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TITAN EC

ββ-decay matrix elements:
Some surprises in nuclear physics

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

TRIUMF: ββ–decay and ion-traps

Charge-exchange reactions

- ^{48}Ca published data → (d,^{2}He) and (^{3}He,t)
- ^{64}Zn published data → (d,^{2}He) and (^{3}He,t)

Very new data from RCNP

- ^{76}Ge fully construct 2νββ-matrix element
- ^{82}Se one „leg“ of 2νββ-matrix element
- ^{96}Zr fully construct 2νββ-matrix element
- ^{100}Mo one „leg“ of 2νββ-matrix element
- ^{128,130}Te one „leg“ of 2νββ-matrix element

EC X-ray from radioisotopes in a trap

Double beta decay

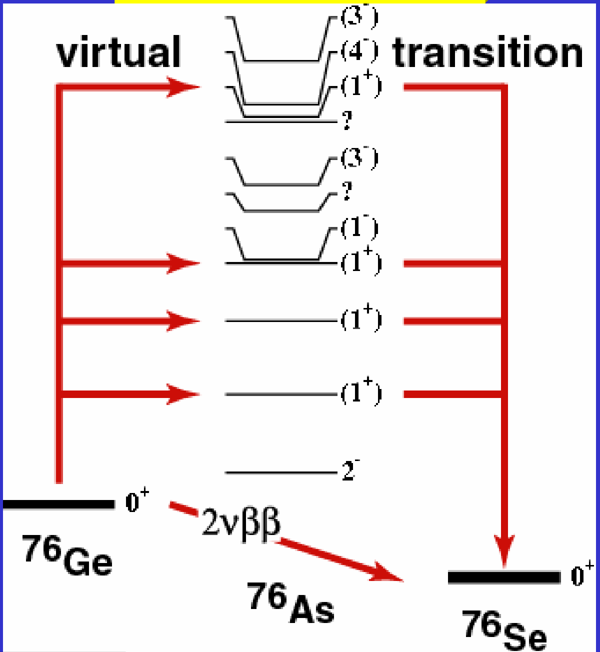
$2\nu\beta\beta$-**decay**

$0\nu\beta\beta$-**decay**

ββ decay

2νββ decay

allowed in SM and observed in many cases



!!!!

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

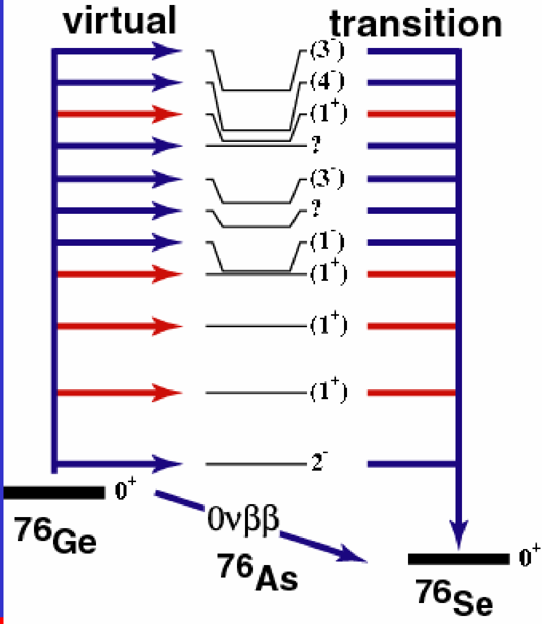
$$= G^{2\nu}(\mathrm{Q,Z}) \left|M^{(2\nu)}_{\mathrm{DGT}}\right|^2$$

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

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

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

ββ decay



0νββ decay

forbidden in MSM
lepton number violated
neutrino enters as virtual particle, → **q~0.5fm^{-1}**

mass of Majorana neutrino!!!

$$\Gamma^{0\nu}_{(\beta^-\beta^-)} = G^{0\nu}(\mathrm{Q,Z})\, g_A^4 \left| M^{(0\nu)}_{\mathrm{DGT}} - \left(\frac{g_V}{g_A}\right)^2 M^{(0\nu)}_{\mathrm{DF}} \right|^2 \left\langle m_{\nu_e} \right\rangle^2$$

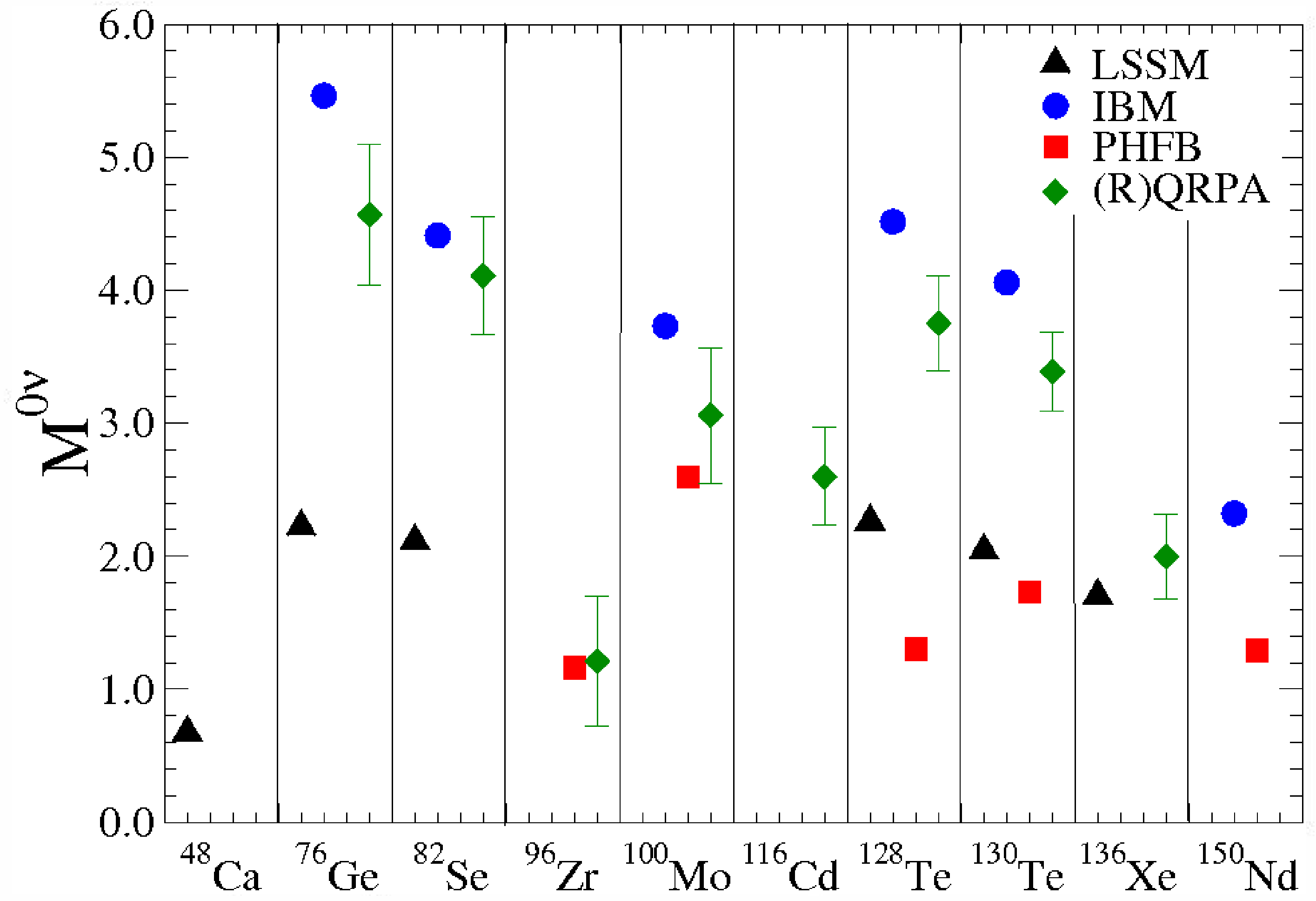
$$\Gamma^{0\nu}_{\beta^-\beta^-} = G^* \left| \sum_m \left\langle 0^{(f)}_{g.s.} \middle\| \mathcal{O}_{\sigma\tau^-}(r,S,L) \middle\| J^{\pi}_{m} \right\rangle \left\langle J^{\pi}_{m} \middle\| \mathcal{O}_{\sigma\tau^-}(r,S,L) \middle\| 0^{(i)}_{g.s.} \right\rangle + \mathrm{Fermi} \right|^2 \left\langle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

nucl. matrix element

NOT accessible thru
charge-exchange reactions

Neutrinoless Double Beta Decay Nuclear Matrix Elements

V.Rodin, A. Faessler, F. Šimkovic, P. Vogel, PRC 68 (2003) 044303;



- **The problem of 0ν-NME:**
  - there is little experimental support
  - the infamous parameter g_{pp}
  - the single decay properties (β^-, EC) cannot be described consistently
  - the g.s. nuclear wave function is not correct

The 2νββ decay NME is the testing ground for nuclear models

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

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

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

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

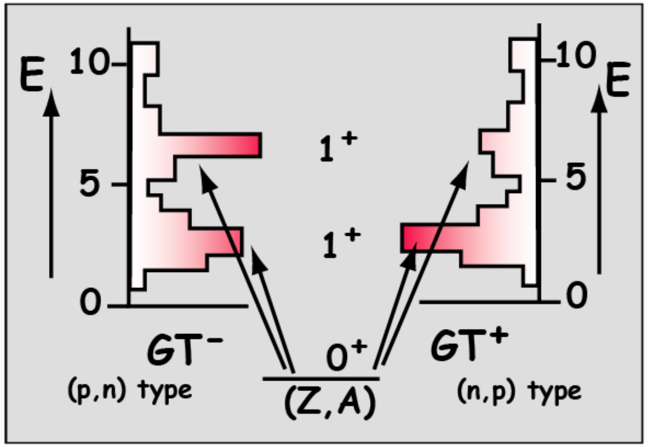
Measure B(GT⁻) through (p,n)-type reactions

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

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



Q: How to connect the weak $\vec{\sigma}\tau$ GT operator with hadronic reactions?

A: at intermediate energies exploit the dominance of $V_{\sigma\tau}$ interaction.

$$M(GT) = \langle 1^+ \| \sigma\tau^{\pm} \| 0^{i}_{g.s.} \rangle$$

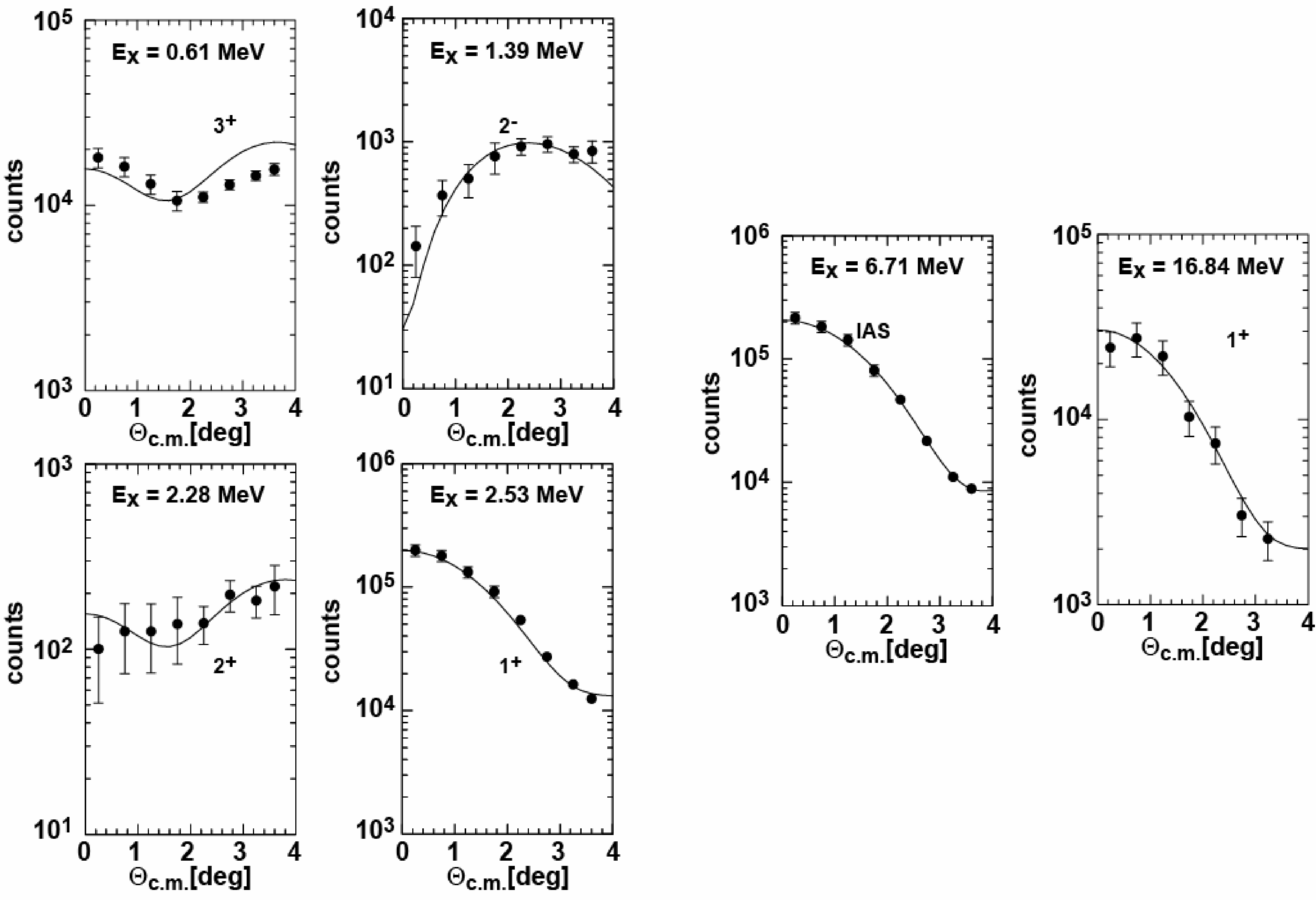
$$B(GT) = \frac{1}{2J_i+1} \, | M(GT) |^2$$

hadronic probes: (n,p), (d,^{2}He), (t,^{3}He)

or (p,n), (^{3}He,t)

$$\left[\frac{d\sigma}{d\Omega} \right] = \left[\frac{\mu}{\pi\hbar^2} \right]^2 \frac{k_f}{k_i} N_d \, \underbrace{|V_{\sigma\tau}|^2}_{\text{largest at 100 - 200 MeV/A}} \, |\langle f \,|\, \sigma\tau \,|\, i \rangle|^2$$

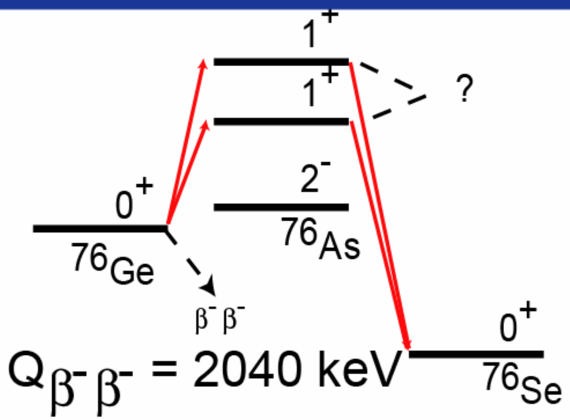
$^{48}Ca(^3He,t)$ angular distribution (examples)



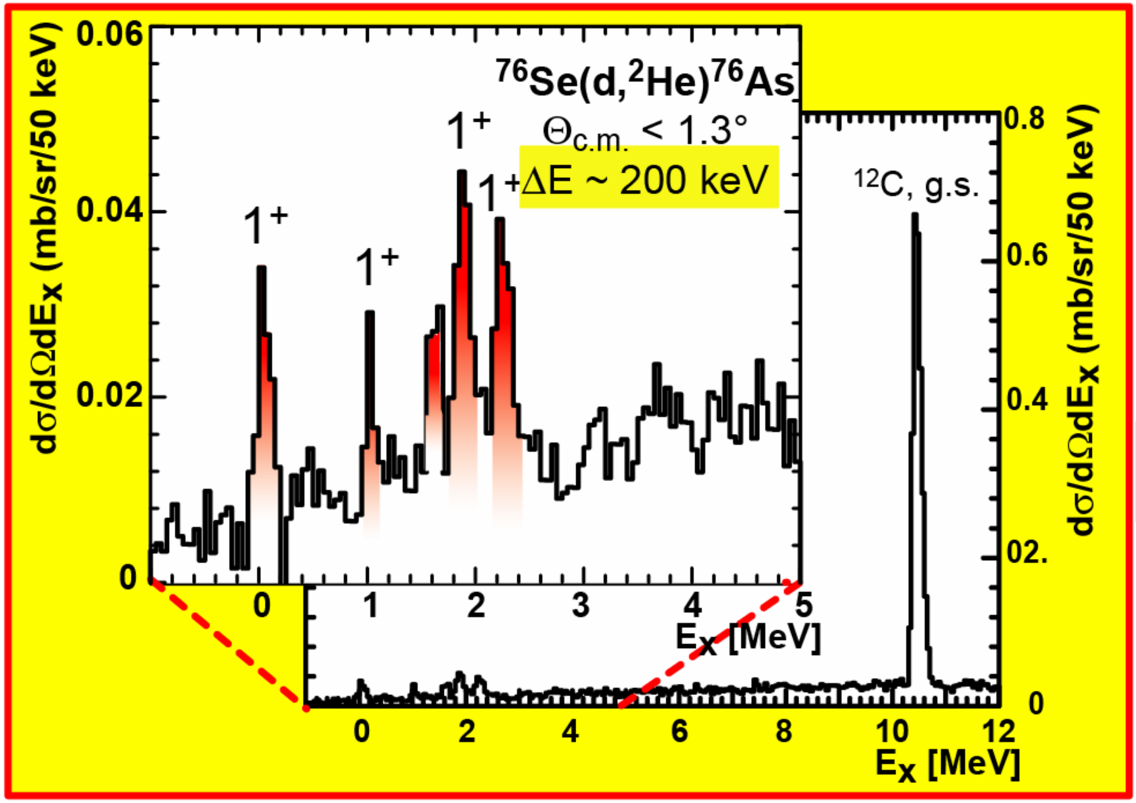
^{76}Ge

the most important
ββ-decaying nucleus

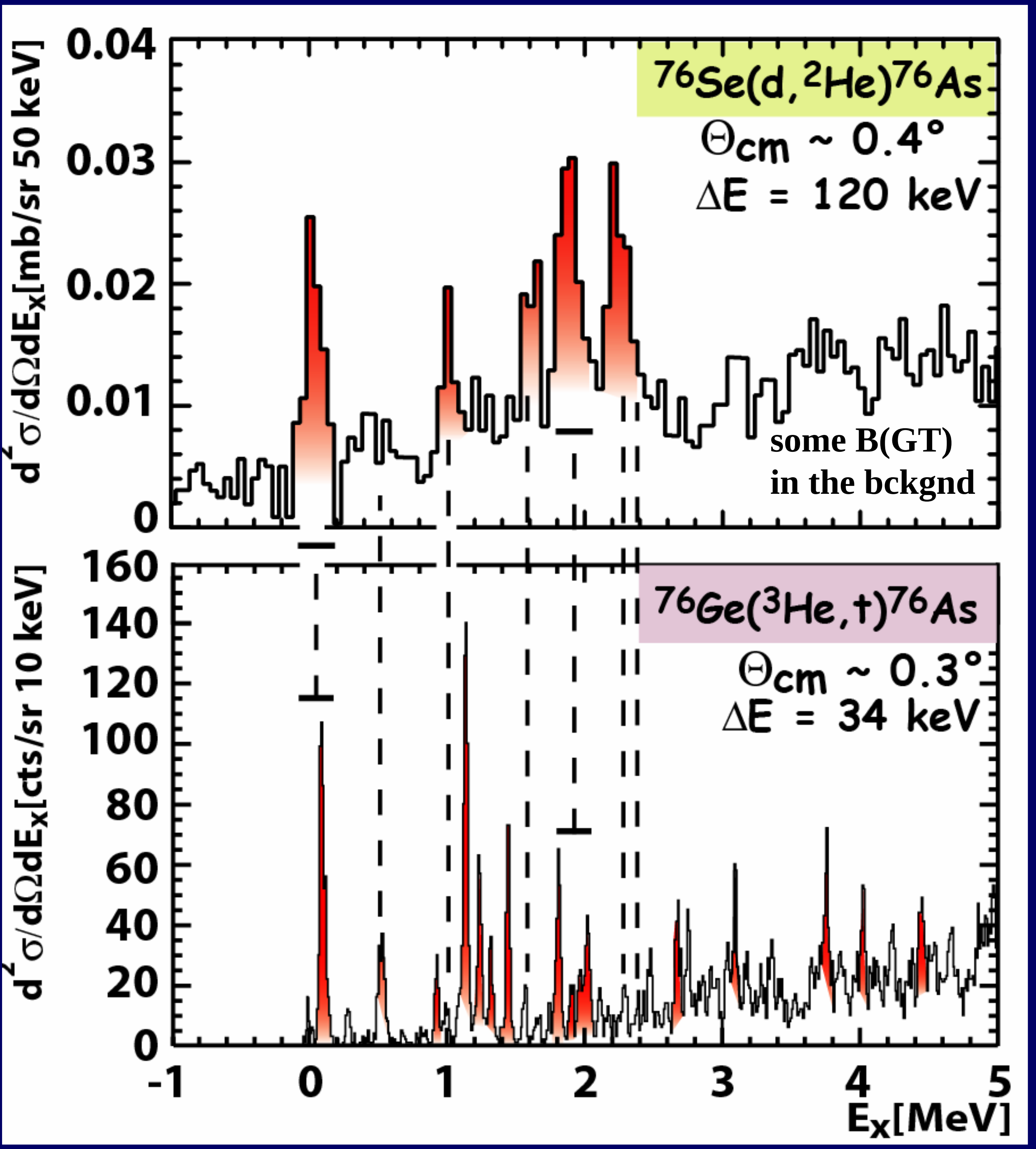
^{76}Ge ββ ^{76}Se



^{76}Se(d,^{2}He)^{76}As



Σ B(GT$^+$) ~ 0.54



some B(GT) in the bckgnd

Again!!

an anticorrelation of strength

(very similar to ^{48}Ca)

! ! ! ! ! ! !

An effect of the difference of deformation ??

^{76}Se:

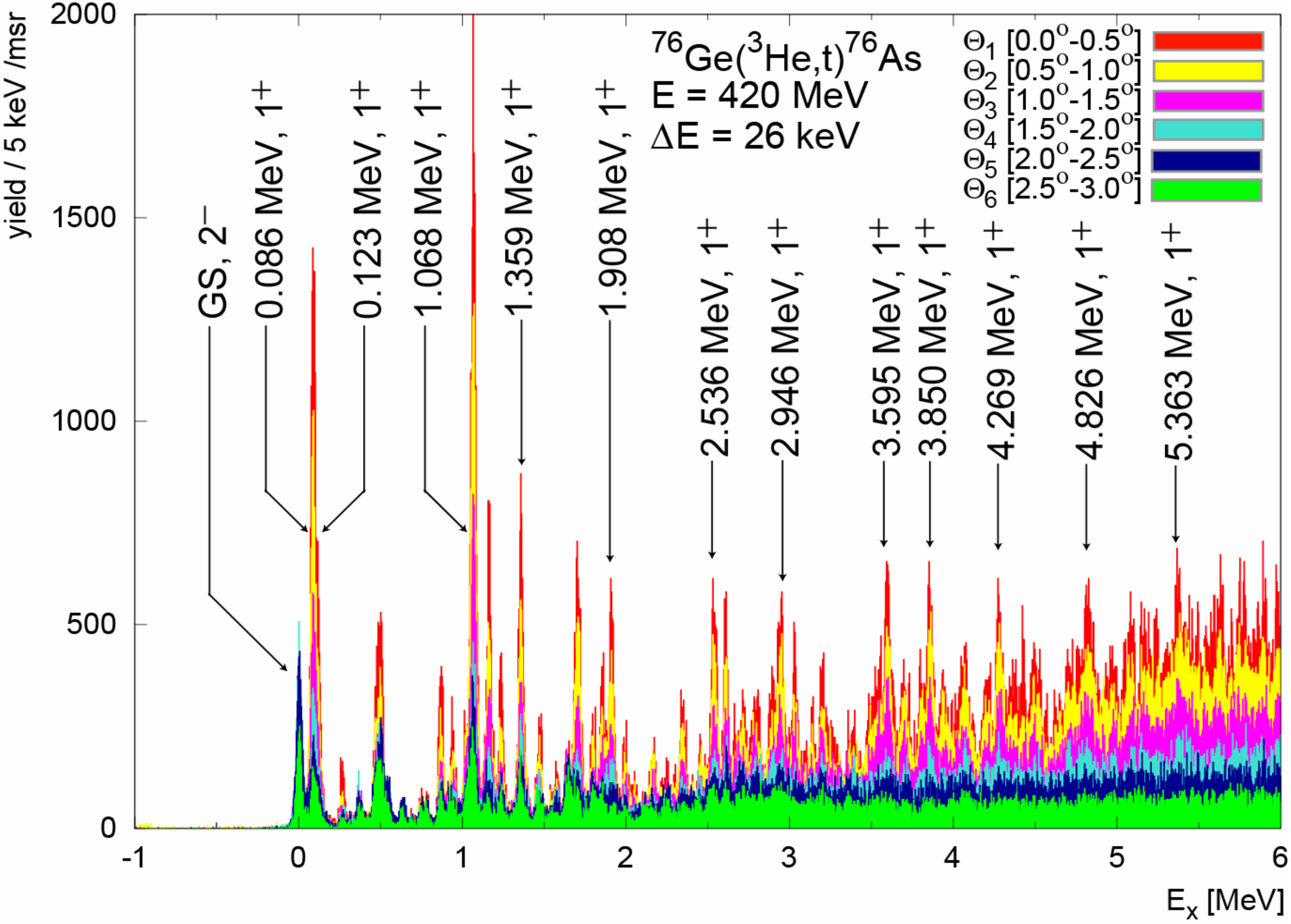
oblate

(β_2 ~ –0.2)

^{76}Ge:

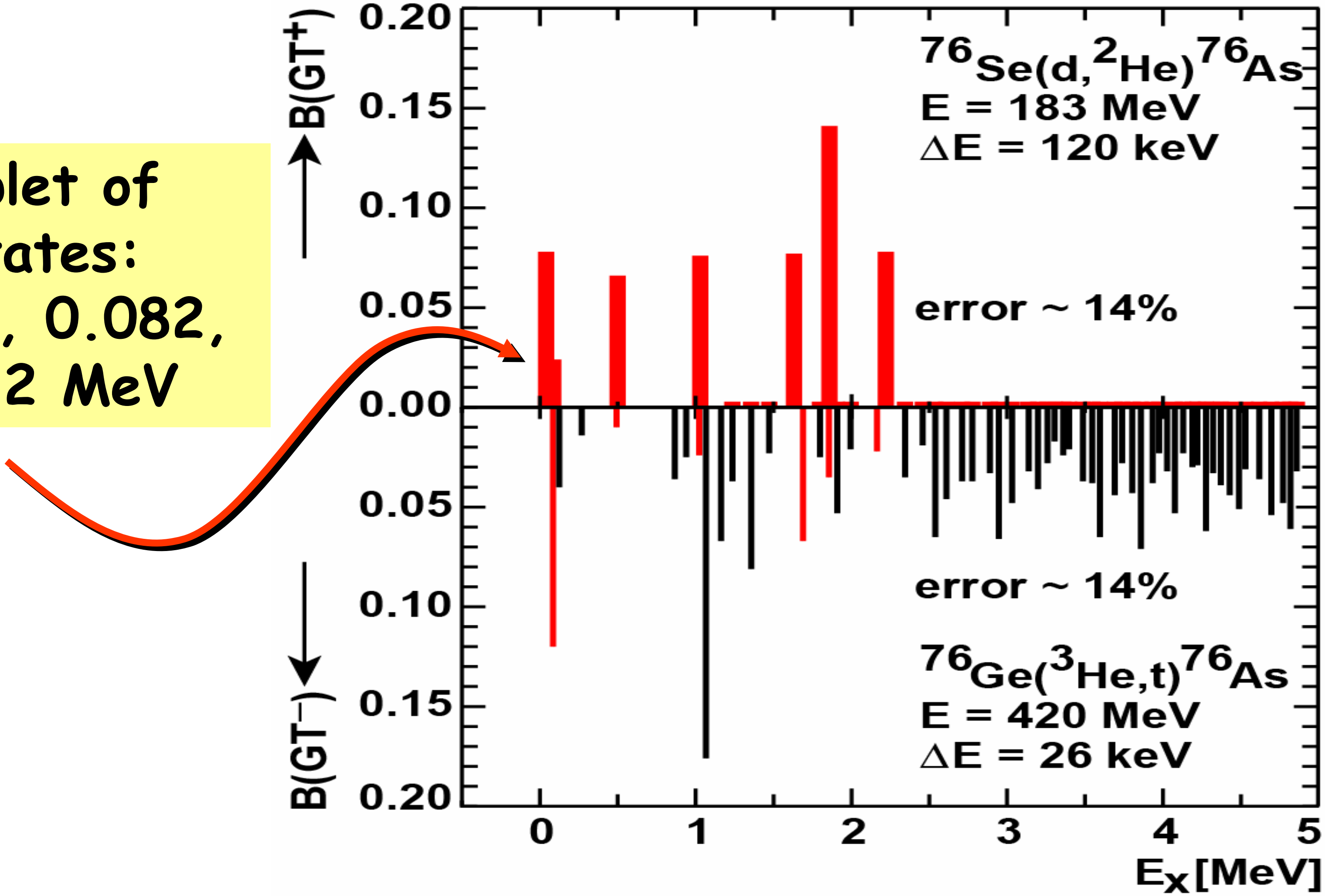
moderately oblate/ prolate

(β_2 ~ 0.1)

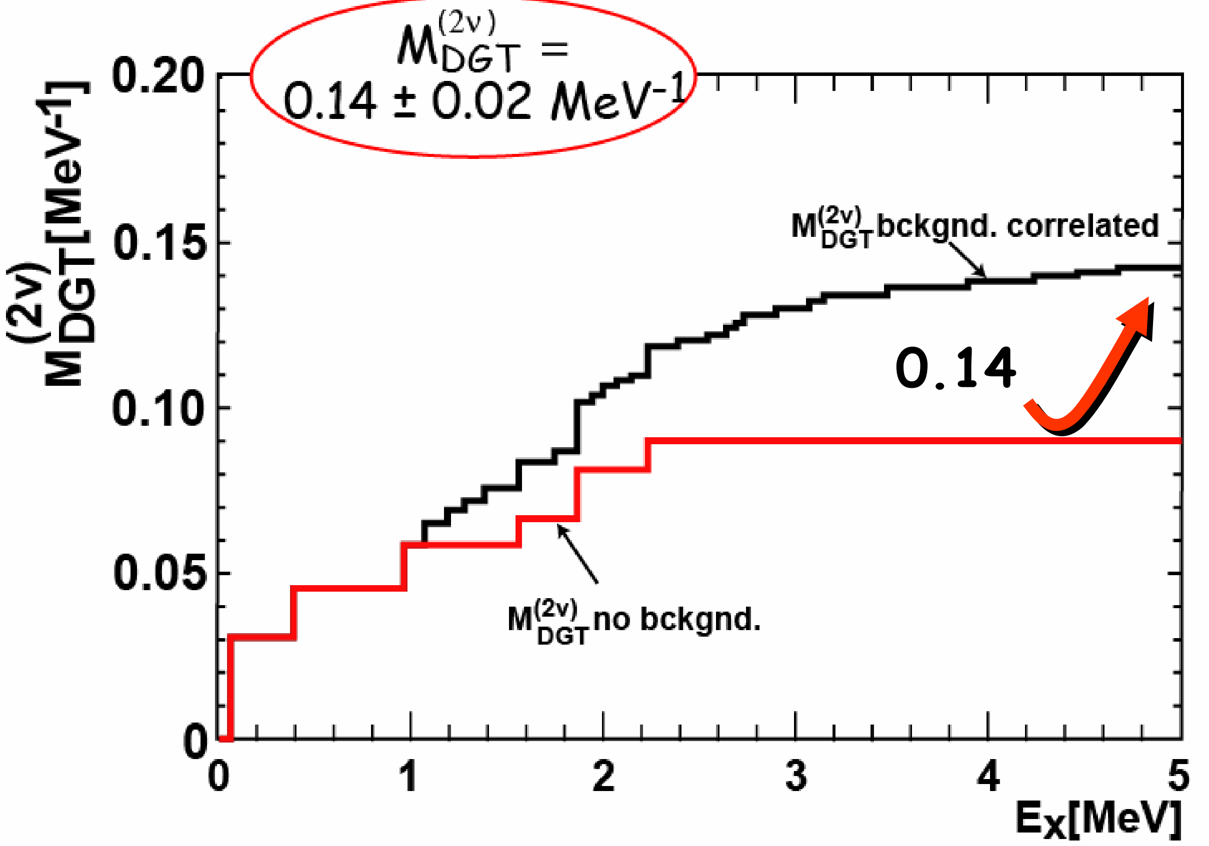


about 60 !! individual levels up to 5 MeV !!!

triplet of states: 0.044, 0.082, 0.12 MeV



Correlate states within the expmtl resolution



Correlated states make up 55% of 2νββ-ME

M_{DGT} =0.09 MeV^{-1}

Adding correlation with undifferentiated bckgnd makes up ~100% of 2νββ-ME

M_{DGT} = 0.14 ± 0. 02 MeV^{-1}

$T_{1/2}$ = (1.5 ± 0.4) x 10^{21} yr

^{96}Zr

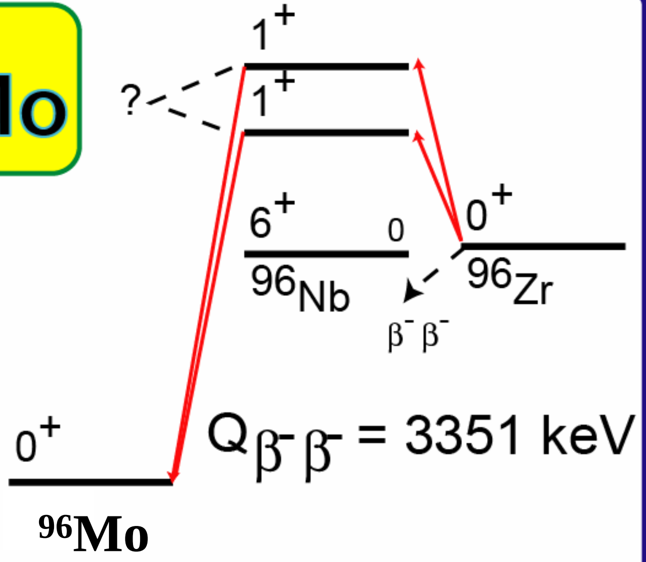
the most neutron-rich
Zr-isotope N-Z=16

first

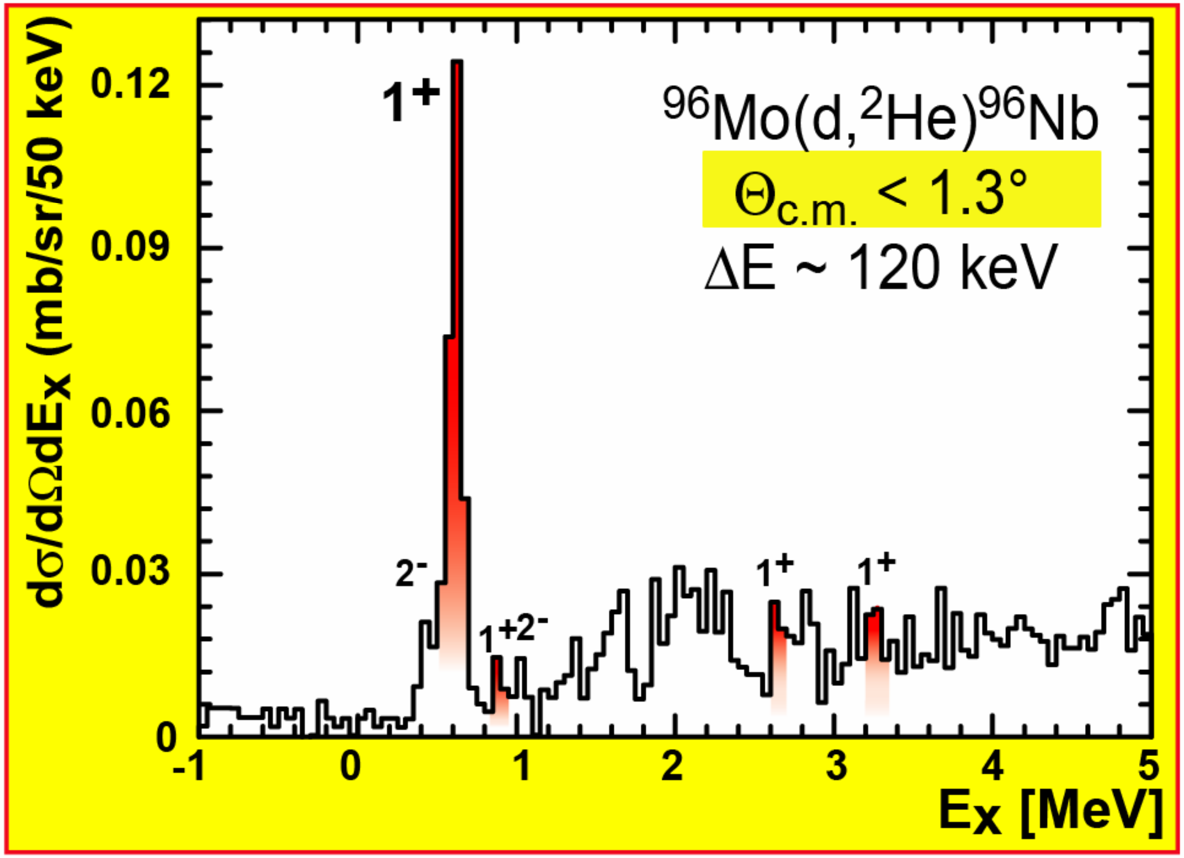
$^{96}Mo(d,{}^{2}He)^{96}Nb$

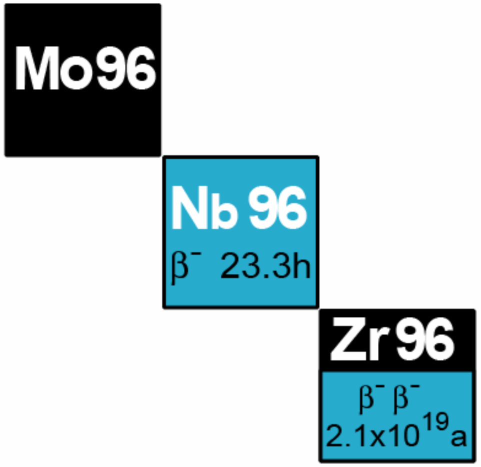
(testing β^- branch)

^{96}Zr - ^{96}Nb - ^{96}Mo

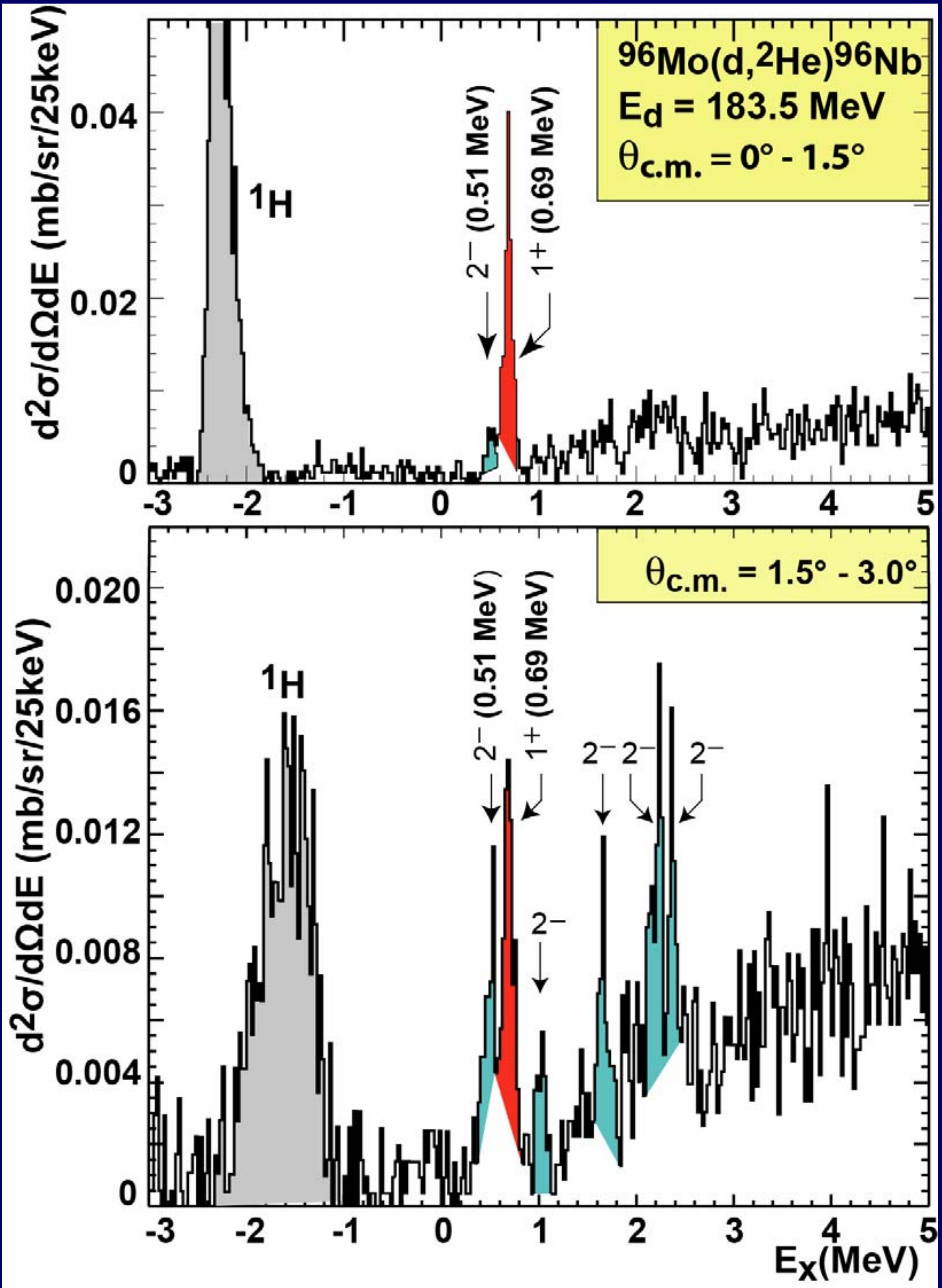


One transition only !!!





B(GT$^+$) ~ 0.3



zero-degree spectrum

only one 1^+ state visibile

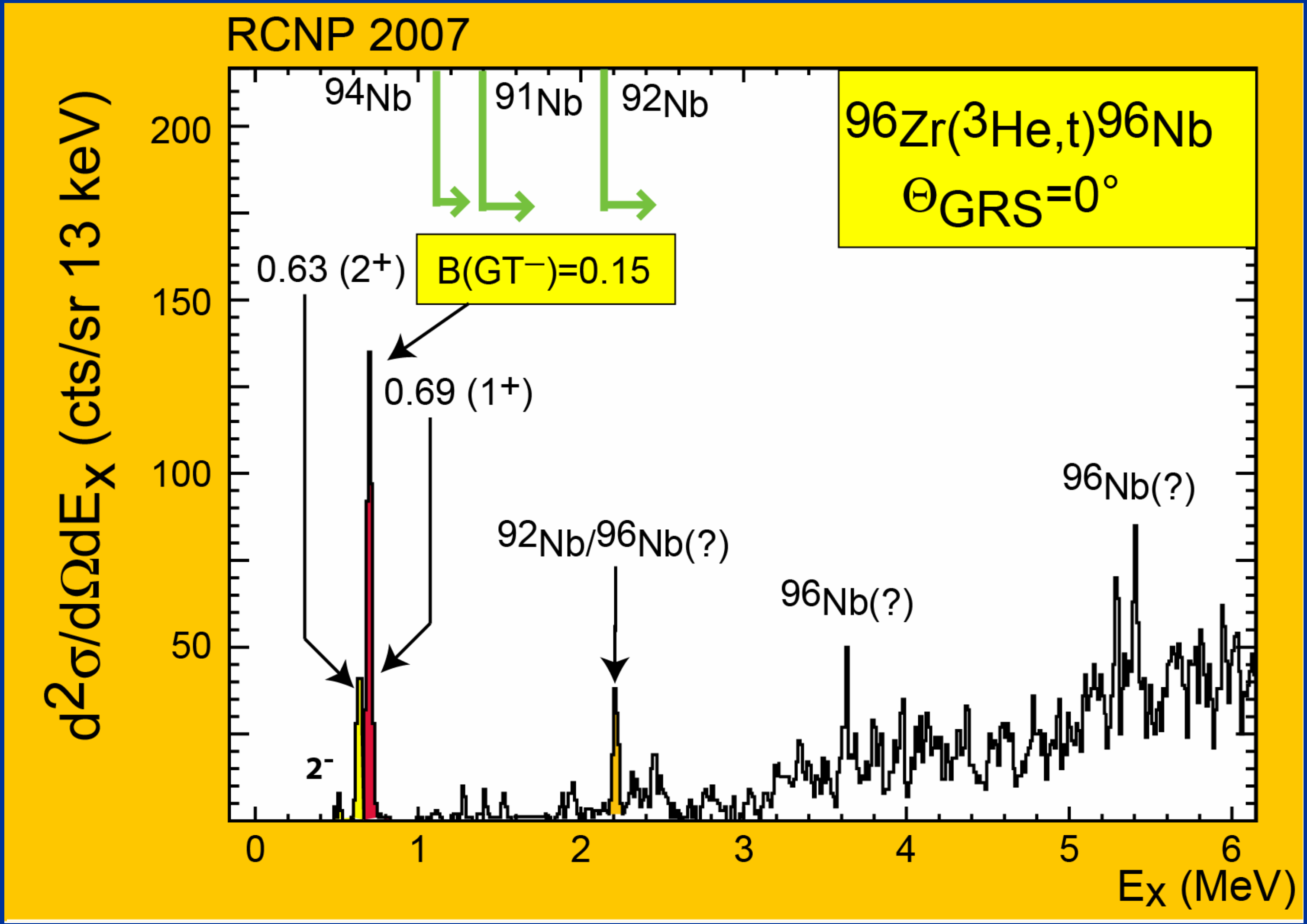
finite-degree spectrum $(\langle \Theta_{cm} \rangle \sim 2^\circ)$

2^- states quickly become visibile

second

^{96}Zr(^{3}He,t)^{96}Nb

(testing β^{+} branch)

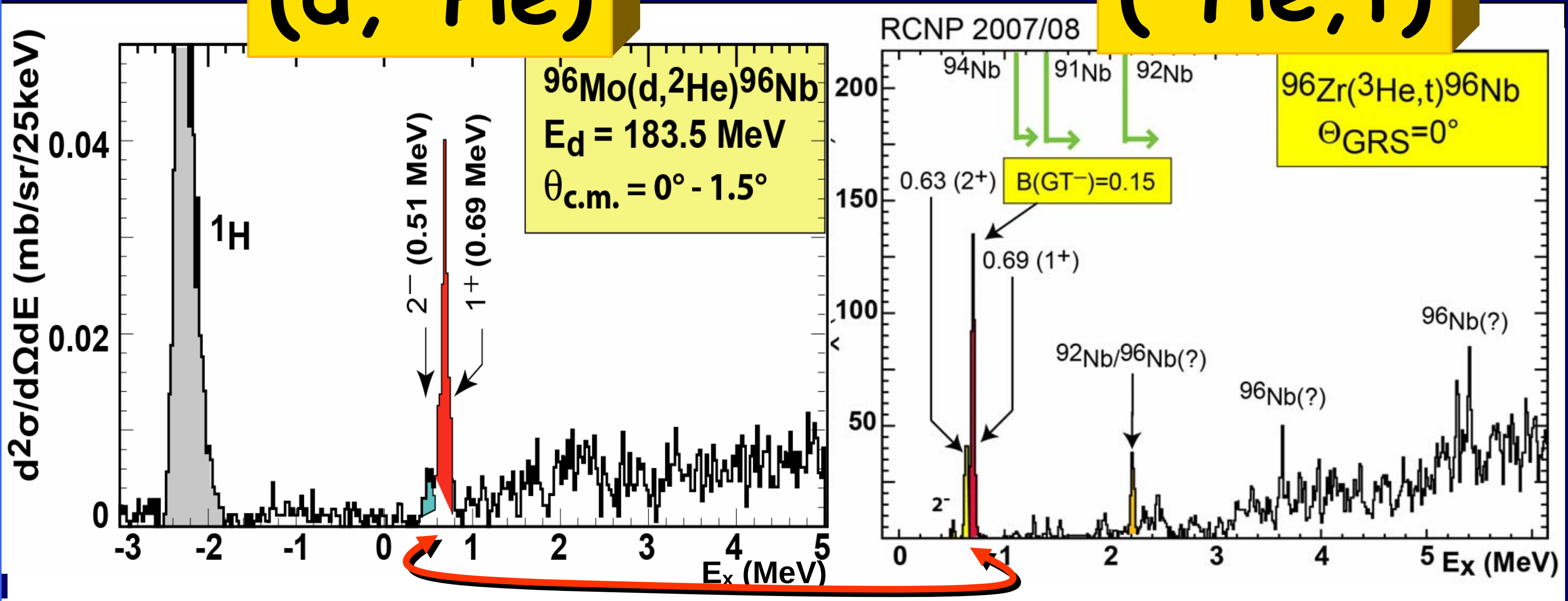


In (p,n) direction:

1 - exceptionally small B(GT$^-$) below 6 MeV

2 - concentrated in one low-lying level only

(d,²He) **(³He,t)**



$B(GT^{+}) = 0.3$

$B(GT^{-}) = 0.15$

Fascination: With this 1 level only:

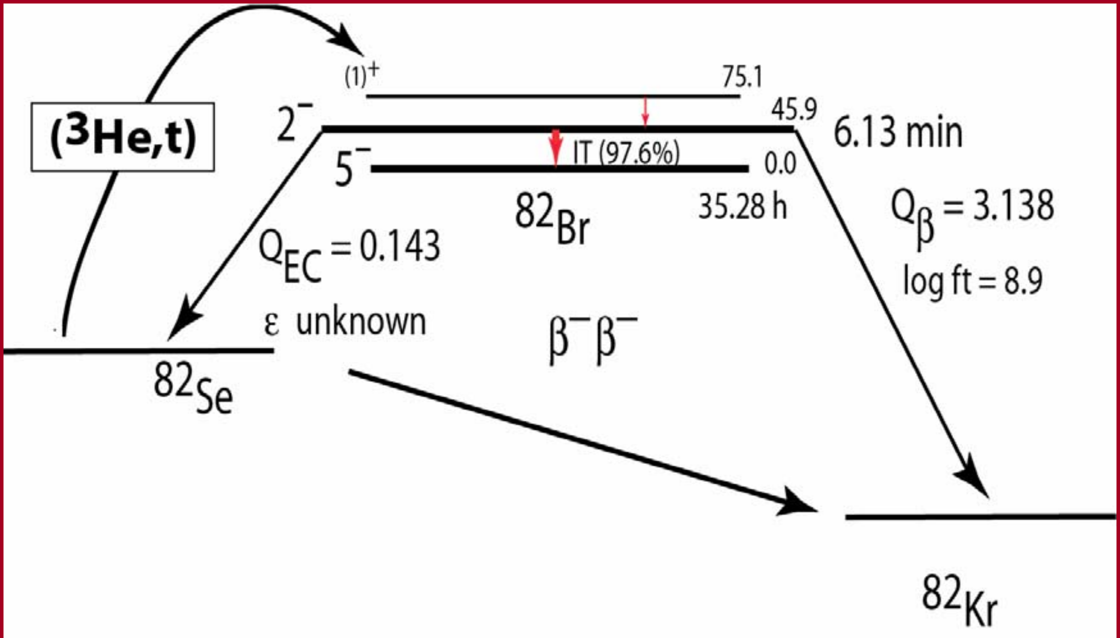
$$T_{1/2}^{calc.}(2\nu\beta\beta) = (2.4 \pm 0.3)\cdot 10^{19}\ \text{years}$$

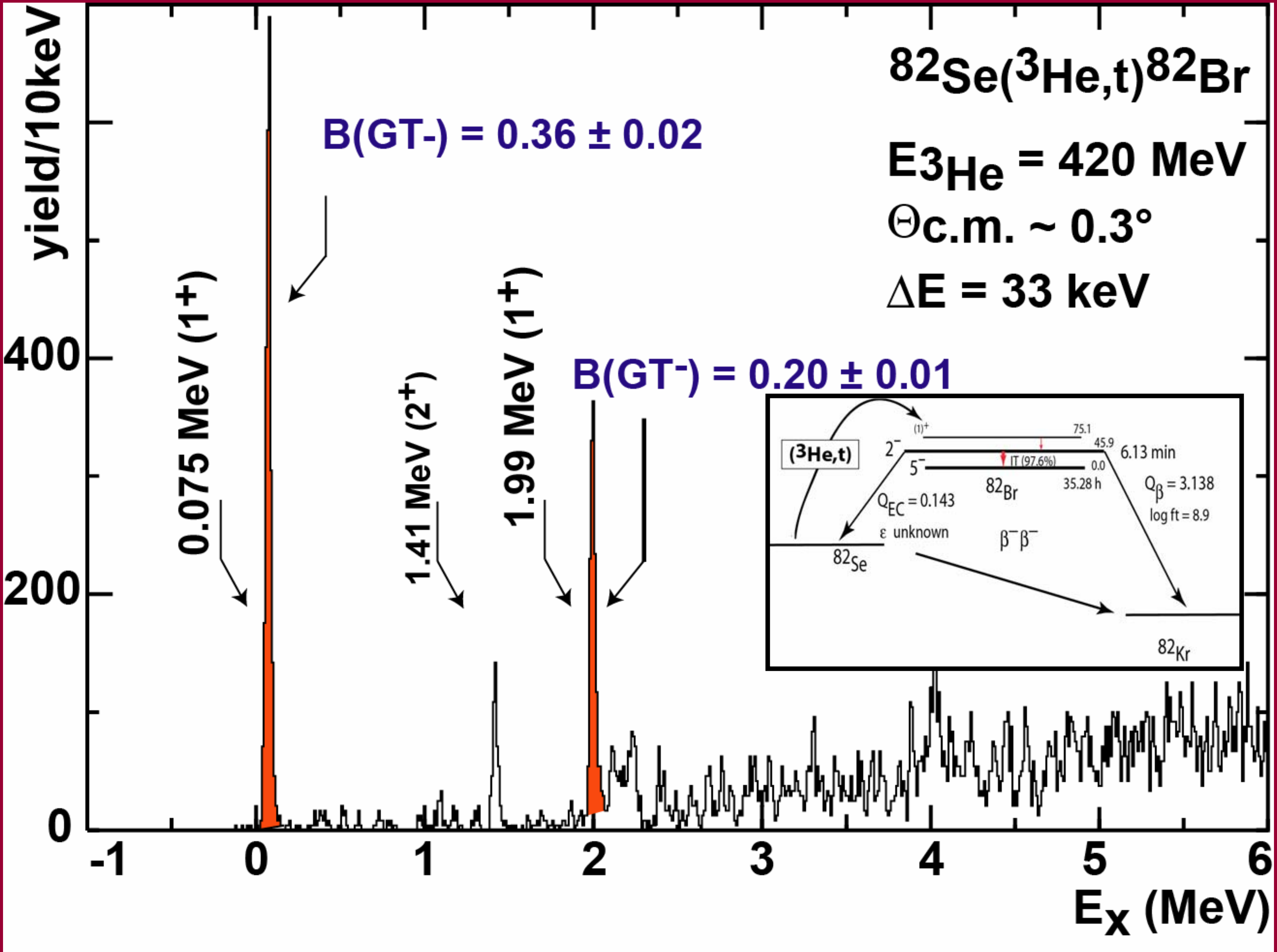
$$T_{1/2}^{exp.}(2\nu\beta\beta = (2.2 \pm 0.4)\cdot 10^{19}\ \text{years}\ \ \text{(NEMO3-result)}$$

^{82}Se

2νββ half-life recently measured
$T_{1/2} = 9.6 \pm 1.0 \times 10^{19}$ y
by NEMO-3

Phys Rev Lett 95, 182302 (2005)

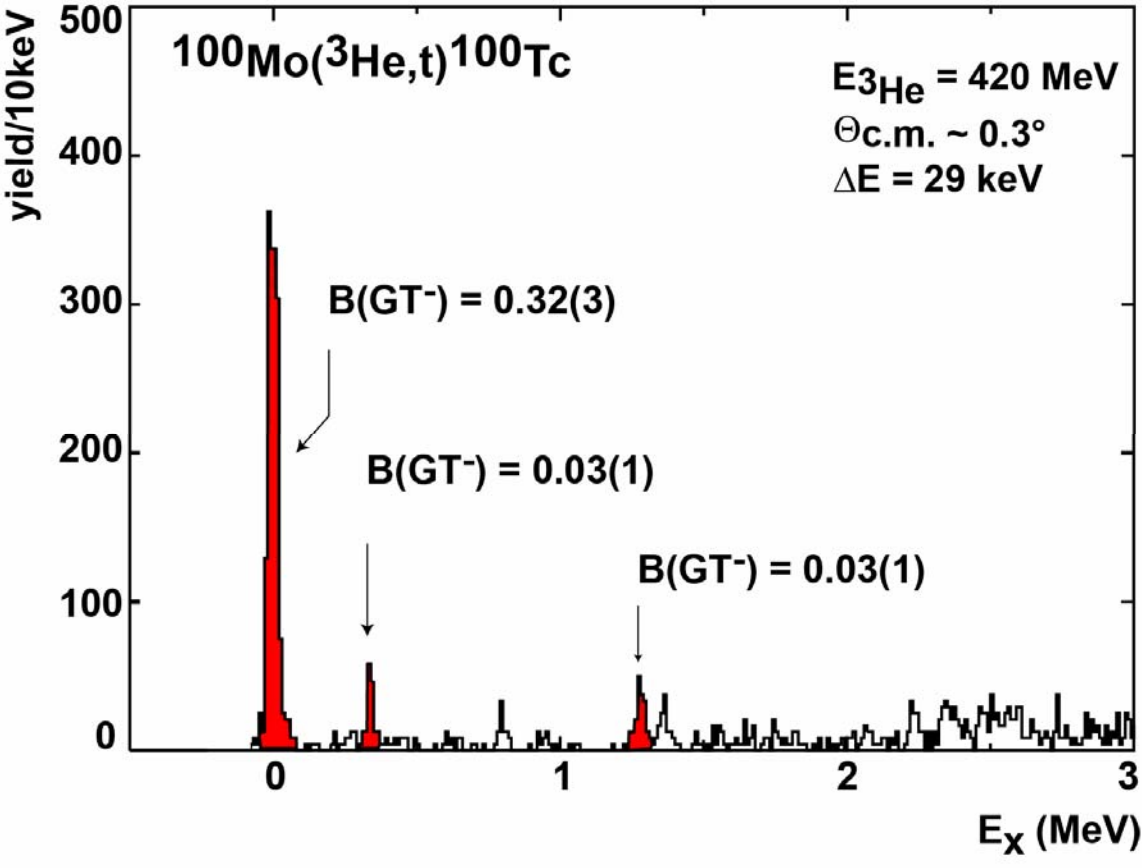


$^{82}Se(^3He,t)^{82}Br$
$E_{^3He}$ = 420 MeV
Θc.m. ~ 0.3°
ΔE = 33 keV
B(GT-) = 0.36 ± 0.02
B(GT$^-$) = 0.20 ± 0.01
0.075 MeV (1+)
1.41 MeV (2+)
1.99 MeV (1+)
yield/10keV
400
200
0
-1
0
1
2
3
4
5
6
E_x (MeV)
(^{3}He,t)
(1)+
75.1
2−
45.9
6.13 min
5−
IT (97.6%)
0.0
^{82}Br
35.28 h
Q_{EC} = 0.143
ε unknown
$\beta^-\beta^-$
Q_β = 3.138
log ft = 8.9
^{82}Se
^{82}Kr

^{100}Mo

Important for
$\beta\beta$-decay
solar neutrino detector
(Q=-168 keV)

SN-neutrino detector
SN-neutrino temperature



entire low-energy GT- strength is concentrated in ONE single state only, i.e. the ground state.

GOOD!!! for SN-ν temperature meas'nt

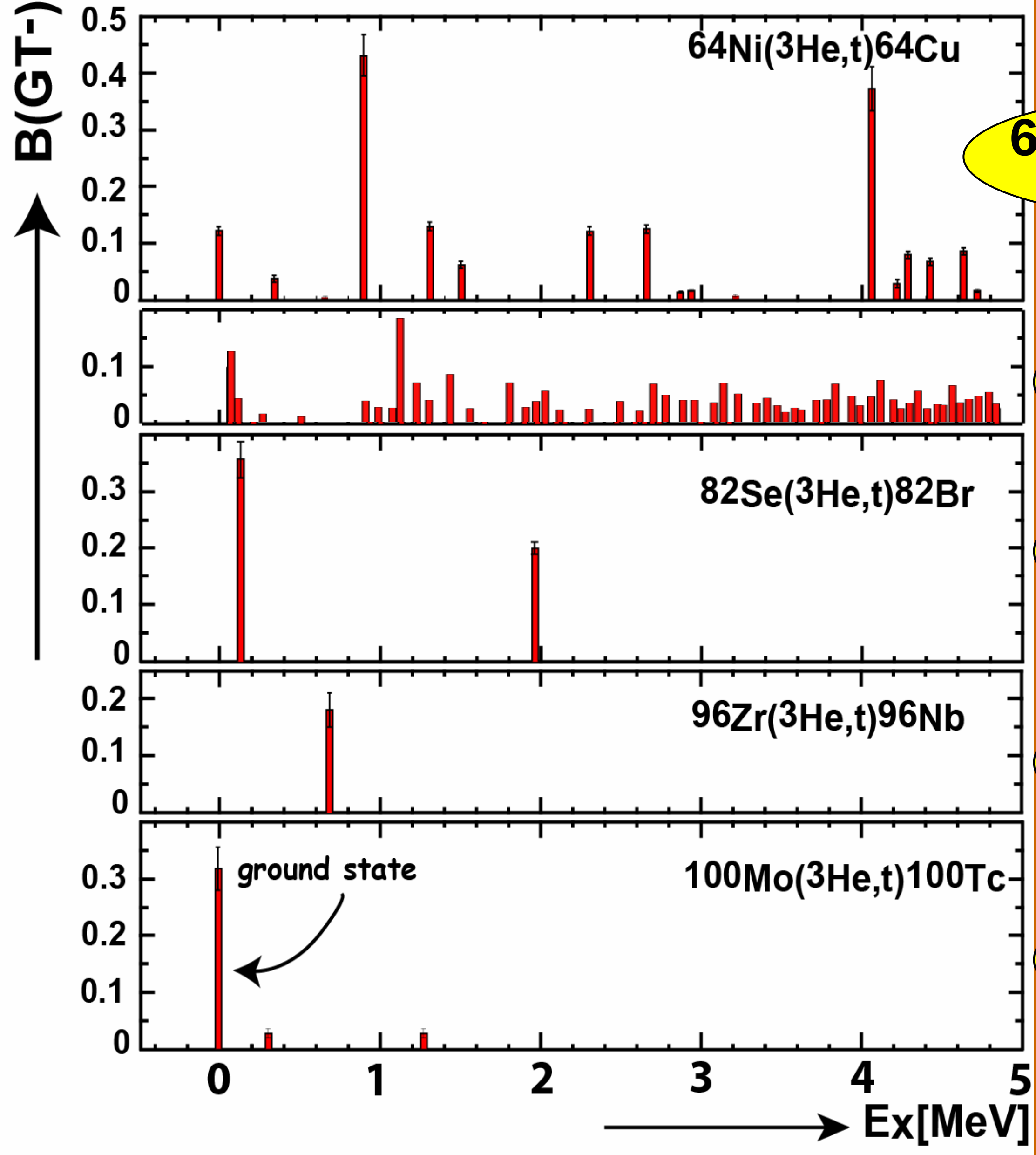
B(GT) =0.32 → logft (EC) = 4.54

In perfect agreement with Ejiri et al. (1998):

B(GT) = 0.33

At variance with recent direct measurement by Garcia:

B(GT) = 0.6 → logft (EC) = 4.3



^{64}Zn(εε, εβ+)

^{76}Ge(β-β-)

^{82}Se(β-β-)

^{96}Zr(β-β-)

^{100}Mo(β-β-)

reduced spreading of GT strength

In all cases:
the ME‘s up to ~5 MeV make up the relevant ME for the 2ν decay

Westfälische
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TRIUMF

TITAN-EC

Double-beta decay and ion traps

Electron capture branching ratios for the odd-odd intermediate nuclei in ββ decay using TITAN-trap

- **Objectives:**
  - experimental determination of nuclear matrix elements for 2νββ decay and 0νββ decay
  - test theory and improve theoretical prediction
  - allow more reliable extraction of Majorana neutrino mass from 0νββ 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

Theoretical situation

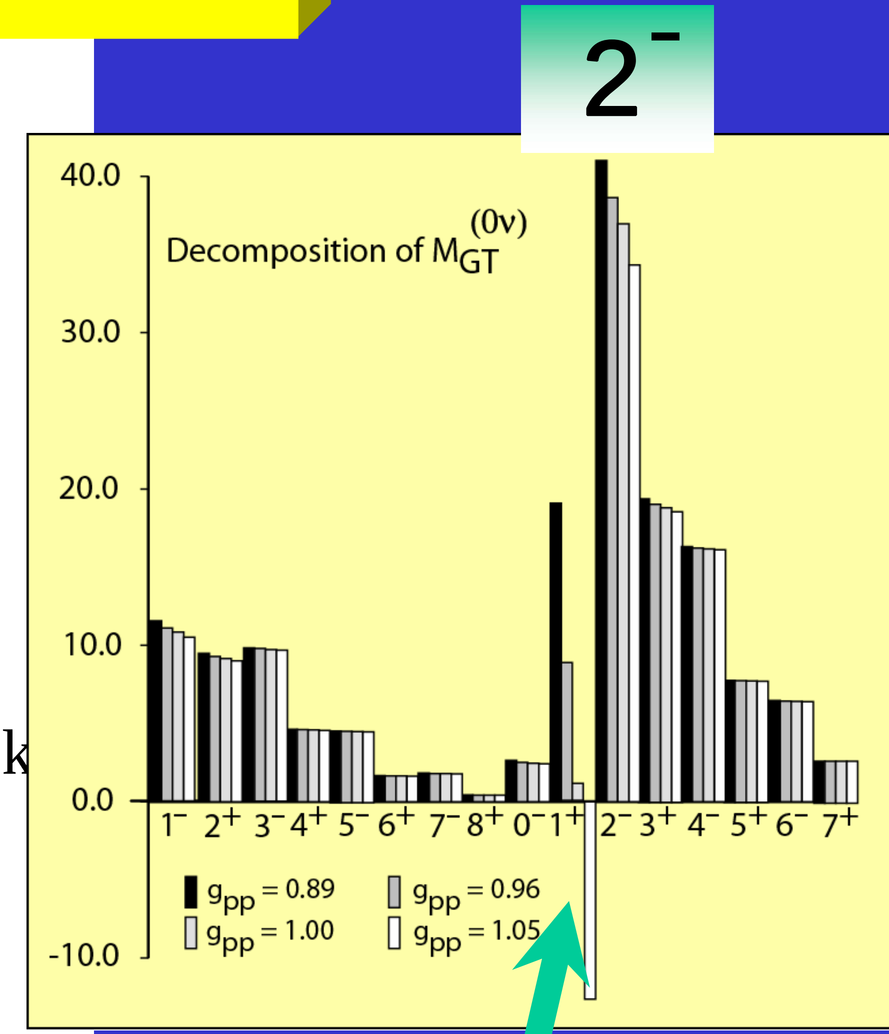
Theory claims:

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} ~1)

BUT

1. there are no intermediate cross check 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!!



sensitivity to 1+ excitations

Recent critical assessment of the theoretical situation

example

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

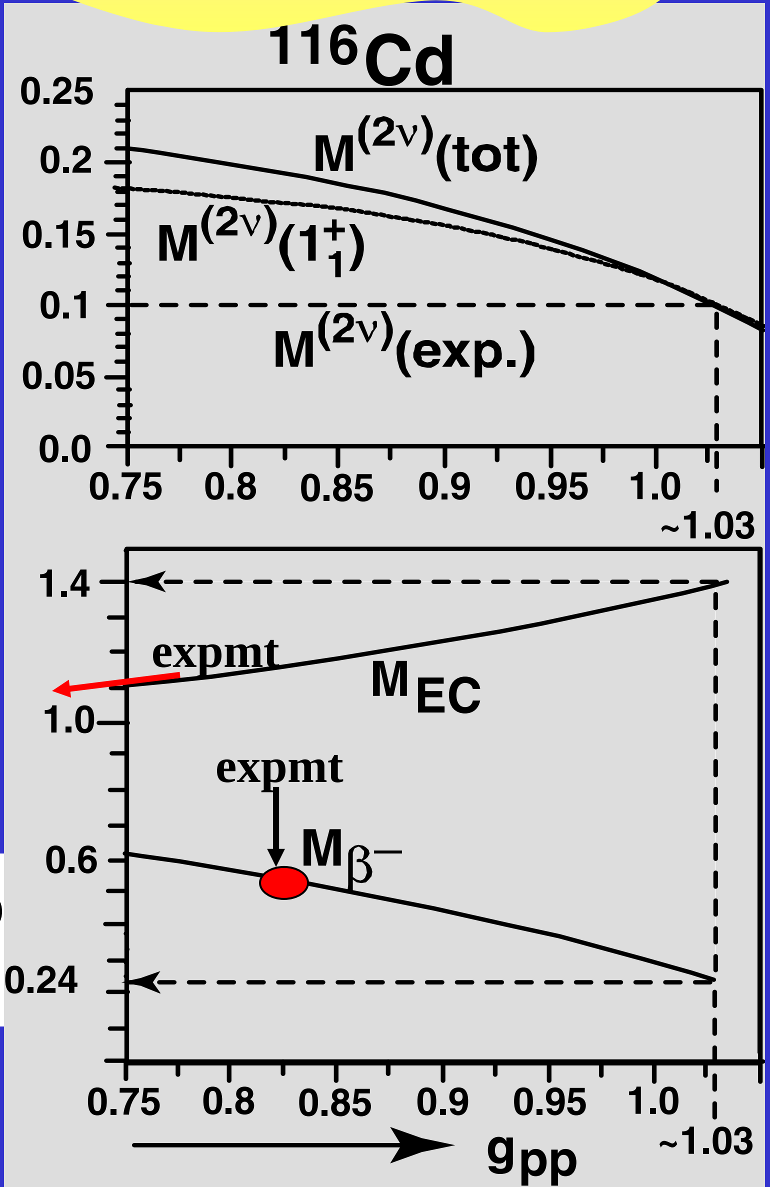
(if EC is known)!

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% *log ft* = 3.77 theo

$M_{EC} = 0.51$ ε = 0.013% *log ft* = 4.6 exp



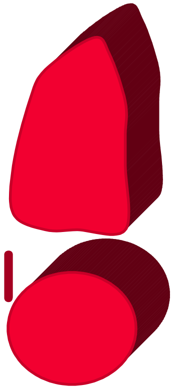
Summarizing the theory

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).

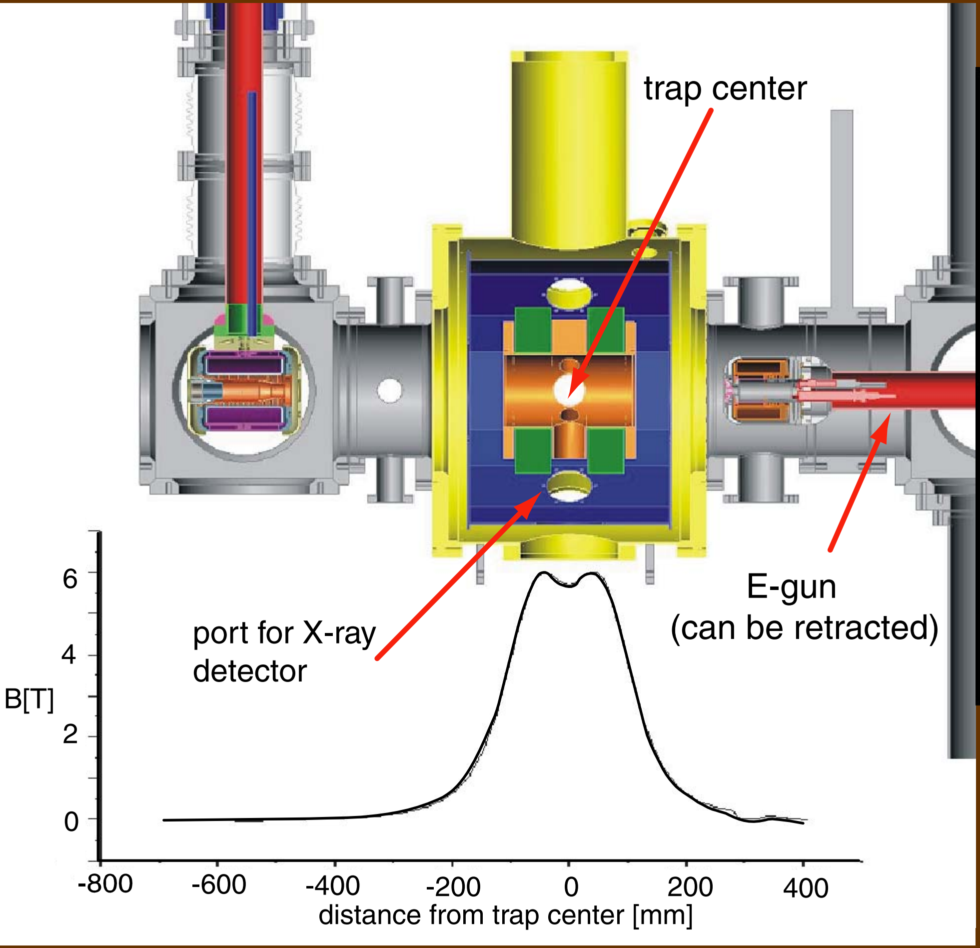
Discrepancies of 1 – 2 orders of magnitude are possible

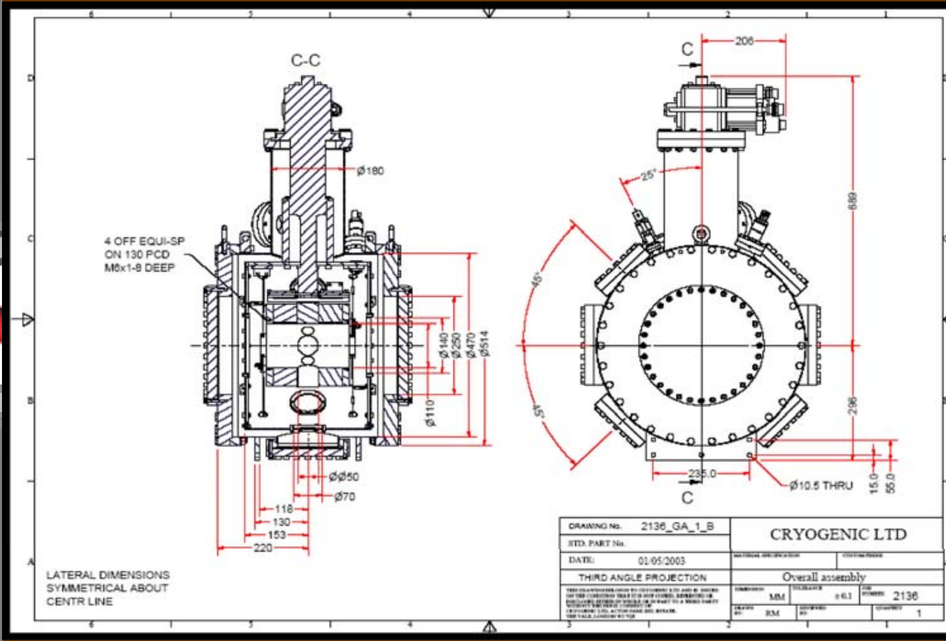
The loose end:

EC rates are badly known, or not known at all



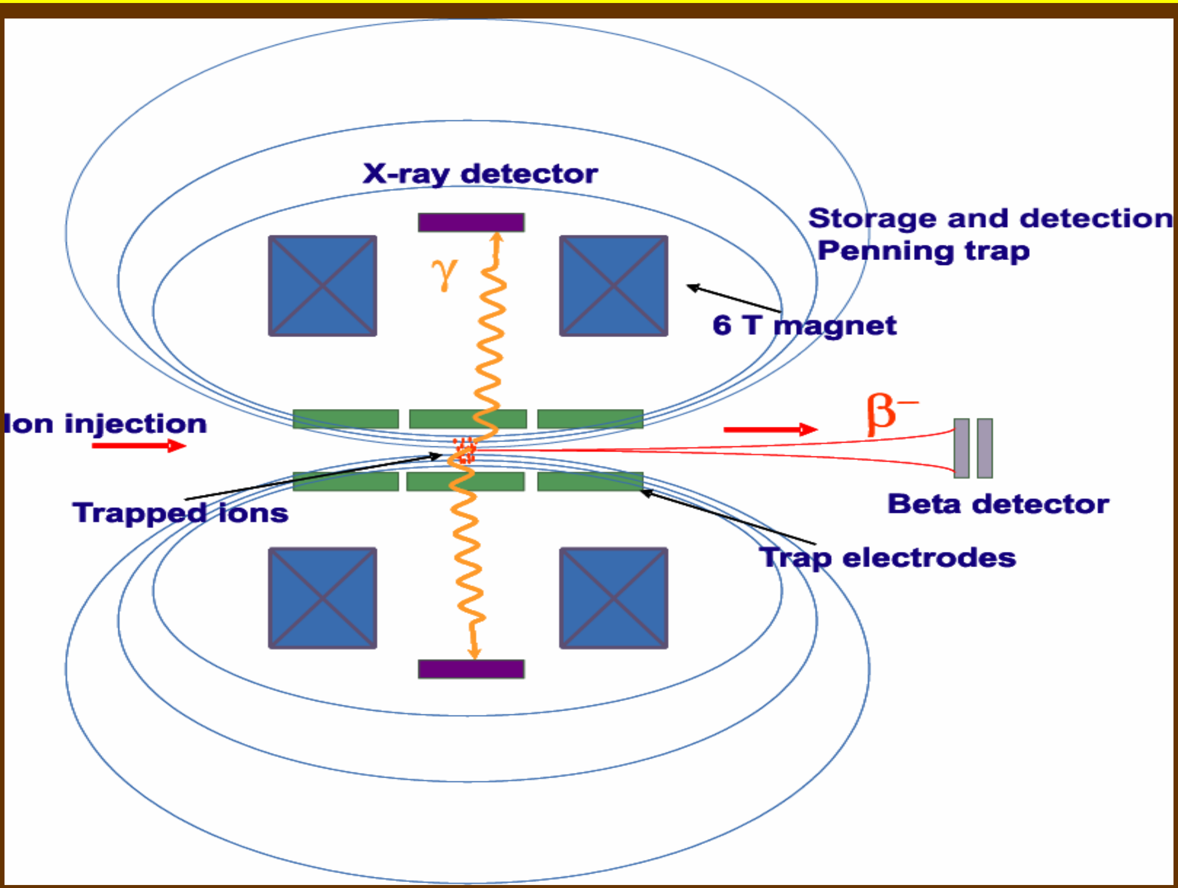
Experiment for EC using EBIT





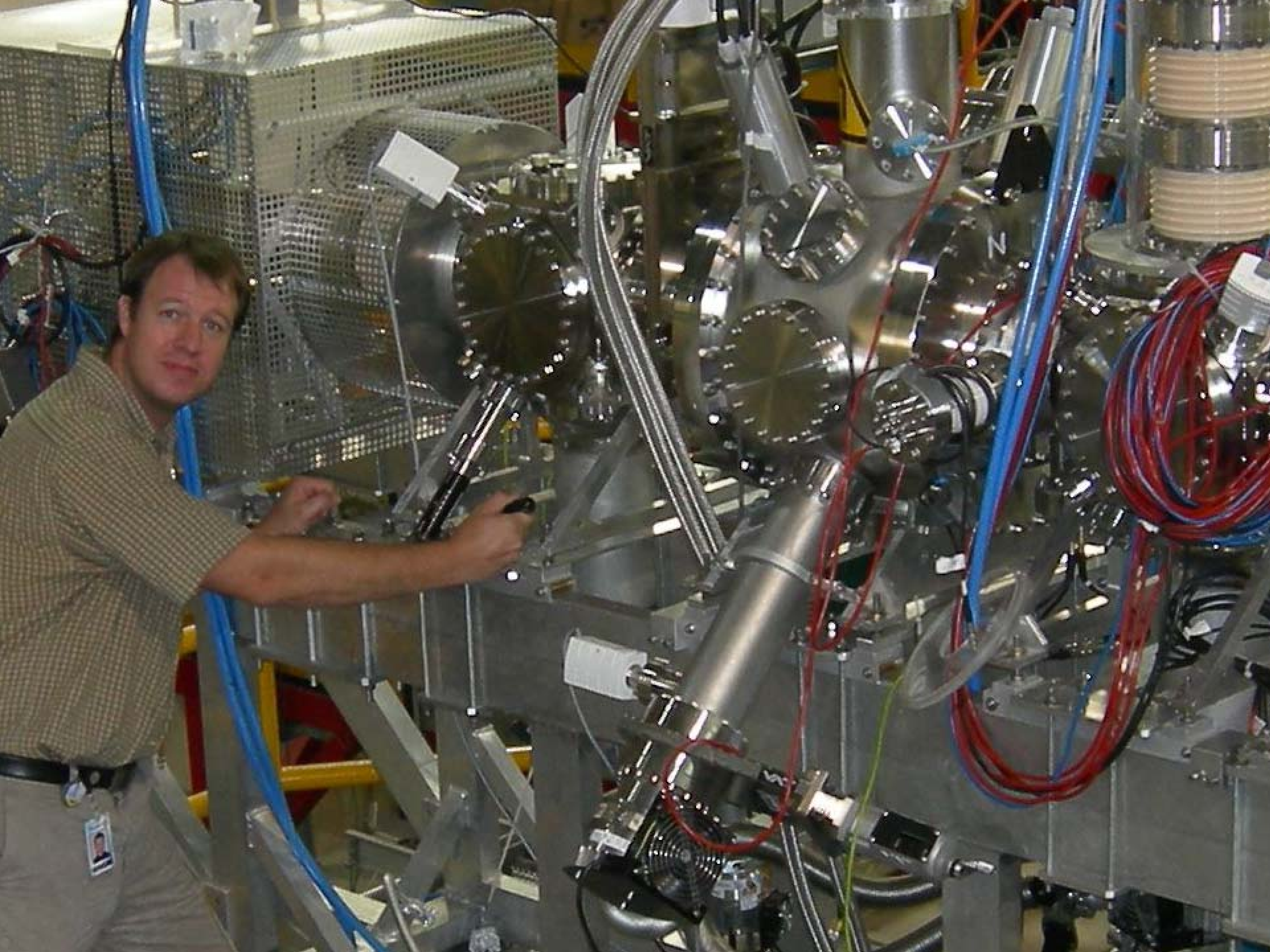
holding 7 ports for X-ray detectors

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

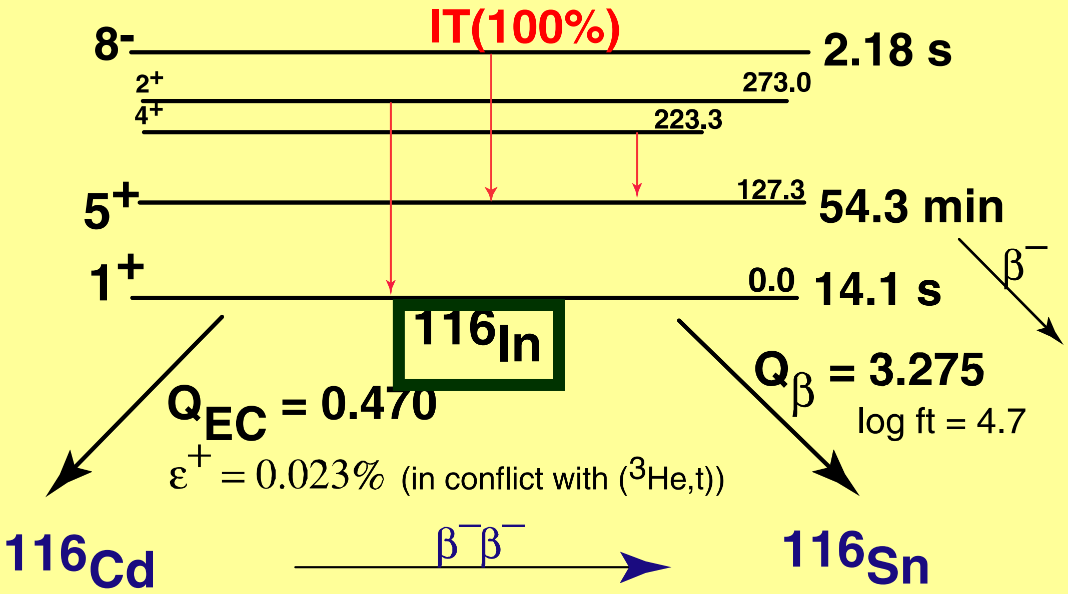

N

A=116

A=100

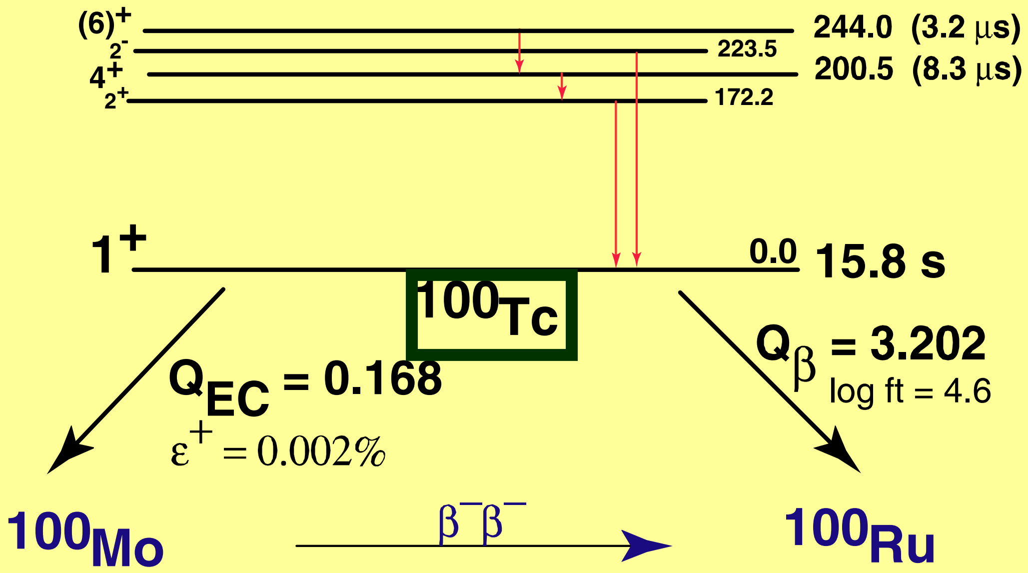
A=82

A=76



Important measurements also because of the present conflicting experimental values.

8 – 100 hours depending on value of ε



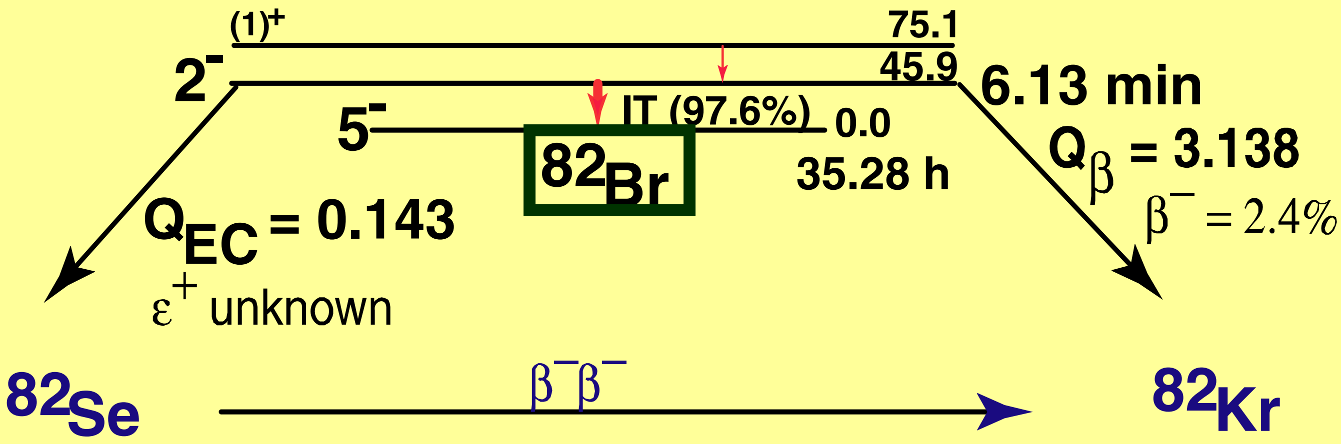
MOON → 1t material
NEMO-3 → 7kg

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

---

90 hours/10% measurement

±



NEMO-3

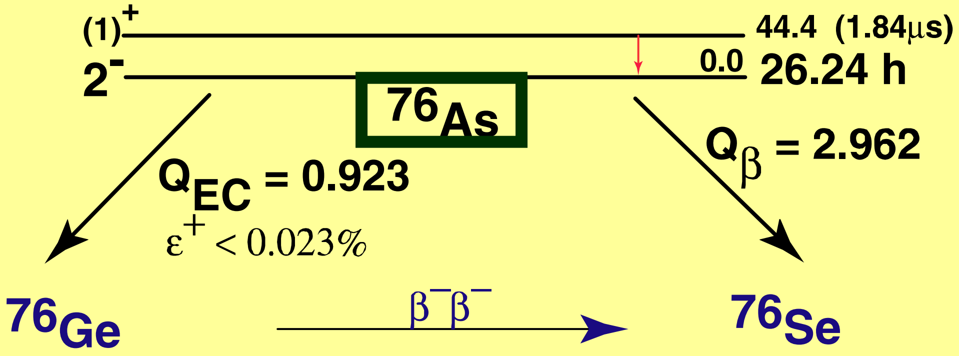
$$T_{1/2}(2\nu\beta\beta) = [9.6 \pm 0.3 \pm 1.0] \cdot 10^{19}\ y$$

First time to measure EC ($2^- \longrightarrow 0^+$)

from an excited state but

a significant expmtl challenge!!

The most important case!!!

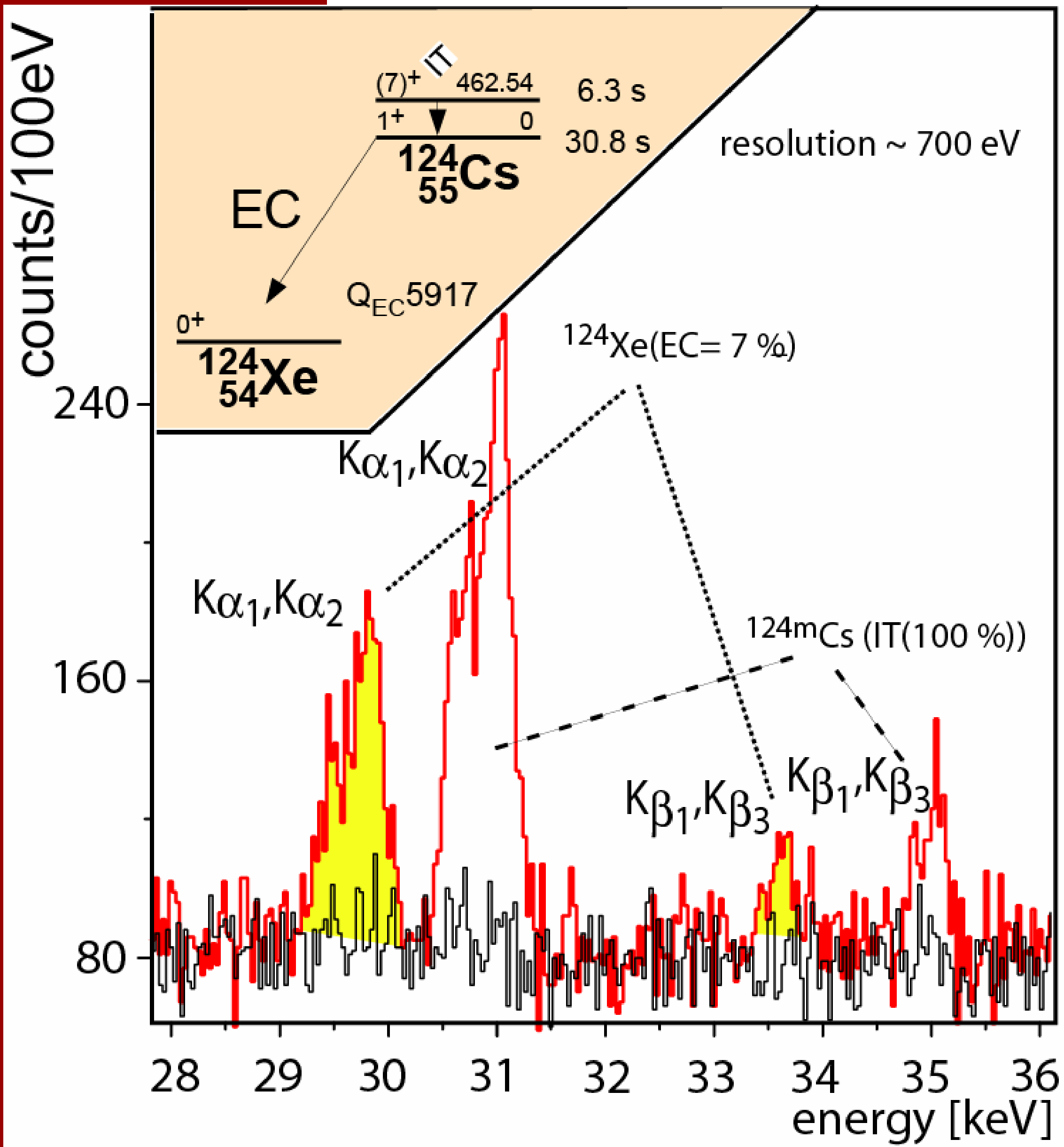


exp. log ft (β^-) = 9.7
if log ft (EC) ~ 9.5

$\varepsilon = 10^{-5}$

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

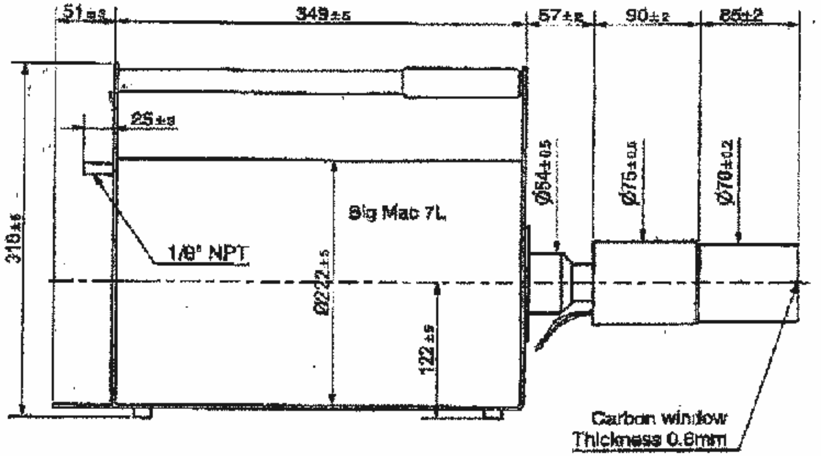
TRIUMF- measurement



radioactive ^{124}Cs ions trapped in a Penning trap

(first meas‘nt of X-rays from trapped ions ever)

Refer to Thomas !!



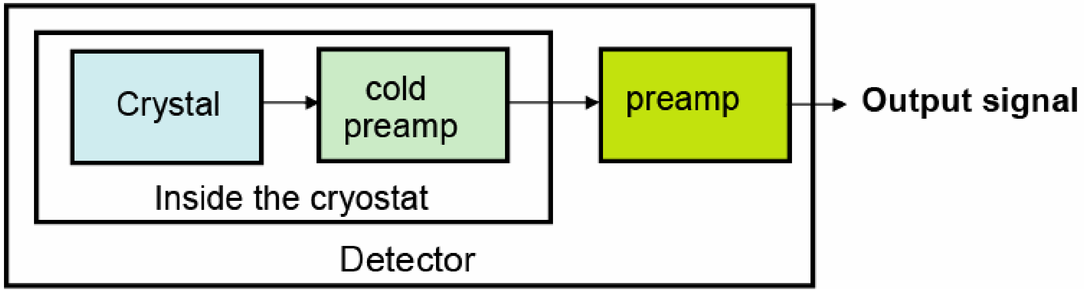
type : Si(Li)
crystal Ø : 50 mm
crystal thickness: 2 mm
active area : ~2000 mm^2
carbon window : 0.8 mm
outer Ø : 70 mm
dewar vol. : 7 l
holding time : 3-5 d
resolution : ~550 eV (@ 6keV)
mounting at any orientation possible
(LED & temp. readout available)

A warm-up is not destructive, but renwed pump down necessary (valve is available)

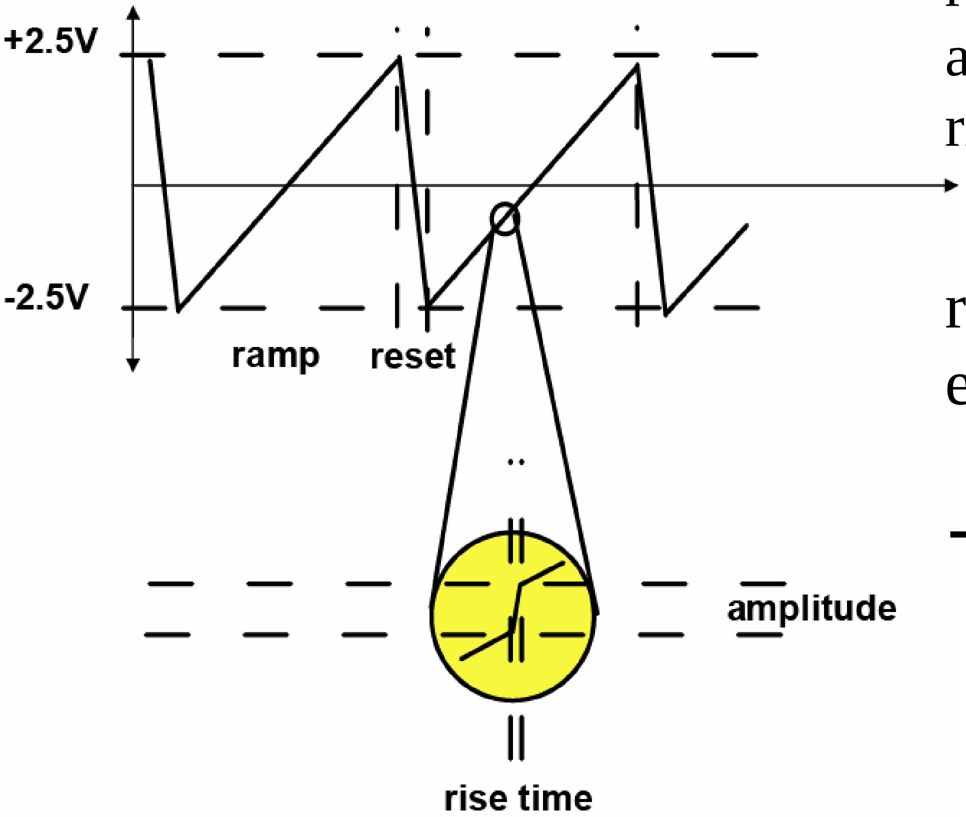
vacuum guaranteed for 3 yrs.

Delivery: **3 by Aug-31**
4 by Sep-30

Scheme of detector



Output signal (V)



reset time: 5 – 7 µs
amplitude: ~ 16 mV for 30 keV
rise time: 100±30 ns (20 – 80%)

ramp time: depends on rate
e.g.: for 100kHz @ 30 keV → 3 ms

→→ # of resets/s: max 325

(Canberra specs)

Components still needed

- HV power supply for 7 detectors (ISEG)
    - cost ~ 10 k$
- amplifiers and shapers
    - (be aware of ground loops!!)
- logic circuits
- Implementation into local DAQ
- support and holding structure
- ....

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