DF

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Experimental determination of nuclear matrix elements for double- beta decay

Westfälische Wilhelms-Universität Münster

Münster,KVI,RCNP:
(d,^{2}He) and (^{3}He,t) reactions

TRIUMF:
Double-beta decay and ion traps

- Charge-exchange reactions
  - (^{48}Ca, ^{116}Cd)
  - ^{64}Zn
  - ^{76}Ge
  - ^{96}Zr
  - (^{100}Mo)
- Double beta decay and ion traps

$^{76}As(2^- \xrightarrow{EC} 0^+)\,^{76}Ge$ ✓

$^{82m}Br(2^- \xrightarrow{EC} 0^+)\,^{82}Se$ ✓

$^{100}Tc(1^+ \xrightarrow{EC} 0^+)\,^{100}Mo$ ✓

$^{110}Ag(1^+ \xrightarrow{EC} 0^+)\,^{110}Pd$

$^{114}In(1^+ \xrightarrow{EC} 0^+)\,^{114}Cd$

$^{116}In(1^+ \xrightarrow{EC} 0^+)\,^{116}Cd$ ✓

$^{128}I(1^+ \xrightarrow{EC} 0^+)\,^{128}Te$

The (d,^{2}He) reaction

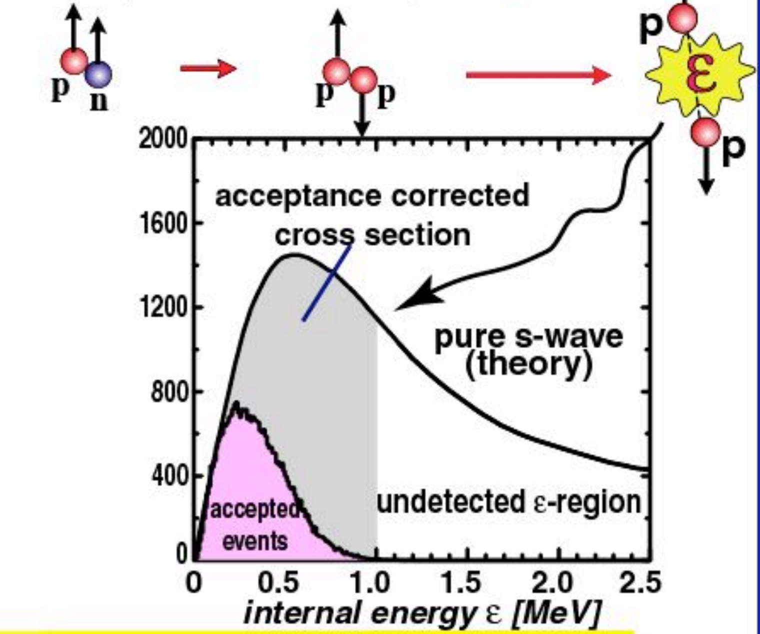
1)- reaction mechanism forces a spin-flip and an isospin-flip !
$\Delta S=1$, $\Delta T=1$ perfect GT filter

2)- coincident detection of two protons from ^{2}He decay
→ background-free spectra
but need large accptnc spectrometer

3)- contributions from higher p-p partial waves? Dont'worry!!

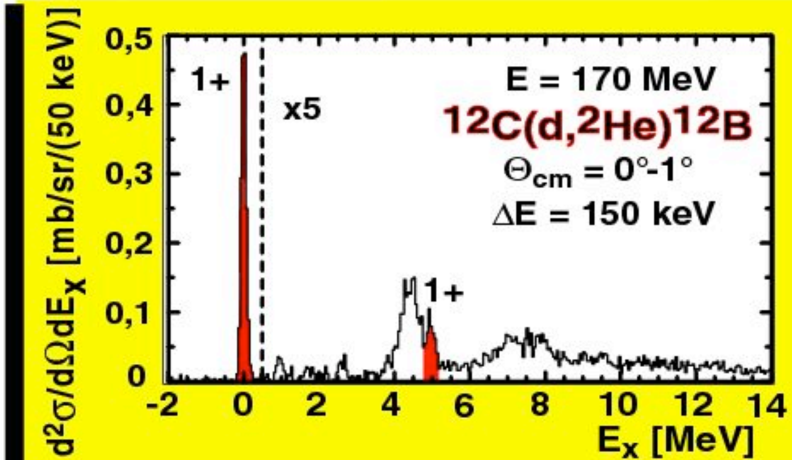
S=1, T=0 → S=0, T=1

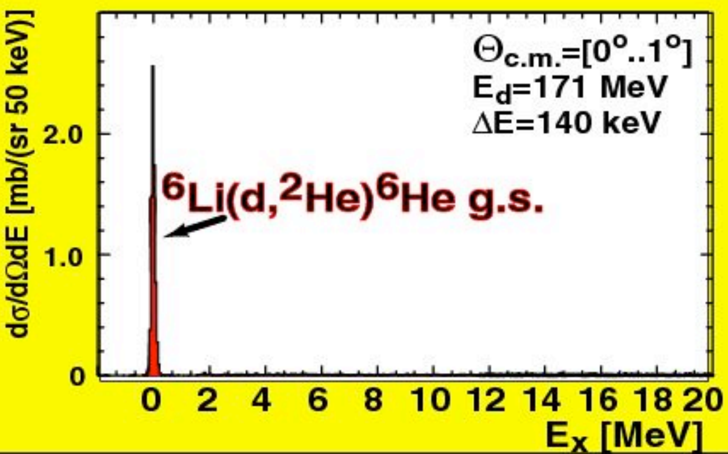
$d(^3S_1) \rightarrow {}^2He(^1S_0) \rightarrow p + p$



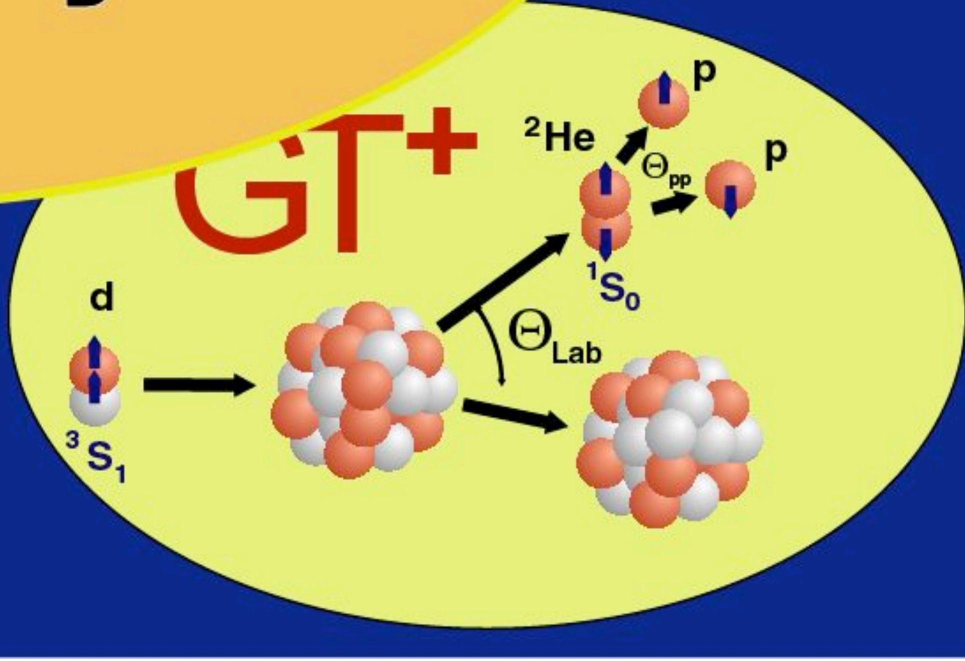
Alternatives:

(n,p) resolution?? Fermi transition
(t,^{3}He) triton beam?? Fermi transition
(HI,HI) resolution?? reaction mechanism??





Double beta decay



Measurement of $M_{DGT}^{(2\nu)}$ thru hadronic probes

$$M_{DGT} = \sum_m \frac{\langle 0^{(f)}_{g.s.} \| \sigma\tau^- \| 1^+_m \rangle \langle 1^+_m \| \sigma\tau^- \| 0^{(i)}_{g.s.} \rangle}{1/2\, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - M_i}$$

$$= \sum_m \frac{M_m^{GT+} \; M_m^{GT-}}{1/2\, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - M_i}$$

2νββ-decay mode only!!

Measure B(GT+) through (n,p)-type reactions

Measure B(GT−) through (p,n)-type reactions

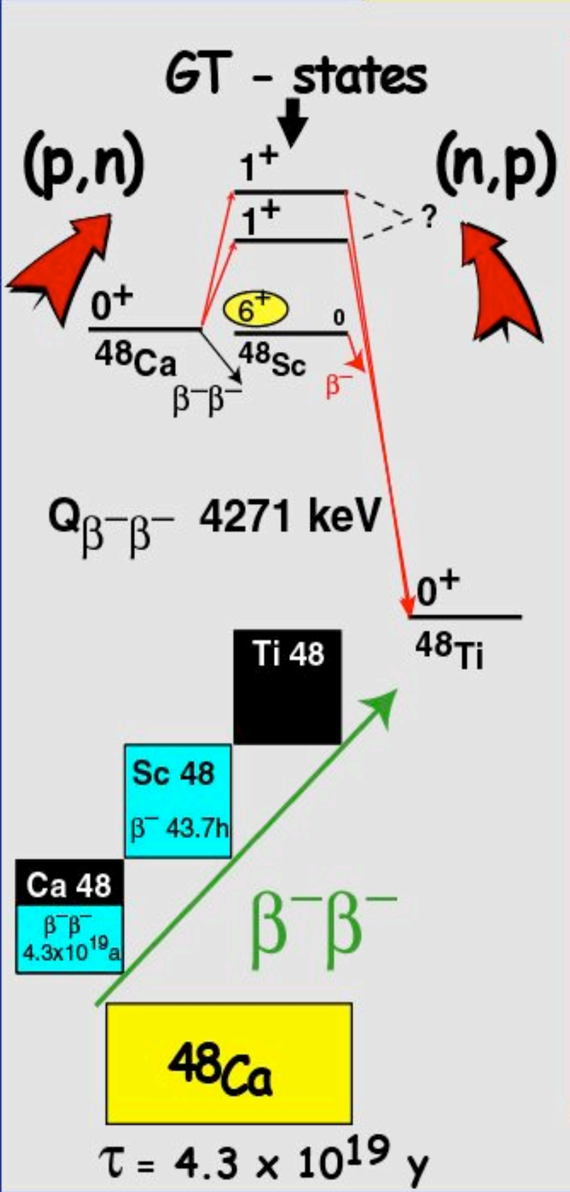
$$B(GT) = \frac{1}{2J_i + 1} \, | M(GT) |^2$$

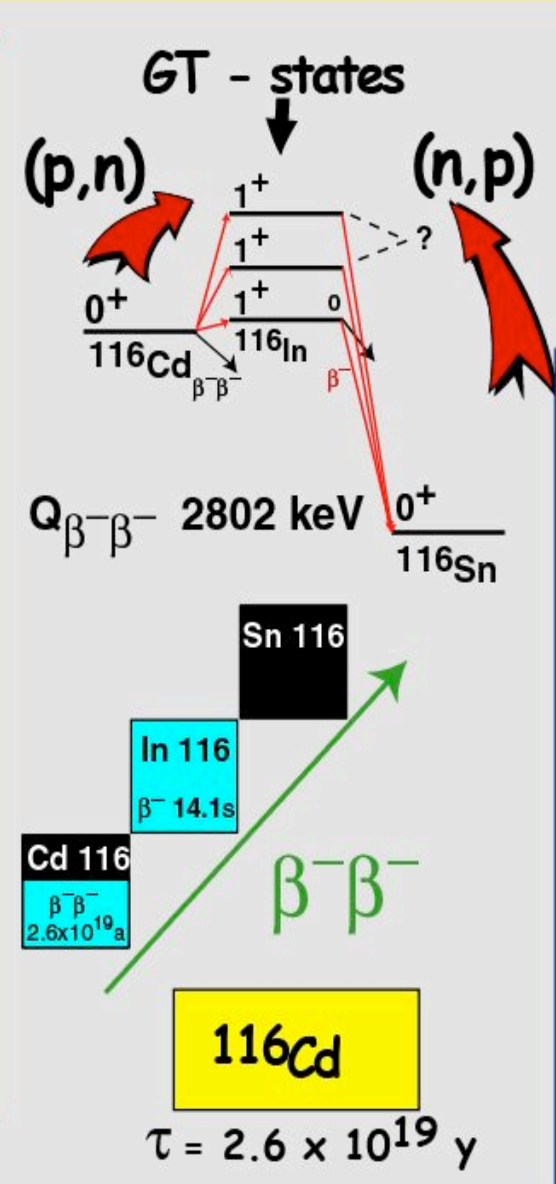
forward angles

$$B(GT) = \hat{\sigma}(GT) \frac{d\sigma(q=0)}{d\Omega}$$

- Phase cannot be measured
- Simple relation σ <-> B(GT)
- Little model dependence

The 2ν double-β decay





τ from counting experiments and as 2nd order weak process ($\beta^- \rightarrow \beta^-$) !!!

Half life:

$$[t_{1/2}]^{-1} = G^{(2\nu)} \, | M_{DGT} |^2$$

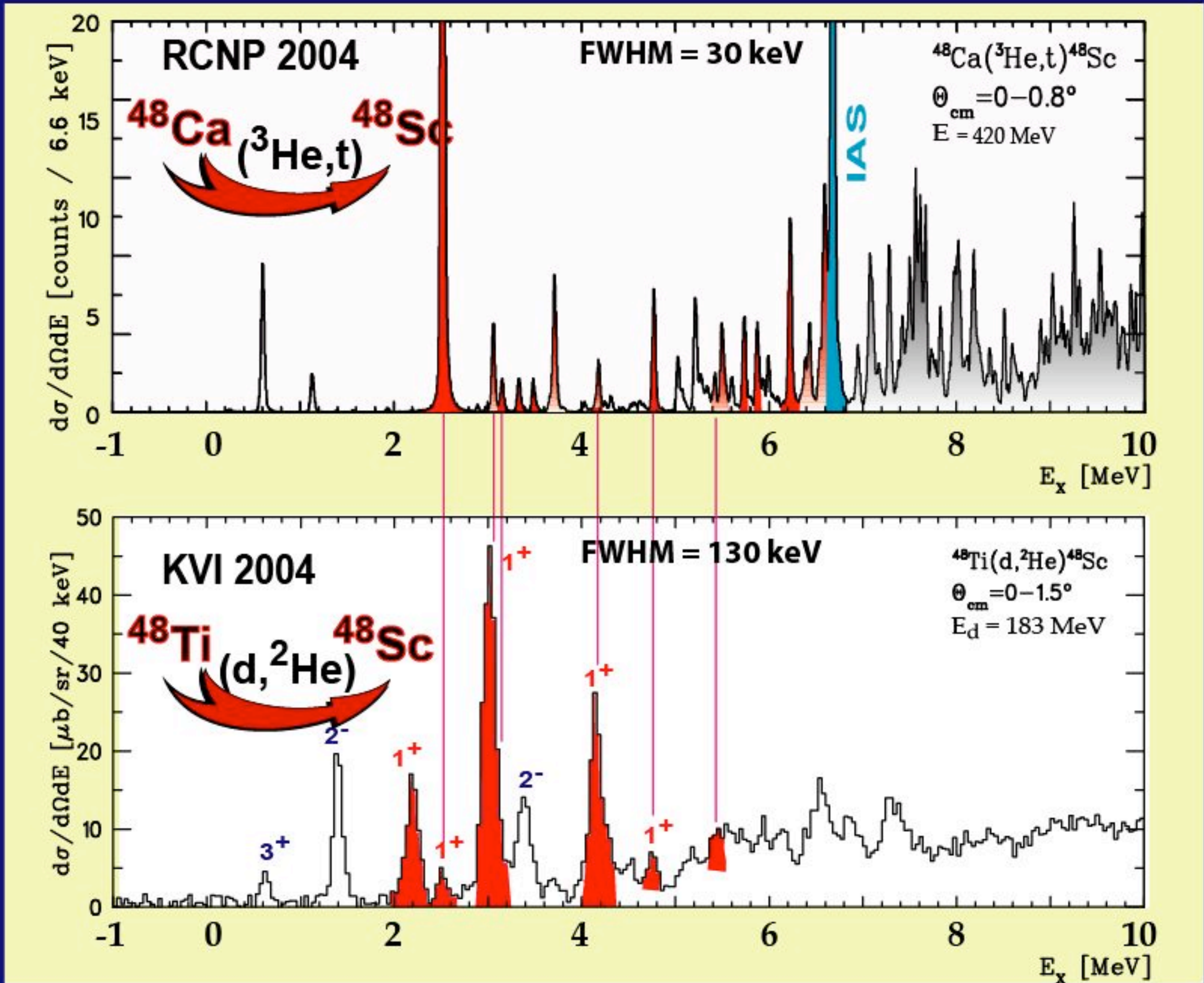
M_{DGT} =

$$\sum_m \frac{\langle 0^{(f)}_{g.s.} || \sigma\tau^- || 1^+_m \rangle \langle 1^+_m || \sigma\tau^- || 0^{(i)}_{g.s.} \rangle}{1/2 \, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - E_0}$$

$$G^{(2\nu)} \sim (Q_{\beta\beta})^{11}$$

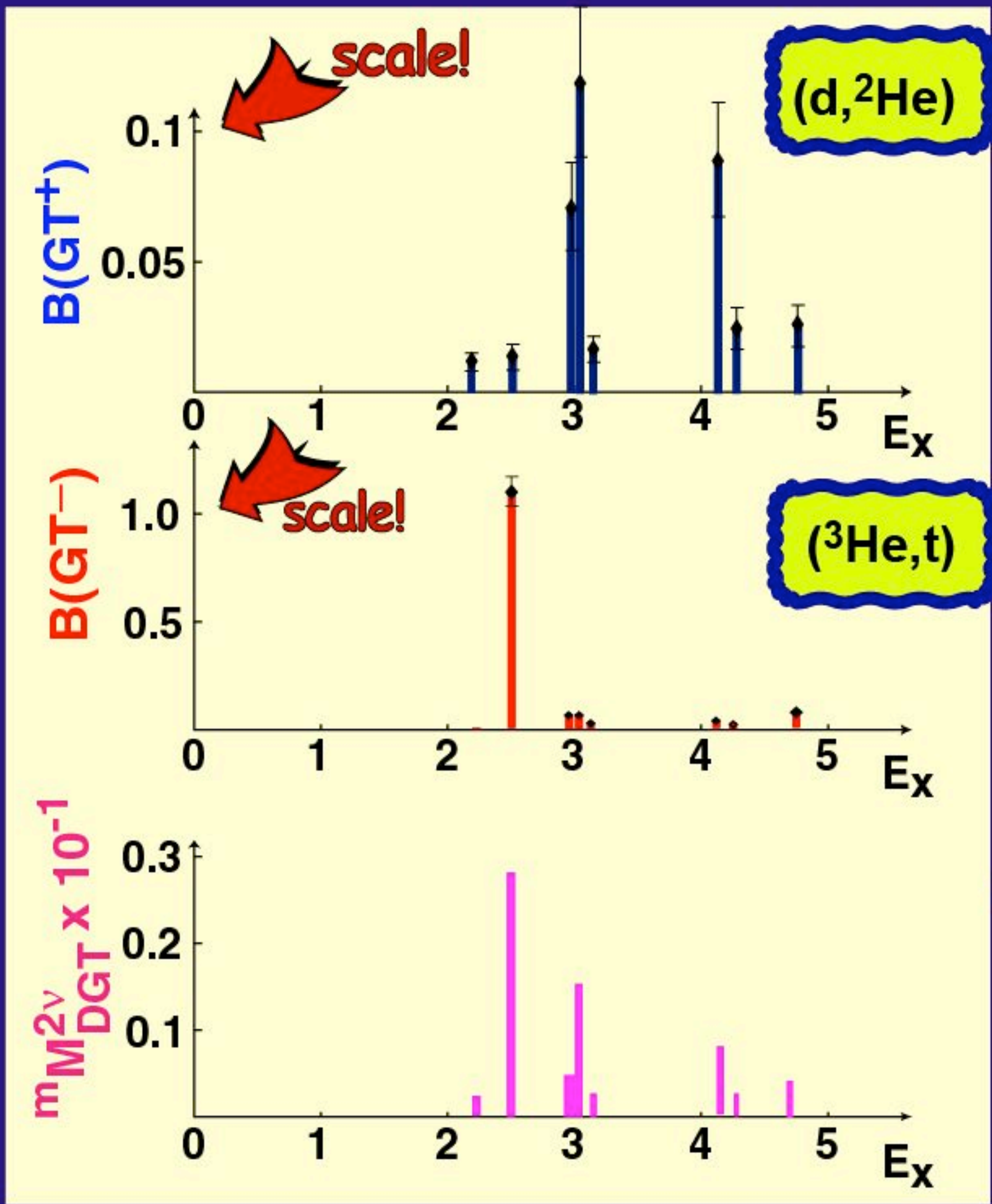
matrix elements available thru (p,n) and (n,p) type reactions

^{48}Ca - ^{48}Sc - ^{48}Ti



(^{3}He,t)

(d,^{2}He)



Experimental matrix elements

$$M_{DGT} = \sum_m {}^mM_{DGT}/E_m$$

$= 0.074 \pm 0.0155$ all positive

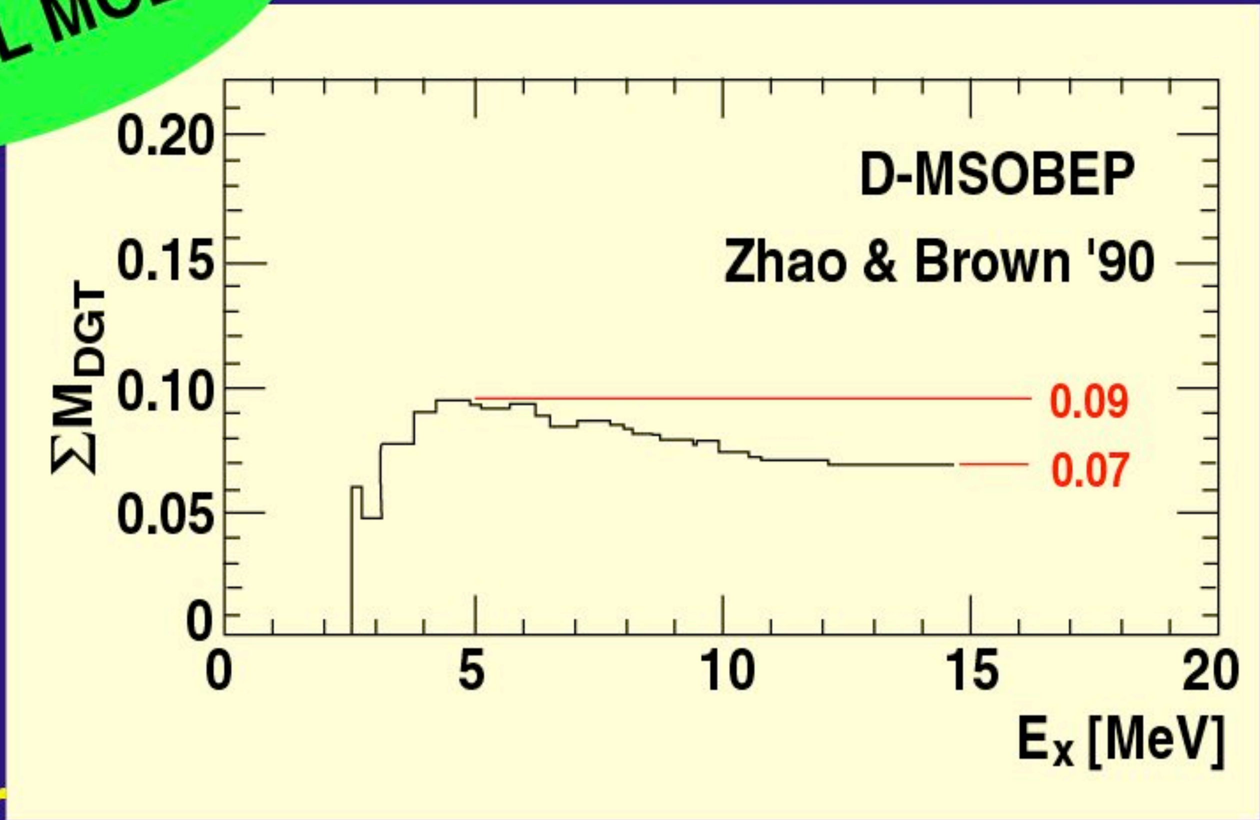
$T_{1/2} =$
$(2.00 \pm 0.42) \times 10^{19}$ yr

Compare to counting exp't:

$T_{1/2} =$
$(4.3 \pm 2.5) \times 10^{19}$ yr

Higher lying states (E_X > 5 MeV)

SHELL MODEL



Reduction of matrix element by ~ 25%

$T_{1/2}$ = $(3.55 \pm 0.8) \times 10^{19}$yr

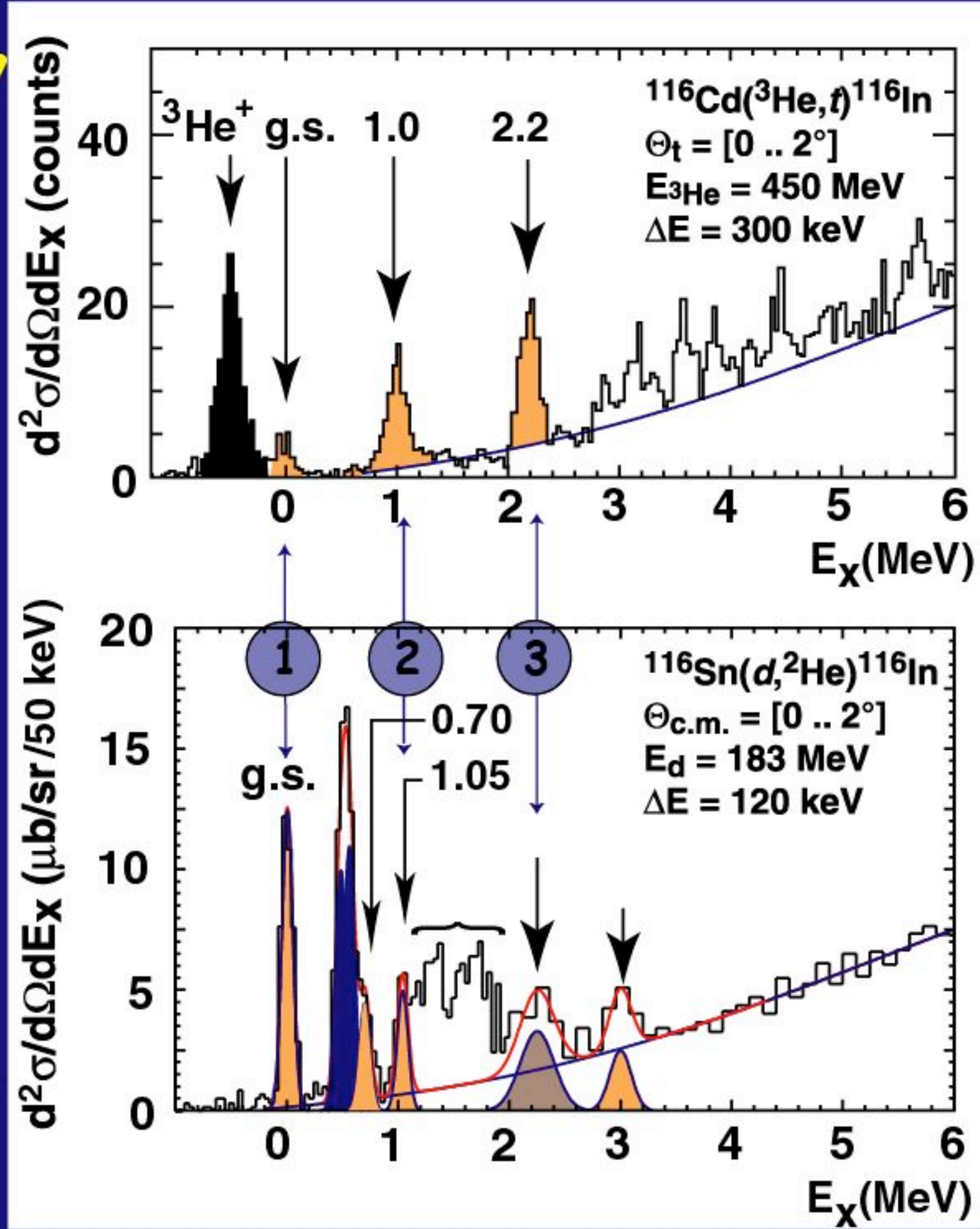
^{116}Cd

The case with conflicting data

^{116}Cd $2\nu\beta\beta$ decay

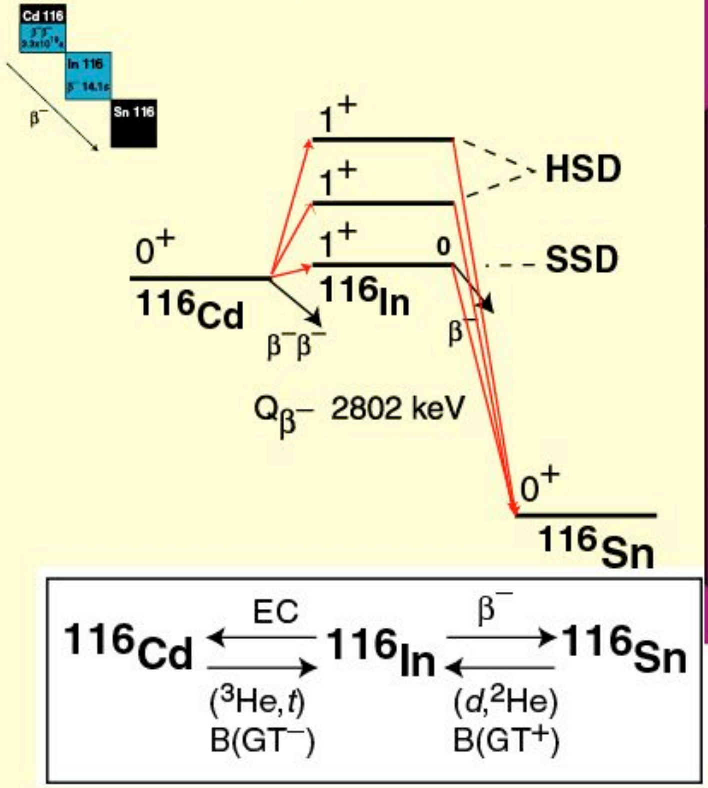
	$B(GT^-)$	$B(GT^+)$	M^m_{DGT}	running sum ΣM_{DGT}
1	0.032	0.256	0.025	0.025
2	0.12	0.11	0.020	0.045
3	0.17	0.07	0.013	0.058

Matrix element from counting experiment:
$\Sigma M_{DGT} = 0.064 \pm 0.007$



Single state dominance and its oddities

the conjecture



the oddity

Case	$B(GT^-)$	$B(GT^+)$	$M(DGT)$	$T_{1/2}^{(2\nu)}$ $[10^{19} y]$
direct	–	–	0.06	3.3
$(^3He,t)/\ \beta^-$	0.032	0.256	0.025	22
$EC/\ \beta^-$	0.47	0.256	0.09	1.5
theory	1.165	0.065	0.07	2.4
$(^3He,t)/(d,^2He)$	0.322*	1.09*	0.05	4.0

^{64}Zn

on the proton-rich side:

Z = 30, N = 34

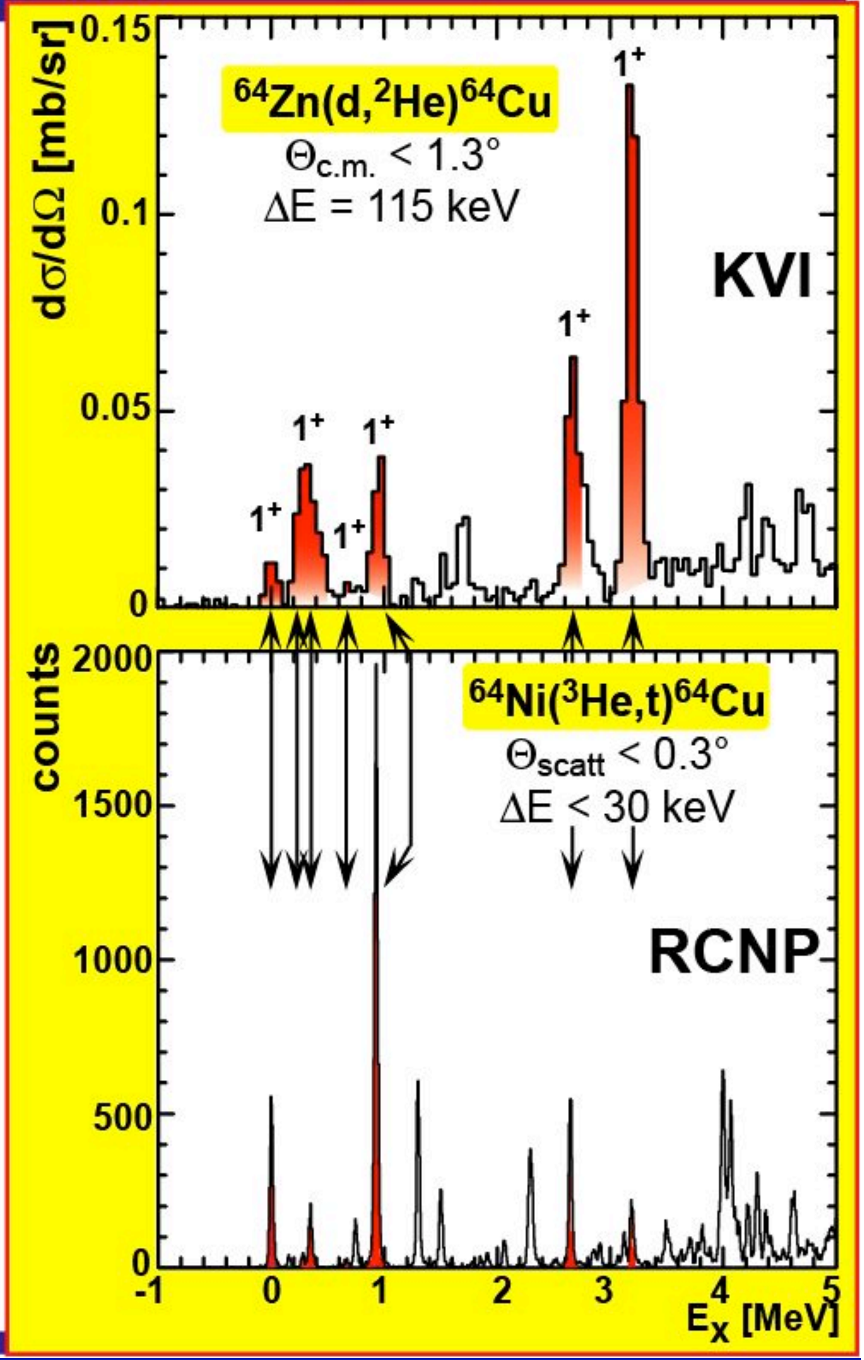
Experiments on ^{64}Ni and ^{64}Zn

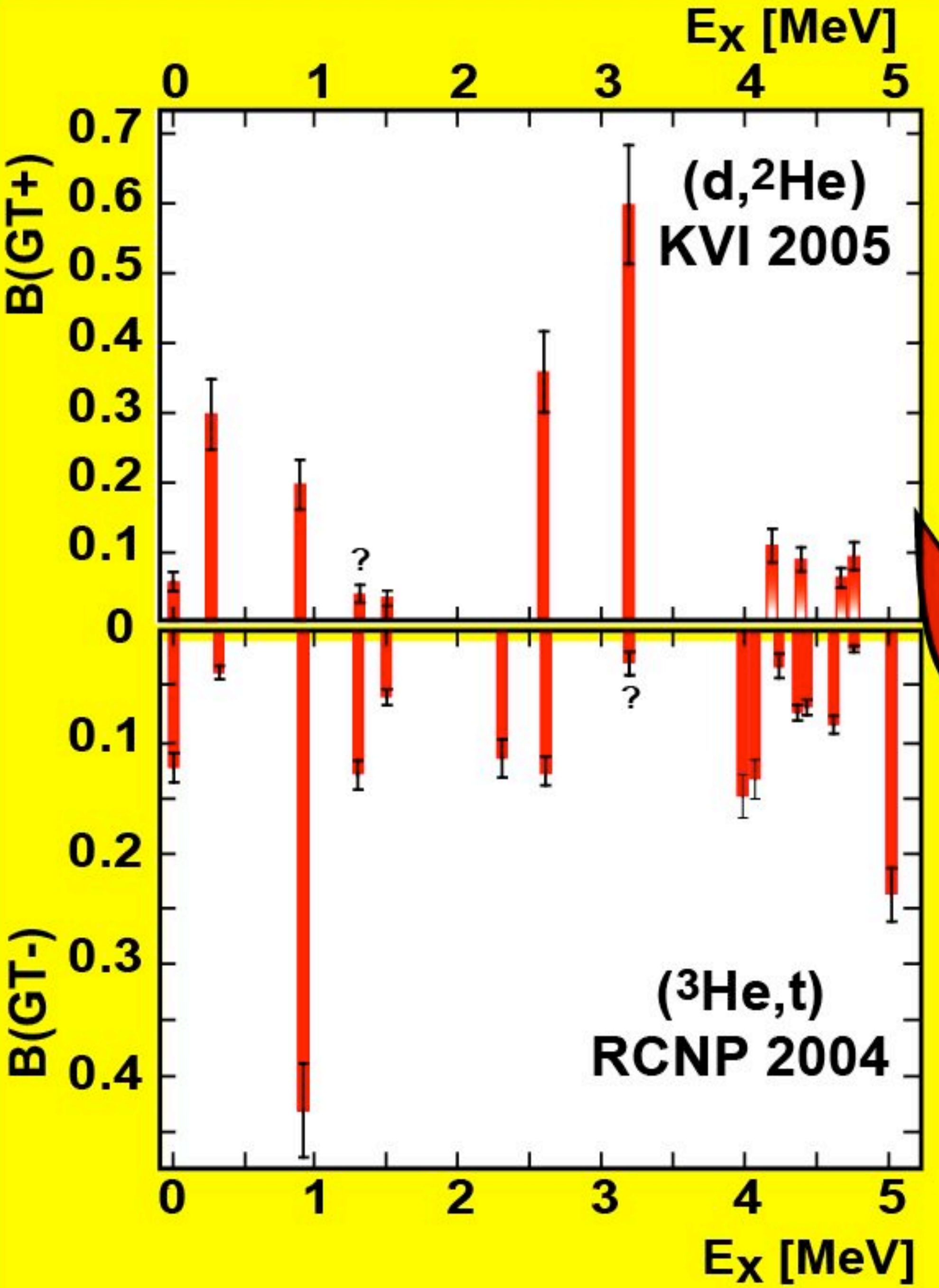
(^{3}He,t) (d,^{2}He)

- **test case for Pauli-blocking**

^{64}Zn: (N-Z) = 4
^{76}Se: (N-Z) = 8
^{96}Mo: (N-Z) = 12

- **g.s. transitions normalized to *ft*-values**
- **energy resolution ΔE = 115 keV and 30 keV for (d,^{2}He) and (^{3}He,t)**
- **may undergo β^+EC or ECEC**





^{64}Ni - ^{64}Cu - ^{64}Zn

GT-strength

^{64}Zn: (N-Z) = 4

Σ B(GT$^+$) = 1.93 ± 0.2

Σ B(GT$^-$) = 1.96 ± 0.2

$\Sigma M_{DGT}^{(2\nu)} = 0.52$

GT sum rule:

(although not quite applicable here)

$S_{\beta^-}(GT) - S_{\beta^+}(GT)$

= 3(N-Z) = 12

^{76}Ge

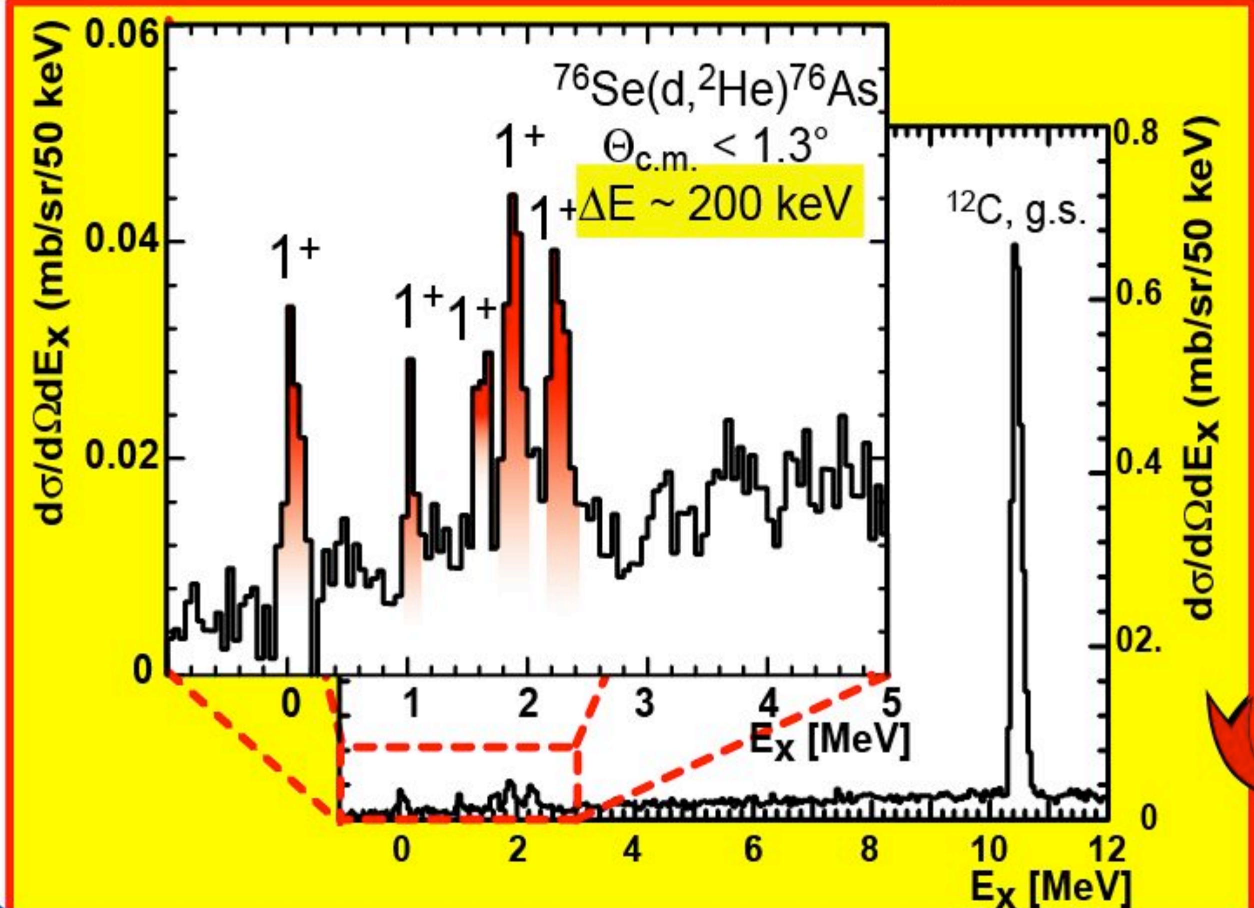
the most important
ββ-decaying nucleus

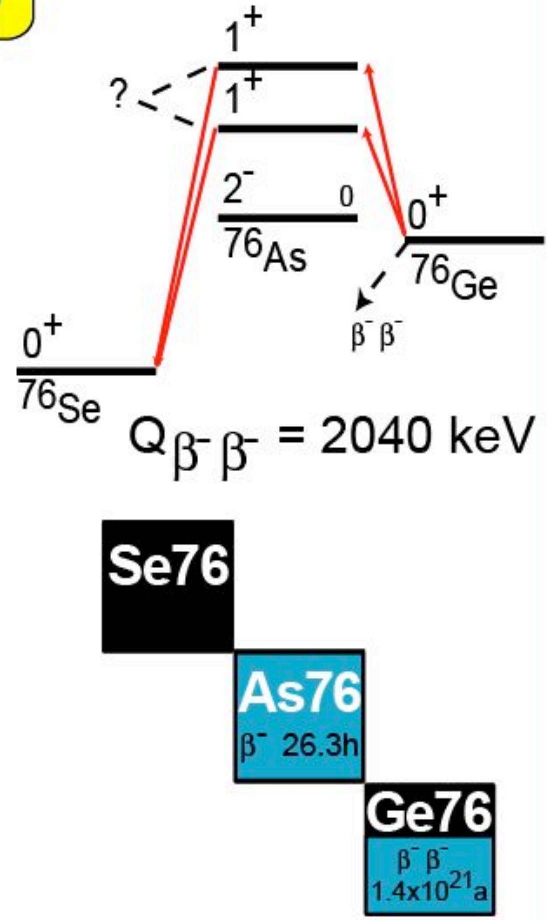
^{76}Ge - ^{76}As - ^{76}Se

- Intensively studied ββ-emitter
- $T_{1/2}$ determined by the Heidelberg-Moscow group: 1.55×10^{21}y
- $T_{1/2}$ deduced from (n,p) and (p,n) data with poor energy resolution

  multipole decomposition: 7.4×10^{20}y

  0°-6° subtraction method: 8.7×10^{21}y





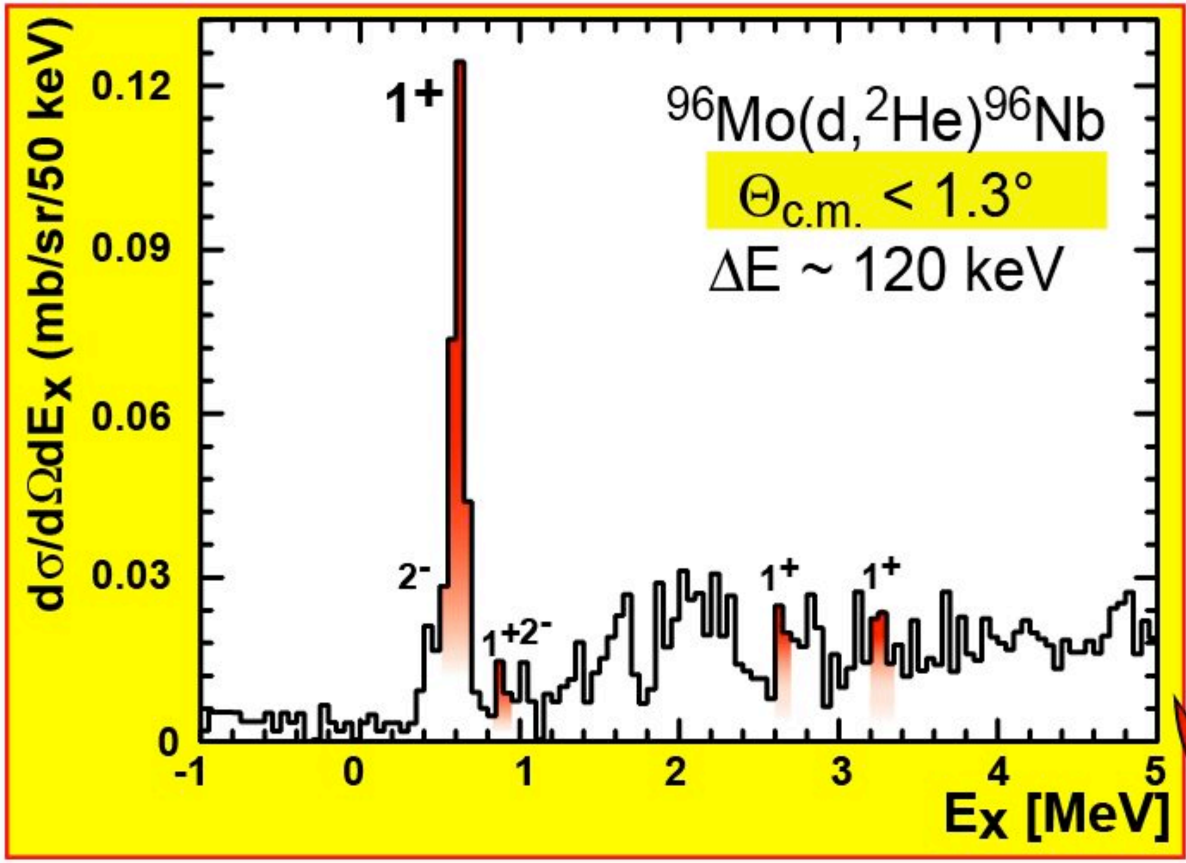
Σ B(GT$^+$) ~ 0.56

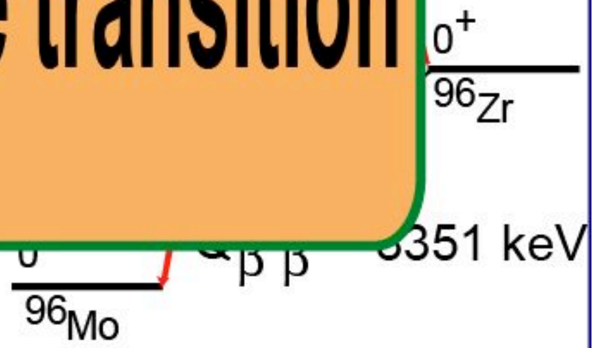
(^{3}He,t) measurement proposed at RCNP

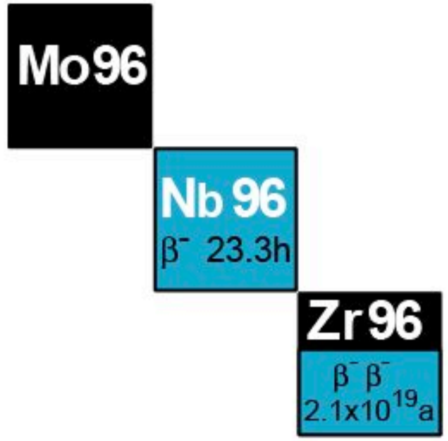
^{96}Zr

the most neutron-rich Zr-isotope N-Z=16

strength concentrated in one transition







$B(GT^+)$ ~ 0.5

(^{3}He,t) measurement proposed at RCNP

Westfälische
Wilhelms-Universität Münster
Institut für Kernphysik

TRIUMF

Double-beta decay and ion traps

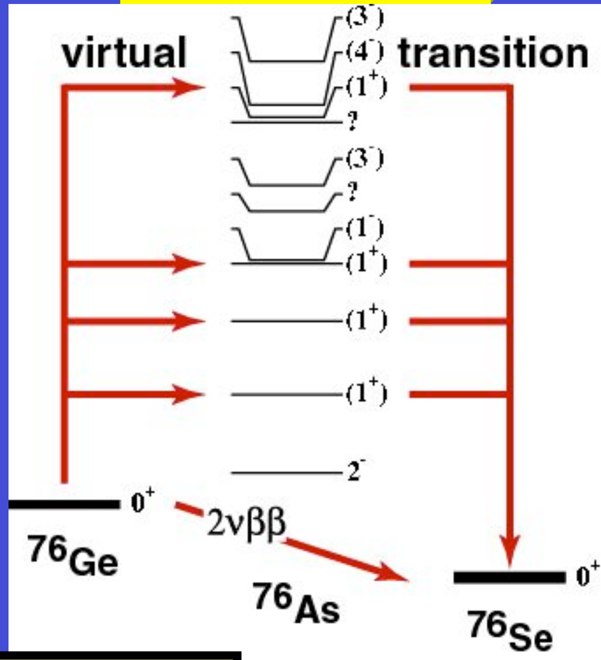
Electron capture branching ratios for the odd-odd intermediate nuclei in $\beta\beta$ decay using TITAN-trap

- **Objectives:**
  - experimental determination of **nuclear matrix elements** for $2\nu\beta\beta$ decay and $0\nu\beta\beta$ decay
  - test theory and improve theoretical prediction
  - allow more reliable extraction of **Majorana neutrino mass** from $0\nu\beta\beta$ decay by using mostly experimental information
- **Technique:**
  - measurement of K-shell EC X-rays using radioactive ions (i.e. intermediate nuclei) trapped in an ion trap (EBIT)
- **Advantages:**
  - no backing material, i.e. no absorption
  - high-purity sample
  - background-free situation, i.e. precision and sensitivity

ββ decay

2νββ decay

allowed in SM and observed in many cases



$$G^{2\nu}(Q,Z) = \left(\frac{G_F \cos(\theta_C)}{\sqrt{2}}\right)^4 F^2_{(-)} \left|M^{(2\nu)}_{DGT}\right|^2 f(Q)$$

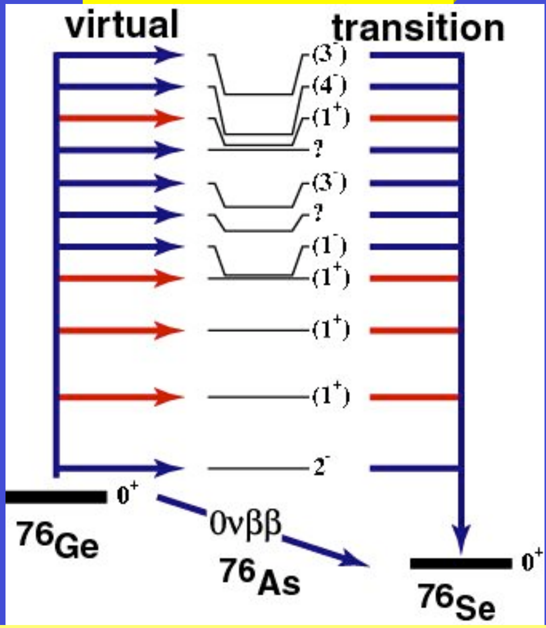
$$= G^{2\nu}(Q,Z)\left|M^{(2\nu)}_{DGT}\right|^2$$

$$M^{(2\nu)}_{DGT} = \sum_m \frac{\left\langle 0^{(f)}_{g.s.}\right|\sum_k \sigma_k \tau_k^+ \left|1^+_m\right\rangle\left\langle 1^+_m\right|\sum_k \sigma_k \tau_k^- \left|0^{(i)}_{g.s.}\right\rangle}{\frac{1}{2}Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - E_0}$$

$$= \sum_m \frac{M_m(GT^+)\,M_m(GT^-)}{E_m}$$

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

ββ decay → 0νββ decay



forbidden in MSM
lepton number violated
neutrino enters as virtual particle, → $q \sim 0.5\,\mathrm{fm}^{-1}$

mass of Majorana neutrino!!!

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

$$G^{0\nu}_{\beta\beta} = G^{0} \left| \sum_m \frac{\langle 0^{(f)}_{g.s.} \| O_{\sigma\tau}(r,S,L) \| J^{\pi}_m \rangle \langle J_m \| O_{\sigma\tau}(r,S,L) \| 0^{(i)}_{g.s.} \rangle}{\frac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(J^{\pi}_m) - E_0} - \text{Fermi} \right|^2 \left\langle m_{\nu_e} \right\rangle^2$$

nucl. matrix element

NOT accessible thru charge-exchange reactions

Theoretical situation

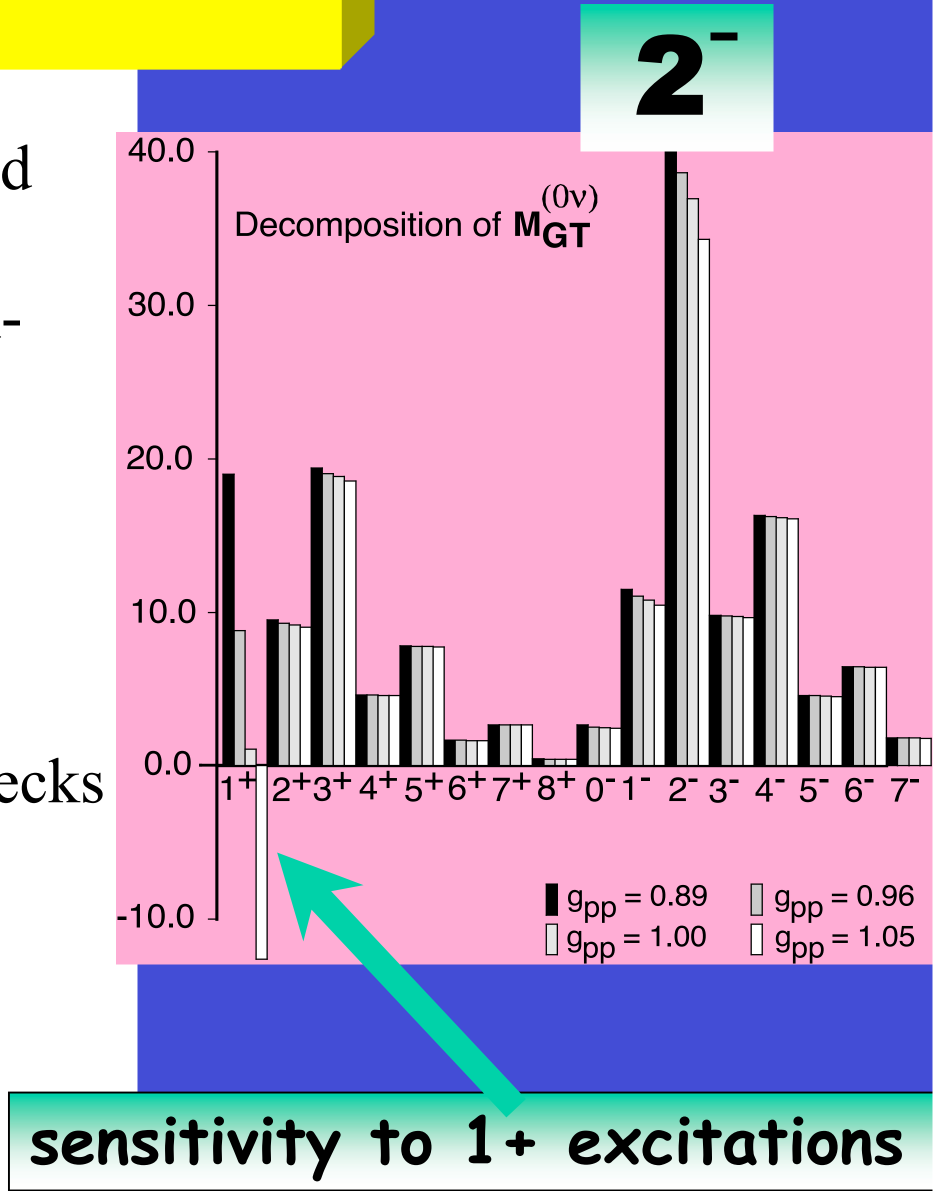
Theory claims:

1. both decay modes can be described with **ONE** parameter only, g_{pp}, which is the p-p part of the proton-neutron two-body interaction
2. g_{pp} is fixed to the experimental $2\nu\beta\beta$ decay half life ($g_{pp} \sim 1$)

BUT

1. there are no intermediate cross checks with experiment
2. $2\nu\beta\beta$ decay is **sensitive** to g_{pp}, $0\nu\beta\beta$ decay is **insensitive** to g_{pp}
3. nuclear structure remains hidden

Theory: **trust us!!**

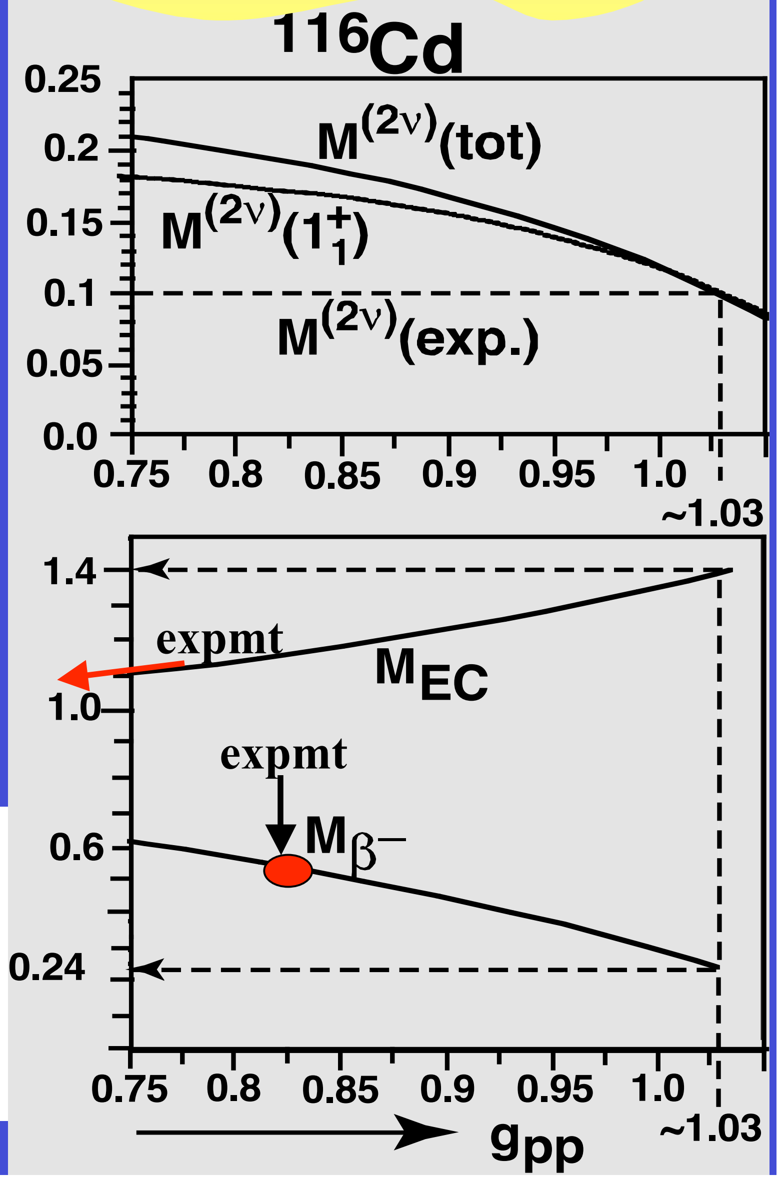


Recent critical assessment of the theoretical situation

1. gpp 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)

example



In case of single state dominance

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

$M_{EC} = 1.4$ $\varepsilon = 0.095\%$ *log ft* = 3.77 theo

$M_{EC} = 0.69$ $\varepsilon = 0.023\%$ *log ft* = 4.39 exp-1

$M_{EC} = 0.18$ $\varepsilon = 0.0016\%$ *log ft* = 5.5 exp-2

$M_{EC} = 0.51$ $\varepsilon = 0.013\%$ *log ft* = 4.6 Sasano

Summarizing the theory

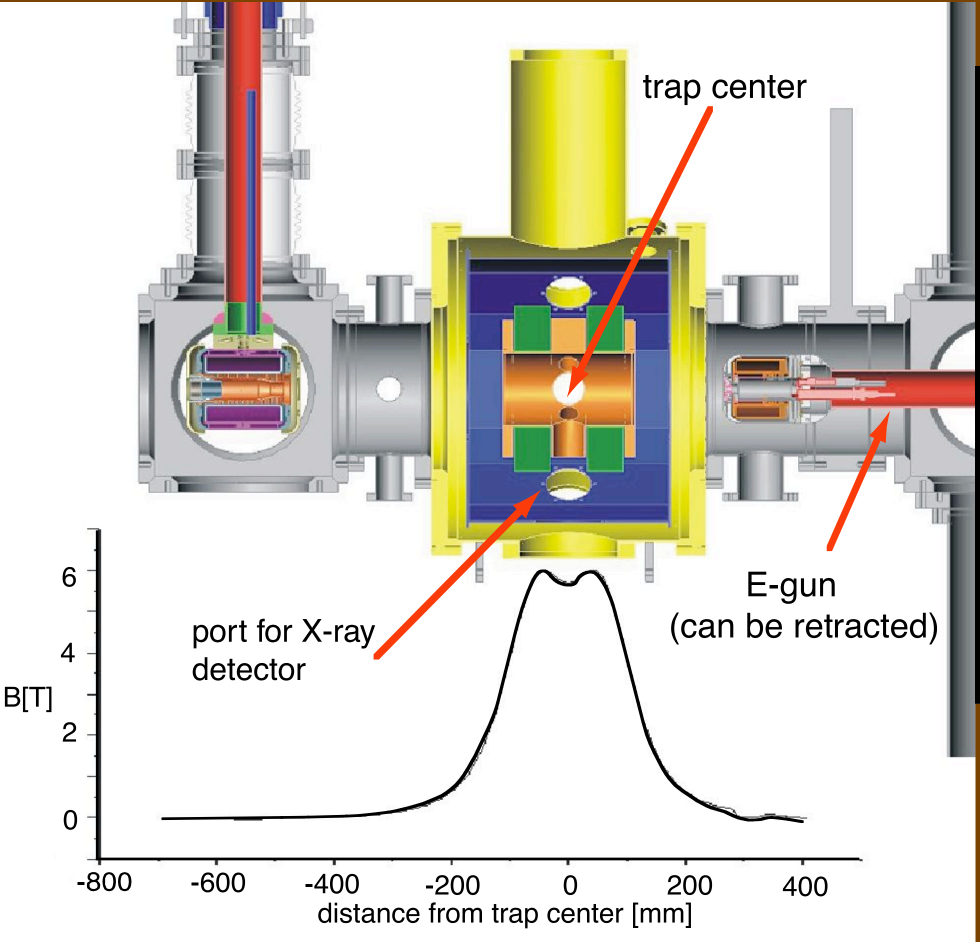
The use of $g_{pp}(\beta\beta) \sim 1.0$ reproduces the $2\nu\beta\beta$ decay half-life via a conspiracy of two errors: a much too large EC matrix element (too fast EC decay) is compensated by a much too small β^- matrix element (too slow β^- decay).

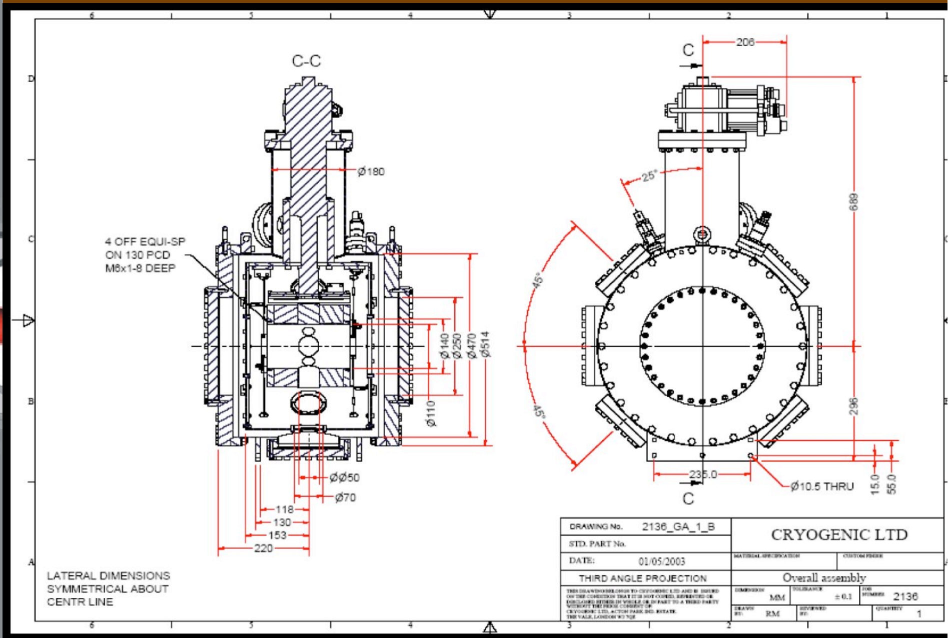
Discrepancies of 1 – 2 orders of magnitude are possible

The loose end:

EC rates are badly known, or not known at all

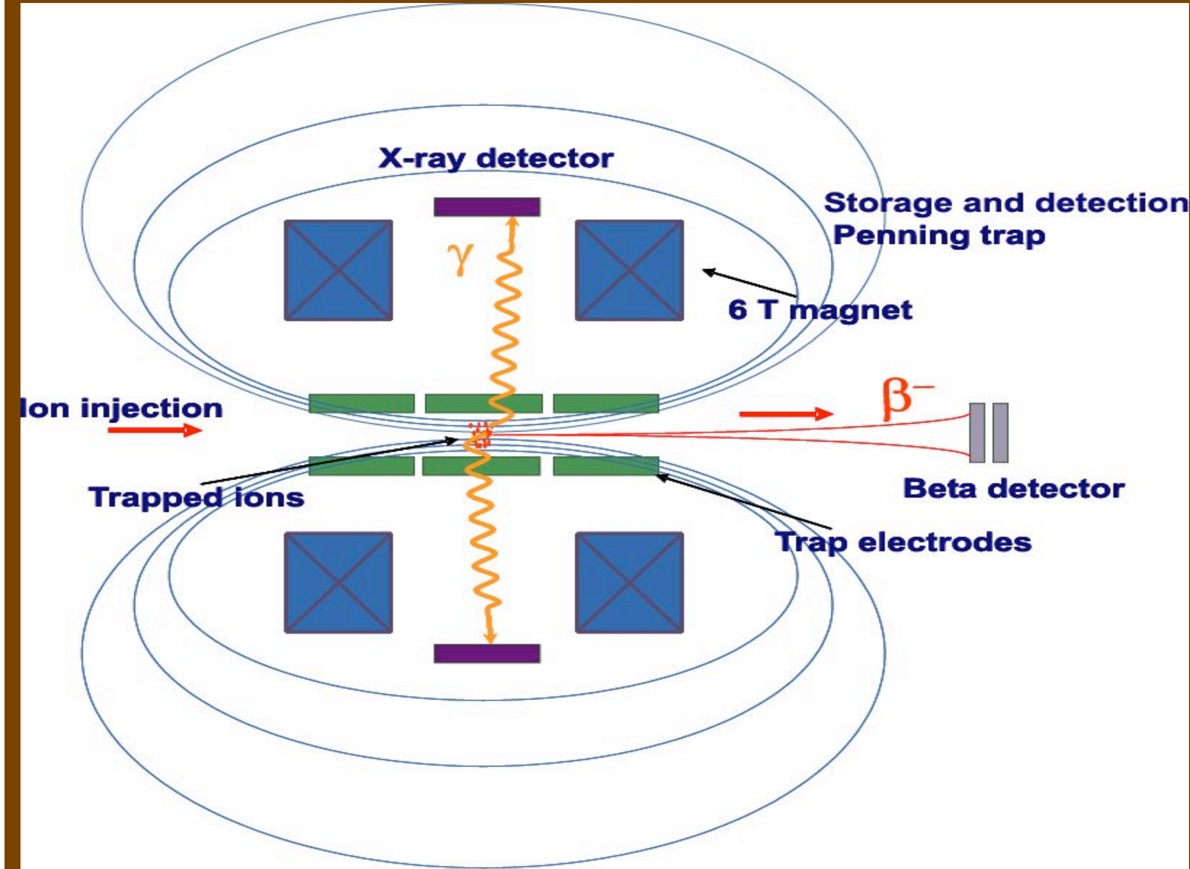
Experiment for EC using EBIT





holding 7 ports for X-ray detectors

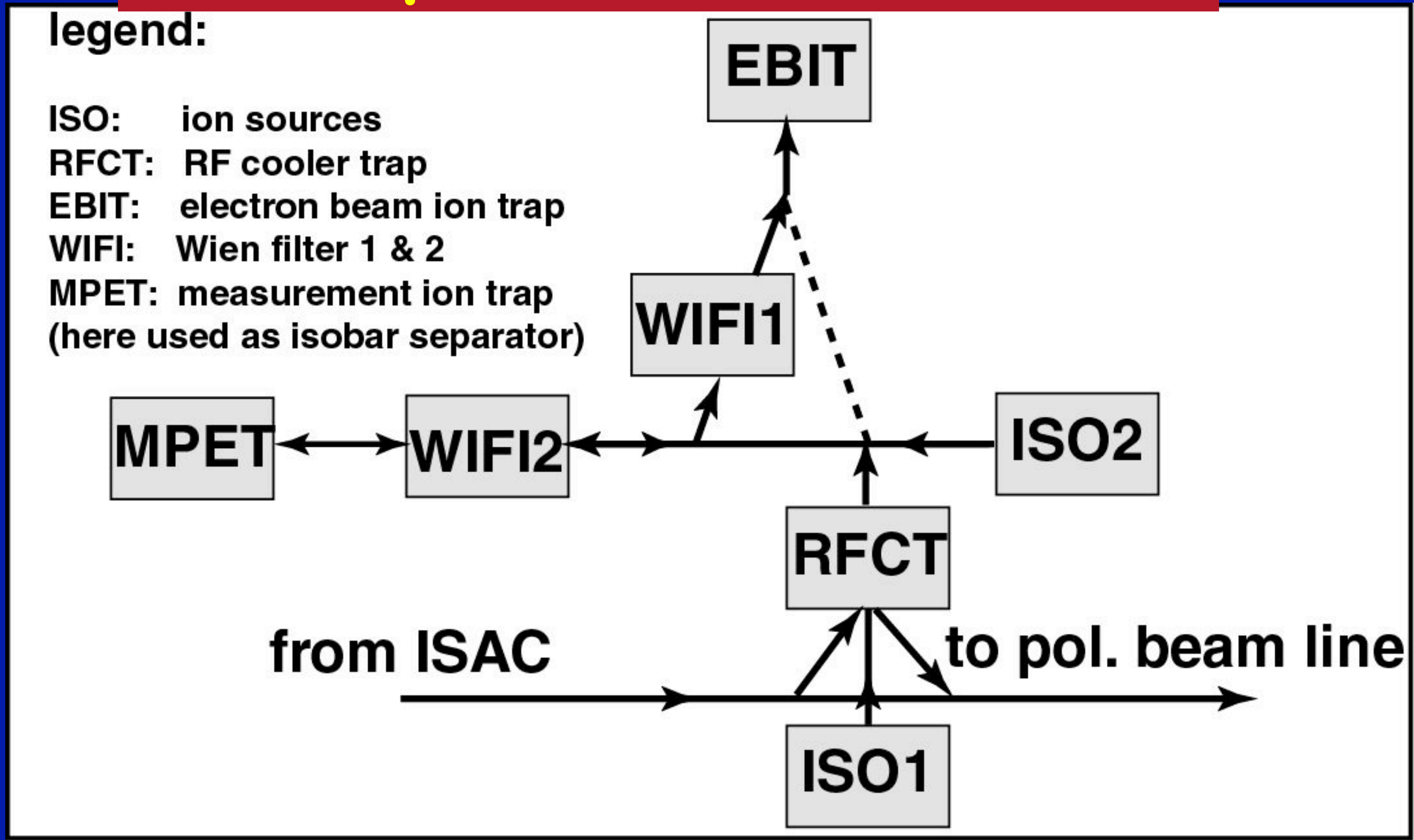
Experiment for EC using EBIT



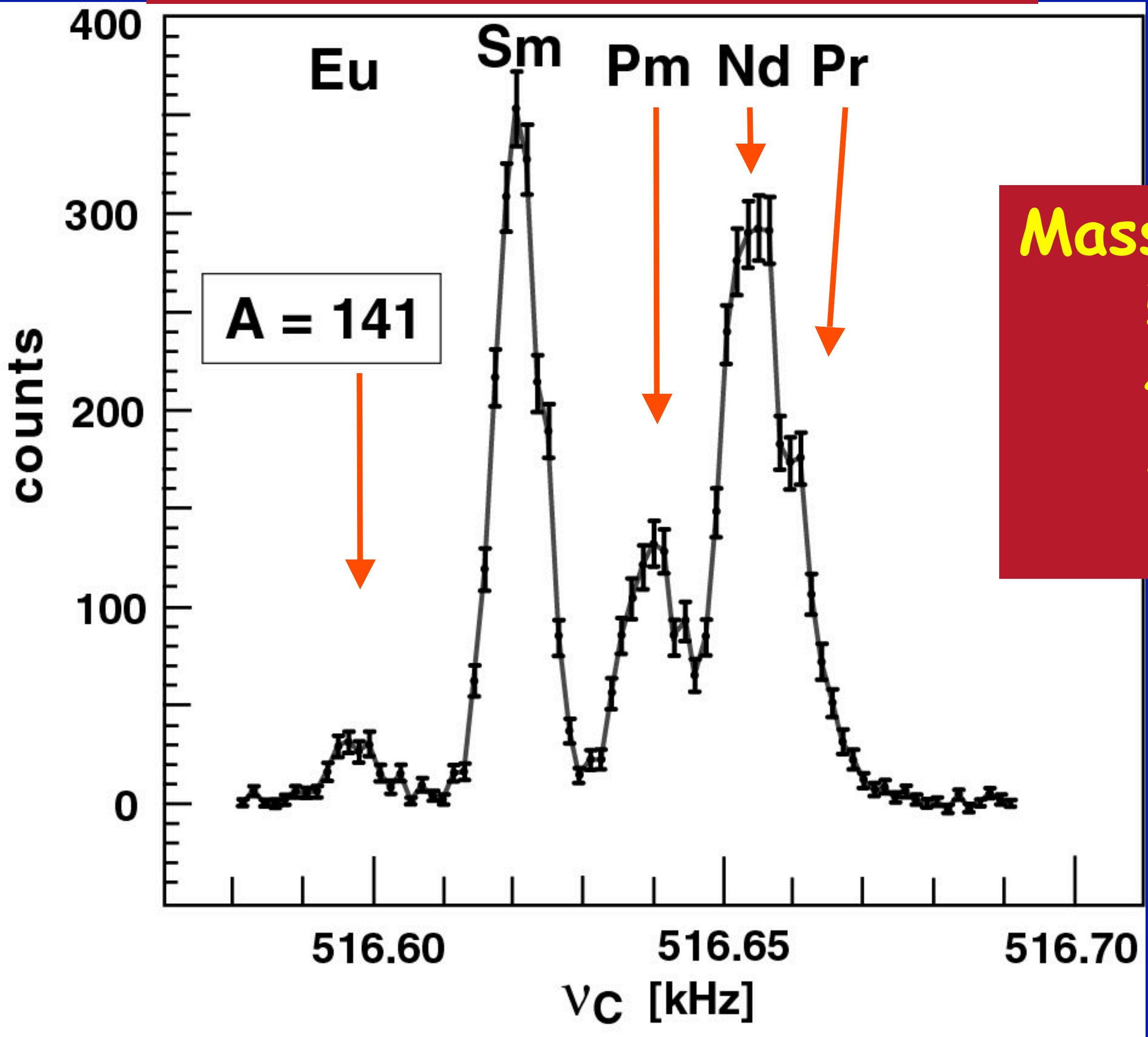
- 7 X-ray detectors
- 2.1% solid angle (can be increased)
- 6T magnetic field
- carrierless suspension of ions in UH vacuum
- $10^5 – 10^6$ ions per load
- holding times: minutes or hours possible

Electrons from β-decay (10^6 times more intense than EC) are giuded away to the exit of the trap and can be used for monitoring by a channeltron

Ion trap network @ TRIUMF

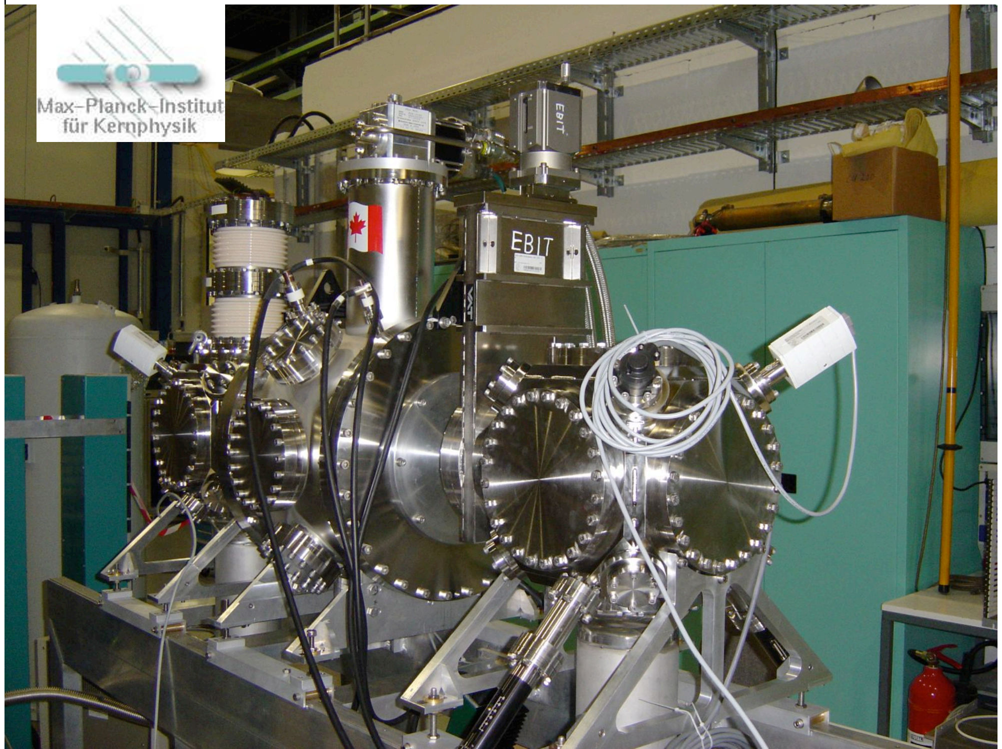


Example for mass resolution
ISOLTRAP @ CERN



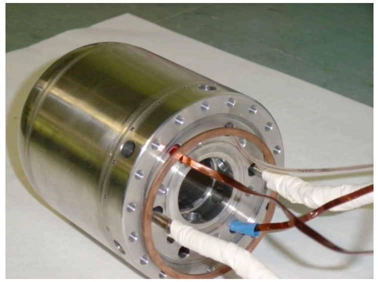
Mass differences:
5.55 MeV
4.53 MeV
3.72 MeV
1.82 MeV

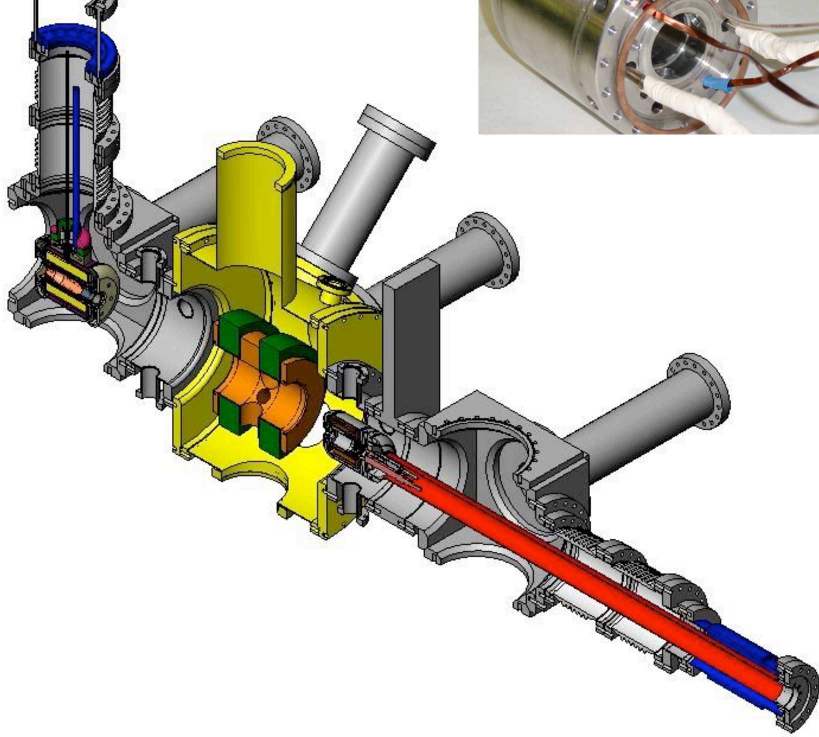
Electron Beam Ion Trap (EBIT)

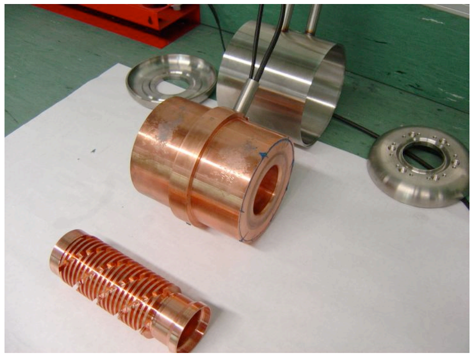


Three different E-guns (0.5A, 1.5A, 5A) assembled, tests underway.

RICH-ebis @ 10 A standard operation, they will go to 20 A!

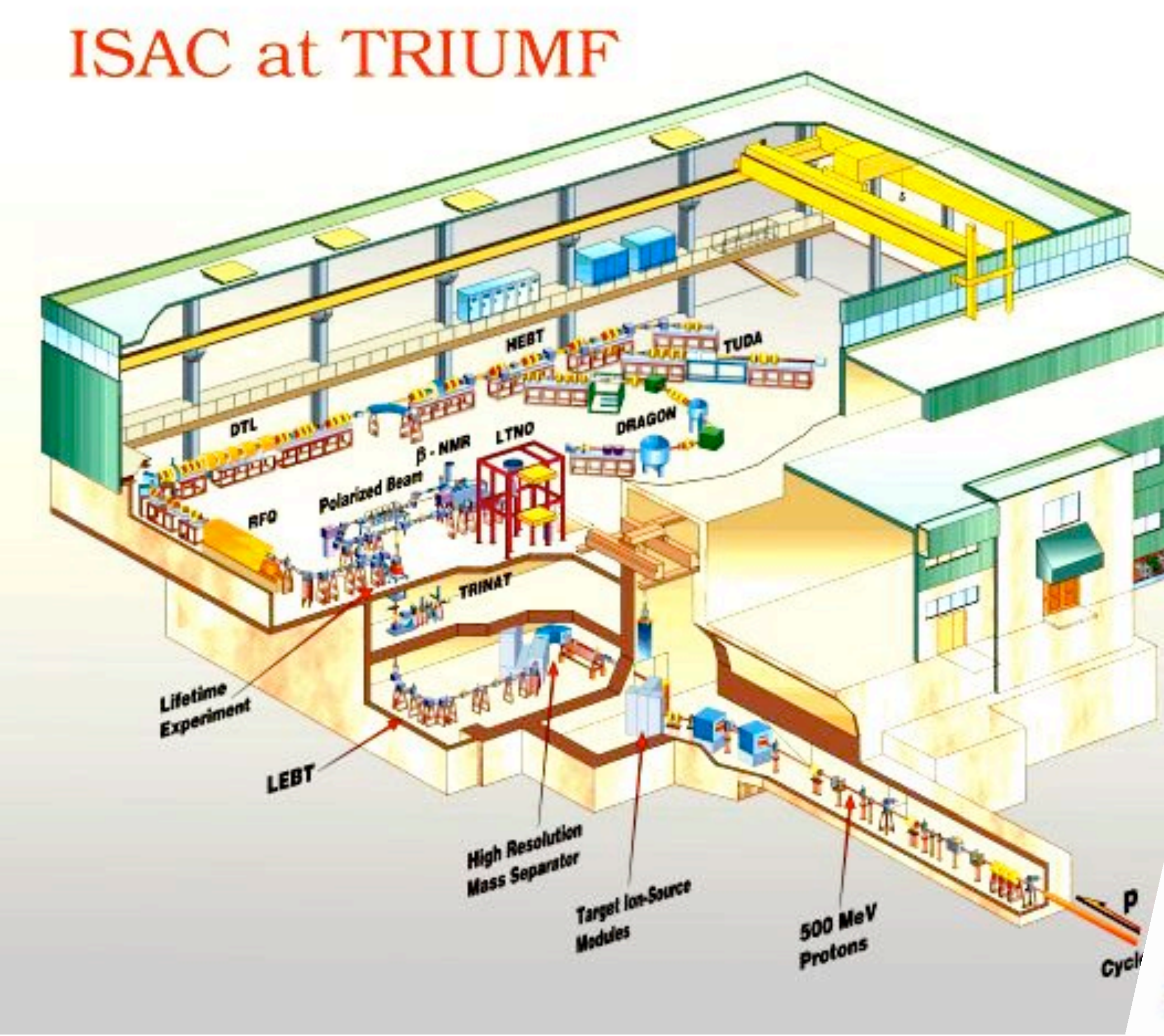






First tests planned for July 2006, move to TRIUMF March 2006

Production of radioactive isotopes @ ISAC/TRIUMF

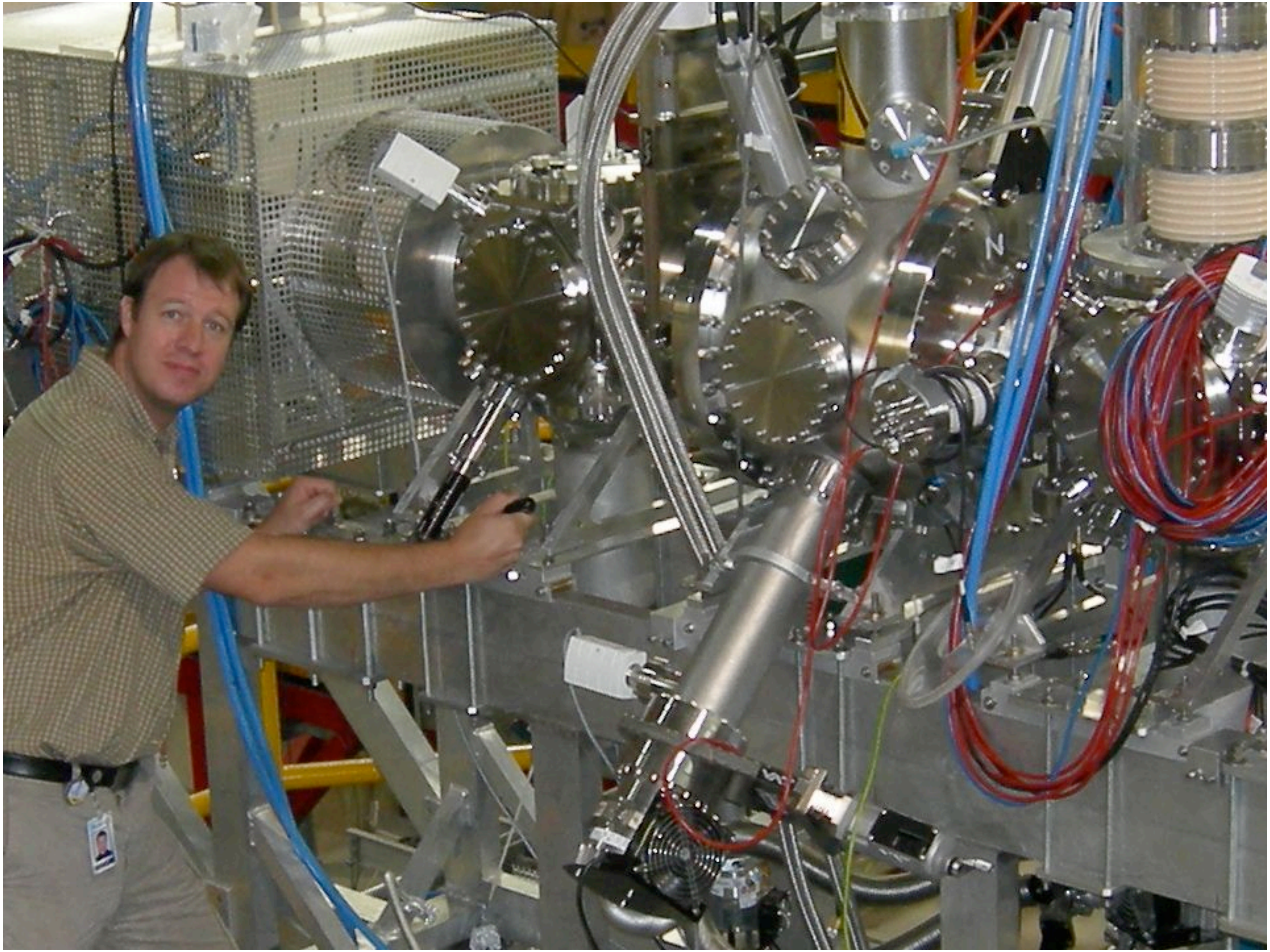


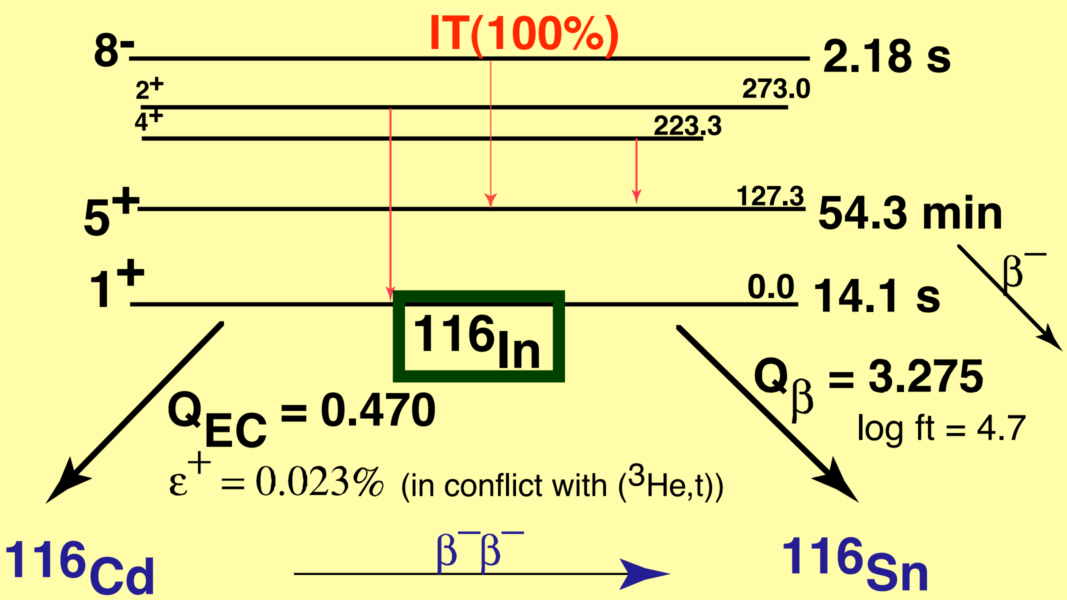
ISAC:
Highest yields for On-Line facilities, can go up to 100μA@500MeV DC proton

Ion-sources:

- Surface ☑
- Resonant-Laser source☑
- Negative, off-line test ☑
- ECR, on-line tests and checks ☑ (changes needed)
- Targets:
- High power target tested on-line and found proton beam to small! Improvements under-way ☑

- Actinide target task force: Plan to do tests 2006





Important measurements also because of the present conflicting experimental values.

8 – 100 hours depending on value of ε

MOON → 1t material
NEMO-3 → 7kg

solar ν detector
SUPERNOVA-detector
^{100}Mo(ν,e$^-$)^{100}Tc → β$^-$

---

90 hours/10% measurement

NEMO-3

$T_{1/2}(2\nu\beta\beta)$ = [9.6 § 0.3 § 1.0]¢ 10^{19} yr

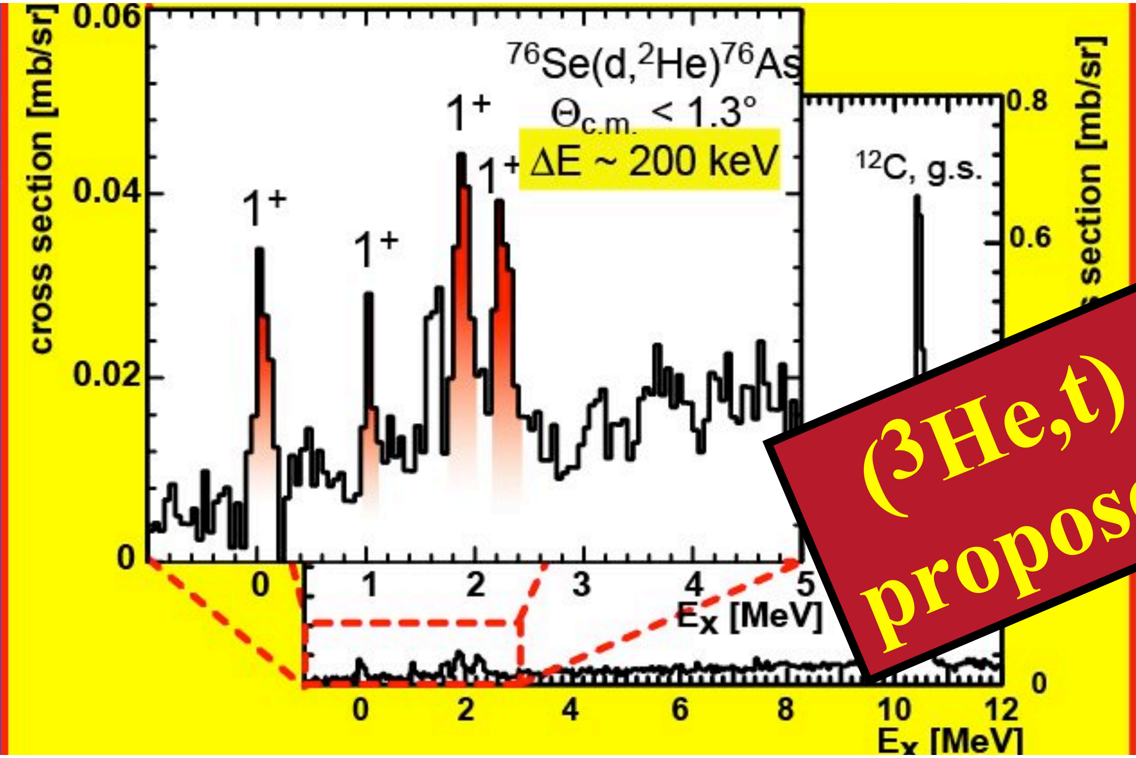
First time to measure EC ($2^{-} \longrightarrow 0^{+}$)
from an excited state but
a significant expmtl challenge!!

The most important case!!!

exp. log ft (β^-) = 9.7
if log ft (EC) ~ 9.5

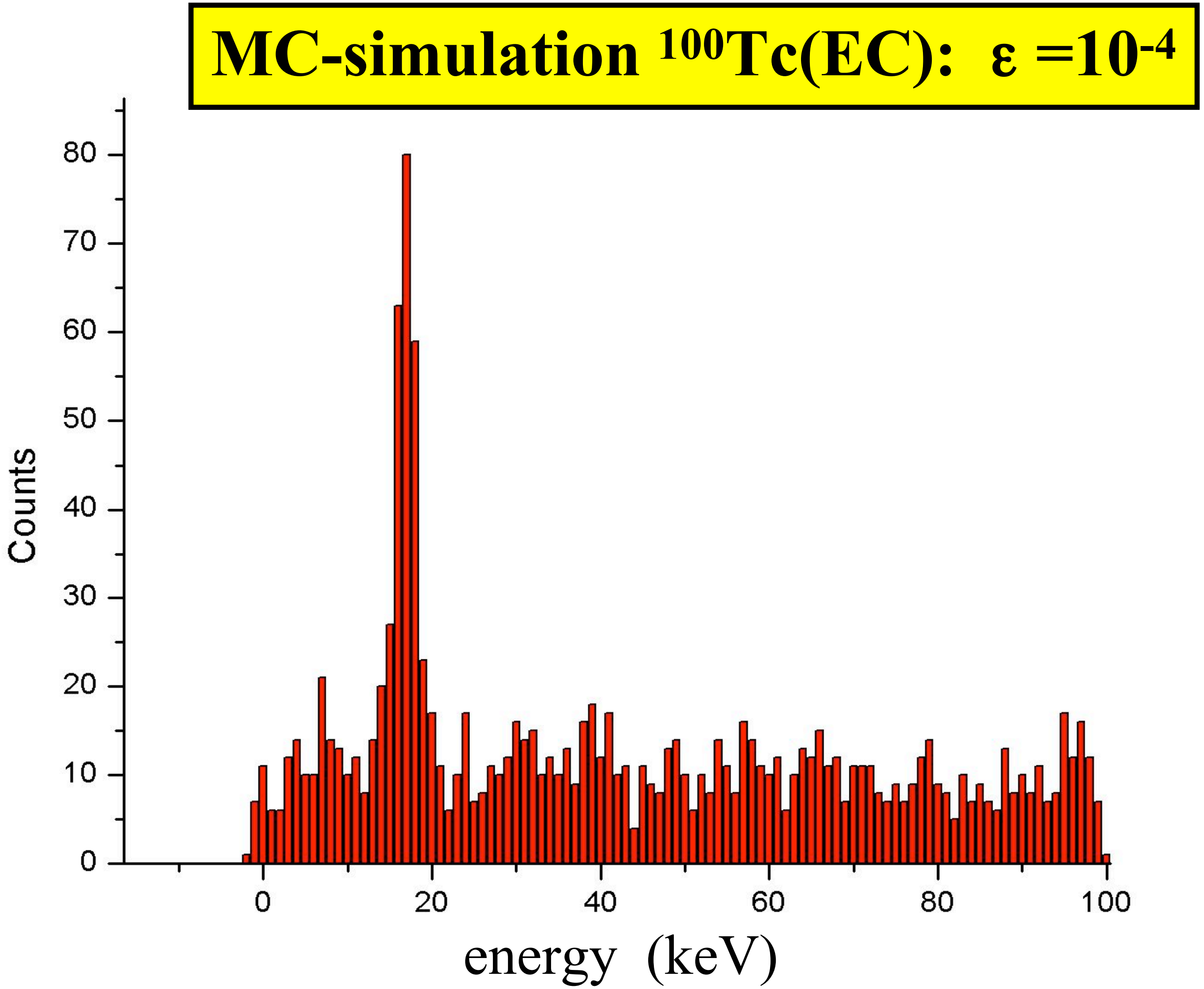
$\varepsilon = 10^{-5}$

Estimated measuring time:
10-20 days (long half-life!)



(^{3}He,t) expmt !!!
proposed at RCNP

X-ray spectrum (1 keV resolution)



Conclusion

1

Charge-exchange reactions for determining double-ββ decay matrix elements will be continuing
i.e. (d,^{2}He) for „GT^{+} leg"
and
(^{3}He,t) for the „GT^{-} leg" (at RCNP)

2

Radioactive beam facilites and ion traps can provide nice tools for getting information about the 0ν-ββ decay matrix elements

3

Theorists and expmt'lists alike should be encouraged to devise new methods to test matrix elements for 0ν-ββ decay

!

Tribute to

Prof. Ejiri