Estimation of the internal radiation background of Sn-Bi bolometers for *TIN.TIN*

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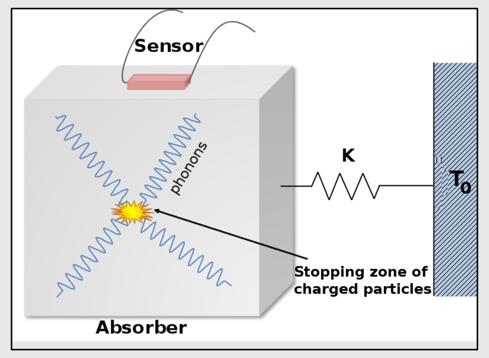
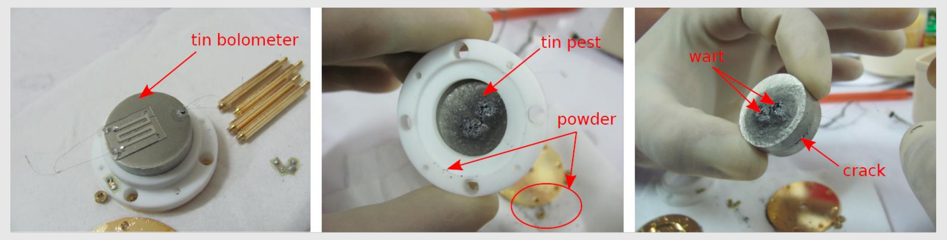
invisibles
neutrinos, dark matter & dark energy physics

Introduction

- Neutrinoless Double Beta Decay (NDBD) studies can reveal the fundamental nature of neutrinos (Majorana or Dirac).
- Experimental signature – peak at $Q_{\beta\beta}$ in the sum energy spectrum of the electrons.
- Tin-based cryogenic bolometer with Neutron Transmutation Doped Ge sensor [1] is being developed to study NDBD in ^{124}Sn in the upcoming underground facility, INO in India [2].
- ^{124}Sn has moderate isotopic abundance (5.8%) and moderate $Q_{\beta\beta}$ (2291.1 ± 1.8 keV) [3].
- Existing experimental limit for NDBD in ^{124}Sn
  $^{124}Sn \rightarrow {}^{124}Te + 2e^{-}$: $T_{1/2}^{0\nu} > 2.0 \times 10^{19}\ y$
  measured at Y2L using tin-loaded liquid scintillator detectors [4].





- Pure tin bolometers are susceptible to tin pest, which is a concern for the long term stability of the bolometer array.

- Several tin alloys were synthesized at TIFR Mumbai and tested for resistance to tin pest, in order to find a suitable candidate for a superconducting bolometer [5]. The best performance was seen in 0.22% Sn-Bi (Bi mass %) which has shown no signs of tin pest for more than a year.
- In the absence of an observed signal:

$$T_{1/2}^{0\nu} > \frac{\ln 2\, N_A i \varepsilon}{A f_{CL}} \sqrt{\frac{Mt}{B\Delta E}}$$

Expt	PID?	Bkg (cts/(keV.kg.y)
CUORE	No	1.4×10^{-2}
CUPID-0	Yes	3.6×10^{-3}

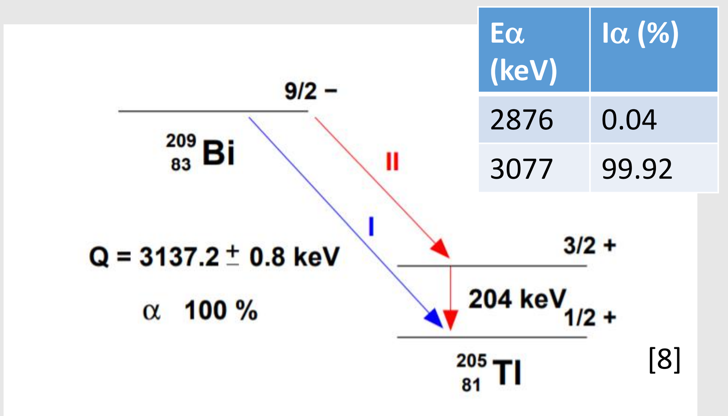
- The sensitivity of NDBD experiments are limited by the background in the region of interest around $Q_{\beta\beta}$ (ROI).
- Primary sources of background for NDBD experiments:
  - Primordial radioactivity from U/Th chains and ^{40}K.
  - Anthropogenic radioisotopes such as ^{137}Cs and ^{90}Sr.
  - Neutron induced reactions in the detector material and surrounding shielding materials.
  - Internal radioactive contamination of the detector.
  - Cosmic ray induced products (neutrons and radioisotopes).

- Internal sources of background are of particular concern as they are often the limiting source of background.
- Introduction of Bi into the Sn matrix can change the background in the ROI and this change needs to be critically evaluated.
- This poster discusses GEANT4 [6] based simulation studies to estimate the internal backgrounds arising in Sn-Bi bolometers. The projected sensitivity of *TIN.TIN* for NDBD was estimated using the total background index.

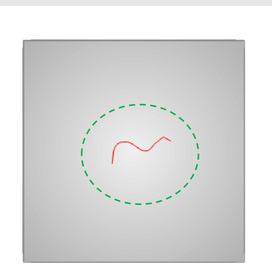
Radioactive background from $^{209}Bi\ \alpha$ decay

- In 2003, measurements using a scintillating BGO bolometer revealed that ^{209}Bi undergoes a rare α decay [7].
- The half-life of the decay is $T_{1/2} = (1.9 \pm 0.2) \times 10^{19}\ y$, which is comparable to that of some $2\nu\beta\beta$ emitters.

Eα (keV)	Iα (%)
2876	0.04
3077	99.92

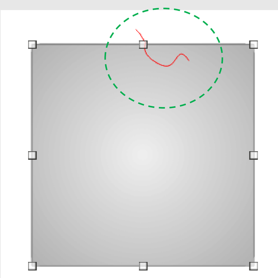


Bulk event



$E_{dep} = E_{\alpha}$

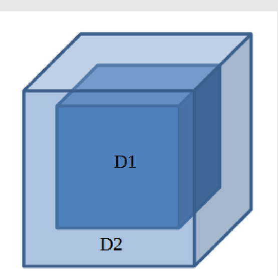
Surface event



E_{dep} = 0 to E_{α}

- Surface events can increase the background in ROI (2291 ± 25 keV) since they can lead to partially contained events.

- GEANT4 simulation code was developed to assess the background from the surface events.



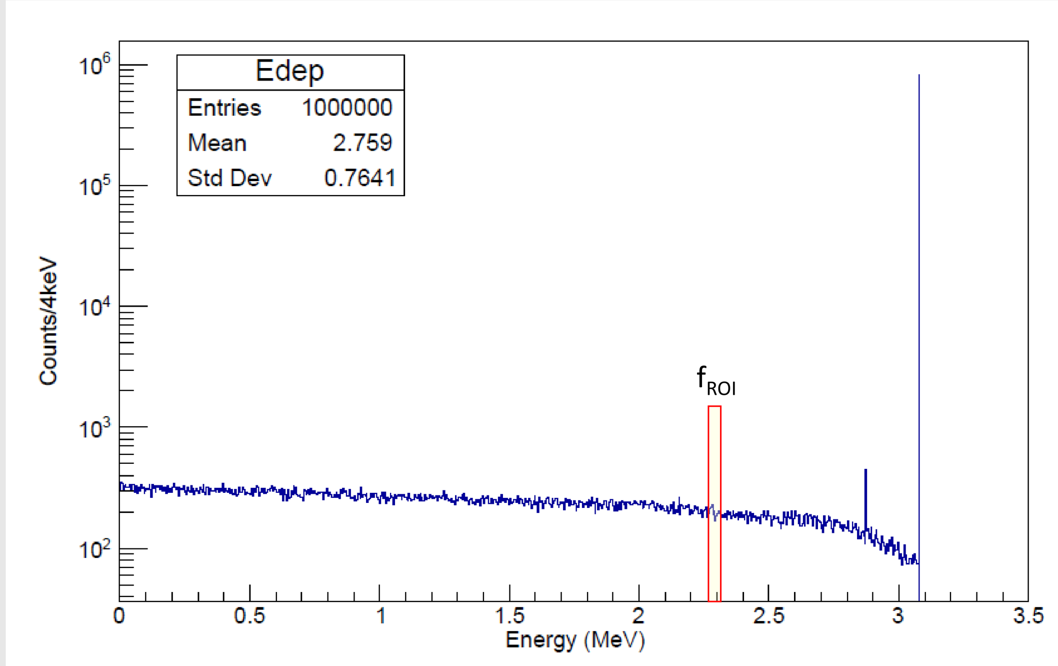
Geometry:
- The bolometer was split into two sensitive detector regions D1 and D2.
- The size of the bolometer was varied – 27 cc, 64 cc and 125 cc.
- The range of a 3 MeV α particle in Sn is ~ 8 μm. The width of D2 was chosen as 10 μm to allow for straggling + additional tolerance.

Material:
- Sn-Bi of various concentrations – 0.25%, 0.50%, 0.75% and 1.00% Sn-Bi (Bi by mass %).
- Natural isotopic concentration was chosen for both Sn and Bi.

Particle Generation:
- Only surface events were generated, in order to make the code computationally efficient.
- Energy of the α particle was generated according to the branching ratios listed on the National Nuclear Data Center [9].
- Initial momentum direction (unit vector) was chosen isotropically in a unit sphere.

Physics:
- The standard physics list QGSP_BERT_HP was used.

Analysis:
- ROOT based analysis codes were developed to extract the fraction of events contributing to the ROI (f_{ROI}) from the total energy deposition spectrum. The corresponding background index was calculated using the f_{ROI}.



0.25 % Bi

Volume	Bkg (cts/(keV.kg.y)
27 cc	2.6×10^{-5}
64 cc	2.0×10^{-5}
125 cc	1.6×10^{-5}

0.50 % Bi

Volume	Bkg (cts/(keV.kg.y)
27 cc	5.3×10^{-5}
64 cc	4.2×10^{-5}
125 cc	3.1×10^{-5}

0.75 % Bi

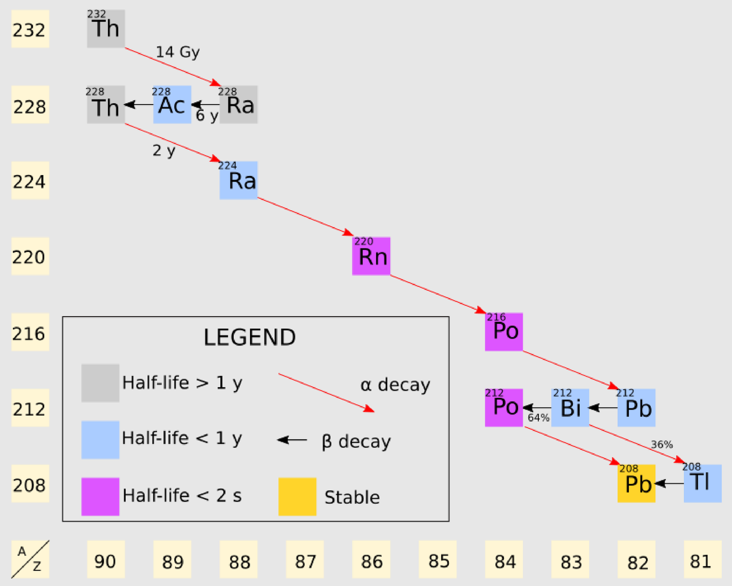
Volume	Bkg (cts/(keV.kg.y)
27 cc	7.8×10^{-5}
64 cc	5.9×10^{-5}
125 cc	4.7×10^{-5}

1.00 % Bi

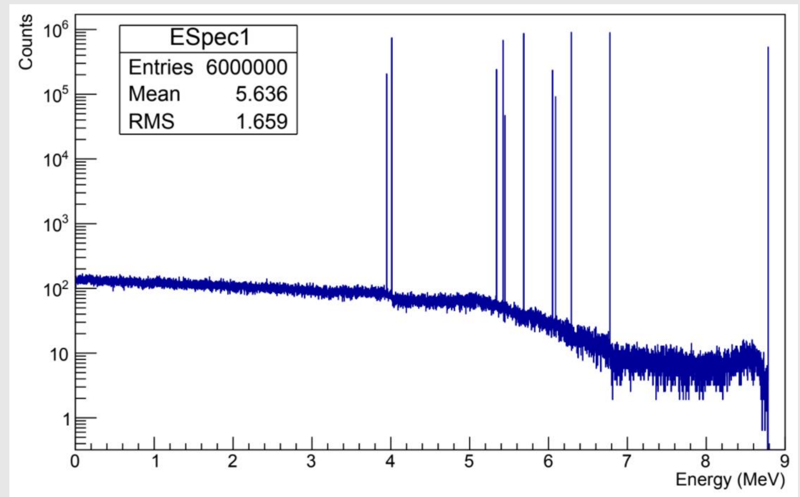
Volume	Bkg (cts/(keV.kg.y)
27 cc	1.1×10^{-4}
64 cc	7.6×10^{-5}
125 cc	6.1×10^{-5}

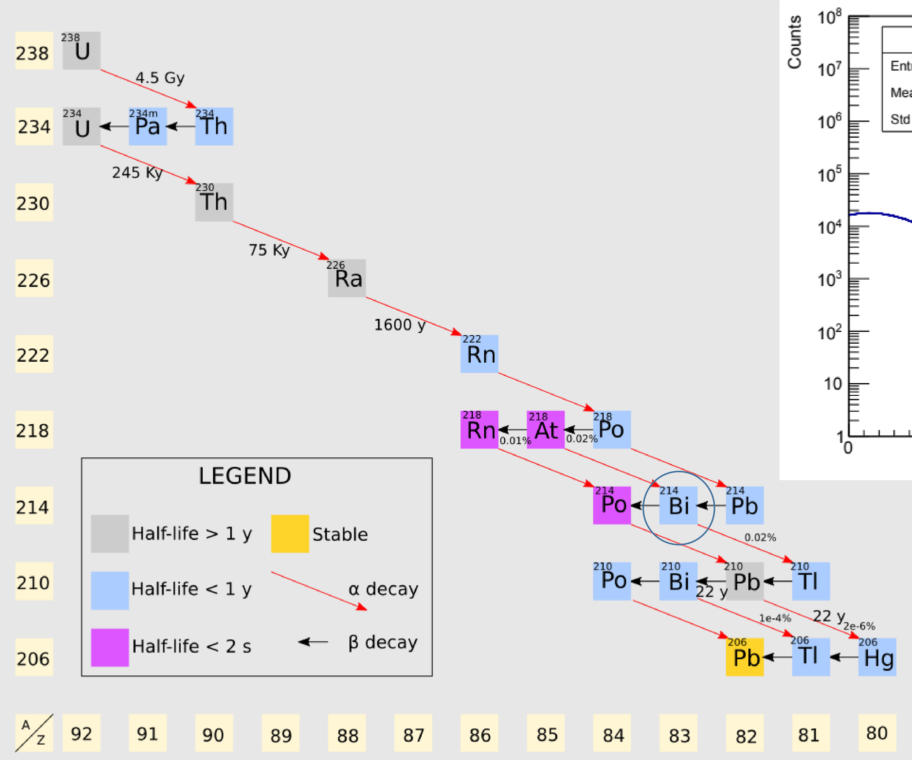
Internal background from ^{238}U and ^{232}Th chain

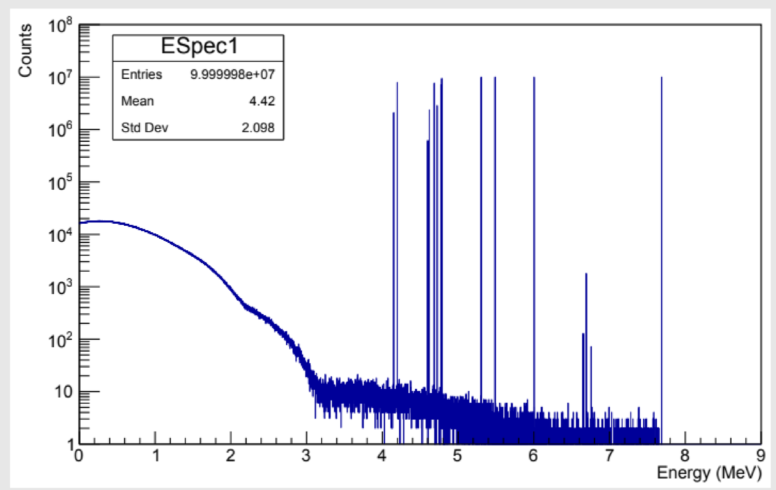
- In the case of the Uranium and Thorium decay chains [9], the progenitors ^{238}U and ^{232}Th have the longest half-lives.
- Secular equilibrium assumed.
- For studying the background from various β emitters, it was necessary to generate bulk events in this case.
- A radioimpurity level of 0.2 ppt was assumed (similar to the radiopurity level of the CUORE bolometer [10]).
- The estimated internal background from ^{238}U/^{232}Th chain was compared to that from ^{209}Bi.



α dominated







β dominated

27 cc

Impurity level	Source	Bkg (cts/(keV.kg.y)
0.2 ppt	Th chain	5.7×10^{-5}
0.2 ppt	U chain	5.6×10^{-3}
0.25%	^{209}Bi	2.6×10^{-5}
Total		5.7×10^{-3}

64 cc

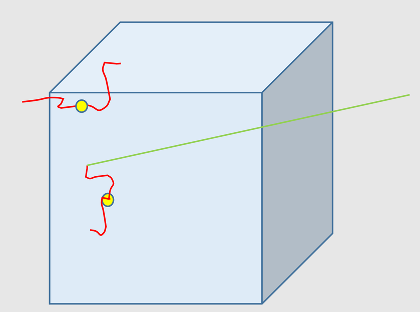
Impurity level	Source	Bkg (cts/(keV.kg.y)
0.2 ppt	Th chain	3.9×10^{-5}
0.2 ppt	U chain	5.7×10^{-3}
0.25%	^{209}Bi	2.0×10^{-5}
Total		5.8×10^{-3}

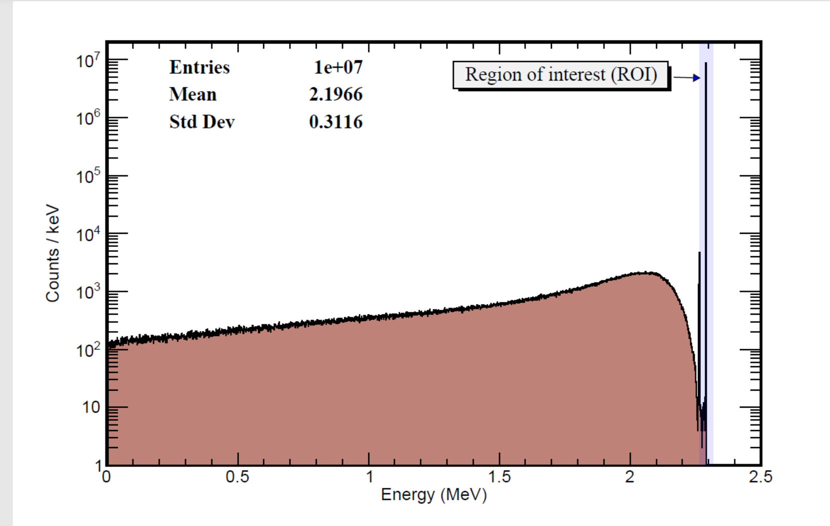
125 cc

Impurity level	Source	Bkg (cts/(keV.kg.y)
0.2 ppt	Th chain	3.1×10^{-5}
0.2 ppt	U chain	5.8×10^{-3}
0.25%	^{209}Bi	1.6×10^{-5}
Total		5.8×10^{-3}

Sensitivity of $Sn - Bi$ bolometers for $0\nu\beta\beta$

$$T_{\frac{1}{2}}^{0\nu}(1\sigma) > \frac{\ln 2\, N_A i \varepsilon}{A} \sqrt{\frac{Mt}{B\Delta E}}$$



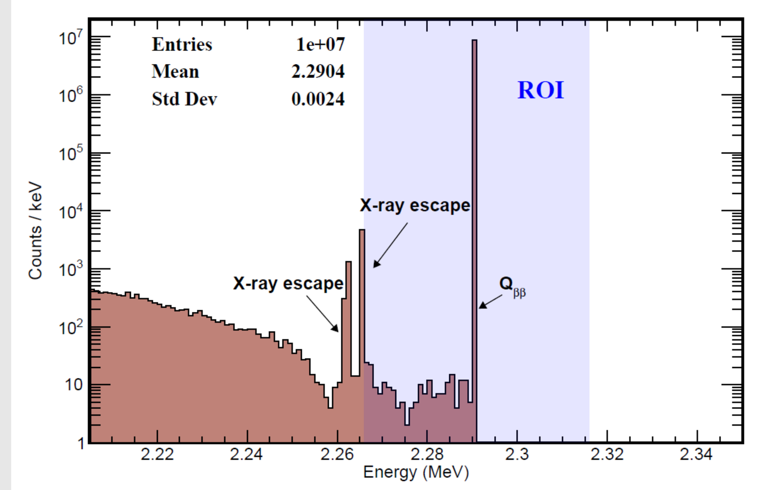


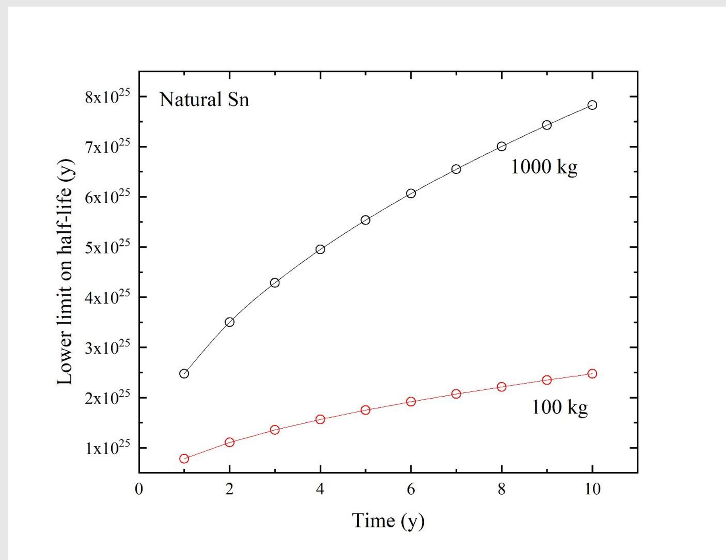
- Loss from surface events
- Bremsstrahlung events (bulk + surface)

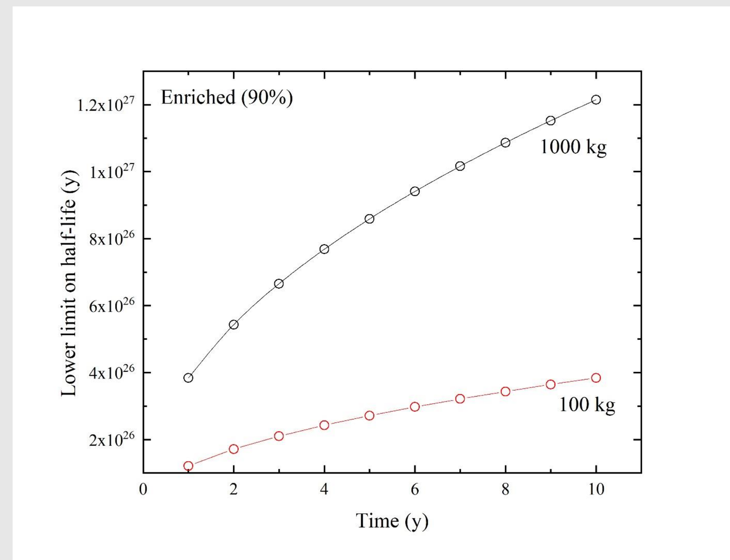
GEANT4 based $0\nu\beta\beta$ event generator

Events were generated isotropically in a unit sphere, neglecting angular correlations between the electrons in the final state.

Detector size	Efficiency (%)
27 cc	86.6 %
64 cc	89.0 %
125 cc	90.7 %







Projected sensitivity for 27 cc bolometer, assuming 5 keV energy resolution (σ_E).

Summary

- The background in the region of interest for cryogenic bolometers is usually limited by backgrounds originating from sources which are internal to the bolometer.
- This poster describes GEANT4 based simulations of two such sources for Sn-Bi bolometers
  - $^{209}Bi\ \alpha$ decay
  - α and β background from ^{238}U and ^{232}Th chain (radioimpurities in the Sn-Bi alloy).
- The radioactivity from $^{209}Bi\ \alpha$ decay was found to be negligible.
- In comparison, the background from ^{238}U dominated by 2 orders of magnitude.
- The total background was within 10^{-2} cts/(keV.kg.y), which is the typical background index for the first gen. expt.
- The projected sensitivity of *TIN.TIN* for NDBD was estimated for natural and 90% enriched (in ^{124}Sn) isotopic abundance.

References

[1] S. Mathimalar *et. al.*, Nucl. Inst. Meth. B **345** (2015), 33.
[2] V. Nanal, EPJ Web of Conferences **66** (2014), 08005.
[3] M. Wang *et. al.*, Chin Phys. C **41** (2017), 030003.
[4] M. J. Hwang *et. al.*, Astropart. Phys. **31** (2009), 412.
[5] A Mazumdar *et. al.*, Mater. Res. Express **6** (2019), 076521.
[6] S. Agostinelli *et. al.*, Nucl. Inst. Meth. A **506** (2003), 250.
[7] P. De Marcillac *et. al.*, Nature **422** (2003), 876.
[8] J.W. Beeman *et. al.*, Phys. Rev. Lett. **108** (2012), 062501.
[9] https://www.nndc.bnl.gov/
[10] F. Alessandria *et. al.*, Astroparticle Physics **35** (2012), 839.

Acknowledgements

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