Determining the Significance of Cobalt-60 in EXO-200

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Abstract

Neutrinos were first proposed by Wolfgang Pauli as a mechanism to conserve energy, momentum, and angular momentum in beta decay. These "little neutral ones" have a very low cross section and a mean free path of about a third of a light-year in solid lead, making them particularly challenging to study and explore. The discovery of neutrino oscillations confirmed that neutrinos have mass, but shed little light on the absolute mass of the particles. The question of neutrino mass, along with a fundamental question about whether or not the neutrino is a Majorana particle that behaves as its own antiparticle, serves as the motivation for the EXO-200 detector. This detector, located 2150 feet underground in Carlsbad, NM, seeks to answer both of these questions by searching for the theorized neutrinoless double beta decay ($0\nu\beta\beta$) of ^{136}Xe. Because of the rarity of these decay events, the EXO-200 collaboration has made every effort to reduce radioactive backgrounds, especially within the energy band where $0\nu\beta\beta$ would be seen. It is not possible, however, to eliminate all background contaminants. EXO-200 is constructed almost entirely of copper which is susceptible to producing ^{60}Co, a radioactive isotope that decays with a half-life of 5.27 years and which creates events near the $0\nu\beta\beta$ energy window. Through simulations and employing maximum likelihood fitting, I have explored the contribution of ^{60}Co to background noise within the region of interest for $0\nu\beta\beta$.

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Neutrinos were first proposed by Wolfgang Pauli as a mechanism to conserve energy, momentum, and angular momentum in beta decay. These "little neutral ones" have a very low cross section and a mean free path of about a third of a light-year in solid lead, making them particularly challenging to study and explore. The discovery of neutrino oscillations confirmed that neutrinos have mass, but shed little light on the absolute mass of the particles. The question of neutrino mass, along with a fundamental question about whether or not the neutrino is a Majorana particle that behaves as its own antiparticle, serves as the motivation for the EXO-200 detector. This detector, located 2150 feet underground in Carlsbad, NM, seeks to answer both of these questions by searching for the theorized neutrinoless double beta decay of ^{136}Xe. Because of the rarity of these decay events, the EXO-200 collaboration has made every effort to reduce radioactive backgrounds, especially within the energy band where $0\bar{\nu}\beta\beta$ would be seen. It is not possible, however, to eliminate all background contaminants. EXO-200 is constructed almost entirely of copper which is susceptible to producing ^{60}Co, a radioactive isotope that decays with a half-life of 5.27 years and which creates events near the $0\bar{\nu}\beta\beta$ energy window. Through simulations and employing maximum likelihood fitting, I have explored the contribution of ^{60}Co to background noise within the region of interest for $0\bar{\nu}\beta\beta$.

I. BACKGROUND

I.1. An Introduction to Neutrino Physics

Neutrinos were first postulated in 1930 by Wolfgang Pauli to explain conservation of energy, momentum, and angular momentum in beta decay. When they were eventually observed by Frederick Reines, they were thought to have no mass[1]. Neutrinos are neutral leptons that come in three flavors, electron, muon, or tau-neutrino, depending on which charged lepton is simultaneously created with it. It was discovered that neutrinos oscillate between these different flavors and this is only possible if they have mass, even if it is small. Although neutrino oscillation was a big breakthrough in neutrino physics, it gave no measure of absolute mass, only the mass differences of the three neutrino mass eigenstates. Experimentally meausuring the absolute mass is difficult, however, because these particles interact solely through the weak and gravitational forces and, thus, have very small cross sections[2].

Additionally, there is an important question regarding the fundamental nature of the neutrino. According to the standard model, all matter particles have corresponding antiparticles that have equal mass and opposite charge. When a particle and its respective antiparticle collide, they annihilate one another. These particles are called Dirac particles[2]. In the 1930s, Ettore Majorana developed an alternative theory in which particles can act as their own antiparticles. Although these Majorana particles have never been experimentally observed, the charge-free neutrino poses as a prime candidate. This question, along with the ambiguity regarding neutrino mass, has motivated many experiments, worldwide, that probe the characteristics of neutrinos.

I.2. Double Beta Decay

The neutrino was first theorized as a way to reconcile what seemed to be energy and momentum loss during beta decay. In standard beta decay, a neutron becomes a proton and emits an electron and an electron antineutrino as shown in equation 1.

$$n \to p + e^- + \bar{\nu}_e \tag{1}$$

Additionally, there is a beta plus decay process which instead converts a proton bound inside a nucleus into a neutron by emitting a positron and an electron neutrino as shown in equation 2.

$$p \to n + e^+ + \nu_e \tag{2}$$

However, several nuclei are stable against ordinary beta decay but, instead, experience double beta decay in which two neutrons are simultaneously changed into protons. The general form of this decay can be seen in equation 3.

$$n + n \to p + p + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e \tag{3}$$

There are many isotopes predicted to exhibit this kind of decay and the mechanism is explained by the standard model. Two-neutrino double beta decay ($2\bar{\nu}\beta\beta$) has been observed for 12 isotopes including, most recently, ^{136}Xe. These reactions constitute the rarest type of radioactive processes and ^{136}Xe was found to have a half life of $2.11 \pm 0.04(stat) \pm 0.21(syst) \times 10^{21} yr$ [1].

There are still other hypothetical decay modes such as neutrinoless double beta decay ($0\bar{\nu}\beta\beta$) in which two neutrons are changed into protons without the emission of electron antineutrinos. Unlike $2\bar{\nu}\beta\beta$, the neutrinoless beta decay reaction violates standard model predictions because it does not conserve lepton number[1]. In $2\bar{\nu}\beta\beta$, the two electrons produced each have a lepton number 1, but they are canceled out by the two electron antineutrinos which each have lepton number -1. In $0\bar{\nu}\beta\beta$, the electrons are produced, but there are no antineutrinos, so there is a net change in lepton number of +2. In addition to that surprising prediction, this process is particularly interesting because it would mean that neutrinos are massive Majorana particles.

To understand the connection between mass and $0\bar{\nu}\beta\beta$ one must consider the idea of handedness. An experiment carried out by Maurice Goldhaber in 1957 showed that neutrinos are always produced as left-handed particles. This means that their momentum and spin are oriented in different directions [2]. This handedness, however, is not absolute. If an observer was traveling behind a neutrino, they could observe the neutrino traveling away from them and the spin traveling towards them. If that observer then overtakes the neutrino, the spin and the momentum will be traveling away from the observer. The only way to prevent this swapping is for the neutrino to be massless because relativity would dictate that the neutrino move at the speed of light. Under this condition, nothing could overtake it and, therefore, the handedness could not change.

For $0\bar{\nu}\beta\beta$ to be possible, however, the two emitted neutrinos must annihilate each other. This means that a neutrino emitted with a certain handedness must be reabsorbed with the opposite handedness. For this to happen, the neutrino must move slower than the speed of light so it can be overtaken by the second neutrino. This implies that neutrinos must have mass. Therefore, the $0\bar{\nu}\beta\beta$ decay rate is essentially a measure of mass, with a higher rate correlating to more neutrinos being overtaken and, therefore, a higher absolute neutrino mass[3].

I.3. EXO-200

The Enriched Xenon Observatory (EXO) is an experiment designed to search for $0\bar{\nu}\beta\beta$ of ^{136}Xe. The 200 in its name comes from the 200 kg of liquid xenon that fills the vessel, creating an active mass of 110 kg of xenon that has been enriched to be 80.6% ^{136}Xe [4]. ^{136}Xe was selected for this detector because it has a high Q-value for $0\bar{\nu}\beta\beta$ that is conveniently located in a region with very few natural radioactive backgrounds which would easily overpower the rare $0\bar{\nu}\beta\beta$ decays. Additionally, ^{136}Xe can be enriched relatively easily, allowing for a more efficient detector [4].

The detector, shown in Figure 1, consists of a time projection chamber (TPC) filled with liquid xenon (LXe). The TPC is a copper cylinder with a cathode grid running through the center, dividing the detector into two equal cylinders. The cathode sets up an electric field in the detector that will cause charged particles in the detector to drift towards the ends of the cylinder. At each end of the cylinder there are two wire grids that allow for a two dimmensional localization of the nuclear recoil events in the detector and measures the energy of the charge deposited on the wires [1]. The radiation depositing energy within the TPC create two different kinds of signals. The first is a scintillation signal that is detected almost instantaneously by photodiodes located at the ends of the cylinder. The second is the ionized particles detected on the crossed wire planes. The third dimensional component of the event can then be reconstructed using the time difference between these two detections and the drift velocity of charged particles in the electric field within the TPC [4].

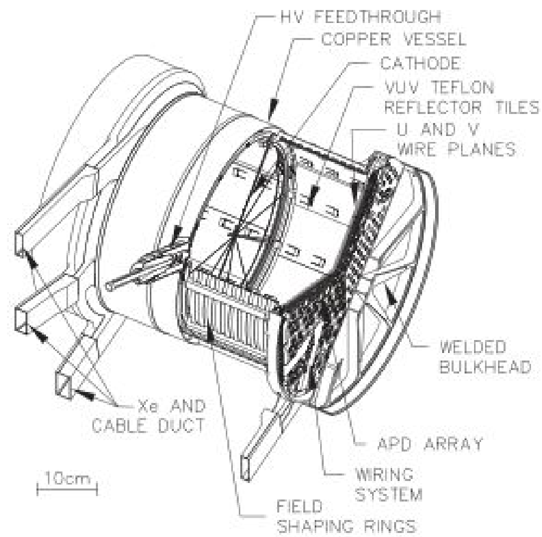

FIG. 1. The design for the TPC used in EXO 200 [1].

EXO can discriminate between $2\bar{\nu}\beta\beta$ and $0\bar{\nu}\beta\beta$ decays by examining the energy spectra produced by these processes. The energy spectrum for $2\bar{\nu}\beta\beta$ is characterized by a broad energy distribution around 1200 keV. This spread of energies is caused by the neutrinos carring away different amounts of energy as they escape from the nucleus. In contrast, the $0\bar{\nu}\beta\beta$ decays should exhibit a sharp energy peak located at 2458 keV [1]. The necessity to differentiate between these types of events means that good energy resolution is essential to EXO's design.

Additionally, EXO can discriminate between multi-site and single-site events. When β particles are ejected from a nucleus, they cannot travel very far before interacting because of their charge. Therefore, most of their energy will be deposited in one location. These kinds of decays are called single-site events. Multi-site events result from γ scattering. When γ rays are ejected from a nucleus, they can move centimeters before interacting with atomic electrons. These interactions change the direction of the γ rays and they scatter off until interacting with another electron. This process continues until the γ ray deposits all of its remaining energy into an electron. A large majority of $0\bar{\nu}\beta\beta$ events will cause single-site detections.

Finally, EXO is maximized to have the lowest possible backgrounds and highest possible energy resolution in the energy region surrounding $0\bar{\nu}\beta\beta$ decays. Very low background levels were acheived by many measures including intentionally selecting construction materials with very low radioactivity rates, carefully cleaning and storing components before assembly, and building the detector in increasingly clean shielding layers. Finally, all of this is housed 2150 ft underground in the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. All of these precautions, combined, are meant to limit the background within a 2 σ energy window around $Q_{\beta\beta}$ to 33 single-site events/y in the 110 kg active mass of LXe [4].

I.4. ^{60}Co Contamination in EXO-200

Although great care is taken to use constuction materials with low radioactivity, these materials can still contribute to backround signals within the region of interest. One of these possible contaminants is ^{60}Co. ^{60}Co is a radioactive isotope that decays with a half-life of 5.27 years. This half-life is short when compared to the age of the Earth and, therefore, any ^{60}Co that is present today has been created through other processes. One possible path is through cosmogenic activation. The majority of the EXO detector is made of copper which, when exposed to cosmic radiation at the surface of the earth, has the potential to produce ^{60}Co.

Even though the experiment is housed underground, the copper used in the EXO TPC components spends about 20 days at sea level during the rolling process and was transported by sea to the US in a 45 day journey [4]. In this time, cosmic-ray activation converted some copper into radioactive ^{60}Co. ^{60}Co decays to ^{60}Ni via beta decay and gamma decay within the region of interest, making it an important background to monitor. This can be seen in Figure 2 which shows different background contributions, including ^{60}Co within the region of interest.

There are conflicting reports regarding the significance ^{60}Co's contribution to the $0\bar{\nu}\beta\beta$ region of interest. Because of the relatively long half life, it is difficult to tell if there is a significant ^{60}Co signal, or if all decays in the $0\bar{\nu}\beta\beta$ region are caused by other background noise.

It is important to have some way of checking the predicted rate of ^{60}Co decays for two reasons. First, knowing the actual ^{60}Co decay rate can constrain the model used in simulations. The models used to create predictions like the one in Figure 2 are complicated and have many floating variables. Determining one variable serves to refine the predictions for all of the other variables. Secondly, determining the significance of ^{60}Co can serve as an independent check of the EXO energy resolution. For example, if the contribution from ^{60}Co was determined to be much smaller than the predicted value, our data would be called into question. The multisite data from the first few months of running clearly shows a peak in the ^{60}Co energy region. If these decays are not actually coming from ^{60}Co decays, then it is would be reasonable to suspect that there could be an issue in the energy resolution and that these decays should actually be part of the 2615 keV peak due to the decay of ^{208}Tl. On the other hand, agreement between sensitivity study results and the predicted levels of ^{60}Co lends confidence to EXO's energy resoltion.

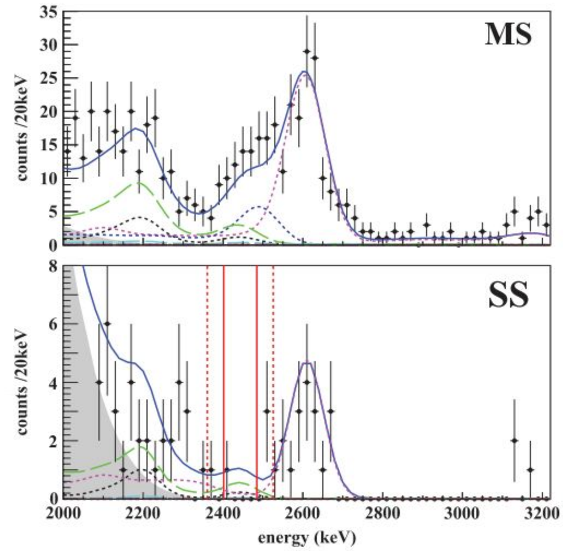

FIG. 2. Energy spectra in the $^{136}Xe\,Q_{\beta\beta}$ region of interest. The blue line indicates the fit for the total background signal. The dashed purple line indicated the fitted contribution corresponding to ^{60}Co. The vertical red lines indicate the region of interest. The top plot shows the predictions for multi-site events, while the bottom plot shows the predictions for single-site events. [3]

I have employed Maximum Likelihood fitting and Monte Carlo simulations in order to determine what the expected sensitivity should be after one year and four years of data collection. This technique is particularly useful because it will use an indepedent method to determine the contribution of ^{60}Co. Whereas the original ^{60}Co fraction was produced by integrating over all time and looking at an energy spectra, my results come from studying the time spectra integrated over a small range of energies. Furthermore, the simulations used in my sensitivity study are independent of any particular data set. This independent verification can lend confidence to that data that EXO has collected in the past year.

II. METHODS

II.1. Maximum Likelihood Fitting

Maximum likelihood (ML) fitting is a fitting method that can be applied to any data set with a known probability density function. ML fitting is much more flexible than other fitting methods such as least-squares (LS) fitting and its computations are based on each individual measured event, as opposed to binned data from a histogram [5]. This gives ML fitting two main advantages over LS fitting. First, in low-statistics experiments, LS fitting becomes dubious because there will not be enough data to ensure Gaussian statistics for each of the histogram bins. Secondly, this act of binning fundamentally leads to a loss of information because the fit is based on data that fits within ranges defined by the histogram bin size, as opposed to individual event measurements. This is particularly important if different measurements follow different probability density functions (PDF)[5]. The PDF describes the behavior that you expect to see present in that data (i.e. exponetial distributions for nuclear decays or flat distributions for background contributions for long lifetime isotopes). In order to use ML fitting, the PDF must be known. In the case of determining the significance of the ^{60}Co signal in EXO-200, this method is clearly superior because of the limited number of decay events and because of the well defined PDF.

In order to employ ML fitting, you begin with a set of N data points that correspond to the measurement of some independent variable, t_i. In the case of fitting for the fraction of ^{60}Co events to total detected events, this variable will represent the time measurement of a decay event. The first term of our PDF will describe the exponential decay of ^{60}Co and the second term will describe the flat background contribution from other long lived radioactive isotopes. The PDF has the form

$$\frac{fe^{-t/\tau}}{\tau(1-e^{\frac{-t_{max}}{\tau}})} + \frac{1-f}{t_{max}} \tag{4}$$

where τ is the mean lifetime of ^{60}Co which is accepted to be 7.60 years. t_{max} is the total time that EXO has been running and collecting data, and f is

$$f = \frac{^{60}Co\ Decays}{Total\ Decays} \tag{5}$$

We fit the data to extract f. This PDF is normalized to one when integrated from 0 to t_{max}, ensuring that the probability of seeing a given decay time is never more than one.

Given this PDF, we can calculate the probability of achieving each of the experimental values for a given value of the fitting parameter, in this case, f. f will range from 0 to 1 where 0 represents no ^{60}Co signal and 1 represents all ^{60}Co signal and no background. We can scan through these values at a set increment, where a smaller increment allows for a more precise fitting for f.

To calculate the likelihood of a given value of f, we take the product of the N probabilities corresponding to each decay time with that f.

$$L(f) = \prod_{i=1}^{N} P_i = P(t_1; f)P(t_2; f)...P(t_N; f) \tag{6}$$

Because the values for each probability are less than one, and some of them much less than one, this product becomes a prohibitively small number, so it is customary to instead calculate the log likelihood $M(f)$, resulting in a sum rather than a product:

$$M(f) = \log\left[L(f)\right] \tag{7}$$

If these log likelihood values are plotted versus the different f values, there will be an absolute maximum that can be identified. The value of f that maximizes the log likelihood function is the value that would recreate the input measurements with the greatest probability and is, therefore, the best fit value for f.

The standard error bars for the ML fit is defined as the change in the fitting parameter, f, which causes the log likelihood to decrease by 0.5. It is worth noting, however, that this definition does not automatically "satisfy the coverage requirement that 68% of all intervals derived via [this criteria] contain the true value of the parameter" [6].

There are some drawbacks to using this type of fitting method. First, there is no standard way of testing the goodness of fit such as the χ^2 test used in LS fitting. The magnitude of the maximim log likelihood is simply a measure of the maximized probability of obtaining the experimental data, and does not speak to the goodness of fit [6]. Additionally, because this method requires a separate calculation for each measured event, as opposed to the LS method which requires computations for binned sets of data, ML fitting might be too slow for very large data samples[5]. This is not an issue, however, for our purposes.

II.2. Determining the Significance of ^{60}Co in the Region of Interest

The EXO-200 experiment has been collecting data for about a year at this point and has amassed a collected a total of around 160 events within the specified region of interest for $0\bar{\nu}\beta\beta$. It is likely that some fraction of these events are decay events caused by ^{60}Co. The ML fitting method can, therefore, be employed to fit for the fraction of ^{60}Co to total decay signals using the times when each of these events occurred. If this value for the fraction of decay events to total candidate events is small, however, the lower error bar may cross over into negative values of f and it may not be possible to state a measurement of that fraction with two sided error bars. Instead, only an upper limit for the fraction can be provided.

This decision regarding whether to report a measurement as opposed to a limit is more complicated than it may seem. Gary Feldman and Robert Cousins point out that "commonly quoted confidence intervals are wrong more than allowed by the stated confidence if one uses the experimental data to decide whether to consult confidence interval tables for upper limits or for central confidence intervals" [7]. This means, in order to state at a 90% confidence level, that there is a contribution from

^{60}Co present, we cannot simply fit our data using maximum likelihood fitting and report a finding if the lower error bar falls above 0 or a limit if it does not.

II.3. ^{60}Co Sensitivity Study

It is common to conduct sensitivity studies that explore, on average, how sensitive reserachers can expect an experiment to be to a certain hypothesis. In this case, we want to answer the question: On average, how long will EXO-200 have to run before it is sensitive to differing values of non-zero ^{60}Co fraction at a 90% confidence level? Or, in other words: How many decay events will EXO need to collect before, on average, the limits on the ^{60}Co fraction transition to measurements with two-sided error bars?

This sensitivity study is preformed by an algorithm written in C++ that scans through different numbers of events and different ^{60}Co fractions ranging from 0 to 1. For each possible combination of ^{60}Co fraction and number of events, it computes 1000 pseudo experiments (PE) with that particular ^{60}Co fraction and number events for a particular observation time. The PE data is generated by assuming the ^{60}Co decay events will follow exponential decay with a half life of 5.27 years and the background decay events from long half-life isotopes follow a flat distribution. Then, after preforming these PE and fitting each one with a ML fitting routine, the algorithm decides whether or not the null hypothesis that there is no ^{60}Co present can be rejected at 90% confidence.

Consider, for example, an experiment that had 100 events and a true ^{60}Co fraction of 0, meaning that all events recorded were background signals that follow a flat, linear distribution. Employing ML fitting, one could find the best fit fraction for that data set. Next, one could imagine conducting 1000 pseudo experiments that fitted generated data sets, each with 100 events and a true fraction of 0. Each of these trials would produce slightly different values of f, but they would fluctuate around the value $f = 0$. If these values were binned in a fine histogram, they would resemble a gaussian distribution where the width is dictated by the number of pseudo exxperiments being conducted. Next, one could integrate 90% of the distribution as is shown in Figure 3. The value of f at this point is the critical value of f, f_{crit}.

Next, consider the same distribution that would be created by conducting 1000 pseudo experiments, each with 100 events, but now with a true ^{60}Co fraction of 0.2. This distribution should be similar to the null distribution, except displaced to the right. One could then integrate this distribution from 0 to f_{crit} as shown in Figure 4.

If this integrated region includes less that 10% of the 1000 pseudo experiment results, then there is less than 10% overlap between the two distributions and we can reject the null hypothese that there is no ^{60}Co signal in this region with 90% confidence. If more than 10% of the second distribution lie to the left of f_{crit}, then we cannot

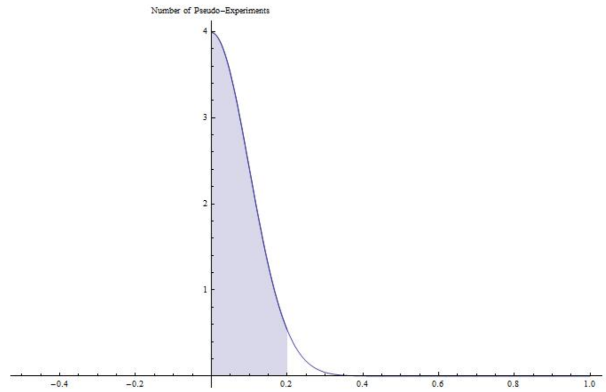

FIG. 3. The distribution for a null fraction. The x axis shows the fraction of decay events to total candidate events. The y axis shows the number of pseudoexperiments that produced a given result. It has been integrated to include 90% of the results.

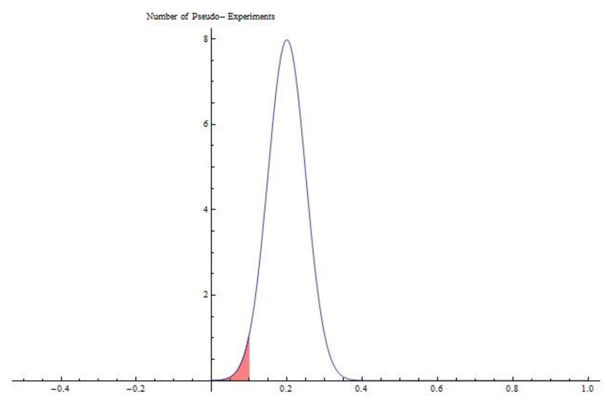

FIG. 4. The distribution for a fraction of 0.2 integrated from $-\infty$ to f_{crit}.

reject the null hypothesis at a 90% C.L.

This result holds for one value of the number of events and one value of true fraction. We must them step through every possible combination in the two dimensional paramter space. As the number of events becomes smaller, the distributions will become wider and a much larger decay fraction will be necessary in order to report the presence of ^{60}Co decay at a 90% C.L. These results trace out the expected sensitivity to ^{60}Co in any experiment. It is important to note that this study is particularly powerful because it is independent of any data set, including EXO. It is simply a statistical analysis that uses the exponential decay of ^{60}Co on top of a flat background. Therefore, agreement between experimental results and the sensitivity study is even more powerful.

III. RESULTS

I conducted the sensitivity study for two different time frames. The first reflects the expected sensitivity after

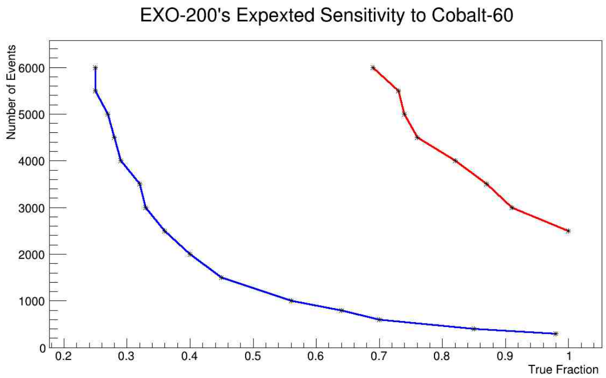

FIG. 5. The expected sensitivity to ^{60}Co in EXO-200. The blue curve represents the expected sensitivity after 4 years and the red curve represents the expected sensitivity after 500 days of running.

the current 500 days of data collection. The second study reflects the expected sensitivity after four years. I chose four years for the second time frame because it represents a reasonable expectation for the total EXO run time. The results from this study can be seen in Figure 5.

Looking at Figure 5, we would expect EXO to be sensitive to any combinations of ^{60}Co fraction and number of events that fall above and to the right of the curves corresponsing to each time frame. Any combinations that fall below and to the left of the curves are beyond EXO's expected sensitivity and we cannot say anything about these combinations at the 90% confidence level.

The difference in the two sensitivity studies results from changing the t_{max} parameter in the PDF. Running for a longer period of time increases the expected sensitivity for two reasons. First, a longer run time will lead to the accumulation of more events. Additionally, if the run time is short compared to the half life of ^{60}Co then the effect will not be as pronounced. Conversely, the exponential decay will be more obvious if the run time included several half-lives of the isotope.

After 500 days, EXO-200 has collected a data set of about 160 multi-site events within the $0\bar{\nu}\beta\beta$, or multi-gamma region of interest ranging from 2400 to 2550 keV in Figure 6. According to the sensitivity study, we should not expect to be sensitive to any ^{60}Co fraction at this time. This result was confirmed by employing the ML fitting routine to fit for the ^{60}Co fraction in the data set. The fit produced an upper limit of 1.0, meaning that the fit could not determine a value for the ^{60}Co fraction with 90% confidence. The time spectrum for this data set can be seen in Figure 7 which includes a fit line using the upper limit for the ^{60}Co fraction.

If the decay rate within the region of interest remains roughly constant for the next 4 years, we would expect to see about 640 decay events. According to this sensitivity study, we would, therefore, expect to be sensitive to a ^{60}Co fraction of about 0.7 at the end of EXO's run.

Next, I examined the decay times from the first 500

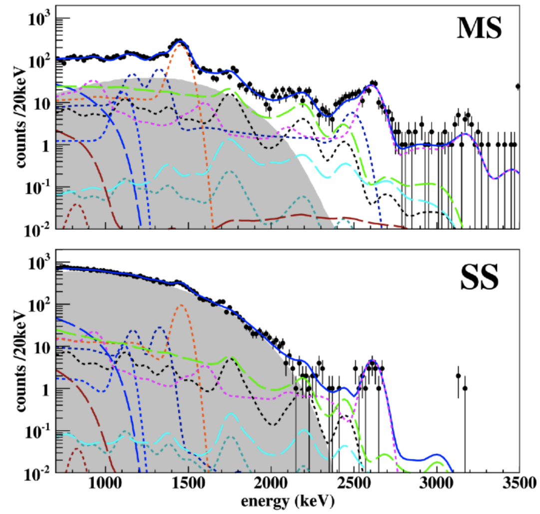

FIG. 6. The full EXO energy spectrum. The single gamma region is located between 1150 and 1480 keV and the multi-gamma region is located between 2400 and 2550 keV.

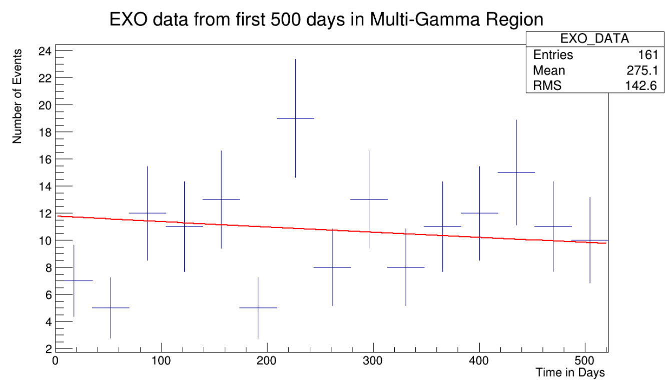

FIG. 7. The data from the first 500 days of running in the multi gamma 2400-2550 keV energy region. The red line represents the fit line for a ^{60}Co fraction of 1. This is the upper limit on the ^{60}Co fraction.

days of running in the single gamma energy region ranging from 1150 to 1480 keV in Figure 6. This energy region will includes ^{60}Co decays where one γ ray enters the detector, but the other γ ray escapes the detector. Using my ML fitting routine, I found the ^{60}Co fraction to be 0.802 ± 0.273 at a 90% confidence level. This data set contains 4914 decay events and is, therefore, in agreement with the sensitivity study. The time spectrum for the single gamma region can be seen in Figure 8.

It is important to note, when comparing EXO data to the sensitivity study, that the study provides an expectation for the average sensitivity. If there is agreement betwee the two results, that is encouraging. If the two results do not agree, however, it does not necessarily mean that one of the results is invalid. It is possible that the

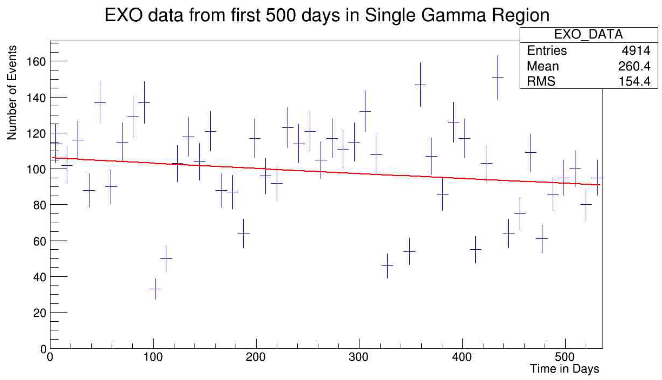

FIG. 8. The data from the first 500 days of running in the single gamma 1150-1480 keV energy region. The red line represents the fit line for a ^{60}Co fraction of 0.802.

actual time distribution of the EXO data could have a higher or lower than average decay rate in the first half of the run time, mimicking an ^{60}Co fraction that is higher or lower than the actual fraction. If the fitted value lies far from the expected sensitivity curve, it is worth investigating what is causing the discrepancy.

IV. CONCLUSIONS AND FURTHER RESEARCH

IV.1. Conclusions

EXO 200 was designed specifically to supress radioactive background signals within the $0\bar{\nu}\beta\beta$ region of interest. ^{60}Co, however, is a particularly difficult contaminant to eliminate. I have conducted a sensitivity study which is independent of EXO data in order to determine how sensitive EXO 200 is to ^{60}Co. At this time, EXO-200 is sensitive to a ^{60}Co fraction of 0.802 ± 0.273 in the single gamma region but is insensitive to any ^{60}Co fraction with the multi-gamma region of interest. Both of these results are in agreement with the sensitivity study. If decays continue at roughly the same rate within the region of interest, we could expect a sensitivity to a ^{60}Co fraction of about 0.7 in the multi-gamma region by the end of EXO 200's total run time.

IV.2. Limitations and Further Reserach

The current sensitivity analysis assumes a flat time distribution. In other words, it assumes that EXO began taking data about 500 days ago and, since that time, it has been continuously running and collecting the data that we use in our analysis. In reality, this is not the case. A considerable amount of time is spent calibrating the detector and, ocasionally, EXO must be shut down for longer periods of time because of maintanance issues. All of these interruptions in data collection, during which the decay rate drops to 0, could combine to effect the reliability of the ML fitting.

This can be seen when fitting for the single gamma data in Figure 8. When a fit line following the PDF and containing an actual ^{60}Co fraction of 0.8 is laid on top of the data, it is clear that it is not the curve that best fits the data. This discrepancy may be caused by assuming the flat time distribution.

Fortunately, the PDF used in the ML fitting can be adjusted to reflect the actual run time of EXO. Instead of using the original PDF that multiplies the last term by 1 over the maximum run time:

$$\frac{fe^{-t/\tau}}{\tau(1-e^{\frac{-t_{max}}{\tau}})} + (1-f)\frac{1}{t_{max}} \tag{8}$$

we can multiply the last term by the fraction of time that EXO was collecting data the day the decay event occured divided by the maximum time multiplied by the average fraction of time that EXO is collecting data:

$$\frac{fe^{-t/\tau}}{\tau(1-e^{\frac{-t_{max}}{\tau}})} + 1 - f\frac{day\,frac}{(t_{max})(time\,frac)} \tag{9}$$

Where

$$day\,frac = \frac{Time\ Collecting\ Data}{Time\ in\ Day} \tag{10}$$

and

$$time\,frac = \frac{\sum day\,frac}{Number\ of\ Days} \tag{11}$$

Implementing this change should produce a ^{60}Co fraction value that more closely fits the data.

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