XENON1T Excess: Some Possible Backgrounds

Based on
arXiv:2006.16172 [hep-ph]
with Biplob Bhattacherjee

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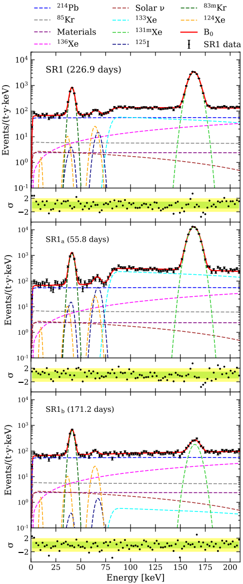
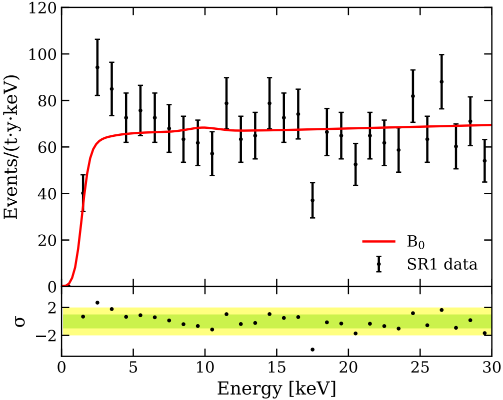
XENON1T: Recent result

[XENON] E. Aprile *et al.*, arXiv:2006.09721





Excess between 1-7 keV

285 events observed

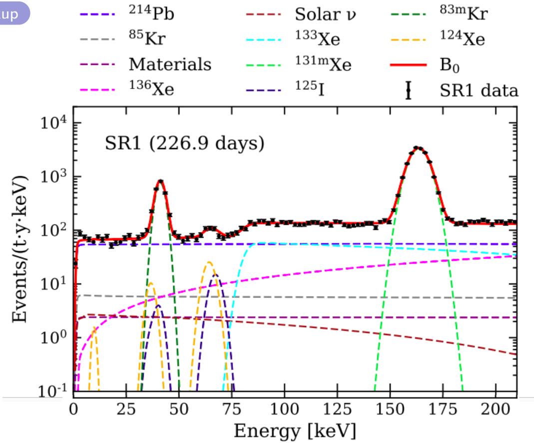
vs.

232 ($\pm$ 15) events expected (from best-fit)

Backgrounds considered by the XENON1T collaboration

[XENON] E. Aprile *et al.*, arXiv:2006.09721

Details in backup

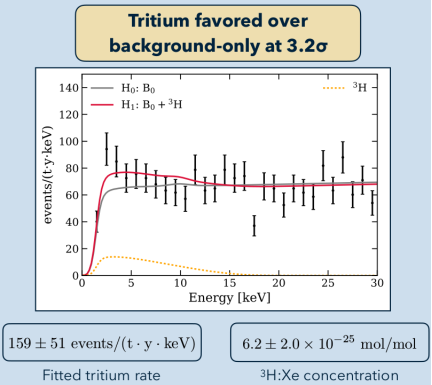


- 10 backgrounds coming from various sources are taken in the background model B_0

The tritium hypothesis

- A new background hypothesis considered by XENON1T collaboration which can explain the observed excess – presence of tritium and its β decay's contribution to the ER spectrum
- It has a half life of 12.3 years and Q-value of 18.6 keV
- Can come from –
  - cosmogenic production
  - traces of tritium present in hydrogen and water
- Cannot be ruled out yet

Slides, Evan Shockley, LNGS Webinar, June 17th, 2020



Taking a more detailed look at other possible backgrounds

- Possible backgrounds have been explored much less after XENON1T's recent result.
  A. E. Robinson, arXiv:2006.13278 [hep-ex]
  M. Szydagis *et al.*, arXiv:2007.00528 [hep-ex]
- This work –
  – **Can there be any other sources of backgrounds which might be present in the XENON1T environment?**; and
  – **How they might affect the low energy region of the ER spectrum?**
- We will look into isotopes having β decays coming from the following –
  - cosmogenic production from Xenon
  - part of the ^{222}Rn decay chain

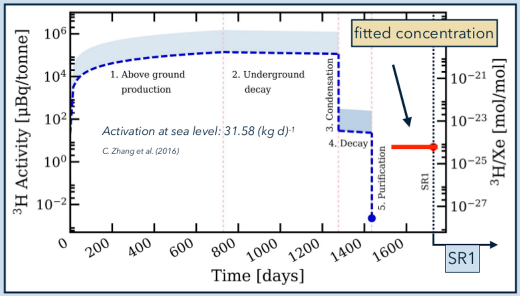
  and also discuss about isotopes which can have low energy monoenergetic transitions.
- We also discuss later some important questions related to purification that need to be addressed.

Isotopes produced from cosmogenic activation of Xenon having a β decay

- The cosmogenic activation of Xenon can produce a number of different isotopes – dominantly produced before transporting Xenon to the LNGS underground hall, since production rates $\propto$ flux of cosmic rays – drops drastically inside the LNGS cavern.
- Available lists of isotopes not overlapping – C. Zhang *et al.*, arXiv:1603.00098 [physics.ins-det] F. Piastra, PhD thesis, Zurich, U., 2017 we have used ACTIVIA1 to identify all possible cosmogenic products that can come from Xenon.

ACTIVIA: J. Back and Y. A. Ramachers, arXiv:0709.3472 [nucl-ex]

Slides, Evan Shockley, LNGS Webinar, June 17th, 2020



Estimated tritium activity. Not measurements.

Half Life

Too small

such isotopes ***won't survive till the data taking*** *runs of the experiment ~ 1000 days*

Too large

such isotopes will have very ***less number of decays within the span of the data taking*** *runs ~ 227 days*

^{135}Cs (2.3x10^{6} years)
^{129}I (1.57x10^{7} years)

Decay of daughter

If the daughter 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****.*

doesn't contribute to low energy

^{133}Xe (5.25 days) —98.5%, β→ ^{133*}Cs (6.283 ns) —80.99 keV γ→ ^{133}Cs

^{135}Xe (9.14 hours) —96%, β→ ^{135*}Cs (0.28 ns) —249.77 keV γ→ ^{135}Cs

might contribute

^{125}Sb (2.76 years) —13.6%, β→ ^{125}Te^{m} (57.4 days) —144.77 keV γ→ ^{125}Te

Q-value = 766.7 keV

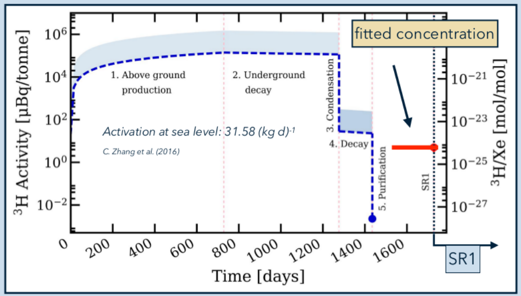
Q-value

Smaller Q-values *— more contribution to lower energy ER*
Larger Q-values *— their presence might still reduce the significance of the excess*

- Many more isotopes, in the list that we get using ACTIVIA1, whose β decay can affect the ER spectrum.

1. ^{106}Ru (39.4 keV)
2. ^{63}Ni (66.977 keV)
3. ^{93}Zr (90.8 keV)
4. ^{79}Se (150.6 keV)
5. ^{14}C (156.476 keV)
6. ^{35}S (167.32 keV)
7. ^{32}Si (227.2 keV)
8. ^{60}Fe (237 keV)
9. ^{45}Ca (259.7 keV)
10. ^{135}Cs (268.9 keV)
11. ^{99}Tc (297.5 keV)
12. ^{90}Sr (545.9 keV)
13. ^{39}Ar (565 keV)
14. ^{42}Ar (599 keV)
15. ^{85}Kr (687 keV)
16. ^{36}Cl (709.53 keV)
17. ^{60}Co (2822.81 keV)

- ^{106}Ru and ^{63}Ni might contribute to the low energy ER excess –
  - Half lives of 371.8 days and 101.2 years respectively – compared to tritium half life of 12.3 years
  - Production cross sections are respectively 3 and 4 orders smaller than tritium production rate ($\sim$ 31.14 per kg per day)

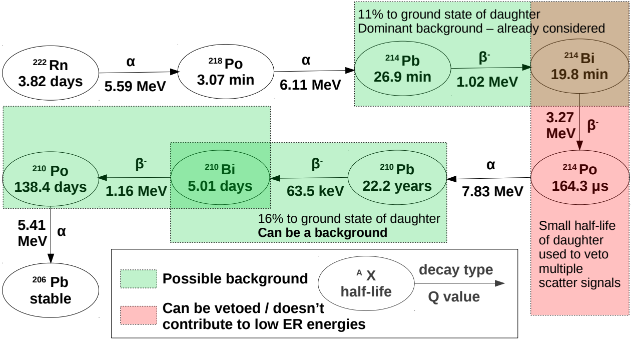


Estimated tritium activity. Not measurements.

- Condensation and purification processes suppress tritium by a factor of $\sim 10^7$
- 3-4 orders of difference in production rates might not matter much if the purification processes are not as effective for ^{63}Ni and ^{106}Ru as for tritium
- These can be present in trace amounts and might be important for the ER spectrum and its low energy excess

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 [XENON] E. Aprile *et al.*, arXiv:1512.07501 [physics.ins-det]
– important due to the ability of Rn to diffuse into liquid Xenon (LXe) and the relatively higher half life of ^{222}Rn (3.8 days) unlike ^{220}Rn (55.6 s).



[XENON] E. Aprile *et al.*, arXiv:1708.03617 [astro-ph.IM]

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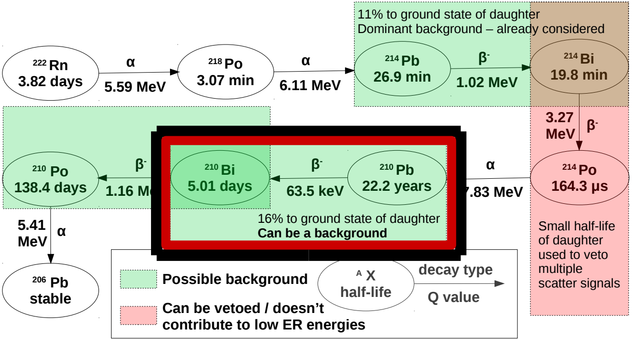


^{210}**Pb**:

- Q-value is quite smaller compared to that of ^{214}Pb $\Rightarrow$ more enhanced β spectrum in the low energy region than ^{214}Pb, might contribute to the excess in low ER energies;
- half life is $\sim$ twice the tritium half life (12.3 years).

Monoenergetic sources of background

- A possible explanation for the low energy excess might be the presence of some background which has a monoenergetic ER spectrum.
- For example, from the monoenergetic X-rays or Auger electrons coming from electron capture of some isotopes.
- These isotopes can come from cosmogenic production in Xenon, like ^{41}**Ca** and ^{49}**V** –
  - having production rates three orders smaller than tritium, and half lives 10^5 years and 330 days respectively;
  - having X-ray lines around 3-4 keV.
- The possibility of this excess coming from the 2.8 keV X-ray line of ^{37}**Ar**, which is a cosmogenic product of Xenon and is also injected during a dedicated calibration campaign in the final months of XENON1T's operation has been studied in detail. M. Szydagis *et al.*, arXiv:2007.00528 [hep-ex]
- The monoenergetic ER spectrum might come from other background sources as well and the observed excess might be a result of presence of many such monoenergetic lines from background.

Few words on purification

- Zirconium-based hot getters used for the Xenon gas purification − can absorb hydrogen, which contains traces of tritium.
- *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*. A. E. Robinson, arXiv:2006.13278 [hep-ex]
- The background rate estimation of ^{125}Sb, 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 ⇒ might be concluded that the getters have quite high efficiency for absorbing Sb.
  L. Baudis *et al.*, arXiv:1507.03792 [astro-ph.IM]; F. Piastra, PhD thesis, Zurich, U., 2017
- The getter's ability to absorb each one of them mostly depends on the electronegativity of the element.
- **The existence of other isotopes might affect the purification for tritium**
  − even if tritium is completely removed from Xenon, then these other isotopes might still be present and can be potential backgrounds.

Analysis and results

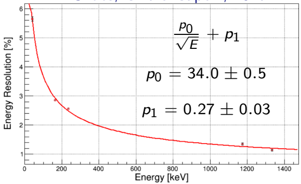
- Out of the many isotopes discussed that might be potential backgrounds, we select one cosmogenically produced isotope and one coming from the ^{222}Rn decay chain – both having β decays –
one with a large Q-value (**^{125}Sb**) and another with a smaller Q-value (**^{210}Pb**).
- We take the β spectra corresponding to the energy level of the daughter particles which do not have prompt decay/transition
for ^{125}Sb, it is the channel where $^{125}Te^m$ is the daughter particle with energy of 144.77 keV
for ^{210}Pb, it is one where the daughter ^{210}Bi is in the ground state.
- We have used the β spectrum as given in IAEA LiveChart (Nuclear Data Services database), which they have obtained using BetaShape.

M. Verpelli and L. Vrapcenjak, LiveChart of Nuclides. IAEA, Nuclear Data Section, 2020.
BetaShape. http://www.lnhb.fr/rd-activities/spectrum-processing-software/.
X. Mougeot, Phys. Rev. C 91 (May, 2015) 055504.

Final spectrum to compare with the XENON1T data is obtained after:

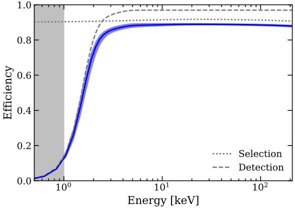
1. smearing by a detector resolution $\sigma_{\text{det}} = 0.45\,\text{keV}$

Slides, Chiara Capelli, 2017



[XENON] E. Aprile *et al.*, arXiv:2003.03825

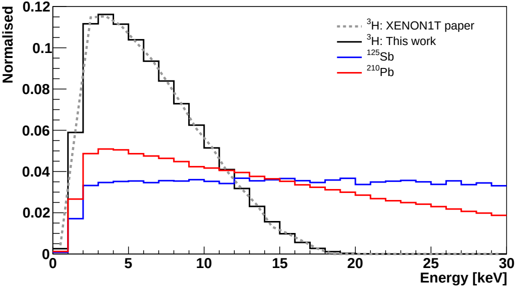
2. multiplying by the efficiency



[XENON] E. Aprile *et al.*, arXiv:2006.09721

3. binning as the available data with bin size of 1 keV

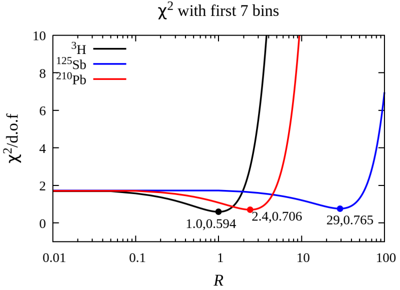
Normalised β decay spectra of ^{3}H, ^{125}Sb and ^{210}Pb

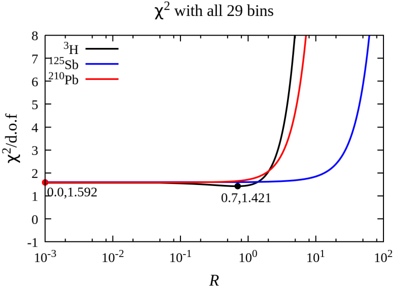


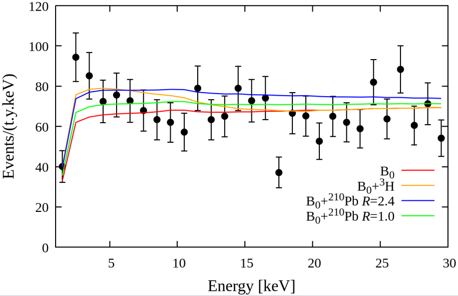
Gray dashed line: distribution of ^{3}H β decay from [XENON] E. Aprile *et al.*, arXiv:2006.09721

$$\chi^2 = \sum_{i=1}^{N} \frac{(n^i_{obs} - n^i_{exp})^2}{\sigma^2_{obs,i}}, \qquad n^i_{exp} = n^i_{B0} + n^i_{^3\mathrm{H}/^{125}\mathrm{Sb}/^{210}\mathrm{Pb}} \times R$$

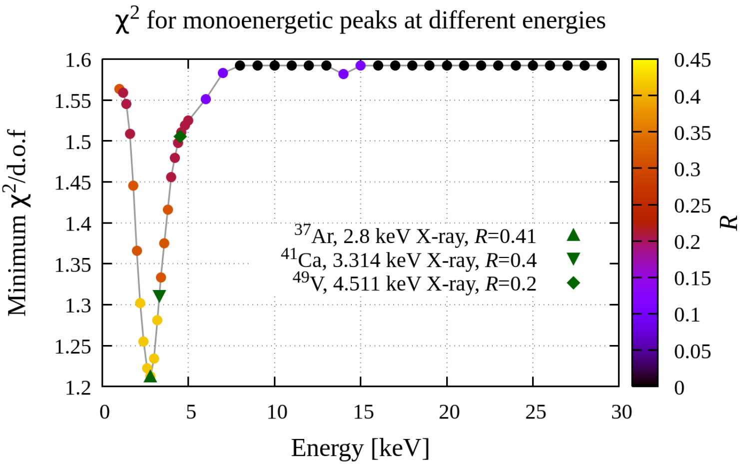
R: rate w.r.t the tritium fitted rate of XENON1T $\sim 159 \pm 51$ events/(t.y)







χ^2/d.o.f remains small for a range of R values for $N = 29$, reduces significance for $N = 7$



- A monoenergetic peak of energy $\sim$2.8 keV with $R = 0.41$ gives the best χ^2 fit to the observed data.
- However, **monoenergetic lines with energies between $\sim$2 keV and $\sim$4 keV can reduce the tension with data**.

Summary and conclusion

- Presence of cosmogenically produced isotopes depends on the purification process
  – one has to consider all of their presence to understand whether the getters get saturated before absorbing them completely.
- There also arises the question of how does one ensure that isotopes coming from other sources, like ^{210}Pb from the ^{222}Rn chain, are not present in amounts that can affect the ER spectrum.
- Our χ^2 analyses show that ^{210}Pb or any isotopes having β decays with smaller Q-values can reduce the tension with observed data.
- Also performed χ^2 with SR2 data – conclusions remain the same.
- A χ^2 scan over different monoenergetic peaks, which can come from atomic transitions of some of the isotopes, suggest that they can also contribute to the excess.
  The excess might also be due to the presence of multiple lines from many such isotopes present in small amounts.

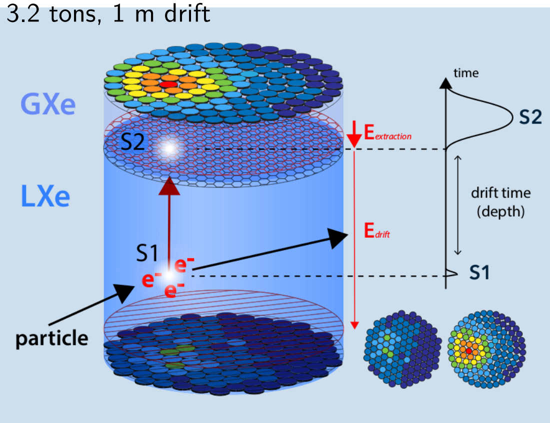
Summary and conclusion

- Many other isotopes can be produced from the cosmogenic activation of the detector materials as well.
  These might also contain some potential backgrounds which have not yet been studied.
- XENON1T performs dedicated calculations to study the low energy discrepancies due to the exchange or screening effects for ^{214}Pb and ^{85}Kr
  – not included properly in the IAEA LiveChart calculations
  – these might also be important for ^{125}Sb and ^{210}Pb and might affect their β spectra at low energies
  – not included in this work.

Many different isotopes exist that might be potential backgrounds to the XENON1T experiment –
this motivates a closer look into the small backgrounds that cannot be ignored anymore as these direct detection experiments move towards lower thresholds.

Thank You.

The Detector



Slides, Evan Shockley, LNGS Webinar, June 17th, 2020

S1 Light signal:
Prompt scintillation photons

S2 Charge signal:
Secondary scintillation photons from electroluminescence in GXe due to drifted electrons

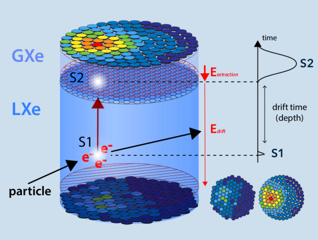
3D vertex reconstruction:
X,Y: S2 hit pattern
Z: drift time S2-S1

Slides, Michael Murra, ICHEP 2018, Seoul

The Detector and energy reconstruction

3.2 tons, 1 m drift

Slides, Evan Shockley, LNGS Webinar, June 17th, 2020



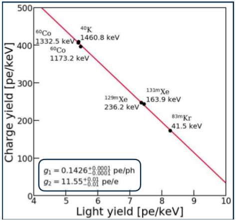
$$S1 \propto n_{ph} \qquad S2 \propto n_e$$
$$E = W(n_{ph} + n_e)$$
$$W = 13.7 \text{ eV/quantum}$$

$$\boxed{E = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)} \qquad (1)$$

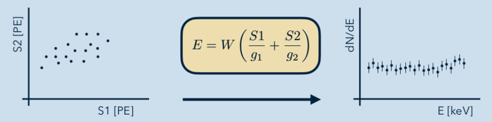
- g_1, g_2 found from fitting a straight line

$$\frac{S2}{E} = -\frac{g_2}{g_1}\frac{S1}{E} + \frac{g_2}{W}$$

to known energy sources



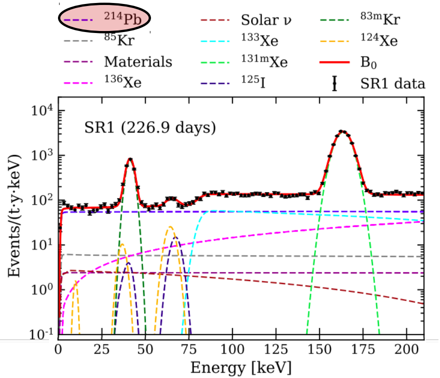
- Once g_1, g_2 known, energy of each event can be reconstructed using (1)



Backgrounds considered by the XENON1T collaboration

Back

[XENON] E. Aprile *et al.*, arXiv:2006.09721

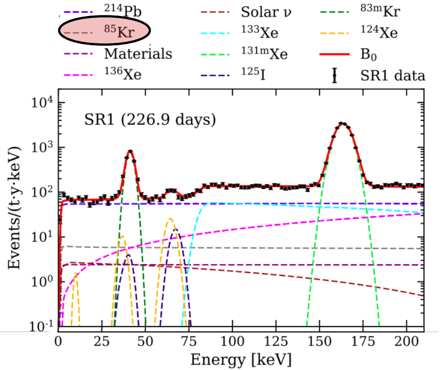


- from ^{222}Rn decay chain which is emanated into Liquid Xenon by materials
- β decays with a half life of 26.9 min and Q-value of 1.02 MeV

Backgrounds considered by the XENON1T collaboration

Back

[XENON] E. Aprile *et al.*, arXiv:2006.09721

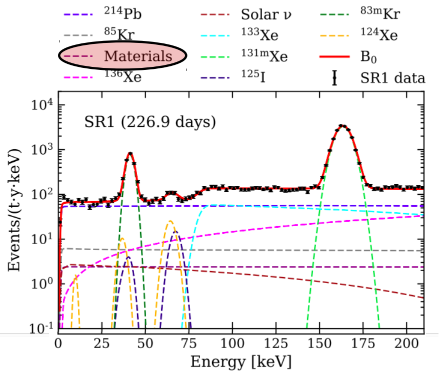


- from intrinsic ^{85}Kr, which is subdominant due to its removal via cryogenic distillation
- β decays with a half life of 10.739 years and Q-value of 687 keV

Backgrounds considered by the XENON1T collaboration

Back

[XENON] E. Aprile *et al.*, arXiv:2006.09721



- from γ emissions from radioimpurities in detector materials that induce Compton-scattered electrons
- subdominant in the region of interest due to the strict fiducial volume selection

Backgrounds considered by the XENON1T collaboration

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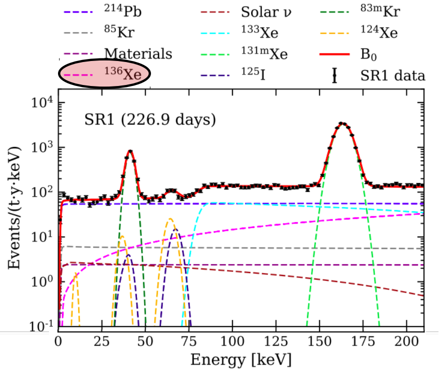
[XENON] E. Aprile *et al.*, arXiv:2006.09721



- it is intrinsic to xenon
- $2\nu\beta\beta$ emitter

Backgrounds considered by the XENON1T collaboration

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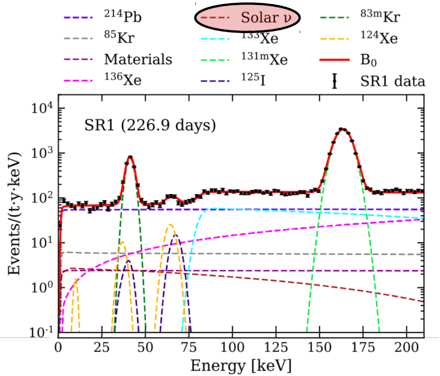
[XENON] E. Aprile *et al.*, arXiv:2006.09721



- elastic scattering of solar neutrinos off electrons expected to contribute subdominantly over the entire region of interest

Backgrounds considered by the XENON1T collaboration

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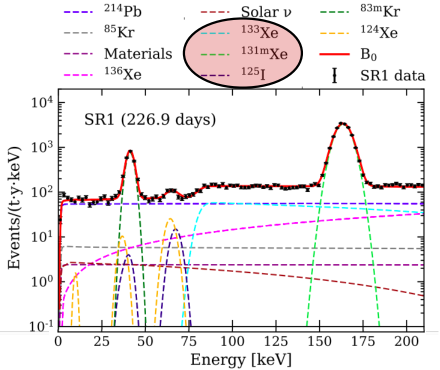
[XENON] E. Aprile *et al.*, arXiv:2006.09721



neutron-activated isotopes:

- ^{133}Xe: β decays to an excited state dominantly, emits an 81 keV prompt $\gamma \Rightarrow$ continuous spectrum starting at $\sim$75 keV
- ^{131}Xe^{m}: Internal Conversion produces a mono-energetic peak at 164 keV
- ^{125}I: a daughter of ^{125}Xe, decays via electron capture of K-shell (67.3 keV), L-shell (40.4 keV), M-shell (36.5 keV), with decreasing probability

Backgrounds considered by the XENON1T collaboration

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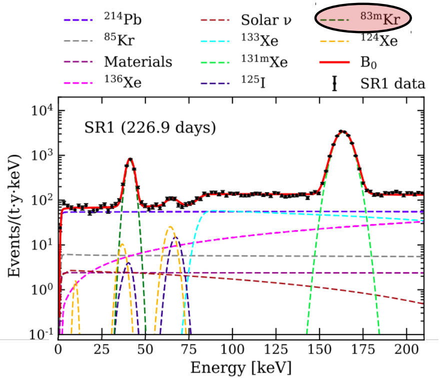
[XENON] E. Aprile *et al.*, arXiv:2006.09721



- from the trace amount of ^{83}Rb (EC, $T_{1/2} \sim 86$ days) in the Xenon recirculation system
- ^{83}Kr^{m} decays in two-steps

– 41.56 keV → 9.41 keV, $T_{1/2} \sim 1.83$ hours

– 9.41 keV → 0.0 keV, $T_{1/2} \sim 154$ ns

many of these events can be removed by vetoing multiple scatterings

A. Manalaysay *et al.*, arXiv:0908.0616 [astro-ph.IM]

Backgrounds considered by the XENON1T collaboration

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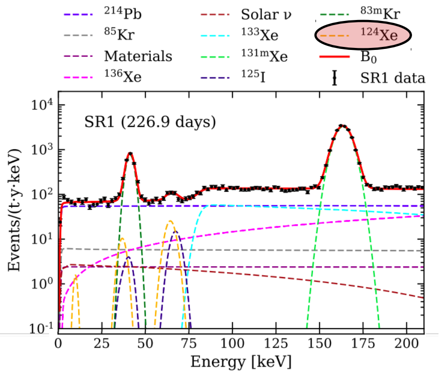
[XENON] E. Aprile *et al.*, arXiv:2006.09721

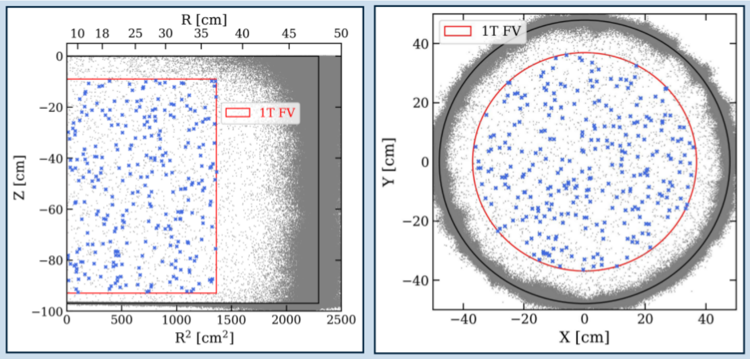


[XENON] E. Aprile *et al.*, Nature 568, 532–535 (2019)

- 2νECEC of ^{124}Xe – recently reported using mostly the same SR1 dataset (but different selection cuts)
- capture of
  - – two K-shell electrons (64.3 keV)
  - – a K-shell and L-shell electron (36.7 keV)
  - – two L-shell electrons (9.8 keV), with decreasing probability

Spatial dependence of the observed events

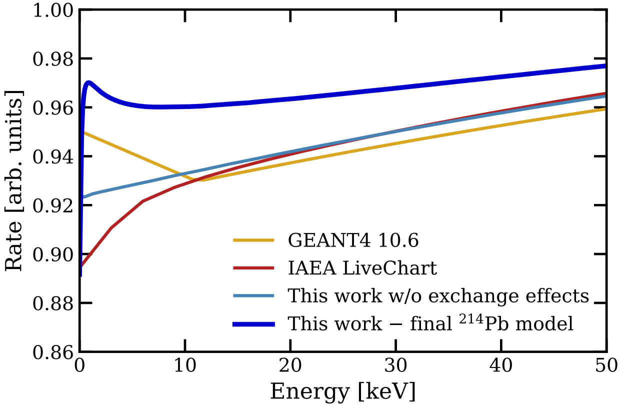
Slides, Evan Shockley, LNGS Webinar, June 17th, 2020



Events below 7 keV are uniformly distributed in the fiducial volume

Atomic screening and exchange effects

[XENON] E. Aprile *et al.*, arXiv:2006.09721



Atomic effects can increase rate at low energies