Electron Capture branching ratio measurements at TITAN-TRIUMF

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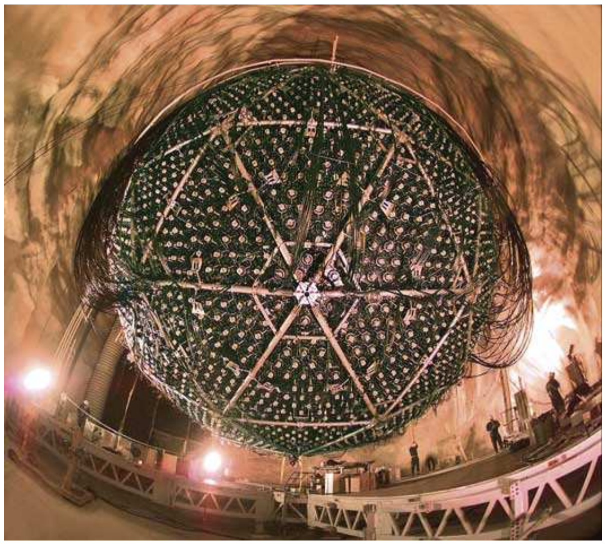
Outline

- Neutrino experiments and the neutrino mass
- Double beta decay experiments and their theoretical description
- Electron Capture Branching Ratio measurements (EC-BR) with the EBIT

Neutrino experiments and the neutrino mass

Neutrino oscillation



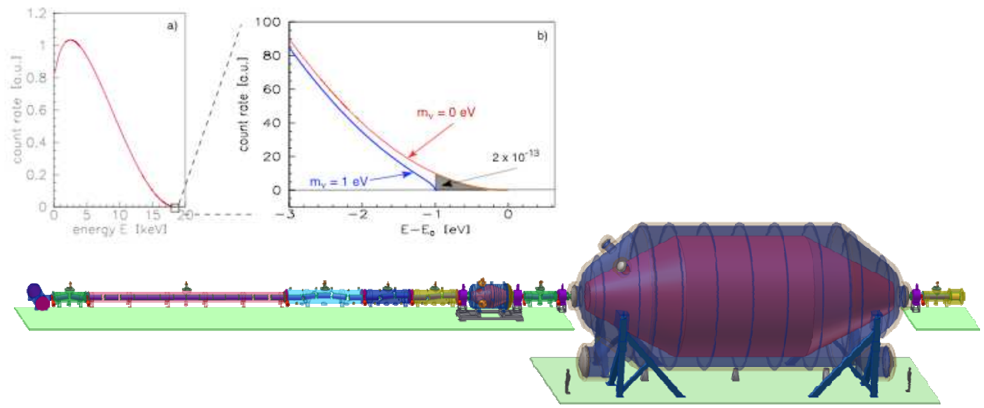
SNO, picture taken from http://www.oit.on.ca

Relative mass scale

- Indicate a neutrino mass [1]
- Determination of mixing angle θ_{ij}
- Indicate mass hierarchy
- Determination of δm^2

[1] T. Kajita and Y. Totsuka, Rev. Mod. Phys. 73(2001)85

Tritium decay



KATRIN, picture taken from http://students.washington.edu

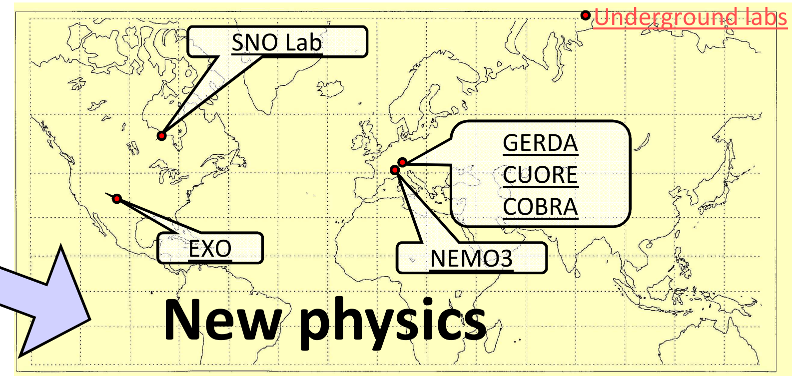
Absolute mass scale

- Endpoint energy of ^3H decay
- Effective mass for degenerated neutrinos:

$$m_\nu^2 = \sum_j \left|U_{e_j}\right|^2 m_j^2$$

Double β decay

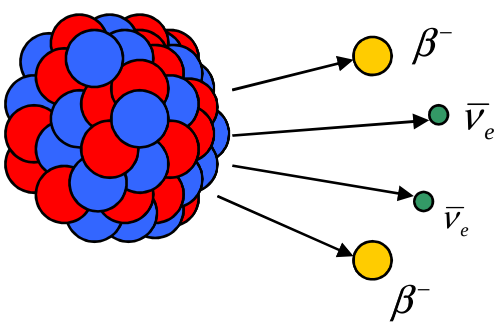
Worldwide topic



Standard model

2ν double β - decay

$$n + n \rightarrow 2\,p + 2\,\beta^{-} + 2\,\overline{\nu}_e$$



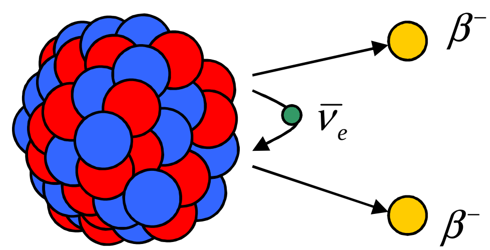
Half life> 10^{17} years (^{76}Ge)

Dirac **- Neutrino**

New physics

0ν double β - decay

$$n + n \rightarrow 2\,p + 2\,\beta^{-} + 0\,\overline{\nu}_e$$



Lepton number violation

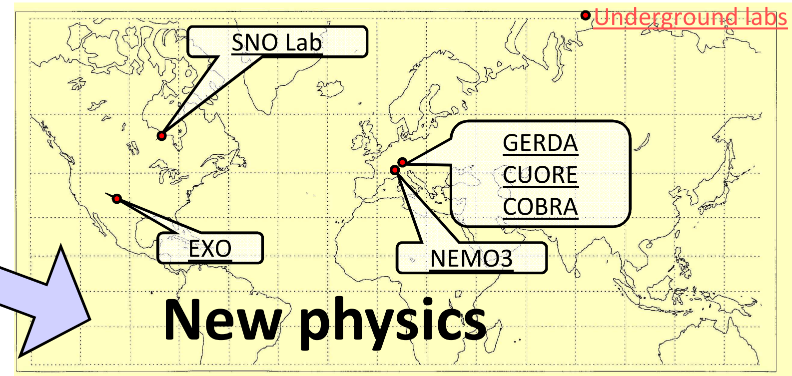
Half life> $1.9\text{x}10^{25}$ years [2] (^{76}Ge)!!!

Majorana **- Neutrino**

[2] C.E. Aalseth et al., Phys. Rev. D65(2002)092007
[3] S.R. Elliott and P. Vogel, Annu. Rev. Nucl. Part. Sci. 52(2002)115

Double β decay

Worldwide topic



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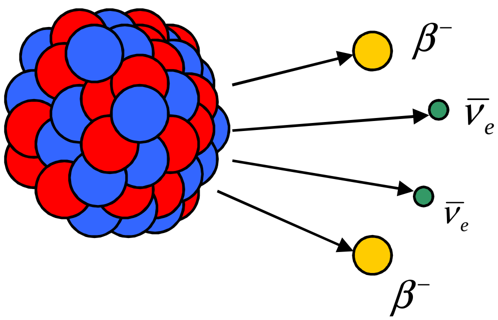

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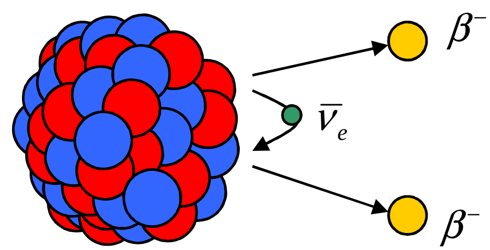


Lepton number violation

If observed:

$$\left|\left\langle m_{\nu_e}\right\rangle\right| = \left(F_N T_{1/2}^{0\nu}\right)^{-1/2} eV \quad [3]$$

Half life> 1.9×10^{25} years [2] (^{76}Ge)!!!

Majorana **- Neutrino**

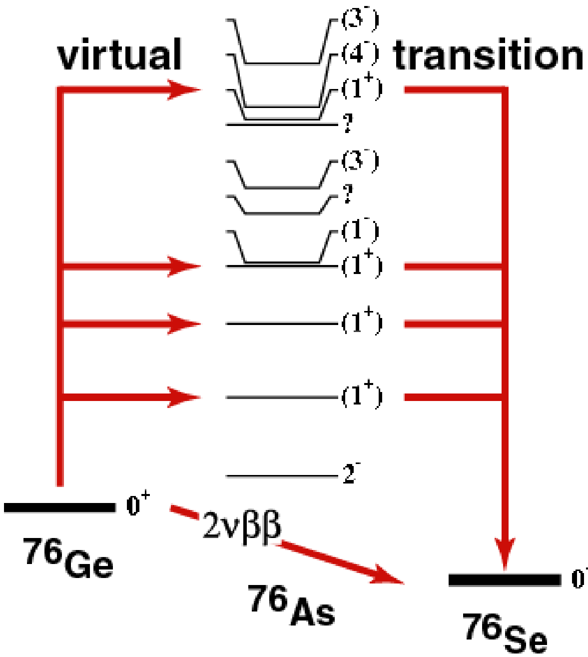
[2] C.E. Aalseth et al., Phys. Rev. D65(2002)092007
[3] S.R. Elliott and P. Vogel, Annu. Rev. Nucl. Part. Sci. 52(2002)115

2νββ decay

$$\Gamma^{2\nu}_{(\beta^-\beta^-)} = \frac{C}{8\pi^7}\left(\frac{G_F}{\sqrt{2}}\cos(\Theta_C)\right)^4 \mathcal{F}^2_{(-)} \left|M^{(2\nu)}_{\mathrm{DGT}}\right|^2 f(\mathrm{Q})$$

$$= G^{2\nu}(\mathrm{Q,Z})\left|M^{(2\nu)}_{\mathrm{DGT}}\right|^2$$

Primakoff-Rosen approximation [4]



$$M^{(2\nu)}_{\mathrm{DGT}} = \sum_m \frac{\left\langle 0^{(f)}_{g.s.}\left|\sum_k \sigma_k \tau^-_k\right|1^+_m\right\rangle\left\langle 1^+_m\left|\sum_k \sigma_k\tau^-_k\right|0^{(i)}_{g.s.}\right\rangle}{\frac{1}{2}\mathrm{Q}_{\beta\beta}(0^{(f)}_{g.s.}) + \mathrm{E}(1^+_m) - \mathrm{E}_0}$$

$$= \sum_m \frac{M_m\left(GT^+\right)M_m\left(GT^-\right)}{\mathrm{E}_m}$$

accessible thru charge-exchange reactions in (n,p) and (p,n) direction (e.g. (d,^{2}He) or (^{3}He,t)) as well thru EC-BR

[4] H. Primakoff and S.P. Rosen, Rep. Prog. Phys. 22(1959)121

0νββ decay

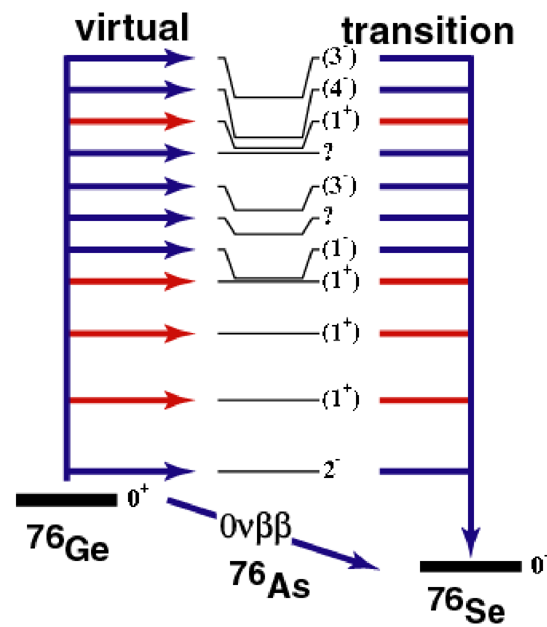
$$\Gamma^{0\nu}_{(\beta^-\beta^-)} = G^{0\nu}\,(\mathrm{Q,Z})\left| M^{(0\nu)}_{\mathrm{DGT}} - \frac{g_V}{g_A}\, M^{(0\nu)}_{\mathrm{DF}} \right|^2 \left\langle m_{\nu_e} \right\rangle^2$$

mass of Majorana neutrino

$$\Gamma^{0\nu}_{\beta^-\beta^-} = G^{0\nu} \left| \sum_m \frac{\left\langle 0^{(f)}_{g.s.} \right\| \mathcal{O}_{\sigma\tau^-}(r,S,L) \left\| J^{\pi}_{m} \right\rangle \left\langle J^{\pi}_{m} \right\| \mathcal{O}_{\sigma\tau^-}(r,S,L) \left\| 0^{(i)}_{g.s.} \right\rangle}{\tfrac{1}{2}\,\mathrm{Q}_{\beta\beta}(0^{(f)}_{g.s.}) + \mathrm{E}(J^{\pi}_{m}) - \mathrm{E}_0} + \mathrm{Fermi} \right|^2 \left\langle \mathrm{m}_{\nu_e} \right\rangle^2$$

nucl. matrix element

NOT accessible thru
charge-exchange reactions



Forbidden in Standard Model
lepton number violated
neutrino enters as virtual particle

J. Dilling et al., Can. J. Phys. 85(2007)57

Theoretical description

- Description of double β decay nuclei with the **proton-neutron Quasiparticle Random Phase Approximation (pn-QRPA)**
- Adjustable particle-particle parameter $\mathbf{g_{pp}}$ in pn-QRPA for all **single** and **double** β decay calculations (The many-particle Hamiltonian is a function of g_{pp})
- Extrapolation of calculated matrix elements to $2\nu\beta\beta$ half life provides g_{pp} ($g_{pp} \sim 1$)
- $2\nu\beta\beta$ decay is **sensitive** to g_{pp}, $0\nu\beta\beta$ decay is **insensitive** to g_{pp}
- Cross check of g_{pp} with single β^- and EC decays

Example ^{116}Cd

Recent critical assessment of the theoretical situation

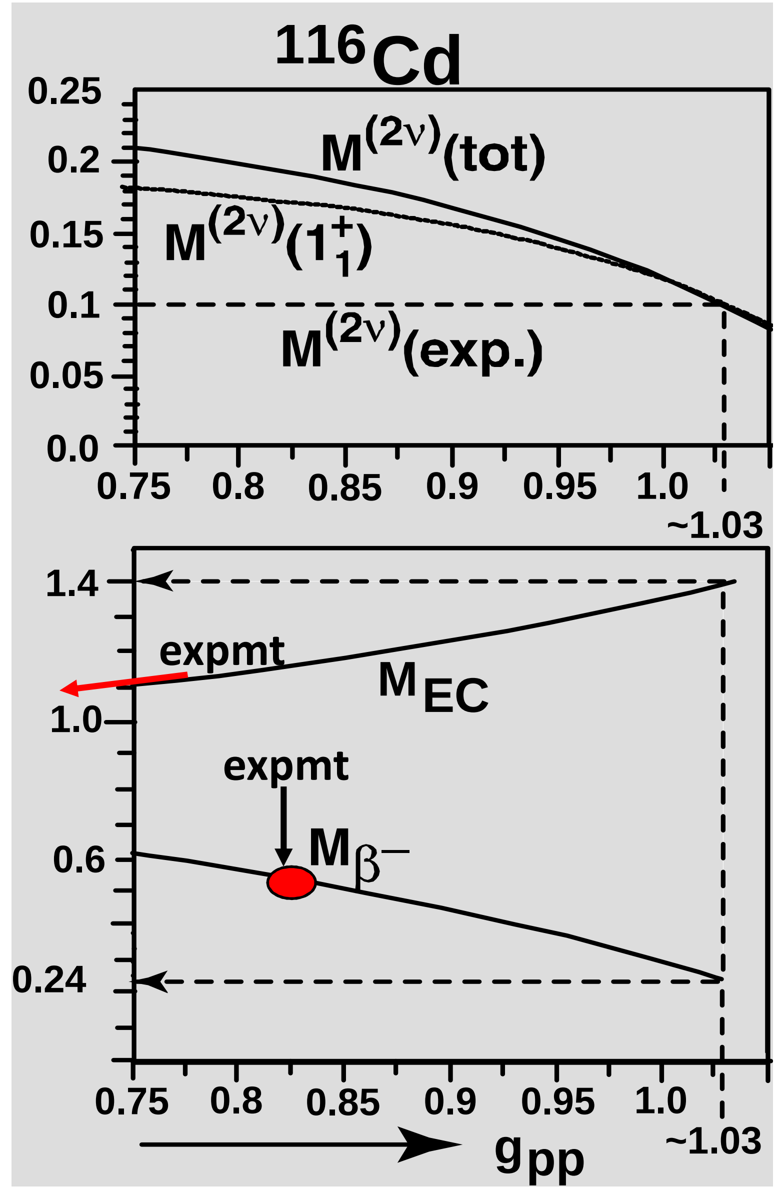
1. g_{pp} also enters into calculation of single β decay
2. this allows to make (in few cases) precise predictions about EC-rates
3. in confronting with experiment, theory fails **BADLY** (if EC is known)

In case of single state dominance:

$$M^{(2\nu)}_{tot} \simeq \frac{M_{EC}\, M_{\beta-}}{\tfrac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E_{g.s.}(1^+) - E_0}$$

M_{EC} = 1.4 ε = 0.095%   theory [5]
M_{EC} = 0.69 ε = (0.0227 ± 0.0063)%   exp 1 [6]
M_{EC} = 0.18 ε = (0.0019 ± 0.003)%   exp 2 [7]

[5] J. Suhonen, Phys. Lett. B607(2005)87
[6] M. Bhattacharya et al., Phys. Rev. C58(1998)1247
[7] H. Akimune et al., Phys. Lett. B394(1997)23



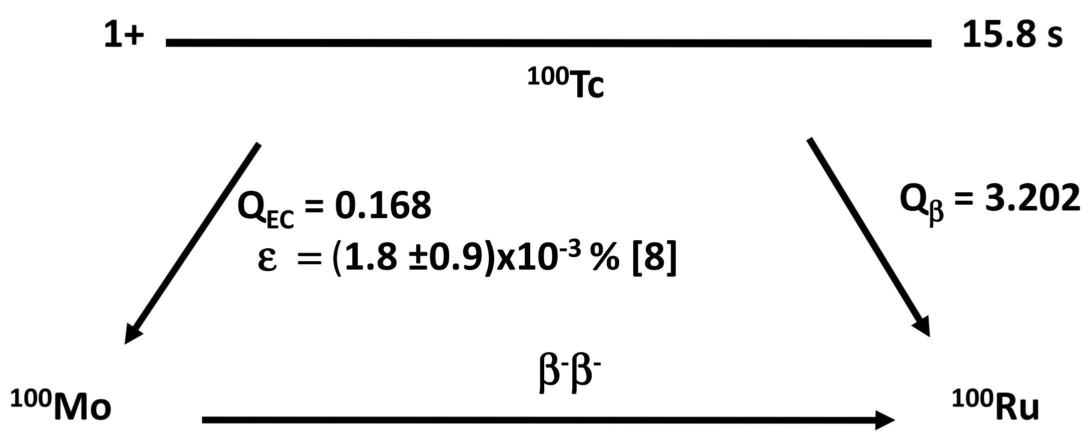
Determination of M_{EC}

$$M^{(2\nu)}_{tot} \simeq \frac{M_{EC}\, M_{\beta-}}{\frac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E_{g.s.}(1^{+}) - E_0}$$

The use of $g_{pp}(\beta\beta)$ ~ 1.0 reproduces the 2νββ decay half-life but not the single EC and β^- decay.

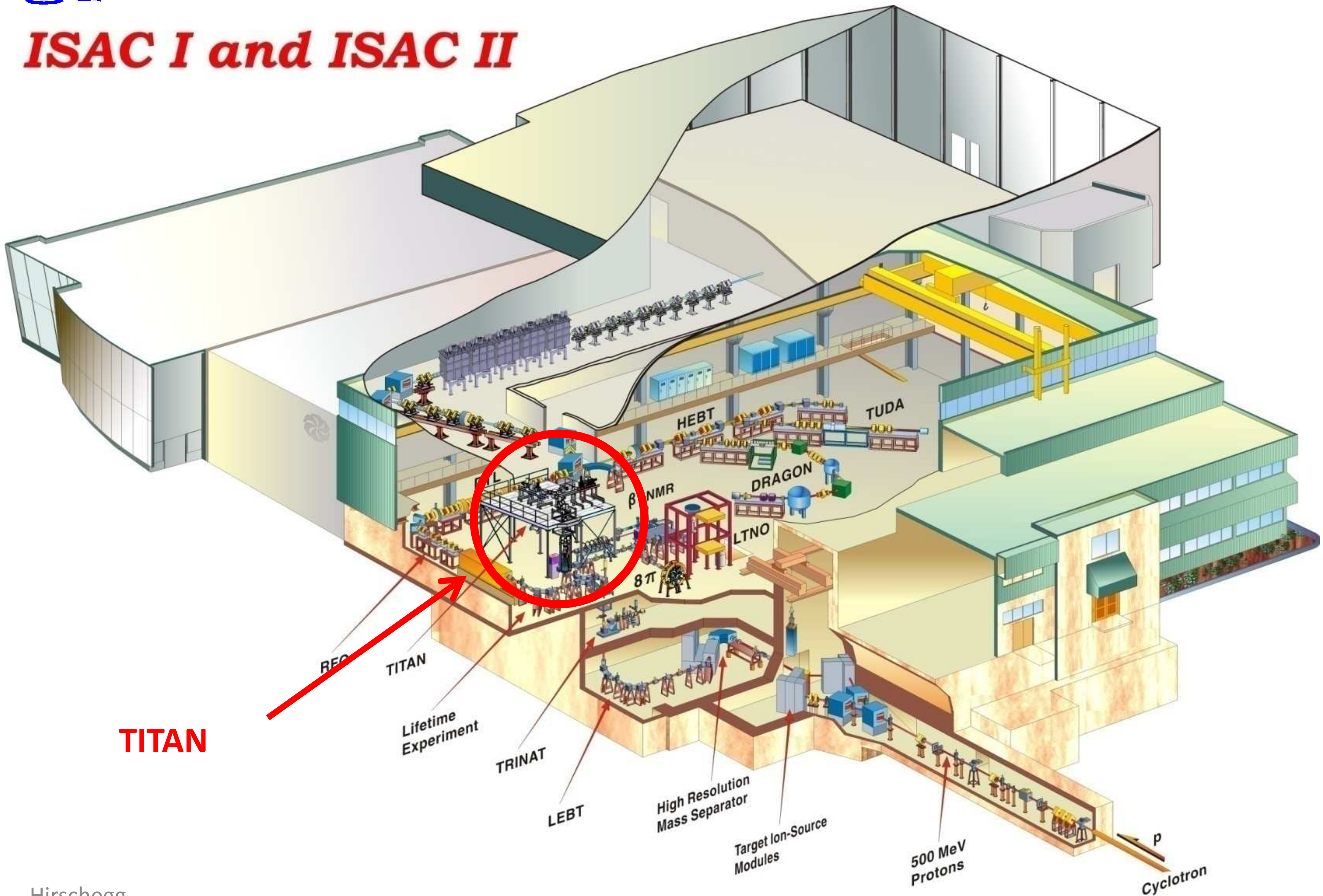
Discrepancies of 1 – 2 orders of magnitude are possible

The loose end:
EC rates are badly known, or not known at all



[8] A. García et al., Phys. Rev. C47(1993)2910

ISAC at TRIUMF



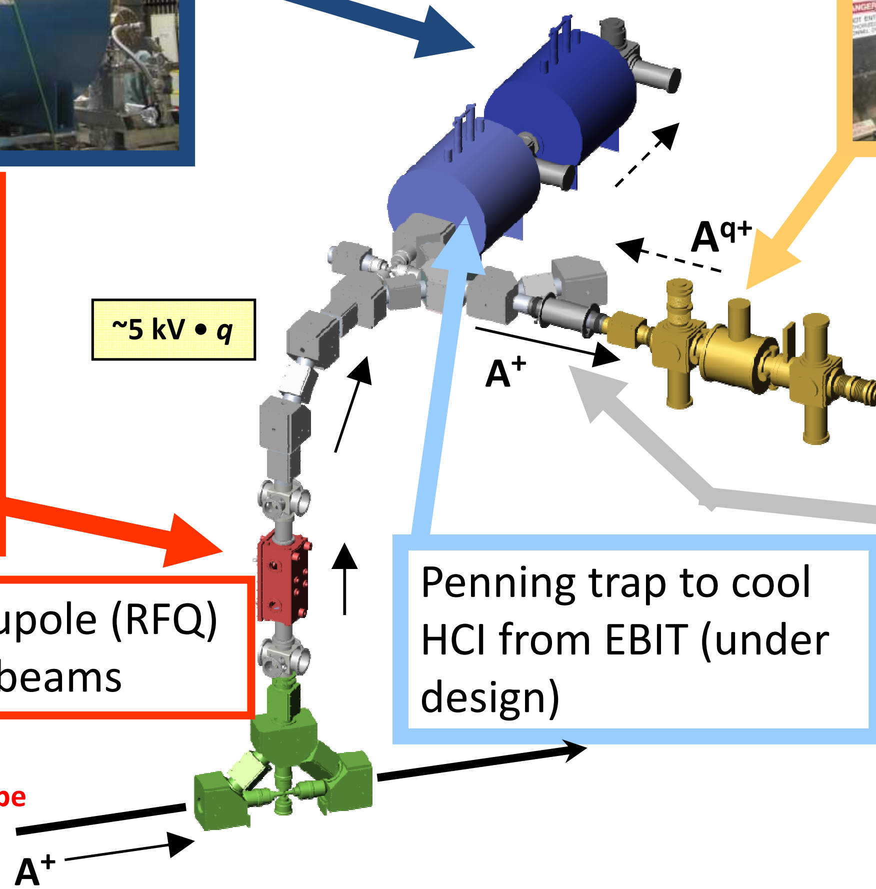
TITAN Facility

TRIUMF Ion Trap for Atomic and Nuclear science

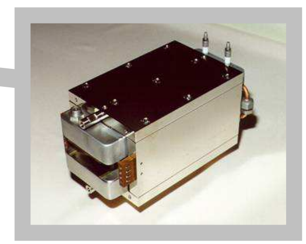
Penning trap for high precision mass measurements

Electron Beam Ion Trap (EBIT) for charge breeding

Radio-Frequency Quadrupole (RFQ) cools and bunches ISAC beams



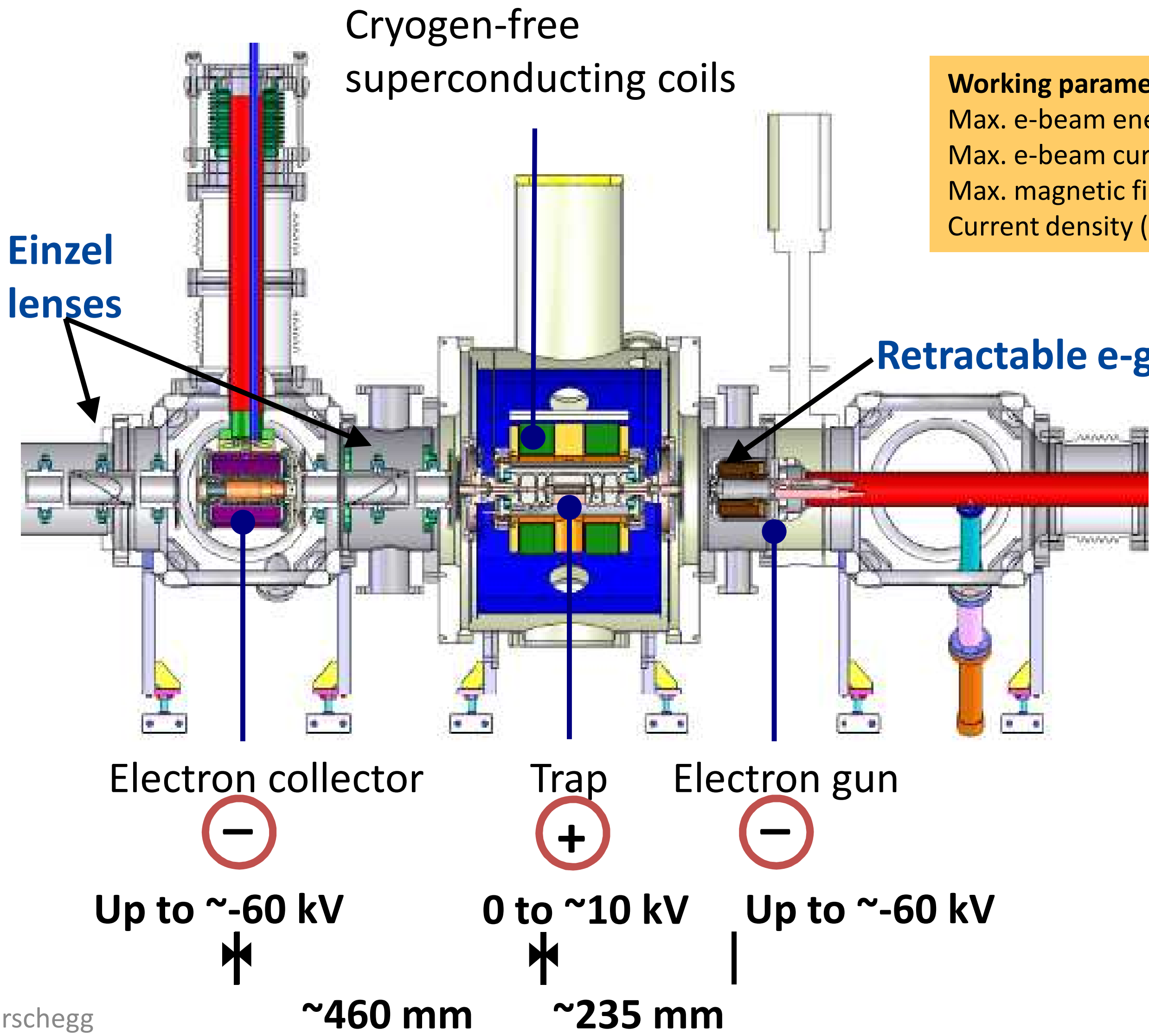
Penning trap to cool HCI from EBIT (under design)



Wien filter: q/m selection

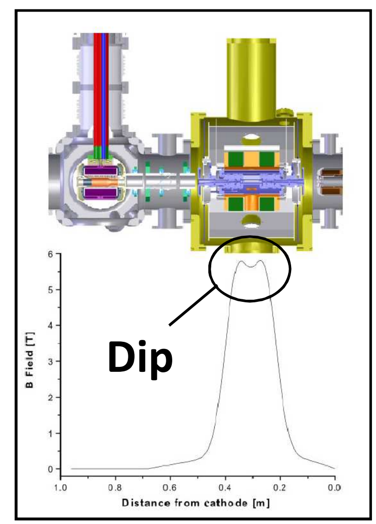
Short-lived isotopes from an Isotope Separator and Accelerator (ISAC)

The EBIT - Schematic



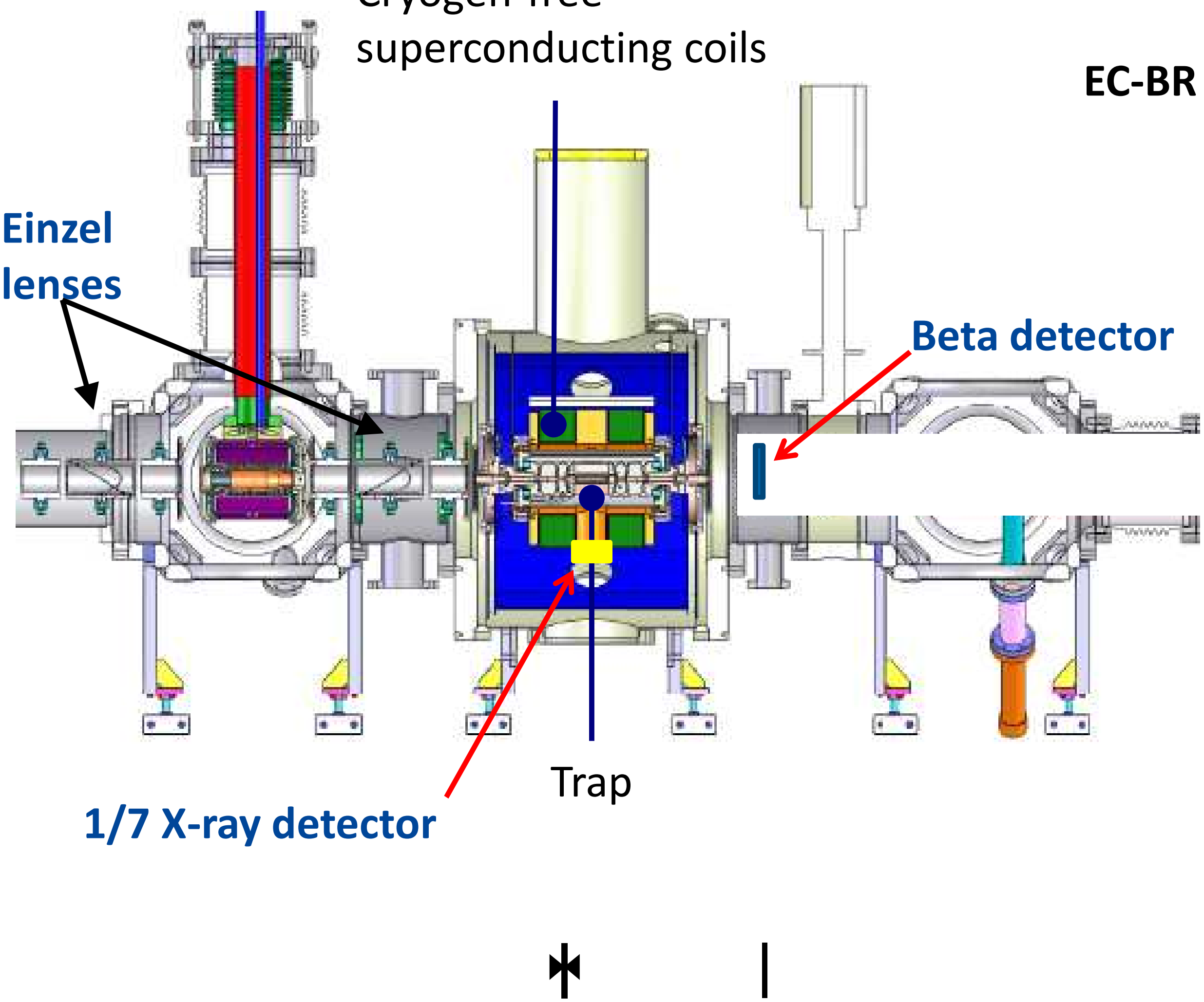
Working parameters:
Max. e-beam energy: ~70 keV
Max. e-beam current: 500 mA **(up to 5 A)**
Max. magnetic field strength: 6 T
Current density (center): 10^4 - 10^5 A/cm^2

Magnetic-field distrib.
Taken from M. Froese

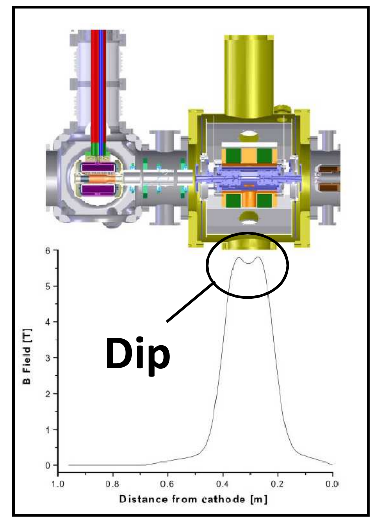


The EBIT - Schematic

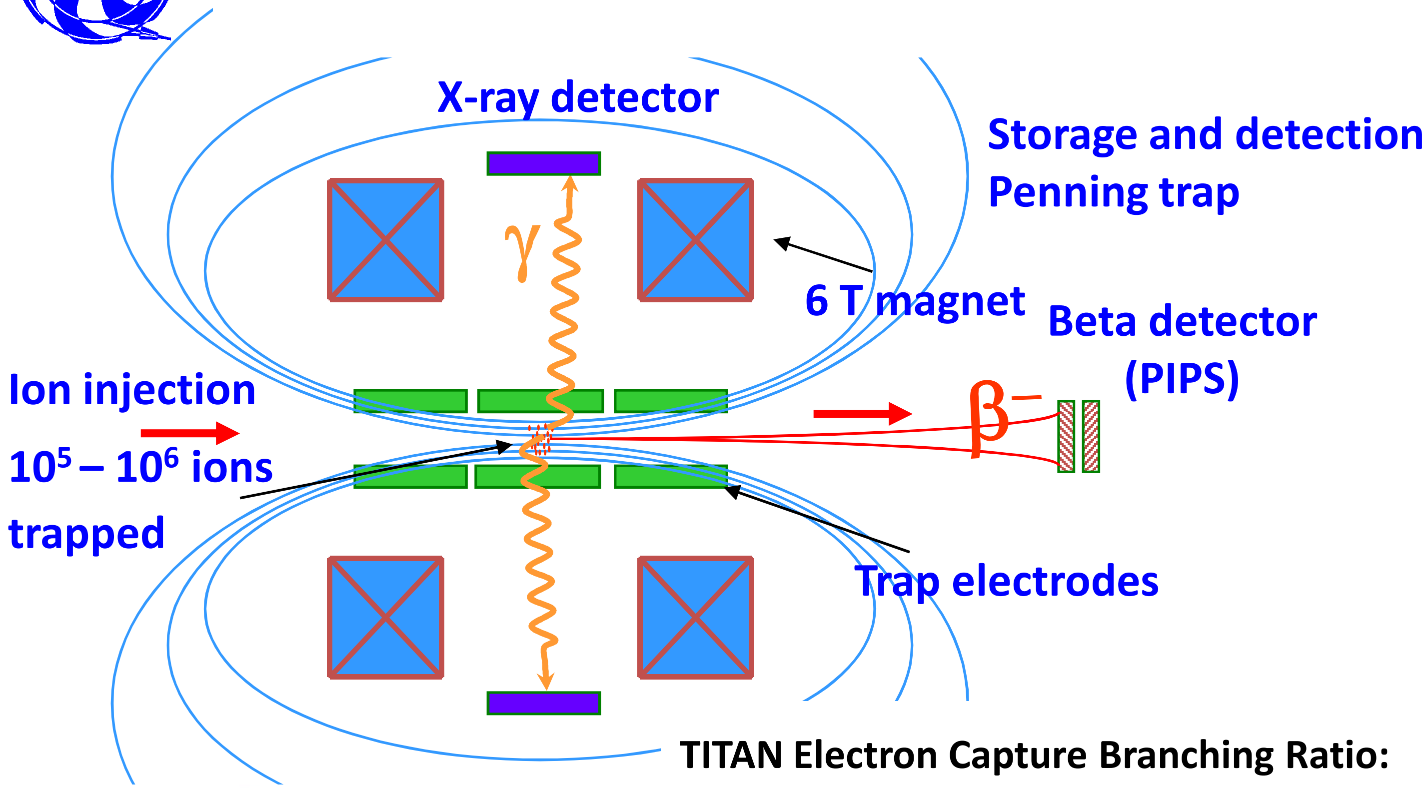
EC-BR measurements

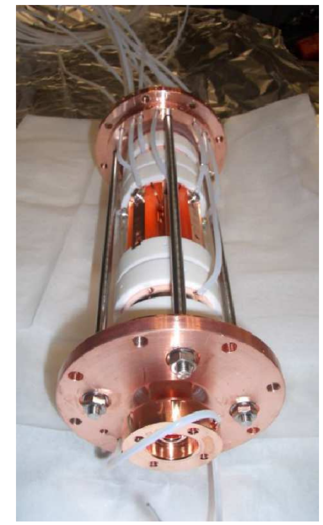


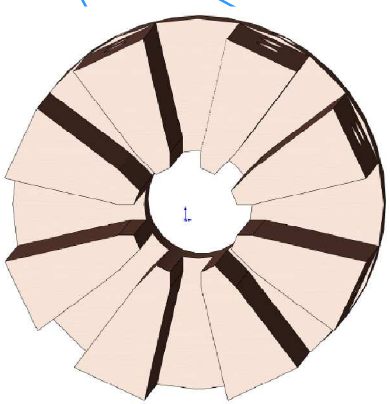
Magnetic-field distrib.
Taken from M. Froese



Setup ECBR measurements



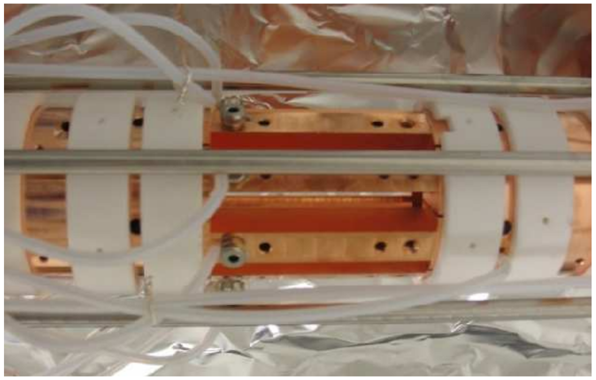


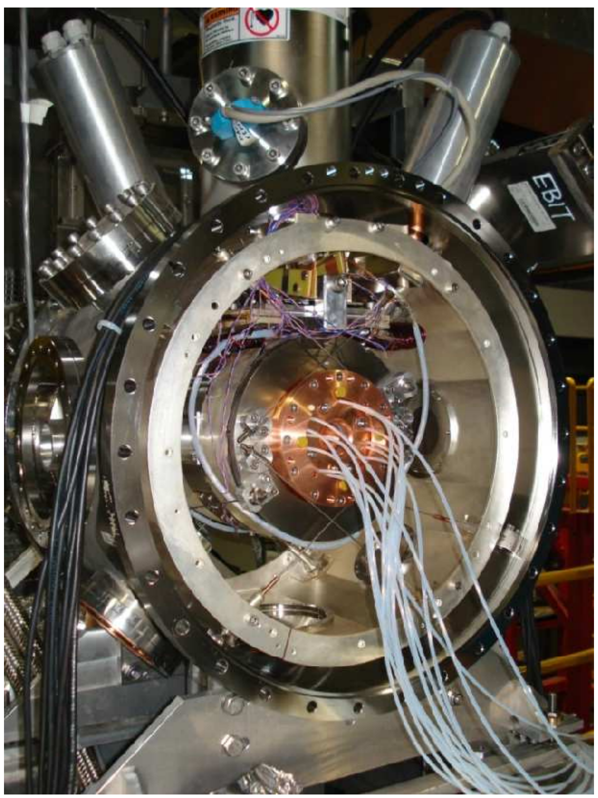


TITAN Electron Capture Branching Ratio:

- New approach: spatial separation of X-ray and β^- detection
- Seven X-ray detectors around segmented trap
- 2.1% solid angle for X-ray detection after EC
- No electron background at X-ray detectors due to strong magnetic field (6T)
- Long holding times in vacuum of $P < 10^{-11}$ mbar

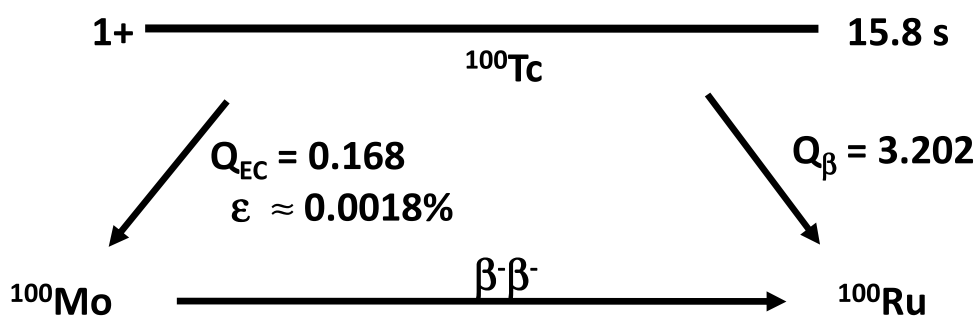
Branching Ratio Measurements





CANDIDATES FOR BRANCHING RATIO MEASUREMENTS

^{100}Mo :	^{100}Tc (EC)	[1+→ 0+, T1/2 = 15.8 s]	K_{α} = 17.5 keV
^{110}Pd :	^{110}Ag (EC)	[1+→ 0+, T1/2 = 24.6 s]	K_{α} = 21.2 keV
^{114}Cd :	^{114}In (EC)	[1+→ 0+, T1/2 = 71.9 s]	K_{α} = 25.3 keV
^{116}Cd :	^{116}In (EC)	[1+→ 0+, T1/2 = 14.1 s]	K_{α} = 25.3 keV
^{82}Se :	^{82m}Br (EC)	[2-→ 0+, T1/2 = 6.1 min]	K_{α} = 11.2 keV
^{128}Te :	^{128}I (EC)	[1+→ 0+, T1/2 = 25.0 min]	K_{α} = 27.5 keV
^{76}Ge :	^{76}As (EC)	[2-→ 0+, T1/2 = 26.2 h]	K_{α} = 9.9 keV



10^5 ions in trap with one half-life measurement cycle:

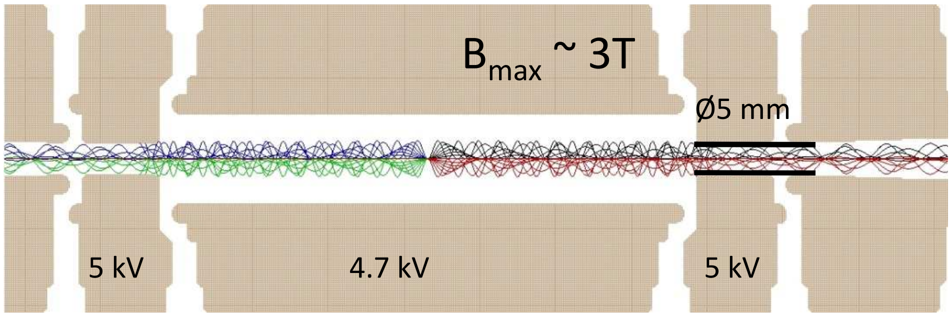
- solid angle: 2.1%
- detection efficiency: 30%

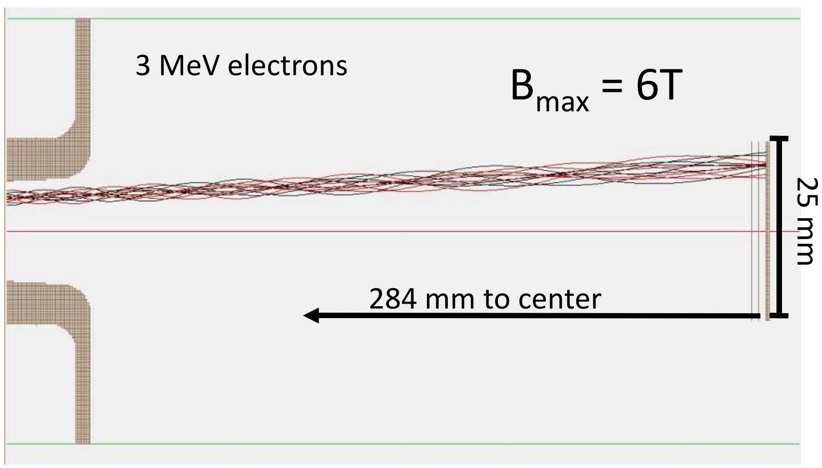
} 5.7 x 10^{-3} EC counts/cycle

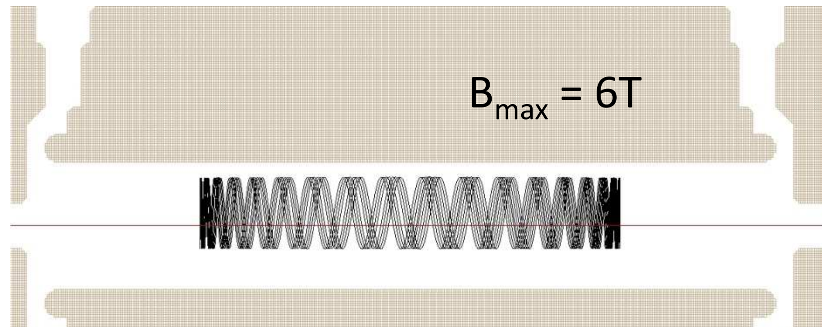
100 EC counts → 17636 EBIT fills → 74h

88h proposed for ^{100}Tc

Simulations

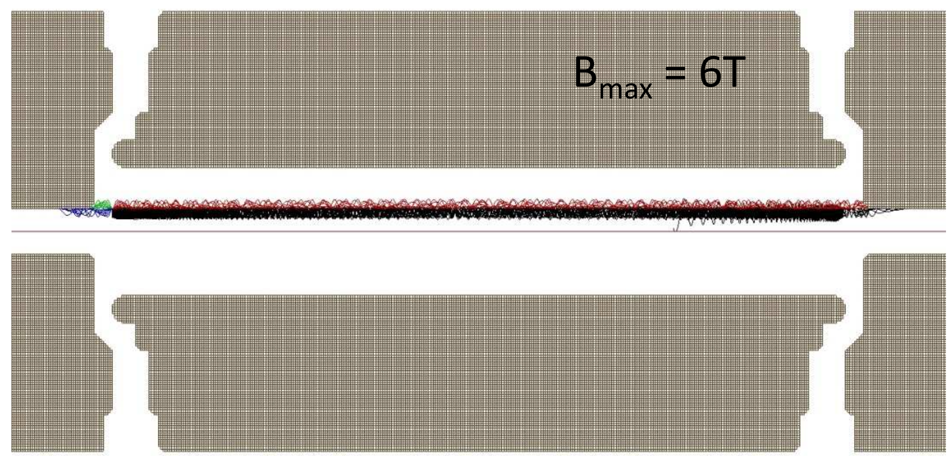






Loss through magnetic bottle for θ > 79deg:

$$\left(\frac{v_{\parallel}}{v_{\perp}}\right)_{crit} = \sqrt{\frac{B_{max}}{B_{min}} - 1}$$

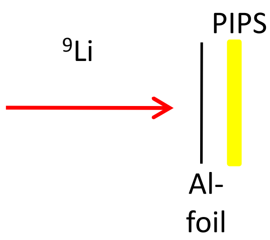


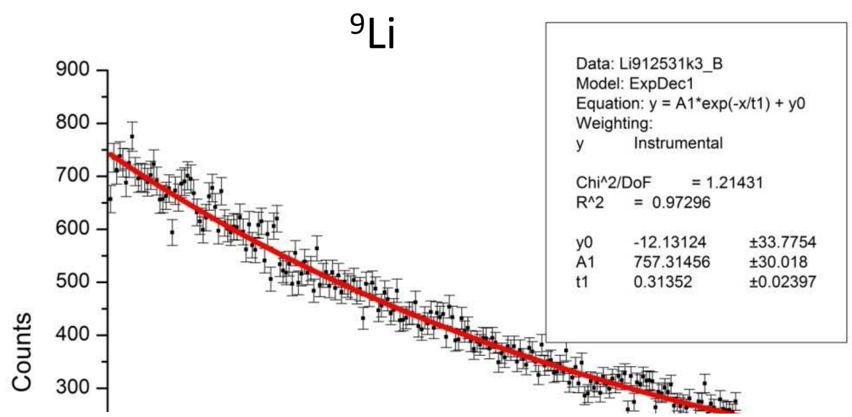
Loss through wall collisions

→ **Rotating wall cooling or side-band cooling**

β - detector

Passivated Implanted Planar Silicon detector

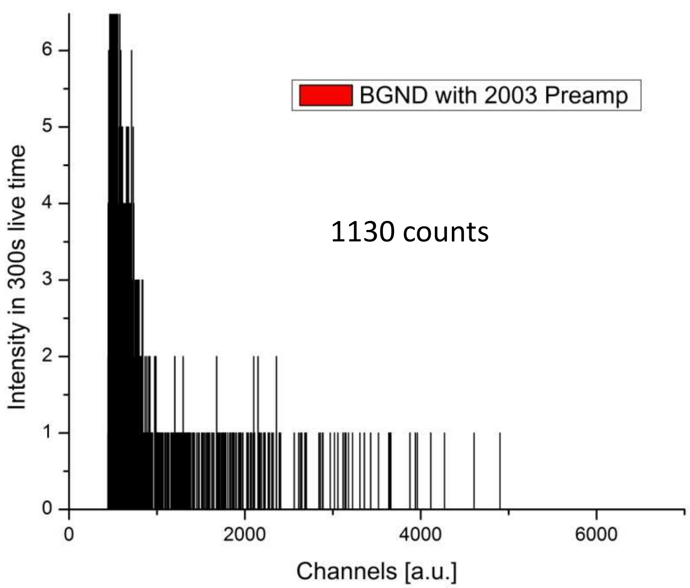


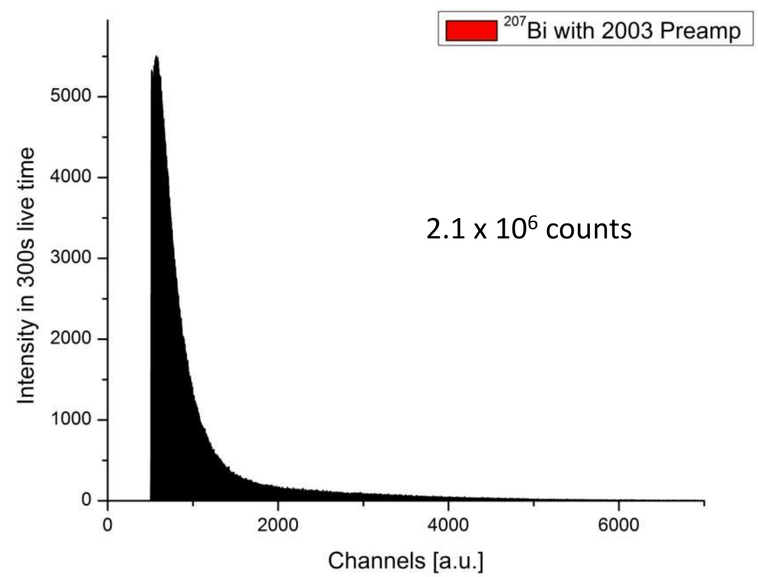


Q = 13.6 MeV

$T_{½}$ [lit] = 178.3ms

$T_{½}$ [PIPS] = 217.3(16.6)ms





Summary

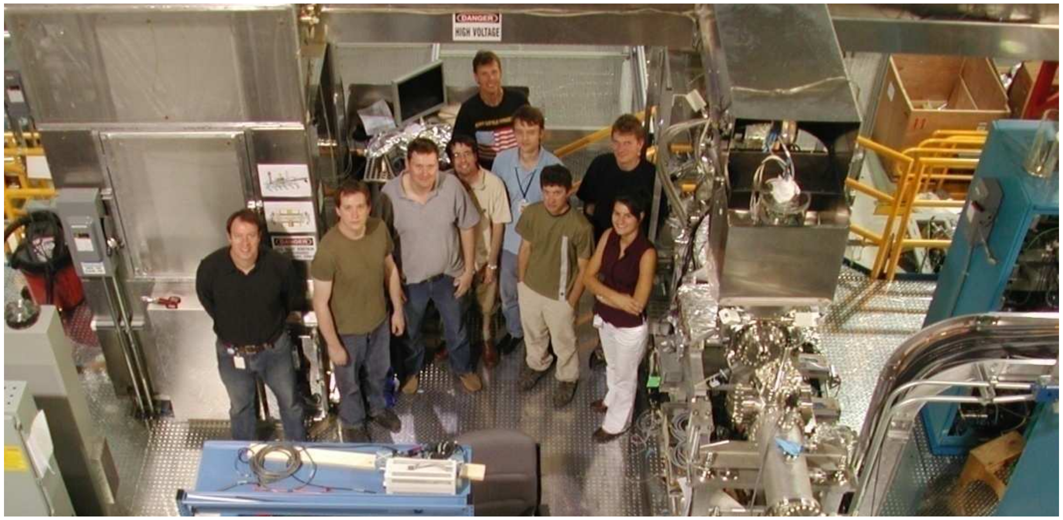
- There are discrepancies in the description of $2\nu\beta\beta$ within the pn-QRPA
- M_{EC} and M_{β} for single decays do not agree with those extrapolated from $2\nu\beta\beta$ decay
- TITAN EBIT offers a novel approach for EC-BR measurements
    - Long storage times
    - Low background at X-ray detector

…for the future

- TITAN EBIT will be connected to the TITAN beam line (EBIT was commissioned in August 2006).
- First EC branching ratio measurements with the EBIT by the end of this year

People/Collaborations

M. Brodeur, T. Brunner, C. Champagne, J. Dilling, P. Delheij, S. Ettenauer, M. Good, A. Lapierre, D. Lunney, C. Marshall, R. Ringle, V. Ryjkov, M. Smith, and the TITAN collaboration.



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