Maximum Likelihood Signal Extraction Method Applied to 3.4 years of CoGeNT Data

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CoGeNT has taken data for over 3 years, with 1136 live days of data accumulated as of April 23, 2013. We report on the results of a maximum likelihood analysis to extract any possible dark matter signal present in the collected data. The maximum likelihood signal extraction uses 2-dimensional probability density functions (PDFs) to characterize the anticipated variations in dark matter interaction rates for given observable nuclear recoil energies during differing periods of the Earth’s annual orbit around the Sun. Cosmogenic and primordial radioactivity backgrounds are characterized by their energy signatures and in some cases decay half-lives. A third parameterizing variable – pulse rise-time – is added to the likelihood analysis to characterize slow rising pulses described in prior analyses. The contribution to each event category is analyzed for various dark matter signal hypotheses including a dark matter standard halo model and a case with free oscillation parameters (i.e., amplitude, period, and phase). The best-fit dark matter signal is in close proximity to previously reported results. When systematic uncertainties in the PDF models are included, the significance of the extracted dark matter signal remains below the evidentiary (i.e., 3σ) level. These results show the extracted signal is dependent on the choice of model PDFs, but is otherwise a viable method for cases when the signal and background distributions are well known.

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I. INTRODUCTION

The CoGeNT detector has operated stably for over three years at the Soudan Underground Laboratory. Prior publications have analyzed data from the CoGeNT detector testing the collected data for any signature of dark matter interactions. Those prior results have shown a preference for an excess of events above the expected background. If this excess is treated as a dark matter signal, a best fit is found for a low mass (≈10 GeV/c²) dark matter particle with large (≈10⁴⁷ cm²) interaction cross-section. These results are based on analyzing the CoGeNT data for both the recoil nuclear energy spectral signature and separately the expected temporal variation of the event rate with an annual period and summer to winter phase. In all cases the statistical significance of these observations are just beneath evidentiary (i.e., 3σ). While the significance of the CoGeNT results (and other recent findings) do not rise to the level of discovery, the possible detection of the first non-Standard Model particle should not be blithely ignored nor accepted without irrefutable evidence. Thus a detailed analysis of the released 3.4 year CoGeNT data set is pursued. The objective is to use models of the backgrounds present in the CoGeNT data set – parameterized by energy and time – to test for a possible dark matter signal using a fully unbinned maximum likelihood signal extraction method. The principle underlying this method is generic and applicable in current and future dark matter searches, thus a focus on reporting the methodology is presented in this article. Finally, this maximum likelihood methodology provides a quantifiable way to test for the effect of systematic uncertainties associated with understanding of the signal and background distributions.

Of particular interest in this analysis is addressing a background having a similar energy spectral shape to that expected from dark matter induced nuclear recoil interactions (e.g., a falling exponential as a function of increasing energy). This background is due to energy depositions in the high voltage contact surface layers of the germanium crystal. The surface event pulses on average have longer rise-time than bulk events. In recent published analysis, the fast and slow pulse rise-time distributions were shown to be well approximated by log-normal functions, a model qualitatively justified by the impact of electronic signal noise on the determination of individual pulse rise-times. The separation between fast and slow pulses is very good at higher energies, with the separation becoming worse at lower energies as the risetime distributions broaden. Figure 1 shows distributions of the log-normal functions fitted to the data in
three energy ranges: 0.5–0.7 keV, 2–3 keV, and 4–5 keV (additional energy ranges are shown in Ref. [3]). It is clear the separation becomes very poor at low energies and is the primary source of uncertainty in this analysis. Panels b and c of figure 1 show the log-normal functions are good approximations for the fast and slow pulse distributions at higher event energies.

In the analysis presented here an unbinned maximum likelihood signal extraction is performed on 1136 live-days of data seeking to extract any possible dark matter signal in the presence of backgrounds. The backgrounds included are the L-shell x-ray peaks (constrained by K-shell x-ray peak intensities), a muon-induced neutron background (constrained by analysis of the cosmic ray veto panel data), a flat Compton distribution from external gamma rays (constrained by the flat continuum under the K-shell x-ray peaks), and a surface event background from external gamma rays (studied as a dominant contributor to the systematic uncertainty). There are no rise-time cuts applied in this analysis, instead probability density functions (PDFs) in rise-time for bulk and surface events are used to determine the relative contributions from these categories of events. As the contribution to each event population is dependent on the details of the model PDF, effort is applied to understanding the effect of systematic uncertainties associated with the PDF models used.

II. LIKELIHOOD SIGNAL EXTRACTION METHOD

In a maximum likelihood signal extraction, the most likely level of contribution to the data set from each of the known backgrounds and any possible signal are estimated (See Ref. [11] Ch. 35 and 36). For likelihood signal extraction applied to the CoGeNT data set, the total probability for any event is given by

\[ P_i = \alpha_1 P_L + \alpha_n P_n + \alpha_{flat} P_{flat} + \alpha_{surf} P_{surf} + \alpha_X P_X , \]  

(1)

where \( P_L \) represents the probability that the event is one of the L-shell x-rays, \( P_n \) is the probability that the event being is a neutron, \( P_{flat} \) is the probability the the event is a part of a "flat" linear background, \( P_{surf} \) is the probability that the event is a surface event, and finally \( P_X \) is the probability that the event is due to a dark matter interaction. The various \( \alpha \)'s are the size of the contributions from each of the signal groups in the data. There are ten separate background signals in the maximum likelihood extraction. For the cosmogenic backgrounds we have the L-shell x-rays for \( ^{68}\text{Ge} \), \( ^{68}\text{Ga} \), \( ^{65}\text{Zn} \), \( ^{73,74}\text{As} \), \( ^{56,57,58}\text{Co} \), \( ^{55}\text{Fe} \), and \( ^{54}\text{Mn} \). The other backgrounds are muon-induced neutrons, the bulk Compton continuum, and surface gamma rays.

The ten background PDFs are parameterized as

\[ P_{bkg}(E, rt, t) = P(rt, E) \times P(t) . \]  

(2)

FIG. 1. The rise-time distributions for various energy ranges from the 3.4 year data set. The distributions are fit with pairs of log-normal distributions for the fast and slow rise-time distributions. The solid curves are the individual fitted log-normal functions and the dashed curves are the combined functions. For the panel (c), the solid and dashed curves overlap completely therefore we only show the combined function.
Using the product rule, equation \( \text{2} \) can be written using the conditional probability distribution function, \( P(rt|E) \):

\[
P_{\text{bkg}}(E,rt,t) = P(rt|E) \times P(E) \times P(t), \tag{3}
\]

which is the form we use in our signal extraction. The probability distribution \( P(E) \) describes the detector’s expected spectral energy response to the background, \( P(t) \) describes the expected temporal variation of the background with time, and \( P(rt|E) \) is a conditional probability distribution function describing the detector’s expected pulse rise-time response for a given event energy. For the case of the standard halo model, the dark matter signal PDF is parameterized as

\[
P_{\chi}(E,t,rt) = P(rt|E) \times P(E,t). \tag{4}
\]

The probability distribution \( P(E,t) \) describes the detector’s energy-spectral and temporal response to dark matter interactions as a fully two-dimensional PDF. The probability distribution \( P(rt|E) \) has the same meaning as described above for backgrounds. For the case of a signal extraction with fully free WIMP oscillation parameters, equation \( \text{3} \) is parameterized exactly like equation \( \text{3} \). In these PDFs the variables \( E, t, \) and \( rt \) are energy, time, and pulse rise-time, respectively. To extract the signal contribution we minimize the log of the likelihood function

\[
\mathcal{L}_{\text{log}} = -2 \sum_{i=0}^{N} \log(P_i). \tag{5}
\]

where the summation is over all \( N \) events selected (see Sec. \( \text{V} \) for event selection discussion).

**A. Constraints in the Likelihood fit**

It is possible additional information is available regarding the relationships between the different PDFs that is not or need not be represented in the three-variable parameter space of \( E, t, \) and \( rt \) for which the event populations have constructed PDFs. This information can include expected intensity ratios between the event populations or secondary measurements that limit the range of contribution from a particular event category. These ‘external’ constraints can be included in the maximum likelihood signal extraction. Equation \( \text{7} \) describes how this is done if \( \alpha \) is the fitted value, \( x \) is the external measurement of that value, and \( \sigma_x \) is the uncertainty on the external measurement.

\[
p_{c} = \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{(x-p_{c})^2}{2\sigma_x^2}}, \tag{6}
\]

\[
\mathcal{L}_{\text{log}} = \mathcal{L}_{\text{log}} - 2\log(p_c). \tag{7}
\]

The constrained log-likelihood function, \( \mathcal{L}_{\text{log}} \), is the function we minimize in our signal extraction.

**III. PROBABILITY DENSITY FUNCTION DESCRIPTIONS**

Each of the PDFs for the background contributions to the CoGeNT data set are described in this section. In general, one should consider the maximum likelihood signal extraction as performed on data from the high-energy channel (CH1) \( \text{3} \), compromised of events falling in the 0.5-3.0 keV energy range. However, where it is possible to provide constraints, other channels of information from the CoGeNT data acquisition \( \text{3} \) are used. These details are described in this section. The dark matter signal PDF, \( P_{\chi} \), is described alongside the signal extraction results in a later section as several forms of \( P_{\chi} \) are explored in the analysis presented in this article.

**A. Pulse rise-time distributions, \( P(rt|E) \)**

The most effective way to separate surface from bulk events is through pulse rise-time \( \text{3} \). The bulk events have, on average, faster pulse rise-times than surface events. In the maximum likelihood signal extraction we use the two dimensional PDFs shown in figure \( \text{2} \) to determine the correlation between pulse rise-time and event energy. These PDFs are expressed as \( P(rt|E) \) in equations \( \text{2} \) and \( \text{4} \). The rise-time PDFs are binned in 0.25 keV wide energy bins and 0.1 \( \mu \text{sec} \) wide rise-time bins. The rise-time distributions for each energy bin are all normalized to unity. Therefore these PDFs provide for the variation of the rise-time distribution as a function of energy. The conditional probability distribution functions shown in figure \( \text{2} \) are generated by fitting log-normal functions to the rise-time distributions of the collected 1136 live-day data set when placed into 0.25 keV-wide energy bins. Ideally we would like to use calibration data to determine the shape of these conditional PDFs. However, until these calibrations are collected in future detector characterization runs, we use the existing PDFs created from the collected data to demonstrate the viability of the maximum likelihood signal extraction method.

**B. L-shell X-rays, \( P_L \)**

Cosmogenic activation of the germanium crystal takes place when the crystal is on the surface during fabrication. This results in radioactive isotopes present uniformly through-out the germanium crystal (isotopes labeled in figure 3 of Ref. [1]). The presence of electron capture decay isotopes are identified by the characteristic K-shell x-rays emitted and immediately reabsorbed in the germanium crystal. The K-shell x-rays in the high energy data channel are fit directly to determine their intensity and as a check for the appropriate isotope’s decay half-life. Figure \( \text{3} \) shows the result of the signal extraction in the high-energy region compared to the data in the high energy channel. The fit K-shell contributions
in the high-energy region are used as constraints on the L-shell peaks for the signal extraction on the low-energy data.

The L-shell energy PDFs, $P(E)$, are Gaussian peaks with resolutions taken from the energy resolution versus energy equation given in \cite{8}. The mean energies for each L-shell x-ray peak are taken from \cite{6}, and the K- to L-shell intensity ratios that are used are from \cite{12}. The time evolution of the individual L-shell x-ray contribution PDFs, $P(t)$, is taken from the standard isotopic half-life values \cite{6}. For decays occurring in the small (<14% by volume) region of partial charge collection near the detector surface, the reduced charge collection results in most of these events being degraded to below the analysis energy threshold. However, some of the K-shell x-rays in the surface transition region will be above threshold. See section III E for a description of how degraded energy values are calculated for events in the partial charge collection surface region. Figure 4 shows the relative scale of the L-shell peak events relative to the K-shell surface events for the case of $^{68}$Ge x-rays. In the forthcoming signal extraction we include PDFs for both the bulk L-shell peaks and the associated surface event contribution, which is mostly from the K-shell x-rays. However, we do not fit for the size of the K-L shell surface event contributions, but rather scale these PDFs to be the size of the corresponding L-shell contribution $\times$ the L-shell to surface component ratio that is given by the Monte-carlo (figure 4 shows this ratio for $^{68}$Ge).
C. Neutrons, \( P_n \)

The neutron PDF represents neutrons produced by cosmic ray muons passing through the CoGeNT shield. Prior analysis \(^3\) presented the results from a GEANT Monte-carlo simulation of this process and the resulting nuclear recoil event energy spectrum in germanium. That simulation provides the shape of the \( P(E) \) PDF for these neutrons. The temporal modulation amplitude for muons has been measured to be \( \sim 2\% \) at the Soudan Underground Laboratory \(^4\). For the purpose of this analysis the time PDF, \( P(t) \), is treated as constant in time. This is sensible when the modulation of the muon rate is a \( \sim 2\% \) effect on a small contribution to the total CoGeNT data set; this is estimated at a \( O(0.1\%) \) effect in the CoGeNT data \(^3\).

The final PDF needed to describe the neutron event population is the risetime-energy PDF, \( P(rt|E) \). Neutrons will interact uniformly throughout the germanium crystal. A small fraction will interact in the previously mentioned surface transition region. Further, application of a partial charge collection model (See Section IIIE) in this region means even fewer of the low energy nuclear recoils produced by this class of muon induced neutrons will produce events that are above the energy threshold of the analysis. To take into account the neutrons depositing their energy in the transition region, there are two categories of neutron PDFs, bulk neutrons and transition region neutrons. The relative scale between these is fixed in the maximum likelihood signal extraction and this scale is determined from Monte-carlo. Figure 5 shows the neutron energy distribution for both surface and bulk energy depositions and their relative scale. The muon-induced neutron Monte-carlo is computationally intensive, since it starts with muons impinging on the CoGeNT shield from the cavern and propagates all secondary particles produced. This limits the statistics in the PDFs shown in figure 5. We have used both these PDFs and functional form approximations to these PDFs in the signal extraction. Both PDF types produce very similar results.

A constraint on the muon-induced neutron background contribution is inferred from measurements of the germanium detector coincidences with the muon-veto panel rate and a simulation of muon-induced events in the CoGeNT shielding. A prior analysis \(^3\) examined the coincidence rate between the muon-veto panel array and the germanium detector. The prediction for this coincidence rate is based on the known muon rate at the Soudan Underground Laboratory \(^5\) and was shown to closely match the actual measured coincidence rate (See Fig. 17 in Sec. IV.A. of Ref. \(^3\)). The measured germanium-veto coincidences rate per day of 0.67±0.12 is used as a constraint on the extracted number of neutron events. The constraint is applied via equation 7 in the maximum likelihood minimization. This constraint is important because the nuclear recoil energy spectrum shape from muon-induced neutron scatters can potentially closely mimic the energy recoil spectrum shape from dark matter interactions. Together this rate constraint and the time components of the PDFs, \( P(t) \), should in principle separate the muon-induced neutron contribution from any dark matter interaction contribution. Later in this analysis the impact of freeing this constraint on the muon-induced neutron contribution is studied.

D. Flat Background, \( P_{\text{flat}} \)

The "flat" linear continuum background PDF represents high energy gamma-ray Compton-scattering interactions in the bulk of the crystal, mostly due to uranium and thorium contamination in the surrounding materials. The energy PDF, \( P(E) \), for this background is assumed to be constant in the 0.5-12 keVee region. This has been verified by Monte-carlo simulations of uranium and thorium chain gamma rays \(^3\). Figure \( \text{FIG. 5} \) shows the energy distribution, determined from simulations, of the uranium and thorium chain gammas depositing their energy in the bulk of the crystal. For the time component of this background, \( P(t) \), three different PDF types were tested: constant in time, modulating in time, and decaying over time. As the flat continuum events represent events taking place in the bulk of the crystal the \( P(rt|E) \) PDF for these events is represented only by fast rising bulk events (i.e., Fig. \( \text{FIG. 5} \) (a)).

E. Surface Events, \( P_{\text{surf}} \)

The same Monte-carlo employed above to investigate the energy spectrum due to uranium and thorium gamma-rays Compton-scattering in the bulk of the germanium crystal (See Section IIID) is used to study the impact of the partial charge collection transition region of the germanium detector. In this partial charge collec-
tion region analysis we include the dead and transition regions on the high voltage contact surface of the germanium crystal. The assumptions for the thickness of these regions were taken from [1, 10, 14]. We assume that the thickness of both the dead and transition regions is 1 mm, since analysis on the other detectors has yielded similar dimensions. From the Monte-carlo simulation we get the energy distribution for the events depositing their energy in the surface transition regions. In the Monte-carlo we use the 2-parameter sigmoid functional form for the charge collection efficiency as a function of depth into the Ge crystal given in [3]. In this way we are able to generate the energy PDF, $P(E)$, for the surface events. The charge collection efficiency decreases very rapidly with distance into the transition region from the bulk, therefore large energy depositions in the surface transition region can have resulting energies that are within our signal region. Figure 6 shows the results of this simulation for both surface-only and bulk-only events. The relative scale between the surface and bulk events in figure 6 comes directly from the Monte-carlo and is determined by the thickness of the transition region and the charge collection efficiency profile.

The Monte-carlo energy distribution for surface events shown in figure 6 is compared to a population of surface event data in the next section. Figure 8 shows a comparison of the Monte-carlo simulation of surface events to the data. The Monte-carlo does not give us the pulse rise-time distribution of the surface events. This surface event population is the single most difficult background to address in the analysis so additional attention is given to the PDF modeling of this event class in the following section.

As with the bulk gamma-ray events described in Section III D, the temporal variation $P(t)$ of the event rate for the surface events is described in correspondence with the three different PDF types of constant in time, modulating in time, and decaying over time.

The slow-pulse surface event distribution and the Compton continuum extend into the high-energy region, therefore fitting in the high-energy region can also place constraints on those contributions. This is done via the constrained log-likelihood function, $L_{\text{con}}$, given in equation 7.

IV. SYSTEMATIC STUDIES OF THE SURFACE EVENT DISTRIBUTION

The largest uncertainty in the signal extraction comes from our understanding of the distributions of events that have energy deposition in the transition region near the surface of the crystal. This is the event population described in the maximum likelihood signal extraction formulation as $P_{\text{surf}}$. Studies of surface events have been done on other detectors, see for example [10], [14], and [3]. However, no surface event calibration has been done on the CoGeNT detector. Thus, for our nominal surface event energy distribution we directly apply the transition region charge collection efficiency described in [3] and [9]. To study the systematic uncertainty on this choice of energy distribution we look at high rise-time events in the CoGeNT detector to select a high purity surface event sample. The determination of the systematic uncertainty from the surface event energy distribution proceeds as follows: (a) Select eight samples of surface events with different rise-times (rise time > $1\, \mu$sec, rise time > $1.5\, \mu$sec, rise time > $2\, \mu$sec, rise time > $2.5\, \mu$sec, etc.), (b) Fit the corresponding energy distribution for each rise-time selection to an exponential function, (c) fit a functional form to the resulting exponential constants determined from step (b) to extrapolate the resulting exponential constant at risetime > $0\, \mu$sec, (d) Propagate uncertainties from step (c) to determine bounds on the surface event energy distribution. We then perform the WIMP signal extraction using surface event distributions taken from both extrema of the energy distributions determined in the systematic study. Figure 7 illustrates the steps taken to determine the uncertainties on the surface event energy distribution. As a validation of the surface event Monte-carlo, we compare the energy distribution of surface events taken from Monte-carlo to the extrapolated energy distribution taken from figure 7. This comparison is shown in figure 8. While the comparison is not perfect, it shows that the Monte-carlo and data are relatively close in terms of the surface event energy distributions.

We did not study the systematic uncertainty resulting from varying the thickness of the transition region in the Monte-carlo. Varying the thickness of this region has a direct effect on the number of surface and bulk events. However, the size of the surface event signal group is allowed to float in the signal extraction. Therefore we do not expect the uncertainty in the transition layer thickness to translate into a large systematic uncertainty.
V. SIGNAL EXTRACTION RESULTS

We performed the likelihood signal extraction to determine the size of a possible WIMP signal on low energy events (high-gain channel, 0.5–3 keVee). Any possible low-mass (∼10 GeV) WIMP signal would be predominantly in the 0.5–3 keVee region. The PDFs used in the signal extraction are described in the previous sections.

A. Signal extraction with the standard halo model

A signal extraction on the CoGeNT data was done using the standard WIMP halo model parameters of $v_0 = 220$ km/s, $v_{esc} = 550$ km/s, and $\rho = 0.3$ GeV / $c^2$ cm$^3$. In this extraction the 2-dimensional PDF shown in figure 9 is used for the WIMP component in the extraction. The resulting best-fit WIMP mass from the signal extraction in the 0.5–3 keVee region is ∼10 GeV. The number of fitted WIMP events is $184 \pm 56$ in 1136 live days. This corresponds to a spin-independent WIMP-nucleon cross-section of $5.2 \times 10^{-42}$ cm$^2$. Taking into account the systematic uncertainty from the surface event energy distribution the resulting best-fit cross-section is $(5.2 \pm 1.6 \text{ (stat.)} \pm 1.8 \text{ (sys.)} \times 10^{-42}$ cm$^2$. With the systematic uncertainty included, the null result is only excluded at 2.5 $\sigma$. This cross-section is considerably lower than that reported in [3]. We attribute the lower cross-section obtained with the maximum likelihood signal extraction method to the inclusion of the significant muon-induced neutron component in the fit. Both Monte–carlo simulations and muon veto data point to a large neutron component. The energy PDF for neutrons is similar to that for WIMPs. Therefore there is significant cor-
FIG. 8. Comparision of the simulation of surface events from uranium and thorium chain gammas (blue line) to data with risetime > 1 µsec (data points) and the extrapolation determined from figure [2] (dashed line).

FIG. 9. The 2-D energy vs time PDF used for the WIMP event category in the standard WIMP halo model signal extraction.

relation between these two event categories. When the neutron component is not included in the signal extraction the extracted WIMP cross-section is much larger, see table [1].

B. Signal Extraction with free oscillation parameters

A signal extraction was also performed where the WIMP oscillation parameters of amplitude, period, and phase were allowed to float. The signal extraction with free oscillation parameters is favored over the standard halo model extraction at 2.7 σ. The contours shown in figure [11] are derived from the free oscillation parameter likelihood minimization.

1. Signal Extraction with Constant Backgrounds

The first signal extraction with free oscillation parameters was performed with the surface event and Compton backgrounds constant in time. In this scenario, the best-fit WIMP mass is (11.4 ± 1.8) GeV and the number of fitted WIMP events is 261 ± 78, corresponding to a cross-section of $5.8 \times 10^{-42}$ cm$^2$. Figure [10] panel (a) shows the fit results for this analysis compared to data in terms of energies, and figure [10] panel (b) shows the fit results with free WIMP oscillation parameters compared to the data in 30 day time bins. If we include the uncertainty on the surface event energy distribution then the cross-section is $(5.8 \pm 1.7 \text{ (stat.)} ^{+1.0}_{-1.0} \text{ (sys.)}) \times 10^{-42}$ cm$^2$. The best fit oscillation parameters are $T = 388 \pm 18$, $t_{\text{max}} = 106 \pm 24$, and an oscillation amplitude of $S = (84 \pm 32)\%$. These values are in agreement with those found in [2, 4], and the period and phase are in agreement with the DAMA results [5].

2. Signal Extraction with Time-varying Backgrounds

The signal extraction was also performed with time-varying surface and Compton backgrounds. Both decaying and modulating backgrounds were considered. The minimization favored the decaying background case over the modulating backgrounds and the constant-in-time backgrounds. The best-fit half-life of the Compton background (flat in energy) was $4143 \pm 1812$ days, and for the surface backgrounds it was $6424 \pm 5140$ days. The half-life of the flat background is remarkably similar to the $^3$H half-life of 4500 days, however we also note that we do not believe $^3$H to be a large component of the flat background. The surface event background is also similar to the $^{210}$Pb half-life of 8140 days, indicating that some fraction of the surface background may be due to $^{210}$Pb on the detector surface. We do not however draw any conclusions due to the very large uncertainty on the extracted surface event half-life. With decaying backgrounds, the best-fit WIMP mass is 12.8 GeV, and the cross-section is $2.8 \times 10^{-42}$ cm$^2$. The 90% C.L. contour for this version of the signal extraction is shown in figure [11]. The significance of this result is only 1.9 σ from the NULL hypothesis.

3. Modulation before and after the Soudan fire

To study the consistency of the modulation results with the free modulation parameter signal extraction the data set was split into two periods, one before the Soudan fire and the other after. The data set before the Soudan fire was from the same data taking period as used in [1, 2]. The signal extraction on the two data periods resulted in oscillation parameters that were within statistical uncertainty. However, large differences were seen in the oscillation phase and overall magnitude of the extracted WIMP
FIG. 10. The extracted WIMP and background signals compared to the CoGeNT data in both energy and time. The comparison in time is in 30 day bins. This fit was performed with the WIMP oscillation amplitude, phase, and period all allowed to float.

signal. For the data before the Soudan fire the extracted phase is $114 \pm 28$ days, and for after the fire it was $174 \pm 91$ days. The overall extracted number of WIMP type events before the Soudan fire is $171 \pm 74$, and after it is $81 \pm 48$. While the two numbers are consistent given the large statistical uncertainty, we note that this difference is even larger when considering that the livetime for the data set after the fire is larger than for the data before the fire by $\sim 50\%$. The statistical uncertainty on these results does not allow us to rule out the possibility of the modulation having a WIMP origin.

C. Summary of extraction results

Table I summarizes the signal extraction results for all the extractions attempted.

As a check of the validity of the signal extraction we compare the extracted neutron background with the measurement of the veto-germanium coincident rate. The signal extraction gives a neutron rate of $(0.64 \pm 0.13)$ cpd, which is in excellent agreement with the veto-coincident rate of $(0.67 \pm 0.12)$ cpd.

D. Allowed regions and WIMP sensitivity

We generate likelihood contours from the maximum likelihood signal extraction with free oscillation parameters and time-varying backgrounds. To take into account the systematic uncertainty due to our understanding of the surface events we also determined a contour with the shape of the surface event energy distribution allowed to float in the likelihood signal extraction. Figure 11 shows our 90% C.L. contours compared to recent CDMS results and the previous CoGeNT result. The same figure shows the WIMP sensitivity curves ($2\sigma$ upper limits) derived from the likelihood analysis. The more conservative exclusion limit is determined from fixing the neutron component in the likelihood extraction to 0. In this case, there are more extracted WIMP events to compensate for the events that would be normally classified as neutrons, therefore resulting in worse sensitivity. The lower exclusion curve in figure 11 is the result of allowing the neutron component in the likelihood extraction to be completely free. This produces better sensitivity limits, especially at low masses, since it allows for more neutron events, and thus less WIMP events, if favored by the likelihood minimization.

FIG. 11. The 90% C.L. contours derived from the maximum likelihood signal extraction with fixed surface event background energy distribution (red solid) and where the shape of the surface background energy distribution was allowed to float in the extraction (red dashed). Shown also are the 68% C.L. and 90% contours from the CDMS silicon result [5]. Also shown are the exclusion limits for various assumptions about the neutron component (see text).
TABLE I. Summary of extracted WIMP mass and cross-section for the various signal extractions attempted. The fits differ by the choice of background and signal PDF parameters (indicated in the table).

| PDF parameters | WIMP mass and cross-section |
|----------------|----------------------------|
| Standard halo parameters | $\sim 10$ GeV, $5.2 \times 10^{-42}$ cm$^2$ |
| Standard halo parameters with time-decaying flat background | $\sim 10$ GeV, $5.2 \times 10^{-42}$ cm$^2$ |
| Free oscillation parameters | $11.4$ GeV, $5.8 \times 10^{-42}$ cm$^2$ |
| Free oscillation parameters with time-decaying backgrounds | $12.8$ GeV, $2.8 \times 10^{-42}$ cm$^2$ |
| Free oscillation parameters with time-decaying backgrounds and zero neutrons | $12.5$ GeV, $1.3 \times 10^{-41}$ cm$^2$ |

VI. CONCLUSIONS

We have performed a likelihood signal extraction on the CoGeNT data using multi-dimensional PDFs for the backgrounds and a WIMP distribution. The background PDFs are based on extensive Monte-carlo simulations done in [3]. In the signal extraction we use both the standard halo model and free WIMP oscillation parameters. Taking into account the systematic uncertainty, this result does not rise to the level of discovery. We also observe that depending on the PDF assumptions, the results can have large variations. We believe however that the method of a maximum likelihood signal extraction with floating background and signal PDFs is a powerful technique at extracting a WIMP signal. Using this method we improve upon the previous CoGeNT WIMP sensitivity since we are better able to separate backgrounds from a possible WIMP signal. This method becomes even more robust when the background distributions are well understood. We conclude that this approach can be readily applied to other dark matter experiments especially in the low-mass WIMP region where a zero-background is often not achievable.

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