Electron capture branching ratio measurements for double β decay experiments at TITAN-TRIUMF

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and the TITAN-EC collaboration
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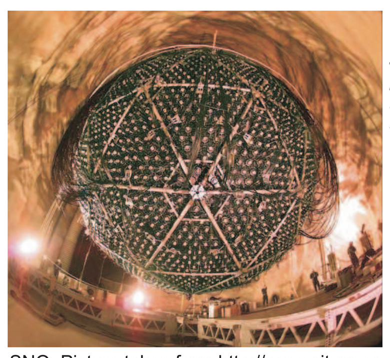
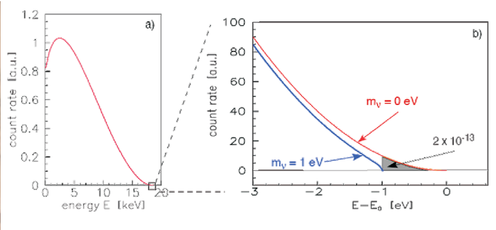
Physics beyond the Standard Model

Neutrino oscillation experiments:

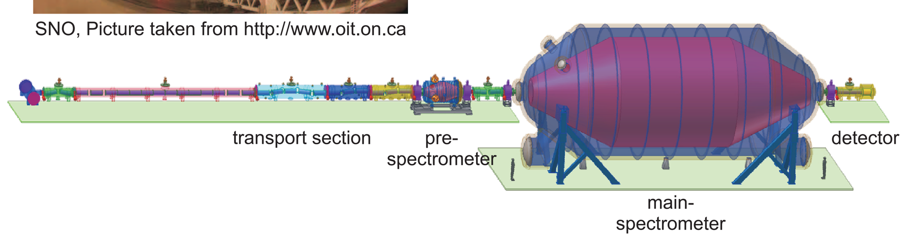
- Indicate that the neutrino is a massive particle [1]
- Only provide mixing angle θ and δm^2
- Experiments: SNO, SuperK, T2K



SNO, Picture taken from http://www.oit.on.ca



Expected spectra from KATRIN and schematics of the experiment http://students.washington.edu/mleber/researchProposal.pdf

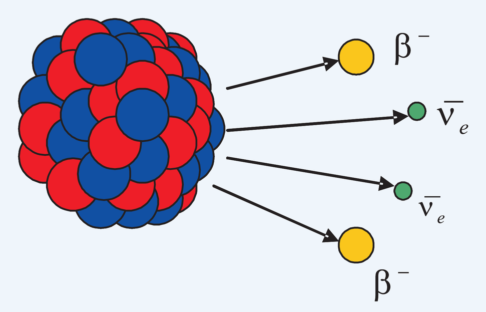


Absolute neutrino mass:

- Effective mass for degenerated neutrinos from ^{3}He decay experiments $m_{\nu_e}{}^2 = \Sigma_j |U_{ej}|^2\, m_j^2$ [2]
- Astrophysical limits
- ββ decay experiments

2νββ decay

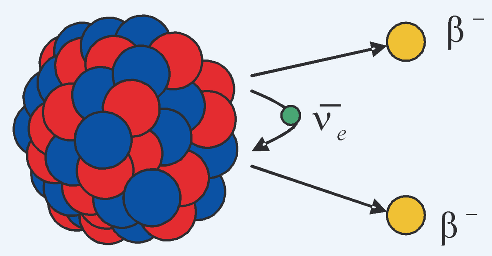
- Allowed in Standard Model
- $T_{1/2} > 10^{17}$y
- Neutrino is a Dirac particle within the Standard Model



$n + n \rightarrow 2p + 2\beta^- + 2\nu$

0νββ decay

- Physics beyond Standard Model
- Lepton number violating process
- $T_{1/2} > 1.5 \bullet 10^{25}$y [3]
- Majorana mass term enters neutrino mass



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

0νββ decay rate: $\Gamma_{0\nu} = G_{0\nu}\, |M_{0\nu}|^2 <m_{\nu e}>^2$ [4]

$G_{0\nu}$ phase space factor $M_{0\nu}$ nuclear matrix element

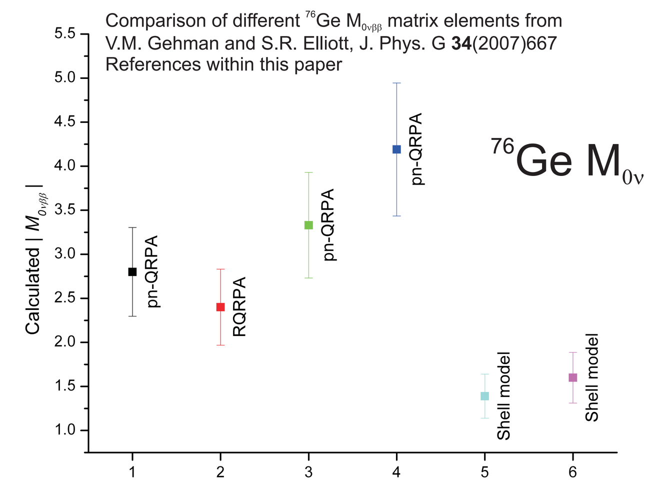
$m_{\nu e}$ effective neutrino mass

[1] T. Kajita and Y. Totsuka, *Rev. Mod. Phys.* 73(2001)85
[2] KATRIN design report 2004
[3] C.E. Aalseth et al., *Phys. Rev. D* 65(2002)092007
[4] S.R. Elliott and P. Vogl, *Annu. Rev. Nucl. Part. Sci.* 52(2002)115

The 0νββ matrix element $M_{0\nu}$

Theoretical models:

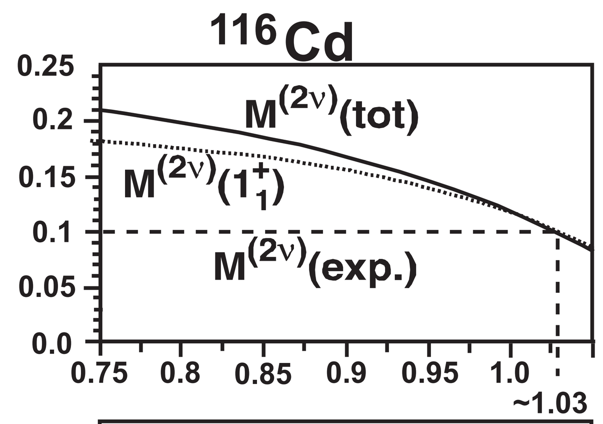
- Nuclear shell model [5]
- Interacting boson model [6]
- Proton-neutron Quasiparticle Random Phase Approximation (pnQRPA) [7]

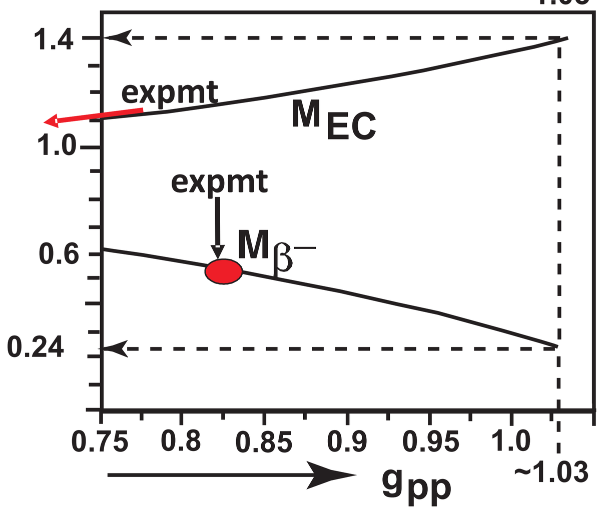


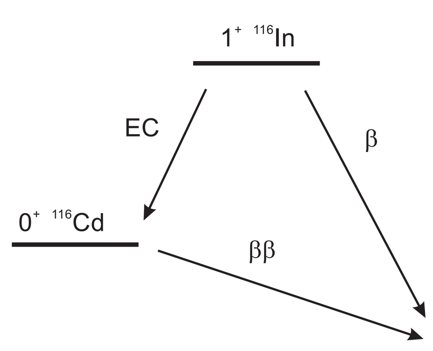
pnQRPA

- Adjustable particle-particle parameter g_{pp}
- Fix g_{pp} with 2νββ decay (very sensitive on g_{pp}) to calculate $M_{0\nu\beta\beta}$
- 0vββ decay much less dependent on g_{pp}
- Calculated $M_{0\nu\beta\beta}$ vary by a factor 2-5
- $M_{0\nu\beta\beta}$ needed with an uncertainty of less than 20% [8]
- Same g_{pp} enters single β decay and Electron Capture (EC) calculations

⇒**Electron Capture Branching Ration measurements ideal benchmark experiment to test theoretical models**







Example: ^{116}Cd

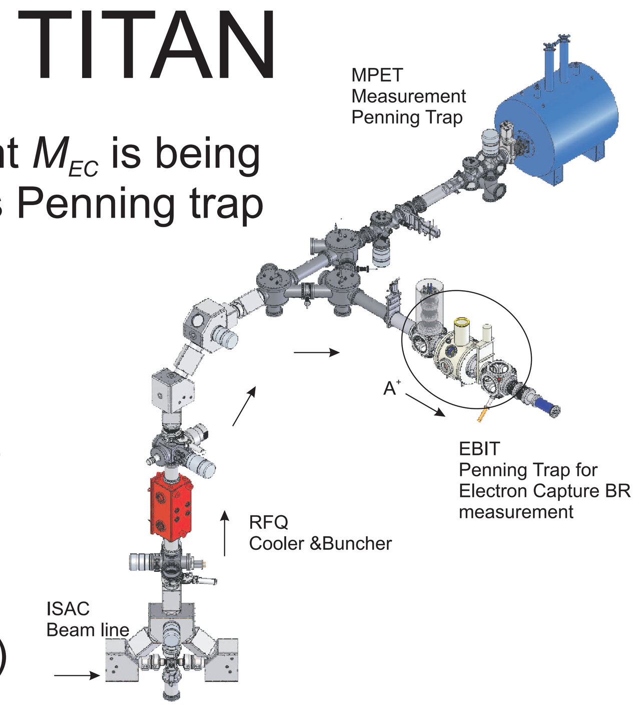
MEC = 1.4	ε = 0.095%	theory	[9]
MEC = 0.69	ε = (0.0227 ± 0.0063)%	exp 1	[10]
MEC = 0.18	ε = (0.0019 ± 0.003)%	exp 2	[11]

[5] E. Caurrier et al., *Nucl. Phys. A* 654(1999)973c
[6] J. Barea and F. Iachello, *Phys. Rev. C* 79(2009)044301
[7] V. Rodin et al., *Phys. Rev. C* 68(2003)044302
[8] V.M. Gehman and S.R. Elliott, *J. Phys. G* 34(2007)667
[9] J. Suhonen, *Phys. Lett. B* 607(2005)87
[10] M. Bhattacharya et al., *Phys. Rev. C* 58(1998)1247
[11] H. Akimune et al., *Phys. Lett. B* 394(1997)23

BUT ... in many cases there is a conflict: experiment ↔ theory
EC rates poorly known or not known at all

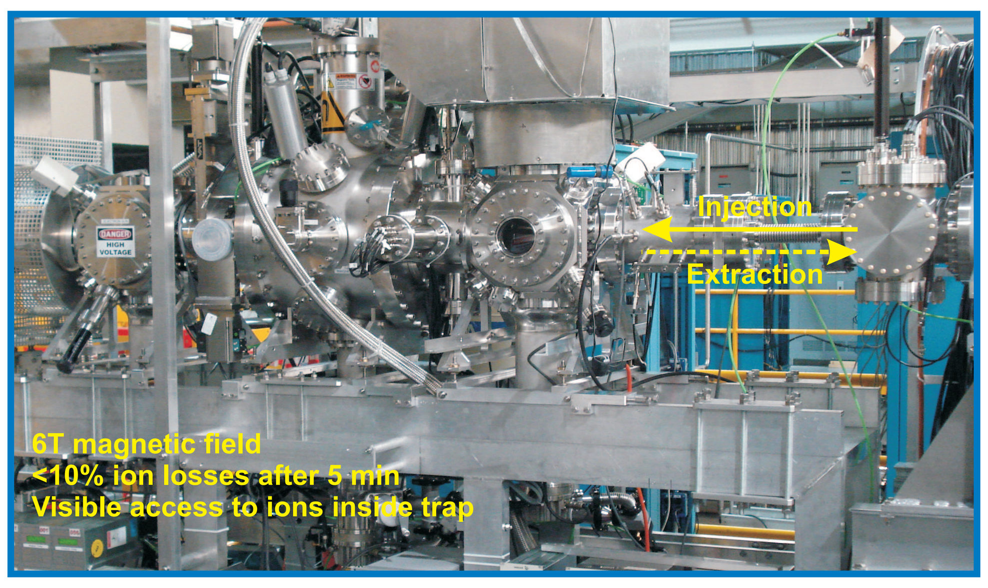
Determination of M_{EC} at TITAN

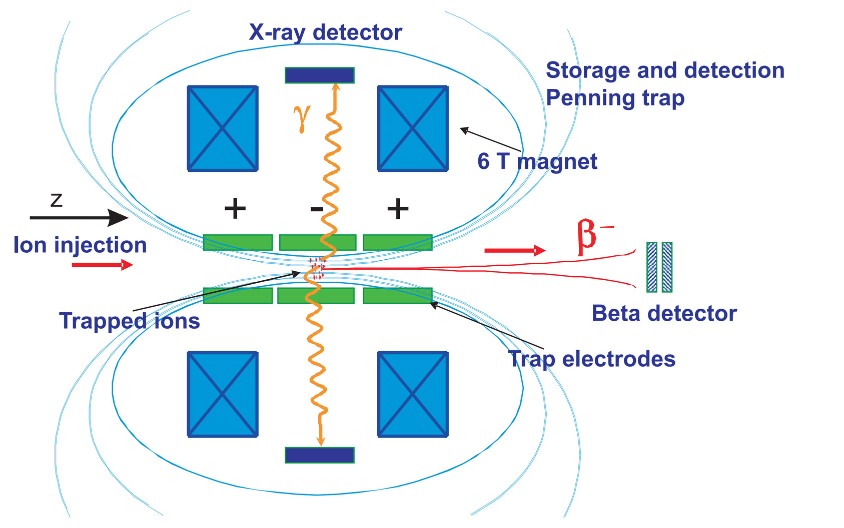
A novel approach to determine the electron capture matrix element M_{EC} is being developed at the TITAN facility, using the EBIT as an open access Penning trap



- Radioactive isotopes are delivered by TRIUMF's ISAC facility
- Deceleration, cleaning and cooling of ions happens in TITAN's RF cooler and buncher
- The cryogenic Penning trap (EBIT) allows the storage of 10^5 to 10^6 ions due to a good vacuum (P_{trap}<10^{-10}mbar)
- Helmholtz coil geometry allows visible access to trapped ions
- Up to 7 X-ray detectors can be installed radially around trap to detect X-rays following an electron capture (solid angle ~2.1%)
- A β detector at the trap exit is used to monitor the number of ions stored inside the trap
- Spatial separation of β and X-ray detection due to 6T B-field

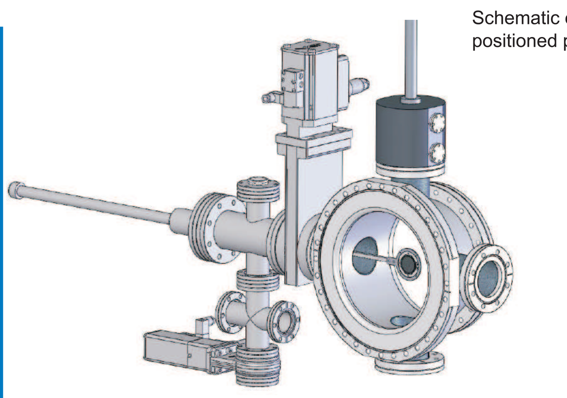
⇒**contamination and bremsstrahlungs free measurement of EC-BR**

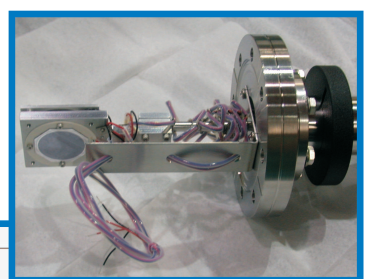




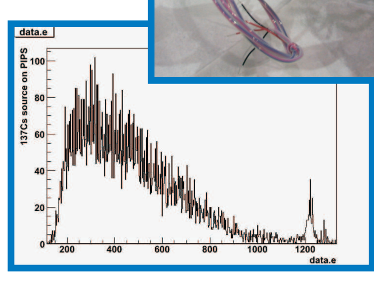
Schematic of the trap and the detector assembly along z axis. The X-ray detectors are positioned perpendicular to the ion beam, the β-detector is situated at the exit of the trap.

LeGe X-ray detector
The detector can be installed inside the vacuum as close as 10 cm to the trap center. The magnetic field of ~2T at the detector position has no influence on the signal.

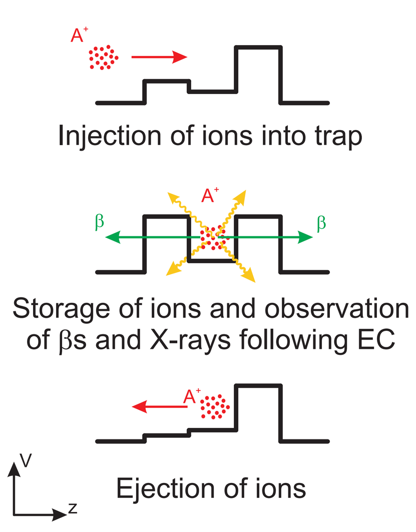




Silicon detector for β detection
The β signal is used to monitor the number of ions stored inside the trap and as soft anti-coincidence signal with X-rays



Measurement procedure



Injection of ions into trap

Storage of ions and observation of βs and X-rays following EC

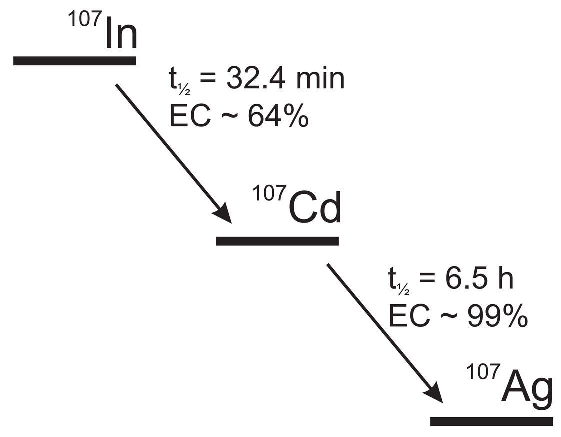
Ejection of ions

Proof of principle

^{107}In ($t_{1/2}$=32.4min) experiment to show feasibility of EC-BR measurement

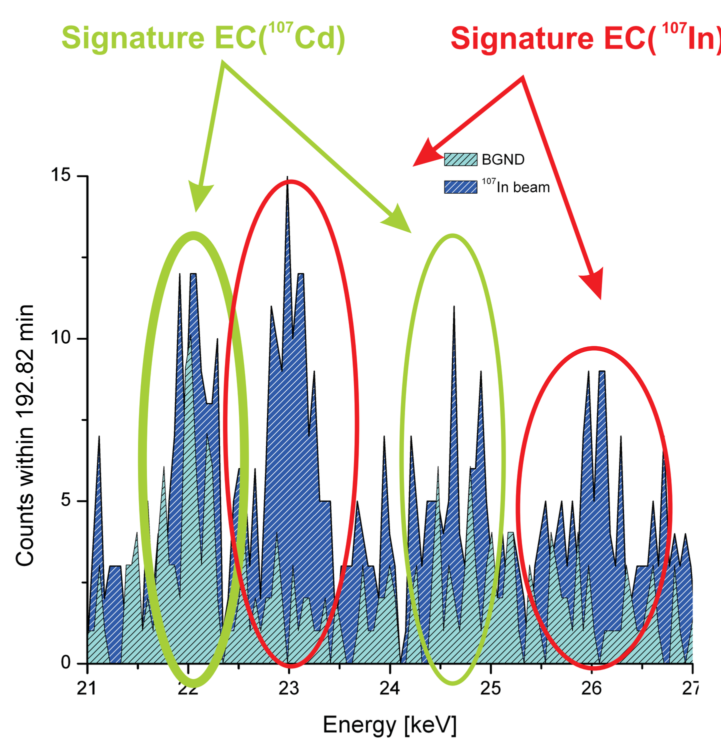
Goals for ^{107}In experiment

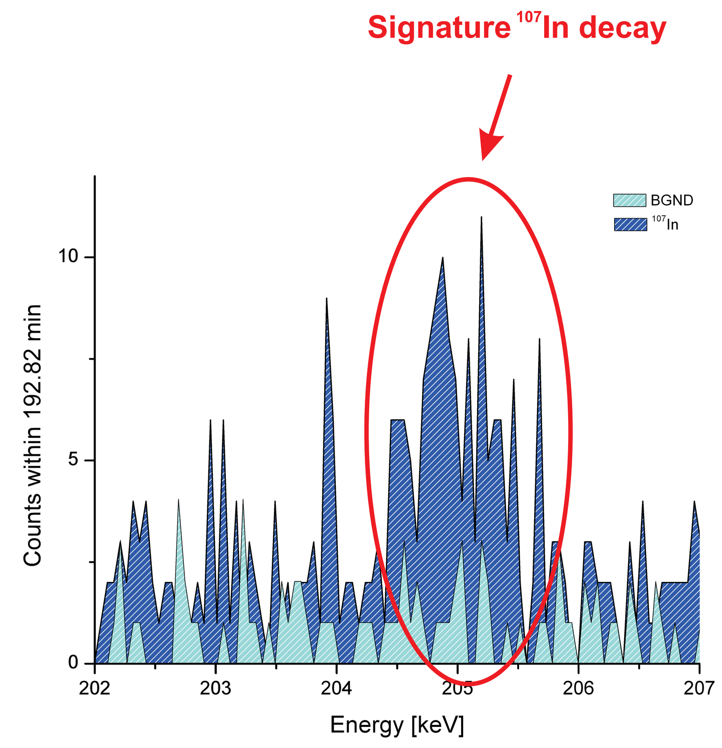
- Inject ions into trap √
- Identify ^{107}In after trap on a Si detector √
- Store radioactive ions inside trap √
- Observe X-rays following an EC of ions stored inside the trap √
- Identify these X-rays from EC √
- Observe electrons from β decays X
- Use of Ge and LeGe detector √



Analysis of ^{107}In spectra:

Low energy Ge detector





- Spectra of 192.82 min run time
- Only one detector
  ⇒ 0.02% solid angle
- **Clear signature** of ^{107}In decay

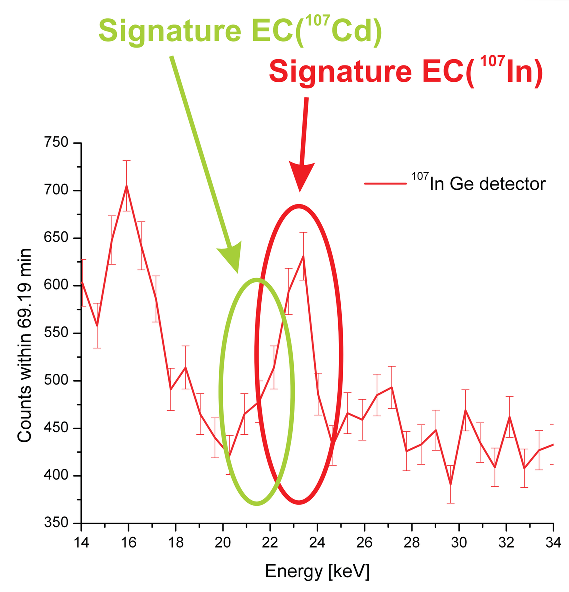
- **Clear signature** of electron capture of ^{107}In and ^{107}Cd
- Contamination of trap with ^{107}Cd after β^+ decay

Ge detector

- Spectrum of 69.19 min run time
- Energy resolution worse than LeGe
- Solid angle of 0.25%

Peak	Intensity [%]	
23 keV k_α	32.1 ± 8.7	this work
	40.5 ± 2.8	literature [13]
26 keV k_β	6.8 ± 4.4	this work
	7.84 ± 0.67	literature [13]

[13] http://www.nndc.bnl.gov



⇒ BR(EC) = (53 ± 15)% this work
literature = (64 ± 3)% [13]

FIRST observation of an electron capture of isotopes stored in a Penning trap

For the future:

- Apply sideband cooling to increase the number of ions inside the trap
- Test anti-coincidence during an experiment with ^{126}Cs in July
- First EC-BR measurement for ββ decay matrix elements in November

Electron Capture BR program at TITAN

ββ decay candidates that are under investigation in experiments such as Majorana, EXO, COBRA, CUORE and others [12]:

^{100}Mo : ^{100}Tc(EC)	[$1^+ \rightarrow 0^+$, $T_{1/2}$ = 15.8s]	$K_{\alpha 1/2}$ = 17.5keV
^{110}Pd : ^{110}Ag(EC)	[$1^+ \rightarrow 0^+$, $T_{1/2}$ = 24.6s]	$K_{\alpha 1/2}$ = 21.2keV
^{114}Cd : ^{114}In(EC)	[$1^+ \rightarrow 0^+$, $T_{1/2}$ = 71.9s]	$K_{\alpha 1/2}$ = 25.3keV
^{116}Cd : ^{116}In(EC)	[$1^+ \rightarrow 0^+$, $T_{1/2}$ = 14.1s]	$K_{\alpha 1/2}$ = 25.3keV
^{82}Se : ^{82m}Br(EC)	[$2^- \rightarrow 0^+$, $T_{1/2}$ = 6.1min]	$K_{\alpha 1/2}$ = 11.2keV
^{128}Te : ^{128}I(EC)	[$1^+ \rightarrow 0^+$, $T_{1/2}$ = 25.0min]	$K_{\alpha 1/2}$ = 27.5keV
^{76}Ge : ^{76}As(EC)	[$2^- \rightarrow 0^+$, $T_{1/2}$ = 26.2h]	$K_{\alpha 1/2}$ = 9.9keV

[12] J. Dilling et al., *Can. J. Phys.* 85(2007)57

Run plan for ^{100}Tc

- Accumulating 10 spills in trap →100000 ions in trap
- Storage time of 15s calculates to 50000 β^-decays ~0.9 EC decays $5.6 \bullet 10^{-3}$ detected EC in 15s
- A 10% accuracy needs 100 detected events:

~17.700 trap fills	→ 74h
20% overhead	→ 14h
Total estimated time	→ 88h

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