Low-level radon detection in the SuperNEMO detector

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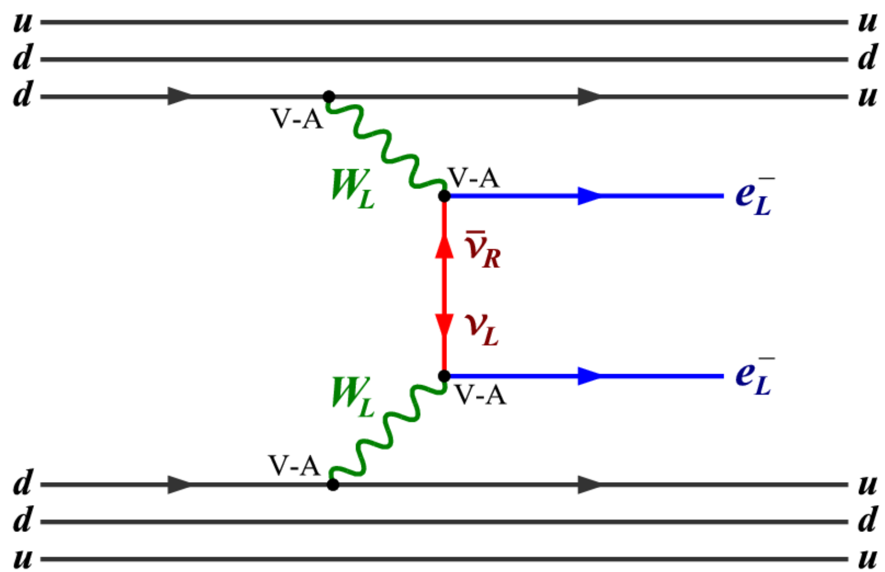
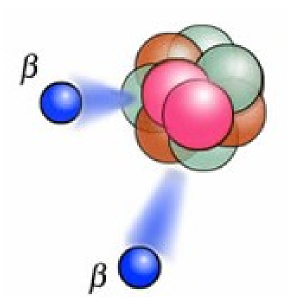
Neutrinoless Double Beta Decay (0νββ)

- 0νββ is a lepton-number violating transition:

$$2n \rightarrow 2p + 2e^-$$



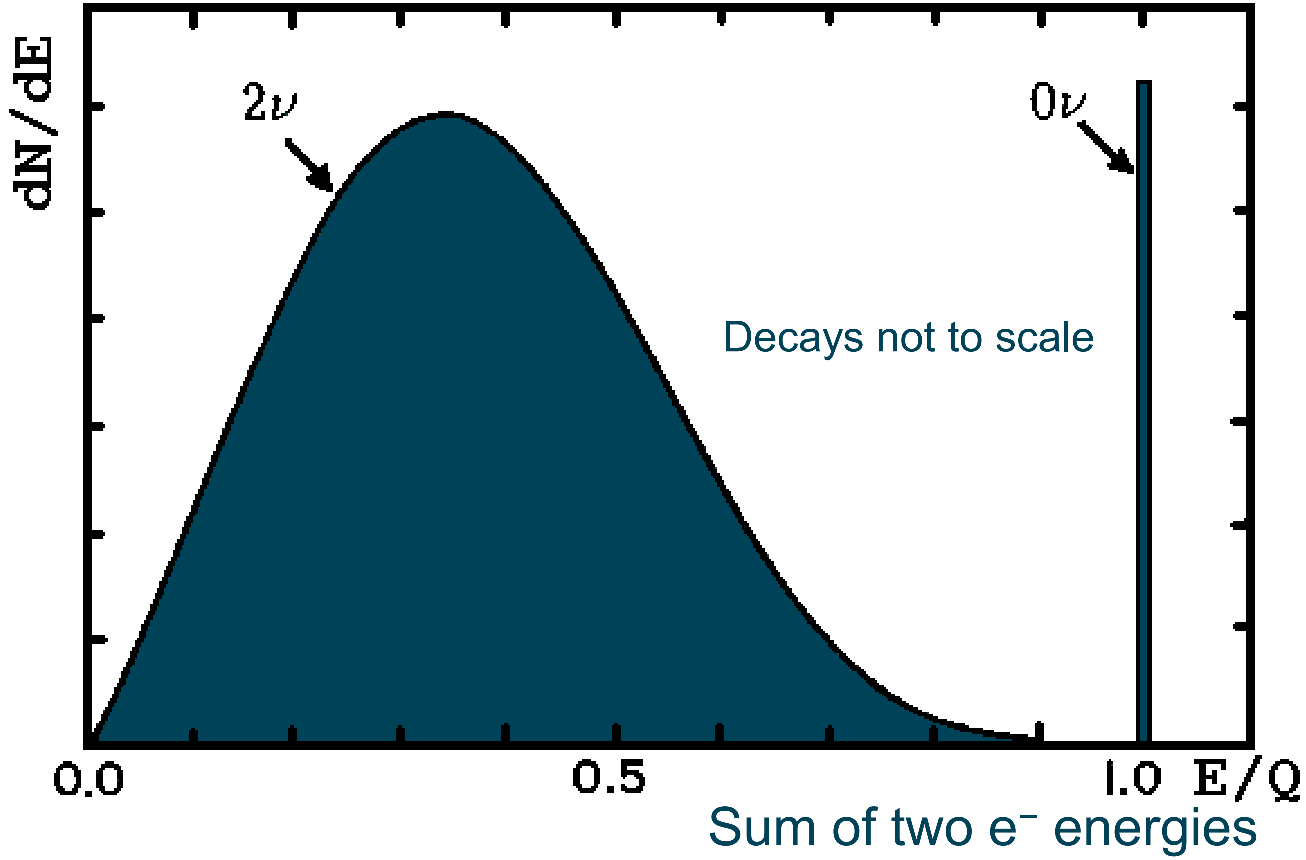
One possible mechanism: Light Majorana neutrino exchange



- 0νββ is one of the most promising ways to answer:
  - Is the neutrino a Majorana or Dirac particle?
  - What is the absolute neutrino mass scale?

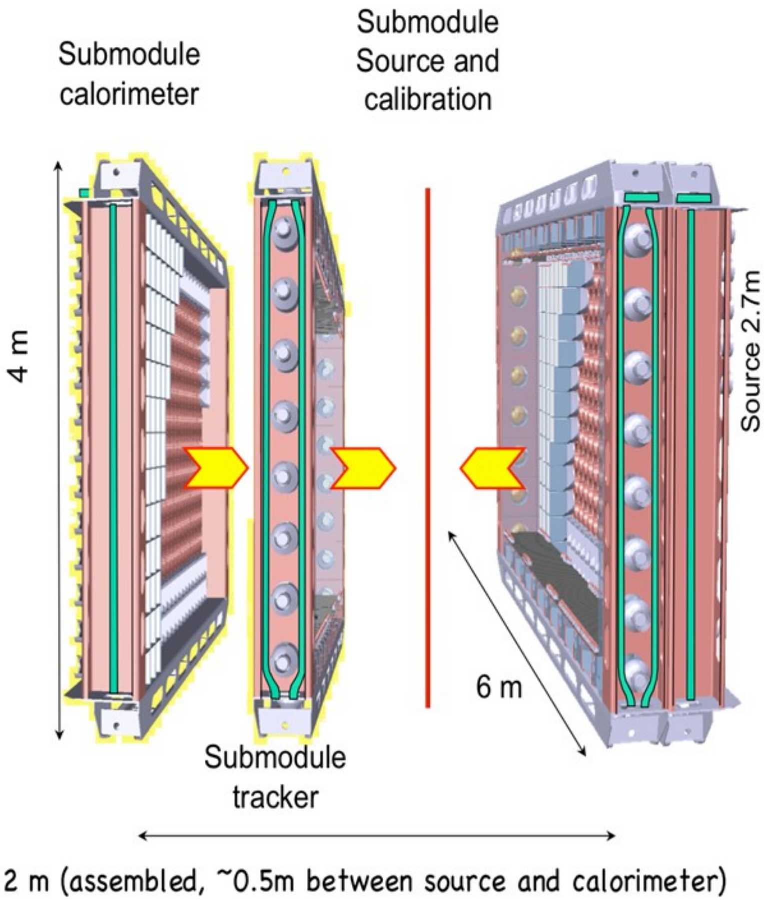
0νββ: Experimental Signature

- The majority of experiments measure the sum of the energy of the two electrons to identify the decay.
- The signal for 0νββ is a line at $Q_{\beta\beta}$ for the isotope:



The SuperNEMO Experiment

- SuperNEMO is a next-generation 0νββ experiment.
- It uses the same tracking and calorimeter techniques as NEMO-3



- It will consist of 20 identical planar modules, each containing:

- **Source foil:** ~ 7 kg of ^{82}Se (or ^{150}Nd/^{48}Ca)
- **Tracker:** Drift chamber with ~ 2000 vertical cells in He, Ar and alcohol.
- **Calorimeter:** 500 PMTs & plastic scintillator blocks

- Design allows particle ID, topology reconstruction & strong background rejection
- Aims to study half-life up to 10^{26} yr

($\langle m_{\beta\beta}\rangle$ = 40 - 100 meV)

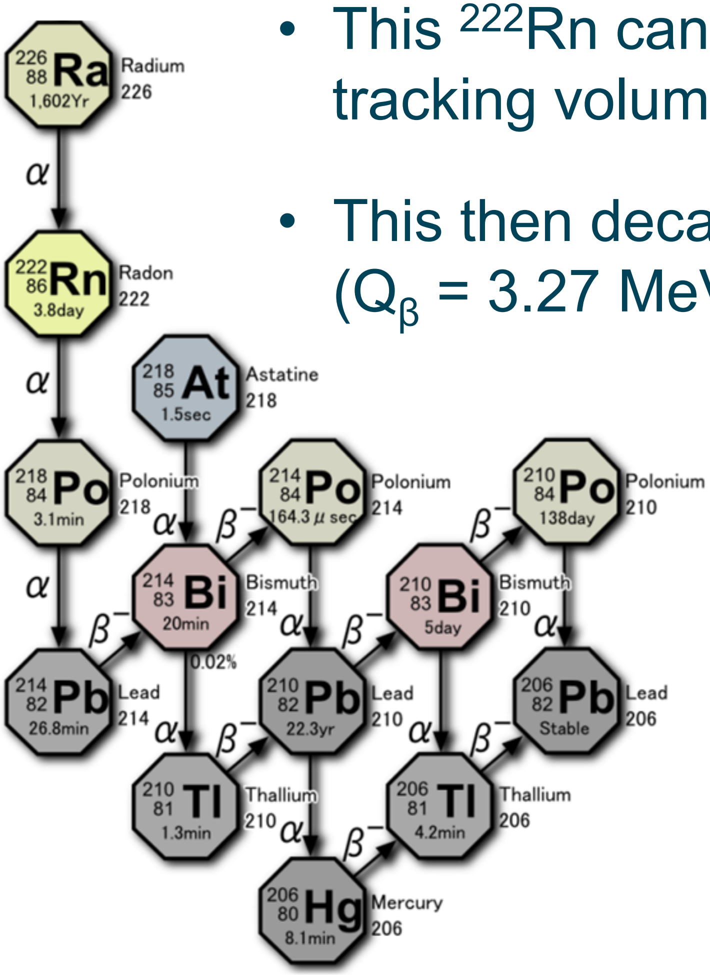
From NEMO-3 to SuperNEMO...

NEMO-3	→	SuperNEMO
^{100}Mo	Isotope	^{82}Se (or ^{150}Nd or ^{48}Ca)
10 kg	Mass	100+ kg
< 5 mBq/m^3	^{222}Rn in tracker	< 0.15 mBq/m^3
8% @ 3 MeV	Energy Resolution (FWHM)	4% @ 3 MeV
$T_{1/2} > 10^{24}$ y $\langle m_\nu \rangle$ < 0.3 - 0.9 eV	Sensitivity	$T_{1/2} > 10^{26}$ y $\langle m_\nu \rangle$ < 40 - 100 meV

- 1st SuperNEMO module is being built will be installed by 2014.
- By 2016 it will be able to probe the controversial Klapdor claim to have observed $0\nu\beta\beta$ with $\langle m_\nu \rangle \sim 0.4$ eV.
- It will be followed by 19 similar modules, to be built from 2015 and achieving full sensitivity by 2019.

Radon as a SuperNEMO background

- All materials contain small traces of ^{226}Ra which decays to ^{222}Rn.



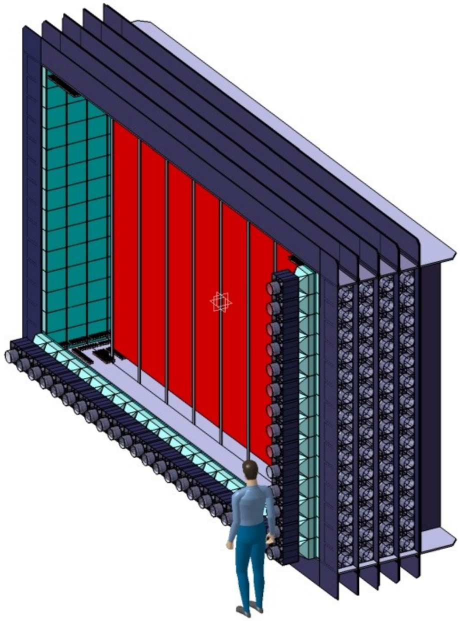
- This ^{222}Rn can diffuse out of the detector materials into the tracking volume.

- This then decays to ^{214}Bi which has a problematic β decay (Q_β = 3.27 MeV)

- ^{222}Rn concentration in the tracker must be < 0.15 mBq/m^3 to achieve the target sensitivity.

- Best radon detectors (electrostatic collection) are typically sensitive to ~1 mBq/m^3 so to measure our target level we need a different technique.

Radon Concentration Line: Concept



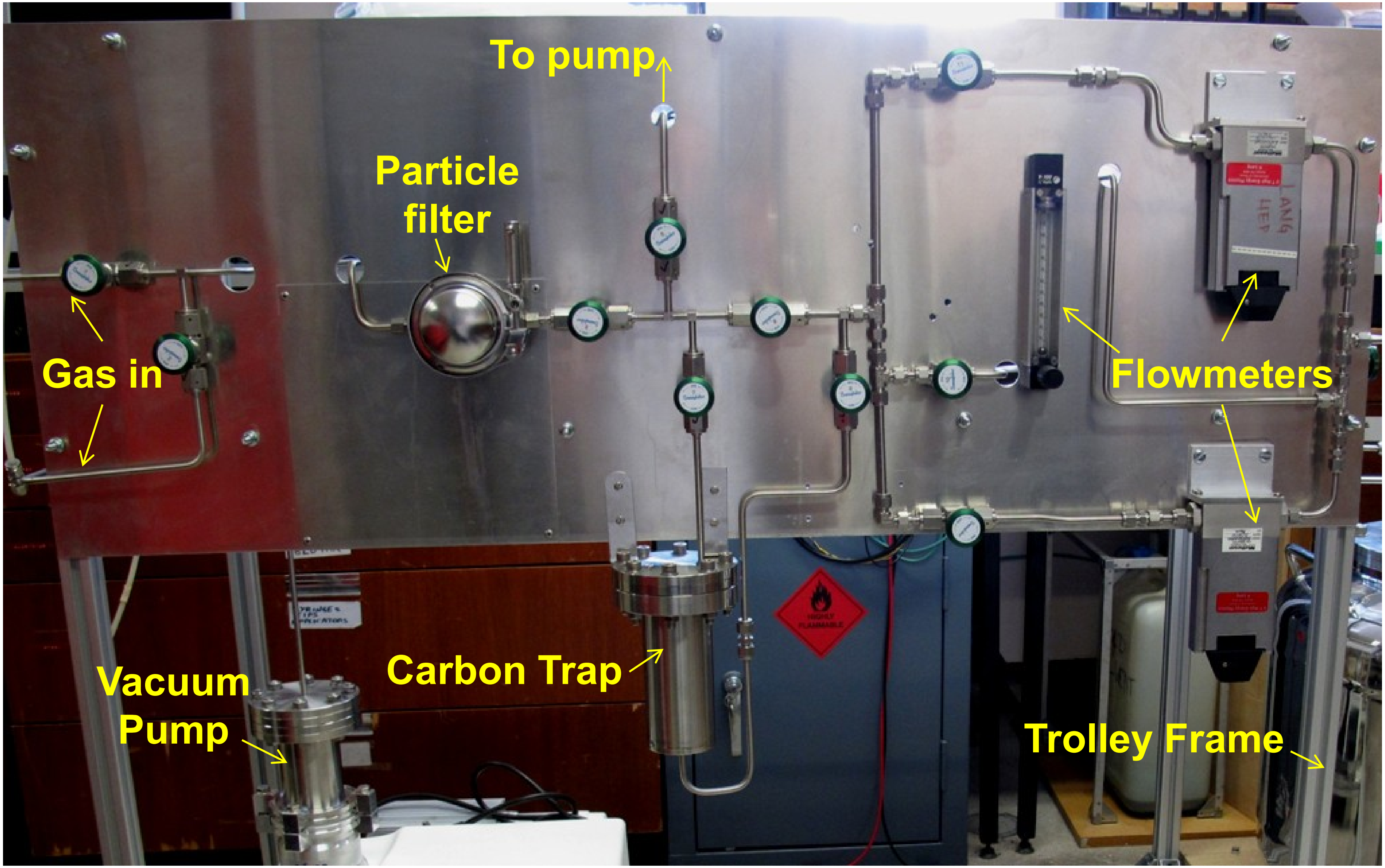
SuperNEMO tracker sub-module (~ 14m^3)

Radon concentration line

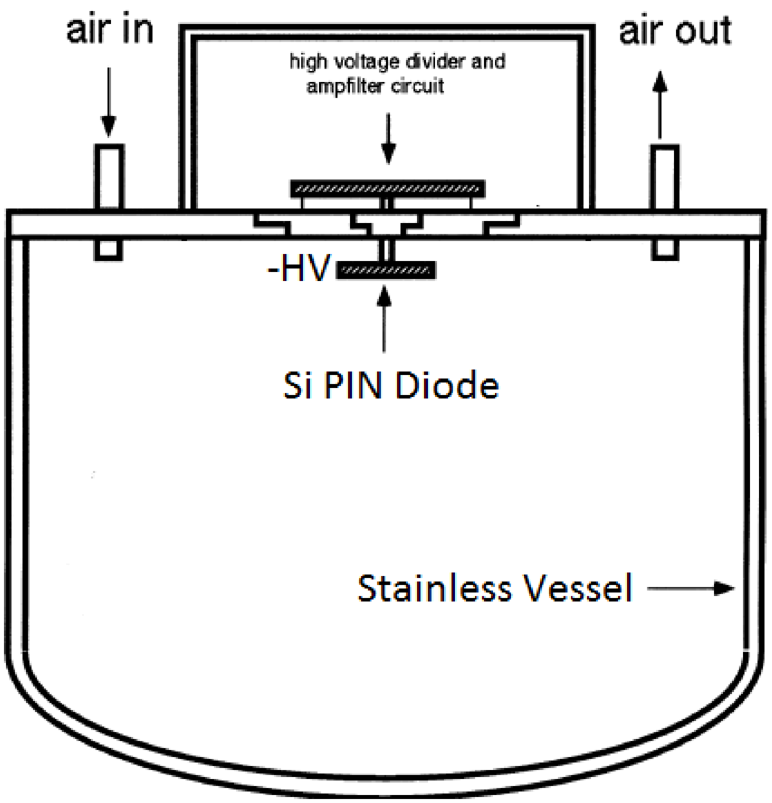
Electrostatic detector

- Gas from the tracker is pumped through a cooled ultra-pure carbon trap and the ^{222}Rn in the gas is adsorbed.
- The concentrated sample is then heated and transferred to an electrostatic detector via helium purge.

Radon Concentration Line: Real Life

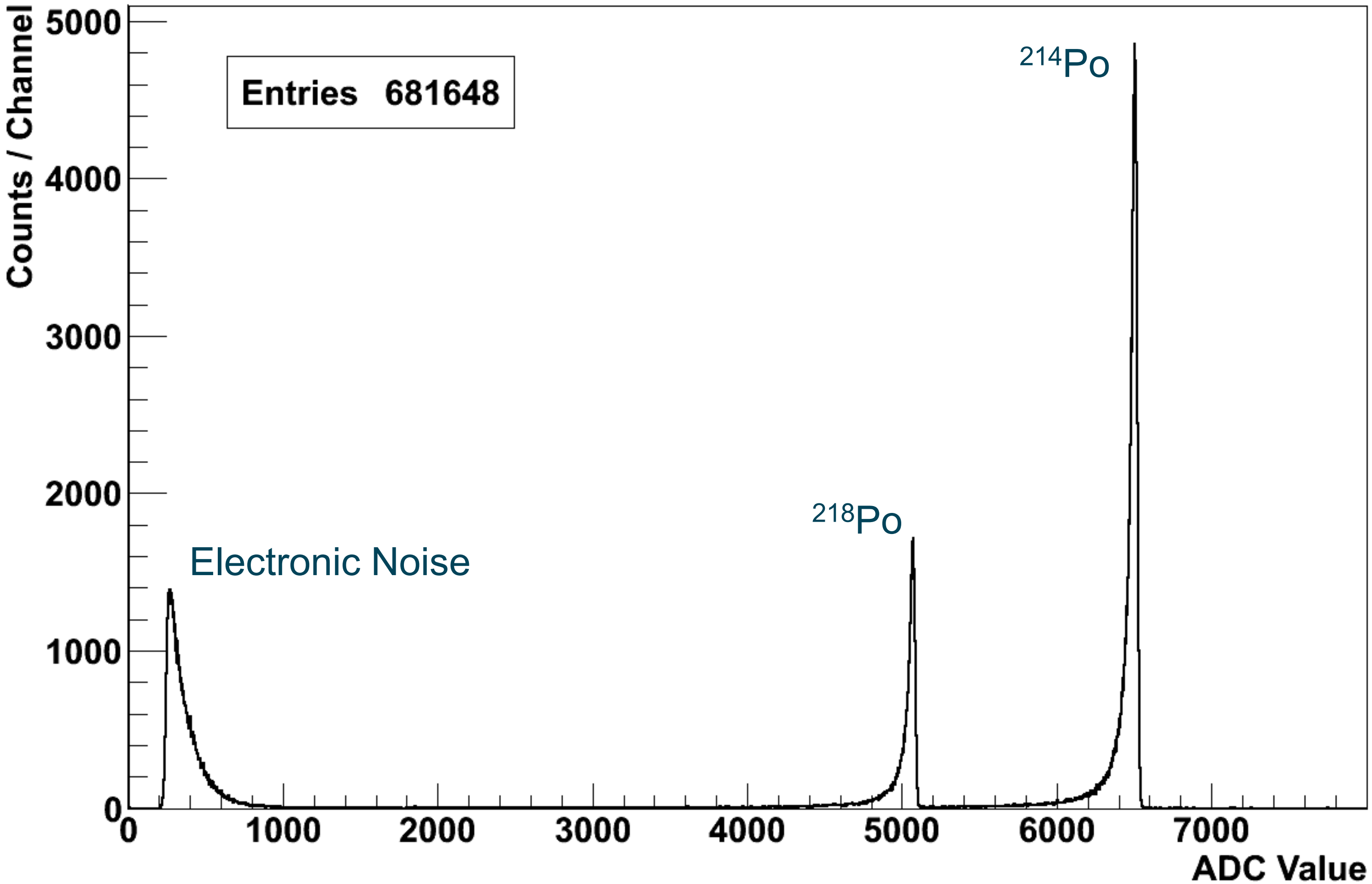


Electrostatic Detector: Principle of Operation



- ^{222}Rn is pumped into the vessel where it decays.
- Daughters of ^{222}Rn decay are mostly positive ions.
- These ions collect on the PIN diode due to the applied negative HV.
- Once on the photodiode, they decay and ^{218}Po, ^{214}Po & ^{210}Po alphas can be identified by the energy deposited.
- ^{214}Po is the most commonly used isotope for measuring ^{222}Rn.

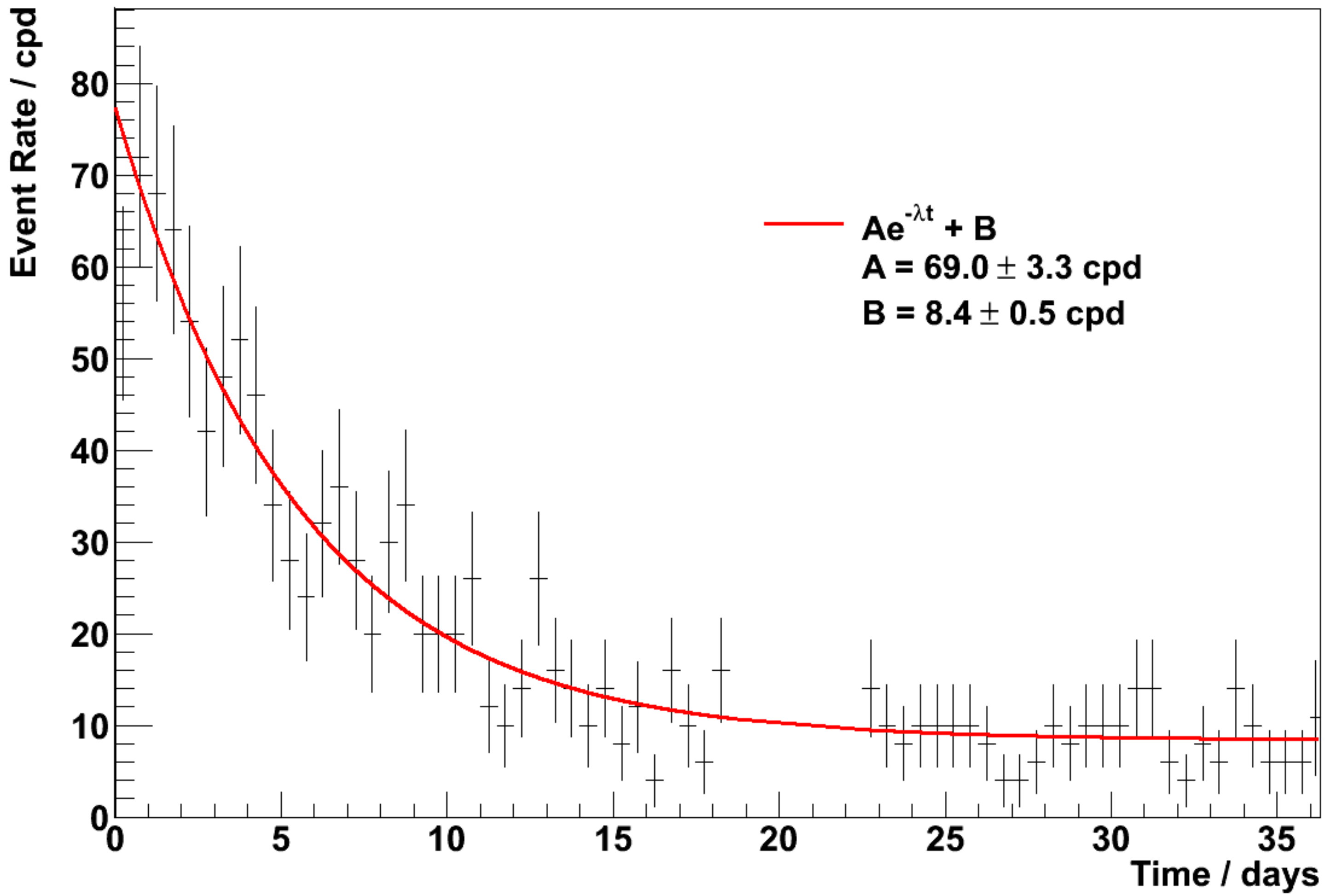
Electrostatic Detector: Energy Spectrum



- Peaks from ^{218}Po (6.1 MeV) and ^{214}Po (7.9 MeV) are visible and have excellent resolution

Electrostatic Detector: Background Rate

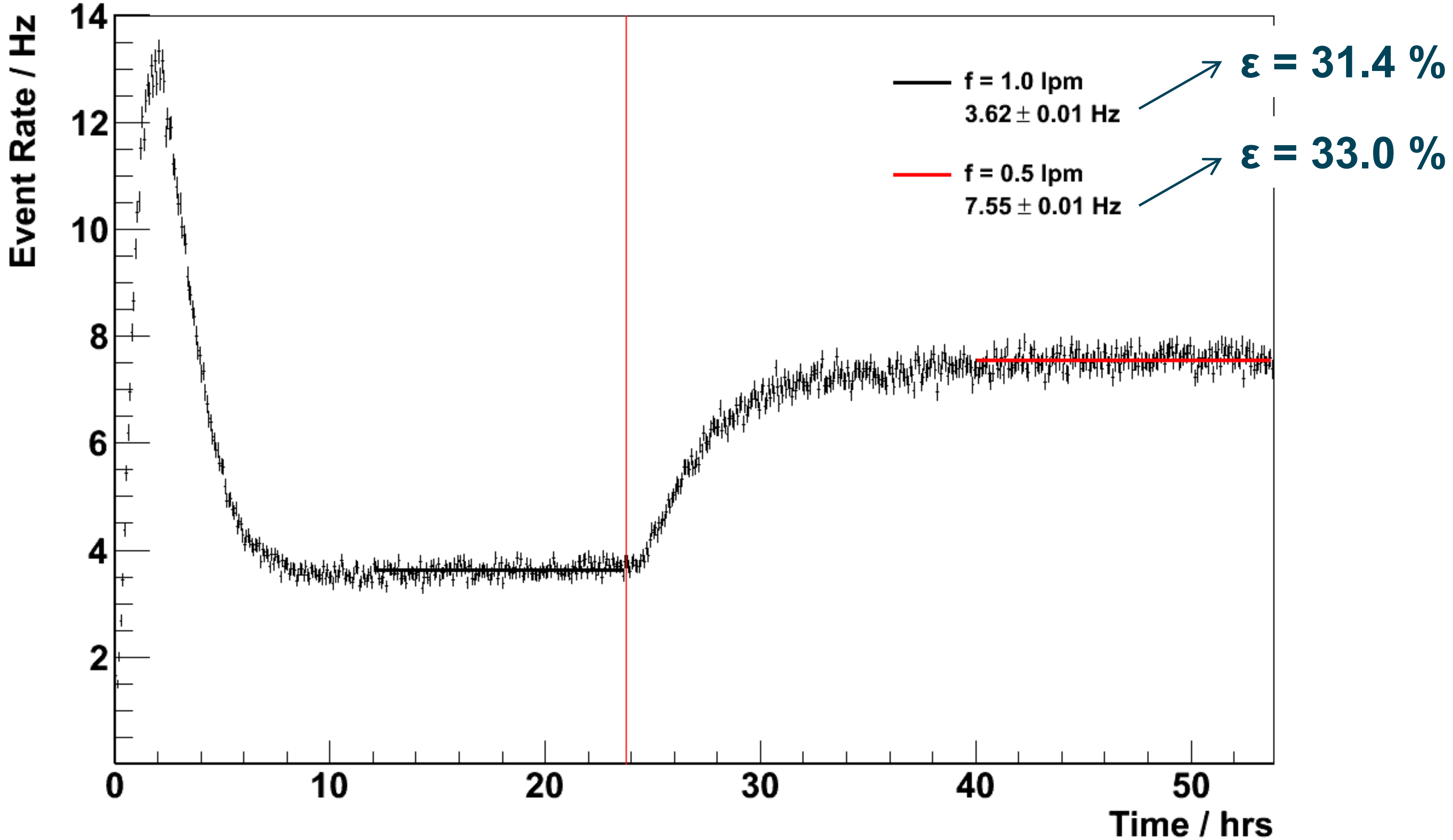
- Look at the rate of ^{214}Po events to measure detector background:



- BG Rate of detector is measured to be **8.4 ± 0.5 cpd**

Electrostatic Detector: Efficiency

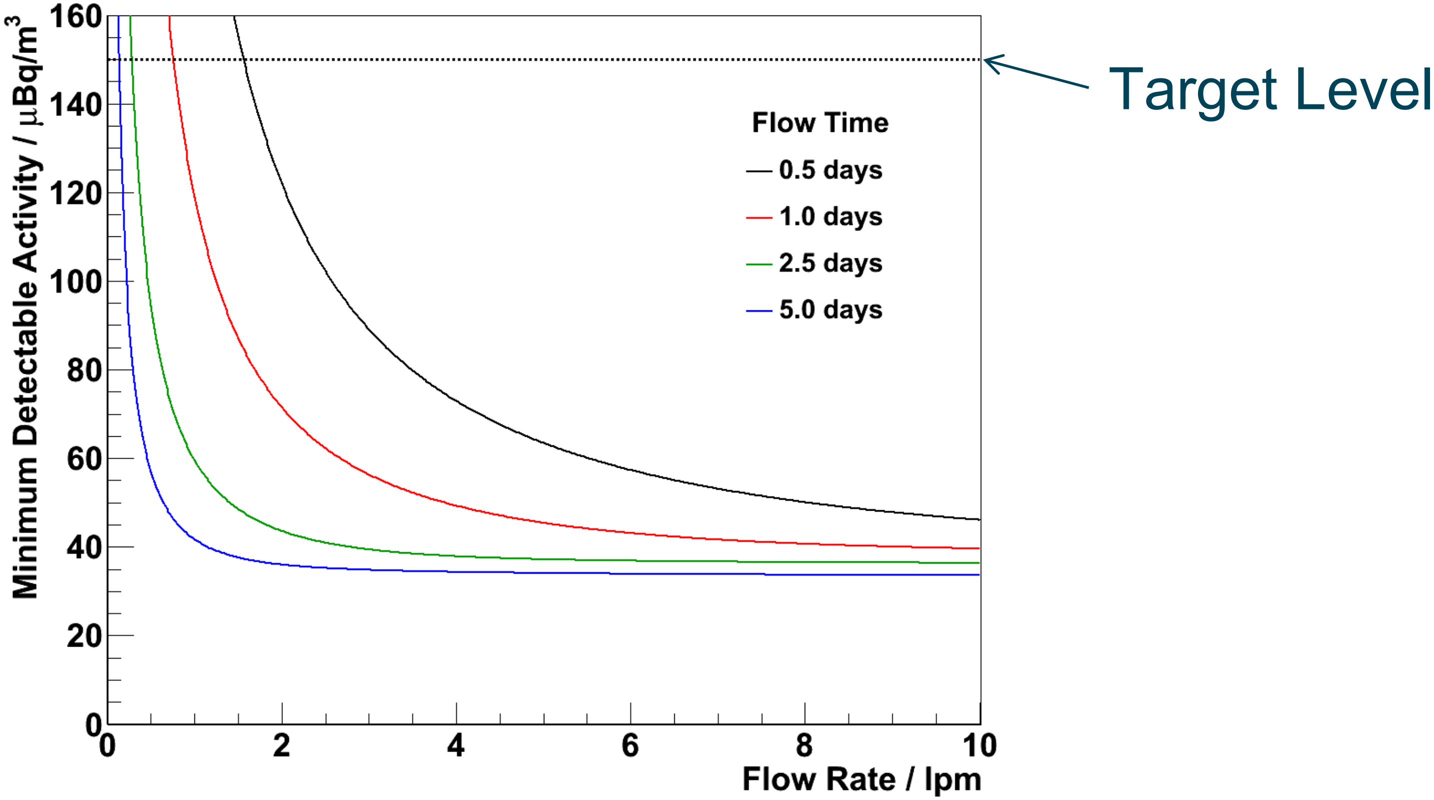
- Use a calibrated flow-through ^{222}Rn source at different flow rates to measure efficiency of ^{222}Rn detection



- Efficiency of detector is preliminarily measured to be ~ 30%

RnCL & Detector: Sensitivity

1. Measurement of emanation from quarter sub-section of SuperNEMO tracker:



2. Measurement of gasses to select the cleanest cylinders:
   - Sensitive to **C_{Rn} ≥ 20 μBq/m^3** for one cylinder

Future work

- **Soon:**
  - Finish calibration of detector and measure trapping and transfer efficiency
  - Measure N_2, He and Ar from different cylinders to find the ones most suitable for use with the SuperNEMO demonstrator

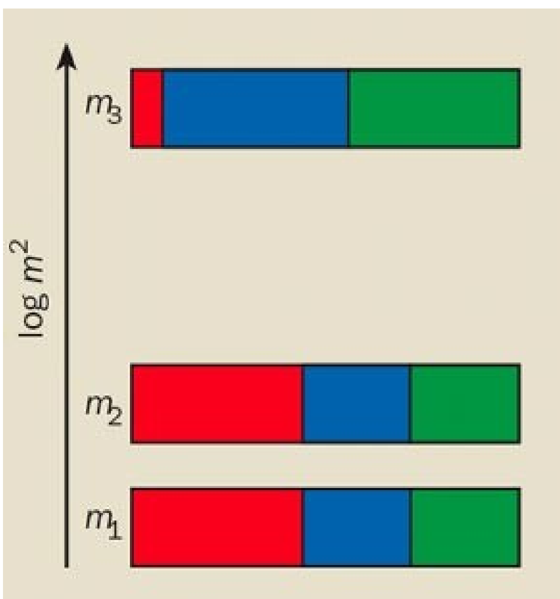
- **Longer Term:**
  - Measure the emanation of radon from detector materials in the SuperNEMO tracker before it goes underground
  - Analyse NEMO-3 data for ^{82}Se – the baseline isotope for SuperNEMO

END

Supplementary Slides

Neutrinos: Oscillations & Mass

- Neutrino oscillation experiments have shown us that neutrinos must have non-zero mass
- Two-neutrino case : $$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$
- So oscillation experiments are unable to offer any information about the absolute mass scale or (with current precision) hierarchy:



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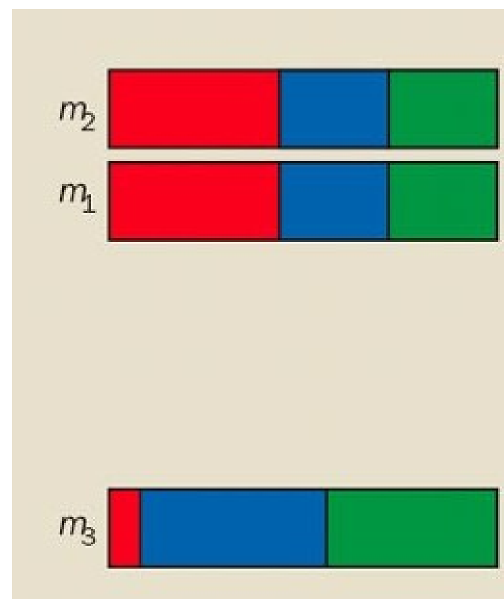


Neutrino Mass: Current Limits

- **0νββ:**

  Heidelberg-Moscow Experiment: $\langle m_{\beta\beta} \rangle < 0.3 - 0.8\text{eV}$

- **Tritium decay:**

  Based on kinematics of end-point of decay so is model independent.

  PDG : $m_{\nu_e} < 2\text{eV}$

- **Cosmology**

  Shaun Thomas: $\sum_{\nu} m_{\nu} < 0.28\text{eV}$

0νββ vs. 2νββ: Half-life and Neutrino Mass

- The half-life for 0νββ can be related to neutrino mass by:

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(Q_{\beta\beta},Z)\left|M^{0\nu}\right|^2 \left\langle m_{\beta\beta}\right\rangle^2$$

where $G^{0\nu}$ is the (exactly calculable) phase space

$M^{0\nu}$ is the nuclear matrix element (NME)

$\langle m_{\beta\beta}\rangle$ is a lepton number violating parameter

- In the light-neutrino exchange mechanism, $\langle m_{\beta\beta}\rangle$ is the effective Majorana neutrino mass, given by:

$$\left\langle m_{\beta\beta}\right\rangle = \left|\sum_k m_k U_{ek}^2\right|$$

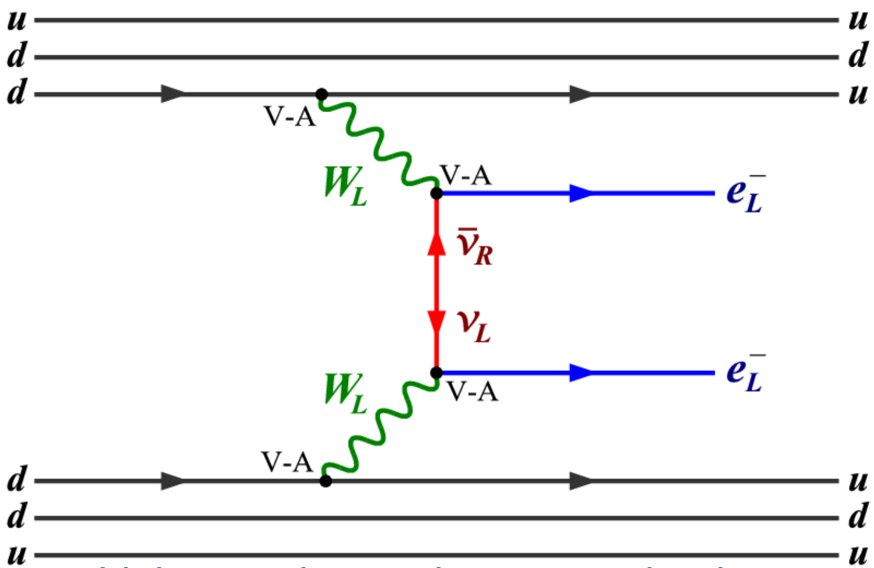
- In 2νββ, we can get no information about neutrino mass:

$$\left[T_{1/2}^{2\nu}\right]^{-1} = G^{2\nu}(Q_{\beta\beta},Z)\left|M^{2\nu}\right|^2$$

- But NME is important for reducing the error in the 0νββ NME.

0vββ: Light neutrino exchange mechanism

- Can break down 0vββ into two parts:



Light neutrino exchange mechanism

i) $n \rightarrow p + e^- + \nu_{e\,R}^M$

ii) $n + \nu_{e\,L}^M \rightarrow p + e^-$

- Process requires that the neutrino must be its own antiparticle and must flip helicity.

- Helicity flip is possible if we consider a reference frame moving faster than the neutrino
- Implies that neutrinos must be **Majorana** and have **mass**

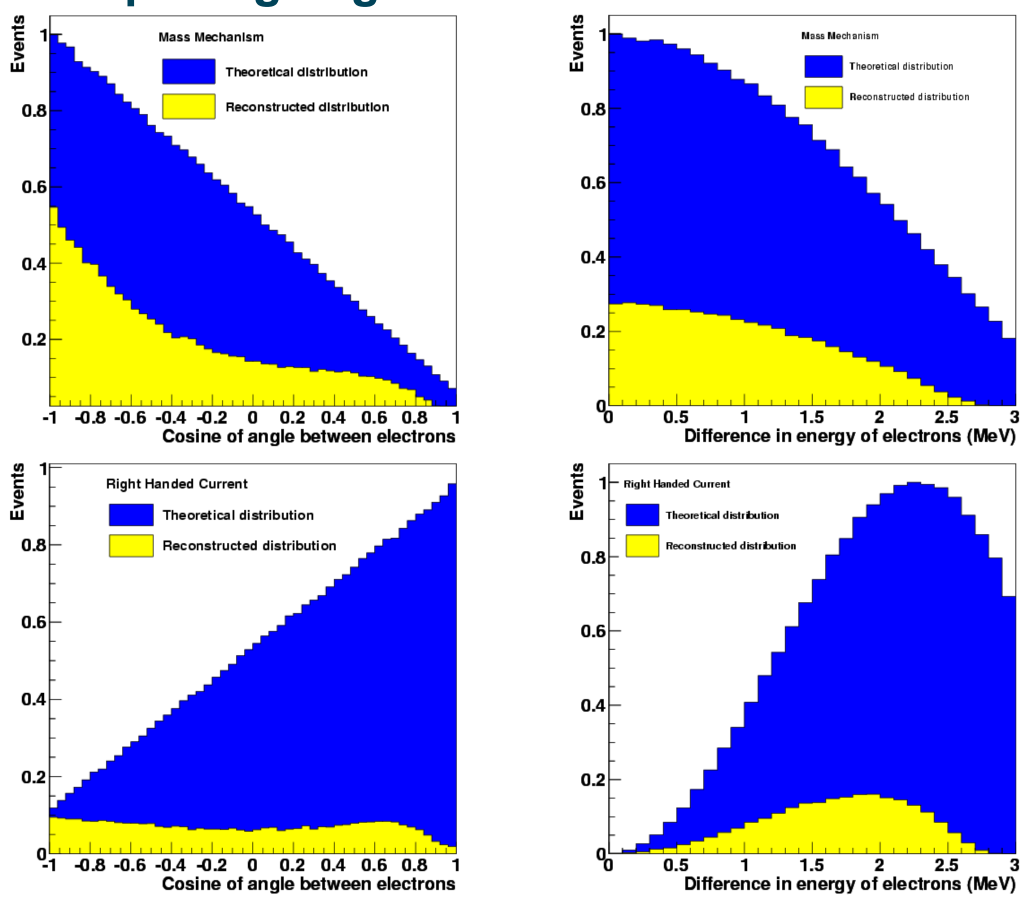
0νββ: Signatures for different mechanisms

- SuperNEMO is unique among the next generation 0νββ experiments as it may allow us to disentangle the physics mechanism, for example:

Cosine of electron opening angle | **Electron energy difference**

Mass Mechanism

Right Handed Current



Theoretical Distribution

Reconstructed Distribution

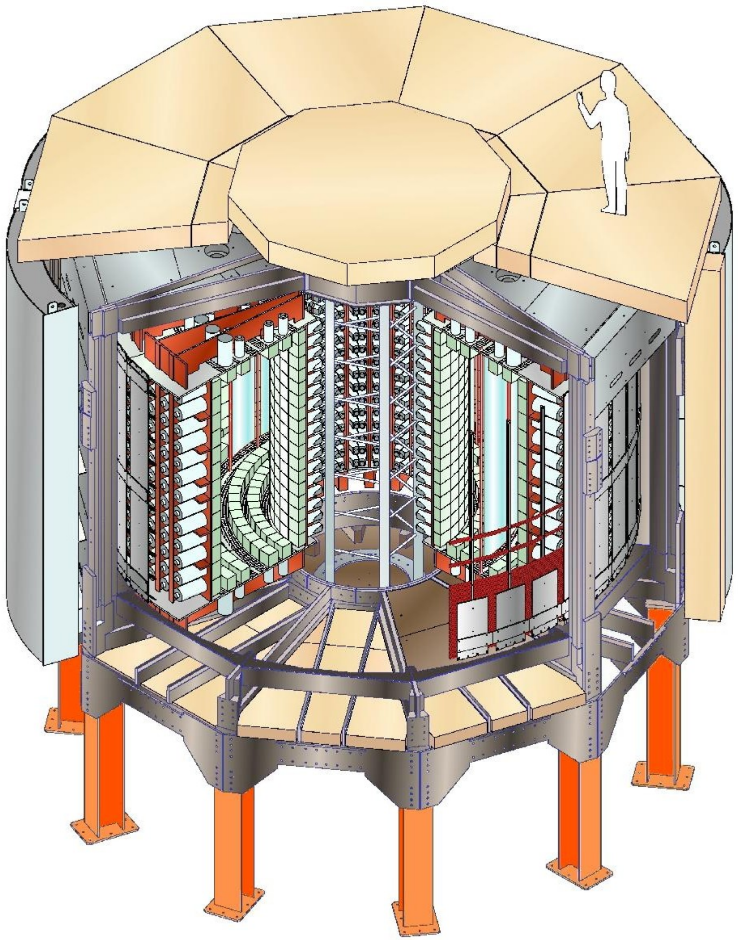
$0\nu\beta\beta$: Notable Experiments

Experiment	Isotope	Mass / kg	$\langle m_{\beta\beta} \rangle$ lower limit / meV	Current Status	Start of data taking
SuperNEMO	^{82}Se	100	40	R & D	~2013 – 2015
GERDA	^{76}Ge	40	70	Running	2011
		1000	10	R & D	~2015
CUORE	^{130}Te	200	20	In progress	~2013
SNO+	^{150}Nd	56	100	In progress	~2012
		500	40	R & D	~2015
EXO	^{136}Xe	200	100	Running	2011
		1000	30	R & D	~2015
KamLAND-ZEN	^{136}Xe	400	40	In progress	~2012
		1000	25	R & D	~2013 – 2015
MAJORANA	^{76}Ge	30 – 60	70	In progress	~2013
		1000	10	R & D	~2015

From A.S Barabash (2011) arXiv:1101.4502v1 [nucl-ex]

The NEMO-3 Experiment

- NEMO-3 was the predecessor to SuperNEMO, which ran from Feb 2003 – Jan 2011.



- Cylindrical design with source foils of different ββ isotopes surrounded by a gas tracker and a calorimeter.
- Employed a 'smoking-gun' approach:
  - Particle ID, event topology reconstruction & strong background rejection
  - Compromise on energy resolution
- World's best $T_{1/2}$ measurements of seven 2νββ isotopes (out of only 12 observed):

^{100}Mo, ^{82}Se, ^{150}Nd, ^{96}Zr, ^{48}Ca, ^{116}Cd, ^{130}Te

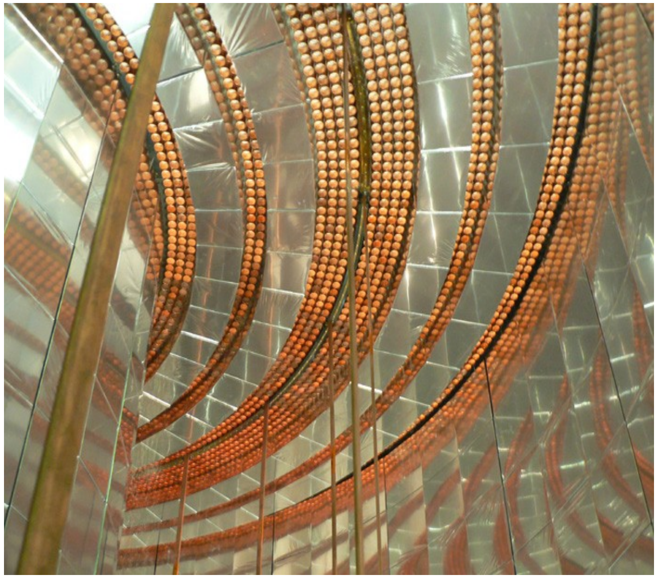
The NEMO-3 Experiment

Source foil: 10kg of different ββ isotopes

Tracker: Drift chamber with 6180 vertical cells in He, Ar, alcohol & water.

Calorimeter: 1940 PMTs & plastic scintillator blocks

Shielding: Wood, iron & borated water to stop different external backgrounds

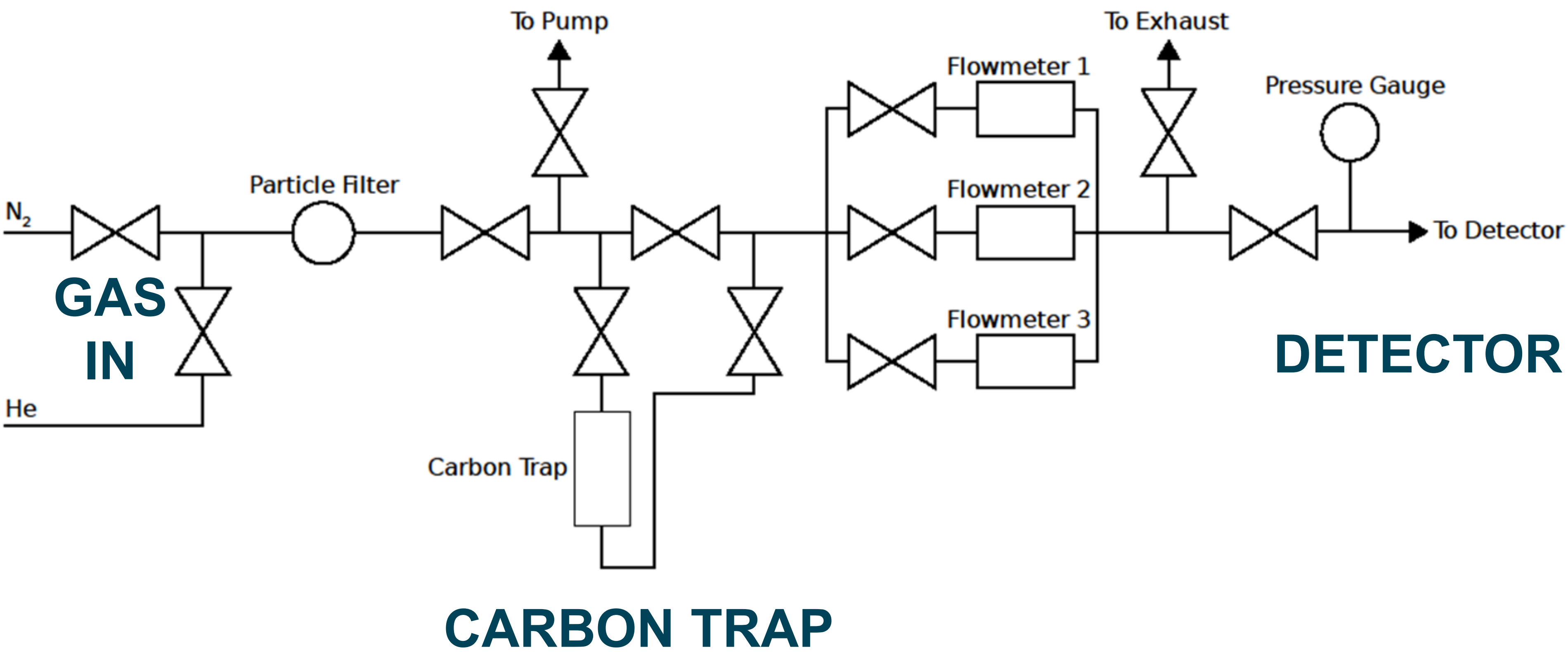


Some important measurements:

^{100}Mo: $T_{1/2}(2\nu) = [7.16 \pm 0.01(stat) \pm 0.54(sys)] \times 10^{18}$ y
$T_{1/2}(0\nu) > 1.0 \times 10^{24}$ y @ 90% CL

^{82}Se: $T_{1/2}(2\nu) = [9.6 \pm 0.1(stat) \pm 1.0(sys)] \times 10^{19}$ y
$T_{1/2}(0\nu) > 3.2 \times 10^{23}$ y @ 90% CL

RnCL: Schematic Diagram



RnCL: Method

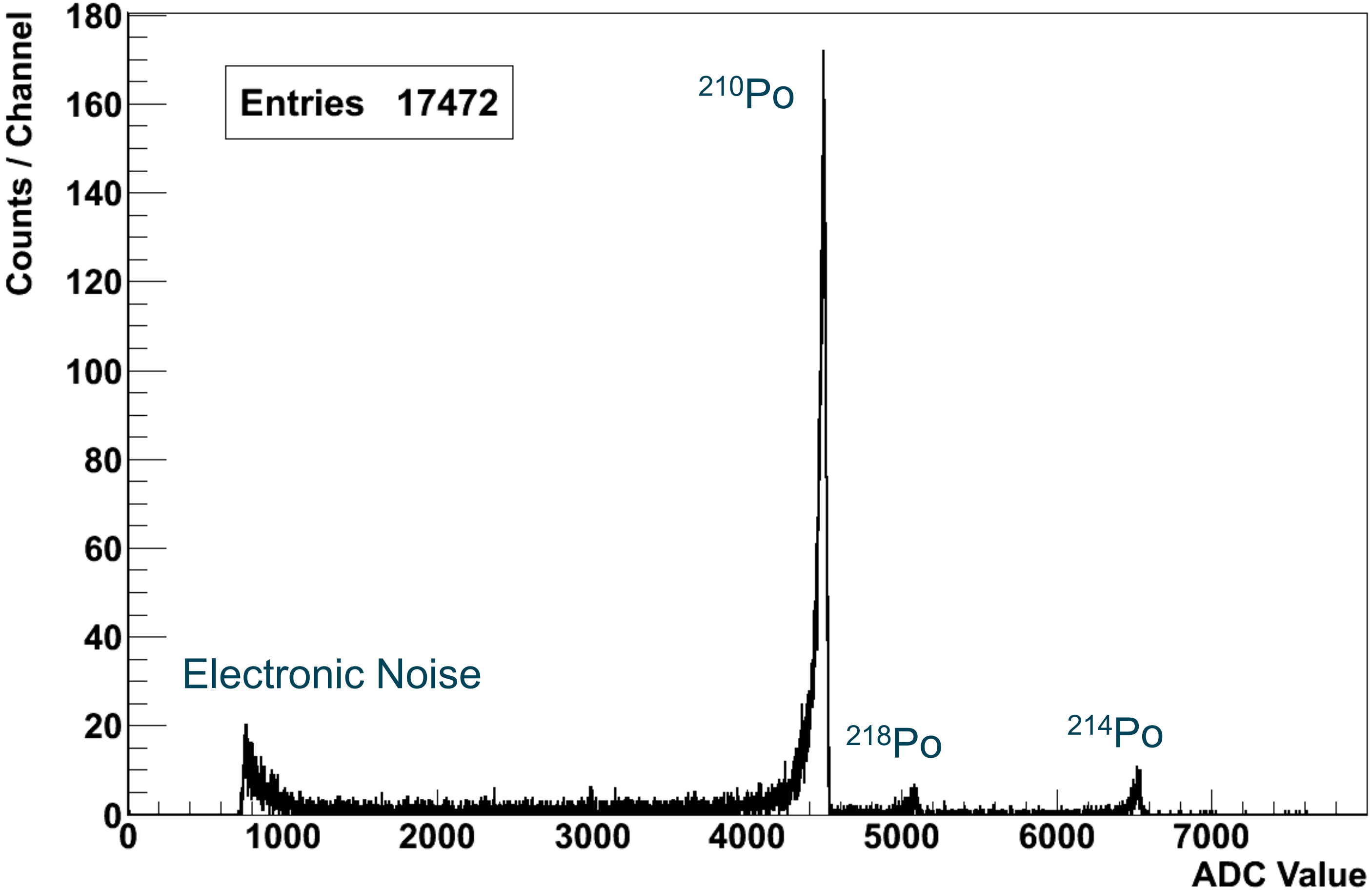
- Operation of the RnCL is as follows:

1. Evacuate system down to 10^{-7} mbar.
2. Cool trap down to -196 °C in Dewar containing liquid N_2.
3. Pump gas to be measured through carbon trap – ^{222}Rn is adsorbed.
4. After collection of the sample, evacuate trap at -196 °C and then at -100 °C.
5. Heat trap and transfer ^{222}Rn to detector by He purge.

RnCL: Real Life – in situ

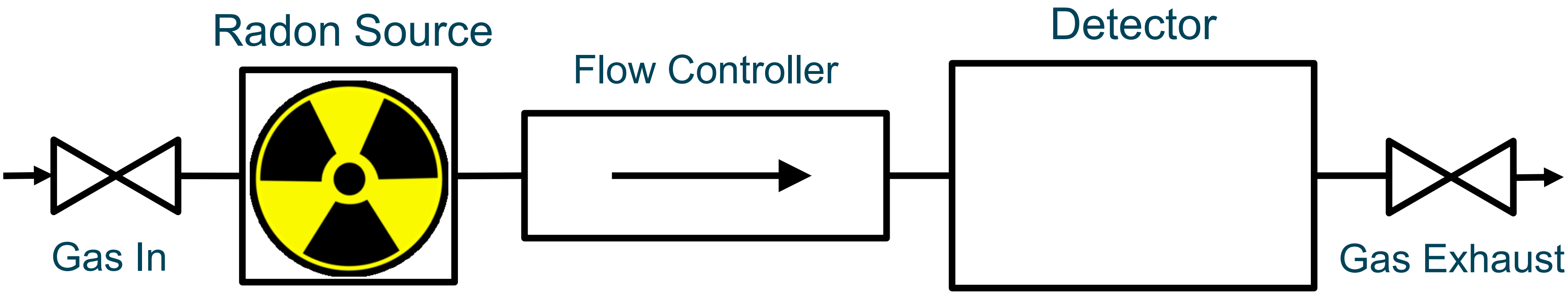
Electrostatic Detector: Background Spectrum

- Close the detector and allow ^{222}Rn to decay. Then take a long run to get background spectrum of detector:



- Peak from ^{210}Po (5.3 MeV) has now appeared.

Flow-through Calibration Method



- Flow gas at constant rate through source and detector.
- In equilibrium, activity in detector is given by:

$$A = \frac{A_0 \lambda}{\left(\lambda + {}^{f}\!/_{V_D}\right)}$$

Electrostatic Detector: Signal

- A ^{226}Ra source was attached to the detector and alpha events were seen: