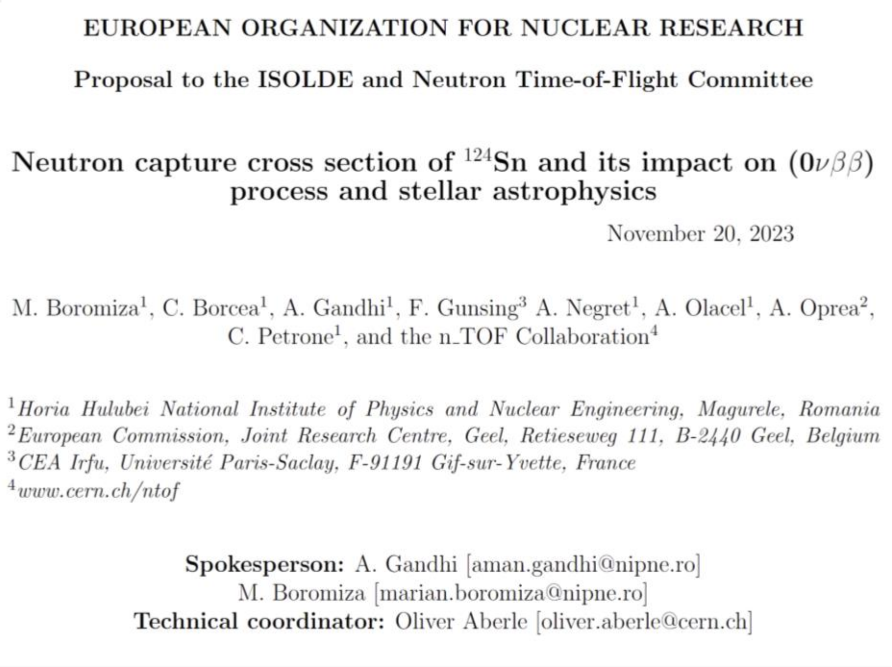

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Neutron capture cross section of ^{124}Sn and its impact on $(0\nu\beta\beta)$ process and stellar astrophysics

November 20, 2023

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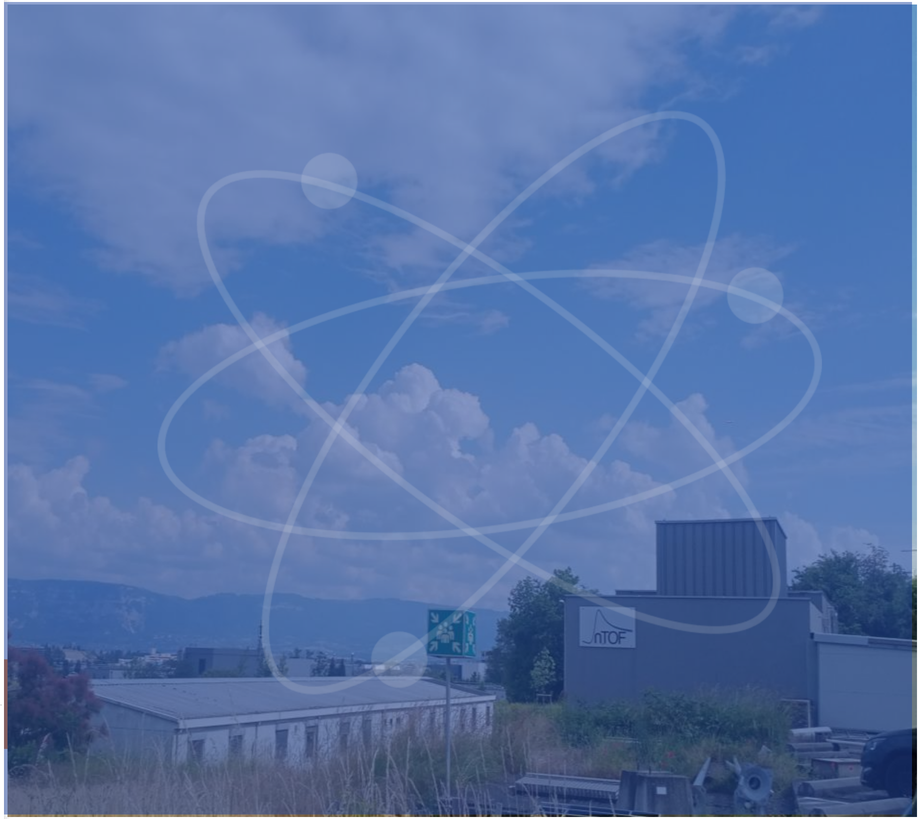
Technical coordinator: Oliver Aberle [oliver.aberle@cern.ch]



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Motivation-

Why do we need ^{124}Sn(n,γ) cross section data?

Background assessment of 0$\nu\beta\beta$ decay experiments

Background: Neutrons

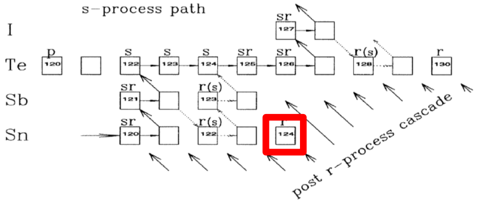
Cosmogenically-produced neutrons

Aharmim, B., et al. Physical Review D 100.11 (2019): 112005.

Rocks [^{nat}Th, ^{nat}U] (α,n)-produced neutrons

s-r process nucleosynthesis modeling

MACS estimation for r-only nuclei



M. Arnould, K. O. H. J. I. Takahashi,Reports on Progress in Physics 62.3 (1999): 395

Motivation-

Worldwide experiments done or planned for neutrinoless double-β decay studies for ^{124}Sn ----> ^{124}Te:

India

In future

Lab: *Indian Neutrino Observatory (INO)*

Detector: Sn cryogenic superconducting bolometer (TIN.TIN -The India based TIN detector)

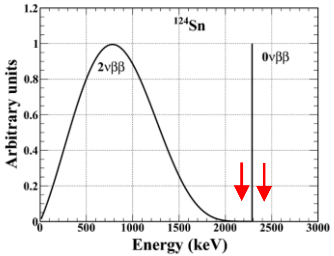
Nanal, Vandana.EPJ Web of Conferences, EDP Sciences 66 (2014)

South Korea

Lab: *YangYang Underground Laboratory (Y2L)-2009*

Detector : tin-loaded liquid scintillator for an active source-detector technique

Hwang, M. J., et al., Astroparticle Physics 31.6 (2009): 412-416.



Singh, M.K., et al. Indian J Phys 94, 1263-1270 (2020).

Background assessment of $0\nu\beta\beta$ decay experiments

- ❑ ^{124}Sn is one of the neutrinoless double beta decay ($0\nu\beta\beta$) candidates
- ❑ To measure this decay process is to measure the $0\nu\beta\beta$ decay peak which is at an energy equal to the Q-value of the process, i.e., 2292.7 (4) keV
- ❑ $0\nu\beta\beta$ is a second order weak interaction process and the event rates are very low since $T_{1/2} > 10^{21}$ y -> the neutron-induced background is a big limiting factor**
- ❑ Such measurements are extremely sensitive to **background signals which can mimic the signal of interest**: the neutron-induced background can produce γ-ray events in and around the region of interest (ROI) i.e., the Q-value region

*Dawson, J., et al., Physical Review C 78.3 (2008): 035503

**Gupta, G., et al., Applied Radiation and Isotopes 158 (2020): 108923*

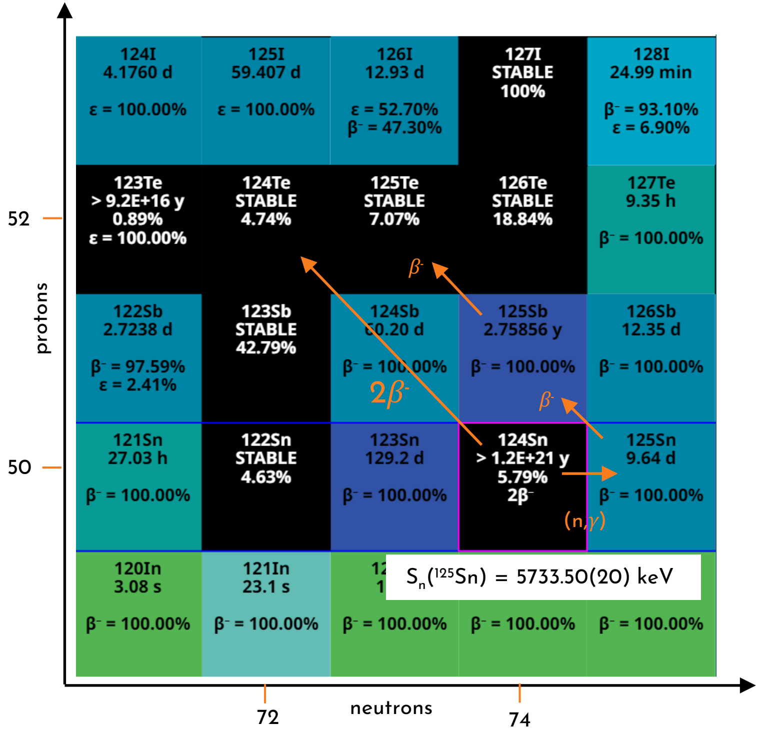
Motivation-

Background assessment of 0$\nu\beta\beta$ decay experiments

- ❑ Gammas following neutron capture on ^{124}Sn can mimic the 0$\nu\beta\beta$ decay signal
- ❑ Literature* shows that, after bombarding a ^{124}Sn sample with a neutron thermal flux and measuring the offline/delayed γ-rays following neutron capture and subsequent beta decays with a HPGe detector, a strong summing peak of 2288.2 keV has been observed*

$Q_{2\beta^-}$ = 2292.7 (4) keV

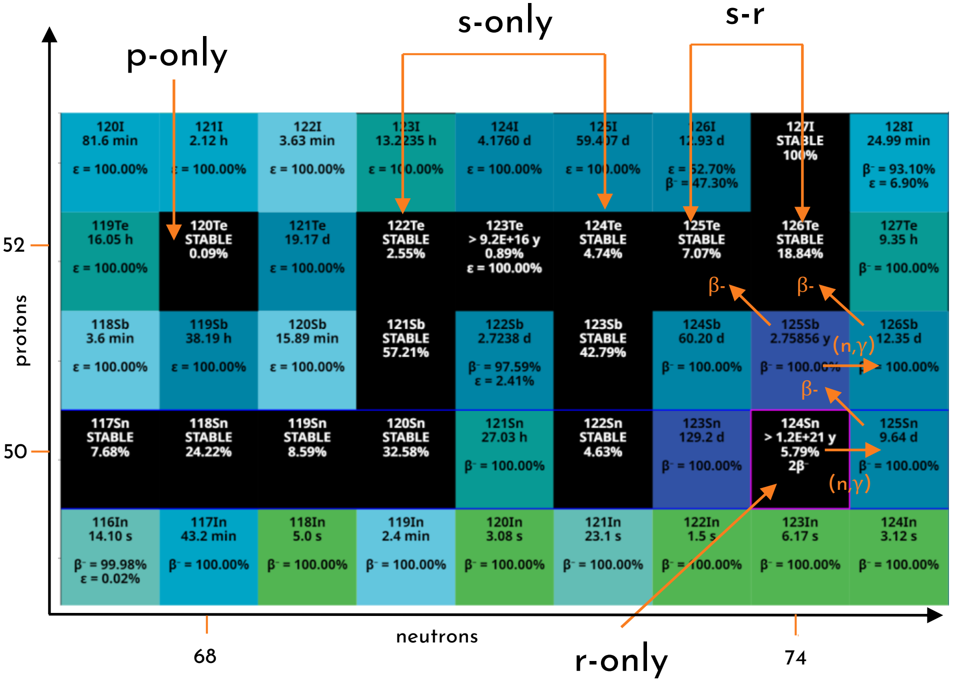
*Gupta, G., et al., Applied Radiation and Isotopes 158 (2020): 108923



124I 4.1760 d ε = 100.00%	125I 59.407 d ε = 100.00%	126I 12.93 d ε = 52.70% β^- = 47.30%	127I STABLE 100%	128I 24.99 min β^- = 93.10% ε = 6.90%
123Te > 9.2E+16 y 0.89% ε = 100.00%	124Te STABLE 4.74%	125Te STABLE 7.07%	126Te STABLE 18.84%	127Te 9.35 h β^- = 100.00%
122Sb 2.7238 d β^- = 97.59% ε = 2.41%	123Sb STABLE 42.79%	124Sb 60.20 d β^- = 100.00%	125Sb 2.75856 y β^- = 100.00%	126Sb 12.35 d β^- = 100.00%
121Sn 27.03 h β^- = 100.00%	122Sn STABLE 4.63%	123Sn 129.2 d β^- = 100.00%	124Sn > 1.2E+21 y 5.79% 2β^-	125Sn 9.64 d β^- = 100.00%
120In 3.08 s β^- = 100.00%	121In 23.1 s β^- = 100.00%	12 1 β^- = 100.00%	β^- = 100.00%	β^- = 100.00%

$S_n(^{125}Sn)$ = 5733.50(20) keV

Motivation-



120I 81.6 min ε = 100.00%	121I 2.12 h ε = 100.00%	122I 3.63 min ε = 100.00%	123I 13.2235 h ε = 100.00%	124I 4.1760 d ε = 100.00%	125I 59.407 d ε = 100.00%	126I 12.93 d ε = 52.70% β^- = 47.30%	127I STABLE 100%	128I 24.99 min β^- = 93.10% ε = 6.90%
119Te 16.05 h ε = 100.00%	120Te STABLE 0.09%	121Te 19.17 d ε = 100.00%	122Te STABLE 2.55%	123Te > 9.2E+16 y 0.89% ε = 100.00%	124Te STABLE 4.74%	125Te STABLE 7.07%	126Te STABLE 18.84%	127Te 9.35 h β^- = 100.00%
118Sb 3.6 min ε = 100.00%	119Sb 38.19 h ε = 100.00%	120Sb 15.89 min ε = 100.00%	121Sb STABLE 57.21%	122Sb 2.7238 d β^- = 97.59% ε = 2.41%	123Sb STABLE 42.79%	124Sb 60.20 d β^- = 100.00%	125Sb 2.75856 y β^- = 100.00%	126Sb 12.35 d β^- = 100.00%
117Sn STABLE 7.68%	118Sn STABLE 24.22%	119Sn STABLE 8.59%	120Sn STABLE 32.58%	121Sn 27.03 h β^- = 100.00%	122Sn STABLE 4.63%	123Sn 129.2 d β^- = 100.00%	124Sn > 1.2E+21 y 5.79% $2\beta^-$	125Sn 9.64 d β^- = 100.00%
116In 14.10 s β^- = 99.98% ε = 0.02%	117In 43.2 min β^- = 100.00%	118In 5.0 s β^- = 100.00%	119In 2.4 min β^- = 100.00%	120In 3.08 s β^- = 100.00%	121In 23.1 s β^- = 100.00%	122In 1.5 s β^- = 100.00%	123In 6.17 s β^- = 100.00%	124In 3.12 s β^- = 100.00%

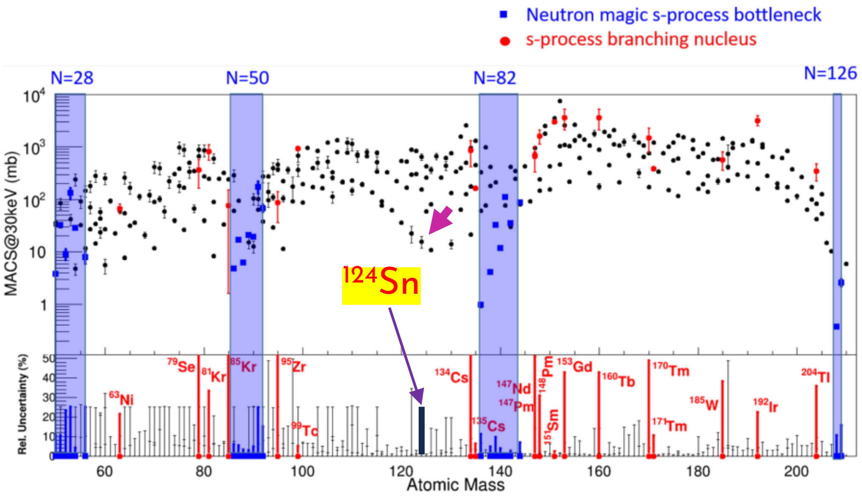
M. Arnould, K. O. H. J. I. Takahashi,Reports on Progress in Physics 62.3 (1999): 395

s-r process nucleosynthesis modeling

- ☐ Several neutron-rich stable isotopes in the A=124 mass region, including ^{124}Sn, are not reached by the s-process because of their short-lived neighbours. ^{124}Sn is synthesized by the r-only neutron capture process

- ☐ To better quantify the solar system s-process-generated abundance of 'Te' stable isotopes, which also have r-process contributions, using stellar models requires, among other things, reliable and low uncertainty Maxwellian Averaged Cross Sections (MACS) for ^{124}Sn

Present status of ^{124}Sn(n,γ) MACS data - where are we?



Domingo-Pardo, C., Babiano-Suarez, V., Balibrea-Correa, J. et al., Eur. Phys. J. A 59.8 (2023)

MACS status in kadonis1.0 (2013) database:

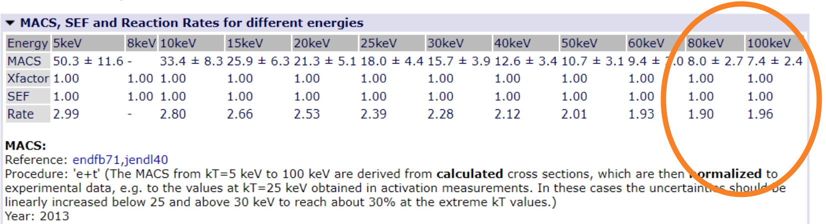
Recommended value (Total MACS): 15.7 ± 3.9 mb (24%)
Partial cross section to isomer: 9.79 ± 0.11 (1.12%)

Experimentally-extracted MACS:

V. Timokhov et al., (1989): @30 keV: 16.0 ± 2.4 mb (15%)

W. Stadler, Diploma Thesis TUV, (1998):
@25 keV: 11.25 ± 0.13 (1.15%)-Partial cross section to ^{125m}Sn:
@52 keV: 9.33 ± 0.16 (1.71%)-Partial cross section to ^{125m}Sn:

Extrapolated values to: 5 keV & 100 keV:



▾ MACS, SEF and Reaction Rates for different energies

Energy	5keV	8keV	10keV	15keV	20keV	25keV	30keV	40keV	50keV	60keV	80keV	100keV
MACS	50.3 ± 11.6	-	33.4 ± 8.3	25.9 ± 6.3	21.3 ± 5.1	18.0 ± 4.4	15.7 ± 3.9	12.6 ± 3.4	10.7 ± 3.1	9.4 ± .0	8.0 ± 2.7	7.4 ± 2.4
Xfactor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SEF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rate	2.99	-	2.80	2.66	2.53	2.39	2.28	2.12	2.01	1.93	1.90	1.96

MACS:
Reference: endfb71,jendl40
Procedure: 'e+t' (The MACS from kT=5 keV to 100 keV are derived from **calculated** cross sections, which are then **ormalized** to experimental data, e.g. to the values at kT=25 keV obtained in activation measurements. In these cases the uncertaint s shoul e linearly increased below 25 and above 30 keV to reach about 30% at the extreme kT values.)
Year: 2013

https://exp-astro.de/kadonis1.0/selementquery.php?isotope=124Sn

Additional Motivation-

- Nb_3Sn* compound is a component of the super-conducting wires used in the electromagnets surrounding the hot plasma during the ITER fusion experiment, or in the beam guiding system of the LHC & FCC @CERN**

- These super-conducting magnets are exposed to a very intense neutron field coming from hot plasma or LHC interaction point

- The initial neutron flux has energies in the MeV region (see figure) but after thermalization these neutrons can be captured

- Due to large radiation sensitivity of Nb_3Sn superconducting state, it is essential to examine how its superconducting properties are affected by radiation damage, in particular, by the neutron capture channel on ^{124}Sn

*Nishimura, A., et al., Superconductor Science and Technology 32.2 (2019): 024004

**Baumgartner, Thomas, et al. Superconductor Science and Technology 27.1 (2013): 015005.

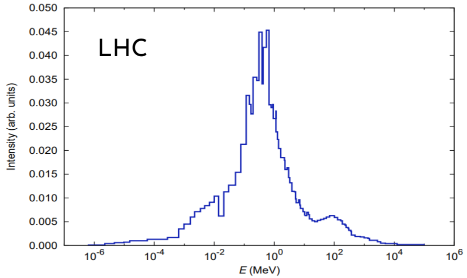


Figure 1.1.: Calculated neutron spectrum at the inner winding of quadrupole Q2 [24].

Baumgartner, Thomas. Effects of fast neutron irradiation on critical currents and intrinsic properties of state-of-the-art Nb_3Sn wires. na, 2013.

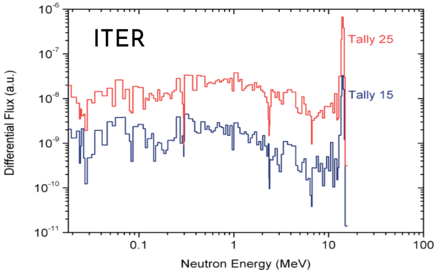
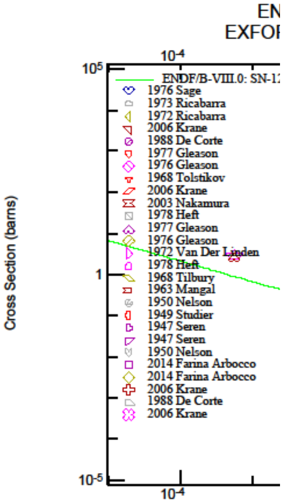
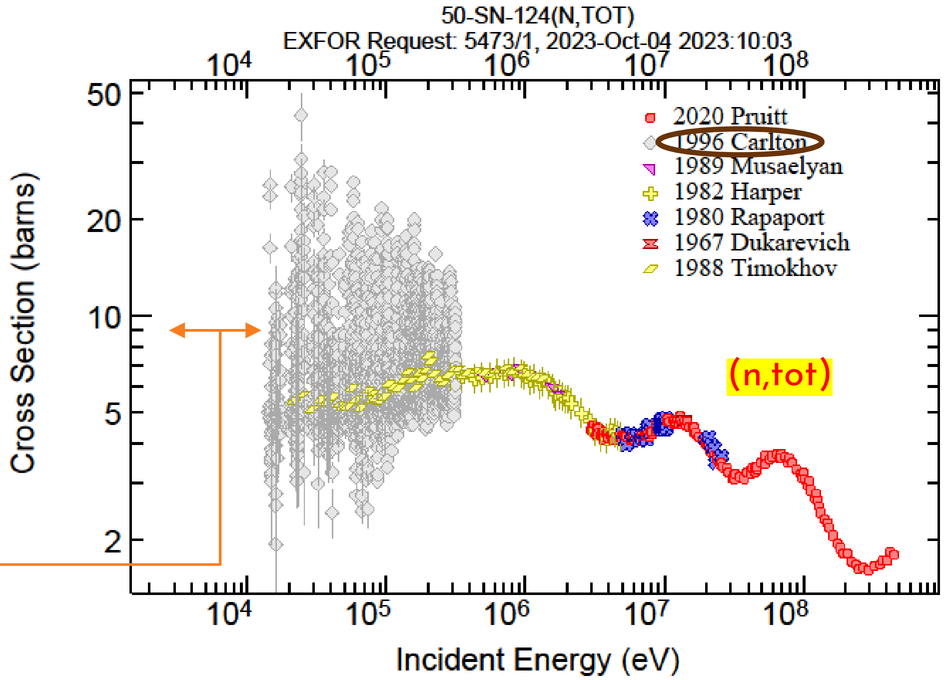


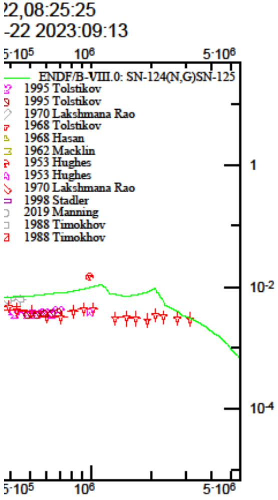
Figure 14. Neutron spectra at tally 15 and tally 25.

Krasilnikov, Vitaly, MunSeong Cheon, and Luciano Bertalot. Advanced Technologies and Applications of Neutron Activation Analysis (2019): 71-87.

Present status of ^{124}Sn(n,γ) cross section data - where are we?

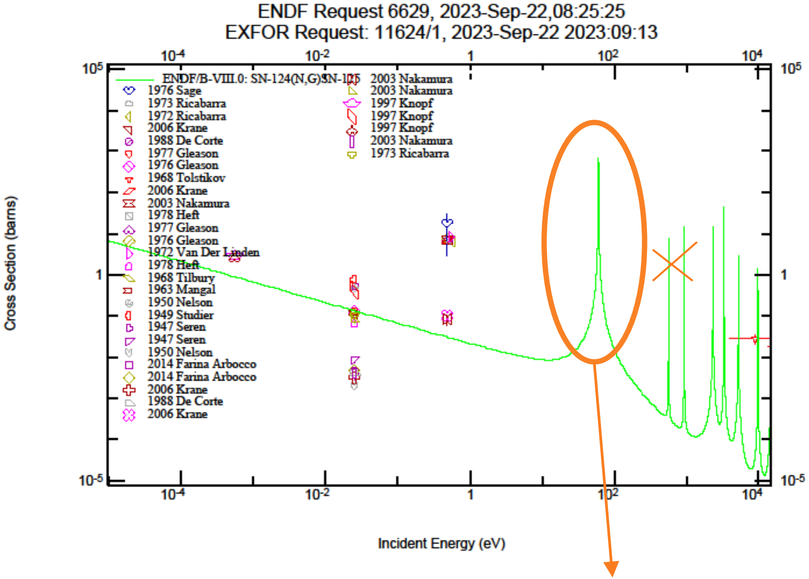


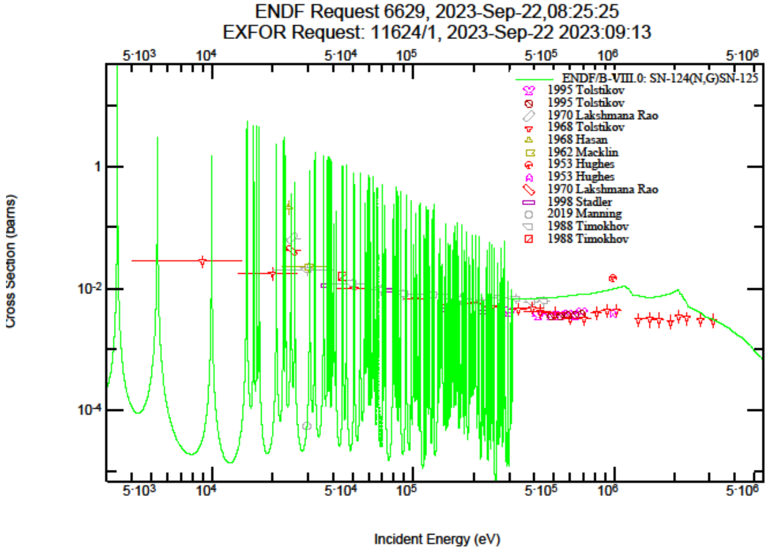




By Fukuta (1963) and Adamchuk (1965) R.P available in Mughabghab (2018)

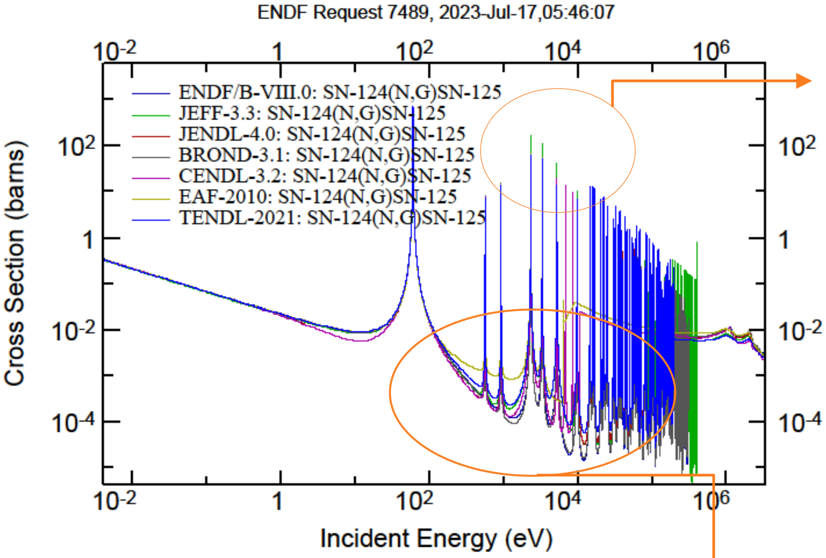
Present status of ^{124}Sn(n,γ) cross section data - where are we?

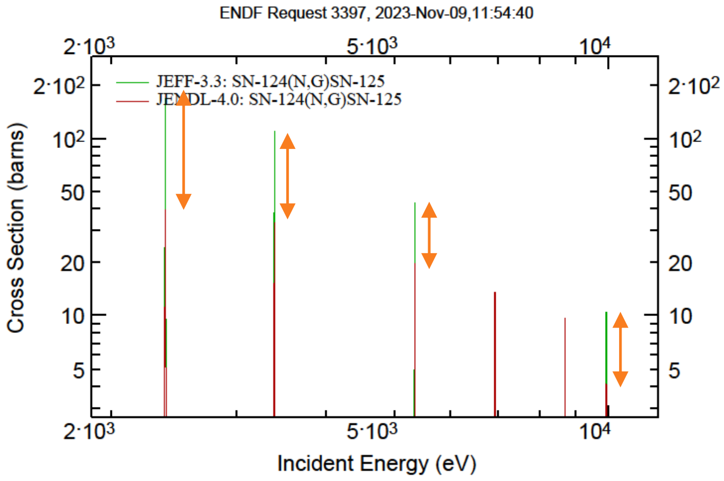


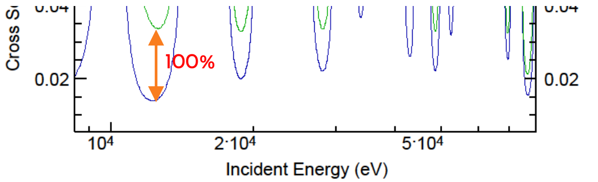


A. Kimura et al., EPJ Web of Conferences 146, 11031 (2017) in ANNRI at MLF/J-PARC (ND2016 proceedings)

Present status of ^{124}Sn(n,γ) cros







Experimental Details-

Where & How the $^{124}Sn(n,\gamma)$ cross section will be measured ?

EAR1 or EAR2 ?

- ❑ Depends on neutron energy resolution of EAR1 versus EAR2

- ❑ Depends on the mass & enrichment of sample

Experimental Details-

EAR1 or EAR2 - Neutron Energy resolution?

Table: Average distance in-between resonances and energy resolution at EAR1 versus EAR2:

Neutron Energy range	No. of resonances (ENDF/B-VIII.0)	Avg. distance between Capture Resonances	Energy resolution in EAR1 *	Energy resolution in EAR2 *
50 eV to 10 keV	7	1200 eV	10 eV	200 eV
10 keV to 100 keV	67	1300 eV	300 eV	3000 eV
100 keV to 200 keV	68	1500 eV	800 eV	-
200 keV to 314 keV	47	2400 eV	1200 eV	-

*Guerrero, C., et al. The European Physical Journal A 49 (2013): 1-15.

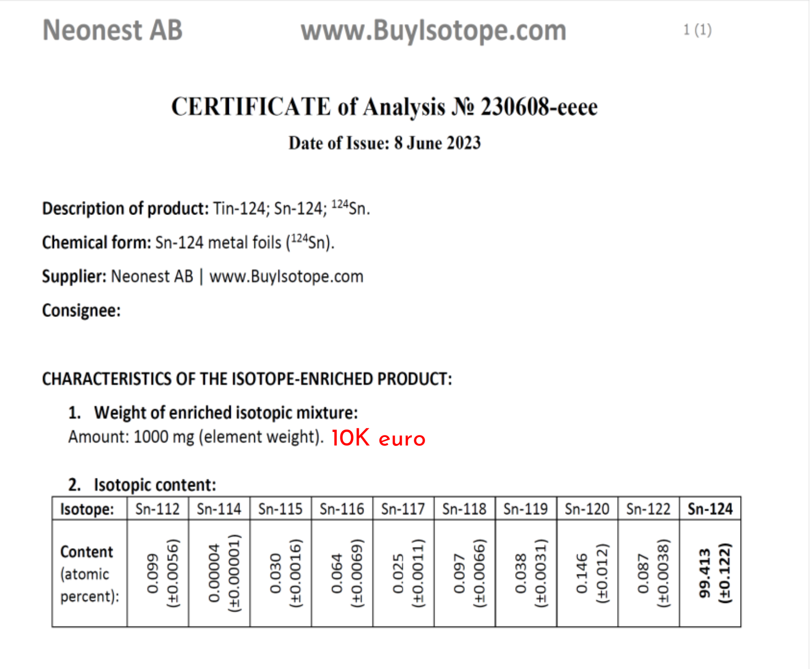
*Lerendegui-Marco, J., et al. The European Physical Journal A 52 (2016): 1-10.

To resolve up to 10 keV

To resolve up to 100 keV

Experimental Details-

^{nat}Sn or Enriched ^{124}Sn - Why enriched sample?



Neonest AB www.BuyIsotope.com 1 (1)

CERTIFICATE of Analysis № 230608-eeee

Date of Issue: 8 June 2023

Description of product: Tin-124; Sn-124; ^{124}Sn.

Chemical form: Sn-124 metal foils (^{124}Sn).

Supplier: Neonest AB | www.BuyIsotope.com

Consignee:

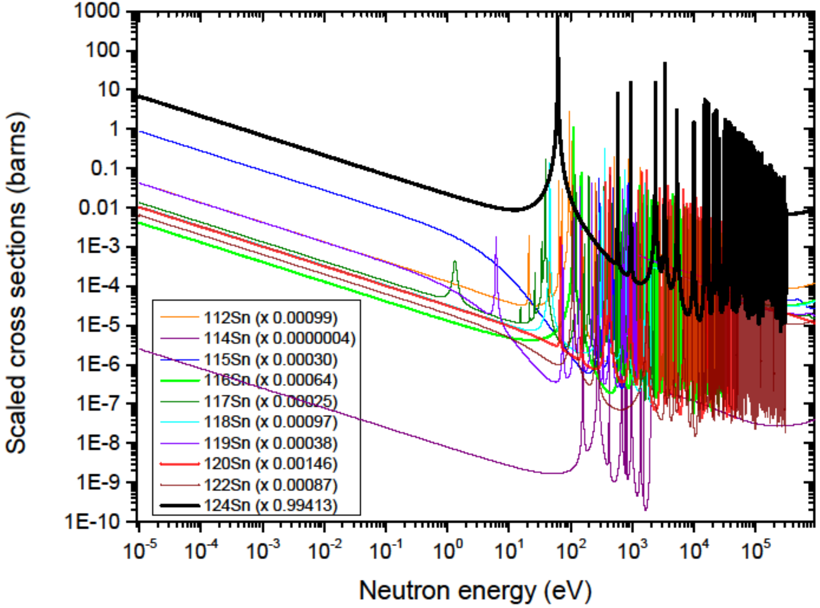
CHARACTERISTICS OF THE ISOTOPE-ENRICHED PRODUCT:

1. **Weight of enriched isotopic mixture:**
Amount: 1000 mg (element weight). 10K euro

2. **Isotopic content:**

Isotope:	Sn-112	Sn-114	Sn-115	Sn-116	Sn-117	Sn-118	Sn-119	Sn-120	Sn-122	**Sn-124**
Content (atomic percent):	0.099 (±0.0056)	0.00004 (±0.00001)	0.030 (±0.0016)	0.064 (±0.0069)	0.025 (±0.0011)	0.097 (±0.0066)	0.038 (±0.0031)	0.146 (±0.012)	0.087 (±0.0038)	**99.413 (±0.122)**

Enriched ^{124}Sn



Experimental Details-

EAR1 or EAR2 - sample mass?

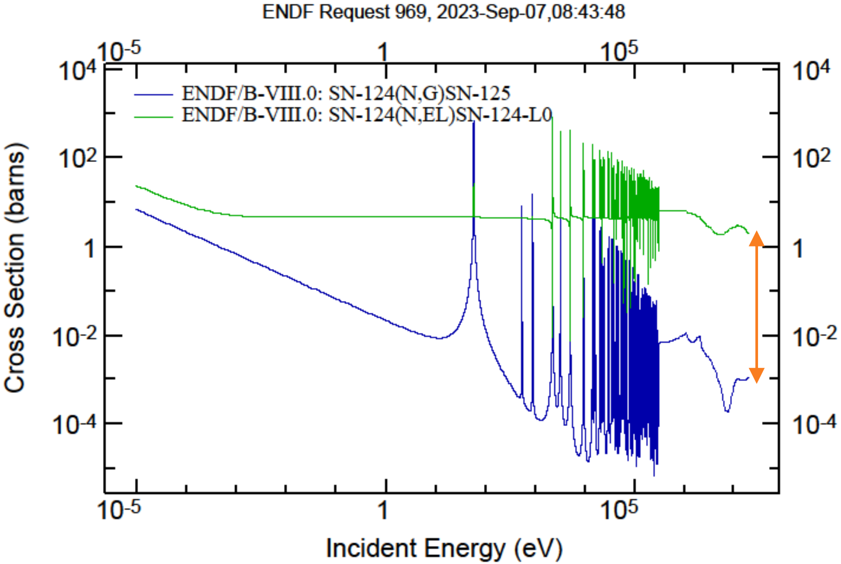
- In EAR2 : 1.0 g sample
- RRR up to 10 keV only
- No MACS at high energy

- In EAR1 : 3.0 g sample
- RRR up to, probably, 100 keV
- MACS @ 100 keV

Experimental Details [EAR1]-

How will ^{124}Sn(n,γ) be measured in EAR1?

- ☐ We hope to measure the thermal-to-500 keV range
- ☐ We will use 3.0 g of enriched material (~99.4% of ^{124}Sn) to lower as much as possible the contamination from other isotopes
- ☐ Setup of four C_6D_6 detectors (At what distance?)
- ☐ We will also measure a ^{nat}Sn, ^{197}Au, ^{nat}C, ^{nat}Pb and a Dummy/Empty



Proton Requests [EAR1]-

Counts estimation using Transport Code (TC):

Input parameters:

- ☐ $^{124}Sn(n,\gamma)$ cross section : ENDF/B-VIII.0 evaluation
- ☐ Atoms/barn: 0.00464

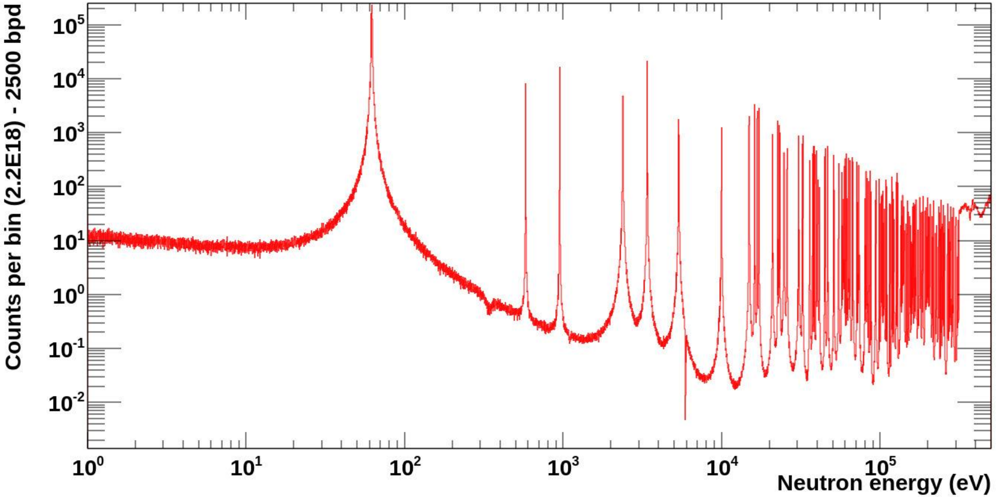
(3 g weight and a disk: 2 cm diameter)

- ☐ Hbins: 13750 in Energy(eV) range from 10^0 to $5e10^5$

  bpd: 2500

- ☐ efficiency: 8%

~2.0% for each C_6D_6 at ~9cm



Proton Requests [EAR1]-

For ^{124}Sn and ^{nat}Sn: ~2.2x10^{18} protons and ~0.5x10^{18} protons, respectively

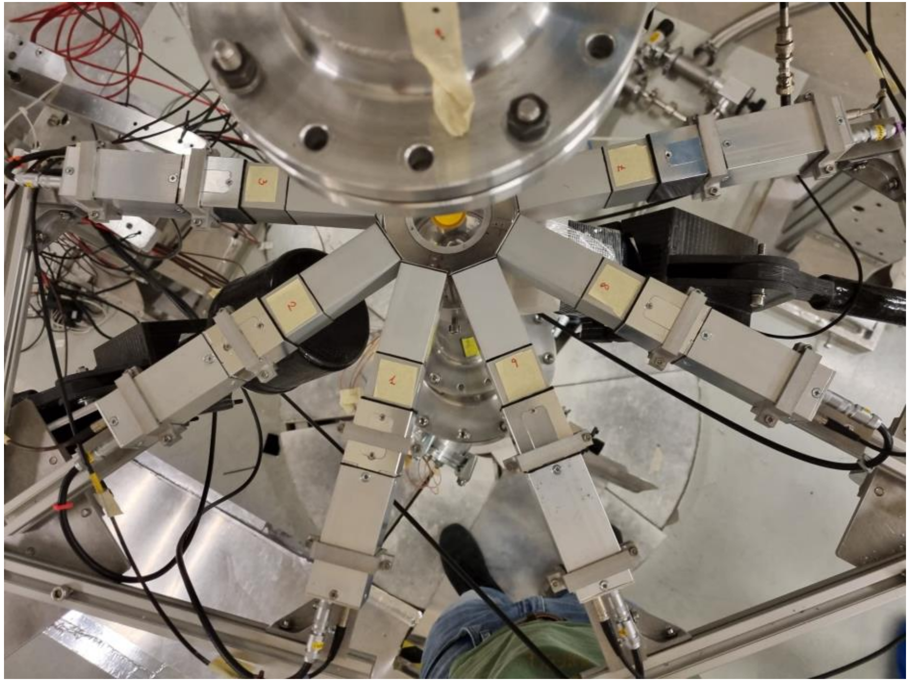
For normalisation and background (dummy) estimation: ~0.2x10^{18} protons and ~0.8x10^{18} protons, respectively

In total: ~3.7x10^{18} protons with the rate estimation 1.0x10^{17} proton per day (~37 days beam time)

Experimental Details [EAR2]-

How will $^{124}Sn(n,\gamma)$ be measured in EAR2?

- ☐ We hope to measure the thermal-to-10 keV range
- ☐ We will use 1.0g of enriched material (~99.4% of ^{124}Sn) to lower as much as possible the contamination from other isotopes
- ☐ Setup of array of nine sTED and two C_6D_6 detectors
- ☐ We will also measure a ^{nat}Sn, ^{197}Au, ^{nat}C, ^{nat}Pb and a Dummy/Empty



Array of sTED and C_6D_6 setup at EAR2 used in $^{160}Gd(n,\gamma)$ experiment

Proton Requests [EAR2]-

Counts estimation using Transport Code (TC):

Input parameters:

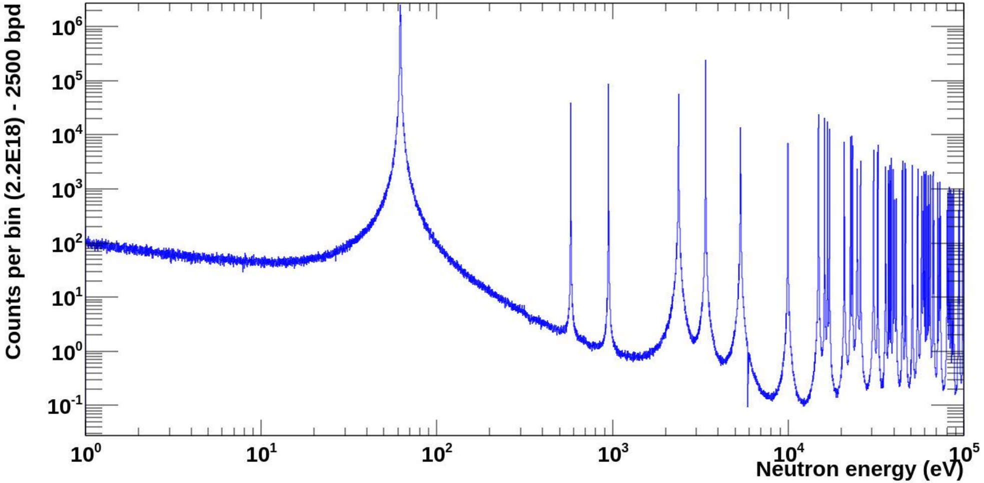
- ☐ ^{124}Sn(n,γ) cross section : ENDF/B-VIII.0 evaluation
- ☐ Atoms/barn: 0.001547

(1.0 g weight and disk: 2 cm diameter)

- ☐ Hbins: 12500 in Energy (eV) range from 10^0 to 10^5
  bpd: 2500

- ☐ efficiency: 4.5%

~0.5% for each sTED [9 detector] at ~5 cm



Proton Requests [EAR2]-

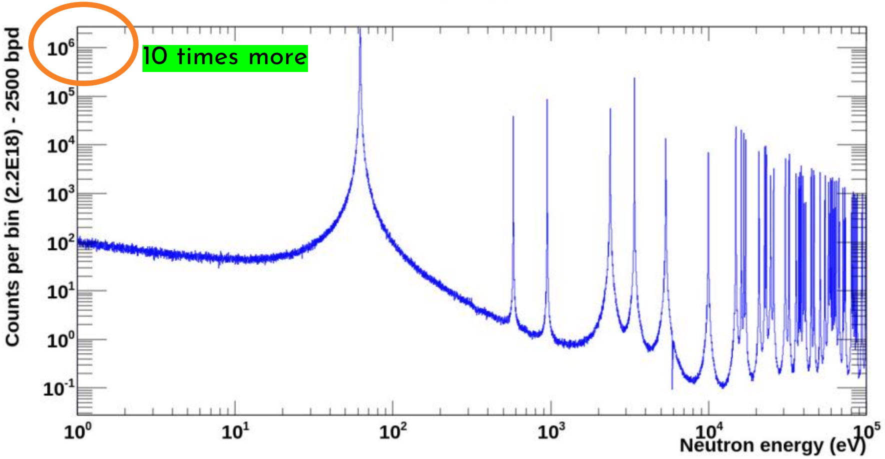
For ^{124}Sn and ^{nat}Sn: ~2.2x10^{18} protons and 0.5x10^{18} protons, respectively

For normalisation and background (dummy) estimation: ~0.2x10^{18} protons and 0.8x10^{18} protons, respectively

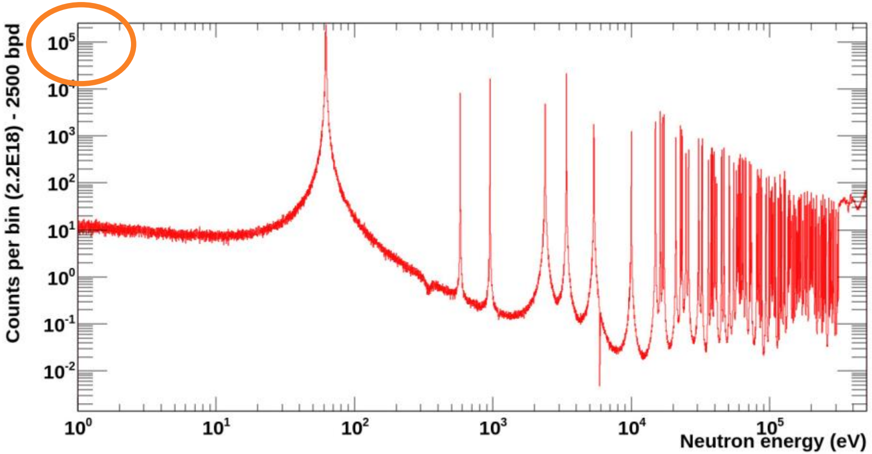
In total: ~3.7x10^{18} protons with the rate estimation 1.0x10^{17} proton per day (~37 days beam time)

EAR1 vs EAR2 - 2.2x10^{18} proton flux (22 days) on ^{124}Sn

- In EAR2 : 1.0 g sample


10 times more

- In EAR1 : 3.0 g sample



Summary-

❑ Motivation:

- $0\nu\beta\beta$, Nuclear Astrophysics, and Nb_3Sn semiconductor

❑ Status of data:

- No high resolution ToF neutron capture data exist to map out CN resonances (only very short flight path ~2 m data were reported)
- There is only a single transmission measurement reported in EXFOR which extracted resonance parameters (10 keV to 320 keV)

❑ Proposal [proton requests]:

Case 1: EAR1-3.0g 37 days

Energy range: Thermal to 500 keV

Sample	Protons
^{124}Sn	2.2×10^{18}
^{nat}Sn	0.5×10^{18}
C, Pb, Dummy	0.8×10^{18}
Au	0.2×10^{18}
Total	**3.7×10^{18}**

Case 2: EAR2-1.0g 37 days*

Energy range: Thermal to 10 keV

Sample	Protons
^{124}Sn	2.2×10^{18}
^{nat}Sn	0.5×10^{18}
C, Pb, Dummy	0.8×10^{18}
Au	0.2×10^{18}
Total	**3.7×10^{18}**

* 10 times more statistics than EAR1

❑ Experiment goals:

- ✓ To provide reliable, low uncertainty and high resolution neutron capture ToF data from thermal to 500 keV
- ✓ To provide lowered-uncertainty (ideally 5-10%) neutron capture data for the MACS from kT=5 keV to (ideally) 100 keV relevant for modelling the s & r-process in the A=124 mass region
- ✓ To better understand the neutron-induced background for neutrinoless double beta decay ($0\nu\beta\beta$) experiments
- ✓ Very optimistically, to at least partially clarify the differences between the different evaluations

Thanks

Do you have any questions?

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Available to use for n_TOF measurement from Czech group

Nuclear Physics Institute, Czech Academy of Sciences (Tomandl/ marek]

Available to use for n_TOF measurement from IFIN-HH Target lab

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Summary of presentation:

1. **0vBB** (cosmic ray-rocks-neutron-thermal-capture-124Sn-gammas-mimic-Q-value-ROI-delayed-prompt-probality-yield of such gammas rays-capture cross section)

2. **Astrophysics**-r-only- proton shell closure-small cross section-contribution of r-only abundance in 125-126Te stable isotope-precise MACS-only experiment MACS @30 kT [tof], 25kT, 52kT [activation]-r-only-means high temp-means higher neutron energies-100 kT-extrapolated 5 kT to 100 kT-motive to provide experiment capture cross section precise-which help in get precise experiment extracted MACS.

3 **Additional motivation**-Nb3Sn-super semiconductor-facilities like ITER-radiation damage-fast neutrons-thermalised-capture channel can help

4. **Status of data**: thermal energy (activation)-above 10 keV (activation and TOF both)-TOF with short flight path-latest JPARC-at 62 eV through gamma spectroscopy-transmission data reported above 10 keV up to 320 keV-less than 10 keV unpublished 1962-Mughlabad 1973-so new precise TOF resolved resonance region data helps in map out the CN resonance-also which help further in estimating the precise MACS-

5. **ENDF status**: comparison between different evaluation-two problem-first in between the resonance-100% difference-same in peak height difference in the RRR <10 keV

6. **EAR1 versus EAR2**-depend on energy resolution available in both Areas- Natural versus Enriched (or mass)-EAR1(up to 100 keV)-EAR2 (up to 10 keV)-3g for EAR1-1g for EAR2-enriched by 98%

7. **How to measure**-C6D6 in EAR1- as elastic to capture ratio is of the order 3 difference--sTED & C6D6-for both to reduce signal to background and elastic channel background-

8. **Proton request**: EAR1 (35 days beam time)- EAR2-(35 days beam time)-for 124Sn and normalization and background

9. **Counts comparison** between EAR1 (3g) and EAR2(1g)

10. **Summary**-Precise neutron capture data from thermal to 500 keV (included RRR data)-Precise **MACS** extraction from 5 kT to 100 kT- improve or solve the difference between evaluations-help the **0vBB** community-background assessment

Er (eV)	Dist. (eV)
62	517
579	371
950	1430
2380	1010
3390	1970
5360	4610
9970	4892
14862	

Distance between capture resonances

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Er(keV)	Er (keV)	Dist. (keV)	Dist. (eV)
14.862	14.977	0.115	115
14.977	16.138	1.161	1161
16.138	16.745	0.607	607
16.745	17.18	0.435	435
17.18	20.913	3.733	3733
20.913	22.621	1.708	1708
22.621	23.032	0.411	411
23.032	23.238	0.206	206
23.238	23.305	0.067	67
23.305	24.731	1.426	1426
24.731	25.829	1.098	1098
25.829	30.628	4.799	4799
30.628	32.383	1.755	1755
32.383	32.497	0.114	114
32.497	35.848	3.351	3351
35.848	35.906	0.058	58
35.906	37.358	1.452	1452
37.358	37.883	0.525	525
37.883	38.159	0.276	276
38.159	38.561	0.402	402
38.561	39.518	0.957	957
39.518	39.556	0.038	38
39.556	40.344	0.788	788
40.344	41.301	0.957	957
41.301	44.577	3.276	3276
44.577	44.906	0.329	329
44.906	44.979	0.073	73
44.979	46.504	1.525	1525
46.504	46.676	0.172	172
46.676	50.854	4.178	4178
50.854	51.036	0.182	182

Er(keV)	Er (keV)	Dist. (keV)	Dist. (eV)
51.036	54.641	3.605	3605
54.641	54.834	0.193	193
54.834	57.463	2.629	2629
57.463	58.617	1.154	1154
58.617	59.468	0.851	851
59.468	59.68	0.212	212
59.68	60.133	0.453	453
60.133	60.82	0.687	687
60.82	61.845	1.025	1025
61.845	62.953	1.108	1108
62.953	63.257	0.304	304
63.257	64.413	1.156	1156
64.413	66.784	2.371	2371
66.784	66.951	0.167	167
66.951	67.422	0.471	471
67.422	71.05	3.628	3628
71.05	72.12	1.07	1070
72.12	73.066	0.946	946
73.066	73.717	0.651	651
73.717	80.261	6.544	6544
80.261	80.403	0.142	142
80.403	81.447	1.044	1044
81.447	82.784	1.337	1337
82.784	82.927	0.143	143
82.927	84.24	1.313	1313
84.24	84.457	0.217	217
84.457	86.051	1.594	1594
86.051	86.108	0.057	57
86.108	87.472	1.364	1364
87.472	87.602	0.13	130
87.602	93.261	5.659	5659
93.261	93.576	0.315	315
93.576	94.144	0.568	568
94.144	98.646	4.502	4502
98.646	99.236	0.59	590
99.236	0		1278.394

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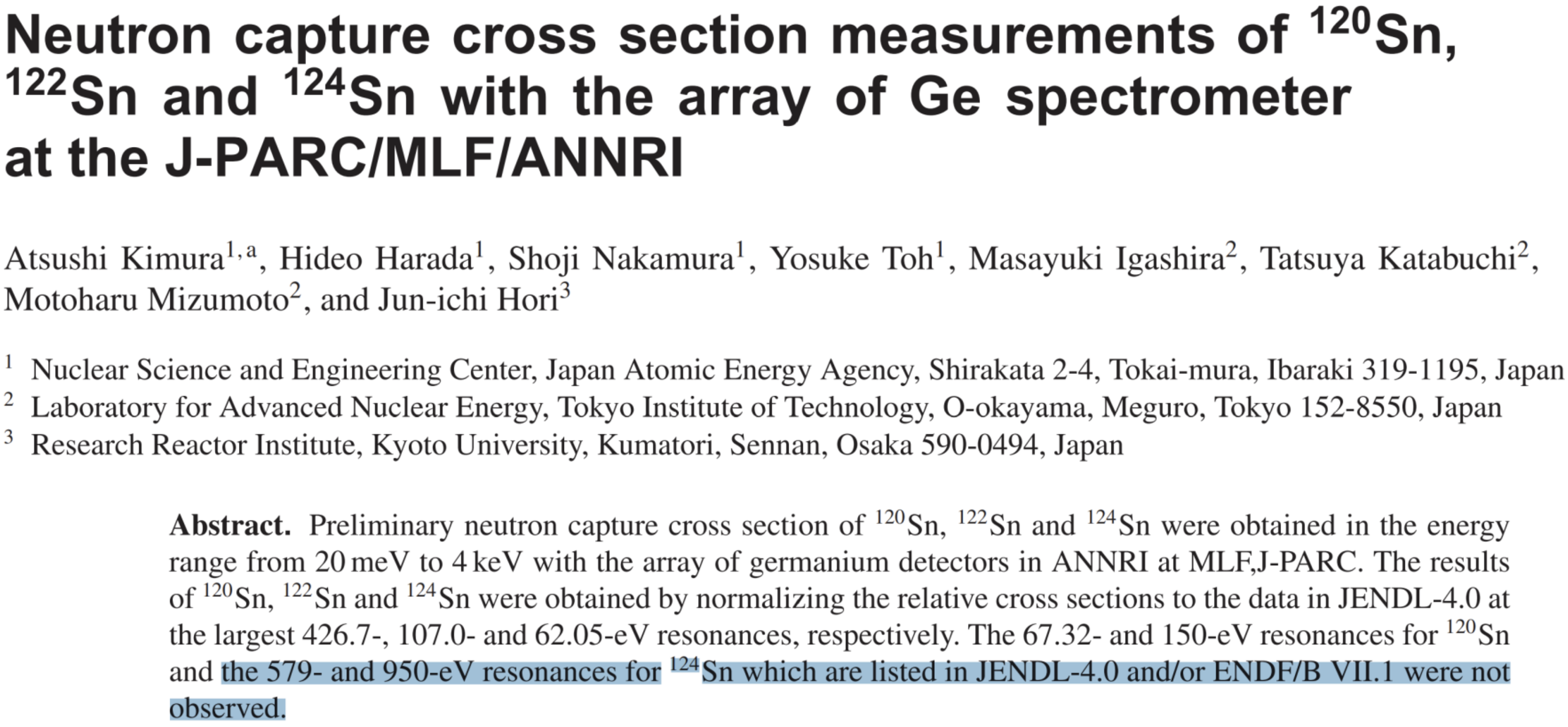

Neutron capture cross section measurements of ^{120}Sn, ^{122}Sn and ^{124}Sn with the array of Ge spectrometer at the J-PARC/MLF/ANNRI

Atsushi Kimura[1,a], Hideo Harada[1], Shoji Nakamura[1], Yosuke Toh[1], Masayuki Igashira[2], Tatsuya Katabuchi[2], Motoharu Mizumoto[2], and Jun-ichi Hori[3]

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Abstract. Preliminary neutron capture cross section of ^{120}Sn, ^{122}Sn and ^{124}Sn were obtained in the energy range from 20 meV to 4 keV with the array of germanium detectors in ANNRI at MLF,J-PARC. The results of ^{120}Sn, ^{122}Sn and ^{124}Sn were obtained by normalizing the relative cross sections to the data in JENDL-4.0 at the largest 426.7-, 107.0- and 62.05-eV resonances, respectively. The 67.32- and 150-eV resonances for ^{120}Sn and the 579- and 950-eV resonances for ^{124}Sn which are listed in JENDL-4.0 and/or ENDF/B VII.1 were not observed.

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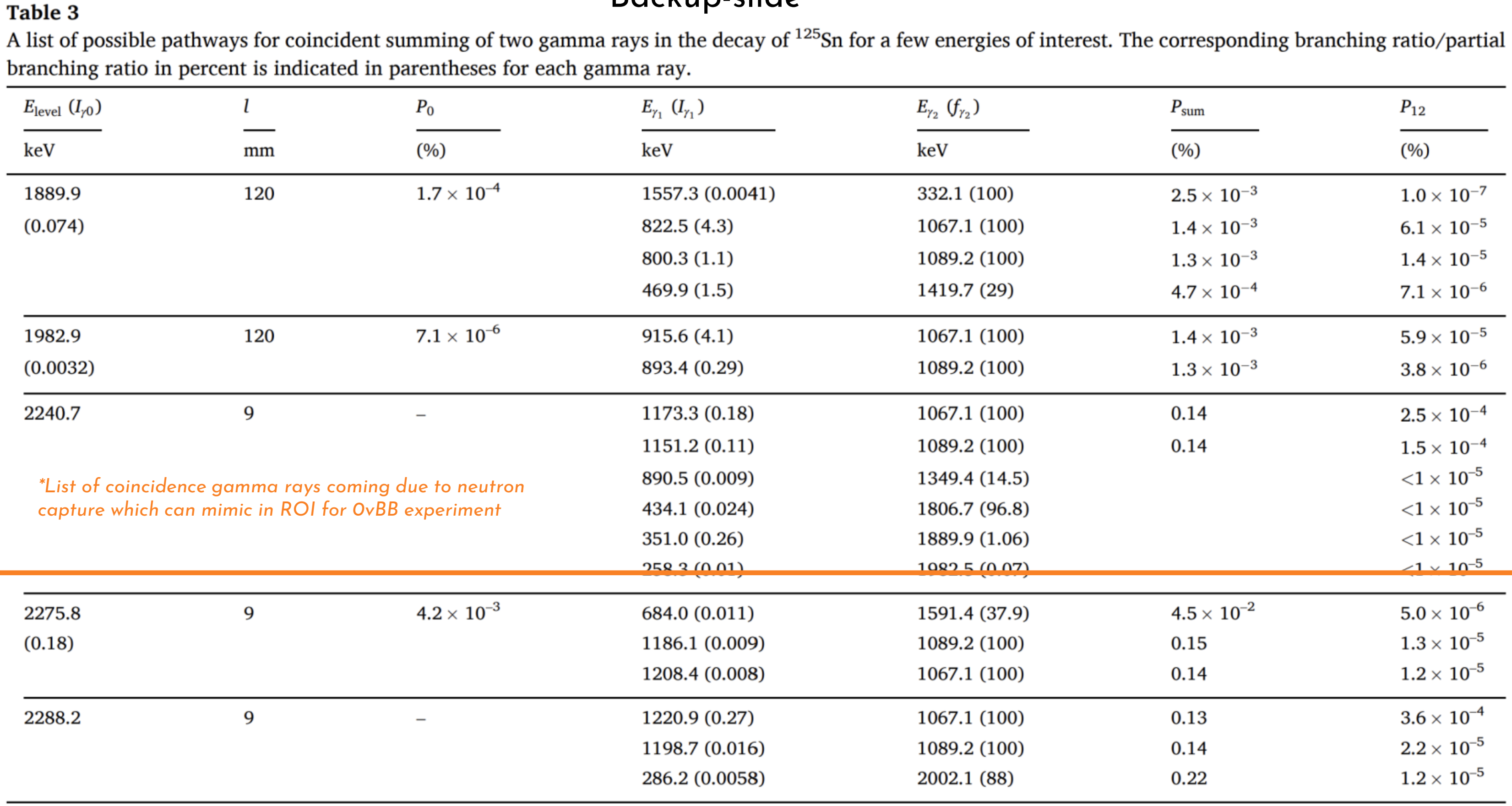

Table 3

A list of possible pathways for coincident summing of two gamma rays in the decay of ^{125}Sn for a few energies of interest. The corresponding branching ratio/partial branching ratio in percent is indicated in parentheses for each gamma ray.

E_{level} ($I_{\gamma 0}$) keV	l mm	P_0 (%)	E_{γ_1} (I_{γ_1}) keV	E_{γ_2} (f_{γ_2}) keV	P_{sum} (%)	P_{12} (%)
1889.9	120	1.7×10^{-4}	1557.3 (0.0041)	332.1 (100)	2.5×10^{-3}	1.0×10^{-7}
(0.074)			822.5 (4.3)	1067.1 (100)	1.4×10^{-3}	6.1×10^{-5}
			800.3 (1.1)	1089.2 (100)	1.3×10^{-3}	1.4×10^{-5}
			469.9 (1.5)	1419.7 (29)	4.7×10^{-4}	7.1×10^{-6}
1982.9	120	7.1×10^{-6}	915.6 (4.1)	1067.1 (100)	1.4×10^{-3}	5.9×10^{-5}
(0.0032)			893.4 (0.29)	1089.2 (100)	1.3×10^{-3}	3.8×10^{-6}
2240.7	9	–	1173.3 (0.18)	1067.1 (100)	0.14	2.5×10^{-4}
			1151.2 (0.11)	1089.2 (100)	0.14	1.5×10^{-4}
			890.5 (0.009)	1349.4 (14.5)		$<1 \times 10^{-5}$
			434.1 (0.024)	1806.7 (96.8)		$<1 \times 10^{-5}$
			351.0 (0.26)	1889.9 (1.06)		$<1 \times 10^{-5}$
			258.3 (0.01)	1982.5 (0.07)		$<1 \times 10^{-5}$
2275.8	9	4.2×10^{-3}	684.0 (0.011)	1591.4 (37.9)	4.5×10^{-2}	5.0×10^{-6}
(0.18)			1186.1 (0.009)	1089.2 (100)	0.15	1.3×10^{-5}
			1208.4 (0.008)	1067.1 (100)	0.14	1.2×10^{-5}
2288.2	9	–	1220.9 (0.27)	1067.1 (100)	0.13	3.6×10^{-4}
			1198.7 (0.016)	1089.2 (100)	0.14	2.2×10^{-5}
			286.2 (0.0058)	2002.1 (88)	0.22	1.2×10^{-5}

**List of coincidence gamma rays coming due to neutron capture which can mimic in ROI for 0vBB experiment*

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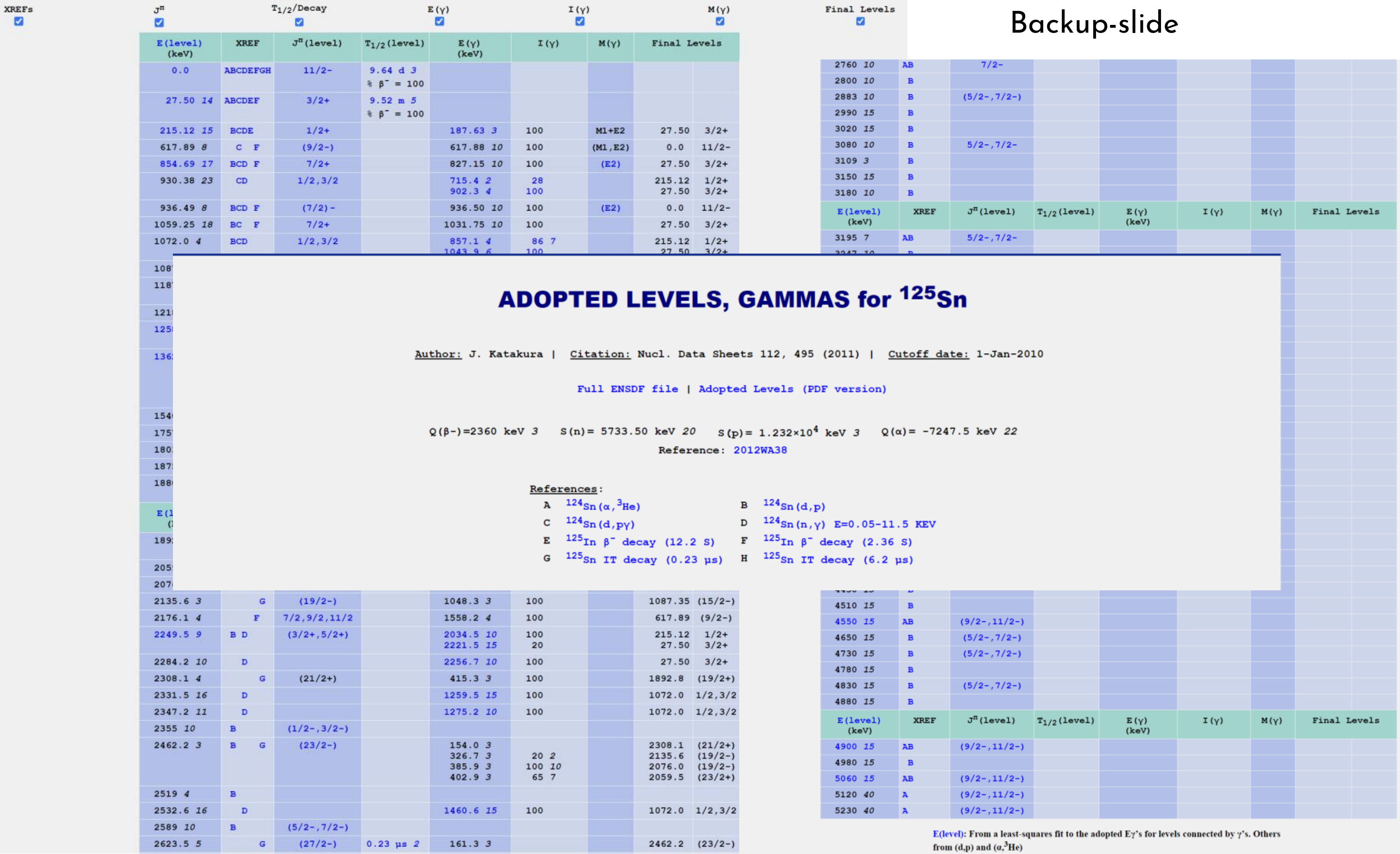


XREFs ☑ J^π ☑ $T_{1/2}$/Decay ☑ E(γ) ☑ I(γ) ☑ M(γ) ☑ Final Levels ☑

ADOPTED LEVELS, GAMMAS for ^{125}Sn

Author: J. Katakura | Citation: Nucl. Data Sheets 112, 495 (2011) | Cutoff date: 1-Jan-2010

Full ENSDF file | Adopted Levels (PDF version)

$Q(\beta-)$=2360 keV 3   S(n)= 5733.50 keV 20   S(p)= 1.232×10^4 keV 3 $Q(\alpha)$= -7247.5 keV 22
Reference: 2012WA38

References:

A	^{124}Sn(α,^{3}He)	B	^{124}Sn(d,p)
C	^{124}Sn(d,pγ)	D	^{124}Sn(n,γ) E=0.05-11.5 KEV
E	^{125}In β⁻ decay (12.2 S)	F	^{125}In β⁻ decay (2.36 S)
G	^{125}Sn IT decay (0.23 μs)	H	^{125}Sn IT decay (6.2 μs)

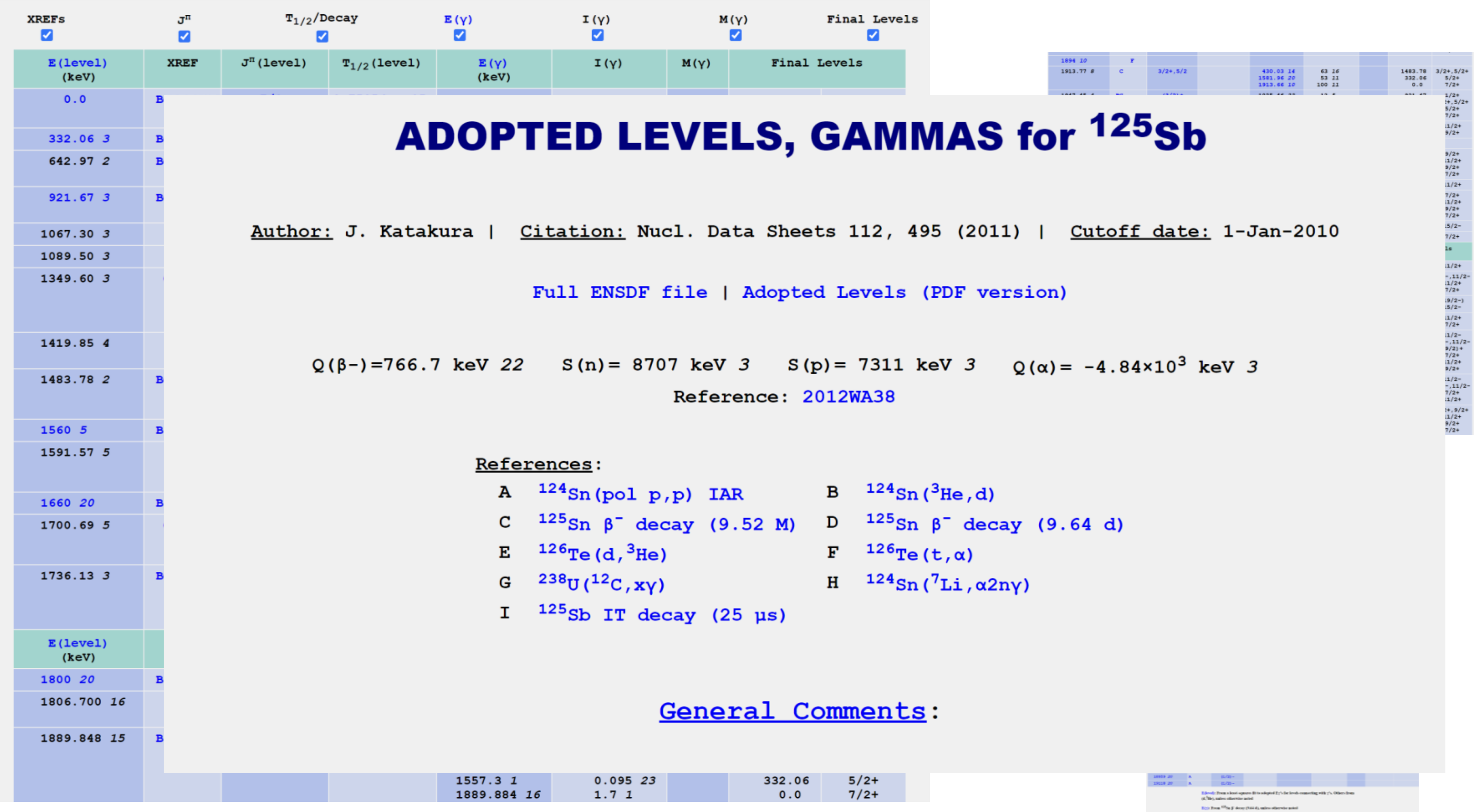
E(level) (keV)	XREF	J^π(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
0.0	ABCDEFGH	11/2-	9.64 d 3 % β⁻ = 100					
27.50 14	ABCDEF	3/2+	9.52 m 5 % β⁻ = 100					
215.12 15	BCDE	1/2+		187.63 3	100	M1+E2	27.50	3/2+
617.89 8	C F	(9/2-)		617.88 10	100	(M1,E2)	0.0	11/2-
854.69 17	BCD F	7/2+		827.15 10	100	(E2)	27.50	3/2+
930.38 23	CD	1/2,3/2		715.4 2 902.3 4	28 100		215.12 27.50	1/2+ 3/2+
936.49 8	BCD F	(7/2)-		936.50 10	100	(E2)	0.0	11/2-
1059.25 18	BC F	7/2+		1031.75 10	100		27.50	3/2+
1072.0 4	BCD	1/2,3/2		857.1 4 1043.9 6	86 7 100		215.12 27.50	1/2+ 3/2+

E(level) (keV)	XREF	J^π(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
2135.6 3	G	(19/2-)		1048.3 3	100		1087.35	(15/2-)
2176.1 4	F	7/2,9/2,11/2		1558.2 4	100		617.89	(9/2-)
2249.5 9	B D	(3/2+,5/2+)		2034.5 10 2221.5 15	100 20		215.12 27.50	1/2+ 3/2+
2284.2 10	D			2256.7 10	100		27.50	3/2+
2308.1 4	G	(21/2+)		415.3 3	100		1892.8	(19/2+)
2331.5 16	D			1259.5 15	100		1072.0	1/2,3/2
2347.2 11	D			1275.2 10	100		1072.0	1/2,3/2
2355 10	B	(1/2-,3/2-)						
2462.2 3	B G	(23/2-)		154.0 3 326.7 3 385.9 3 402.9 3	 20 2 100 10 65 7		2308.1 2135.6 2076.0 2059.5	(21/2+) (19/2-) (19/2-) (23/2+)
2519 4	B							
2532.6 16	D			1460.6 15	100		1072.0	1/2,3/2
2589 10	B	(5/2-,7/2-)						
2623.5 5	G	(27/2-)	0.23 μs 2	161.3 3			2462.2	(23/2-)

E(level) (keV)	XREF	J^π(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
2760 10	AB	7/2-						
2800 10	B							
2883 10	B	(5/2-,7/2-)						
2990 15	B							
3020 15	B							
3080 10	B	5/2-,7/2-						
3109 3	B							
3150 15	B							
3180 10	B							
E(level) (keV)	**XREF**	**J^π(level)**	**$T_{1/2}$(level)**	**E(γ) (keV)**	**I(γ)**	**M(γ)**	**Final Levels**	
3195 7	AB	5/2-,7/2-						

E(level) (keV)	XREF	J^π(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
4510 15	B							
4550 15	AB	(9/2-,11/2-)						
4650 15	B	(5/2-,7/2-)						
4730 15	B	(5/2-,7/2-)						
4780 15	B							
4830 15	B	(5/2-,7/2-)						
4880 15	B							
E(level) (keV)	**XREF**	**J^π(level)**	**$T_{1/2}$(level)**	**E(γ) (keV)**	**I(γ)**	**M(γ)**	**Final Levels**	
4900 15	AB	(9/2-,11/2-)						
4980 15	B							
5060 15	AB	(9/2-,11/2-)						
5120 40	A	(9/2-,11/2-)						
5230 40	A	(9/2-,11/2-)						

E(level): From a least-squares fit to the adopted Eγ's for levels connected by γ's. Others from (d,p) and (α,^{3}He)



ADOPTED LEVELS, GAMMAS for ^{125}Sb

Author: J. Katakura | **Citation:** Nucl. Data Sheets 112, 495 (2011) | **Cutoff date:** 1-Jan-2010

Full ENSDF file | Adopted Levels (PDF version)

Q(β-)=766.7 keV *22*   S(n)= 8707 keV *3*   S(p)= 7311 keV *3*   Q(α)= -4.84×10^3 keV *3*

Reference: 2012WA38

References:

A	^{124}Sn(pol p,p) IAR	B	^{124}Sn(^{3}He,d)
C	^{125}Sn β^- decay (9.52 M)	D	^{125}Sn β^- decay (9.64 d)
E	^{126}Te(d,^{3}He)	F	^{126}Te(t,α)
G	^{238}U(^{12}C,xγ)	H	^{124}Sn(^{7}Li,α2nγ)
I	^{125}Sb IT decay (25 μs)		

General Comments:

XREFs ☑ Jπ ☑ $T_{1/2}$/Decay ☑ E(γ) ☑ I(γ) ☑ M(γ) ☑ Final Levels ☑

E(level) (keV)	XREF	Jπ(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
0.0	B							
332.06 *3*	B							
642.97 *2*	B							
921.67 *3*	B							
1067.30 *3*								
1089.50 *3*								
1349.60 *3*								
1419.85 *4*								
1483.78 *2*	B							
1560 *5*	B							
1591.57 *5*								
1660 *20*	B							
1700.69 *5*								
1736.13 *3*	B							
E(level) (keV)								
1800 *20*	B							
1806.700 *16*								
1889.848 *15*	B			1557.3 *1* 1889.884 *16*	0.095 *23* 1.7 *1*		332.06 0.0	5/2+ 7/2+

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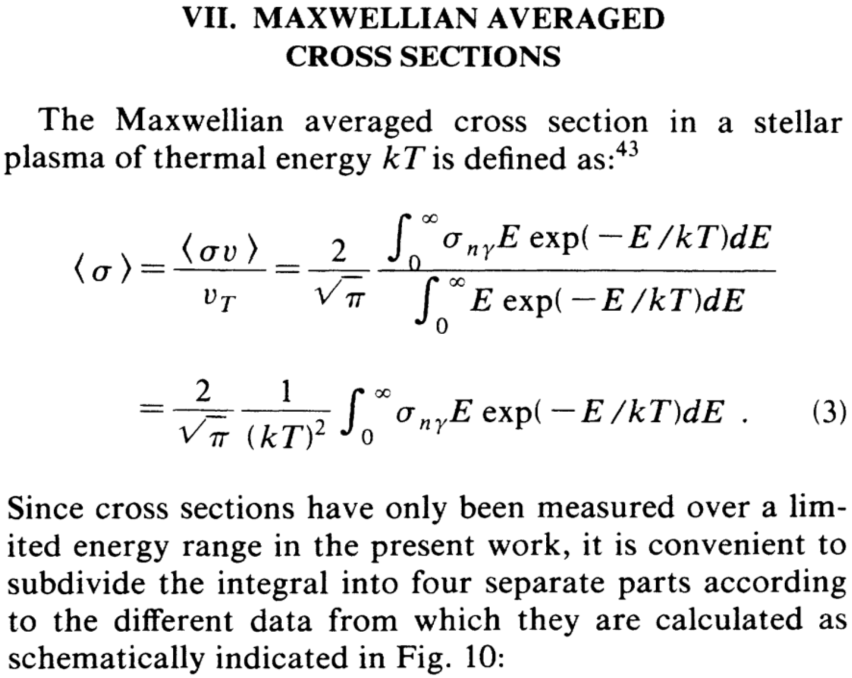


VII. MAXWELLIAN AVERAGED CROSS SECTIONS

The Maxwellian averaged cross section in a stellar plasma of thermal energy kT is defined as:[43]

$$\langle \sigma \rangle = \frac{\langle \sigma v \rangle}{v_T} = \frac{2}{\sqrt{\pi}} \frac{\int_0^\infty \sigma_{n\gamma} E \exp(-E/kT) dE}{\int_0^\infty E \exp(-E/kT) dE}$$

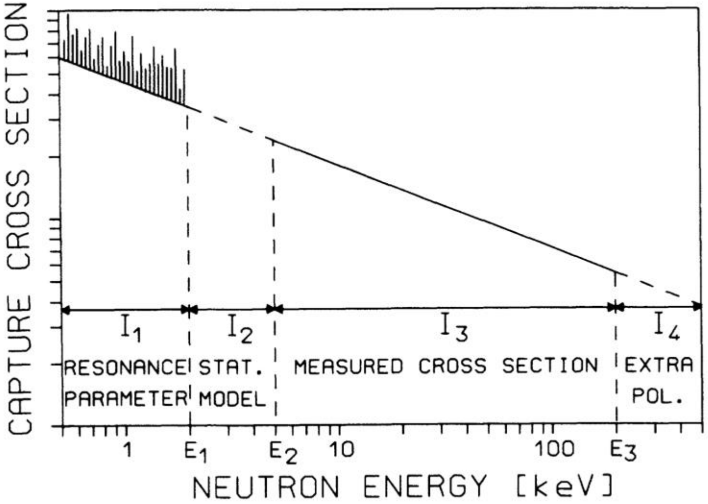
$$= \frac{2}{\sqrt{\pi}} \frac{1}{(kT)^2} \int_0^\infty \sigma_{n\gamma} E \exp(-E/kT) dE \ . \qquad (3)$$

Since cross sections have only been measured over a limited energy range in the present work, it is convenient to subdivide the integral into four separate parts according to the different data from which they are calculated as schematically indicated in Fig. 10:

https://journals.aps.org/prc/pdf/10.1103/PhysRevC.42.1731

K. Wisshak, F. Voss, F. Käppeler, and G. Reffo

Phys. Rev. C **42**, 1731 – Published 1 October 1990



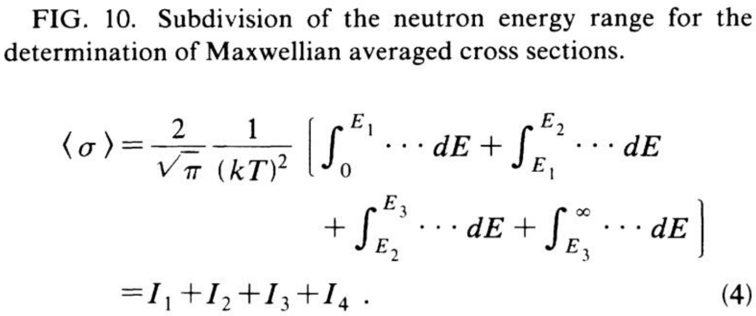


FIG. 10. Subdivision of the neutron energy range for the determination of Maxwellian averaged cross sections.

$$\langle \sigma \rangle = \frac{2}{\sqrt{\pi}} \frac{1}{(kT)^2} \left[\int_0^{E_1} \cdots dE + \int_{E_1}^{E_2} \cdots dE + \int_{E_2}^{E_3} \cdots dE + \int_{E_3}^{\infty} \cdots dE \right]$$

$$= I_1 + I_2 + I_3 + I_4 \ . \qquad (4)$$

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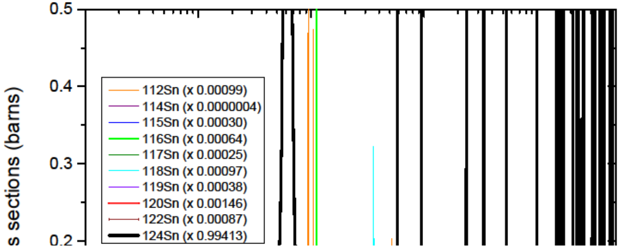

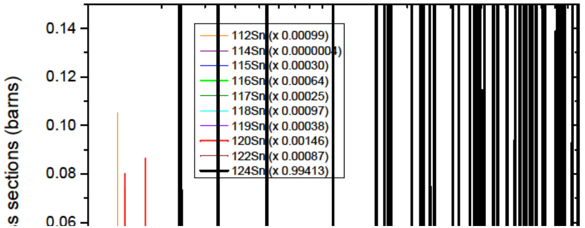

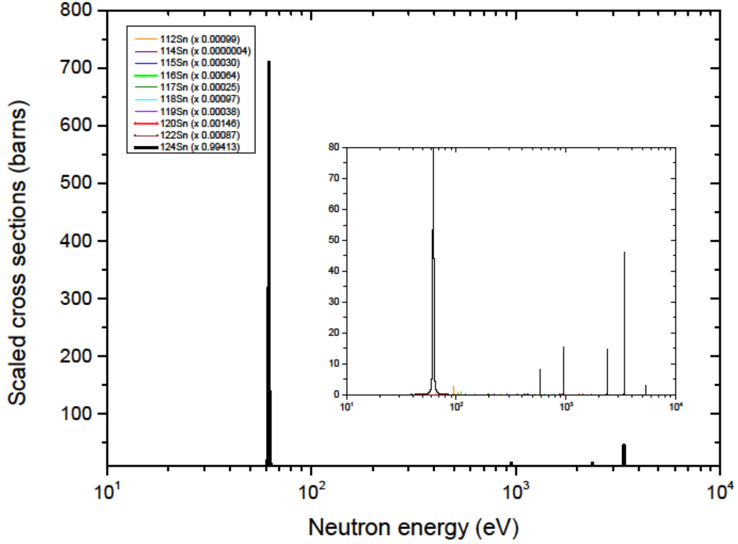

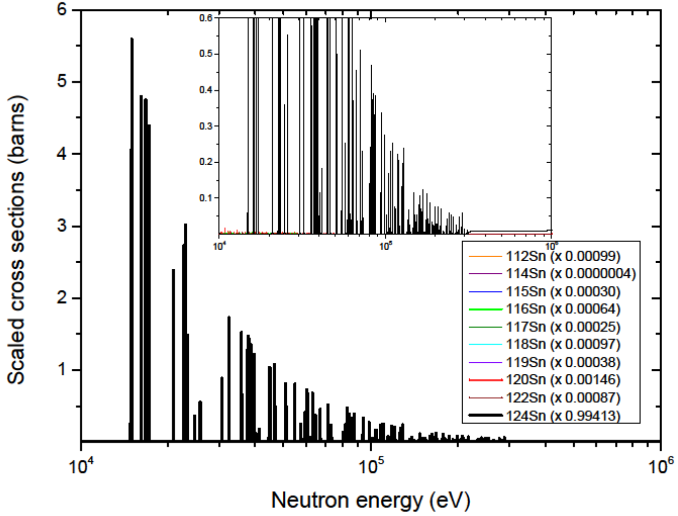

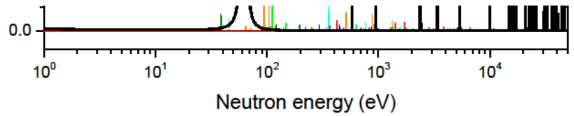

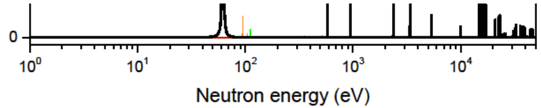

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Giunti, Carlo, and Chung W. Kim. Oxford university press Book, (2007). https://doi.org/10.1093/acprof:oso/9780198508717.001.0001

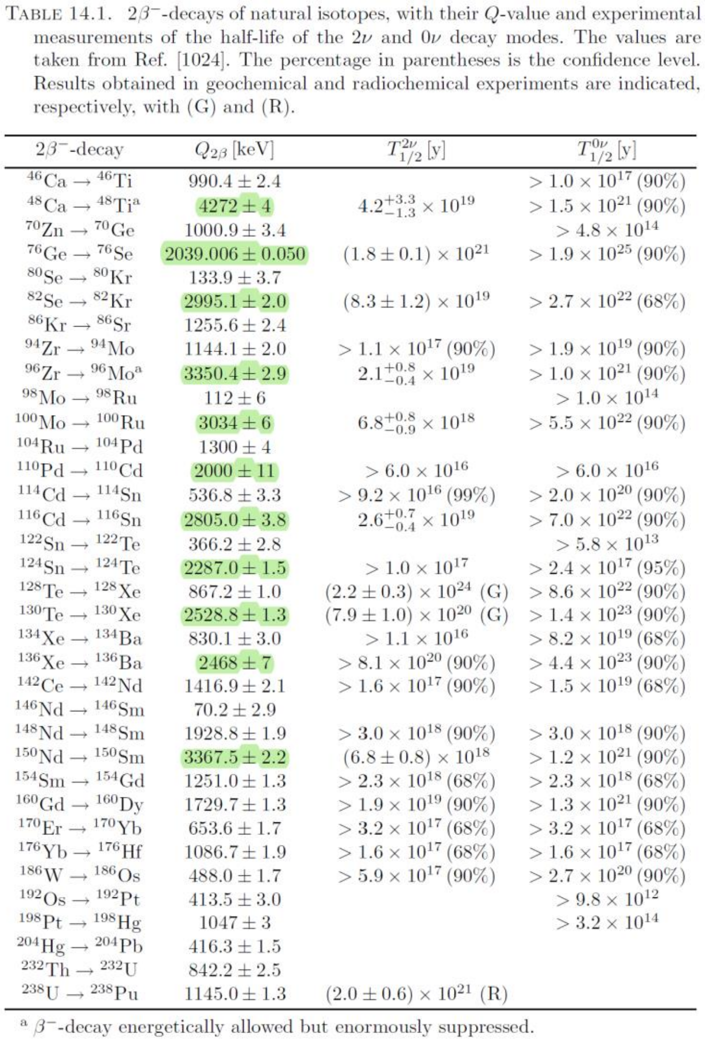
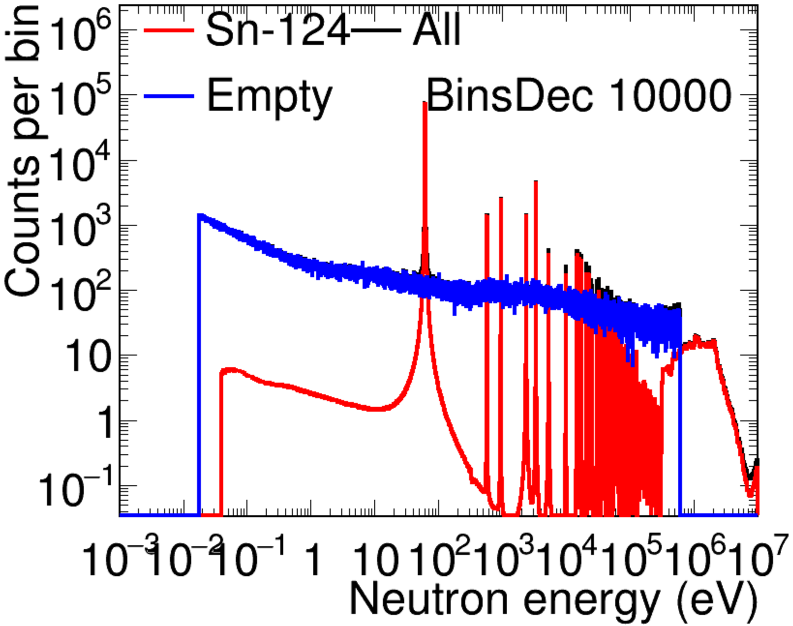
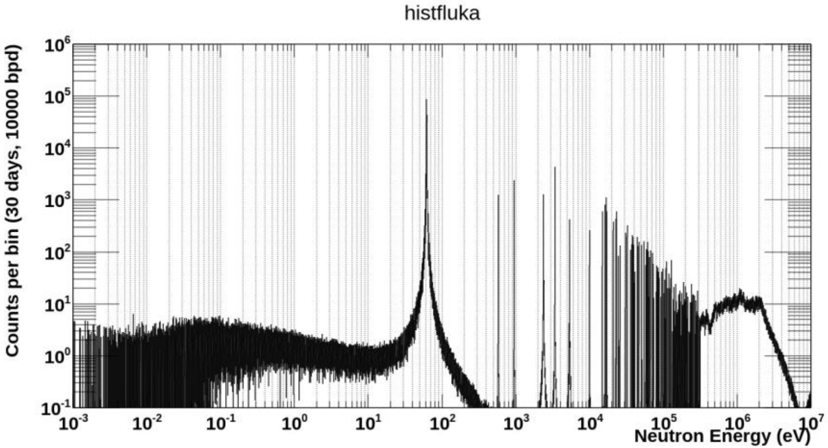


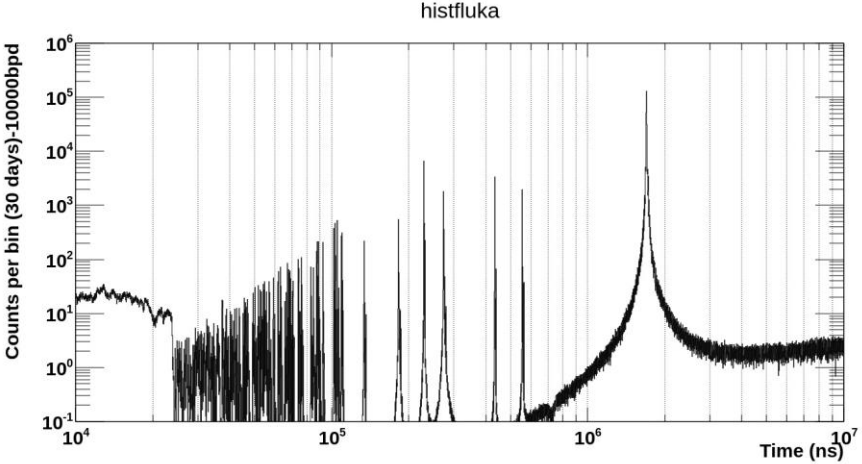
TABLE 14.1. $2\beta^-$-decays of natural isotopes, with their Q-value and experimental measurements of the half-life of the 2ν and 0ν decay modes. The values are taken from Ref. [1024]. The percentage in parentheses is the confidence level. Results obtained in geochemical and radiochemical experiments are indicated, respectively, with (G) and (R).

$2\beta^-$-decay	$Q_{2\beta}$ [keV]	$T^{2\nu}_{1/2}$ [y]	$T^{0\nu}_{1/2}$ [y]
$^{46}\mathrm{Ca} \to {}^{46}\mathrm{Ti}$	990.4 ± 2.4		$> 1.0 \times 10^{17}$ (90%)
$^{48}\mathrm{Ca} \to {}^{48}\mathrm{Ti}^{a}$	4272 ± 4	$4.2^{+3.3}_{-1.3} \times 10^{19}$	$> 1.5 \times 10^{21}$ (90%)
$^{70}\mathrm{Zn} \to {}^{70}\mathrm{Ge}$	1000.9 ± 3.4		$> 4.8 \times 10^{14}$
$^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se}$	2039.006 ± 0.050	$(1.8 \pm 0.1) \times 10^{21}$	$> 1.9 \times 10^{25}$ (90%)
$^{80}\mathrm{Se} \to {}^{80}\mathrm{Kr}$	133.9 ± 3.7		
$^{82}\mathrm{Se} \to {}^{82}\mathrm{Kr}$	2995.1 ± 2.0	$(8.3 \pm 1.2) \times 10^{19}$	$> 2.7 \times 10^{22}$ (68%)
$^{86}\mathrm{Kr} \to {}^{86}\mathrm{Sr}$	1255.6 ± 2.4		
$^{94}\mathrm{Zr} \to {}^{94}\mathrm{Mo}$	1144.1 ± 2.0	$> 1.1 \times 10^{17}$ (90%)	$> 1.9 \times 10^{19}$ (90%)
$^{96}\mathrm{Zr} \to {}^{96}\mathrm{Mo}^{a}$	3350.4 ± 2.9	$2.1^{+0.8}_{-0.4} \times 10^{19}$	$> 1.0 \times 10^{21}$ (90%)
$^{98}\mathrm{Mo} \to {}^{98}\mathrm{Ru}$	112 ± 6		$> 1.0 \times 10^{14}$
$^{100}\mathrm{Mo} \to {}^{100}\mathrm{Ru}$	3034 ± 6	$6.8^{+0.8}_{-0.9} \times 10^{18}$	$> 5.5 \times 10^{22}$ (90%)
$^{104}\mathrm{Ru} \to {}^{104}\mathrm{Pd}$	1300 ± 4		
$^{110}\mathrm{Pd} \to {}^{110}\mathrm{Cd}$	2000 ± 11	$> 6.0 \times 10^{16}$	$> 6.0 \times 10^{16}$
$^{114}\mathrm{Cd} \to {}^{114}\mathrm{Sn}$	536.8 ± 3.3	$> 9.2 \times 10^{16}$ (99%)	$> 2.0 \times 10^{20}$ (90%)
$^{116}\mathrm{Cd} \to {}^{116}\mathrm{Sn}$	2805.0 ± 3.8	$2.6^{+0.7}_{-0.4} \times 10^{19}$	$> 7.0 \times 10^{22}$ (90%)
$^{122}\mathrm{Sn} \to {}^{122}\mathrm{Te}$	366.2 ± 2.8		$> 5.8 \times 10^{13}$
$^{124}\mathrm{Sn} \to {}^{124}\mathrm{Te}$	2287.0 ± 1.5	$> 1.0 \times 10^{17}$	$> 2.4 \times 10^{17}$ (95%)
$^{128}\mathrm{Te} \to {}^{128}\mathrm{Xe}$	867.2 ± 1.0	$(2.2 \pm 0.3) \times 10^{24}$ (G)	$> 8.6 \times 10^{22}$ (90%)
$^{130}\mathrm{Te} \to {}^{130}\mathrm{Xe}$	2528.8 ± 1.3	$(7.9 \pm 1.0) \times 10^{20}$ (G)	$> 1.4 \times 10^{23}$ (90%)
$^{134}\mathrm{Xe} \to {}^{134}\mathrm{Ba}$	830.1 ± 3.0	$> 1.1 \times 10^{16}$	$> 8.2 \times 10^{19}$ (68%)
$^{136}\mathrm{Xe} \to {}^{136}\mathrm{Ba}$	2468 ± 7	$> 8.1 \times 10^{20}$ (90%)	$> 4.4 \times 10^{23}$ (90%)
$^{142}\mathrm{Ce} \to {}^{142}\mathrm{Nd}$	1416.9 ± 2.1	$> 1.6 \times 10^{17}$ (90%)	$> 1.5 \times 10^{19}$ (68%)
$^{146}\mathrm{Nd} \to {}^{146}\mathrm{Sm}$	70.2 ± 2.9		
$^{148}\mathrm{Nd} \to {}^{148}\mathrm{Sm}$	1928.8 ± 1.9	$> 3.0 \times 10^{18}$ (90%)	$> 3.0 \times 10^{18}$ (90%)
$^{150}\mathrm{Nd} \to {}^{150}\mathrm{Sm}$	3367.5 ± 2.2	$(6.8 \pm 0.8) \times 10^{18}$	$> 1.2 \times 10^{21}$ (90%)
$^{154}\mathrm{Sm} \to {}^{154}\mathrm{Gd}$	1251.0 ± 1.3	$> 2.3 \times 10^{18}$ (68%)	$> 2.3 \times 10^{18}$ (68%)
$^{160}\mathrm{Gd} \to {}^{160}\mathrm{Dy}$	1729.7 ± 1.3	$> 1.9 \times 10^{19}$ (90%)	$> 1.3 \times 10^{21}$ (90%)
$^{170}\mathrm{Er} \to {}^{170}\mathrm{Yb}$	653.6 ± 1.7	$> 3.2 \times 10^{17}$ (68%)	$> 3.2 \times 10^{17}$ (68%)
$^{176}\mathrm{Yb} \to {}^{176}\mathrm{Hf}$	1086.7 ± 1.9	$> 1.6 \times 10^{17}$ (68%)	$> 1.6 \times 10^{17}$ (68%)
$^{186}\mathrm{W} \to {}^{186}\mathrm{Os}$	488.0 ± 1.7	$> 5.9 \times 10^{17}$ (90%)	$> 2.7 \times 10^{20}$ (90%)
$^{192}\mathrm{Os} \to {}^{192}\mathrm{Pt}$	413.5 ± 3.0		$> 9.8 \times 10^{12}$
$^{198}\mathrm{Pt} \to {}^{198}\mathrm{Hg}$	1047 ± 3		$> 3.2 \times 10^{14}$
$^{204}\mathrm{Hg} \to {}^{204}\mathrm{Pb}$	416.3 ± 1.5		
$^{232}\mathrm{Th} \to {}^{232}\mathrm{U}$	842.2 ± 2.5		
$^{238}\mathrm{U} \to {}^{238}\mathrm{Pu}$	1145.0 ± 1.3	$(2.0 \pm 0.6) \times 10^{21}$ (R)	

[a] β^--decay energetically allowed but enormously suppressed.







124Sn EAR-1

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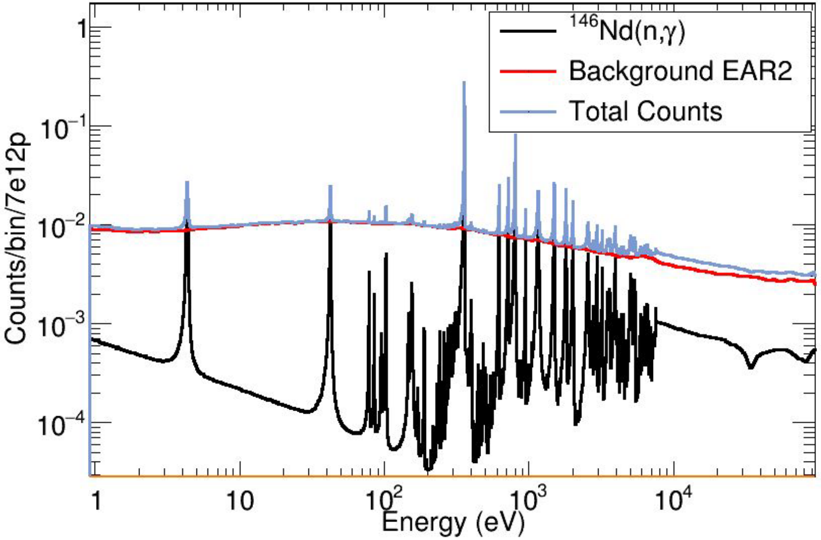
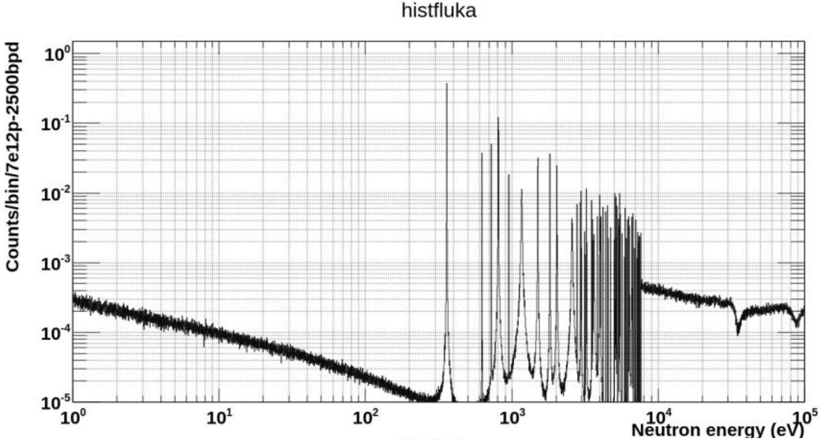
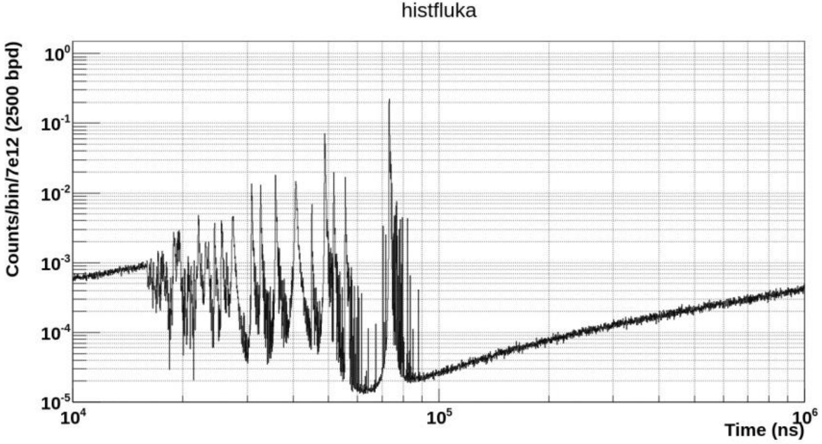


146Nd-EAR2





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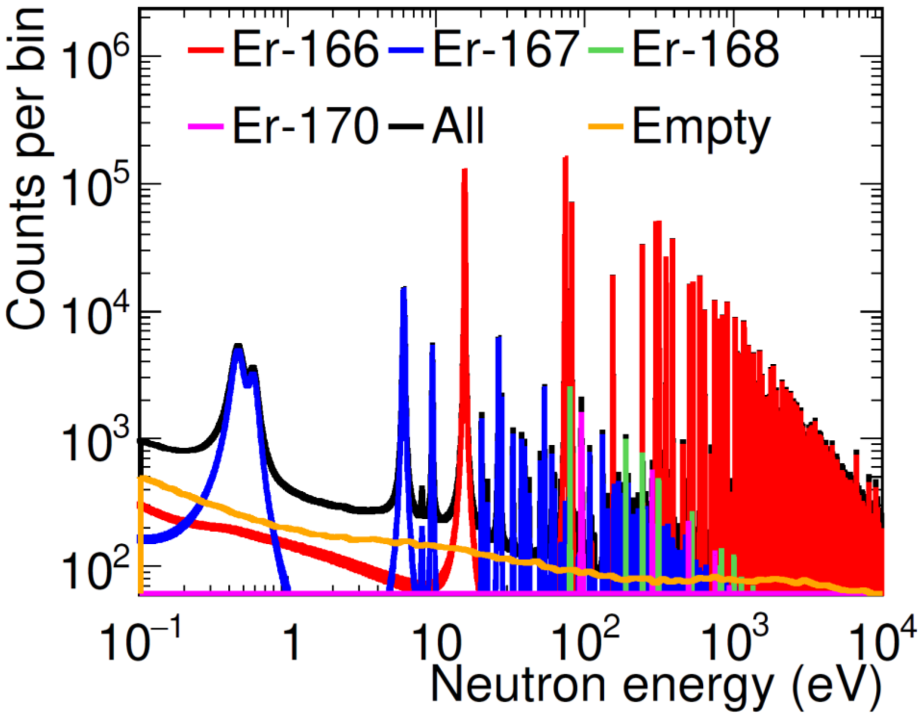
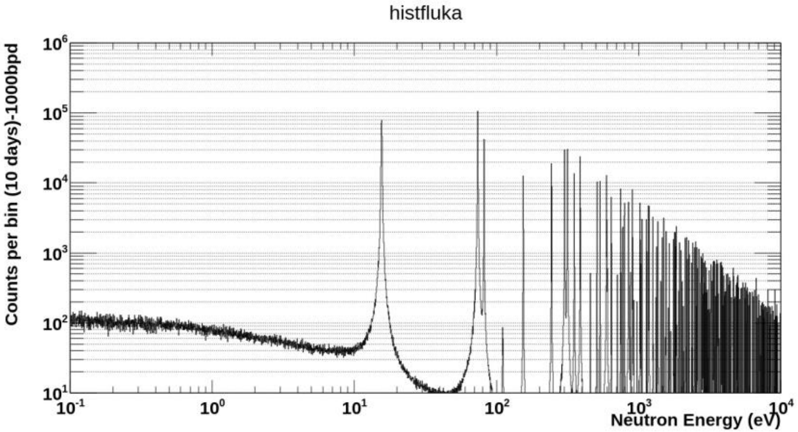
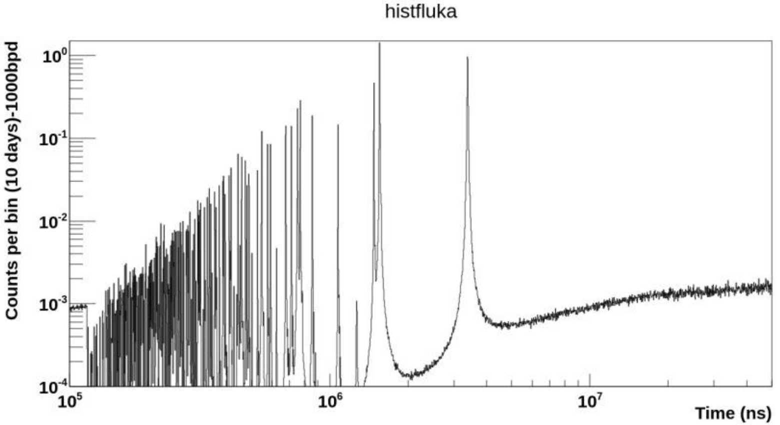


166Er-EAR1





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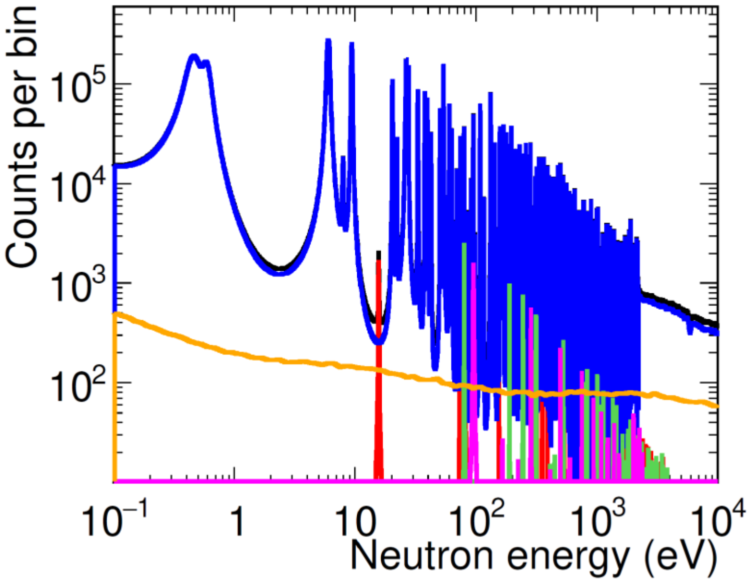

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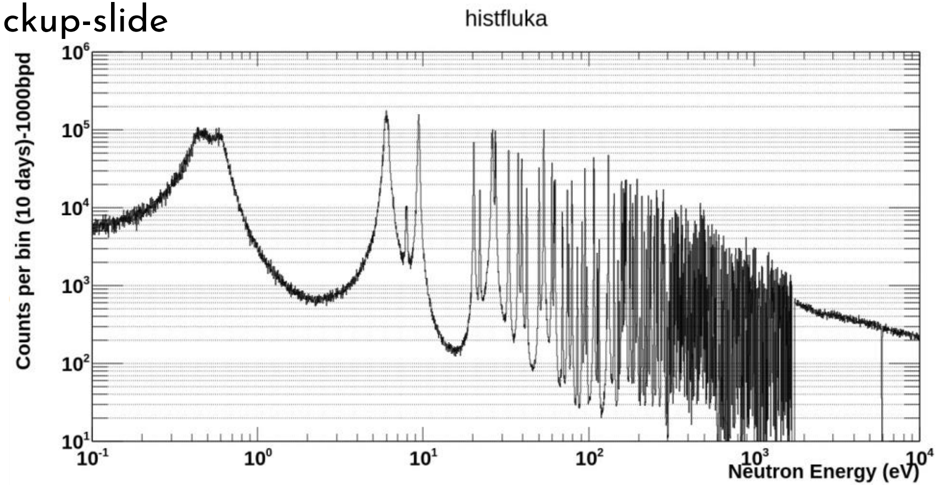

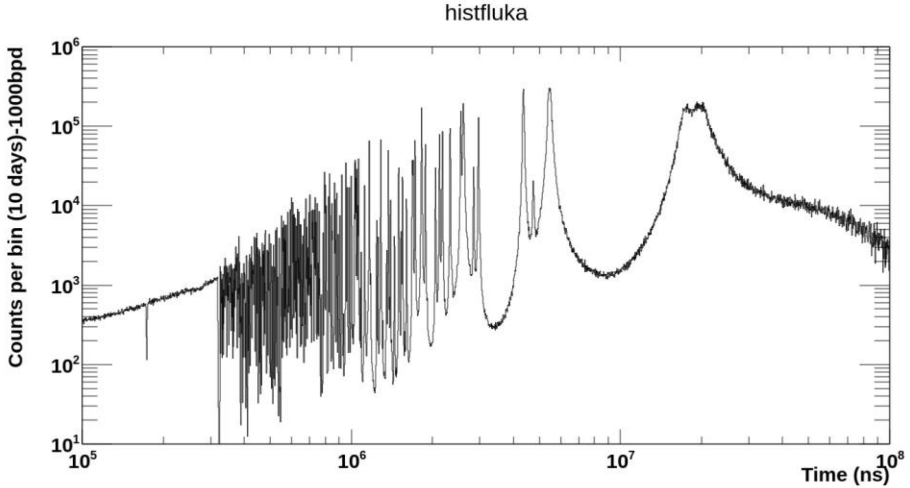

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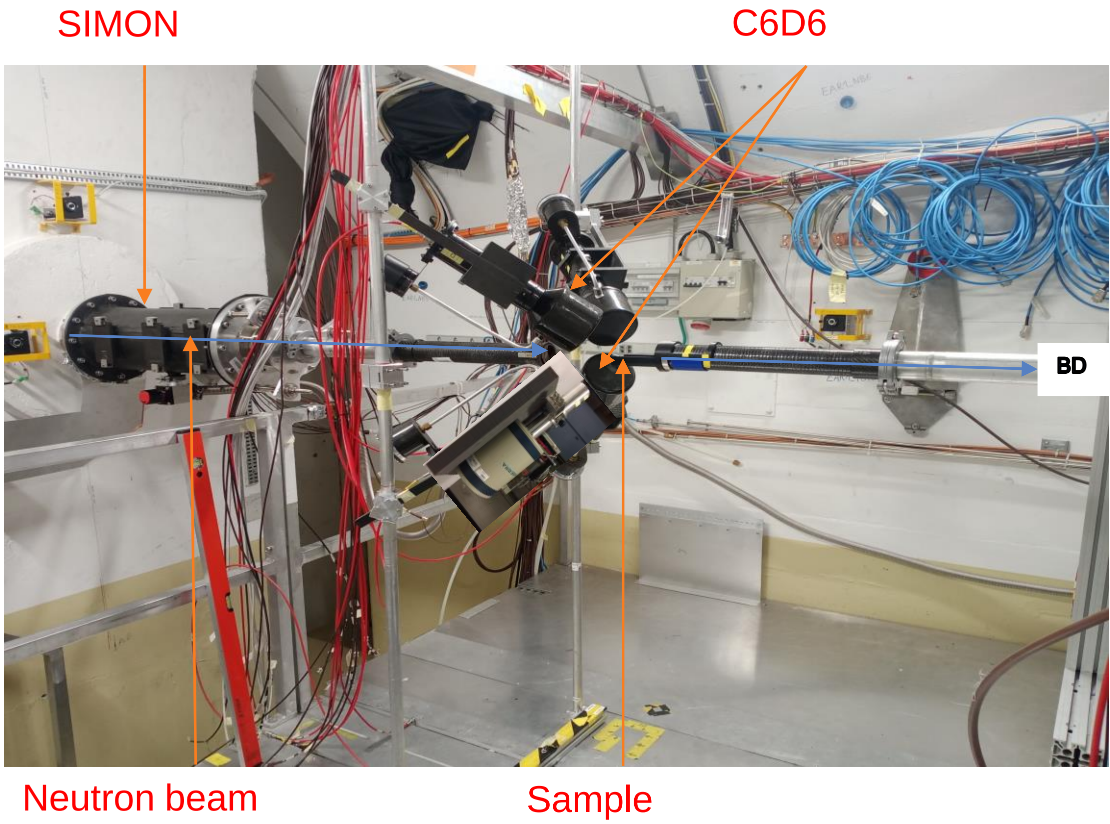

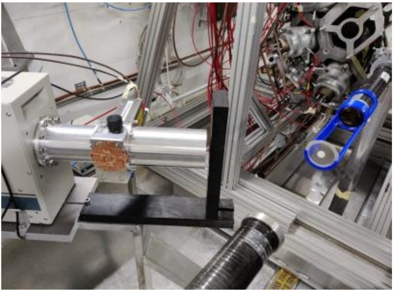

Complimentary or test experiment with an array of both C6D6 and HPGe/Labr3 for getting the capture events(C6D6) and capture cascade event in HPGe together.

Backup-slide

Question to be discuss:

- At what distance? What efficiency?)
- Anisotropy
- Amount of sample
- Experimental area
- Offline without beam measurement for isomers
- Negligible contribution from contamination of other isotopes impurities

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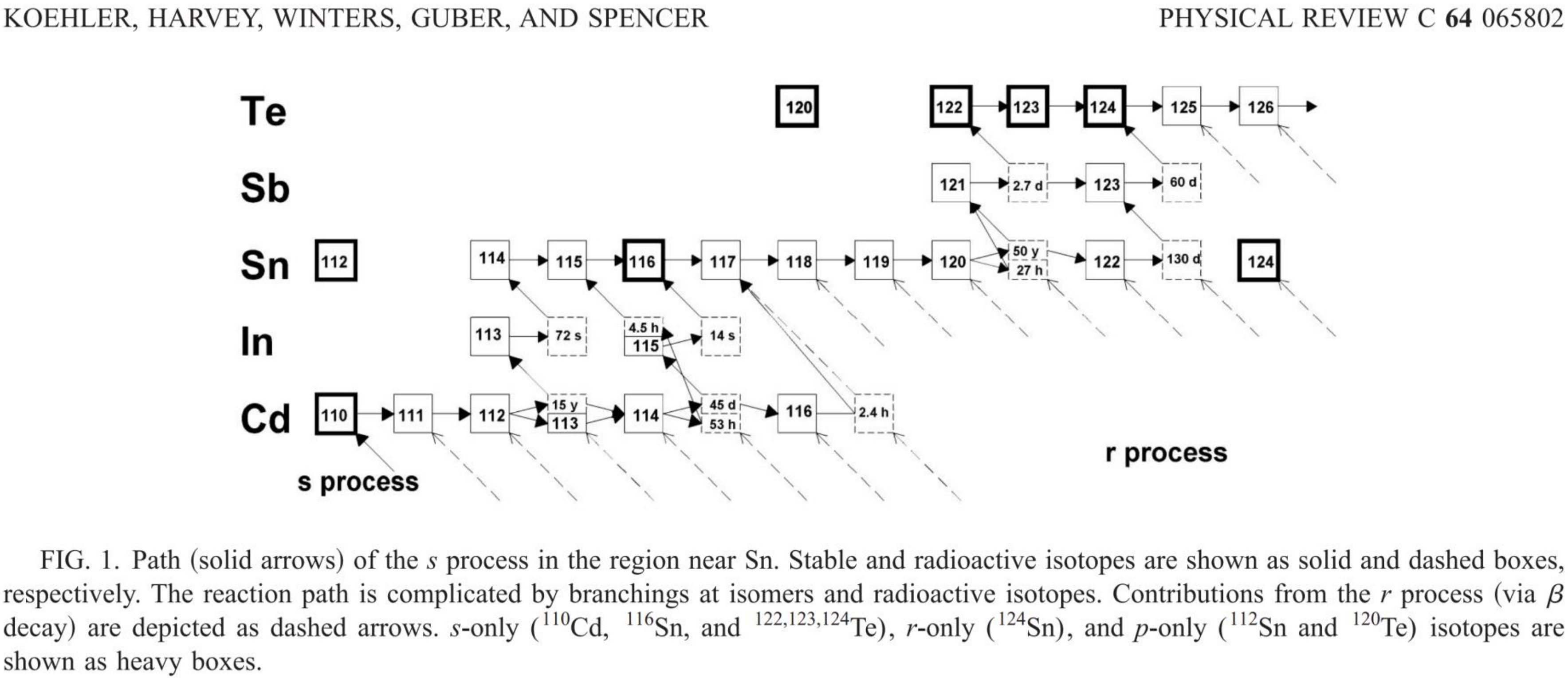

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FIG. 1. Path (solid arrows) of the *s* process in the region near Sn. Stable and radioactive isotopes are shown as solid and dashed boxes, respectively. The reaction path is complicated by branchings at isomers and radioactive isotopes. Contributions from the *r* process (via β decay) are depicted as dashed arrows. *s*-only (^{110}Cd, ^{116}Sn, and ^{122,123,124}Te), *r*-only (^{124}Sn), and *p*-only (^{112}Sn and ^{120}Te) isotopes are shown as heavy boxes.

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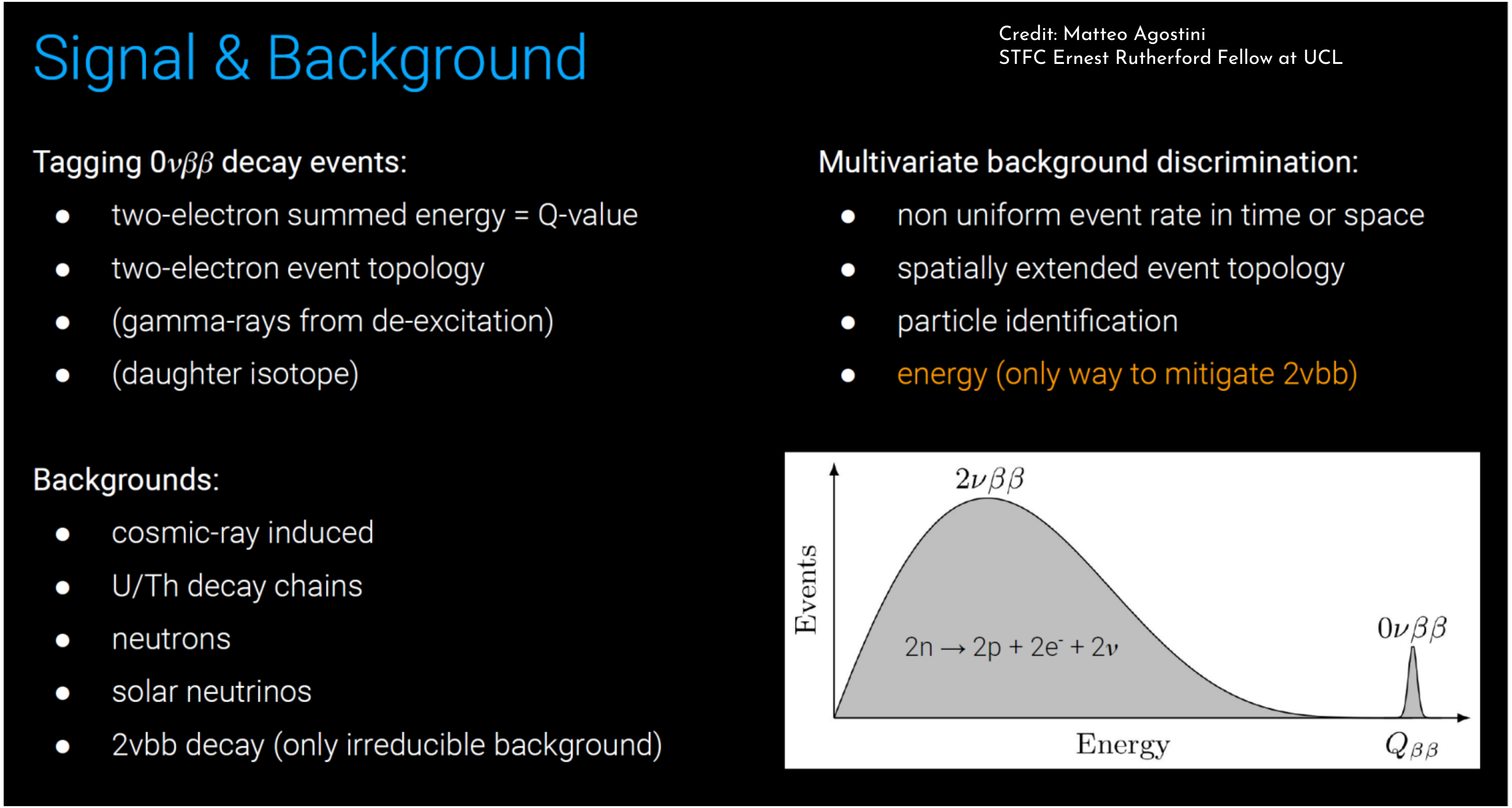

Signal & Background

Credit: Matteo Agostini
STFC Ernest Rutherford Fellow at UCL

Tagging $0\nu\beta\beta$ decay events:

- two-electron summed energy = Q-value
- two-electron event topology
- (gamma-rays from de-excitation)
- (daughter isotope)

Backgrounds:

- cosmic-ray induced
- U/Th decay chains
- neutrons
- solar neutrinos
- 2vbb decay (only irreducible background)

Multivariate background discrimination:

- non uniform event rate in time or space
- spatially extended event topology
- particle identification
- energy (only way to mitigate 2vbb)

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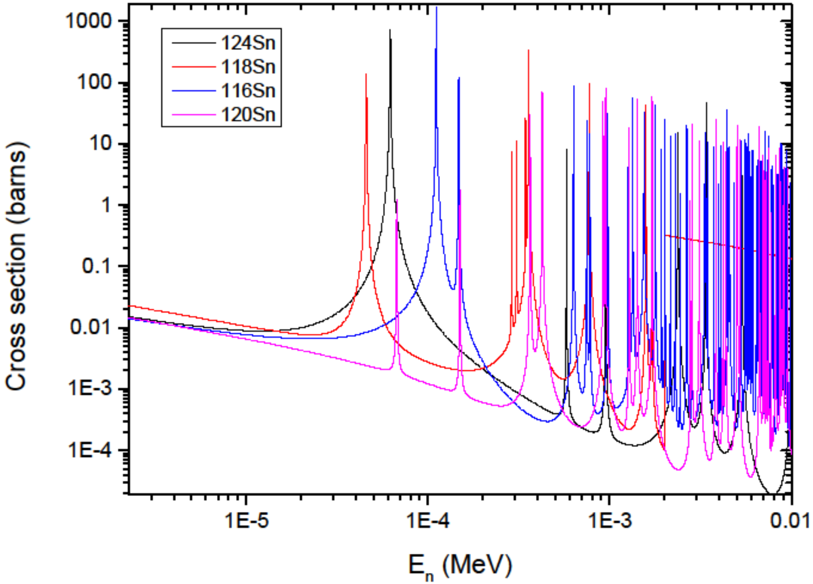
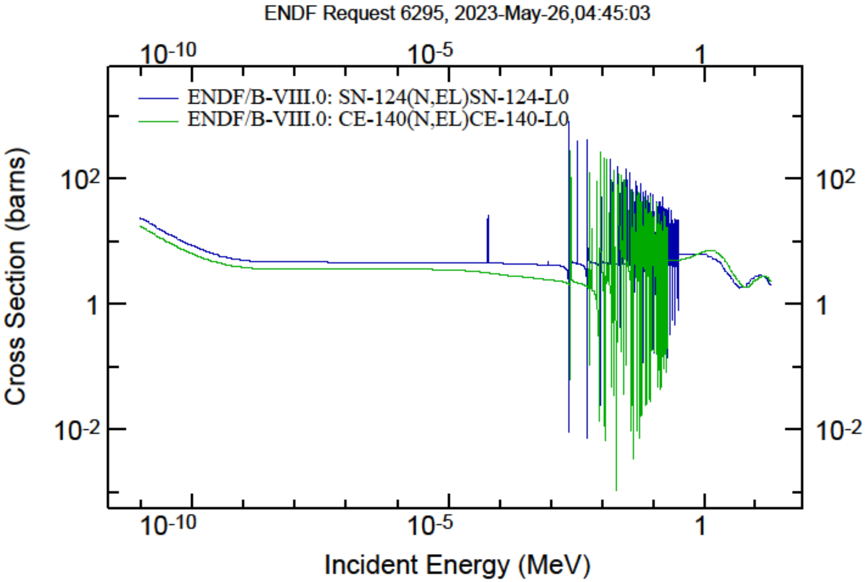


**Comparison of resonance from other Sn isotopes which can contribute more in the 124Sn resonance region.*



**140Ce and 124Sn elastic cross section comparison.*

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LHC

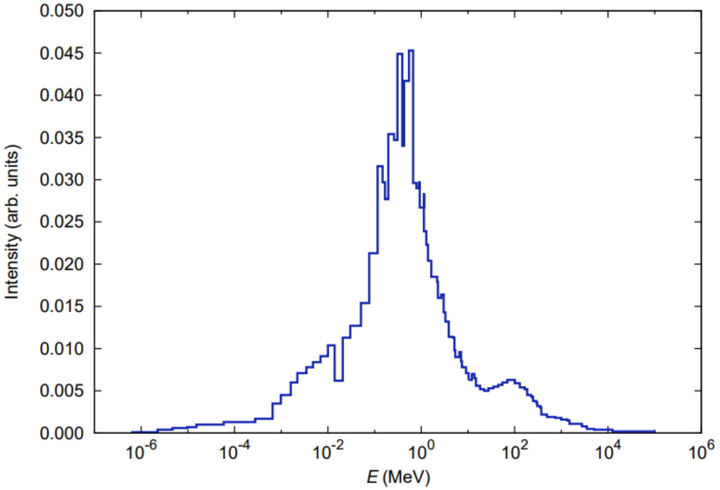

Figure 1.1.: Calculated neutron spectrum at the inner winding of quadrupole Q2

*Baumgartner, Thomas. *Effects of fast neutron irradiation on critical currents and intrinsic properties of state-of-the-art Nb3Sn wires.* na, 2013.

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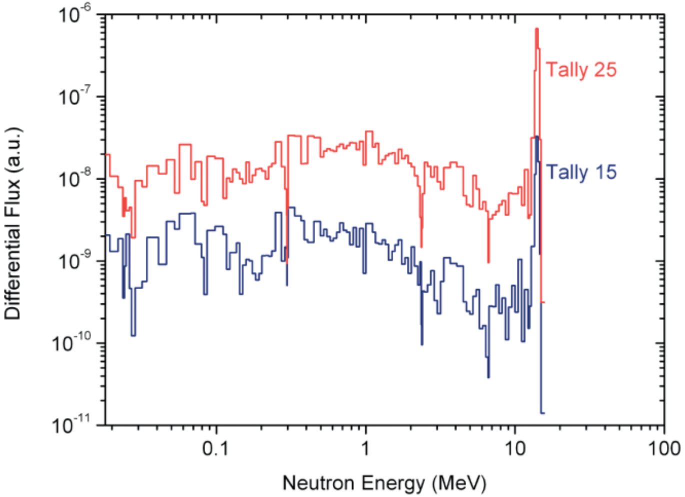

Figure 14. Neutron spectra at tally 15 and tally 25.

Krasilnikov, Vitaly, MunSeong Cheon, and Luciano Bertalot. "Neutron activation system for ITER tokamak." Advanced Technologies and Applications of Neutron Activation Analysis (2019): 71-87.

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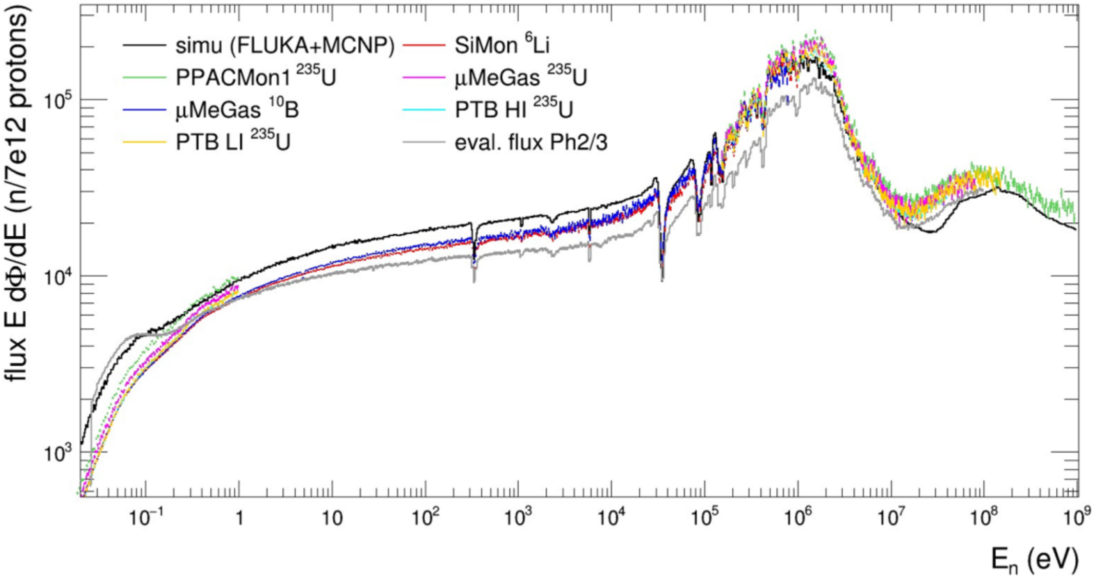
proton beam momentum	20 GeV/c
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)



Neutron Energy range	Energy Resolution
50 eV to 10 keV	200 eV
10 keV to 100 keV	3000 eV
100 keV to 200 keV	ear2
200 keV to 314 keV	