Internal calibration of the LUX detector using tritiated methane

LUX Collab List

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Abstract

We have developed a new method to inject tritiated methane into detectors which utilize liquid and gas phase noble gases as an internal calibration source. The ability to use internal calibration sources is critical in large scale particle physics experiments. Our system uses volume sharing techniques to inject a finely tuned amount of tritiated methane into the detector, and uses a zirconium getter to remove the tritiated methane after the calibration has been completed. We present data from the LUX detector to prove our tritiated methane system can calibrate electron recoil events and remove the internal source to undetectable levels afterward.

I. Introduction

The LUX collaboration recently reported results from its first underground science run, placing new constraints on WIMP dark matter with masses between 6 GeV and 1 TeV[**?**]. LUX is a large dual-phase liquid xenon (LXe) time projection chamber (TPC) with an active mass of ??270?? kg. The primary scintillation light from particle interactions (S1) is collected by two arrays of photomultiplier tubes (PMTs) at the top and bottom of the detector, and the charge signal is converted to light via secondary scintillation at the anode (S2). Measurement of both S1 and S2 allows the event to be located in all three dimensions, and allows discrimination between nuclear recoil (NR) events from electron recoil (ER) events via the ratio (S2/S1).

One of the primary advantages of the liquid TPC technology is its high efficiency for the rejection of external gamma backgrounds via self-shielding. This has enabled the exploration of three orders of magnitude in WMP-nucleon cross-section over the last decade. On the other hand, self-shielding also reduces the effectiveness of external gamma sources such as ^{137}Cs or ^{228}Th for detector calibration purposes, particularly in the center of the detector and at the low energies relevant for dark matter. In the case of LUX, external gamma source are unable to produce a useful rate of ER calibration events in the fiducial region.

To address this issue, internal calibration sources that can be dissolved into the liquid xenon and thereby defeat its self-shielding have been developed[**?**]. LUX has deployed two such internal calibration sources; the first based upon ^{83m}Kr , and the second based upon tritium (^{3}H). ^{83m}Kr is a source of two internal conversion electrons at energies of 9.4 keVee and 32.1 keVee separated in time by an intermediate state with a half life of 154 ns. Because it produces two lines in the energy spectrum, ^{83m}Kr is

well adapted for tracking the spatial and time dependence of the S1 and S2 signals. However, because both ^{83m}Kr electrons are above the energy range of interest for dark matter (1.3 - 8 levee), and because the S2 signals from the two electrons generally overlap with each other in the detector, ^{83m}Kr is less useful for constraining the electron recoil (ER) band of the S2/S1 discriminant.

In this article we describe the development and use of the LUX tritium source, which plays a complementary role to the ^{83m}Kr source. Unlike ^{83m}Kr , tritium is a single-beta emitter, with a Q value of 18.6 keVee. Its spectral maximum is at 2.5 keVee, and 75% of its beta decays are below 8 keVee. This allows the detector's ER band to be precisely characterized in a short calibration run without saturating the DAQ. In addition, the tritium spectrum has a finite decay rate extending down to zero keVee, allowing the threshold response of the detector to be studied.

Unlike ^{83m}Kr , however, tritium is long-lived, with a half-life of 12.3 years, compared to 1.8 hours for ^{83m}Kr . So while the ^{83m}Kr is naturally removed from the detector after roughly a day, the tritium must be removed from the liquid xenon by purification. Secondly, tritium must be introduced into the detector in a manner which will not impair the charge or light collection properties of the detector. This is less of a concern with ^{83m}Kr , because it can be passed through the LUX getter prior to entering the detector owing to its noble nature.

Tritiated methane (CH_3T) was chosen as the appropriate host molecule to deliver the activity into LUX. Methane has several desirable chemical and physical properties compared to T_2: first, its diffusion constant (D) times solubility (K) is ten times smaller in common LUX materials such as teflon (PTFE) and polyethylene (PE)[**?**], mitigating the problem of back-diffusion of activity into the liquid xenon after purification; it is chemically inert, so it is not expected to adhere to surfaces (as the T_2 molecule is known to do), and it is consistent with good charge transport in liquid xenon.

Our goal was to develop a (CH_3T) source which could be safely injected into LUX and removed such that any residual activity that remained (due to back-diffusion from plastics or inefficient purification) should be no more than 0.33 μBq, which is 5% of the LUX ER background rate design goal for a 30,000 kg·days exposure. We desired to collect a LUX calibration dataset of ∼15,000 tritium events, roughly a factor of 100 larger than the number of expected ER background events in LUX.

II. Tritiated Methane Removal

CH_3T removal efficiency of zirconium getters had previously been studied at the University of Maryland. It was found that ..... [ATTILA'S PAPER]. Additionally, a table top gaseous xenon system was developed at the University of Maryland to examine the effects of residuals contamination after injecting CH_3T. It was found that a SAES MC1-905F methane purifier placed in series immediately after the CH_3T source bottle was required to prevent tritium from non-methane species from contaminating the plumbing. Using the result of these two studies, a small scale tritiated methane injection system was integrated into a liquid xenon system at the University of Maryland. After cumulatively injecting over 68,000 Bq of observed CH_3T we were able to achieve purification efficiencies ranging from 99.983% - 100%, with an average purification efficiency of 99.999% in our liquid experiments, where we define our purification efficiency to be

$$\text{Purification Efficiency} = 1 - \tfrac{A-B}{I-B},$$

where A is the background event rate after injecting CH_3T, B is the background event rate prior to injecting CH_3T, and I is the injected CH_3T activity as observed by out PMTs.

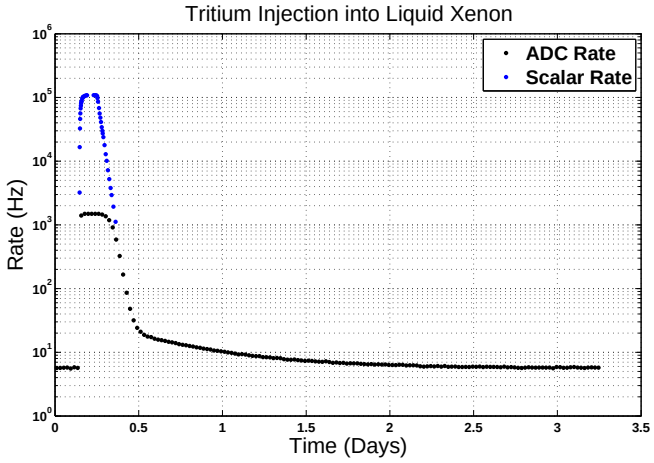

Figure 1: A time histogram of the event rate during a tritium injection into our small scale detector. The event rate greatly exceeded the limits of our ADC (black data points), so a analog scalar was used to count the true event rate (blue data points).

The liquid system was also used to study the effect of out gassing from plastics on the residual background rate after a CH_3T injection. We found that the addition of plastic curtains around our PMTs does not impair our ability to remove CH_3T at $> 99.998\%$ levels.

III. Simulations

Using Duhamel's priciple, the analytic solution to Fick's second law on a half-infite line is

$$\phi(x,t) = KC_{out} - \int_0^t erf(\frac{x}{\sqrt{4D(t-\tau)}})KC_{out}^{\cdot}(\tau)d\tau - KC_{out}(0)erf(\frac{x}{\sqrt{4Dt}}),$$

where K is the solubility of the material, D is the diffusion constant, and C_{out} is the outside concentration of the material. [?] For the out gassing process we are only able to detect the flux of material out of the plastic. This is given by Fick's first law evaluated at $x = 0$,

$$J_{out}(t) = -K\sqrt{\frac{D}{\pi}}(\int_0^t \frac{C_{out}^{\cdot}(\tau)}{\sqrt{t-\tau}}d\tau + \frac{C_{out}(t)}{\sqrt{t}}),$$

where the sign has been flipped since the flux of material is outward. We see that it is no longer possible to evaluate K and D separately, since the diffusion in and out of the plastic is completely determined by the time-dependent concentration outside of the plastic. To simplify our model, we define a new constant

$$G = K\sqrt{\frac{D}{\pi}}.$$

We can fit the integral of our equation for the flux out of the plastic over time to out gassing data collected in Maryland's liquid xenon system to extract a value for the constant G. With this method we constrain $G \leq 0.01\ \frac{cm}{\sqrt{day}}$.

A. Implications for LUX

With a constraint on G taken from the analytic solution to Fick's second law, we turn to numerical simulation to answer the question of how much initial CH_3T activity to inject into LUX to meet our calibration conditions. Several assumptions are made to simplify the numerical model. First, we approximate the diffusion into plastic as being a one dimensional process. Since the plastic in our detector at Maryland and in LUX can be approximated by a cylindrical shell, there is no dependence on the azimuthal or z coordinates. Since r is large compared to the thickness of the plastic shell, $\frac{\delta^2\phi}{\delta r^2} \gg \frac{1}{r}\frac{\delta\phi}{\delta r}$, so Fick's laws in a one dimensional

approximation become

$$J = -D\frac{\delta\phi}{\delta r}\vec{r}$$

$$\frac{\delta\phi}{\delta t} = D\frac{\delta^2\phi}{\delta r^2}.$$

We assume the concentration of CH_3T in LUX is uniform throughout its volume, since the design of LUX creates currents which stir the liquid xenon. With perfect mixing the effect of the purifier can be modeled by adding an exponential time dependence to the outer volume. The time constant of this decay has an upper limit equal to the time it takes xenon to recirculate through the LUX detector, although in reality the mass transport from diffusion in the liquid and gaseous xenon decreases this time constant.

We use a simple implementation of the first order Euler method for our numerical simulations. The diffusion is simulated by setting the concentration at the boundary of the piece equal to KC_{out}, where C_{out} is the concentration of CH_3T in the xenon. This concentration is dependent on time according to

$$\frac{\delta C_{out}}{\delta t} = J_{out}\frac{A_{plastic}}{V_{xenon}} - \frac{C_{out}}{\tau},$$

where $A_{plastic}$ is the surface area of the plastic cylinder, V_{xenon} is the total volume of xenon in the fiducial region, and τ is the time it takes for one full purification cycle. The first term on the right of this equation models out gassing of CH_3T from the plastic cylinder, while the second term models removal of CH_3T through purification. Using the first order Euler method, we arrive at an expression for C_{out} given by

$$C_{j+1} = C_j + \Delta t[(J_{1,j} - J_{N_x,j})\frac{A_{plastic}}{V_{xenon}} - \frac{C_j}{\tau}].$$

The initial concentration is defined by dividing the desired injection activity by the volume of the fiducial region. We choose $D = 2.3 \times 10^{-9}\frac{cm^2}{sec}$ so that the half-infinite boundary conditions in our diffusion model is valid, and combine this with our allowed range of values for G to extract a value for K. We use this model to predict the total number of calibration events as well as the time required to return to <5% of the nominal background rate for any CH_3T injection into LUX.

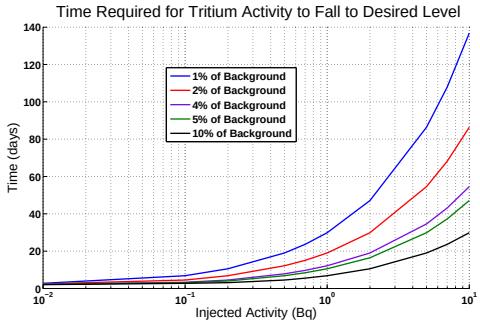

Figure 2: Time required to remove CH_3T from LUX after various injections.

IV. Experimental Setup

The setup of our triated methane calibration technique can be separated into three parts: the tritiated methane source bottle,the injection system, and the zirconium getter.

A. The tritiated methane source

The tritiated methane source bottle for our calibration technique consists of a 2250 cc stainless steel bottle which is filled with a mixture of tritiated methane and xenon. The purpose of this xenon is to serve as a carrier gas for the triaited methane. The total activity in the source bottle is set by mixing a small amount of tritiated methane from a reservoir into the source bottle via volume sharing.

B. The injection system

The injection system for our tritiated methane calibration technique consists of a series of expansion volumes which are used to fine tune the amount of CH_3T that is injected. Once the CH_3T source bottle is opened it flows through a methane gas purifier (SAES MC1-905F) to remove any sources of potential contamination, such as bare tritium. The CH_3T then flows into the expansions volumes set by the user. Once the expansion volumes have filled, the flow of xenon in the gas system is diverted through the expansion volumes to sweep the CH_3T into the detector. We continue to flow through the expansion volumes for one hour, which is equivalent to flushing out the expansion volumes over 1000 times, since LUX flows at 20 SLPM and the full 384.5 cc of the expansion volumes are filled with 1590 torr of the xenon and CH_3T mixture. A pump out port allows the expansion volumes to be evacuated in preparation for each use of the injection system. Note that each injection will lower the total activity in the CH_3T source bottle via volume sharing, results in a smaller, yet calculable, injection activity with subsequent injections.

C. The zirconium getter

The LUX gas system uses a hot zirconium getter (SAES-PS4MT15R1) downstream of the CH_3T injection system to remove CH_3T from the xenon. Extensive R&D was conducted using a smaller zirconium getter (SAES-PF4C3R1) at the University of Maryland to learn about the CH_3T removal efficiency of these purifiers. Details of these studies is discussed in section II.

V. Injection Strategy

The LUX collaboration agreed upon a three phase plan for a safe and successful tritium injection. The first phase of this plan was a natural methane injection using the tritiated methane injection system for the purpose of determining the purification time constant in LUX. The second phase of the plan was a small tritium injection into LUX. This small injection would highlight any potential problems before injecting a larger amount of tritium, and it would determine if any scaling factor was needed between the absolute injection activity and the observed injection activity. Additionally, the small tritium injection would allow us to measure the fraction of tritium that goes into the fiducial volume. Finally, the third phase of the plan was to use what we learned from the first two phases to safely inject a larger amount of tritium for the purpose of measuring the ER rejection factor of LUX and cross-checking the NEST prediction of the ER band.

A. Phase One

During phase one 0.02 grams of natural methane were injected into LUX using the tritium injection system. Purity samples from the detector were collected over the next few days, and a purification time constant of 5.90 ± 0.07 hours was determined using data collected with the LUX gas sampling system.

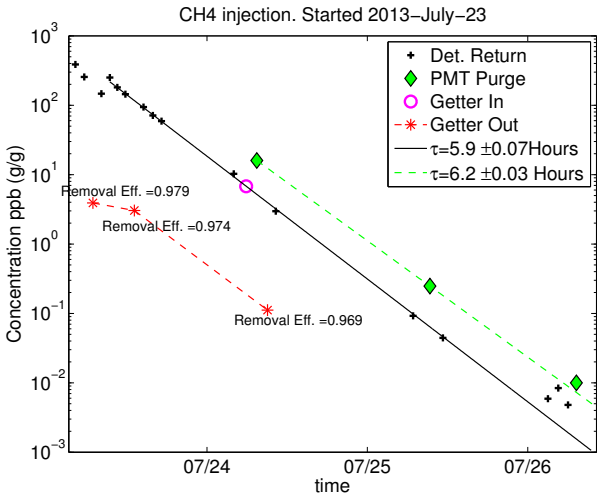

Figure 3: Removal of natural methane observed by the xenon sampling system prior to the tritiated methane injections.

B. Phase Two and Three

The first, smaller tritiated methane injection on Aug-08-2013 was done to confirm the purification model established by a natural methane purification campaign the previous week. An absolute activity of 20 mBq of tritiated methane was injected, while actively purifying. A purification time constant of 6.7 hours was observed, consistent with the natural methane purification rate measured by the sampling system. After a day of circulating through the getter the tritium decay had fallen below detectable amounts confirming the effective removal of the tritiated methane with the getter. On Aug-13-2013 a larger injection of 800 mBq was performed. The second injection produced 20,000 beta decay events in the LUX detector before being completely removed, 5000 of those events could be used the calibrate the ER band in the WIMP search region of 0-30 Phe (pulse area in photo electrons). Figure 7 shows the two tritium injections and the subsequent CH3T purification. Figure 5 shows the rate of events in the ER band before and after the tritium injection and removal. The CH3T was injected at the getter output but had passed through a special methane purifier to remove O2 and H2O or other impurities that could cause a degradation in election lifetime. The injections were performed with the getter in purify mode to maintain detector purity, as soon as the CH3T was injected is was immediately being removed. The rate of tritiated methane removal was consistent with the removal of natural methane observed by the xenon sampling system which was used to first verify the removal of methane to $1/10^5$. Figure 7.

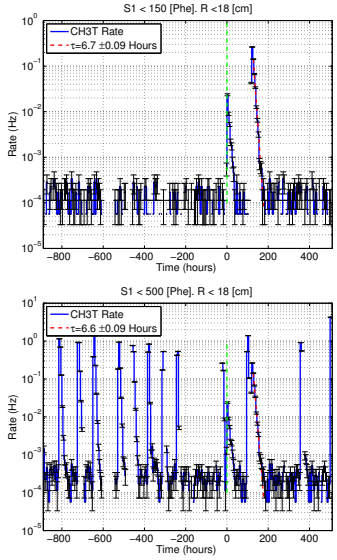

Figure 4: Left: Rate of events in the WIMP search region over a two month window. The dashed, vertical green line represents the time of the fist tritiated methane injection. Right: The S1 threshold extended to 500 Phe to include rate spikes from the ^{83}Kr injections, used for detector calibration during the science run.

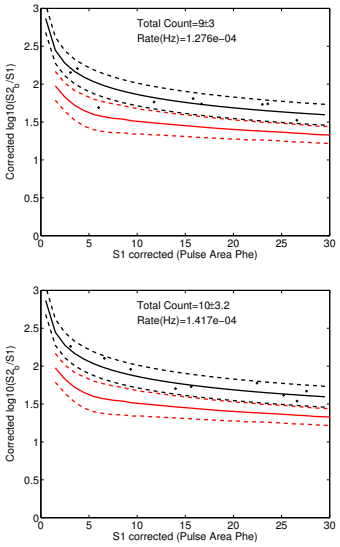

Figure 5: Left: 100 Hour time window in the WIMP search region before the tritiated methane injection. Right: 100 Hour time window in the WIMP search region after the purification of the tritiated methane.

VI. Results from the Tritiated Methane Calibration

A. Tritium as a Calibration Source

Due to the self shielding properties of liquid xenon it is virtually impossible to perform a low energy electronic recoil (ER) calibration within the fiducial volume of a +100 kg detector using an external source. The fiducial volume of the LUX detector is surrounded by more than than 6 [cm] of liquid xenon providing excellent shielding from both external backgrounds and calibration sources. For example, a 100 keV gamma has a mean free path of about 2 [mm] in liquid xenon and would require thirty mean free paths to penetrate into the fiducial volume. A higher energy source such as ^{137}Cs (662 keV) has a longer mean free path of 4 cm however, the probability of a low energy deposit from forward scattering is greatly suppressed. Further, calibrating within the fiducial volume by relying on gammas from an external source to forward scatter brings along systematic uncertainties from high energy deposits near the edge, DAQ rate and having to use multi scatter event selection instead of a standard set of single scatter WIMP search cuts. An ideal ER calibration source for current and next generation noble gas detectors should consist of single scatter events depositing sub 10 keV energies uniformly distributed in the fiducial region. These requirements are all satisfied by tritium beta decay. With a Q value of 18.6 keV, peaked at 2.5 keV, tritium is an ideal internal calibration source as long as it can removed after calibration [ref]. To mitigate the effect of hydrogen diffusion into plastics, [link], we use tritiated methane instead of just tritium. The tritium atom is bound to the methane molecule lessening its diffusion into detector internals [described in sections] also, the molecular bond does not impact the nuclear physics of the tritium beta decay [ref]. We have studied the removal of methane by the commonly used SAES heated zirconium getter and found that significant amounts of methane can be removed from xenon at flow rates commonly employed in large scale liquid xenon experiments[Purifier paper].

In an experimental setup at UMD it was demonstrated that tritiated methane can be injected directly into a liquid xenon vessel containing plastics and removed [link section in this paper]. This new calibration source provided an unprecedented low energy electronic recoil calibration for the LUX dark matter search [PRL Ref]. Two tritiated methane injections were conducted at the end of the LUX science run in August 2013. First, a smaller injection was done to confirm the purification model established by observing the removal of natural methane from the LUX detector to ppt (parts per trillion g/g) levels using an

integrated xenon gas sampling system [Ref sampling and EXO results, paper to come]. An absolute activity of 20 mBq of tritiated methane was injected into the liquid volume at the purifier's outlet while circulating. A methane removal time constant of 6.7 hours was observed, consistent with the natural methane purification rate measured by the sampling system, 7 and 8. After a day of circulating through the getter the tritium rate had fallen below levels amounts confirming the effective removal of the tritiated methane with the getter. A second, larger injection of 800 mBq was performed a week later yielding a similar removal time constant. The second injection produced 20,000 beta decays in the LUX detector before being completely removed, 7000 of those decays were in the fiducial volume and could be used the calibrate the ER band in the WIMP search region of 1-50 Phe (about 1-7 keVee). The CH_3T (tritiated methane) was injected at the getter output and had passed through a special methane purifier to remove O_2, H_2O and other electronegative impurities that could cause a degradation in election lifetime. The injections were performed while circulating and with the getter actively purifying in order maintain detector purity and stability. Prior to LUX detector upgrades in December of 2013 a total of 10 Bq of tritiated methane was injected into the LUX detector and successfully removed providing over 150,000 beta decays within the fiducial volume.

B. Mixing of Tritiated Methane in Liquid Xenon

Tritium events appear uniformly distributed in the liquid volume thirty minutes after injecting the tritiated methane inline with the xenon gas circulation path. Figure 6 shows the XY and Z distribution of tritium events thirty minutes after an injection. The events shown cover the region from the gate to the cathode and radially out to the edge of the detector [LUX diagram? probably not needed]. An additional cut requiring that the event be between $\pm 3\sigma$ of the ER mean was made to minimize the leakage of residual alphas from the walls and cathode, though the event rate consisted overwhelmingly of tritium events. The tritiated methane dispersed uniformly throughout the liquid decaying in all regions on the detector. Uniform mixing of the tritiated methane within the liquid xenon volume is crucial for minimizing systematic uncertainties assisted with such a calibration.

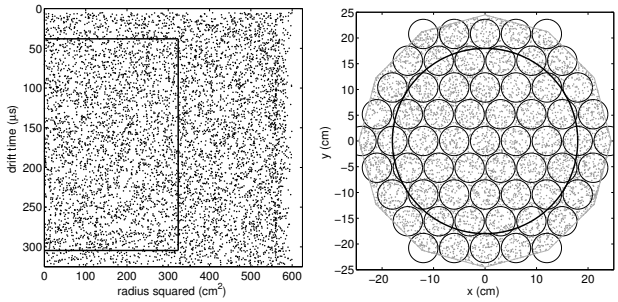

Figure 6: Left: The distribution of tritium events vs. detector radius squared. The solid black line represents the fiducial volume. Right: The distribution of tritium events vs. XY in the region between the gate and the cathode. The solid black line represents the fiducial volume and the black circles represent the locations of PMTs (photo multiplier tubes).

C. Definition of Electronic Recoil Band and Comparison with NEST Model

Using the tritium calibration source we have calibrated the electronic recoil band in the fiducial volume of the LUX detector to unprecedented accuracy. Figure 9 shows the measurement of the ER band along with the 90% confidence bounds obtained from the beta decay of tritium in comparison to the NEST simulation predictions at an extraction field of 180 V/cm

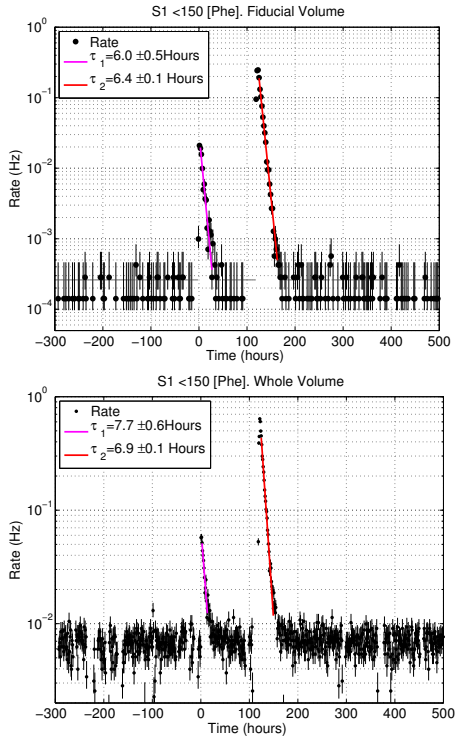

Figure 7: Left: Rate of single scatter events with S1 below 150 Phe in the fiducial volume. 150 Phe in S1 is about 18.6 keVee, the endpoint to the tritium beta spectrum. The magenta and red curves are fits to the first and second tritium injection's removal rate. Right: The rate of single scatter events with S1 below 150 for the whole detector volume. Note the removal of tritiated methane is consistent with the natural methane removal rate measured independently.

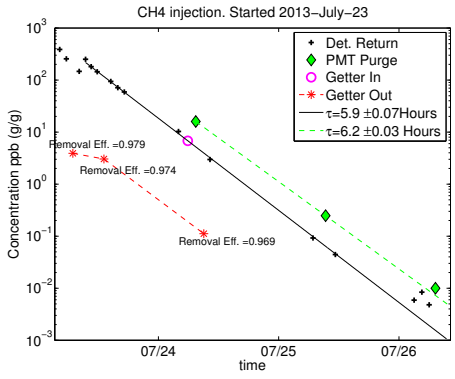

Figure 8: Removal of natural methane observed by the integrated xenon sampling system prior to the tritiated methane injections.

[ref to NEST]. The results of the leakage fraction per 2 Phe bins in S1 are also shown.

WIMPs primarily interact with the atomic nuclei xenon atoms in LUX causing nuclear recoils whereas the vast majority of residual radioactivity within the detector are gammas which result in electronic recoils. Thus, knowing the separation of the ER from the NR band allows for a measure of the background rejection of a liquid xenon WIMP search experiment. We define the measure of background rejection as leakage fraction, reported here as the fraction of events in the ER band that spill into the lower half of the NR band. Over 115,000 tritium decays were used for the ER band calibration, between 1-50 Phe in S1, and were found using standard WIMP search cuts within the fiducial volume. Two methods are used to calculate the leakage fraction in figure 9 . First a simple cut and count, the number of tritium events populating the lower half of the NR band are compared to the total number of tritium events in the selected S1 range. Second, assuming a Gaussian distribution of the ER and NR bands vs. S1 we calculate the overlap. Both methods are in good agreement which indicated that the distribution of ER events vs. S1 (primary scintillation Phe) is mostly Gaussian. Figure 9 shows the leakage fraction per 2 Phe bins in S1. The mean leakage fraction between 1-50 Phe (1-7 $\mathrm{keV_{ee}}$) in the fiducial region was found to be 0.50% $\pm$ 0.02%, see Figure 9. In this case the simple cut and count method is the most accurate measure of leakage since less than three out of 115,000 events are

expected to be non tritium in figure 9. [BG paper reference]. The NR band used is from NEST version 4c and is vetted with AmBe, ^{252}Cf and DD neutron generator calibrations.

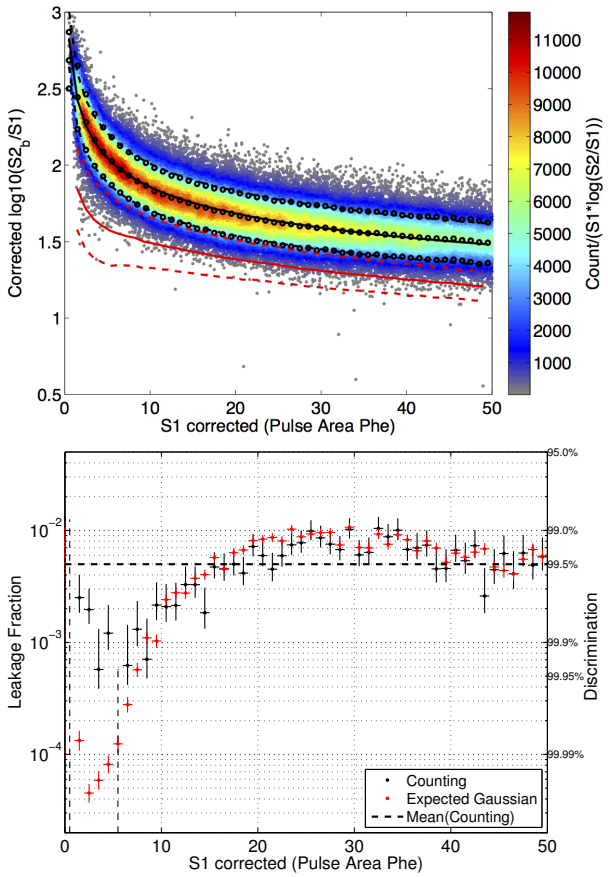

Figure 9: Discrimination vs. S1 using over 115,000 tritium beta decays between 1 and 50 Phe in S1 (about 1-7 keV). On average from 1 to 50 Phe the discrimination is 99.50%, defined by the number of events of events below the mean of the nuclear recoil band. The red band represents the NEST nuclear recoil band (version 4c) vetted with an AmBe, ^{252}Cf and DD neutron generator calibration.

Figure 10 shows the comparison between simulation(NEST) and the data for the ER band. The agreement between simulation and data is good down to 7 Phe in S1. This is expected since at sub 2 keVee (7 Phe in S1) data is limited and the NEST model has yet to be vetted at such low energies[Matthew/ Erik Dahl Thesis]. The newly acquired ER data below 2 keVee from tritium will be used improve upon the NEST model at the extration field of 180 V/cm [ref?].

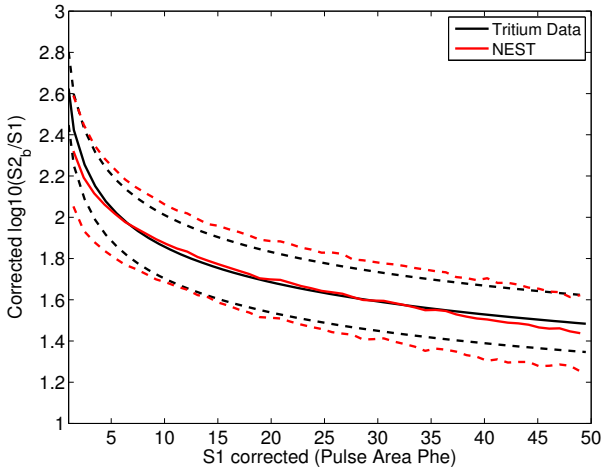

Figure 10: ER band measured using tritium data in black with 90% confidence bounds ($\pm 1.3\sigma$) compared with the NEST prediction in red.

D. Threshold Determination

The tritiated methane calibration source can also be used to determine detector efficiency for both S1 (primary scintillation) and S2 (secondary scintillation) down to sub 1 keV electronic recoils.The ultimate limitation of single scatter event is typically the S1 since the signal size of the S1 is one to three orders of magnitude less than the S2. We measured the threshold by comparing the NEST model of a tritium beta spectrum to the data, we find good agreement to

the threshold determined from LED calibration, figure 11(need to add to plot). The threshold for the S2 (bottom PMT array) shown is entirely due to the S1 threshold. We use only the bottom PMT array for the S2 signal because the secondary scintillation light is more uniformly distributed along the bottom PMTs than the top PMTs. Figure 12 shows the tritium beta spectrum measured in the LUX detector along with the NEST prediction, note at the 180 V/cm drift field NEST has been vetted form 2 to 10 keVee.

VII. Scintillation Yield and Ionization Yield from Tritium Beta Decay

Scintillation and ionization yield are measured using the tritiated methane calibration source from the S1, S2 and reconstructed energy of each beta decay. The energy of each decay is determined using a prescription described in [Erik Dahl], see equations 1 and 2.

$$\begin{aligned} n_\gamma &= \frac{S1}{g1} \\ n_{e^-} &= \frac{S2}{g2} \end{aligned} \tag{1}$$

$$\begin{aligned} E &= \frac{1}{W}(n_\gamma + n_{e^-}) \\ E &= \frac{1}{W}(\frac{S1}{g1} + \frac{S2}{g2}) \end{aligned} \tag{2}$$

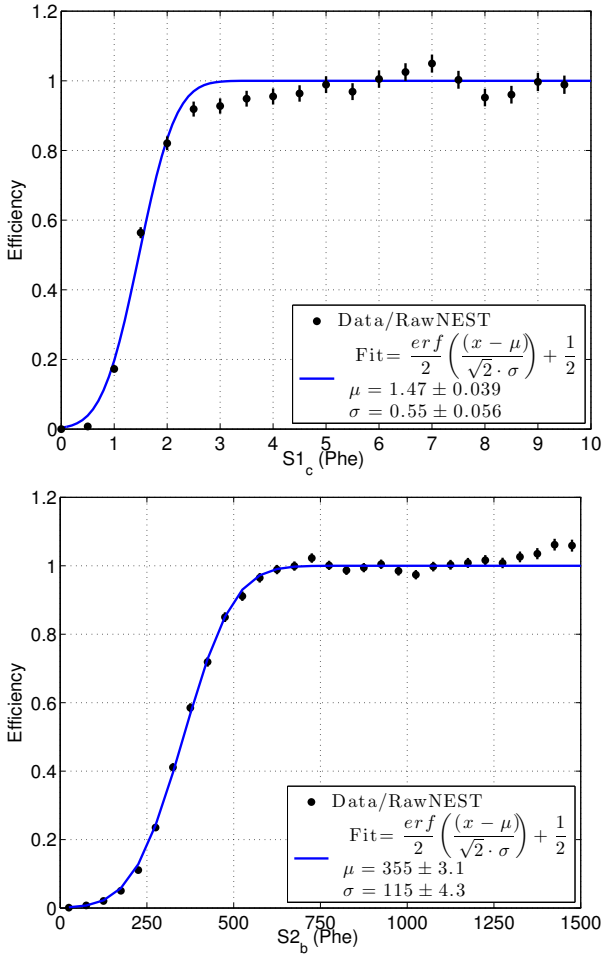

Figure 11: S1 Threshold determined from Tritium. S2 Threshold determined from Tritium.

The values of the work function W and gains g1, g2 have been measured using other calibration sources and are energy independent [ref]. Using equations 1 and 2 we calculate the number of photons and electrons along with the energy of each tritium beta decay event to determine the yields. Scintillation and ionization yield are defined as [Photons/keV] and [Electrons/keV] respectively and the tritiated methane calibration source provides betas ranging from >1 to 18 keV, with an exponential decline in event rate above 5 keV. For the results shown in figure 13 over 150,000 beta decays in the fiducial volume were used to measure scintillation and ionization yield at 180 [V/cm]. A correction was applied for the beta spectral shape and the finite resolution of S1, S2 when measuring ionization and scintillation yield, the correction was found to be less than 10% and is described in [my thesis]. Figure 13 also shows the comparison of the

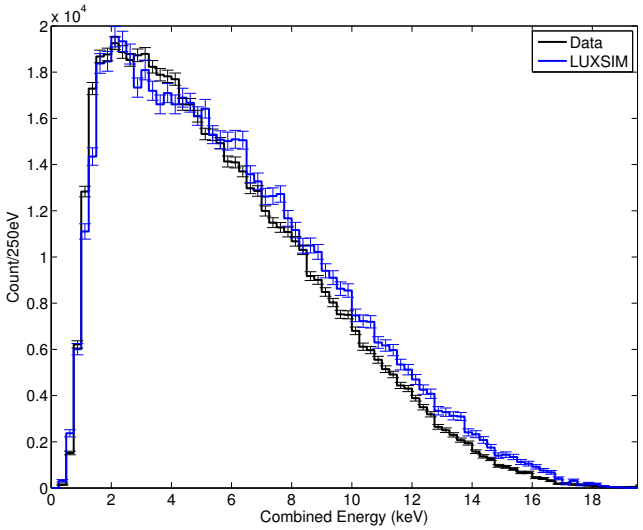

Figure 12: Combined energy spectrum of the tritium data and LUX SIM.

results with the NEST model which has been vetted between 2 and 10 keVee. Also show are the measurements of light yield from a ^{83m}Kr source, the 32.1 keV decay from ^{83m}Kr is typically used as a standard calibration. (The second 9.4 keV decay from ^{83m}Kr shown in the figure is for decays that occur more than 1000 ns after the initial 32.1 keV decay).

We find good agreement with the NEST model in the regions that have been vetted (2-10 keVee), see figure 13. Below 2 keVee the light yield is lower than predicted by NEST and the charge yield is higher. The discrepancy between the data and the NEST model above 10 keVee is due to limited data available for the model and also due to the track lengths of betas and gammas beginning to deviate above this energy. Note, under 10 keVee track lengths of betas gammas are nearly identical.

Figure 14 includes our light and charge yield measurements at 100 and 180 V/cm along with the recent Compton scattering measurement down to 1.5 keVee from [Baudis] at 450 V/cm. The error bars show in the figure include uncertainties from W, g1, g2 and the spectral shape correction. Unlike the measurement made using Compton scattering we can reconstruct energy using both the light and charge channels for each decay allowing for a powerful calibration down to 1 keVee (corresponding to 80% threshold at 2 Phe in S1). We find a lower light yield than the centroids of the measurements in [ref Budias], however the the measurement is within reported errors. At our lower fields a higher light yield is expected than that measured at 450 V/cm due to less free charge separation. The light yield of the 32.1 keV gamma from ^{83m}Kr is shown on the figure as a measure of systematic uncertainty between the experiments. For the case of the standardized ^{83m}Kr calibration source we find the expected behavior between the two experiments, a higher extraction field leads to lower light yield.

VIII. All the things we can do with Tritium

- Define the ER band.
- Binned leakage fraction, and potentially optimize for spacial dependent leakage fraction in XYZ plane.
- S1, S2 threshold. (Energy is a bit convoluted let's not go there). Requires NEST
- Combined energy calibration to about 0.5 keVee. Requires NEST
- Light Yield, Charge Yield. Requires some trivial smearing model, 10% effect.
- Fano-like factor vs. energy. Requires some trivial smearing model, sub 2% effect.

- Fiducial mass calculation, optimized for low energy S2s making it more WIMP like.
- g1 and g2 calculation by competing tritium spectrum with NEST, or multiple E fields
- ER band Gaussianity.
- ... anything else?

IX. Summary

We have presented our new technique for injecting and removing CH_3T as an internal calibration source in detectors which utilize liquid and gas phase noble gases. We discussed the assembly of our CH_3T calibration system, motivated by gas and liquid phase R&D experiments at the University of Maryland. We have used data from the LUX detector to show that our system can safely inject CH_3T for the purpose of internal calibration.

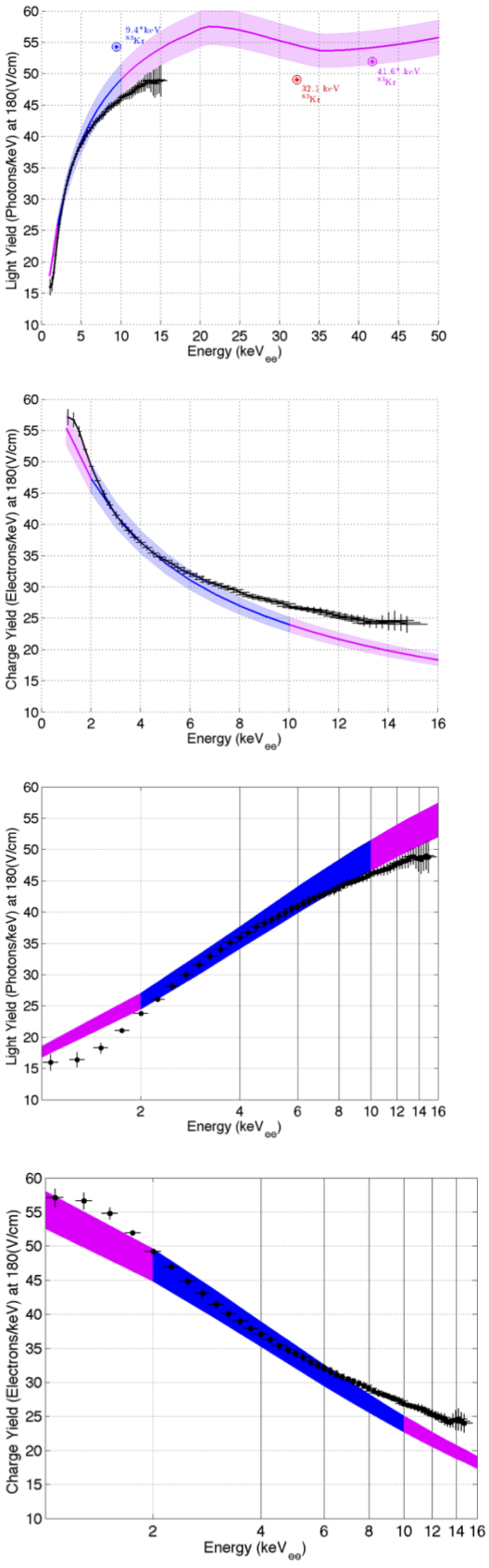

Figure 13: 180 [V/cm], corrected for spectral shape. Top Left: Mean scintillation yield vs. combined energy using tritium beta decay (black line). ^{83}Kr lines

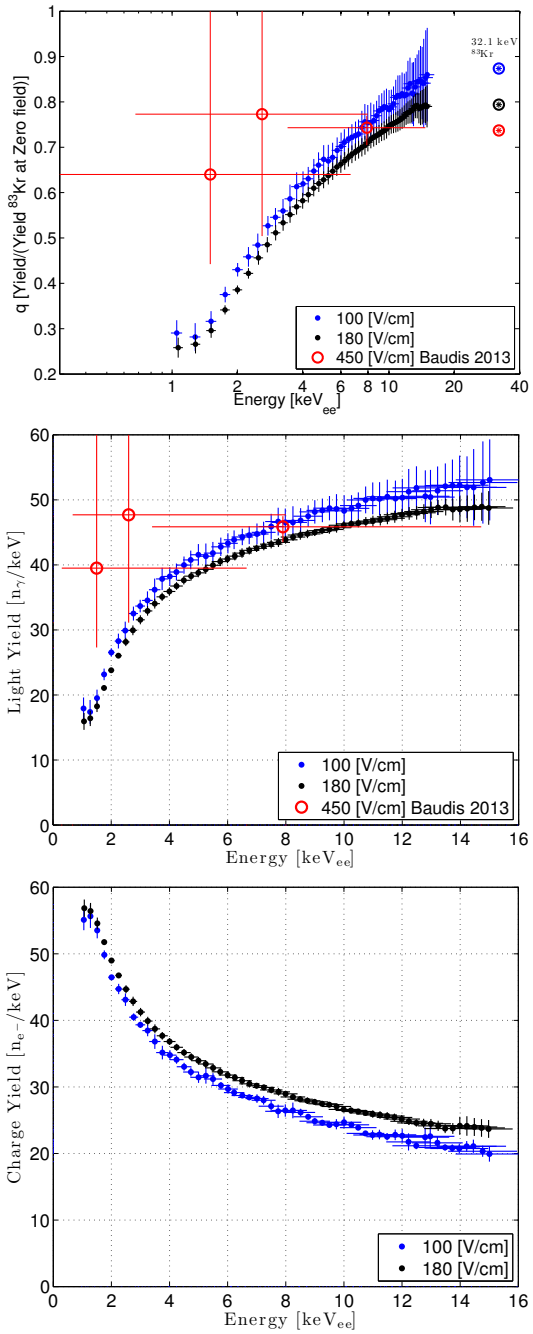

Figure 14: Top: Scintillation yield relative to the yield of the 32.1 gamma of [keV] ^{83}Kr vs. Energy. Shaded blue curve is tritium at 100 [V/cm], shaded black curve is tritium at 180 [V/cm], red points represent a recent Compton scattering measurement at 450 [V/cm]. Also shown are the corresponding quenching of the 32.1 [keV] gamma of ^{83}Kr (star inside circle). Bottom: scintillation yield [Photons/keV] vs. Energy. Shaded blue curve is tritium at 100 [V/cm], shaded black curve is tritium at 180 [V/cm], red circles represent a recent Compton scattering measurement at 450 [V/cm].