Tellurium Preparation for the SNO+ Neutrinoless Double Beta Decay Search

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For the SNO+ Collaboration

SNO+

- SNO heavy water replaced by 780 tonnes of liquid scintillator
- ~9500 PMTs
- 1700 + 5700 tonnes ultra-pure water shielding
- New rope net to hold down the 6m radius acrylic vessel
- 6800’ underground in SNOLAB

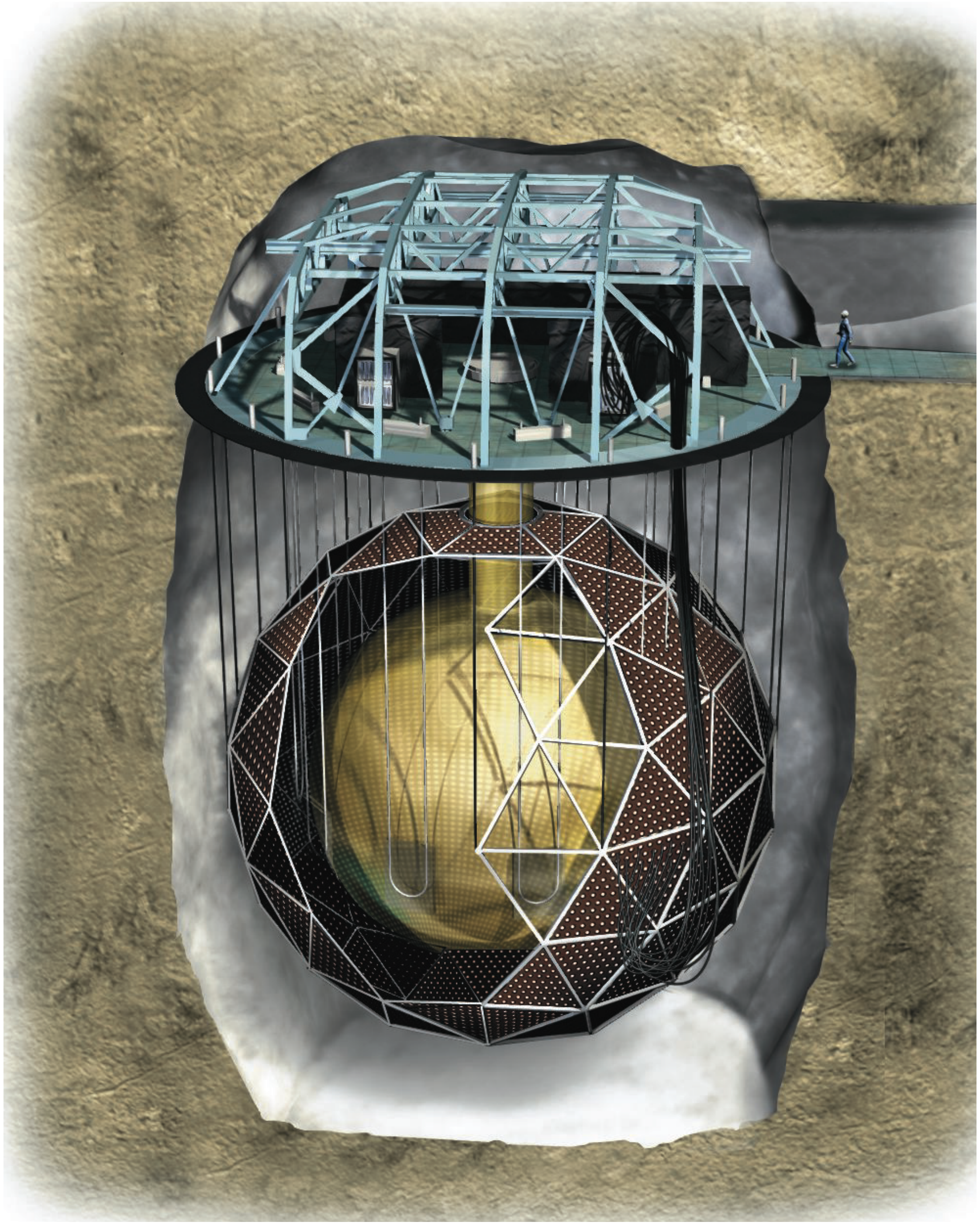


Image courtesy National Geographic

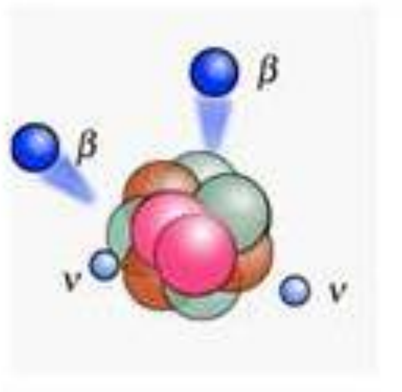
Neutrinoless Double Beta Decay

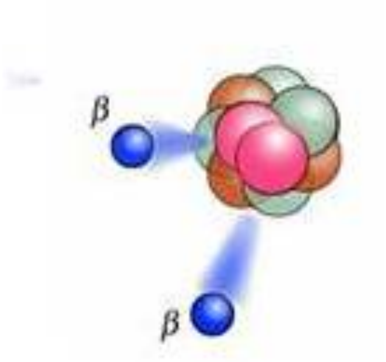
- Are neutrinos Majorana or Dirac particles?
  - Are they their own anti-particles?
- In double beta decay, a nucleus releases two electrons and two antineutrinos:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$$

- If neutrinos are Majorana, sometimes neutrinoless double beta decay occurs:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-$$





Detection of neutrinoless double beta decay proves that neutrinos are Majorana and provides information about the neutrino mass.

Neutrinoless Double Beta Decay

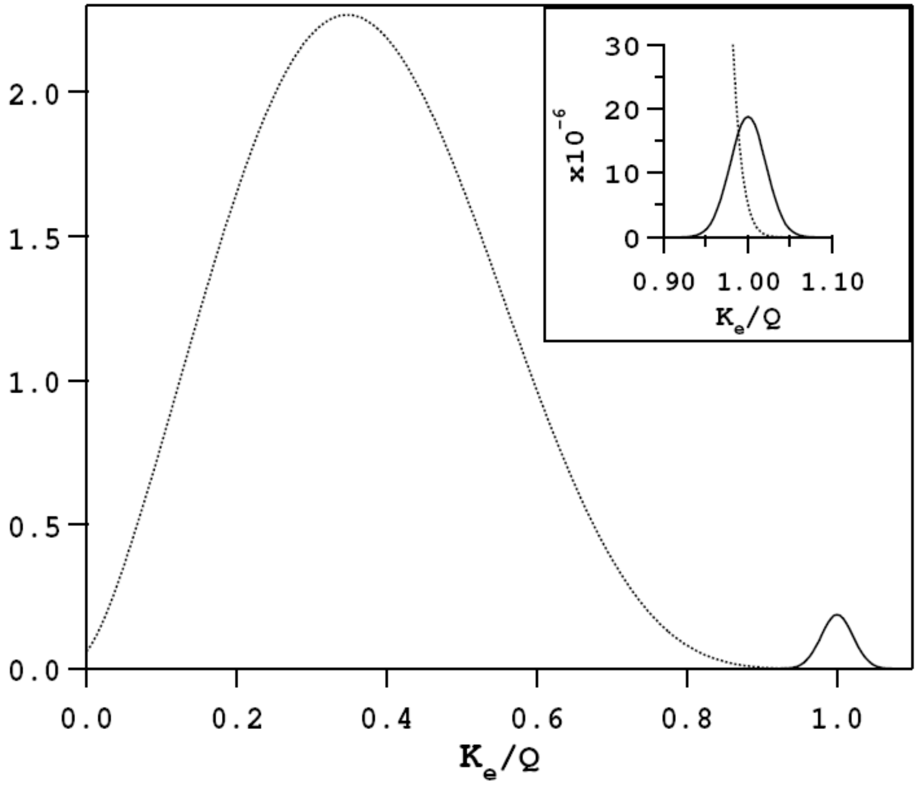


Image from Elliott and Vogel, hep-ph/0202254

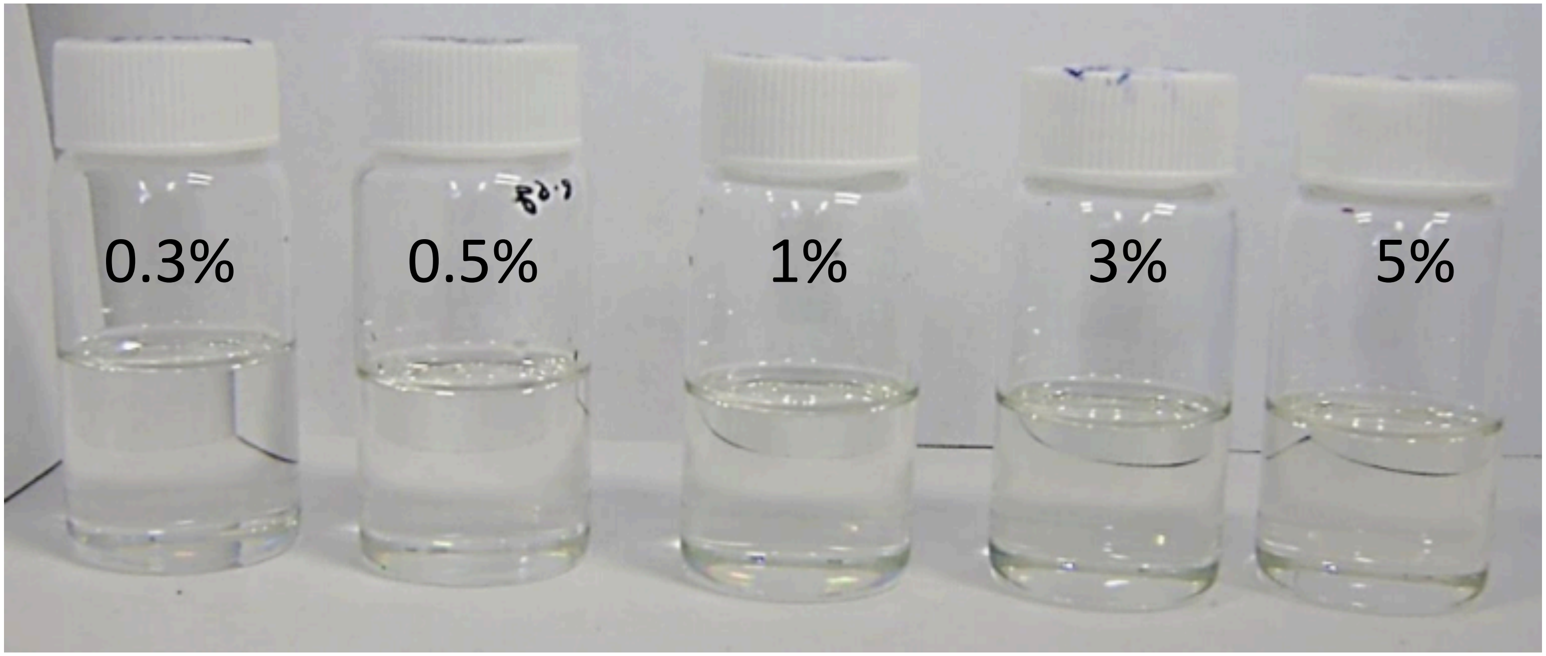
Searching for neutrinoless double beta decay involves looking for a tiny monoenergetic peak at the end of a large double beta decay continuum.

D.B.D. experiments need good energy resolution, low backgrounds, and large amounts of isotope.

Load Tellurium into the SNO+ Scintillator

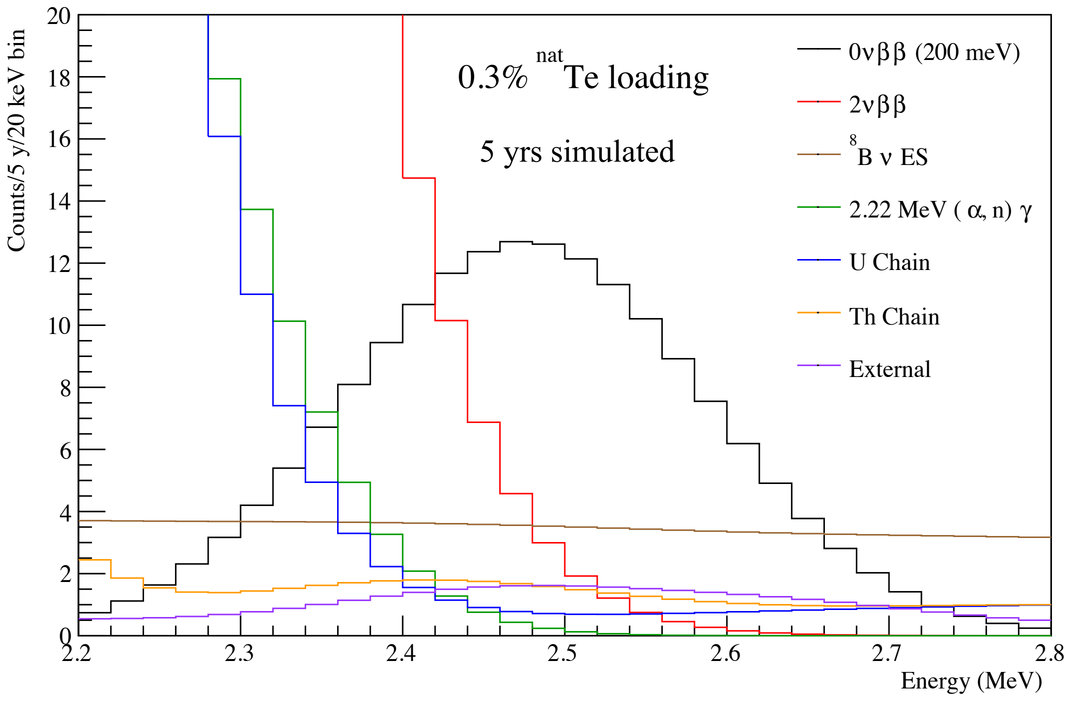
- 760 tonne detector and high ^{130}Te isotopic abundance gives large isotope mass
  - 0.3 – 0.5% Te (by weight) in SNO+ Phase I is 2.34 – 3.9 tonnes of Te or **800 – 1333 kg** of ^{130}Te
  - Percent-level loading is feasible
    - 3% Te in SNO+ Phase II would give **8 tonnes** of ^{130}Te
      - Te cost would be ~$15M

LAB scintillator with different Te loading



Load Tellurium into the SNO+ Scintillator

- Very low backgrounds are achievable in large liquid scintillator detectors
  - The U chain background (^{214}Bi-^{214}Po) in the energy range around the ^{130}Te endpoint (2.53 MeV) can be rejected by factor >5,000 using delayed coincidences
  - The 2νββ for Te is relatively small
  - External backgrounds controlled by fiducialization



Extremely low background compensates for modest energy resolution.

If the TeLS is sufficiently radiopure, the dominant background in SNO+ will be ^{8}B solar neutrinos. Then sensitivity scales directly with Te loading!

Tellurium Purification

- Two main classes of Te intrinsic background:
  - “Standard” decay chains of long-lived radioisotopes
    - Need 10^{-14}-10^{-15}g/g ^{238}U, ^{232}Th, “raw” tellurium has ~10^{-12}g/g
  - Te cosmogenics have longish half-lives and decays that overlap the 0$\nu\beta\beta$ energy region
- Need a purification technique that separates other metals from tellurium at the 10^4-10^6 level

Cosmogenic Backgrounds in SNO+ ROI – year 1	
^{22}Na	15309
^{26}Al	0.048
^{42}K	565
^{44}Sc	102
^{46}Sc	43568
^{56}Co	2629
^{58}Co	25194
^{60}Co	6906
^{68}Ga	37343
^{82}Rb	18047
^{84}Rb	11850
^{88}Y	390620
^{90}Y	823
^{102}Rh	276189
^{102m}Rh	133848
^{106}Rh	1534
^{110m}Ag	69643
^{110}Ag	939
^{124}Sb	3101138
^{126m}Sb	240
^{126}Sb	358996

See: V. Lozza and J. Petzoldt *Cosmogenic activation of a natural tellurium target*. Submitted to Astropart. Phys.

pH Selective Telluric Acid Recrystallization

- Telluric acid obeys the following equilibrium:

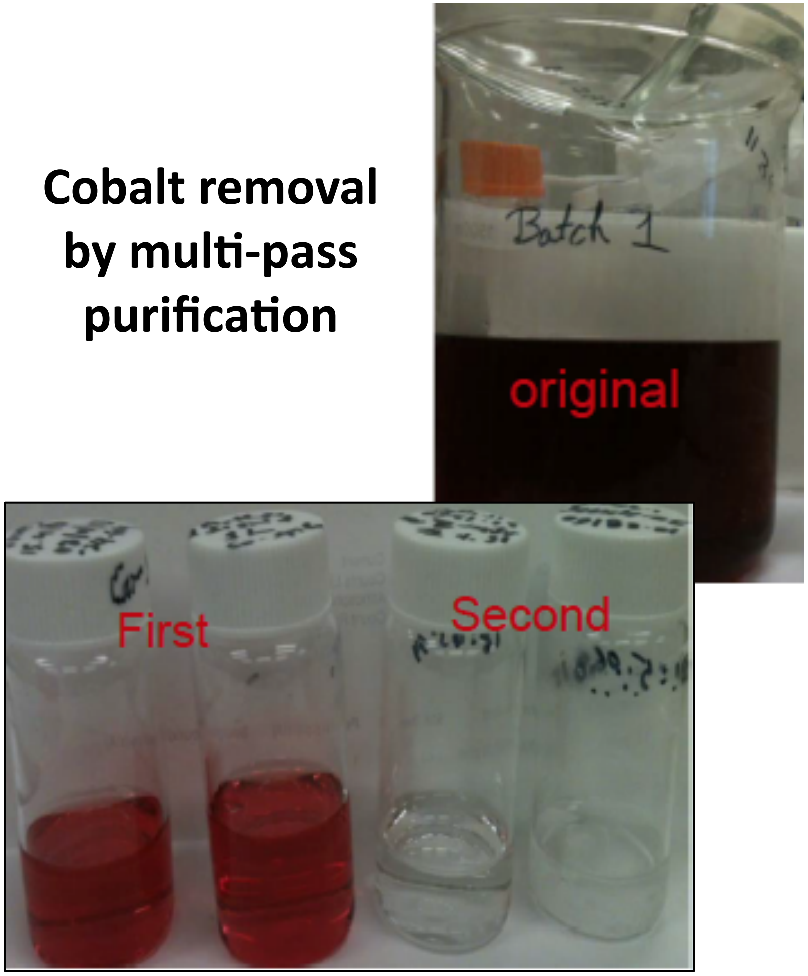
$$Te(OH)_6 \leftrightarrow Te(OH)_5O^- + H^+$$

Insoluble

Soluble

  - pH determines the equilibrium state
- Purification basics:
  1. Dissolve telluric acid in water and filter it
     - Removes insoluble impurities
  2. Add nitric acid to force the telluric acid to recrystallize/precipitate, pump away the liquid, rinse with ethanol
     - Removes soluble impurities
- By “tuning” the process pH’s, this can be quite specific to telluric acid – most other chemicals are removed with high efficiency

Cobalt removal by multi-pass purification



See S. Hans et. al. *Purification of Telluric Acid for SNO+ Neutrinoless Double Beta Decay Search*. In preparation.

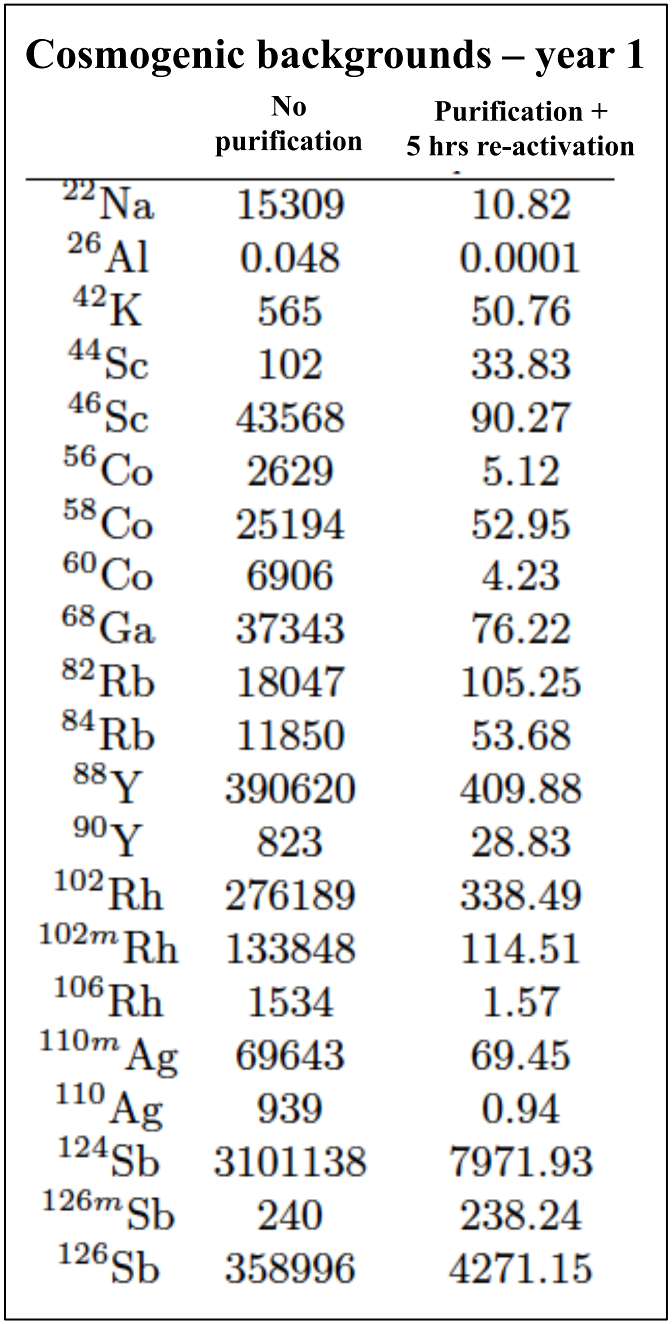
Measured Single Pass Purification Factors

Element	Reduction Factors From Spike Tests	Non-spiked, before purification (ppb)	Non-spiked, after purification (ppb)
Sn	$>1.67\times10^2$	20	<20
Zr	$>2.78\times10^2$	70	<10
Ti		40	<10
Co	$(1.62\pm0.34)\times10^3$	<10	<10
Mn		150	<5
Fe		40	<30
Ag	$>2.78\times10^2$	<10	<10
Y	$>2.78\times10^2$	<10	<10
Sc	$>1.65\times10^2$	<10	<10
Sb	$>2.43\times10^2$	20	<20
Th	$(3.90\pm0.19)\times10^2$	<0.02	<0.02
Ra	$(3.97\pm0.20)\times10^2$		
Ba		1400	<5
Pb	$(2.99\pm0.22)\times10^2$	440	<3
Bi	$(3.48\pm0.81)\times10^2$	300	<10
U	$(3.90\pm0.19)\times10^2$	<0.02	<0.02

Two-pass purification should meet our purity goals.

Re-Growth of Cosmogenics

- The nitric acid recrystallization process must be done above ground for safety
- Cosmogenic isotopes re-develop between the end of purification and moving the Te underground
  - Even with a 5 hour transit time (our goal) the cosmogenic re-generation is too great
  - Half-lives of regenerated isotopes are mainly short, but too long for them to decay away sufficiently on SNO+ timescales



Cosmogenic backgrounds – year 1

	No purification	Purification + 5 hrs re-activation
^{22}Na	15309	10.82
^{26}Al	0.048	0.0001
^{42}K	565	50.76
^{44}Sc	102	33.83
^{46}Sc	43568	90.27
^{56}Co	2629	5.12
^{58}Co	25194	52.95
^{60}Co	6906	4.23
^{68}Ga	37343	76.22
^{82}Rb	18047	105.25
^{84}Rb	11850	53.68
^{88}Y	390620	409.88
^{90}Y	823	28.83
^{102}Rh	276189	338.49
^{102m}Rh	133848	114.51
^{106}Rh	1534	1.57
^{110m}Ag	69643	69.45
^{110}Ag	939	0.94
^{124}Sb	3101138	7971.93
^{126m}Sb	240	238.24
^{126}Sb	358996	4271.15

Underground “Polishing” Process

- The solubility of telluric acid in water is also temperature dependent
  - Can re-crystallize by dissolving to saturation in warm water and then cooling
  - Less efficient, but good enough to remove cosmogenic re-growth with two passes (need factor of 100 suppression)
  - Te yield is low (~70%/pass)
    - Take residual solution back to surface and process with nitric to recover Te

Element	Single Pass Reduction Factor
Ag	>144
Co	240
Ge	86
Sb	76
Sc	198
Sn	99
Y	500
Zr	104

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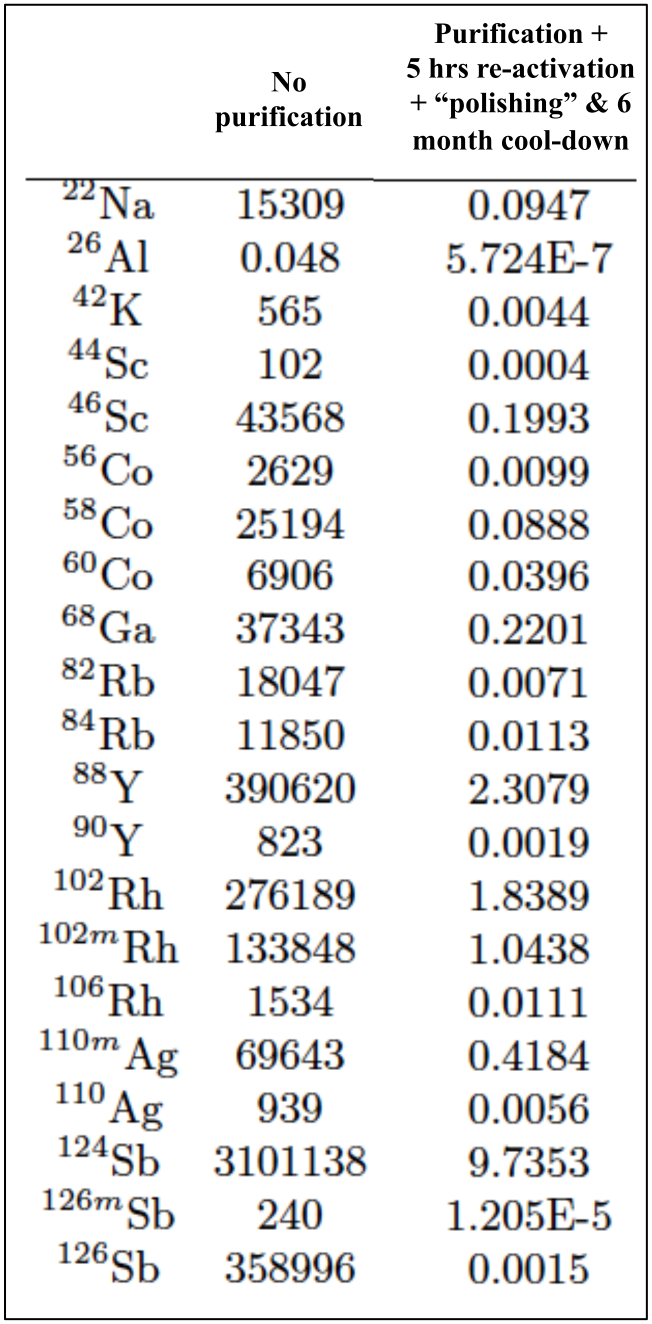

	No purification	**Purification + 5 hrs re-activation + "polishing" & 6 month cool-down**
^{22}Na	15309	0.0947
^{26}Al	0.048	5.724E-7
^{42}K	565	0.0044
^{44}Sc	102	0.0004
^{46}Sc	43568	0.1993
^{56}Co	2629	0.0099
^{58}Co	25194	0.0888
^{60}Co	6906	0.0396
^{68}Ga	37343	0.2201
^{82}Rb	18047	0.0071
^{84}Rb	11850	0.0113
^{88}Y	390620	2.3079
^{90}Y	823	0.0019
^{102}Rh	276189	1.8389
^{102m}Rh	133848	1.0438
^{106}Rh	1534	0.0111
^{110m}Ag	69643	0.4184
^{110}Ag	939	0.0056
^{124}Sb	3101138	9.7353
^{126m}Sb	240	1.205E-5
^{126}Sb	358996	0.0015

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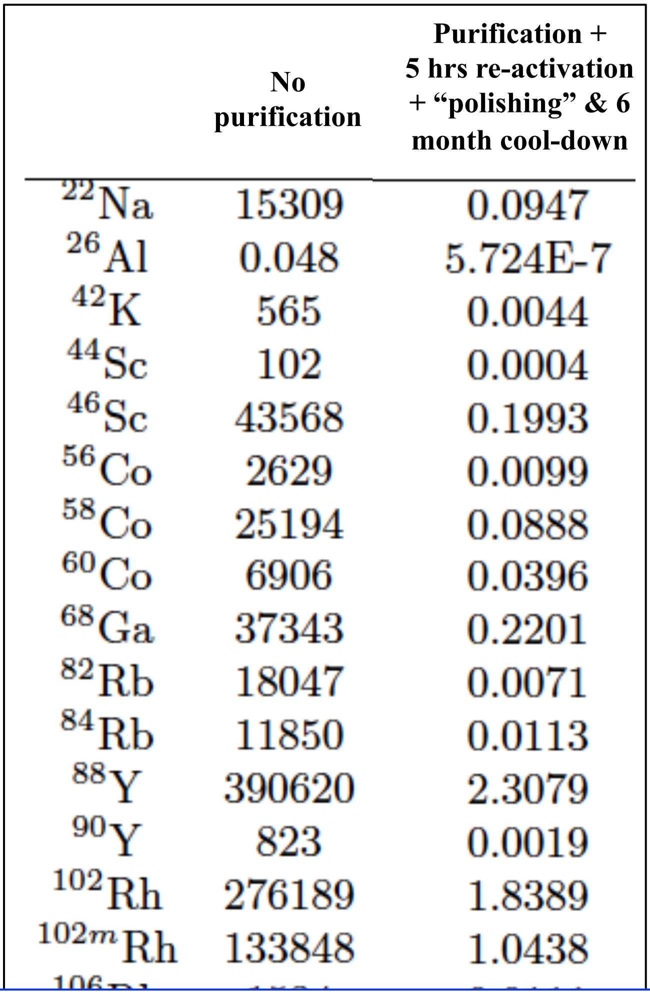
  - Can re-crystallize by dissolving to saturation in warm water and then cooling
  - Less efficient, but good enough to remove cosmogenic re-growth with two passes (need factor of 100 suppression)
  - Te yield is low (~70%/pass)
    - Take residual solution back to



	No purification	**Purification + 5 hrs re-activation + “polishing” & 6 month cool-down**
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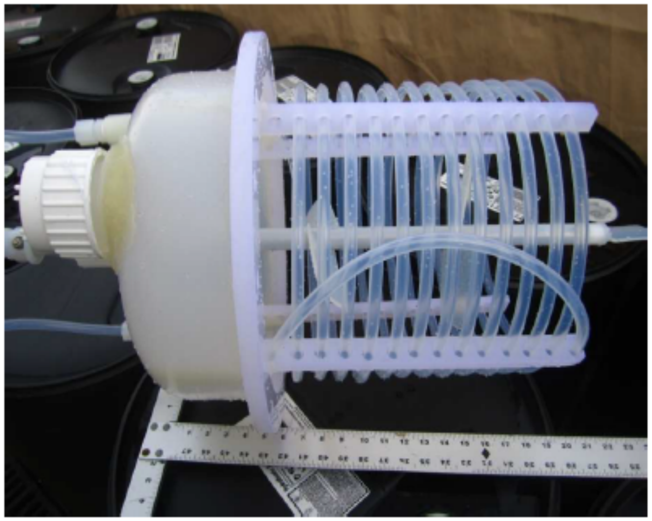
^{102}Rh	276189	1.8389
^{102m}Rh	133848	1.0438

Two passes each of nitric acid recrystallization and “polishing” reduces both long-lived and cosmogenic isotope backgrounds to acceptable levels.

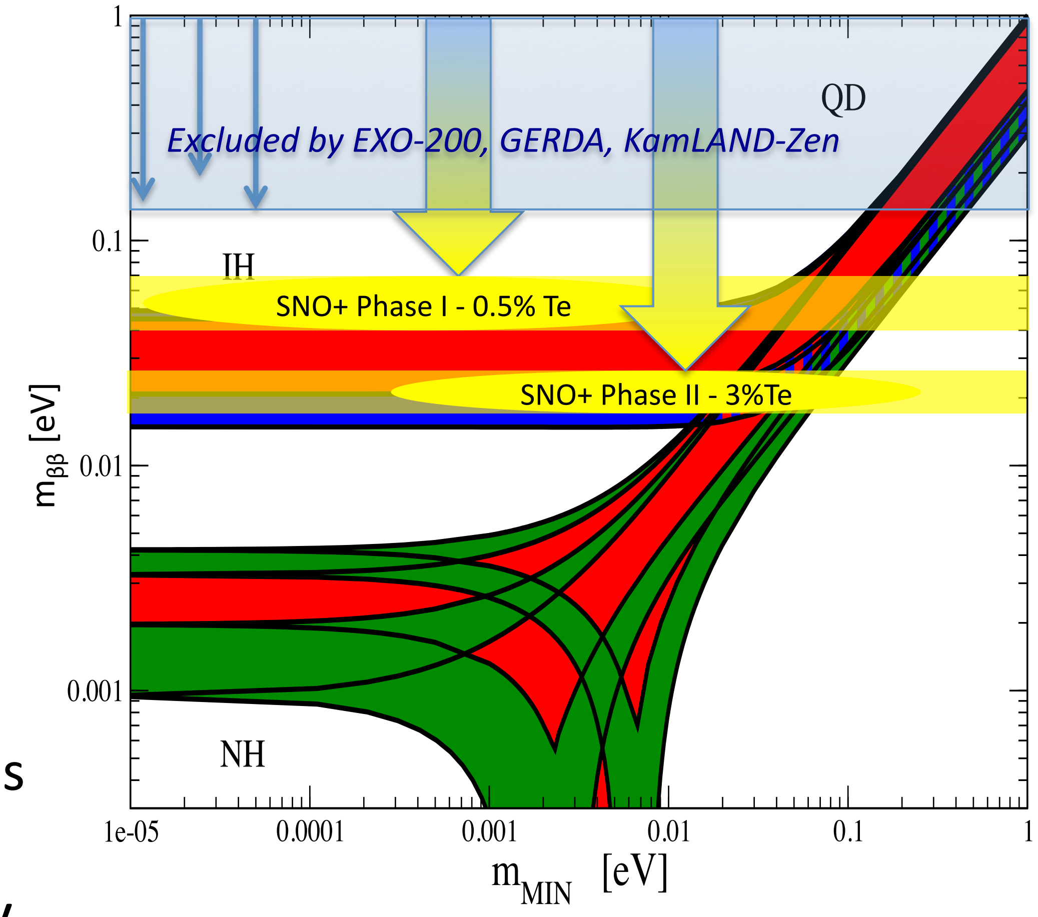
Scale-Up



- Working with an industrial partner (SeaStar Chemicals, Sydney, BC) to scale processes up to ~200kg batch size
  - A few months to process the 4 tonnes of telluric acid for 0.3% loading
- Currently operating a 10kg pilot-scale plant
- Plan to have the full-scale system at SNOLAB this winter

Summary

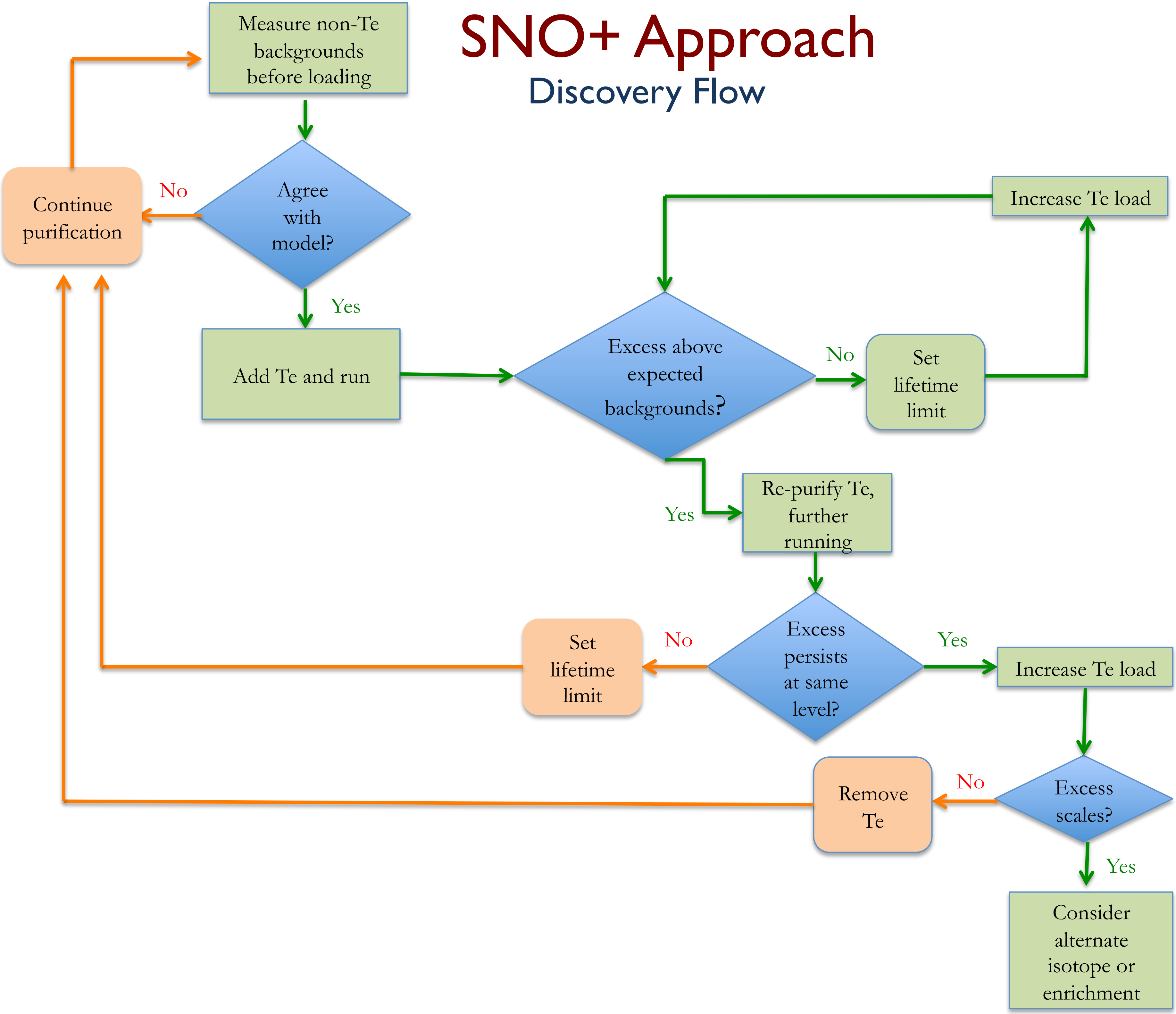
- SNO+ will search for neutrinoless double beta decay by dissolving Te into the liquid scintillator
  - Initial phase with 0.3 – 0.5% loading
  - Higher loadings possible in the future
- Techniques for removing radioactive impurities from the tellurium have been developed and successfully tested
  - Development of the large scale Te purification plant is in progress
- Clean Te will help SNO+ to achieve world-leading sensitivity to neutrinoless double beta decay



Background plot adapted from PRD 77, 113003 (2008)

SNO+ Approach

Discovery Flow



Measure non-Te backgrounds before loading

Agree with model?

No

Continue purification

Yes

Add Te and run

Excess above expected backgrounds?

No

Set lifetime limit

Increase Te load

Yes

Re-purify Te, further running

Excess persists at same level?

No

Set lifetime limit

Yes

Increase Te load

Excess scales?

No

Remove Te

Yes

Consider alternate isotope or enrichment

Isotope	$T_{1/2}$ [1] [d]	Q-value [1] [MeV]	R (ϕ from [2][3]) [μBq/kg]	Events Y1 t_{exp}=1 yr
^{22}Na	950.6	2.84	1.01	1138
^{26}Al	2.62E+8	4.00	0.67	0.000
^{42}K (direct and daughter of ^{42}Ar)	0.51 (1.20E+4)	3.53	1.33 (0.24)	11
^{44}Sc (direct and daughter of ^{44}Ti)	0.17 (2.16E+4)	3.65	1.19 (0.052)	5.34
^{46}Sc	83.79	2.37	1.97	37
^{56}Co	77.2	4.57	0.13	1
^{58}Co	70.9	2.31	1.29	0.000
^{60}Co (direct and daughter of ^{60}Fe)	1925.27 (5.48E+8)	2.82	0.81 (0.367)	877
^{68}Ga (direct and daughter of ^{68}Ge)	4.70E-2(271)	2.92	3.14 (1.28)	373
^{82}Rb (daughter of ^{82}Sr)	8.75E-4(25.35)	4.40	(2.44)	446
^{84}Rb	32.8	2.69	1.29	18
^{88}Y (direct and daughter of ^{88}Zr)	106.63 (83.4)	3.62	3.14 (8.11)	35750
^{90}Y (direct and daughter of ^{90}Sr)	2.67 (1.05E+4)	2.28	0.69 (0.165)	0.000
^{102}Rh (direct and daughter of ^{102m}Rh) [a]	207.3	2.32	11.77 (0.03)	0.000
^{102m}Rh	1366.77	2.46	11.77	82
^{106}Rh (daughter of ^{106}Ru)	3.47E-4 (371.8)	3.54	(0.06)	23
^{110m}Ag	249.83	3.01	2.39	3475
^{110}Ag (daughter of ^{110m}Ag)[b]	2.85E-4	2.89	(0.03)	4
^{124}Sb	60.2	2.90	182.0	177396
^{126m}Sb (direct and daughter of ^{126}Sn)	0.01 (8.40E+7)	3.69	71.42 (7.91)	10
^{126}Sb (direct and daughter of ^{126m}Sb)[c]	12.35 (0.01)	3.67	89.65 (^{126m}Sb)	6888

[a] 0.23% from ^{102m}Rh IT decay.

[b] 1.33% from ^{110m}Ag IT decay

[c] 14% from ^{126m}Sb IT decay.

[1] Nudat website, `http://www.nndc.bnl.gov/nudat2/`.

[2] T.W. Armstrong, K.C. Chandler, J. Barish, J. Geophys. Res. **78** (1973) 2715.

[3] N. Gehrels, Nucl. Instr. and Meth. A **239** (1985) 324.

Isotope	Events Y1		
	t_{exp}=1 yr	PF stage 1 t_{exp}=5h surf	PF stage 2 t_{cool}=6 mo. UG
^{22}Na	15309	10.82	0.0947
^{26}Al	0.048	0.0001	5.724E-7
^{42}K	565	50.76	0.0044
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