from the WIMP-search analysis at this point simply because redoing the analysis with the inclusion of the cQShare data set is not practical on the timescale of this dissertation. There is, in principle, nothing wrong with this approach, as long as the WIMP-detection efficiency is appropriately calculated. The possible impact of inclusion of the cQShare events on the final results is mentioned in Section 8.4.
Figure 8.10: Single-scatter photon and electron recoil-energy spectra for veto-anticoincident cQin-Only events. Solid: photons. Dashed: electrons. Note that the energy range is 0 to 300 keV.
Figure 8.11: Single-scatter photon and electron recoil-energy spectra for veto-anticoincident cQShare events. Solid: photons. Dashed: electrons.
Figure 8.12: Single-scatter photon and electron recoil-energy spectra for veto-anticoincident cQout-Only events. Solid: photons. Dashed: electrons.
Figure 8.13: Distributions of ionization yield for veto-anticoincident cQinOnly single-scatter events in two recoil-energy bins. Dashed: ionization-search threshold. Dashed-dotted: nuclear-recoil-acceptance region for pre-April 3 data. Solid vertical lines: nuclear-recoil-acceptance region for post-April 3 data. The ionization-search thresholds and acceptance-region edges are averaged over the recoil-energy bins. Also shown are the number of nuclear-recoil candidates and the total number of events in each histogram, determined using the fully energy-dependent nuclear-recoil-acceptance regions.
Figure 8.14: Distributions of ionization yield for veto-anticoincident cQShare single-scatter events. Legend as in Figure 8.13.
Figure 8.15: Distributions of ionization yield for veto-anticoincident cQoutOnly single-scatter events. Legend as in Figure 8.13.
Definition of WIMP-Search Data Set, Expected Numbers of Misidentified Photons and Electrons

The search for WIMP-induced nuclear recoils is restricted to cQinOnly events in BLIPs 4, 5, and 6 between 10 and 100 keV. The rationale for discarding events outside the 10-to-100-keV window was discussed in Section 7.5; it is also clear from the ionization-yield plots that the band of surface events intrudes into the nuclear-recoil-acceptance region below 10 keV. BLIP3 is discarded because of its clear contamination. The reasons for discarding cQoutOnly and cQShare events are discussed in the previous section.

Prior to considering the nuclear-recoil data set defined by the above cuts, it is useful to determine the expected numbers of misidentified photons and electrons passing these cuts. The observed photon and electron events rates can be combined with the photon- and electron-calibration data to set Bayesian 90% CL upper limits on the expected numbers of misidentified photons and electrons. Both the photon- and electron-calibration data are discussed in Chapter 4. Recall that the electron-calibration data set consists of BLIP3/BLIP4 double scatters arising from BLIP3’s surface contamination; detailed justification for the definition of the electron-calibration set is discussed in Section 8.2.2. I describe the method for calculating the upper limit in detail for electrons; an analogous formalism holds for photons. This formalism is overkill for the single-scatter data, but it is useful to present it for the simple case of single-scatter misidentification to clarify the discussion of double-scatter misidentification later. Recall that \( \beta_\beta \equiv N_\beta/N_\beta \), where \( N_\beta \) is the number of misidentified single-scatter electrons (the number that leak into the nuclear-recoil-acceptance region) and \( N_\beta \) is the number of correctly identified single-scatter events (the number that appear between the nuclear-recoil-acceptance region and the bulk electron-recoil band). Note that the denominator is not \( N_{tot} = N_\beta + N_\beta \); these definitions of \( \beta_\beta \) and \( N_\beta \) make the formulae simpler. \( \mu^b_i \) is defined to be the expected number of misidentified single-scatter electron events for the veto-anticoincident single-scatter ("background") data set. An upper limit will be set on \( \mu^b_i \). Let \( \mu^c_i \) be the expected number of misidentified electron events in the calibration set. Define \( \lambda = 1/\beta_\beta \). The expected values for the observables \( N^b_\beta, N^c_i, \) and \( N^c_\beta \) — the number of correctly identified single-scatter electrons in the background set, the number of misidentified electrons in the calibration set, and the number of correctly identified electrons in the calibration set, respectively — are

\[
\begin{align*}
\langle N^b_\beta \rangle &= \lambda \mu^b_i \\
\langle N^c_i \rangle &= \mu^c_i \\
\langle N^c_\beta \rangle &= \lambda \mu^c_i
\end{align*}
\]

The likelihood function for these data is given by

\[
\mathcal{L}(N^b_\beta, N^c_i, N^c_\beta | \mu^b_i, \mu^c_i, \lambda) = \frac{(\lambda \mu^b_i)^{N^b_\beta} e^{-\lambda \mu^b_i}}{N^b_\beta!} \frac{(\mu^c_i)^{N^c_i} e^{-\mu^c_i}}{N^c_i!} \frac{(\lambda \mu^c_i)^{N^c_\beta} e^{-\lambda \mu^c_i}}{N^c_\beta!}
\]

which is just the product of Poisson distribution functions with the appropriate expected values. To calculate a Bayesian upper limit on \( \mu^b_i \), it is necessary to integrate over the "nuisance" parameters \( \mu^c_i \) and \( \lambda \) and calculate the confidence interval based on the resulting function of \( \mu^b_i \) only. The 90%
Table 8.2: Veto-anticoincident cQinOnly single-scatter-electron misidentification estimates, calculated by the method discussed in the text. The first column is the number of single-scatter-electron events observed in the background data for the given energy bin, coadded over BLIPs 4, 5, and 6. The second two columns list the calibration data used, which come from the BLIP3 column of Table 4.6. Recall that the calibration data set consists of the BLIP3/BLIP4 veto-anticoincident double-scatter events. The fourth column is the Bayesian 90% CL upper limit on the number of misidentified single-scatter electrons. Because of the large values of \( N^{\beta}_{c} \) and \( N^{\beta}_{b} \), these values are very close to what one gets by calculating a Bayesian 90% CL upper limit on \( \beta^{\gamma} \) from the electron calibration and multiplying by \( N^{\beta}_{b} \). The fifth and sixth columns give the Bayesian 10% CL and 50% CL upper limits on \( \mu^{\beta}_{b} \). The large spread among the 10%, 50% and 90% CL values indicates the impact of the low statistical precision of the electron calibration.

<table>
<thead>
<tr>
<th>Event set</th>
<th>( N^{\beta}_{b} )</th>
<th>( N^{\gamma}_{c} )</th>
<th>( N^{\beta}_{c} )</th>
<th>( \mu^{\beta}_{b,90} )</th>
<th>( \mu^{\beta}_{b,10} )</th>
<th>( \mu^{\beta}_{b,50} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 – 30 keV</td>
<td>101</td>
<td>1</td>
<td>46</td>
<td>8.9</td>
<td>1.2</td>
<td>3.7</td>
</tr>
<tr>
<td>30 – 100 keV</td>
<td>180</td>
<td>0</td>
<td>39</td>
<td>11.1</td>
<td>0.5</td>
<td>3.2</td>
</tr>
<tr>
<td>10 – 100 keV</td>
<td>281</td>
<td>1</td>
<td>85</td>
<td>13.1</td>
<td>1.8</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Note that a uniform integration measure is used for the integrals; in the Bayesian formalism, this choice is a matter of judgment. (A logarithmic measure for \( \lambda \) may be more appropriate, but, in general, the choice of measure does not significantly affect the result). It is necessary to invoke this machinery because \( \beta^{\beta} \) and \( \beta^{\gamma} \) are determined with significant statistical uncertainty: in both calibrations, the number of misidentified events is in the range 0 to 2. As a general point, this formalism is also necessary if \( N^{\beta}_{b} \) is small enough that it has significant statistical uncertainty, though, if \( \beta^{\beta} \) is determined with negligible uncertainty, the formalism simplifies greatly because the calibration pieces of the likelihood function become \( \delta \)-function-like.

The denominator can be calculated analytically, but the numerator cannot: one of the integrals can be done analytically, but the remaining two are nontrivial. Instead, the numerator is calculated numerically. Tables 8.2 and 8.3 show the resulting upper limits on misidentified single-scatter electrons and photons, respectively. In the photon case, an approximation has been made: \( N^{\gamma}_{b} \) has been taken to be only the number of events in the photon band, while \( N^{\gamma}_{c} \) included both photons and electrons in the photon-calibration set. This introduces a negligible error because bulk electron recoils make up approximately 97% of photon-calibration events [132].

Based on the above analysis, photon misidentification contributes a negligible number of nuclear-recoil candidates. The upper limit that can be set on electron misidentification is not nearly so useful. This occurs for two reasons. First, the electron calibration is statistics limited: even if no misidentified events had been seen in the electron calibration, the 50% CL and 90% CL upper limits would still be nonnegligible. Second, the one event seen in the nuclear-recoil band in the electron calibration \( Y^{2}_{\beta,2} \) plot (Figure 4.52) looks like a multiple-scatter neutron. The above analysis
CHAPTER 8. BACKGROUND-PARTICLE RATES AND CONSTRAINTS ON THE WIMP-NUCLEON CROSS SECTION

<table>
<thead>
<tr>
<th>Event set</th>
<th>$N^b_\gamma$</th>
<th>$N^c_i$</th>
<th>$N^c_\gamma$</th>
<th>$\mu^b_{1.90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLIP 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 – 30 keV</td>
<td>187</td>
<td>0</td>
<td>1613</td>
<td>0.27</td>
</tr>
<tr>
<td>30 – 100 keV</td>
<td>154</td>
<td>0</td>
<td>1694</td>
<td>0.21</td>
</tr>
<tr>
<td>10 – 100 keV</td>
<td>341</td>
<td>0</td>
<td>3307</td>
<td>0.24</td>
</tr>
<tr>
<td>BLIP 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 – 30 keV</td>
<td>147</td>
<td>0</td>
<td>1623</td>
<td>0.21</td>
</tr>
<tr>
<td>30 – 100 keV</td>
<td>156</td>
<td>0</td>
<td>2556</td>
<td>0.14</td>
</tr>
<tr>
<td>10 – 100 keV</td>
<td>293</td>
<td>0</td>
<td>4179</td>
<td>0.16</td>
</tr>
<tr>
<td>BLIP 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 – 30 keV</td>
<td>156</td>
<td>2</td>
<td>1425</td>
<td>0.58</td>
</tr>
<tr>
<td>30 – 100 keV</td>
<td>198</td>
<td>0</td>
<td>1359</td>
<td>0.34</td>
</tr>
<tr>
<td>10 – 100 keV</td>
<td>354</td>
<td>2</td>
<td>2784</td>
<td>0.68</td>
</tr>
<tr>
<td>Coadded</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>10 – 30 keV</td>
<td>490</td>
<td>2</td>
<td>4661</td>
<td>0.56</td>
</tr>
<tr>
<td>30 – 100 keV</td>
<td>498</td>
<td>0</td>
<td>5609</td>
<td>0.20</td>
</tr>
<tr>
<td>10 – 100 keV</td>
<td>988</td>
<td>2</td>
<td>10270</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 8.3: Veto-anticoincident cQinOnly single-scatter-photon misidentification estimates, calculated by the method discussed in the text. The first column is the number of single-scatter-photon events observed in the background set in the given energy bin. The other two columns list the calibration data used, which are given by the histograms in Figure 4.49. As one would expect from the large values of $N^c_\gamma$ and $N^b_\gamma$, the final upper limits are very close to what one gets by calculating a Bayesian 90% CL upper limit on $\beta_\gamma$ from the calibration and multiplying by $N^b_\gamma$.

conservatively assumes it is a misidentified surface event.

**WIMP-Search Data Set**

The WIMP-search data set consists of the veto-anticoincident cQinOnly single-scatter nuclear-recoil candidates passing the cuts described in Chapter 7 and the previous section; it contains 13 events. From the ionization-yield plots for the cQinOnly data, it is clear on an intuitive level that these events are not electrons: there is clear separation of the nuclear-recoil candidates from the low-energy-electron band at suppressed ionization yield. The expected numbers of misidentified photons are calculated above, rigorously demonstrating that misidentified photons contribute negligibly to the 13 observed events. Such a strong statement cannot be made for electrons because of the small number of events in the electron calibration. However, an electron interpretation is strongly disfavored by the observation of four double-scatter nuclear recoils with negligible electron leakage, as is discussed in Section 8.2.2: this double-scatter rate predicts a single-scatter rate consistent with the observed number of single-scatter nuclear recoils, as is discussed in Section 8.3.2. Given these arguments, the single-scatter nuclear-recoil candidates are interpreted as real nuclear recoils rather than misidentified photons or electrons.

Figure 8.16 shows the recoil-energy spectrum of these 13 nuclear-recoil events, coadded
over BLIPs 4, 5, and 6. Also shown is the overall efficiency function for nuclear recoils as calculated in the previous chapter, normalized to have peak efficiency of 1. The exposure corresponding to the peak is 10.6 kg \text{d}. The exposure and efficiency function have been fully corrected for the cuts defining the data set. The spectrum has been normalized to the peak exposure, but has \textit{not} been corrected for the energy dependence of the efficiency function. It is not helpful to do so here because of the small number of events; the energy dependence is correctly taken into account in later analysis. One conservative approximation has been made — the volume of the detector corresponding to cQinOnly events has not been corrected in the way discussed in Section 4.5.1. That is, the cQinOnly cut is taken to accept 40\% of the detector volume, as is naively suggested by the neutron calibration, rather then the apparent 46\% one derives after the two corrections discussed in that section. This decreases the exposure artificially by about 15\%. Note that the use of 10.6 kg \text{d} is an approximation only for WIMPs; veto-anticoincident neutrons are subject to the same scattering physics as the calibration-source neutrons, so it is true that only 40\% of veto-anticoincident neutron scatters are accepted by the cQinOnly cut.

Appendix D lists most of the useful parameters of these 13 nuclear-recoil events — their recoil energies and ionization yields, veto information, trigger-time information, etc. In this section, a number of Kolmogorov-Smirnov tests are performed on these events to establish that they exhibit no unusual characteristics. A Kolmogorov-Smirnov test compares the cumulative distribution of the events in a given event parameter to the expected distribution. It finds the point that deviates furthest from the expected cumulative distribution function (CDF) and assesses how many experiments would have observed events with larger deviations. For a detailed description of the formalism of the KS test, please consult [142] or [143].

The first, most obvious test is to check that the events exhibit no unexpected correlation with veto activity. A KS test of the last veto-trigger times for these events is shown in Figure 8.17. This test is only performed on the 10 ionization-trigger events. These times should follow an expo-
nential distribution corresponding to the last veto-trigger times being randomly distributed relative to the event time. The test indicates that 36% of experiments would have observed distributions that deviate further from the expected distribution. A different test, using the nearest veto-trigger time rather than the last veto-trigger time, could be performed for the 3 remaining events that are phonon triggers, but is not done because it would not be powerful with so few events. I also note that the events that occurred during the period that veto ADC information was available exhibit vanishing low and high veto pulse integrals for all counters, again indicating no simultaneous activity in the veto.

It is also possible to test the time distribution of the events. Each event has a live time and a number of live detectors (0 to 3) associated with it. (Fewer than three detectors may be alive at any given time because of downtime due to detector misbehavior or electronics problems). The coadded live time per event is the product of these two quantities and an average cut efficiency. Since the cut efficiencies are not strong functions of time or of detector, this last factor is taken to be a constant; since the test is performed on the cumulative coadded live time normalized to the total coadded live time, this constant factor cancels and can be ignored. The expected CDF is thus the cumulative fraction of events observed as a function of the cumulative fractional coadded live time. Note that this distribution includes events where BLIPs 4, 5, and 6 did not trigger; they were alive and could have triggered, so the live time of these events is included. The inverse of the slope of the CDF is the average fractional coadded live time per fraction of the number of events. The main contributions to variations in this number are discrete changes in the number of detectors alive at a given time (reasons for single detectors being dead are described in Chapter 7) or discrete changes in the trigger rate due to certain detectors’ triggers being disabled. For example, the expected distribution shows a slope change at the point where BLIPs 1 and 2 were turned off: the average coadded live time per event increases because the overall trigger rate decreases. It is important to stress that the live times of BLIPs 1 and 2 (and BLIP3) are not included in the coadded live time per event; however, the BLIPs 4/5/6 live time for events in which BLIPs 1, 2, or 3 triggered and none of BLIPs 4, 5, or 6 triggered must be included to give the correct coadded live time. The KS test indicates 19% of experiments would have observed distributions that deviate further from the expected distribution. The observed distribution for the 13 events appears to systematically deviate at early live time. While troubling, the 19% probability indicates that this deviation is not cause for significant worry.

The distribution in ionization yield of the nuclear recoils can be compared to the expected distribution. The normalized deviation, termed $Y^*_{\nu R}$ in Andrew Sonnenschein’s dissertation [8], is defined by:

$$Y^*_{\nu R} = \frac{Y_R - Y_{NR}(E_R)}{\sigma_{NR}(E_R)}$$

where $Y_{NR}(E_R)$ is the position of the center of the nuclear-recoil band in ionization yield and $\sigma_{NR}(E_R)$ is the standard deviation in $Y_R$ of the band, both functions of $E_R$. The usefulness of $Y^*_{\nu R}$ is that it puts nuclear recoils at different $E_R$ on the same footing. In the absence of cuts in $Y_{\nu R}$ defining the acceptance region, the expected distribution is a simple Gaussian with mean 0 and standard deviation 1. The cuts that define the nuclear-recoil band truncate the distribution in an $E_R$-dependent manner. One ambiguity arises in calculating the effect of these cuts on the expected distribution. Without these cuts, the expected distribution of $Y^*_{\nu R}$ at all recoil energies is the same, so combining $Y^*_{\nu R}$ distributions from different recoil energies is trivial. With the cuts implemented,
Figure 8.17: Kolmogorov-Smirnov tests for veto-anticoincident cQinOnly single-scatter nuclear-recoil candidates. "KS Percentile" indicates the percentage of experiments expected to observe larger deviation (larger KS statistic). Solid lines indicate expected distributions. Upper left: last veto-trigger-time distribution for ionization triggers. Upper right: cumulative coadded live time distribution. Lower left: pre-April 3 $Y_R^*$ distribution. Lower right: post-April 3 $Y_R^*$ distribution.
however, one must choose a weighting in $E_R$ to apply when combining the expected distributions from different $E_R$. As is seen later, the recoil-energy spectrum fits the spectrum expected for external-neutron scattering well, so this spectrum, corrected by the overall efficiency function, is used as a weighting. The spectra of calibration-source, internal, and external neutrons are not different enough for it to matter which one is used. It is important, however, that a reasonable spectral weighting be used because it determines the relative importance of the cuts at low and high $Y_R^*$ in modifying the distribution. Also, it is necessary to do the test separately for events before and after the April 3 power outage because the nuclear-recoil bands change at this point. Figure 8.17 shows this test for the 13 nuclear recoils. The data and distributions for BLIPs 4, 5, and 6, have been combined, weighting by each detector’s exposure. The KS tests indicate that 54% and 62% (pre/post-April 3) of experiments would observe distributions that deviate further from the expected distribution. This level of agreement is important because misidentified electron events would be expected to have a distribution either flat in $Y_R$ or weighted toward high $Y_R$.

Similar tests could be done for almost any event parameter. The above tests are most sensitive to the possibility that the 13 nuclear-recoil candidates are not veto-anticoincident nuclear recoils. These results indicate there is nothing unusual about these events at a statistically significant level.

### 8.2.2 Double-Scatter Data Set

In addition to the cuts described in the previous chapter, the veto-anticoincident double-scatter data set is defined by the following restrictions:

- at least one detector out of BLIPs 4, 5, and 6 has an inner-electrode event;
- exactly two detectors out of BLIPs 4, 5, and 6 trigger;
- and the recoil energies of both triggered detectors are between 10 and 100 keV.

The detailed rationale for these cuts was discussed in Section 7.5. Broadly, the purpose of these restrictive cuts is to discard events that are not double-scatter neutrons while maximizing the efficiency for observing these neutrons; a similar set of cuts has been made on the neutron-calibration and muon-coinicident data sets and the resulting efficiency reductions are discussed in Chapter 7. These cuts discard triple-scatter neutrons, but the rate of such events relative to double scatters is only about 10%, so they contribute little to the analysis.

Ionization yield vs. recoil energy plots for this event set are shown in Figure 8.18. The events are distributed among the different ionization-partition cuts, so the summed-ionization signal is used for calculating the ionization yield to put all the events on the same footing; the added noise is not important here. BLIP3 is not shown because, by definition of the event set, it has no events. The cleanliness of these plots is remarkable. There are 8 scatters tagged as nuclear recoils, which appear in pairs. This last fact is quite important — there are no double-scatter events for which one recoil is a nuclear recoil and the other is not.

To better understand the physics of the double-scatter event set, plots of ionization yield vs. ionization yield ("$Y_R^{2n}$" plots) for detector pairs are shown in Figures 8.19 and 8.20. The first figure shows double scatters among BLIPs 4, 5, and 6 only, with the aforementioned cuts. The second figure shows double scatters between BLIP3 and one of the other detectors, with the same
Figure 8.18: Ionization yield vs. recoil energy for veto-anticoincident BLIPs 4/5/6 double scatters in which at least one detector of BLIPs 4, 5, and 6 contains a cQinOnly event and both recoils are between 10 and 100 keV. Nuclear-recoil candidates are circled. Hyperbolic dashed line: ionization-search threshold. Light solid line: center of nuclear-recoil band, pre-April 3. Light dashed line: center of nuclear-recoil band, post-April 3. Dark solid line: nuclear-recoil-acceptance region, pre-April 3. Dark dashed line: nuclear-recoil-acceptance region, post-April 3.
Figure 8.19: Ionization yield vs. ionization yield for veto-anticoincident BLIPs 4/5/6 double scatters in which at least one detector of BLIPs 4, 5, and 6 contains a cQinOnly event and both recoils are between 10 and 100 keV. Circles and squares indicate events identified as nuclear recoils by the x-axis and y-axis detectors, respectively.
Figure 8.20: Ionization yield vs. ionization yield for veto-anticoincident double scatters in which BLIP 3 triggers, at least one detector (of all four) contains a cQinOnly event, and both recoils are between 10 and 100 keV. Circles and squares indicate events identified as nuclear recoils by the x-axis and y-axis detectors, respectively. The event marked by a circle and not a square is just above the nuclear-recoil-acceptance region of BLIP3, consistent with the less-than-unity acceptance of the cut. A similar explanation holds for the event marked by a square and not a circle. Note that the full electron-calibration data set discussed in Chapter 4 corresponds approximately to the BLIPs 3/4 plot, with the additional inclusion of events in which at least one detector has a cQShare event.
cuts except that BLIP3 is required to belong to each double scatter. (At least one detector is required to have a cQinOnly recoil, as above). The two sets of plots thus show all double-scatter events in which any detector has a cQinOnly recoil and both recoils are between 10 and 100 keV.

Consider first detector pairs that are not neighbors — BLIPs 3/5, BLIPs 4/6, etc. With the exception of 2 events in the BLIPs 3/5 pair, all such events are seen with similar \( Y_R \) in both detectors at either \( Y_R \sim 1 \) or \( Y_R \sim 0.3 \). These events are therefore unambiguously identified as either double-scatter penetrating photons (i.e., bulk electron recoils) or double-scatter neutrons, respectively. When adjacent detector pairs are considered, low-yield events appear between the bulk electron recoils and neutrons. If an event appears at low yield in both detectors, it is most easily interpreted as a low-energy electron. If an event appears at low yield in one detector but at \( Y_R \sim 1 \) in the other detector, the event may be one in which a photon scatters very near the surface of one detector, ejecting a low-energy electron that hits the adjacent detector. This seems an unlikely explanation of the BLIPs 3/5 events of this type, though.

The BLIPs 3/4 plot is striking because it clearly shows a population of events that appear at low yield in both detectors and that is separated from both the double-scatter bulk electron recoils and the double-scatter neutrons. These events are interpreted as double-scatter low-energy electrons emitted from the contaminant on BLIP3 that scatter in both BLIPs 3 and 4. The absence of a similar population in the BLIPs 3/5 and BLIPs 3/6 plots supports this interpretation — low-energy electrons emitted by BLIP3 cannot traverse BLIP4 to reach BLIPs 5 and 6.

The most important conclusion to be drawn from these plots is that the identification of double-scatter nuclear-recoils, once the cuts listed previously are made, is unambiguous, with 4 double-scatter nuclear recoils appearing in the BLIPs 4/5/6 data set. To establish this point numerically, the BLIPs 3/4 “electron-calibration” data set is used. As is clear from the \( Y_R^2 \) plots, the BLIPs 3/4 sample contains an electron source. These events can be used as a low-statistics electron calibration. It is important to note that this electron-calibration data set is completely disjoint from the BLIPs 4/5/6 single- and double-scatter data sets. The analysis of this electron calibration is presented in Section 4.5.3 and the estimated value of the electron-misidentification parameter, \( \beta_3 \), for various ionization-partition cuts (cQinOnly, cQShare, and cQoutOnly) and energy bins are shown in Table 4.6. In using the electron calibration to estimate the number of double-scatter nuclear-recoil candidates arising from misidentified electrons, it is important to make use of the fact that, while the double-scatter electrons do cluster around \( Y_R \sim 0.75 \), there appears to be no correlation in the deviations from this central value of the ionization yields observed in the two detectors. This is clear from the BLIPs 3/4 plot in Figure 8.20 — the electron events do not form a line with slope 1. In order to be misidentified as a double-scatter neutron, a double-scatter electron must therefore be misidentified in both detectors; such misidentification is suppressed by a factor \( \beta_3^2 \) rather than only \( \beta_3 \).

This last point is nontrivial: one might have assumed that there would be significant correlation because the penetration depth of the electron would scale with its energy, and thus a very low-energy electron (say, 15 keV) would appear at lower yield in both interactions than a higher-energy electron (say 50 or 60 keV). There may be such a correlation, but the BLIPs 3/4 plot indicates that, when averaged between 10 and 100 keV using the energy spectrum of electrons emitted by the BLIP3 contaminant, the correlation becomes negligible. Furthermore, Figure 4.53 indicates that the bulk of the events in the electron-calibration data set are at low recoil energies, below 30 keV, and thus the electron calibration probes the possibility of correlation at low energies,
where it would be most likely. Clearly, correlation is not important.

There may be a straightforward explanation for the apparent lack of correlation. Because electrons are charged, they lose energy continuously rather than in a pointlike interaction, as is typical for photons. Furthermore, because electrons are so light, they experience significant deflection on each scattering — their path in the detector is not a straight line but is very jagged. A double-scatter electron is so deflected that it exits the crystal again. The deposited energy is therefore not a strong function of the electron energy — it depends on the track length in the crystal, which may be short for a high-energy electron if it is backscattered. The ionization yield is, however, likely to be well correlated with the track length: shorter tracks are also likely to be more shallow. Thus, for double-scatter electrons, the ionization yield for one scatter, while likely correlated with the deposited energy, may not be a good predictor of the actual electron energy, and thus may not be a good predictor of the ionization yield observed in the second recoil.

Numerically, the expected number of misidentified double-scatter electrons in the double-scatter nuclear-recoil sample is calculated as follows. Let \( N_l \) be the number of double-scatter electrons misidentified by both detectors and let \( N_s \) be the number of double-scatter electrons correctly identified by both detectors. The latter is the number of events that appear between the nuclear-recoil-acceptance region and the bulk electron-recoil band in both triggered detectors. A correction must be made because, as is seen in Figure 8.19, some events appear as electrons in one detector and as bulk electron recoils in the second detector. These events are artificially included in the double-scatter-electron set; this is conservative because photon misidentification is far less likely than electron misidentification.

The formalism developed for calculation of the 90% CL upper limit on the expected number of misidentified single-scatter electrons can be used, with the modifications

\[
\langle N^b_\beta \rangle = \lambda^2 \mu^b_l
\]  

and

\[
\mathcal{L}(N^b_\beta, N^c_\beta, N^c_\beta | \mu^b_l, \mu^c_l, \lambda) = \frac{(\lambda^2 \mu^b_l)^{N^b_\beta} e^{-\lambda^2 \mu^b_l}}{N^b_\beta!} \frac{(\mu^c_l)^{N^c_\beta} e^{-\mu^c_l}}{N^c_\beta!} \frac{(\lambda \mu^c_l)^{N^c_\beta} e^{-\lambda \mu^c_l}}{N^c_\beta!}
\]  

(8.6)

where, essentially, \( \lambda \) has been replaced by \( \lambda^2 \) everywhere in the background-data parts of the formulae. (Recall that \( \lambda \equiv 1/\beta_\beta. \) This expresses the lack of ionization-yield correlation: if the expected number of double-scatter electrons misidentified as double-scatter neutrons is \( \mu^b_l \), then the expected number of correctly identified double-scatter electrons is \( \lambda^2 \mu^b_l \).

In applying the above, one complication arises: the double-scatter electrons in the background set are distributed among the three ionization-partition cuts, so in principle one has to do a more complex analysis, dividing the data into different ionization-partition sets, using the appropriate calibration-data sets, and calculating the combined likelihood function. This results in many more nuisance parameters and becomes intractable. Instead, the following approximate approach is taken. As is shown in Table 8.4, the double-scatter background-data events are primarily cQinOnly events, as with the calibration data. They are as or more concentrated in the cQinOnly cut than the BLIP3 calibration data. Therefore, the limit is calculated using the background data and BLIP3 calibration data summed over the three ionization-partition cuts. The BLIP4 calibration data are more concentrated in the cQinOnly cut and thus would yield too aggressive a limit. The BLIP3 calibration data are also expected to probe the bias polarity in which the ionization-collection tails are worse (see Section 4.2). A sum over energies is done — the background data appear to have a
Table 8.4: Double-scatter-electron misidentification estimates, calculated by method discussed in text. The first column is the number of double-scatter-electron events observed for the given energy bin and ionization-partition cut. Since a given double scatter can be distributed among two different bins and cuts, this number is derived by dividing by 2 the number of recoils (not events) seen in the bin. Also listed are estimates combining the ionization-partition cuts for a given energy bin and combining energy bins for a given ionization-partition cut. The number on which to focus is the one at the lower right, which gives the expected number of double-scatter-electron events misidentified as double-scatter nuclear recoils, summing over all ionization-partition cuts and energy bins. Note that the estimates are, in many cases, significantly higher than one would find by calculating a Bayesian 90% CL upper limit on $\beta_\beta$ from the calibration data and estimating the leakage by $N^b_\beta \beta_\beta$; this occurs because $N^b_\beta$ is small and its fluctuations significantly weaken the final upper limits.

<table>
<thead>
<tr>
<th>Event set</th>
<th>$N^b_\beta$</th>
<th>$N^f_\beta$</th>
<th>$N^c_\beta$</th>
<th>$\mu_{\beta,90}^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 – 30 keV</td>
<td>8/2 = 4</td>
<td>1</td>
<td>46</td>
<td>0.08</td>
</tr>
<tr>
<td>Qin</td>
<td>1/2 = 0.5</td>
<td>1</td>
<td>35</td>
<td>0.04</td>
</tr>
<tr>
<td>QShare</td>
<td>4/2 = 2</td>
<td>0</td>
<td>9</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>13/2 = 6.5</td>
<td>2</td>
<td>90</td>
<td>0.05</td>
</tr>
<tr>
<td>30 – 100 keV</td>
<td>14/2 = 7</td>
<td>0</td>
<td>39</td>
<td>0.09</td>
</tr>
<tr>
<td>Qin</td>
<td>3/2 = 1.5</td>
<td>0</td>
<td>27</td>
<td>0.06</td>
</tr>
<tr>
<td>QShare</td>
<td>2/2 = 1</td>
<td>0</td>
<td>5</td>
<td>3.73</td>
</tr>
<tr>
<td>Total</td>
<td>19/2 = 9.5</td>
<td>0</td>
<td>71</td>
<td>0.03</td>
</tr>
<tr>
<td>10 – 100 keV</td>
<td>22/2 = 11</td>
<td>1</td>
<td>85</td>
<td>0.05</td>
</tr>
<tr>
<td>Qin</td>
<td>4/2 = 2</td>
<td>1</td>
<td>62</td>
<td>0.02</td>
</tr>
<tr>
<td>QShare</td>
<td>6/2 = 3</td>
<td>0</td>
<td>14</td>
<td>0.44</td>
</tr>
<tr>
<td>Total</td>
<td>32/2 = 16</td>
<td>2</td>
<td>161</td>
<td>0.03</td>
</tr>
</tbody>
</table>

spectrum no softer than the calibration data. For completeness, limits are also calculated for each electrode cut and each energy bin separately. Since a given double-scatter event may appear in different energy bins and ionization-partition cuts in the two detectors, some prescription must be used in determining the “number of double scatters” in a given energy bin and ionization-partition cut. The prescription used here is to divide the number of recoils (not events) for each cut and energy bin by 2. This is exactly correct for the sum over all ionization-partition cuts and energy bins.

The double-scatter-electron misidentification limits are shown in Table 8.4. Clearly, the limits are on the whole very stringent except in cases where the number of electron-calibration events is low. To conclude, the double-scatter data set defined here shows that double-scatter neutrons are unambiguously identified and that the expected misidentification of double-scatter electrons as double-scatter neutrons is negligible. Four double-scatter-neutron events are seen.
8.3 The Neutron Interpretation

Thirteen single-scatter and four double-scatter nuclear-recoil candidates are observed in the veto-anticoincident data set. It has been argued that these events are indeed nuclear recoils, not low-energy-electron surface events. The only possible particles that can cause these recoils are neutrons and WIMPs. Given the 10.6 kg d exposure, this number of single-scatter nuclear recoils corresponds to an integral event rate of about 1.3 kg^{-1} d^{-1} above 10 keV. This event rate approaches interesting MSSM WIMP models and is in the neighborhood of the rate expected from a WIMP with mass and cross section yielding the annual-modulation signal observed by the DAMA collaboration [88].

However, there are a number of reasons to believe that these events are due to neutrons, not WIMPs. First, the observation of 4 double scatters rules out WIMPs as the source of these events: since the WIMP single-scatter rate is so low (~1 kg^{-1} d^{-1} and lower), WIMPs, for all practical purposes, do not multiply scatter. Put in more practical terms, the mean free path of a WIMP with a 1 kg^{-1} d^{-1} event rate in germanium is about 10^{10} meters of germanium. Second, a WIMP interpretation is further disfavored by the observation of 4 nuclear recoils in the Run 18 data set obtained with a Si ZIP detector. If WIMPs caused these four events, then an unacceptably high number of WIMP events are expected in the Run 19 Ge data set. Finally, via the simulations discussed in Chapter 3, it is seen that the 13 single-scatter Ge events, 4 double-scatter Ge events, and 4 Si events are consistent (though not impressively so) with a neutron-background interpretation.

The most straightforward interpretation is therefore that these events are due to neutron scattering. These neutrons must be veto-anticoincident, so they are most probably neutrons (and their secondaries and tertiaries) generated by fast muons in the tunnel walls. The expected rates and recoil-energy spectra for these "external" neutrons are discussed in Chapter 3. In this section, I present in detail the argument for this neutron interpretation.

8.3.1 Run 18 Si Detector Nuclear-Recoil Event Rate

In CDMS Run 18, which occurred during 1998, 33 live days of data were taken with a 100-g Si ZIP detector ("Alex," after the first prime minister of Canada). The Si run yields a 1.6 kg d exposure after cuts. Four nuclear recoils are observed in the Si data set. Based on a separate electron calibration, the upper limit on the expected number of misidentified surface events is 0.76 events (90% CL). The Run 18 veto-anticoincident data are displayed in Figure 8.21.

The ZIP Detector and Data Set

A brief digression to discuss this detector and data set is warranted. Z-sensitive Ionization and Phonon-mediated (ZIP) detectors sense the athermal phonons produced by a recoiling particle. The Run 18 Si detector employs Schottky-barrier contacts for the ionization measurement, which are briefly discussed in Chapter 4. The detector geometry is similar to the BLIP geometry: the detectors are cylindrical, 7.5 cm in diameter and 1-cm thick. The ionization electrodes are segmented radially with a nominal 0.85:0.15 inner/outer volume ratio. The detector edges are not curved and the cylindrical detector wall is left bare. The athermal phonons are collected and sensed by Quasiparticle-Trap-Assisted Electro-Thermal-Feedback Transition-Edge Sensors (QTA-ETF-TES, or QET for short) deposited on one crystal face. Though the Schottky-barrier contacts
also have a dead-layer problem (see Section 4.2), the athermal-phonon signal allows rejection of
dead-layer events because this pulse shape is sensitive to the proximity of an interaction to the
detector surface. A 90% CL lower limit on surface-event rejection of 98.8% above 15 keV was
established by a laboratory exposure of the Run 18 Si ZIP detector to an electron source. Thus,
this detector is capable of discriminating nuclear recoils from dead-layer events in the presence of
a low-energy-electron surface-event rate of 60 kg$^{-1}$ d$^{-1}$ between 15 and 100 keV. An upper limit
of 0.76 misidentified surface events is derived from this event rate and the surface-event-rejection
lower limit. It should be noted that, above 20 keV, the surface-event-rejection lower limit is 99.7%
and the expected number of misidentified surface events is only 0.26 events. A value of 0.76 events
is used in calculation of exclusion limits to be conservative.

The ZIP detector technology has been developed by Blas Cabrera’s group at Stanford
over the last few years. The electron calibration and Run 18 data set is described in detail in
Roland Clarke’s dissertation [102]. (The detector is referred to as a Fast, Large Ionization- and
Phonon-mediated (FLIP) detector in this reference.) The electron calibration and surface-event
rejection are also described in [144]. A paper in preparation will present the Run 18 Si ZIP data
and analysis [103]. The baseline detector for CDMS II is a ZIP detector using the above athermal-
phonon sensing technology and the $\alpha$-Si/Al-Schottky ionization contacts discussed in Section 4.2.
Three silicon and three germanium ZIP detectors are being operated in CDMS Run 20, which
began in March, 2000. Physics results from this run are not yet available.

Implications of the Silicon Detector Data

The four nuclear-recoil events observed in the Run 18 Si ZIP data cannot be WIMPs:
whether their interactions with target nuclei are dominated by spin-independent or spin-dependent
couplings, WIMPs yielding the observed Si nuclear-recoil rate would cause an unacceptably high

Figure 8.21: Run 18 Si ZIP detector veto-anticoincident data. Light solid line: center of nuclear-
recoil band. Dark solid lines: nuclear-recoil-acceptance region. Dashed line: nuclear-recoil analysis
threshold (15 keV). Figure provided by R. Clarke/R. Schnee.

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whether their interactions with target nuclei are dominated by spin-independent or spin-dependent
couplings, WIMPs yielding the observed Si nuclear-recoil rate would cause an unacceptably high
number of nuclear recoils in the Ge data set. As discussed in Chapter 2, the WIMP-nucleus cross section scales as $A^2$ for WIMPs with spin-independent interactions. Expected recoil-energy spectra in germanium and silicon for a WIMP with spin-independent interactions are shown in Figure 2.10. Ge and Si differ by a factor of 5 to 7 in differential rate between 0 and 100 keV. One thus expects of order 30 to 50 times the number of WIMPs in the Ge data set as in the Si data set given the exposures and this rate ratio. The argument is more complicated for spin-dependent interactions, but it also holds that there should be many more nuclear recoils in the Run 19 Ge data set than are observed. Furthermore, the spin-dependent cross section corresponding to the observed Si event rate is significantly larger than expected from the MSSM. As is shown below, the observation of 4 Si nuclear recoils is consistent with the external-neutron-background interpretation of the 13 single-scatter and 4 double-scatter nuclear recoils in the Ge data set.

### 8.3.2 Comparison of Observed and Simulated Rate Ratios

The simulation of the external-neutron background is discussed in Chapter 3. As indicated there, a number of issues lead to a large normalization uncertainty, making it difficult to accurately predict the absolute flux of unvetoed external neutrons. However, normalization-independent predictions of the simulation, such as relative rates of single scatters and double scatters, relative rates in Si and Ge detectors, and the shapes of nuclear-recoil spectra, are accurately simulated. Therefore, only these normalization-independent quantities are used to test the consistency of the observed data with the external-neutron-background simulation. It is important to note that these predictions of the simulation are also insensitive to reasonable changes in the external-neutron energy spectrum. In Chapter 3, it is seen that the high-energy tail of the external-neutron spectrum has little effect on the spectrum of neutrons incident on the detectors that dominate the detector event rate — high-energy external neutrons produce many secondary and tertiary neutrons with energy spectra similar to internal neutrons, and the neutron-interaction cross section strongly favors interactions of low-energy neutrons.

The ratios of Ge double scatters $N_d$ to Ge single scatters $N_s$ and of Si neutron events $N_{Si}$ to Ge single scatters for the data and the simulation are shown in Table 8.5. Schematically, the data and simulation can be compared in two ways: normalizing the simulation by the neutron-background rate that best fits $N_s$, $N_d$, and $N_{Si}$ jointly, or normalizing by the neutron-background rate that best fits $N_d$ and $N_{Si}$ and predicting $N_s$. The latter is the intuitive interpretation of using the Ge doubles and Si events to predict the neutron background in the Ge singles set. These comparisons are shown in Figure 8.22.

More rigorously, a likelihood-ratio test can be used to compare the hypothesis that the three numbers of events are derived from a single neutron background with relative rates given by the simulation to the hypothesis that the three event sets arise from three different neutron-
background sources. Effectively, the latter hypothesis corresponds to three arbitrary background sources for the three event types, the most general possible hypothesis. The likelihood ratio of the two hypotheses is

$$R = \frac{L(N_s, N_d, N_{Si}|\hat{n})}{L(N_s|\hat{n}_1)L(N_d|\hat{n}_2)L(N_{Si}|\hat{n}_3)} \quad (8.7)$$

where $L(N_s, N_d, N_{Si}|\hat{n})$ is the likelihood of the three observed values calculated at the number of Ge (single + double) nuclear recoils $\hat{n}$ that maximizes their likelihood, and $L(N_s|\hat{n}_1)$, $L(N_d|\hat{n}_2)$, and $L(N_{Si}|\hat{n}_3)$ are the individual likelihoods of the three observed values separately, calculated at the values of the number of Ge events that maximize each likelihood separately. $R$ is limited from above by 1, which occurs when the best fit values $\hat{n}_1$, $\hat{n}_2$, $\hat{n}_3$, and $\hat{n}$ are all equal. The larger $R$ is, the more consistent the data are with the simulation. In the limit of large numbers of events $N_s$, $N_d$, and $N_{Si}$, $-2\log R$ is distributed as $\chi^2$ for 2 degrees of freedom. With the small numbers of events observed, a Monte Carlo must be performed to determine the expected distribution of $R$ (or $-2\log R$), which then yields the fraction of experiments that would have yielded lower (worse) values of $R$. Since the true neutron background is unknown, the Monte Carlo must be done for different values of the “true” number of Ge events $n$ that is assumed for the Monte Carlo. In doing the Monte Carlo, the assumed value $n$ is used to calculate expected values $\mu_s$, $\mu_d$, and $\mu_{Si}$ for the numbers of each type of event. The Monte Carlo draws observed numbers of events $N_s$, $N_d$, and $N_{Si}$ from Poisson distributions for each quantity given the expected values $\mu_s$, $\mu_d$, and $\mu_{Si}$. The ratio $R$ is calculated for each Monte Carlo outcome, yielding the distribution of $R$ for that assumed $n$. Note that $L$ is calculated at $\hat{n}$, not at the assumed value $n$, for reasons explained below.

Table 8.6 shows the fraction of experiments with worse values of $-2\log R$ as a function of the assumed value of $n$. The advantage of testing the above likelihood ratio is that the calculated confidence level of the observed data is only weakly dependent on the assumed neutron background $n$ — the test does not depend strongly on what normalization for the external-neutron background is assumed for the Monte Carlo. This characteristic results partially from the use of a likelihood ratio...
SECTION 8.3. THE NEUTRON INTERPRETATION

Table 8.6: Likelihood-ratio test of the consistency of the observed nuclear-recoil event sets with the simulation. The first column is the likelihood of the data, $\mathcal{L}_d = \mathcal{L}_d(N_s, N_d, N_{Si}|n)$, given the assumed neutron background $n$. The second column shows the fraction of simulated experiments at the assumed value of $n$ that yield likelihoods lower than the data. The last column shows the fraction of simulated experiments with worse values of the likelihood ratio $R$ than the value given by the data $R_d$ (i.e., with $-2\log R > -2\log R_d$). This last column indicates that the likelihood-ratio test has only weak dependence on the assumed value $n$. Thus, the result, that about 6% of simulated experiments yield worse agreement with the neutron-background simulation than the data, is robust against uncertainty in $n$.

<table>
<thead>
<tr>
<th>assumed $n$</th>
<th>$\log(\mathcal{L}_d(n))$</th>
<th>$P(\mathcal{L}(n) &lt; \mathcal{L}_d(n))$</th>
<th>$P(-2\log R &gt; -2\log R_d)$</th>
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<td>29.0</td>
<td>-11.98</td>
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<td>0.062</td>
</tr>
</tbody>
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8.3.3 Comparison of Observed and Simulated Spectral Shapes

The other normalization-independent quantity available from the simulation is the shape of the recoil-energy spectrum. A Kolmogorov-Smirnov test comparing the integral observed and simulated nuclear-recoil spectra is shown in Figure 8.23. Being a KS test, the test is independent of normalizations. The simulated spectrum has been corrected by the energy dependence of the overall efficiency function. The KS tests for the Ge single-scatters alone and for all Ge events are shown. The fraction of experiments expected to give larger deviations is 86% and 28% in the two cases, respectively. These levels of agreement are generally considered reasonable and
indicate the observed and simulated spectral shapes are consistent. These results should only be taken as support for the consistency of the data with the simulation; they are also consistent with interactions of a WIMP having mass in the 50 to 100 GeV c$^{-2}$ range and so do not alone disfavor a WIMP interpretation. Also shown are the KS tests comparing the data to the \textit{internal}-neutron simulation. It is again clear that the recoil-energy spectrum expected in the detectors is fairly independent of the high-energy tail of the external-neutron spectrum. The consistency of the data with the recoil-energy spectrum expected for external neutrons can also be seen in a differential recoil-energy spectrum, shown in Figure 8.24.

### 8.3.4 On the Possibility of Veto Inefficiency

The possibility that the observed neutron background is due to internal neutrons that appear as veto-anticoincident because of veto inefficiency — \textit{i.e.}, the muon was missed by the veto — should be considered. As discussed in Chapter 3, it is not possible to directly measure the veto efficiency for muons that generate neutrons, but it is possible to measure the efficiency for detector-tagged muons. Figure 3.10 demonstrates that the veto pulse-integral spectra for muons that generate neutrons and for detector-tagged muons are very similar. The veto efficiency for detector-tagged muons had an average value of 99.90\% over the run, with a worst excursion to 99.69\%, as is shown in Figure 8.25. Using the single-scatter \texttt{cQinOnly} muon-coincident-neutron rate of 22 per live day (coadded over BLIPs 3, 4, 5, and 6) shown in Figure 7.26, the total number of internal neutrons seen in BLIPs 4, 5, and 6 over the run is about 1200. The expected number of “missed” internal neutrons is thus about 1, much less than the observed number of Ge nuclear
recoils. However, one may invoke the possibility that internal neutrons may be produced by a subset of muons that pass through particular regions of the veto for which the efficiency is much less than shown above. Such a possibility cannot be ruled out.

However, in practice, it does not matter whether the neutrons are internal or external. It is seen in Chapter 3 that energy spectra of internal and external neutrons incident on the detectors are very similar. Therefore the expected recoil-energy spectra are essentially the same. This is corroborated by the fact that the KS test comparing the expected internal- and external-neutron recoil-energy spectra cannot distinguish the two cases. Furthermore, because the double-scatter/single-scatter and Ge/Si ratios are determined completely by the incident-neutron spectrum, they also are the same to good precision for internal and external neutrons. Thus, because of this degeneracy between the two types of neutrons, it is almost irrelevant whether the neutrons causing the observed nuclear recoils are internal or external. One issue arises, which is that the veto efficiency may have been different for the Run 18 Si data. However, the veto efficiency for detector-tagged muons during Run 18 was \( > 99.99\% \) \[8\], higher than during Run 19, so the Si data presumably can only underestimate the neutron background, making the joint estimate lower. This yields an overly conservative exclusion limit on the WIMP-nucleon cross section.
Figure 8.25: Veto inefficiency for detector-tagged muons over Run 19. The number of detector-tagged muons missed by the veto per 10000 detector-tagged muons is shown. The time bins do not all have the same width because they are defined by containing 10000 muons, not a fixed amount of real time. Variations in the bin width (especially the large ones) are due to intervals when the experiment was not operating. The mean veto efficiency is 99.90% and lowest veto efficiency observed is 99.69%. Figure provided by R. Schnee.
8.4 Exclusion Limits on the WIMP-Nucleon Cross Section

A 90% CL exclusion region in the plane of WIMP mass $M_\delta$ and the WIMP-nucleon spin-independent elastic-scattering cross section $\sigma_{\delta n}$ is determined under the assumption that the neutron-background interpretation of the data is correct. Heuristically, this permits the neutron background predicted by the Ge double-scatter and Si event rates to be statistically subtracted from the Ge single-scatter data, yielding sensitivity to lower WIMP-nucleon cross sections by accounting for the component of the Ge single-scatter data set that is due to neutron scattering.

In practice, a more rigorous method, involving a modification of the Feldman-Cousins “unified” approach [83], is used to calculate the allowed region. The Feldman-Cousins method is most easily understood by specific examples, as are given in the original paper [83]. The Feldman-Cousins approach offers a number of desirable features, whose validity will not necessarily be obvious to the reader immediately, but that will be reiterated later in the context of its application here:

- The first feature is that it is a classical method — in calculating an excluded region of parameter space at, for example, 90% CL, it answers the question “What are the values of the input parameters such that, for those input parameters, the observed data in at least 90% of experiments would have been more consistent with the parameters than the observed experimental data?” This question is independent of the integration measure assumed on the parameter space being constrained and so is usually considered the best question to ask when presenting experimental results. What is meant by “consistent” is ambiguous; Feldman and Cousins use a likelihood ratio,

$$R = \frac{L(X|\mu)}{L(X|\hat{\mu})} \quad (8.8)$$

where $\mu$ are the set of input parameters being tested, $X$ are the experimental data, and $\hat{\mu}$ are the set of parameters that maximize the likelihood of (“best fit”) the experimental data. Use of the likelihood ratio is appropriate because the absolute likelihood of the data has little meaning. For example, consider two experiments that measure the rate of some occurrence, but allow the first experiment to have a much larger amount of data; thus, the statistical uncertainty of the result measured by the first experiment is much smaller than that of the second experiment. Even if both experiments yield the same measured rate and the measured rate coincides exactly with the rate expected for some $\mu$, the first experiment has a much larger $L$ because its statistical uncertainty is smaller and so its likelihood function is narrower and has a larger peak value. The two experiments are equally valid, but the latter has a much smaller $L$. Use of a likelihood ratio normalizes the likelihood by the highest possible likelihood the experiment could yield, thus putting the two experiments on the same footing.

- A second advantage of the Feldman-Cousins approach is that it is “unified” — its results smoothly transition between one-sided upper limits and two-sided confidence intervals. This eliminates the ambiguity as to whether to quote an upper limit or a confidence interval.

- A third advantage is that it ensures full coverage, and possibly overcoverage. This feature is particularly important when considering cases involving background subtraction. Various methods previously in use could yield upper limits or confidence intervals that do not meet their advertised confidence levels in a classical sense. In extreme cases, such methods could yield an empty set for the allowed region.
CHAPTER 8. BACKGROUND-PARTICLE RATES AND CONSTRAINTS ON THE
WIMP-NUCLEON CROSS SECTION

The analysis presented here is somewhat more complicated than the examples discussed in [83] because the prediction of the neutron background is subject to significant uncertainty. The normalization of the neutron background is thus taken as an additional free parameter, \( n \), the total number of Ge neutron scatters, that is constrained by the observed relative rates of Ge single scatters, Ge double scatters, and Si events. The Feldman-Cousins method has been extended in order to project out the neutron-background “nuisance” parameter and give a final confidence region in the \((M_\delta, \sigma_\delta n)\) plane. This extension was developed and implemented by Bernard Sadoulet, Richard Schnee, and Steve Yellin and is described in detail in an internal note by Richard Schnee [145]. I describe the formalism briefly, but the reader should refer to this reference for a comprehensive discussion, including important practical aspects of the implementation. I describe the method in two steps: first, the naive application of the Feldman-Cousins method to the CDMS data to make clear the link to [83]; and then the modifications made to improve the robustness of the method for analyses with nuisance parameters.

The observables are the energies of the Ge single scatters \( E_i \), the number of Ge double scatters \( N_d \), and the number of Si events \( N_{Si} \). The energies of the Ge doubles and Si events are not used because, given the small numbers of such events, including them would significantly increase the computational requirements without significantly improving the accuracy of the result. I do not discuss how the 90% CL upper limit of 0.76 misidentified electrons in the Si event set is included; it can be put into the likelihood function, as is described in [145]. The free parameters for which a confidence region will be calculated are the WIMP mass \( M_\delta \), the WIMP-nucleon cross section \( \sigma_\delta n \), and the expected total number of neutron-scattering events in Ge, \( n \). Naive application of the Feldman-Cousins method involves calculation of the likelihood ratio

\[
R = \frac{L(E_i, N_d, N_{Si}|M_\delta, \sigma_\delta n, n)}{L(E_i, N_d, N_{Si}|\bar{M}_\delta, \bar{\sigma}_\delta n, \bar{n})}
\]

for a grid of physically allowed values of \( M_\delta, \sigma_\delta n, \) and \( n \), where the numerator is the likelihood of the data given the values taken from the grid and the denominator is the likelihood of the data evaluated at the values \((\bar{M}_\delta, \bar{\sigma}_\delta n, \bar{n})\) that maximize the likelihood of the data. Because of the small numbers numbers of events and the physical boundaries, the expected distribution of \( R \) cannot be determined analytically (i.e., it is not just distributed as a \( \chi^2 \)), so a Monte Carlo is performed at each grid point to determine this distribution. Of particular importance is the value \( R_{90}(M_\delta, \sigma_\delta n, n) \) such that 90% of simulated experiments at the grid point give \( R > R_{90} \). The bigger \( R \) is, the more “likely” the particular outcome, so \( R_{90} \) is the lower limit of the 90% most “likely” outcomes. The 90% CL allowed region in the space of triples \((M_\delta, \sigma_\delta n, n)\) is the set of all points for which \( R_{data} > R_{90} \). The WIMP contribution to the expected spectrum is calculated using the formalism outlined in Chapter 2, normalized to the 10.6 kg d exposure, and corrected for the energy-dependent efficiency function shown in Figure 8.16.

The above procedure yields a confidence region in the three-dimensional space of \((M_\delta, \sigma_\delta n, n)\). However, a confidence region in \((M_\delta, \sigma_\delta n)\)-space alone is desired. Therefore, \( n \) must be projected out. The most obvious way to do this is to allow a grid point \((M_\delta, \sigma_\delta n)\) if there is any value of \( n \) for which the triple \((M_\delta, \sigma_\delta n, n)\) is allowed. This makes the allowed region as large as it can possibly be, thereby providing the most conservative excluded region.

The primary disadvantage of the above naive method is that the statistic \( R \) clearly depends on the value of the nuisance parameter \( n \) used. This is undesirable since the nuisance parameter is projected out. The modification designed for this analysis, and more generally applicable to analyses
with nuisance parameters, is to use a different statistic and thereby reduce the dependence of $R$ on $n$. The likelihood ratio is redefined to be

$$R = \frac{\mathcal{L}(E_i, N_d, N_{Si}|M_{\delta}, \sigma_{\delta n}, \tilde{n}^*)}{\mathcal{L}(E_i, N_d, N_{Si}|\hat{M}_{\delta}, \hat{\sigma}_{\delta n}, \hat{n})}$$  \hspace{1cm} (8.10)$$

where $\tilde{n}^*$ is the value of $n$ that maximizes the likelihood of the data for the particular parameter values $(M_{\delta}, \sigma_{\delta n})$. The change in the statistic $R$ is the only modification to the naive approach. The advantage of this method is that $R_{\text{data}}$ now has only weak dependence on the value of $n$. The 90% CL region allowed by the observed data set consists of, as before, all parameter space for which $R_{\text{data}} > R_{90}$ for some value of $n$.

As stated earlier, there are a number reasons for using the above method. First, it is a classical, or frequentist, statistical approach. Since the distribution of the likelihood-ratio statistic $R$ is calculated by Monte Carlo, the edge of the allowed region answers the question “At what values of $M_{\delta}$ and $\sigma_{\delta n}$ would 90% of experiments have yielded values of $R$ greater than that observed for the data, given $M_{\delta}$ and $\sigma_{\delta n}$?” This question pertains to the reproducibility of the experiment, which can be answered without any assumption of “prior” distributions for the parameters to be constrained. Furthermore, the $n$-projection approach taken here is somewhat conservative because the neutron background is allowed to take the value that yields the most conservative limit; conversely, if the neutron background were known precisely, the limit would presumably be more aggressive because some points $(M_{\delta}, \sigma_{\delta n})$ allowed by taking $n$ to a value disfavored by the data would be disallowed. Another reason for using the Feldman-Cousins approach is that it deals correctly with the physical boundaries. This is especially important in the case of a background-subtraction scenario such as this, where a naive Bayesian approach can yield a confidence region that extends to nonphysical parameter space (e.g., $\sigma_{\delta n} < 0$ or $n < 0$) that must be somehow renormalized. Finally, since the number of events is so small, even a Bayesian approach would not satisfy the asymptotic limit — the likelihood function is not Gaussian — and the exclusion limit would have to be calculated numerically anyways, using a method similar to the one discussed in Section 8.2.1.

Figure 8.26 displays the the border of the excluded region. Because all the nuclear recoils may be neutron scatters, the allowed region includes $\sigma_{\delta n} = 0$. Hence the excluded region takes the form of an upper limit. For completeness, the full likelihood function for the data is shown in Figure 8.27. The neutron background is normalized to $n = 17$ events. This is slightly different than the best-fit value $n = 17.5$, but $n$ is not well determined by the data and using $n = 17$ introduces negligible error.

The limit is most sensitive to the number of Ge doubles because their unexpectedly high number pushes the expected number of Ge singles up, improving the background subtraction. The limit is fairly insensitive to the number of Si events. However, even with the high number of Ge doubles, the 90% CL exclusion limit corresponds to an expectation of $\sim 8$ WIMPs in the Ge single-scatter data set for WIMP masses where the shape of the expected recoil spectrum from WIMPs matches the observed spectrum well. In an absolute sense, then, the high number of Ge doubles does not have that significant an effect: even if no neutron-background subtraction had been performed, the limit would only have been approximately a factor of two worse (90% CL upper limit on 13 events is 17.6 events, Bayesian or classical). The high expected number of WIMPs at the 90% CL exclusion limit (more than half the single scatters) gives an indication of the Poisson penalty exacted by the use of such small numbers of Ge multiples and Si singles to constrain the neutron background.
To gauge how likely the calculated limit is, one can simulate an ensemble of experiments assuming the most likely neutron-background normalization $n = 17.5$ and calculate limits for these simulated experiments. The exclusion limit for which 50% of simulated experiments yield less sensitive limits is shown on the exclusion plot (the “median expected 90% CL exclusion limit”). Clearly, we got lucky. However, it is important to note there is nothing incorrect about the calculated limit; the point is that most realizations of this experiment would have set less sensitive exclusion limits.

Regarding the effect of modifying the ionization-partition cut: redoing this analysis with inclusion of the cQShare event sample would yield a more conservative limit since the number of single scatters increases from 13 to 27 (as can be read off of Figures 8.6 and 8.7), the number of double-scatter neutrons is unchanged, and the exposure only increases by about 1/3. Future analysis will include the cQShare events [147].

The limit thus calculated probes the MSSM more deeply than previous limits. In particular, it begins to exclude a significant number of the Gondolo et al. pure gaugino models. The limit also begins to approach the more constrained Corsetti and Nath mSUGRA models, though does not exclude any. Perhaps more importantly, this exclusion limit tests the annual-modulation signal claimed by the DAMA collaboration [88]. The compatibility of this limit and the annual-modulation signal is discussed in detail in Appendix E.
Figure 8.26: Exclusion limit on the spin-independent WIMP-nucleon elastic-scattering cross section based on combined analysis of Run 19 Ge single-scatter and double-scatter nuclear recoils and Run 18 Si nuclear recoils. Dark solid U-shaped curve: 90% CL exclusion limit from these data. Dark dashed U-shaped curve: median expected 90% CL exclusion limit assuming a neutron background $n = 17.5$. Light solid U-shaped curve: DAMA 1996 pulse-shape-analysis 90% CL exclusion limit [146]. Light heart-shaped region: DAMA 2000 annual-modulation $3\sigma$ CL allowed region without application of DAMA 1996 limit [88]. Dark heart-shaped region: DAMA 2000 annual-modulation $3\sigma$ CL allowed region from combined analysis with DAMA 1996 limit [88]. The other curves are the MSSM predictions shown in Figure 2.9. Light solid: Gondolo et al. mixed models [78]. Dark dashed: Gondolo et al. gaugino models. Light dashed: Gondolo et al. Higgsino models. Dark solid: Corsetti and Nath mSUGRA models [79]. Figure from [80].
Figure 8.27: Likelihood function in the \((M_\delta, \sigma_\delta n)\) plane for combined Ge single-scatter, Ge double-scatter, and Si nuclear-recoil data. The neutron background is normalized to \(n = 17\) events. The likelihood is maximized at \(\sigma_\delta n = 0\) (any \(M_\delta\)), below the lower edge of the plot. The contours indicate \(\Delta \log L = -0.5, -2, -4.5, -8,\) and \(-12.5\), with \(-0.5\) the lowermost. The DAMA best-fit \((M_\delta, \sigma_\delta n) = (52 \text{ GeV} \text{ c}^{-2}, 7.2 \times 10^{-42} \text{ cm}^2)\) and \(3\sigma\) CL contour (not using the 1996 exclusion limit) are shown. Figure provided by R. Schnee.
8.5 Residual Background-Particle-Interaction Rates

It is important to assess the interaction rates of all types of background particles in order to determine which sources need to be addressed to achieve the background-rate goals for both CDMS I and CDMS II. Classification by ionization partition and particle type provide a wealth of information in this respect. While only single-scatter events impact WIMP sensitivity, multiple-scatter events can illuminate the sources of the single-scatter events. In this section, I summarize the rates of single-scatter and double-scatter photon and electron events. Triple- and quadruple-scatter events are neglected because such events presumably arise from very energetic particles; such events shed little light on the low-energy processes that dominate single and double scatters. Similarly, events with saturated detectors are neglected. A comprehensive analysis of the data presented here is beyond the scope of this dissertation, but I hope this section provides a starting point.

Ionization-yield plots for the veto-anticoincident double-scatter data set are shown in Figures 8.28, 8.29, and 8.30. Saturated events are excluded, as mentioned above. It should be remembered that the cuts defining the double-scatter data set shown in Figure 8.18 are far more restrictive than those used to define the data plotted in these figures; the elevated number of events in these plots should not be cause for concern.

8.5.1 Exposure Normalization and Particle Identification

It is important to determine the correct normalizations for the various particle rates. As will be seen, the photon rates are dominated by Compton scattering of penetrating high-energy photons and thus volume (or mass) normalization is appropriate. For electrons, which do not penetrate deeply, area normalization is more useful. Table 8.7 lists the assumed volumes and areas of the three ionization-partition cuts. The volume fractions are determined from the neutron-calibration data and simulation as discussed in Section 4.5.1. The cQinOnly and cQShare cuts select regions on the detector flats and thus the accepted areas can be determined trivially. The cQoutOnly area requires an estimate of the total detector area. The curved edge of the detector is assumed to be a circle of radius 0.6 cm, corresponding to half the detector thickness of 1.2 cm, in accordance with the schematic shown in Figure 4.1. The total surface area is given by

\[ A = 2\pi r_{\text{flat}}^2 + 2\pi^2 r_{eq} r_c - 2\pi (\pi - 2) r_c^2; \]

(8.11)

The first term is the area of the two flats, with \( r_{\text{flat}} = 2.55 \) cm. The second two terms give the area of the curved edge, with \( r_{eq} = 3.00 \) cm being the detector radius at the equator and \( r_c = 0.6 \) cm being the edge curvature radius. This form is an approximation because the curved edges are not perfectly circular, but the formula should be correct to a few percent. The area of the cQoutOnly cut is given by subtracting the cQinOnly and cQShare areas from the total area. One can infer radii of 1.95 cm and 2.31 cm for the boundaries separating the cQinOnly, cQShare, and cQoutOnly regions, but these should not be considered exact because of the indentation in the electrode break shown in Figure 4.1. The areas, on the other hand, account for the indentation.

The mass and area exposures for the data presented in this section are listed in Table 8.8. These exposures do not take into account the efficiencies of the energy-dependent cuts, which have negligible effect at low energy and a 10%–15% effect near 100 keV. Because this error is common to all the rates, rate comparisons are subject to much smaller errors.
Figure 8.28: Ionization yield vs. recoil energy for veto-anticoincident cQinOnly recoils belonging to double scatters. Saturated events are excluded. Hyperbolic dashed line: ionization-search threshold. Light solid line: center of nuclear-recoil band, pre-April 3. Light dashed line: center of nuclear-recoil band, post-April 3. Dark solid line: nuclear-recoil-acceptance region, pre-April 3. Dark dashed line: nuclear-recoil-acceptance region, post-April 3.
Figure 8.29: Ionization yield vs. recoil energy for veto-anticoincident cQShare recoils belonging to double scatters. Saturated events are excluded. Legend as in Figure 8.28.
Figure 8.30: Ionization yield vs. recoil energy for veto-anticoincident cQoutOnly recoils belonging to double scatters. Saturated events are excluded. Legend as in Figure 8.28.
### SECTION 8.5. RESIDUAL BACKGROUND-PARTICLE-INTERACTION RATES

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<th>Area [cm$^2$]</th>
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</tbody>
</table>

Table 8.7: Masses, volumes, and areas of ionization-partition cuts.

<table>
<thead>
<tr>
<th>Event set</th>
<th>BLIP3</th>
<th>BLIP4</th>
<th>BLIP5</th>
<th>BLIP6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Exposure [kg d]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qin</td>
<td>4.77</td>
<td>4.64</td>
<td>4.98</td>
<td>5.00</td>
</tr>
<tr>
<td>QShare</td>
<td>1.97</td>
<td>1.92</td>
<td>2.06</td>
<td>2.07</td>
</tr>
<tr>
<td>Qout</td>
<td>3.62</td>
<td>3.54</td>
<td>3.79</td>
<td>3.81</td>
</tr>
</tbody>
</table>

| Area Exposure [cm$^2$ d] | | | | |
| Qin       | 1500  | 1450  | 1560  | 1570  |
| QShare    | 610   | 600   | 640   | 650   |
| Qout      | 2520  | 2470  | 2640  | 2650  |

Table 8.8: Volume and area exposures for photons and electrons. No energy-dependent efficiency corrections have been made, though the veto-anticoincidence cut efficiency has been approximately taken into account using an energy-independent value of 0.85, the value for ionization triggers.

As was discussed in Section 8.2.1, particle identification is based on ionization yield. A straightforward cut enclosing the photon band defines photons; the cut flares out at low energy to allow for the widening of the band. Any event above 300-keV recoil energy is also considered a photon for the purposes of double scatters. Electrons are defined to be all events between the photon and nuclear-recoil bands. For the cQinOnly cut, leakage of electrons into the nuclear-recoil band dominates over true nuclear recoils, so all events below the photon band are taken to be electrons. Finally, for double-scatters, if the second scatter is below 10 keV, the event is separately classified as “unidentifiable” because the bands merge.

### 8.5.2 Photon Rates

Single-scatter photon spectra are shown in Figures 8.10, 8.11 and 8.12. Spectra for photons belonging to double scatters are shown in Figures 8.31, 8.32, and 8.33. The cQinOnly and cQShare spectra are subdivided by the particle identification of the other scatter. No ionization-partition cut is made on the second scatter. The average rates between 10 and 100 keV are summarized in Table 8.9.

The cQinOnly photon spectra are fairly flat, as expected for Compton scatters. The event set is dominated by events in which the second scatter is also a photon, again consistent with Compton scattering. There is an extremely low rate of events with the second scatter being an
electron, at the level of 5–10% of all double scatters. Approximately 10% of double scatters have second hits below 10 keV. BLIP4 shows uniformly higher rates of all multiples. As is evident in many of the ionization-yield plots, BLIP4’s photon band is less well defined, so this may just reflect acceptance of electrons into the photon data set. BLIP4 has a large rate of double-scatter electrons in coincidence with BLIP3 because of BLIP3’s surface contamination, so such misidentification is especially problematic for BLIP4. Such misidentification may also explain the generally higher photon rates seen for BLIP3. Finally, there is some self-shielding against photons, as seen by the variations in overall rates, but it is only at the 20–30% level (assuming electron misidentification is the cause of the elevated BLIP3 and BLIP4 rates). This is also expected, as the penetration length of high-energy photons is large compared to the detector thickness.

The cQShare spectra are also fairly flat. The rates are elevated above both the cQinOnly and cQoutOnly rates, presumably because internal double scatters cause events to be classified as cQShare events though the interactions may not have occurred in the cQShare volume. The cQShare double scatters are again dominated by Compton scatters. Events in which the second scatter is an electron are a small fraction, as for cQinOnly events. It is interesting that the fraction of events in which the second scatter is below 10 keV is elevated. One possible explanation is that these photons also produce a low-energy-photon and -electron continuum in the surface of the detector housing; the cQShare region is not as well shielded as the cQinOnly region. Another geometrical effect may also be important. If a high-energy photon Compton scatters in the cQinOnly volume of a detector, resulting in the emission of low-energy particles from the detector surface that hit the adjacent detector, the incident photon is not severely deflected (because it did not lose much energy), so it is likely to be collimated with the low-energy particle. The scattered photon may thus scatter in the same detector as the low-energy particle, increasing the second scatter’s energy. This effect is presumably less important for cQShare events.

The cQoutOnly photon spectra show a surprising rise below 20 keV. The cause is not clear, though electron confusion is likely. The low-energy region of the photon spectra is explored in Section 8.5.4.

The above discussion is admittedly fairly speculative. To understand in detail these photon rates, and especially the correlations between particle types, a full photon simulation is necessary. However, photon rates are not a particular worry because of the detectors’ excellent photon discrimination. Even at the $1 \text{ keV}^{-1} \text{ kg}^{-1} \text{ d}^{-1}$ rate seen, the expected photon misidentification is at the $0.001 \text{ keV}^{-1} \text{ kg}^{-1} \text{ d}^{-1}$ level, which meets the CDMS II goal [148]. Therefore, further analysis of the photon rates is a low priority.
Table 8.9: Veto-anticoincident-photon rates, averaged between 10 and 100 keV, in keV$^{-1}$ kg$^{-1}$ d$^{-1}$. 

<table>
<thead>
<tr>
<th>Event set</th>
<th>BLIP3</th>
<th>BLIP4</th>
<th>BLIP5</th>
<th>BLIP6</th>
</tr>
</thead>
<tbody>
<tr>
<td>cQinOnly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>single</td>
<td>1.287±0.055</td>
<td>0.825±0.044</td>
<td>0.667±0.039</td>
<td>0.793±0.042</td>
</tr>
<tr>
<td>multi w/photon</td>
<td>0.282±0.026</td>
<td>0.371±0.030</td>
<td>0.312±0.026</td>
<td>0.302±0.026</td>
</tr>
<tr>
<td>multi w/electron</td>
<td>0.047±0.010</td>
<td>0.089±0.015</td>
<td>0.016±0.006</td>
<td>0.016±0.006</td>
</tr>
<tr>
<td>multi w/&lt; 10 keV</td>
<td>0.021±0.007</td>
<td>0.091±0.015</td>
<td>0.038±0.009</td>
<td>0.033±0.009</td>
</tr>
<tr>
<td>multi all</td>
<td>0.350±0.029</td>
<td>0.550±0.036</td>
<td>0.366±0.029</td>
<td>0.351±0.028</td>
</tr>
<tr>
<td>all</td>
<td>1.637±0.062</td>
<td>1.376±0.057</td>
<td>1.033±0.048</td>
<td>1.144±0.050</td>
</tr>
<tr>
<td>cQShare</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>single</td>
<td>1.570±0.094</td>
<td>1.280±0.086</td>
<td>1.394±0.087</td>
<td>1.915±0.101</td>
</tr>
<tr>
<td>multi w/photon</td>
<td>0.638±0.060</td>
<td>0.817±0.069</td>
<td>0.708±0.062</td>
<td>0.446±0.049</td>
</tr>
<tr>
<td>multi w/electron</td>
<td>0.034±0.014</td>
<td>0.041±0.015</td>
<td>0.059±0.018</td>
<td>0.016±0.009</td>
</tr>
<tr>
<td>multi w/&lt; 10 keV</td>
<td>0.164±0.030</td>
<td>0.324±0.043</td>
<td>0.297±0.040</td>
<td>0.113±0.025</td>
</tr>
<tr>
<td>multi all</td>
<td>0.836±0.069</td>
<td>1.182±0.083</td>
<td>1.064±0.076</td>
<td>0.575±0.056</td>
</tr>
<tr>
<td>all</td>
<td>2.405±0.117</td>
<td>2.462±0.119</td>
<td>2.458±0.115</td>
<td>2.490±0.116</td>
</tr>
<tr>
<td>cQoutOnly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>single</td>
<td>2.011±0.079</td>
<td>1.311±0.064</td>
<td>1.205±0.059</td>
<td>1.580±0.068</td>
</tr>
<tr>
<td>multi all</td>
<td>0.359±0.033</td>
<td>0.591±0.043</td>
<td>0.460±0.037</td>
<td>0.385±0.034</td>
</tr>
<tr>
<td>all</td>
<td>2.369±0.085</td>
<td>1.902±0.077</td>
<td>1.666±0.070</td>
<td>1.965±0.076</td>
</tr>
</tbody>
</table>
CHAPTER 8. BACKGROUND-PARTICLE RATES AND CONSTRAINTS ON THE WIMP-NUCLEON CROSS SECTION

Figure 8.31: Recoil-energy spectra for cQinOnly photons belonging to veto-anticoincident double-scatter events. Solid: other scatter is a photon above 10 keV. Dashed: other scatter is an electron above 10 keV. Circles: other scatter is below 10 keV (photon/electron discrimination not possible).
Figure 8.32: Recoil-energy spectra for cQShare photons belonging to veto-anticoincident double-scatter events. Legend as in Figure 8.31.
Figure 8.33: Recoil-energy spectra for cQoutOnly photons and electrons belonging to veto-anticoincident double-scatter events. Solid: photons. Dashed: electrons. Note that these spectra are not analogous to Figures 8.31, 8.32, 8.34, and 8.35 because the events are not subdivided by the identity of the second scatter.
8.5.3 Electron Rates

Single-scatter-electron spectra are shown in Figures 8.10, 8.11 and 8.12. Spectra for electrons belonging to double scatters, analogous to the spectra shown for photons, are shown in Figures 8.34, 8.35, and 8.33. The total areal rates between 10 and 100 keV are summarized in Table 8.10. Note that the spectra are in keV$^{-1}$ kg$^{-1}$ d$^{-1}$ while the table shows rates in cm$^{-2}$ d$^{-1}$.

The contamination of BLIP3 is clearly visible in the BLIP3 and BLIP4 spectra. This contamination dominates these detectors’ electron rates, so they are not useful for constraining residual electron sources. I therefore concentrate on BLIP5 and BLIP6. The lower single-scatter rate in BLIP5 reflects self-shielding. The ratio of double scatters to all events is higher for BLIP5 than BLIP6, as one would expect because one face of BLIP6 is not shielded by other detectors.

A simple model can be constructed to attempt to interpret these rates. Three different fluxes of electrons are assumed:

- $F_\gamma$: the flux of electrons ejected by photons (“photon-induced flux”)
- $F_\beta$: the flux of electrons due to beta emission by a contaminant on the surface of the detector housing, yielding an isotropic flux of electrons (“isotropic-electron flux”)
- $F_s\beta$: the flux of electrons due to beta emission by a surface contaminant on the detector surfaces (“surface-contaminant flux”)

---

Table 8.10: Veto-anticoincident-electron rates, *summed* between 10 and 100 keV, in 10$^{-3}$ cm$^{-2}$ d$^{-1}$.
CHAPTER 8. BACKGROUND-PARTICLE RATES AND CONSTRAINTS ON THE WIMP-NUCLEON CROSS SECTION

$F_{\gamma}$ is assumed to be emitted isotropically from any surface and to be independent of the emitting surface: the housing and detector surfaces emit the same flux $F_{\gamma}$. This is a valid approximation as long as the photons that eject electrons are of sufficiently high energy ($\gtrsim 100$ keV) that their penetration length is large compared to the detector thickness. $F_{i\beta}$ is also assumed to be emitted isotropically by the detector-housing surface and to be homogeneous over the housing surface. Finally, $F_{s\beta}$ is assumed to be emitted isotropically by any detector surface and also to be homogenous. To characterize multiple-scattering and self-shielding for the inner electrodes, three parameters are assumed:

- $m_{\gamma}$: the double-scatter fraction for $F_{\gamma}$ electrons
- $m_{\beta}$: the double-scatter fraction for $F_{i\beta}$ or $F_{s\beta}$ electrons
- $s_s$: the flux-reduction factor for electrons due to self-shielding

Two different double-scatter fractions are assumed because the physical sources of $F_{\gamma}$ and of $F_{i\beta}$ and $F_{s\beta}$ electrons are quite different. A single double-scatter fraction for $F_{i\beta}$ and $F_{s\beta}$ electrons is assumed for simplicity. This may be invalid because $F_{i\beta}$ electrons are likely to have shallow incident angles on the inner electrodes while $F_{s\beta}$ electrons will have more evenly distributed incident angles. Finally, $s_s$ describes the self-shielding for $F_{i\beta}$ electrons. $F_{\gamma}$ electrons are not subject to self-shielding because any surface emits $F_{\gamma}$ electrons. $F_{s\beta}$ electrons are also not subject to self-shielding. Various observable electron rates are defined as follows:

- $R_{B5}^s$: BLIPX’s single-scatter-electron rate
- $R_{B6}^s$: BLIPX’s double-scatter electron rate for events where the second scatter is a photon
- $R_{B5}^\beta$: BLIPX’s double-scatter electron rate for events where the second scatter is an electron or is below 10 keV

These rates are given by the first four rows of Table 8.10. $R_{B5}^\beta$ lumps double scatters with electrons or with < 10-keV events together under the assumption that the latter is dominated by electrons. Photon-electron coincidences are presumably due primarily to Compton scattering of high-energy photons, so the spectrum of energies deposited by the photon should be flat, while the spectrum due to electrons should naturally rise at low energies.

The model consists of the following relations among the fluxes and observed rates:

\begin{align*}
R_{B5}^s &= F_{\gamma} (1 - m_{\gamma}) + F_{i\beta} s_s (1 - m_{\beta}) + F_{s\beta} (1 - m_{\beta}) \quad (8.12) \\
R_{B6}^s &= F_{\gamma} \left(1 - \frac{1}{2} m_{\gamma}\right) + F_{i\beta} \left[\frac{1}{2} + \frac{1}{2} s_s (1 - m_{\beta})\right] + F_{s\beta} \left[1 - \frac{1}{2} m_{\beta}\right] \quad (8.13) \\
R_{B5}^\gamma &= F_{\gamma} m_{\gamma} \quad (8.14) \\
R_{B6}^\gamma &= \frac{1}{2} F_{\gamma} m_{\gamma} \quad (8.15) \\
R_{B5}^\beta &= F_{i\beta} s_s m_{\beta} + F_{s\beta} m_{\beta} \quad (8.16) \\
R_{B6}^\beta &= \frac{1}{2} F_{i\beta} s_s m_{\beta} + \frac{1}{2} F_{s\beta} m_{\beta} \quad (8.17)
\end{align*}
The first line is BLIP5’s single-scatter rate, consisting of the single-scatter photon-induced flux, the self-shielded single-scatter isotropic-electron flux, and the single-scatter surface-contaminant flux. The second line is BLIP6’s single-scatter rate. Because BLIP6 is at the bottom of the stack, only one face is subject to multiple scattering and self-shielding, reflected by the various 1/2’s in the expression. The third and fourth lines are the multiple-scatter photon-induced fluxes; again, BLIP6’s multiple-scatter fraction is reduced by a factor of 2. The fifth and sixth lines are the multiple-scatter electron rates, including self-shielding, with BLIP6’s rate again lower by a factor of 2.

It is clear that the model does not fit the observed rates perfectly; for example, \( R_{B5}^s = 2R_{B5}^\gamma \) does not hold. To rigorously assess the ability of the model to match the data, a standard \( \chi^2 \) quantity can be calculated:

\[
\chi^2 = \frac{(R_{B5}^s - \hat{R}_{B5}^s)^2}{(\delta R_{B5}^s)^2} + \frac{(R_{B6}^s - \hat{R}_{B6}^s)^2}{(\delta R_{B6}^s)^2}
\]

where hats indicate the model rates and the denominators are the statistical uncertainties given in Table 8.10. This is not a \( \chi^2 \) in the usual sense because the number of degrees of freedom equals the number of data points. Regardless, it can be minimized to yield the best-fit parameters \( \hat{F}_\gamma, \hat{F}_{i\beta}, \hat{F}_{s\beta}, \hat{m}_\gamma, \hat{m}_\beta, \) and \( \hat{s}_s \). The best-fit \( \chi^2 \) is 15.8. The best-fit parameter values and resulting expected values for the six observable rates are listed in Table 8.11. Since the expected distribution of \( \chi^2 \) is not known, the probability of observing a higher \( \chi^2 \) cannot be determined without a simulation. However, it is clear from the discrepancies between the expected and observed rates that the model does not fit the data.

The poor fit arises because the model predicts \( R_{B5}^\gamma/R_{B6}^\gamma = 2 \) while the data are statistically precise and have \( R_{B5}^\gamma/R_{B6}^\gamma = 0.5 \). The photon-induced flux model, where only one flux is assumed for all surfaces, may be wrong because of the complex geometry: the convex curved surfaces may shield more than they emit and the concave detector housing surface may emit more than a flat surface that occupies the same solid angle. To check this, \( R_{B6}^\gamma \) can be discarded and the minimization redone, yielding \( \chi^2 = 0.35 \). The best-fit parameters and the expected values of the observables are again listed in Table 8.11. Clearly, the model fits the data reasonably well now. The decrease in \( \chi^2 \) is significantly more than what one would expect from simply discarding a single data point, corroborating the fact that \( R_{B6}^\gamma \) is the crux of the inconsistency.

It is nontrivial to determine the probability of observing a higher value of \( \chi^2 \) because the expected distribution is not analytic (there are \(-1\) degrees of freedom!). The expected distribution can be determined by simulation. The simulated observables are drawn from Gaussian distributions with means determined by the best-fit parameters \( \hat{X}_i \) and widths given by the observed statistical errors. For the \( n \)th simulated outcome, the model parameters \( \hat{X}_{i,n} \) that best fit the simulated observables \( N_{i,n} \) are determined and the quantity \( \chi^2_n = \chi^2(N_{i,n} | \hat{X}_{i,n}) \) calculated. The distribution of \( \chi^2_n \) is the expected distribution. Note that it is necessary to calculate \( \chi^2(N_{i,n} | \hat{X}_{i,n}) \) rather than \( \chi^2(N_{i,n} | \hat{X}_i) \) to minimize the dependence of the expected distribution on the particular values \( \hat{X}_i \).


### Table 8.11: Electron-rate model best-fit parameters and expected rates.

All rates and fluxes are in $10^{-3}$ cm$^{-2}$ d$^{-1}$. $m_\gamma$, $m_\beta$, and $s_s$ are unitless. The “all data” values correspond to fits including both $R^\gamma_{B6}$ and $R^\gamma_{B5}$. For the “wo/ $R^\gamma_{B6}$” and “wo/ $R^\gamma_{B5}$” fits, $R^\gamma_{B6}$ and $R^\gamma_{B5}$, respectively, are not included in the $\chi^2$. $P(>\chi^2)$ is determined by simulation, as described in the text.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>all data</th>
<th>wo/ $R^\gamma_{B6}$</th>
<th>wo/ $R^\gamma_{B5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_\gamma$</td>
<td>11.3</td>
<td>16.4</td>
<td>43.7</td>
</tr>
<tr>
<td>$F_{i\beta}$</td>
<td>52.9</td>
<td>42.7</td>
<td>10.3</td>
</tr>
<tr>
<td>$F_{s\beta}$</td>
<td>0.8</td>
<td>5.9</td>
<td>11.0</td>
</tr>
<tr>
<td>$\bar{m}_\gamma$</td>
<td>0.92</td>
<td>0.47</td>
<td>0.82</td>
</tr>
<tr>
<td>$\bar{m}_\beta$</td>
<td>0.37</td>
<td>0.56</td>
<td>0.53</td>
</tr>
<tr>
<td>$\hat{s}_s$</td>
<td>0.42</td>
<td>0.22</td>
<td>0.48</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>15.8</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>$P(&gt;\chi^2)$</td>
<td>0.001</td>
<td>0.54</td>
<td>0.68</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rate</th>
<th>Observed</th>
<th>Best-Fit Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>all data</td>
<td>wo/ $R^\gamma_{B6}$</td>
</tr>
<tr>
<td>$R^s_{B5}$</td>
<td>15.4±3.1</td>
<td>15.4</td>
</tr>
<tr>
<td>$R^s_{B6}$</td>
<td>40.2±5.1</td>
<td>40.2</td>
</tr>
<tr>
<td>$R^\gamma_{B5}$</td>
<td>7.7±2.2</td>
<td>10.4</td>
</tr>
<tr>
<td>$R^\gamma_{B6}$</td>
<td>17.9±3.4</td>
<td>5.2</td>
</tr>
<tr>
<td>$R^\beta_{B5}$</td>
<td>7.7±2.2</td>
<td>8.4</td>
</tr>
<tr>
<td>$R^\beta_{B6}$</td>
<td>5.1±1.8</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 8.11: Electron-rate model best-fit parameters and expected rates. All rates and fluxes are in $10^{-3}$ cm$^{-2}$ d$^{-1}$. $m_\gamma$, $m_\beta$, and $s_s$ are unitless. The “all data” values correspond to fits including both $R^\gamma_{B6}$ and $R^\gamma_{B5}$. For the “wo/ $R^\gamma_{B6}$” and “wo/ $R^\gamma_{B5}$” fits, $R^\gamma_{B6}$ and $R^\gamma_{B5}$, respectively, are not included in the $\chi^2$. $P(>\chi^2)$ is determined by simulation, as described in the text.

assumed for the simulation. Performing the test using the former statistic is also more conservative because $\chi^2(N_{i,n}|\hat{X}_{i,n}) \leq \chi^2(N_{i,n}|\tilde{X}_i)$. Based on the simulated distribution, the percentage of outcomes with higher $\chi^2$ than observed is 54%, indicating the fit is reasonable. Furthermore, the best-fit value $\hat{s}_s$ is close to the expected value of 0.2 (see Figure 5.5) in this case.

For completeness, the case where $R^\gamma_{B5}$ is discarded is considered. The resulting fit has $\chi^2=0.35$ also. In this case, 68% of experiments would have had higher $\chi^2$. $P(>\chi^2)$ thus does not strongly discriminate between the two models. It is perhaps more reasonable to discard $R^\gamma_{B6}$ because doing so yields $s_s=0.22$, close to expectations. Also, the simulated distribution of $\hat{s}_s$ is flat from 0 to 1 for the case where $R^\gamma_{B5}$ is discarded, indicating there is no sensitivity to $s_s$. However, $F_{i\beta}$ is a factor of 7 larger than $F_{s\beta}$ when $R^\gamma_{B6}$ is discarded. One would expect $F_{i\beta}$ and $F_{s\beta}$ to be comparable since the detector housing is covered in germanium shielding that was handled as or more carefully than the detectors. Furthermore, $m_\gamma$ is surprisingly low for this case. Nevertheless, it may be necessary to accept this conclusion: it is corroborated by a simpler argument made below, the high value of $F_s$ in the case where $R^\gamma_{B5}$ is discarded seems more unreasonable, and $^{210}$Pb on the Detector Interface Boards and IR blockers or in the brass screws for the germanium shielding may serve as the source of the high $F_{i\beta}$ flux.

One could also extend the above model to include cQShare events by adding three new
CHAPTER 8.5. RESIDUAL BACKGROUND-PARTICLE-INTERACTION RATES

Table 8.12: $F_{i\beta}$ and $F_{s\beta}$ via robust method. The values of $F_{i\beta}$ and $F_{s\beta}$ and their contribution to $R_{B5}^s$ as a function of $s_s$ are shown. All fluxes and rates in $10^{-3}$ cm$^{-2}$ d$^{-1}$.

<table>
<thead>
<tr>
<th>$s_s$</th>
<th>Inferred value</th>
<th>Contribution to $R_{B5}^s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>44.4 23.1</td>
<td>0.0 23.1</td>
</tr>
<tr>
<td>0.1</td>
<td>49.0 18.2</td>
<td>4.9 18.0</td>
</tr>
<tr>
<td>0.2</td>
<td>55.5 12.0</td>
<td>11.1 12.0</td>
</tr>
<tr>
<td>0.3</td>
<td>63.3 4.1</td>
<td>19.0 4.1</td>
</tr>
</tbody>
</table>

parameters, $m_{\gamma}$, $m_{\beta}$ and $s_s$, to allow for different multiple-scatter fractions and self-shielding reduction. It would not be self-consistent to add new flux parameters also. This extension is not performed here.

Because of the degeneracy between discarding $R_{B5}^\gamma$ or $R_{B6}^\gamma$, it is useful to step back and ask what robust conclusions can be made independent of the above fitting procedure:

- First, $F_{i\beta}$ does not contribute significantly to the singles rates. On physical and geometrical grounds, $m_{\gamma}$ is expected to be large, certainly bigger than $\sim 0.5$. Therefore, most of $F_{i\beta}$ appears in $R_{B5}^\gamma$ and $R_{B6}^\gamma$ and the contribution of $F_{i\beta}$ to $R_{B5}^s$ and $R_{B6}^s$ is small compared to $R_{B5}^\gamma$ and $R_{B6}^\gamma$. But, $R_{B5}^\gamma$ and even $R_{B6}^\gamma$, are comparable to or smaller than $R_{B5}^s$ and $R_{B6}^s$, so the contribution of $F_{i\beta}$ to $R_{B5}^s$ and $R_{B6}^s$ is small.

- Second, $F_{i\beta}$ is $\sim 0.010$ cm$^{-2}$ d$^{-1}$, since most of $F_{i\beta}$ appears in $R_{B5}^\gamma$ and $R_{B6}^\gamma$.

- Third, $F_{i\beta}$ is large compared to $F_{s\beta}$. Consider only the total rates

$$R_{B5}^{s+\beta} \equiv R_{B5}^s + R_{B5}^\beta = F_{s\beta} + F_{i\beta}s_s$$

$$R_{B6}^{s+\beta} \equiv R_{B6}^s + R_{B6}^\beta = F_{s\beta} + F_{i\beta} \left[ \frac{1}{2} + \frac{1}{2}s_s \right]$$

These rates are insensitive to the multiple-scatter fractions and are determined only by $s_s$, which is robustly estimated to be $s_s \sim 0.2$ purely by geometry (see Chapter 5). They are also insensitive to the problematic photon-induced flux. These rates are $R_{B5}^{s+\beta} = 0.0231 \pm 0.0038$ cm$^{-2}$ d$^{-1}$ and $R_{B6}^{s+\beta} = 0.0453 \pm 0.0054$ cm$^{-2}$ d$^{-1}$. Solving for the fluxes with $s_s = 0.2$ gives $F_{s\beta} = 0.0120$ cm$^{-2}$ d$^{-1}$ and $F_{i\beta} = 0.0555$ cm$^{-2}$ d$^{-1}$. The resulting contributions to $R_{B5}^s$ are $0.0120$ cm$^{-2}$ d$^{-1}$ and $0.0111$ cm$^{-2}$ d$^{-1}$, respectively. This result depends somewhat on $s_s$, as is illustrated in Table 8.12. The table shows that it generally holds that $F_{i\beta}$ is large compared to $F_{s\beta}$, but which one dominates $R_{B5}^s$ is not well constrained.

So, what can be concluded? First, it is clear that self-shielding has a significant effect. The BLIP5 total electron rate is lower than the BLIP6 rate by about a factor of 2. Second, a significant fraction of electrons, of order 50% for BLIP5, can be vetoed by multiple scattering. These two effects yield a nontrivial factor-of-four rate reduction in going from the BLIP6 total electron rate of $0.063$ cm$^{-2}$ d$^{-1}$ to the BLIP5 single-scatter-electron rate of $0.015$ cm$^{-2}$ d$^{-1}$. Third, surface
contamination of the detectors and the housing appear to be the most important residual electron sources. While the fit discarding $R_{B6}^{\gamma}$ yields a $F_\gamma$ contribution of 0.0077 cm$^{-2}$ d$^{-1}$ to the total $R_{B5}^{s} = 0.0154$ cm$^{-2}$ d$^{-1}$ rate, it is hard to believe that $m_\gamma$ is as low as 0.5. With $m_\gamma \sim 0.8 - 0.9$, the contribution of photon-induced electrons is negligible. Unfortunately, the relative importance of $F_{i\beta}$ and $F_{s\beta}$ to $R_{B5}^{s}$ is not clearly determined. However, $R_{B5}^{s}$ will be increased in the future because ZIP detectors do not have curved edges and can be packed with separations as small as 1 mm. Thus, the contribution of $F_{i\beta}$ will be decreased and the most important electron source to address will be detector surface contamination.

To further evaluate what has been learned, it is useful to compare to rates observed in previous runs. The electron rate observed by the Run 18 Ge BLIP detectors, averaged between 20 and 100 keV, is 0.27 keV$^{-1}$ kg$^{-1}$ d$^{-1}$ [8]. Converting to an areal rate summed between 20 and 100 keV gives 0.048 cm$^{-2}$ d$^{-1}$. It is not clear from [8] whether this rate includes multiple-scatter events. However, for the Run 18 geometry, multiple scattering of non-penetrating particles was prevented by the individual copper detector housings; furthermore, the detectors were much further apart than in the Run 19 geometry. It is assumed here that the Run 18 0.048 cm$^{-2}$ d$^{-1}$ rate should be compared to the total Run 19 electron rates. The total Run 19 BLIP5 and BLIP6 areal electron rates, summed between 20 and 100 keV (rather than 10 and 100 keV), are $0.0212 \pm 0.0037$ cm$^{-2}$ d$^{-1}$ and $0.0524 \pm 0.0058$ cm$^{-2}$ d$^{-1}$, respectively. The BLIP6 rate is thus comparable to and the BLIP5 rate about 40% of the Run 18 rate. Clearly, self-shielding has a significant effect.

However, it is surprising that the BLIP6 total rate is the same as the Run 18 rate in spite of its top side being self-shielded. Moreover, the cQShare and cQoutOnly rates are substantially higher. These elevated rates are mysterious, since a number of precautions were taken for Run 19 to reduce contamination of the detectors. Furthermore, the Ge shielding lining the detector package was etched and maintained in at least as clean an environment as the Run 18 detectors. Because of the large difference between the cQinOnly rate and the cQShare and cQoutOnly rates, it is likely the new electron source is not surface contamination of the detectors, which should be uniformly distributed. One possibility is that $^{210}$Pb is present on the circuit boards providing electrical connections to the detectors. This possibility is discussed later in the context of observation of a 46-keV photon line in the cQoutOnly data.

Because of this possible new electron source, it is not possible to determine the effect of the Ge shielding. It is possible that, though the shielding may have attenuated the $F_{i\beta}$ flux from the copper housing, the effect would be masked by the rate due to the new source. It is also possible that the shielding had no effect. As noted above, the sensitivity of the detectors to electrons emitted by the housing will be further decreased in the future by improved self-shielding, so the effect of the Ge shielding has little bearing on the future.

Finally, it is important to realize that the present BLIP5 single-scatter-electron rate roughly meets the CDMS II goals. The $R_{B5}^{s}$ rate corresponds to 0.05 keV$^{-1}$ kg$^{-1}$ d$^{-1}$ and appears to be fairly flat in energy down to about 20 keV (see Figure 8.10). The CDMS II electron-rate goal is 0.02 keV$^{-1}$ kg$^{-1}$ d$^{-1}$ at 15 keV with 95% electron rejection [148]. As mentioned earlier, ZIP detectors have demonstrated approximately 99% electron rejection above 15 keV, so the electron-rate goal can be relaxed by a factor of 5 to 0.1 keV$^{-1}$ kg$^{-1}$ d$^{-1}$. The relaxed rate goal is certainly met above 20 keV and is almost met in the 12–20-keV bin (see Figure 8.10). Furthermore, it is expected that some improvement in surface contamination will be achieved in switching from BLIPs to ZIPs: the ZIP fabrication environment is much cleaner and only photoresist is used for masking. Analysis
of the type presented here should certainly be pursued to solidify these conclusions and, hopefully, to indicate how to push the electron rates well below the CDMS II goals, but significant reduction of surface contamination does not appear to be necessary.
Figure 8.34: Recoil-energy spectra for cQinOnly electrons belonging to veto-anticoincidental double-scatter events. Solid: other scatter is a photon above 10 keV. Dashed: other scatter is an electron above 10 keV. Circles: other scatter is below 10 keV (photon/electron discrimination not possible).
Figure 8.35: Recoil-energy spectra for cQShare electrons belonging to veto-anticoincident double-scatter events. Legend as in Figure 8.35.
CHAPTER 8. BACKGROUND-PARTICLE RATES AND CONSTRAINTS ON THE
WIMP-NUCLEON CROSS SECTION

8.5.4 Spectral Lines

Photon lines can be used to constraint the presence of radioactive contaminants. Figures 8.36, 8.37, and 8.38 show spectra of “prgamma” for veto-anticoincident single-scatter-photon events. “prgamma,” defined in Chapter 6, is the phonon energy divided by $1 + V_b/(3\ eV)$; it gives the recoil energy for photons, for which the ionization energy and recoil energy are equal. The advantage of using prgamma is that it is less noisy than the calculated recoil energy. Spectra for double-scatter events are also shown, though they exhibit no photon lines. The double-scatter spectra exhibit large increases in rate below 20 keV. The reason for this is not known.

All the spectra exhibit the 10.4-keV Ga X-ray. This X-ray arises from two sources. Cosmogenic activation while the detectors are above ground creates $^{68}\text{Ge}$, which decays by electron capture to $^{68}\text{Ga}$ with a 270.8 d half-life. Electron capture removes a K-shell electron; the X-ray is emitted when the empty state is filled. Thermal-neutron capture during neutron calibrations produces $^{71}\text{Ge}$, which decays by electron capture with a 11.4 d half-life, producing a high rate of 10.4-keV Ga X-rays immediately following the neutron calibrations. For both types of X-rays, the source is distributed uniformly through detectors and so the ionization yield is not suppressed. Some work has been done by Richard Schnee to measure the gallium-X-ray rate as a function of time, but is not presented here. It would be interesting to determine the cosmogenic-activation rate using the rate of the 270.8 d decay, but this is also not done here. Though not visible due to the axis ranges of the spectra, BLIP3 has a gallium rate approximately 30% higher than the other detectors. This is probably due to enhanced activation during the neutron calibration: though the neutron directions are highly randomized by scattering, some anisotropy may remain, yielding a higher thermal-neutron flux on BLIP3 than the other detectors. The neutron-capture cross section rises at low energy, so thermal neutrons have much shorter penetration lengths than do the higher-energy neutrons responsible for nuclear-recoil events. Finally, the rise in rate below the gallium line in BLIPs 3 and 4 should not be ascribed any significance; as mentioned earlier, discrimination between photons and electrons becomes difficult below 10 keV.

Also visible in all the spectra is a line at 67 keV. This line was first seen in Run 18 data [8]. As first noted by Rick Gaitskell, this line arises from deexcitation of $^{73m}\text{Ge}$ produced by thermal-neutron capture on $^{72}\text{Ge}$, giving an energy of 66.7 keV for the line [149]. In Andrew Somenschein’s dissertation [8], the rate of this line is used to measure the thermal-neutron background.

Of most interest is the 46-keV line visible in the cQoutOnly spectra. It may also be present in the BLIP6 cQinOnly spectrum, but at a much lower rate and significance. This line arises from the beta decay of $^{210}\text{Pb}$. The decay has $Q = 63.1\ \text{keV}$, but 89% of the time the electron is emitted with 16.6-keV endpoint and the daughter $^{210}\text{Bi}$ nucleus is left in an excited state. Most of the time, the excited $^{210}\text{Bi}$ nucleus decays by internal conversion, ejecting electrons from atomic states. A small fraction of the time (4.05% of all $^{210}\text{Pb}$ decays), the $^{210}\text{Bi}$ nucleus decays by emission of a 46.5-keV photon. This 46-keV line thus indicates the amount of $^{210}\text{Pb}$ present in the surroundings. The absence of these photons, or presence at a much lower rate, in the BLIP3 and BLIP6 cQinOnly spectra suggests that they are emitted by $^{210}\text{Pb}$ present on the sides, but not the endcaps, of the detector housing. One possibility is the Detector Interface Boards (DIBs) and IR blockers: there are a number of electronic components and a good deal of solder on these assemblies. Another possibility is the brass screws holding the germanium shielding in place. The faces of BLIPs 3 and 6 would not see these sources. If $^{210}\text{Pb}$ is directly visible to the detectors, then a large associated electron flux is expected directly from the beta decay. Such a rate may explain the elevated electron
rates in the outer electrodes. The 46-keV line has an intensity of roughly 10 kg$^{-1}$ d$^{-1}$ in each of the detectors. This implies a $^{210}$Pb decay rate of at least 40 d$^{-1}$; of course, a significant fraction of the 46-keV photons may not be emitted toward the detectors, so the actual rate of decays may be higher. Every decay yields at least one electron. An areal event rate of 0.1 cm$^{-2}$ d$^{-1}$ in electrons corresponds to a total event rate of 4 d$^{-1}$ for cQoutOnly, so less than 10% of the emitted electrons would have to reach the detectors and deposit more than 10 keV, which is plausible. To conclusively test this hypothesis, a simulation of a $^{210}$Pb source on the DIBs or in the brass screws would be useful. Such work is beyond the scope of this dissertation.
Figure 8.36: Photon “prgamma” spectra for veto-anticoincident cQinOnly photon events. Solid: single scatters. Light: double scatters.
Figure 8.37: Photon “prgamma” spectra for veto-anticoincident cQShare photon events. Solid: single scatters. Light: double scatters.
CHAPTER 8. BACKGROUND-PARTICLE RATES AND CONSTRAINTS ON THE WIMP-NUCLEON CROSS SECTION

Figure 8.38: Photon “prgamma” spectra for veto-anticoincident cQoutOnly photon events. Solid: single scatters. Light: double scatters.
8.5.5 Tritium

The story of tritium contamination observed in previous runs in both the thermistors and detectors is somewhat of a footnote to the results presented in this dissertation; however, it is useful to summarize the situation and indicate what light Run 19 can shed on the issue.

Concurrent with discovery of tritium in the thermistors (see Chapter 4), a tritium beta-decay spectrum was also observed in the BLIP1 crystal-interaction data set with an overall rate of $120 \text{ d}^{-1}$, or $730 \text{ kg}^{-1} \text{ d}^{-1}$ [111]. These events suffer from suppressed ionization collection and thus could be due to an external source, detector surface contamination, or tritium in the dead layer itself. The observation of tritium in both the thermistor-interaction and crystal-interaction data suggested the possibility that the tritium either diffused from the thermistors into the detector dead layer or evaporated out of the thermistors and plated out on the detector surface during eutectic bonding of the thermistors. The excellent fit to the energy spectrum also suggested the source was not external — one would expect some distortion due to backscattering, though this was not investigated in detail at the time. Another possibility is that tritium was present in the ion beam used to implant boron into the detector surfaces for creation of the ionization electrodes.

A number of tests made it clear that, in fact, the tritium source was external, residing on or in the surfaces of the detector housing. However, the series of tests that finally led to this conclusion was not direct and the chronology is somewhat strange. First, to test the possibility that the tritium was either deposited on the detector surface or had diffused into the dead layer during eutectic bonding, a deep (30-µm) etch was performed on BLIP1. This removes the entire dead layer. The detector was reimplanted, so the implantation hypothesis would not be tested. BLIP2, a detector not previously operated at SUF, but fabricated in the same way as BLIP1, also was subjected to this procedure. BLIPs 1 and 2 were operated at SUF during Runs 18 and 19. These data sets are discussed in detail in Andrew Sonnenschein’s dissertation [8]. In Run 18, the event rates due to tritium in BLIPs 1 and 2 were $120 \text{ d}^{-1}$ and $40 \text{ d}^{-1}$, equal to and one-third of the Runs 15/16 BLIP1 rates, respectively. This test demonstrated that the thermistor hypothesis could not explain the data. Contamination by reimplantation, detector handling, or in the detector housings remained viable. Between Runs 18 and 19, the two detectors’ housings were exchanged. In Run 19, the ratio of rates reversed itself, thus indicating the source of tritium was the detector housings.

Concurrently, a second test was done to see if it was possible to remove the tritium from the thermistors prior to eutectic bonding. Two thermistors were heated to 550 C and 650 C, respectively, for 2 hours to evaporate the tritium [130]. These thermistors were measured at SUF in Run 17, yielding tritium reductions of 99% and 50% for the 650 C and 550 C thermistors, respectively [117].

Thus, while there is indeed tritium in the thermistors that can be removed by baking, this contamination is not related to the source of the crystal-interaction tritium spectrum seen in BLIPs 1 and 2. The thermistor-baking result was available in October, 1997, while the disproval of the thermistor hypothesis was not available until May, 1998. Fabrication of the Run 19 detectors began in early 1998, so the precaution of baking the thermistors prior to bonding to the detectors was taken. An entire wafer of NTD Ge was baked at 650 C in the same way as the test device above and diced into thermistors. These thermistors were eutectically bonded to the detector crystals in the standard way. A second precaution taken for Run 19, against both tritium and higher-energy electrons, was to cover the inside of the detector package with high-purity germanium, as has been described earlier.
Figure 8.39: Thermistor event spectra. Dark: P1. Light: P2. The fitted phonon energies have been scaled down by an empirical factor of 2.7. The curves indicate tritium beta-decay spectra with amplitudes chosen to roughly match the spectra.
Run 19 can add two pieces of information to the story. First, the Run 17 tritium reduction is confirmed. Energy spectra for thermistor events are shown in Figure 8.39; the typical inferred total tritium beta-decay rate is in the range $0.5 \, \text{d}^{-1}$ to $6 \, \text{d}^{-1}$, with large variations among thermistors. The tritium rate observed in Runs 15 and 16 was $570 \, \text{d}^{-1}$, so a reduction factor of at least 100 is confirmed. Second, no tritium is apparent in the Run 19 crystal-interaction data set either; a limit of order 1000 times lower than the 120 $\, \text{d}^{-1}$ observed in BLIP1 can be placed. Given the use of close packing and germanium shielding in Run 19, it may be possible for the Run 19 detector housings to be contaminated with tritium without producing an observable rate in the detectors. The Run 20 detector package eliminates the germanium shielding, so it should be possible to test this hypothesis. However, it is certainly possible that tritium contamination is not a general problem and that, with the the BLIPs 1 and 2 detector packages, we simply were unlucky.

8.6 BLIP3 Electron Misidentification

In terms of systematics, it is important to determine whether the BLIP3 single-scatter data are consistent with the electron-misidentification expectations from the electron calibration. This checks whether the ionization yield for the double-scatter events used in the electron calibration is systematically different from the single-scatter data to which the calibration is applied, clearly an important issue. Expected electron-misidentification numbers for the BLIP3 single-scatter data are calculated in the same way as is done for the BLIPs 4/5/6 data in Section 8.2.1 and are shown in Table 8.13. The observed numbers of nuclear-recoil candidates are also shown. Only about 4 to 5 true nuclear recoils are expected in the cQinOnly sample, small compared to the observed numbers. The numbers are consistent with the expected misidentification. One can also make the important conclusion that, had the BLIP3 single-scatter data set been used as the electron calibration, the expected numbers of misidentified events calculated in Sections 8.2.1 and 8.2.2 would not be significantly changed.
CHAPTER 8. BACKGROUND-PARTICLE RATES AND CONSTRAINTS ON THE WIMP-NUCLEON CROSS SECTION

<table>
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<th>Event set</th>
<th>$\beta^b$</th>
<th>$\beta^c$</th>
<th>$N^b_\beta$</th>
<th>$N^c_\beta$</th>
<th>$\mu^b_{1.90}$</th>
<th>$\mu^b_{1.10}$</th>
<th>$\mu^b_{1.50}$</th>
<th>$N^b_{NR}$</th>
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<td>cQinOnly</td>
<td>10 – 30 keV</td>
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<td>14.2</td>
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<td></td>
<td>30 – 100 keV</td>
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<td>0</td>
<td>39</td>
<td>32.0</td>
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<td>42.3</td>
<td>5.4</td>
<td>17.1</td>
<td>33</td>
</tr>
<tr>
<td>cQShare</td>
<td>10 – 30 keV</td>
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<td>1</td>
<td>35</td>
<td>10.3</td>
<td>1.3</td>
<td>4.2</td>
<td>4</td>
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<td></td>
<td>30 – 100 keV</td>
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<td>0.6</td>
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<tr>
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<td>15.7</td>
<td>2.1</td>
<td>6.6</td>
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</tbody>
</table>

Table 8.13: BLIP3 cQinOnly and cQShare single-scatter-electron misidentification estimates, calculated by method discussed in Section 8.2.1. The first column is the number of single-scatter-electron events observed for the given energy bin. The second two columns list the calibration data used, which come from the BLIP3 column of Table 4.6. The fourth column is the rigorously calculated Bayesian 90% CL upper limit on the number of misidentified single-scatter electrons. Because of the large values of $N^c_\beta$ and $N^b_\beta$, these values are very close to what one gets by calculating a Bayesian 90% CL upper limit on $\beta^c$ from the electron calibration and multiplying by $N^b_\beta$. The fifth and sixth columns give 10% CL and 50% CL upper limits on the number of misidentified electrons to give an idea of the expected range. The final column lists the observed numbers of nuclear-recoil candidates. No attempt has been made to subtract the expected numbers of single-scatter neutrons from these data, but, roughly, there should be 4 to 5 and 2 to 3 neutrons between 10 and 100 keV in the cQinOnly and cQShare data, respectively.
8.7 Veto-Coincident Data

For completeness, I present the veto-coincident data in this section. A detailed discussion of the veto-coincident-neutron spectra is presented in Section 7.5. Otherwise, these data have no bearing on the WIMP-search analysis and on residual background-particle rates, so no serious analysis is attempted. However, some features deserve brief discussion.

Ionization yield plots for cQinOnly, cQShare, and cQoutOnly events for single and multiple scatters are shown in Figures 8.40, 8.41, 8.42, 8.43, 8.44, and 8.45. The most disconcerting feature of these plots is the distribution of low ionization-yield events that follow the shape of the ionization-search threshold. In the single-scatter data, these events are only apparent in the BLIP3 data. In the multiple-scatter data, the rate of such events is progressively higher in the cQShare and cQoutOnly data sets. Events with saturated detectors have been removed, so electrical cross-talk is ruled out as the cause of these events. Cross-talk is also disfavored by the fact that the events have significant phonon energy. The variation of the rate of such events with ionization-partition cut and detector (with BLIP6 generally having the fewest such events, except possibly in the multiple-scatter cQoutOnly data) strongly suggests a physical origin. The absence of such distributions in the veto-anticoincident data corroborates a physical origin for the events. At present, no explanation has been found.

It must be emphasized that the presence of such events does not invalidate the analysis of the muon-coincident nuclear recoils presented in Section 7.5. First, the cQinOnly single-scatter data do not exhibit such events (with the possible exception of BLIP3), so the single-scatter nuclear recoils are free of contamination. Second, recall that extremely restrictive cuts were made to select double-scatter nuclear recoils; these cuts remove these low-yield populations in the double-scatter data set.

Recoil-energy spectra for the veto-coincident data are shown in Figures 8.46, 8.47, and 8.48. Since the low-yield distributions seen in the ionization-yield plots merge into the ionization-search threshold, spectra of the phonon energies for events with only noise charge are also presented, in Figure 8.49. Since these events have only noise charge, the observed ionization energy is not accurate. The phonon energy presumably gives the correct recoil energy for such events. The entire detector volume is used for normalization of the noise-charge spectra. Note that, because these events have only noise charge, it is not possible to determine if they are coincident or anticoincident with the veto. It is likely, based on the rates and the merging of the above-noise-charge distribution into the noise-charge distribution, that the noise-charge events are dominantly veto-coincident.

The cQinOnly and cQoutOnly spectra and, especially, the noise-charge event spectra, exhibit steep rises at low energy due to the low-yield events. The relative single- and double-scatter rates reflect the geometry, with BLIPs 4 and 5 exhibiting higher double-scatter photon fractions than BLIPs 3 and 6. Also, compared to the veto-anticoincident data, the electron double-scatter fractions are quite high, indicating most veto-coincident electrons are produced in showers or are ejected from the detectors and surroundings. This is especially true for the cQoutOnly data. The rise in cQinOnly and cQoutOnly photons and the drop in cQShare photons at low energy, as compared to their fairly flat behavior in the veto-anticoincident data, may indicate that a large part of the low-energy-photon flux is due to fluorescence photons — such photons have energies $\lesssim 100$ keV and thus are unlikely to scatter twice in a single detector, causing the cQShare fraction to drop at low energy.
Little more can be said at this point, except to note that, since the low-yield events appear to be purely veto-coincident and do not contaminate the single-scatter cQinOnly and double-scatter neutron samples, it is not a high priority to understand their origin.
Figure 8.40: Ionization yield vs. recoil energy for veto-coincident cQinOnly single-scatter events. A random 10% of the data is shown. Hyperbolic dashed line: ionization-search threshold. Light solid line: center of nuclear-recoil band, pre-April 3. Light dashed line: center of nuclear-recoil band, post-April 3. Dark solid line: nuclear-recoil-acceptance region, pre-April 3. Dark dashed line: nuclear-recoil-acceptance region, post-April 3.
Figure 8.41: Ionization yield vs. recoil energy for veto-coincident cQShare single-scatter events. A random 10% of the data is shown. Legend as in Figure 8.40.
SECTION 8.7. VETO-COINCIDENT DATA

Figure 8.42: Ionization yield vs. recoil energy for veto-coincident cQoutOnly single-scatter events. A random 10% of the data is shown. Legend as in Figure 8.40.
Veto-Coincident cQinOnly Multiple Scatters

Figure 8.43: Ionization yield vs. recoil energy for veto-coincident cQinOnly multiple-scatter events. Events in which any detector is saturated have been removed. A random 10% of the data is shown. Legend as in Figure 8.40.
Figure 8.44: Ionization yield vs. recoil energy for veto-coincident cQShare multiple-scatter events. Events in which any detector is saturated have been removed. A random 10% of the data is shown. Legend as in Figure 8.40.
Figure 8.45: Ionization yield vs. recoil energy for veto-coincident cQoutOnly multiple-scatter events. Events in which any detector is saturated have been removed. A random 10% of the data is shown. Legend as in Figure 8.40.
Figure 8.46: Recoil-energy spectra for veto-coincident cQinOnly events. Dark solid: single-scatter photons. Dark dashed: single-scatter electrons. Light solid: photons belonging to double scatters. Light dashed: electrons belonging to double scatters.
Figure 8.47: Recoil-energy spectra for veto-coincident cQShare events. Legend as in Figure 8.46.
Figure 8.48: Recoil-energy spectra for veto-coincident cQoutOnly events. Legend as in Figure 8.46.
Figure 8.49: Recoil-energy spectra for noise-charge events. Solid: single scatters. Dashed: double scatters. Note that, because these events have only noise charge, no determination of coincidence or anticoincidence with veto can be made.
Chapter 9

Conclusion and Outlook

The data presented here yield the first significant exclusion limits on the WIMP-nucleon cross section from the Cryogenic Dark Matter Search. Interesting regions of minimal supersymmetric parameter space are being probed. The claimed annual-modulation detection by the DAMA collaboration is being tested, and, perhaps, disproved. CDMS is within sight of its SUF sensitivity goal, shown in Figure 9.1.

The CDMS philosophy of developing new technology has paid off handsomely. The 15-year investment made in understanding the solid-state physics of phonons and electron-hole pairs at low temperature has led to detectors that are making significant impact on one of the most pressing scientific questions of our time. Man-decades of engineering effort have gone into making this experiment, which many considered on the edge of cryogenic feasibility, run smoothly for extended periods.

The analysis presented here also points to open issues. Statistically precise electron and photon calibrations are needed to fully characterize the ionization yield distributions arising from interactions of these particles. More stringent tests and checks of the efficiency calculation are required. An explanation of the 20–30% systematic disagreement between the internal- and calibration-source-neutron data and simulations is necessary. And a more comprehensive understanding of the source of the residual electron background is important. To continue to make progress at the SUF site, and to reach the CDMS II goal at Soudan, all these systematic issues must be addressed.

But the future is bright. CDMS II will deploy 10 times as much detector mass. The $\alpha$-Si/Al-Schottky ionization electrodes employed here and the QET athermal-phonon-sensing technology are being combined to give the CDMS II ZIP detectors an unprecedented ability to identify and reject bulk and surface electron recoils. Moreover, the ability of these detectors to diagnose background sources using position and ionization yield is only beginning to be exploited. With these tools, CDMS II will explore a significant portion of the parameter space available for minimal supersymmetric WIMPs, as shown in Figure 9.1. I personally look forward to seeing this dissertation quickly become obsolete!
Figure 9.1: CDMS SUF and Soudan sensitivity goals. Also shown are the exclusion limit presented in this dissertation, the DAMA annual-modulation claim, and various MSSM models. Dark solid limit curve: exclusion limit from these data. Upper dotted limit curve: CDMS SUF sensitivity goal. Lower dotted limit curve: CDMS Soudan sensitivity goal. Light heart-shaped region: DAMA 2000 annual-modulation $3\sigma$ allowed region without application of DAMA 1996 limit. MSSM models: Light solid: Gondolo et al. mixed models [78]. Dark dashed: Gondolo et al. gaugino models. Light dashed: Gondolo et al. Higgsino models. Dark solid: Corsetti and Nath mSUGRA models [79]. Figure from [80].