XENON1T Excess: Some Possible Backgrounds

Biplob Bhattacherjee, Rhitaja Sengupta
Center for High Energy Physics, Indian Institute of Science, Bangalore
biplob@iisc.ac.in, rhitaja@iisc.ac.in

Abstract

This work is a discussion of some possible background sources in the XENON1T environment which might affect the energy spectrum of electronic recoil events in the lower side and might contribute to the observed excess. We have identified two additional possible backgrounds, $^{125}$Sb coming from cosmogenic production and $^{210}$Pb from the decay chain of $^{222}$Rn emanated in liquid Xenon from the materials. We perform a $\chi^2$ fitting of the $\beta$ spectrum from these backgrounds along with tritium to the observed excess events by varying their individual rates. We also present a discussion in the end on some other possible background sources which must be studied and understood in detail.

1 Introduction

The XENON1T collaboration has recently observed an excess of electronic recoil (ER) events in the low energy region between 1-7 keV [1]. The possible new physics explanations outlined in their work are: solar axions, enhanced neutrino magnetic moment, and bosonic dark matter. However, they have clearly stated that one cannot rule out the hypothesis of beta decay of tritium being the source for this excess since the concentration of tritium in Xenon have not been directly measured as yet. Out of the former three new physics hypotheses, the results of the solar axions are in tension with astrophysical constraints from stellar cooling [2]. There have been many recent works to explain this excess with many different new physics models [3–38].

In this work, we take a different approach by studying some other possible backgrounds and examining how well they are understood. As evident from the history of particle physics, observation of an excess demands that we carefully study our backgrounds in more detail before looking for possible new physics explanations. At the very outset, we would like to acknowledge that we are no experts of this field and this is an attempt to just point out several sources of backgrounds which might be present in the XENON1T environment and can affect the electronic recoil energy spectrum in the lower side. The exact details of the purification process and whether such backgrounds can actually be present at levels discussed in this work are questions that can be better addressed by the XENON collaboration only. This work is aimed at discussing the various sources of backgrounds, including the tritium beta decay, and studying the possible ones which we think might be important to explain the observed excess towards lower energy electronic recoil events.

2 Isotopes produced from cosmogenic activation of Xenon

The cosmogenic activation of Xenon with neutrons or muons can produce a number of different isotopes [39], tritium being one of them. Since the rates of cosmogenic activation scales with the flux of neutrons and muons inside the LNGS cavern, they drop drastically once the Xenon is taken underground. Therefore, the isotopes are dominantly produced before transporting the...
Isotope,  
Half Life   $R_{\text{sea level}}$ (kg$^{-1}$day$^{-1}$)  Decay  Branching,  Mode  Q-value  
$^3$H, 12.3y  31.58  $^3$H$\rightarrow$$^3$He  100% $\beta$−  18.59 keV  
$^{124}$Sb, 60.2d  1.62  $^{124}$Sb$\rightarrow$$^{124}$Te  100% $\beta$−  2.9 MeV  
$^{125}$Sb, 2.8y  1.48  $^{125}$Sb$\rightarrow$$^{125}$Te  100% $\beta$−  766.7 keV  
$^{129}$I, 1.57×10$^7$y  77.35  $^{129}$I$\rightarrow$$^{129}$Xe  100% $\beta$−  189 keV  
$^{133}$Xe, 5.2d  99.19  $^{133}$Xe$\rightarrow$$^{133}$Cs  100% $\beta$−  427 keV  
$^{135}$Xe, 9.1h  60.05  $^{135}$Xe$\rightarrow$$^{135}$Cs  100% $\beta$−  1.2 MeV  
$^{135}$Cs, 2.3×10$^6$y  

Table 1: Isotopes produced from the cosmogenic activation of Xenon which satisfy the conditions as described in the text.

Xenon to the LNGS underground hall, and only isotopes with large half lives can survive and be present during the data taking runs of the experiment. However, if the decay chain of any of these isotopes contain another isotope of longer half life, then that might also be present inside the detector. Unless these are removed to a large extent by purification, their decays or transitions will contribute as backgrounds.

A list of various isotopes which are cosmogenically produced in Xenon gas along with their production rates at the sea level is given in Table 1 of [39]. We use this as our starting point, and trace all possible decay chains of these isotopes. We are only interested in those decay chains which have at least one isotope with half life long enough for it to survive the time gap between placing the Xenon underground and starting of data taking (around 1000 days). Also, we are mostly interested in isotopes with $\beta$ decays since $\beta$ decays have continuous spectra and are most likely to affect the lower energy region of electronic recoils. We include monoenergetic transitions only if the transition energy falls within our region of interest (ROI), $E_{\text{er}} \in [1, 30]$ keV. With these criteria, we list the isotopes that might be important and shall be studied in table 1. In the last row, $^{135}$Cs comes from the $\beta$ decay of $^{135}$Xe, which itself has a short half life of few hours but the decay product has longer half life and can be still present in the detector while data taking. However, since its half life is few million years, we might expect very less number of decays of this isotope within the span of the data taking runs (around 227 days). Similar argument applies for the $^{129}$I isotope whose half life is one order greater than $^{135}$Cs.

The isotopes of Xenon, $^{133}$Xe and $^{135}$Xe have quite short half lives and will decay before the start of the data taking. However, they can also be produced with neutron activation inside the detector once the data taking starts. There is another important point which determines which isotopes can be a possible background for the ER events apart from the half life factor. If the daughter particle of the isotope is dominantly produced in an excited state where it can emit prompt photons, then these fast emissions can shift the effective energy to the higher side. For example, $^{133}$Xe decays dominantly (98.5%) to an excited state of $^{133}$Cs (80.99 keV) which emits a prompt photon ($T_{1/2} = 6.283$ ns), and therefore, this gives a continuous energy background starting near this value. This background is already taken into consideration by the XENON1T collaboration. Similarly, the dominant decay of $^{135}$Xe is to $^{135}$Cs which is at an excited state of 249.77 keV (96%), and the latter emits photon with a half life of 0.28 ns. Therefore, this also does not contribute to the low energy ER spectrum.

From table 1, the only other isotope having a half life of the order of the tritium half-life is $^{125}$Sb, which is few years. Its Q-value is on the higher side, however, the $\beta$ spectrum still has a slightly increasing slope towards lower energies. Therefore, we study this background in detail in this work. Along the lines discussed just above, most of the $^{125}$Te daughters of $^{125}$Sb are in

1The cosmogenic production rate of tritium is estimated to be 71.5 atoms/kg/day in [25], which is quite larger than the rate given in [39]. Still the final tritium concentration estimated by the former work shows that the cosmogenic production of tritium cannot explain the low energy excess by itself.
excited states which radiate a photon promptly. However, there is one metastable state, $^{133m}$Te, with an energy of 144.77 keV which has a half-life of 57.4 days. This particular decay has a branching of 13.6% and can be a background to the ER events.

Till now, we have not taken into account the purification process. Zirconium-based hot getters are used for the Xenon gas purification. The tritium background can come from traces of tritium in hydrogen molecule and these zirconium getters absorb hydrogen. Therefore, the concentration of tritium present in Xenon will be dependent on the ability of the zirconium getters to absorb hydrogen. If the getters get saturated before the concentration of $H_2$ in Xenon is brought down to few ppb, this might account for the amount of tritium required to explain the low energy ER excess as has been pointed out in [25].

These getters can also absorb $^{125}$Sb and its background rate estimation assuming that the zirconium getters don’t remove Sb significantly is quite large than the measured low energy ER background rate at the LUX experiment as has been shown in [40, 41]. Therefore, we might conclude that the getters have quite high efficiency for absorbing Sb. However, we could not find a detailed study which quantifies this efficiency with both hydrogen and Sb present. The presence of both hydrogen and Sb might affect the getter’s ability to absorb them and their individual efficiencies must be studied in this case.

In this work, we take an agnostic approach and treat the concentration of $^{125}$Sb as a floating parameter to estimate how the presence of this background affects a $\chi^2$ fit with the observed data. We discuss our analysis and results in section 4.

3 The $^{222}$Rn decay chain

The dominant source of background in the XENON1T experiment for the ER events is the $\beta$ decay of $^{214}$Pb, which is a part of the $^{222}$Rn decay chain. $^{222}$Rn comes from the $^{238}$U decay chain which is present in the detector materials, like, stainless steel and PTFE [42]. It is important due to its relatively higher half life of 3.8 days and also due to the ability of Rn to diffuse into liquid Xenon (LXe). Due to the much shorter half life of $^{220}$Rn (55.6 s), it has much less probability to diffuse into the active LXe volume.

In the decay chain of $^{222}$Rn, $^{214}$Pb is the first daughter that has a $\beta$ decay. As we have discussed in section 2, having a $\beta$ decay is not enough for a nuclide to be a possible background, it has to decay to a state which has a delayed transition. For $^{214}$Pb, which itself has a half life of 27 mins, there is a 11% branching to the ground state of $^{214}$Bi, which has a half life of around 20 mins. Therefore, it is a dominant background. $^{214}$Bi also has a $\beta$ decay, however, its daughter $^{214}$Po $\alpha$ decays to $^{210}$Pb with a very small half life of 164.3 $\mu$s and this helps to remove this background by vetoing the multiple scatter signals [43].

The $^{210}$Pb also has a $\beta$ decay and decays to the ground state of $^{210}$Bi with 16% probability, where the latter also has a half life of 5 days. Therefore, this can be a possible background for the ER events. Also, it has a Q-value of 63.5 keV, which is quite smaller compared to the Q-value of the $^{214}$Pb ($\sim$1 MeV), where the latter is one of the dominant background of XENON1T. This implies that $^{210}$Pb will have a more enhanced $\beta$ spectrum in the low energy region than $^{214}$Pb and therefore, might contribute to the excess in low ER energies. The half life of $^{210}$Pb is 22.2 years and this limits the number of $\beta$ decays observed within the span of the experiment. In this work, we study the effect of inclusion of this background on the recent observed ER data of the XENON1T experiment.

4 Analysis and Results

In this work, we do a simple binned $\chi^2$ fitting of the observed data with two additional possible backgrounds, coming from the $\beta$ decay of $^{125}$Sb and $^{210}$Pb, that we have described in the previous
Figure 1: Normalised distribution of energy from the $\beta$ decay of tritium ($^3$H), Antimony ($^{125}$Sb) and Lead ($^{210}$Pb) after applying the detector efficiency and resolution. Also shown in gray is the distribution of $^3$H $\beta$ decay as obtained in [1]. The agreement in the shape validates our setup.

two sections. If $n_{\text{obs}}^i$ and $n_{\text{exp}}^i$ are the number of events observed in data and expected from our hypothesis in bin $i$ respectively, then the $\chi^2$ for $N$ total bins is defined as follows:

$$\chi^2 = \sum_{i=1}^{N} \frac{(n_{\text{obs}}^i - n_{\text{exp}}^i)^2}{\sigma_{\text{tot},i}^2}$$

where $\sigma_{\text{tot},i} = \sqrt{\sigma_{\text{obs},i}^2 + n_{\text{exp}}^i}$.  

For the error associated with data, i.e., $\sigma_{\text{obs},i}$, we have used the numbers as extracted from the XENON1T result, and for the error associated with our hypothesis, we use $\sigma_{\text{exp},i} = \sqrt{n_{\text{exp}}^i}$.

Before proceeding with the $\chi^2$ fitting, we apply the detection and selection efficiencies as well as the energy resolution of the detector on the $\beta$ spectrum of each of the backgrounds. As a validation to this, we reproduce the energy spectrum coming from the tritium $\beta$ decay as given in the XENON1T paper [1]. Fig.1 shows that these two (the solid black line and the gray dashed line) match very well and our setup is therefore validated. We now apply these efficiencies and resolutions on the $\beta$ decay distributions of $^{125}$Sb and $^{210}$Pb. We take the $\beta$ spectra corresponding to the energy level of the daughter particles which does not have a very small half life ($< O(1)$ ns) for reasons discussed in the previous sections. For $^{125}$Sb, it is the channel where $^{125m}$Te is the daughter particle with energy of 144.77 keV and for $^{210}$Pb, it is one where the daughter $^{210}$Bi is in the ground state. We have used the $\beta$ spectrum as given in IAEA LiveChart (Nuclear Data Services database) [44], which they have obtained using BetaShape [45] and [46]. The IAEA LiveChart (Nuclear Data Services database) calculations does not include exchange effects [46] according to [1], and therefore, they perform dedicated calculations to study the low energy discrepancies due to the exchange or screening effects for $^{214}$Pb and $^{85}$Kr. These effects might also be important for $^{125}$Sb and $^{210}$Pb and might affect their $\beta$ spectra at low energies. Such calculations are beyond the scope of this work, however, they must be included properly for a complete analysis. Fig.1 shows the normalised energy distributions coming from the $\beta$ decays of $^{125}$Sb and $^{210}$Pb along with that of tritium. Comparing the shapes, we find that tritium is more peaked towards the lower energy region than $^{210}$Pb, and the $^{125}$Sb is flatter than both the other backgrounds.

We now perform the $\chi^2$ fitting – one with the first 7 bins since the observed excess is contained in this region, and another one over all the 29 bins corresponding to the energy range of 1-30 keV. We keep the rates of the additional backgrounds as floating parameters and perform
Figure 2: $\chi^2$ fitting of the individual rates of tritium ($^3$H) and Lead ($^{210}$Pb) in the top panel and Antimony ($^{125}$Sb) in the bottom panel with varying factors of their rate with respect to the tritium rate fitted in [1] for $N = 7$ (left) and $N = 29$ (right).

The $\chi^2$ with varying rates of these over the standard backgrounds that have been considered in [1], and find out the rate of each component corresponding to the minimum $\chi^2$/d.o.f. As another validation, we use the tritium spectrum which has been fitted to the observed data by the XENON1T collaboration from [1], and perform our $\chi^2$ fitting on that with the rate varied as a factor of the one that gives their fitted tritium $\beta$ spectrum. Therefore, a minimum $\chi^2$/d.o.f close to 1 shows that our $\chi^2$ predicted rate is equal to that found out in [1], where an unbinned profile likelihood is used for fitting in the latter. For the rates of the other two backgrounds from $^{125}$Sb and $^{210}$Pb, we use the central value of the best fit tritium rate from [1], found out to be $159 \pm 51$ events/(t.y), as the reference. According to our new background hypothesis, the expected number of events in each bin is as follows:

$$n_{exp}^i = n_{B0}^i + n_{3H/125Sb/210Pb}^i \times R$$

where $R$ is the rate of the additional background with respect to the tritium fitted rate of XENON1T. We would like to remind here that these rates are the decay rates of the background isotopes and their actual concentration in Xenon can be found out from these rates using their half lives and the branching to this particular decay channel.

Fig.2 shows the variation of the $\chi^2$/d.o.f with varying rates of $^3$H (top), $^{125}$Sb (bottom) and $^{210}$Pb (top) w.r.t. the fitted tritium rate in [1] for the first 7 bins (left) and for all 29 bins (right). For tritium, the minimum $\chi^2$/d.o.f is at $R=1.05$ and 0.75 when $N = 7$ and 29 respectively. Therefore, the best fit rate for $N = 7$ is in agreement with that in [1], however, when performing the $\chi^2$ over all 29 bins, the favoured rate is 75% of the rate quoted by the XENON1T.

For $^{210}$Pb, the best fit rates from minimising the $\chi^2$/d.o.f when $N = 7$ and 29 are $R=2.5$ and 0.3 respectively. Although the $\chi^2$ fitting over all 29 bins has minimum at a quite low rate of $^{210}$Pb, the really small variation of the $\chi^2$/d.o.f till $R = 2$ suggests that even if the rate for $^{210}$Pb is twice the tritium best fit value, it won’t affect the $\chi^2$ for $N = 29$ drastically. However,
such a rate will reduce the $\chi^2$ for the first 7 bins. Fig. 3 shows the XENON1T observed data in the 1-30 keV region along with their $B_0$ fit and $B_0 + ^3$H fit [1]. We also show the $B_0 + ^{210}$Pb fits with the $R$ values that provide the best $\chi^2$ fit for $N = 7$ and 29. We conclude that the presence of $^{210}$Pb can also reduce the tension of $B_0$ with the observed data in the first 7 bins, where the excess is reported. However, this rate affects the $\chi^2$ for all the 29 bins. Still, there is some scope to have $^{210}$Pb rate in between the $R$ values giving best fit for $N = 29$ and $N = 7$ (say, $R \sim 1$), which can reduce the tension of data with the $B_0$ hypothesis in the first 7 bins, along with little effect on the $\chi^2$ fit for the later bins.

For $^{125}$Sb, the best fit rates from minimising the $\chi^2$/d.o.f when $N = 7$ and 29 are $R = 30$ and 0 respectively. Again the variation of $\chi^2$/d.o.f for $N = 29$ is quite small up to $R = 10$, and therefore, such a rate for $^{125}$Sb will not have significant effect on the data. The large rate required to minimise the $\chi^2$/d.o.f when $N = 7$ is due to the flatter $\beta$ spectrum as observed in fig. 1, and therefore, it needs large rates to explain the excess at low energy bins.

From the above discussion, we find that although the fit for $^3$H is the best among the three, presence of $^{210}$Pb can also fit the excess at low ER energies quite well, almost comparable to $^3$H. The best fit rate from $\chi^2$ with $N = 7$ does not agree well with the data at higher energies. However, for a range of $^{210}$Pb rates, the low energy tension can be reduced as well as the high energy data can be fitted reasonably well. Also the presence of both $^{125}$Sb and $^{210}$Pb are not highly constrained by the observed data.

We now do a two-dimensional $\chi^2$ analysis with $^{210}$Pb and tritium as well as $^{125}$Sb and tritium. The constant $\chi^2$/d.o.f contours for different $R$ values of the components, $^3$H vs $^{210}$Pb and $^3$H vs $^{125}$Sb are shown in the top and bottom panels of fig. 4 respectively for $N = 7$ (left) and $N = 29$ (right). We find that in both the cases, the minimum $\chi^2$ corresponds to the tritium-only hypothesis (for both $N = 7$ and 29 bins), and the minimum position as well as the $\chi^2$/d.o.f values match with the one-dimensional $\chi^2$ results of tritium.

If we concentrate on the first 7 bins, the value of the constant $\chi^2$ contours for $^3$H vs $^{210}$Pb case changes quite slowly with increasing $R$ for $^{210}$Pb. Also, there is a correlation between the $^3$H and $^{210}$Pb rates – along the constant $\chi^2$ lines increasing $R$ for $^{210}$Pb decreases $R$ for $^3$H. Since both $^3$H and $^{210}$Pb have a peak around the low energies, this is expected as a larger rate for one prefers a smaller rate for the other. However, since the peak is more pronounced for tritium,
its contribution dominates in fitting the data and that explains the 2D $\chi^2$ minimum at an $R$ of $(^{210}\text{Pb}: 0, ^3\text{H}: 1.05)$ for $N = 7$. When $N = 29$, the rates of $^{210}\text{Pb}$ that can be accommodated without changing the $\chi^2$ much becomes smaller than the $N = 7$ case, however, it’s not zero. The correlation observed between the rates of $^3\text{H}$ and $^{210}\text{Pb}$ is also different than the $N = 7 \chi^2$ fitting.

For the $^3\text{H}$ vs $^{125}\text{Sb}$ case, the constant $\chi^2$ lines are mostly dependent on the tritium rate, and the rate of $^{125}\text{Sb}$ does not affect the fitting much for $N = 7$. The reason for this is the flat energy spectrum for $^{125}\text{Sb}$ and therefore, we do not have a correlation between the rates as we had for the $^{210}\text{Pb}$ case. As we do the complete $\chi^2$ over 29 bins, the magnitude of slope of the constant $\chi^2$ lines increase a little and decreases the rate of $^{125}\text{Sb}$ for a particular $\chi^2$ value and $R$ for $^3\text{H}$, which was also true for the individual $^{125}\text{Sb} \chi^2$ fitting. Finally, in this case also, the minimum occurs at $R$ of $(^{125}\text{Sb}: 0, ^3\text{H}: 1.05)$ for $N = 7$, implying that the most favoured hypothesis is the tritium-only one. We have also done a three dimensional $\chi^2$ study when all the three components
are taken together and we find the minimum corresponding to the tritium-only case.

5 Discussions

Many isotopes can be produced from the cosmogenic activation of Xenon and other detector materials and the lists given in [39] and [41] are not completely overlapping. Therefore, it is essential to have an exhaustive list of all isotopes that can be produced cosmogenically and to quantify how the purification steps affect each of them to ensure that they won’t contribute as potential backgrounds.

The rates of cosmogenic production of isotopes at the LNGS underground hall suffers from the suppressed muon and neutron flux ($\sim 10^6$ suppression). However, radiogenic neutrons can come from $(\alpha, n)$ reactions and spontaneous fission in the detector’s materials [47]. It is important to have a thorough knowledge of these rates and a comprehensive list of all isotopes that can be produced from such neutrons.

Also, the muons induced reactions, which are vetoed using the Cherenkov Muon Veto [48], can produce isotopes which can have delayed decays or transitions. These decay products will still remain in the detector and can be potential background sources if they have decay channels or transitions satisfying all the selection criteria of the experiment. It is therefore necessary to understand and estimate these processes as well to make sure that we are not missing anything.

While looking at the list of isotopes that can be cosmogenically produced, we found the isotope $^7$Be which has a half life of 53.3 days and decays to $^7$Li. Due to its smaller half life compared to around 700 days after which Xenon is transported underground, most of the $^7$Be decays to give $^7$Li which is stable. However, $^7$Li can produce tritium in an endothermic reaction with high energy neutrons consuming 2.466 MeV:

$$^7\text{Li} + n \rightarrow ^4\text{He} + ^3\text{H} + n$$

We expect these numbers to be quite small from a naive estimation. We do not know exactly whether such high energy neutrons can be produced in the XENON1T experiment, and whether the rate of this reaction can have significant contribution to the tritium production, and therefore, they must be studied more carefully. Also, whether the purification systems can remove $^7$Li and at what percent, might be pertinent questions. All such different production modes of tritium, including the production from ternary fission, must be identified and studied in detail.

Another important point might be to scan the low energy region for the presence of monochromatic photon lines of few keV coming from standard transitions of various elements and then checking the possibility of these elements to be present in the XENON1T environment.

There are many recent studies which attempt to explain XENON1T excess using various new physics models. Our endeavour in this work has been to examine how well we understand the backgrounds. In this work, we have taken two additional background sources, one coming from the cosmogenic activation of Xenon, $^{125}\text{Sb}$, and the other from the $^{222}\text{Rn}$ decay chain, $^{210}\text{Pb}$. We have performed $\chi^2$ fitting of the observed XENON1T data with the $\beta$ spectrum from the decay of these isotopes after applying the detector efficiency and resolution, with varying rates w.r.t the best fit tritium rate. We conclude that although $^3\text{H}$ gives the best fit for the data even in the presence of the other two, the $^{210}\text{Pb}$ background can also reduce the tension to the observed data to a large extent. There might be some discrepancies in the low energy region of the $\beta$ spectra used in this work due to exchange and screening effects. This needs dedicated calculation, as done in [1] for $^{214}\text{Pb}$ and $^{85}\text{Kr}$, which is beyond the scope of this work. However, since the low energy region is the most important here, these effects must be included to check whether they can improve the $\chi^2$. 

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