Westfälische Wilhelms-Universität Münster

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Recent experimental results on ββ decay matrix elements

or

what did we learn after many years of charge-exchange reactions?

KVI (NL), RCNP(JP), TRIUMF(CAN)

OUTLINE

talk about

1) ββ -decay & nuclear ββ decay matrix elements

(some suprises in nuclear physics)

- charge-exchange reactions (d,^{2}He) and (^{3}He,t)

  ^{48}Ca, ^{64}Zn, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo,

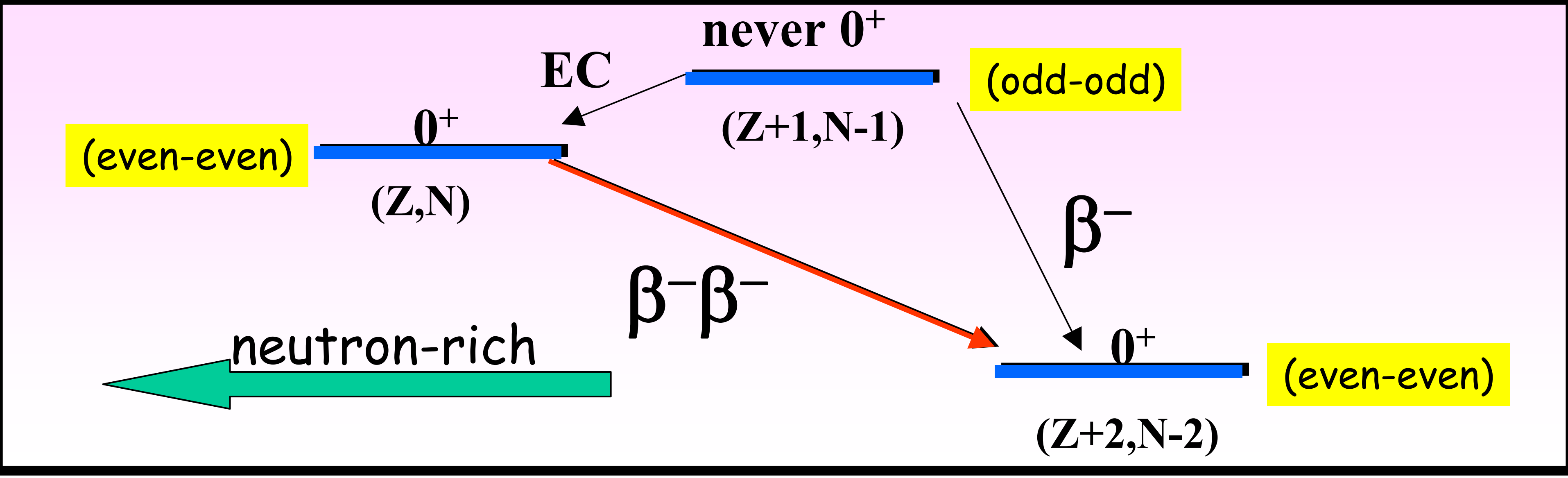
  ^{116}Cd, $^{128/130}$Te, ^{136}Xe, ^{150}Nd

  (KVI, RCNP)

2) electron-capture & radioactive-ion traps

(TRIUMF)

$\beta^-\beta^-$ decay



$2\nu\beta^-\beta^-$ decay: $$\Gamma = \underset{\text{5-body}}{\text{(ph-spc)}} \times \left| \underset{\text{allowed}}{NME} \right|^2$$

$0\nu\beta^-\beta^-$ decay: $$\Gamma = \underset{\text{3-body}}{\text{(ph-spc)}} \times \left| \underset{\text{any degree}}{NME} \right|^2 \times \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

Quick reminder of neutrino mass problem

$$\Gamma \propto \left| \quad NME \quad \right|^2 \cdot \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

$$U = V \cdot \mathrm{diag}(e^{-i\Phi_1}, e^{-i\Phi_2}, 1)$$ ⟵ **2 extra Majorana phases**

$$V_{\alpha i} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{13}c_{23}s_{13}e^{-i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{-i\delta} & c_{13}c_{23} \end{pmatrix}$$

known quantities:

$$\Theta_{12} = 0.6 \pm 0.1 \quad \rightarrow \approx \pi/6$$

$$\Theta_{23} = 0.7 \pm 0.2 \quad \rightarrow \approx \pi/4$$

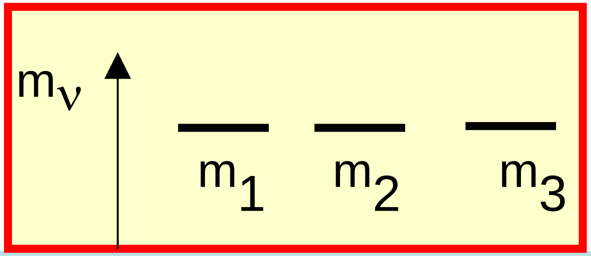
$$\Theta_{13} < 0.12$$

$$\Delta m_{atm}^2 = \left| m_3^2 - m_2^2 \right| \approx 2.6 \times 10^{-3}\,\mathrm{eV}^2 \approx (0.05\mathrm{eV})^2$$

$$\Delta m_{sol}^2 = \left| m_2^2 - m_1^2 \right| \approx 7.9 \times 10^{-5}\,\mathrm{eV}^2 \approx (0.009\mathrm{eV})^2$$

Neutrino mass scenarios:

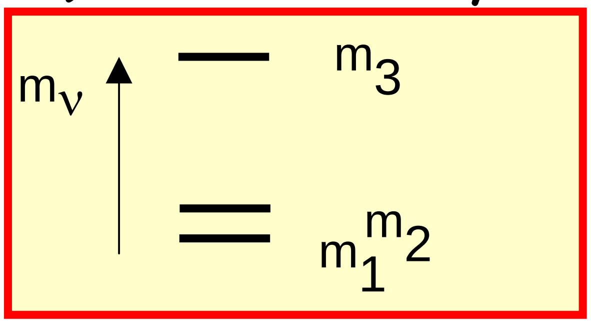
1) degenerate:



$$\left| m_{\nu_e} \right| \approx 0.2 eV$$

best of all cases

2) normal hierarchy:

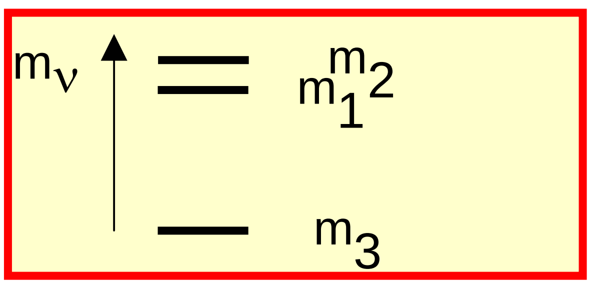


$$\left| m_{\nu_e} \right|^2 \propto \Delta m_{sol}^2 \times \left| \frac{3m_1}{\Delta m_{sol}} + e^{-2i(\Phi_2-\Phi_1)} + (<0.5) e^{-2i(\delta-\Phi_1)} \right|^2$$

= zero!! for:

$$\Theta_{13} \sim 0 \quad (\Phi_2 - \Phi_1) = \frac{\pi}{2} \quad \frac{3m_1}{\Delta m_{sol}} = 1$$

3) inverted hierarchy:



$$\left| m_{\nu_e} \right|^2 \propto \Delta m_{atm}^2 \times \left| 3 + e^{-2i(\Phi_2-\Phi_1)} \right|^2$$

if inverted hierarchy were determined

(by LHC or spectral distortion of SN-neutrinos)

THEN: $\left| m_{\nu_e} \right| \approx \Delta m_{atm}$

or the neutrino is a Dirac particle

NME important

NME

$2\nu\beta^-\beta^-$ decay

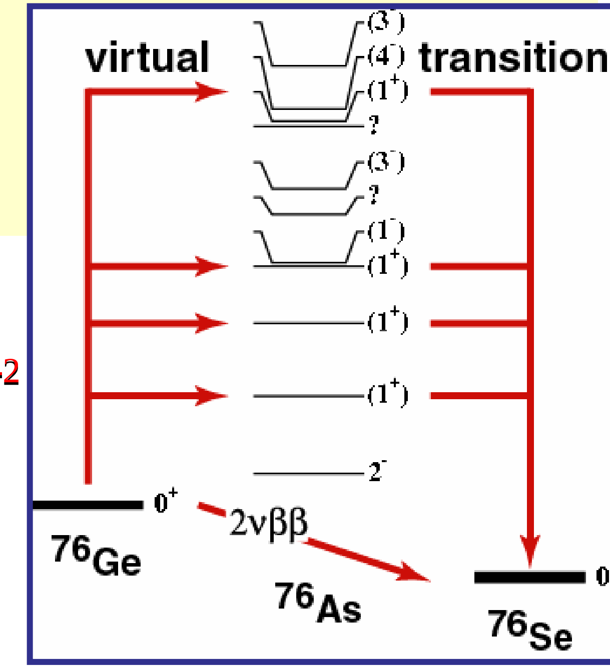
q-transfer like ordinary β-decay
(q ~ 0.01 fm^{-1} ~ 2 MeV/c)
only allowed decays possible

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

!!

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

$$\propto Q^{10}\cdot Z^2 \qquad \overset{\exp}{\approx} 10^{-3}\ \mathrm{MeV}^{-2} \qquad \propto \frac{1}{N-Z}$$

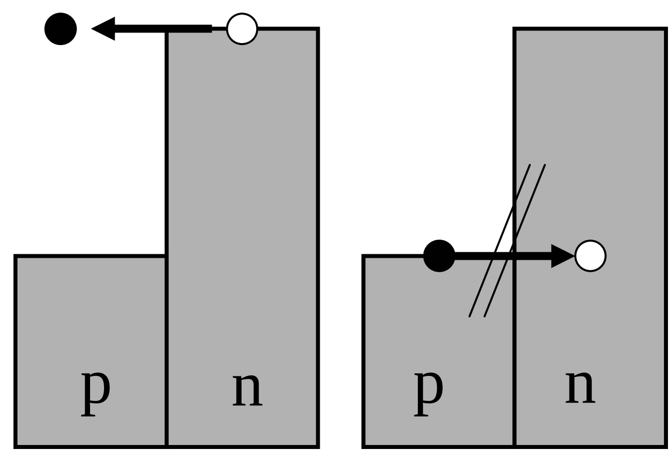


favorable:

1. High Q-value
2. High Z

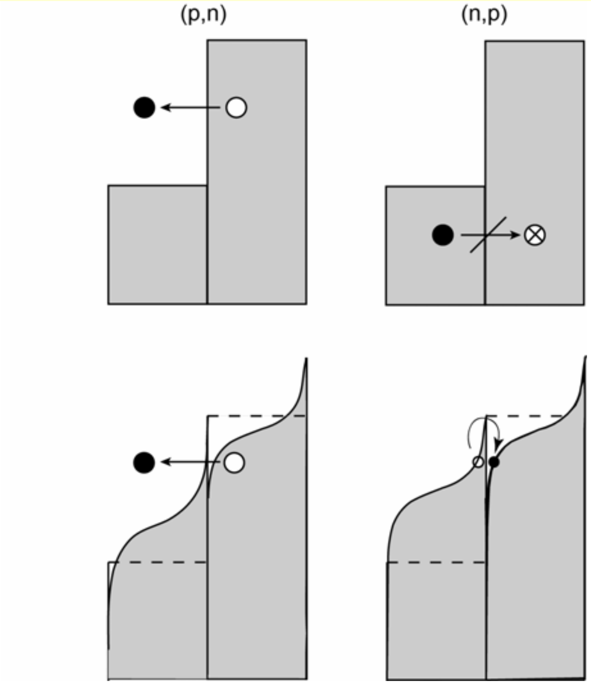
Unfavorable:

1. high neutron excess
   (because of Pauli-Blocking)



A layman's sketch of thePauli-blocking

remember: GT requires $\Delta\hbar\omega=0$!!



Extreme case:

(p,n) completely open
(n,p) completely blocked

Soft surface case:

(p,n) still largely open
(n,p) still largely blocked
yet probabilities could be finite but tiny

FSQP-model (Ejiri 2009,2012)

$$M_{DGT}^{(2\nu)} = \sum_{i,j} \frac{M_{i,j}^{+} M_{i,j}^{-}}{E_{i,j}}$$

large

$$M_{i,j}^{-} = g_{-}^{eff}\, v_n^i(A_N)\, u_p^j(A_Z)\, m_{GT}(i \rightarrow j)$$

$$M_{i,j}^{+} = g_{+}^{eff}\, u_n^i(A_{N-2})\, v_p^j(A_{Z+2})\, m_{GT}(i \rightarrow j)$$

small

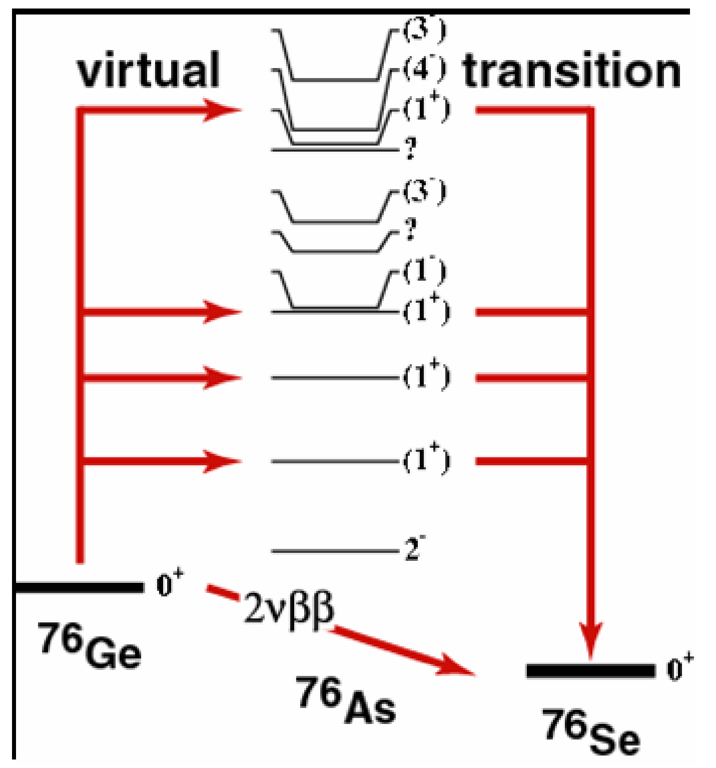
$$M^{(2\nu)}_{DGT} = \sum_m \frac{\left\langle 0^{(f)}_{g.s.} \left| \sum_k \sigma_k \tau_k^- \right| 1^+_m \right\rangle \left\langle 1^+_m \left| \sum_k \sigma_k \tau_k^- \right| 0^{(i)}_{g.s.} \right\rangle}{\frac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - E_0}$$

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

To note:

1. two sequential & „allowed" β^--decays of „Gamov-Teller" type
2. „first-" oder „higher order forbidden" decays negligible
3. Fermi-transitions don't contribute (because different isospin-multiplet)

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



NME
$0\nu\beta^-\beta^-$ decay

neutrino enters as virtual particle,
$q \sim 0.5 fm^{-1}$ (~ 100 MeV/c)
degree of forbiddeness weakened

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

!!

$\propto Q^5 \cdot Z^4$

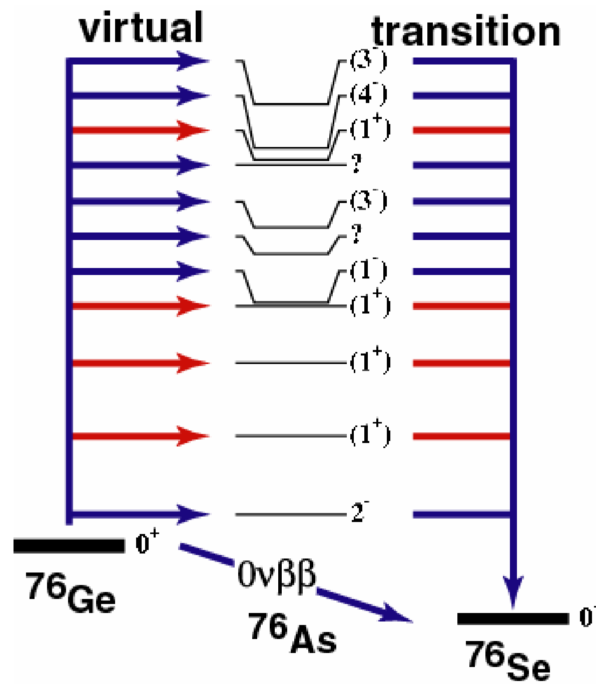
$\overset{\text{theory}}{\approx} 10$!!
indepnt. of (A,Z)
(except for magic nuclei)

Mass of Majorana-ν !

To note:

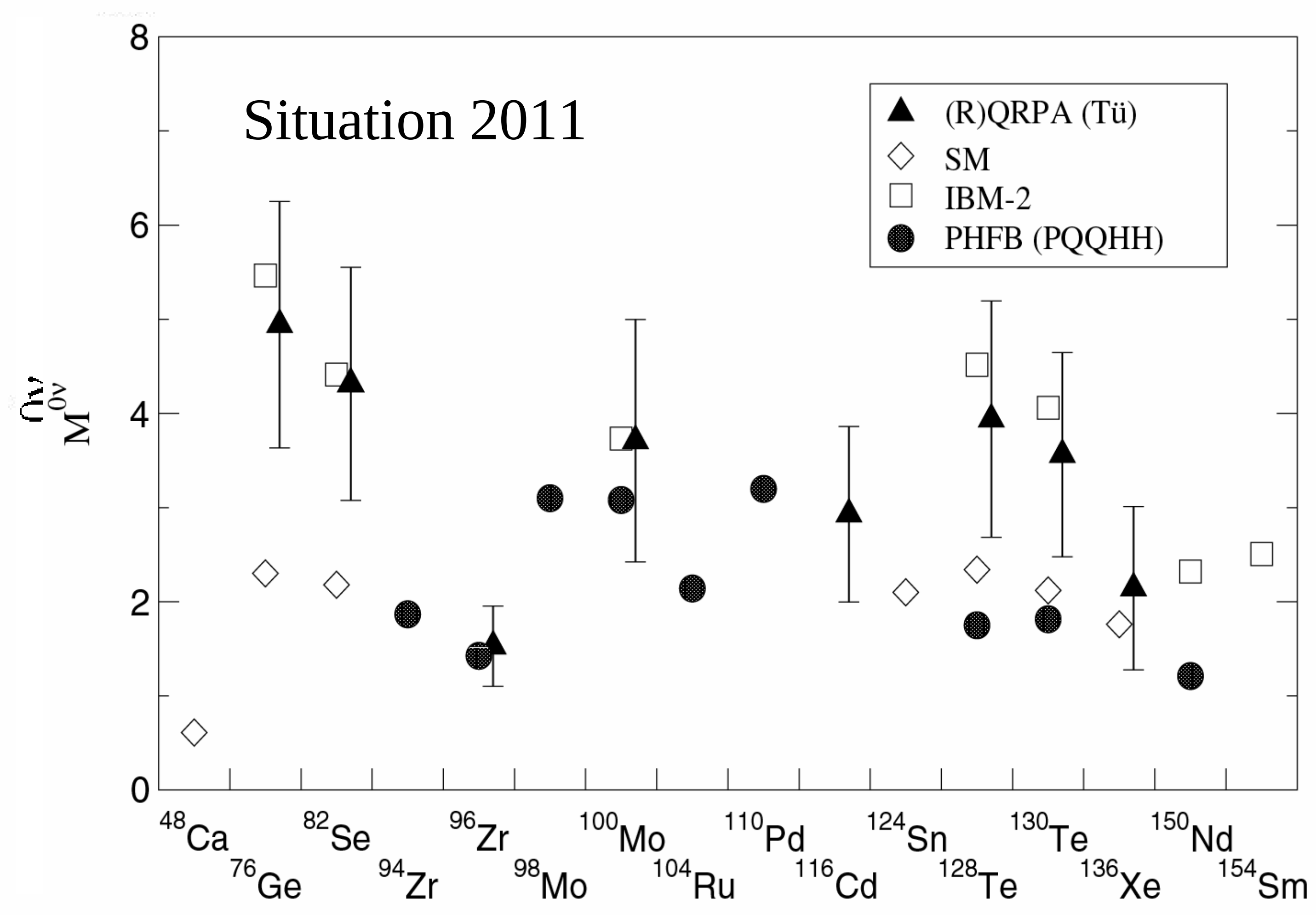
1. „first-" or „higher order forbidden" transitions important
2. Fermi -transitions important
3. Pauli-blocking largely lifted
4. high Q-value, high Z important

NOT accessible thru charge-exchange reactions



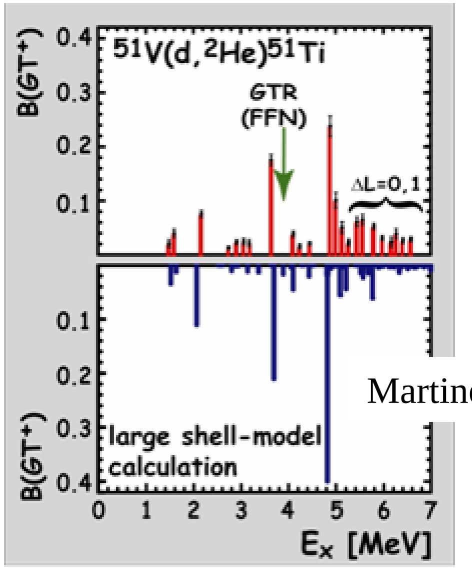
Neutrinoless Double Beta Decay Nuclear Matrix Elements

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



The message after many years of expmlt studies of 2νββ!! -NME

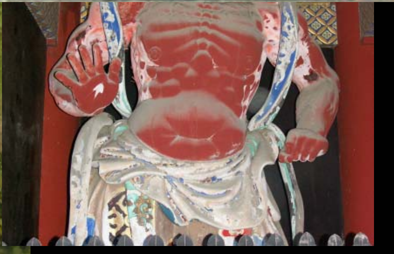
1. In all cases the low-energy part of GT-excitation makes up most of the NME.
2. The GT giant resonance has little to no effect on NMEs (Pauli-blocked from the 2nd leg).
3. A large difference of the nuclear shape between mother and grand-daughter leads to a suppression of the NME (case: ^{76}Ge).
4. There are some very special and simple cases (^{96}Zr, ^{100}Mo). ^{100}Mo has the LARGEST of all NMEs !! Why ??
5. What is wrong with ^{136}Xe - why is it so stable ? It has the smallest of all NMEs !! Why ??
6. What is the effect of 2n-pair in ^{128,130}Te ? Is it valuable spectroscopic input?
7. **Finally**: There is a level of disappointment about theoretical models !! Note: στ is the simplest of all excitations!! → **BUT**
   - expmtl. low-energy GT$^+$ / GT$^-$ distribution poorly described, ecept
   - GT-resonance contribution to NMEs is overestimated
   - **Yet**, final number OK.

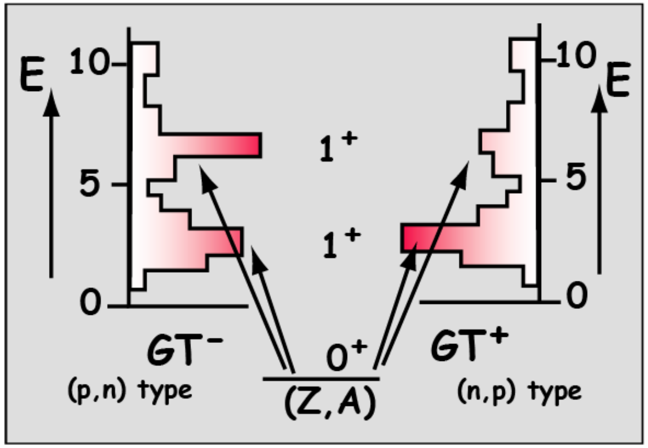


Martinez-Pinedo

Back to $2\nu\beta\beta$ decay and charge-exchange reactions


RCNP - Osaka





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.

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

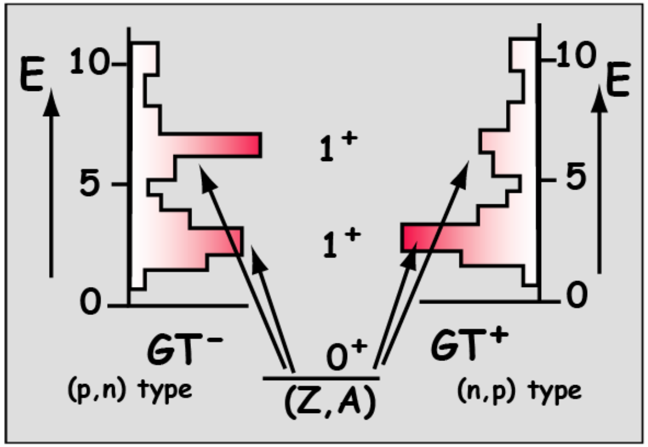
$$B(GT) = \frac{1}{2J_i+1} \, | M(GT) |^2$$

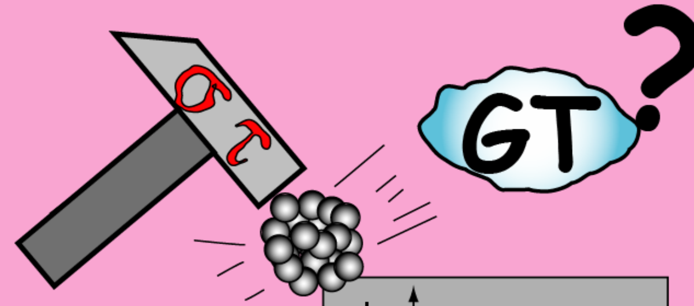
hadronic probes: (n,p), (d,^{2}He), (t,^{3}He)

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

$$\left[\frac{d\sigma}{d\Omega} \right] = \left[\frac{\mu}{\pi\hbar} \right]^2 \frac{k_f}{k_i} N_d \, |V_{\sigma\tau}|^2 \, | \langle f \, | \, \sigma\tau \, | \, i \rangle |^2$$

largest at 100 - 300 MeV/A



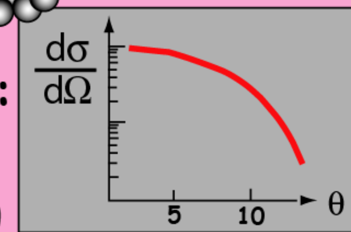


Gentle Touch:

→ $q_{tr} = 0$

→ $\Delta l = 0$

→ $0\hbar\omega$ excitation



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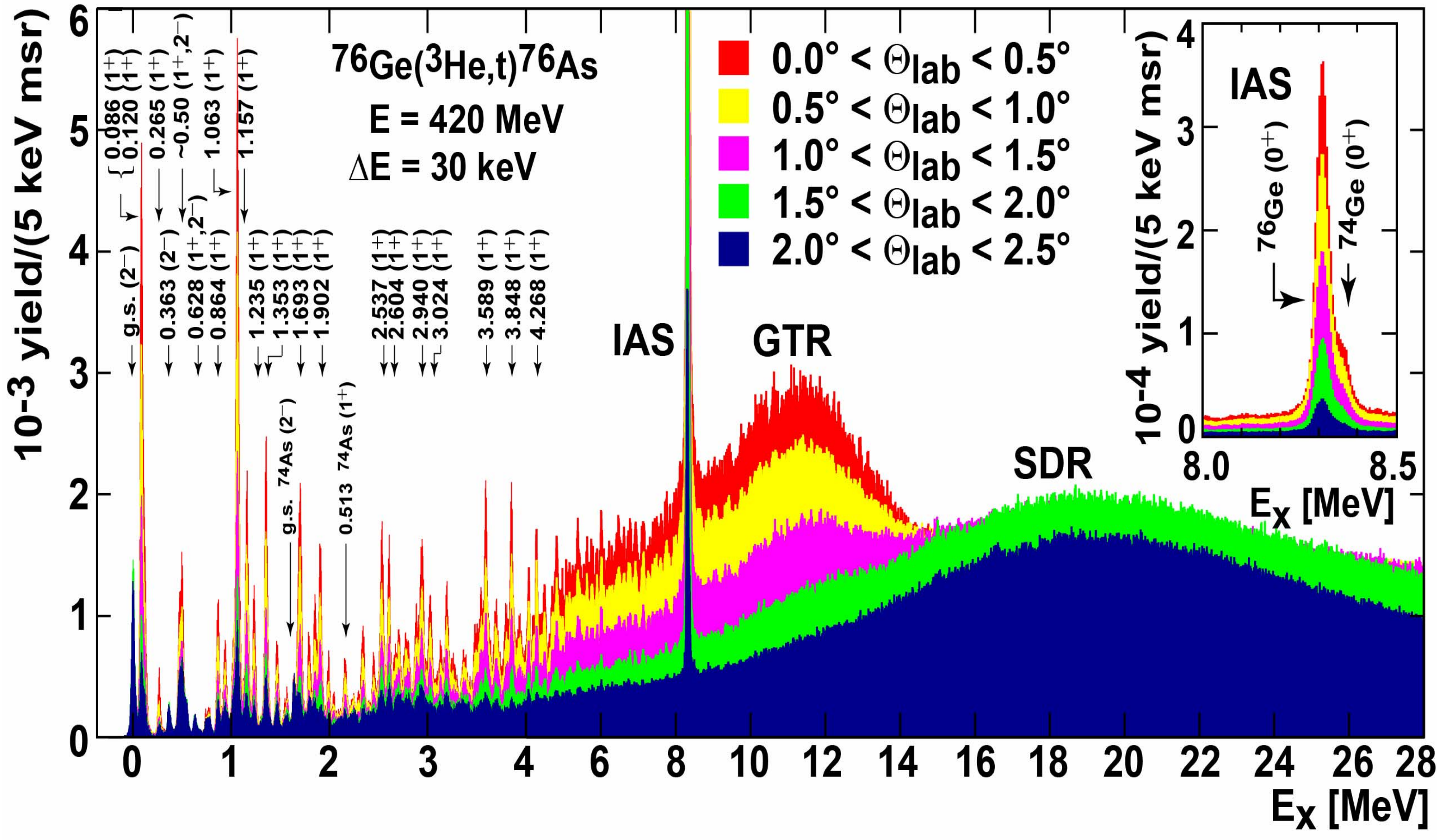
largest at 100 - 200 MeV/A

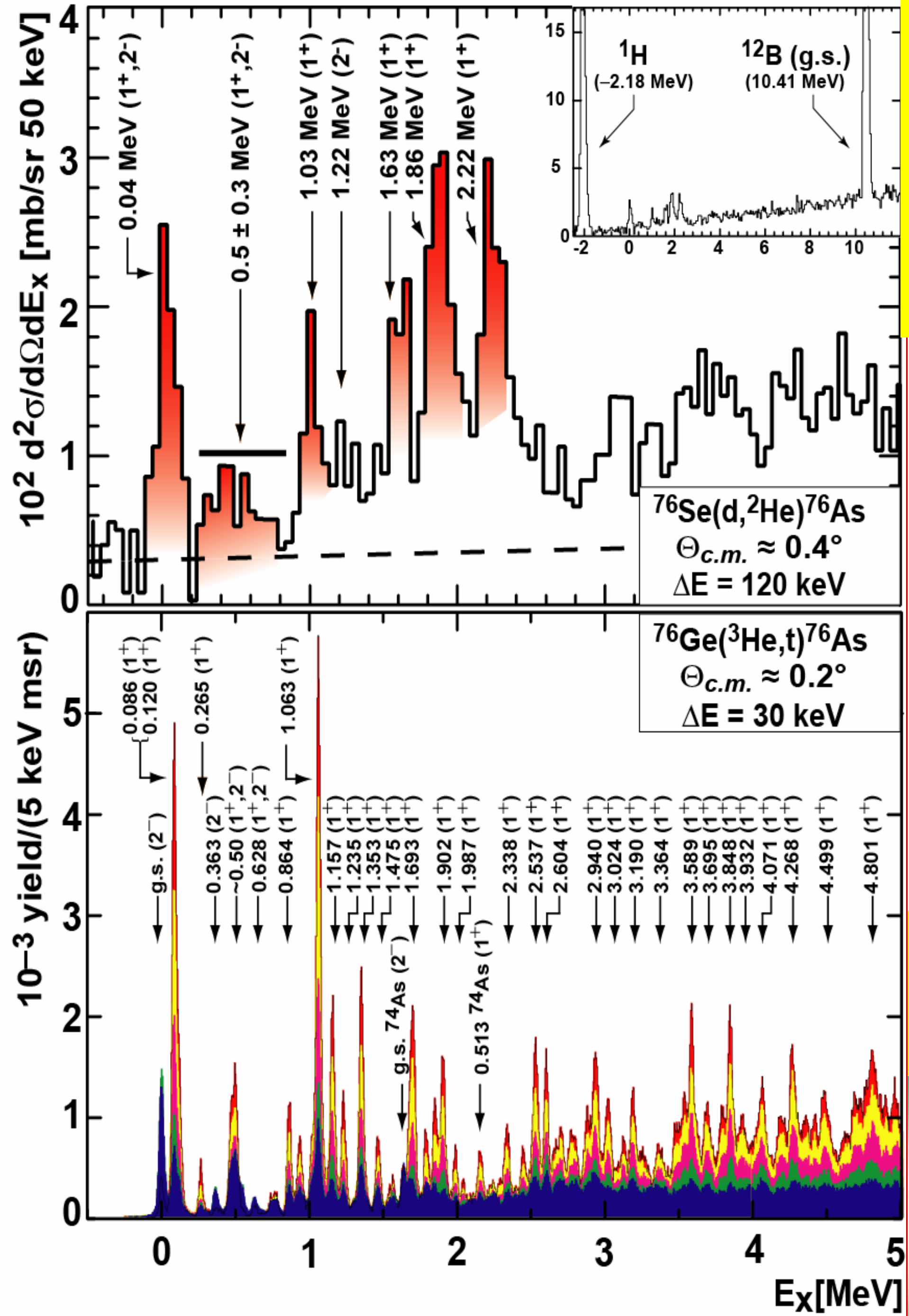
^{76}Ge

the most important $\beta\beta$-decaying nucleus

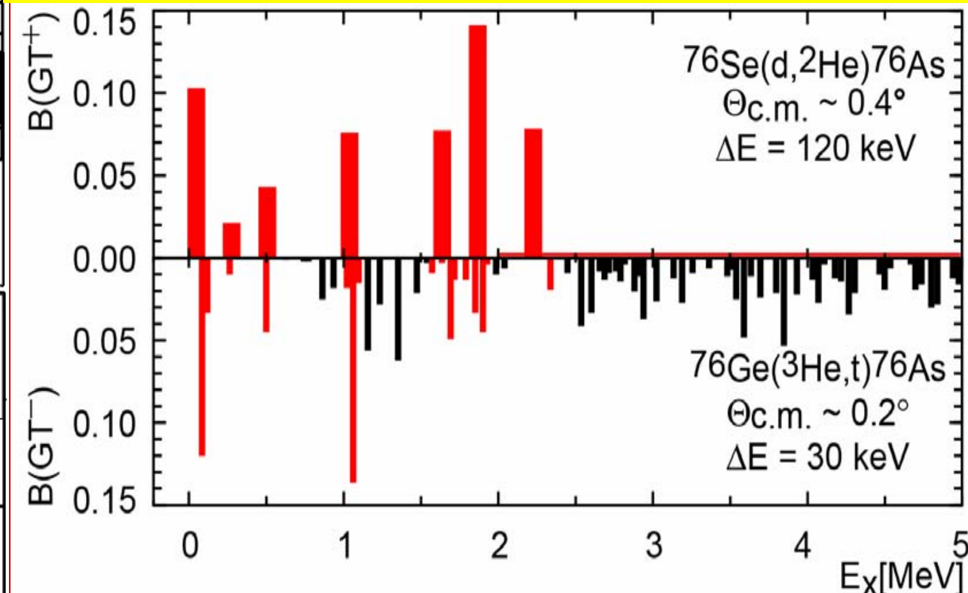
Resolution is the key issue !!!



about 70 !! individual levels up to 5 MeV !!!

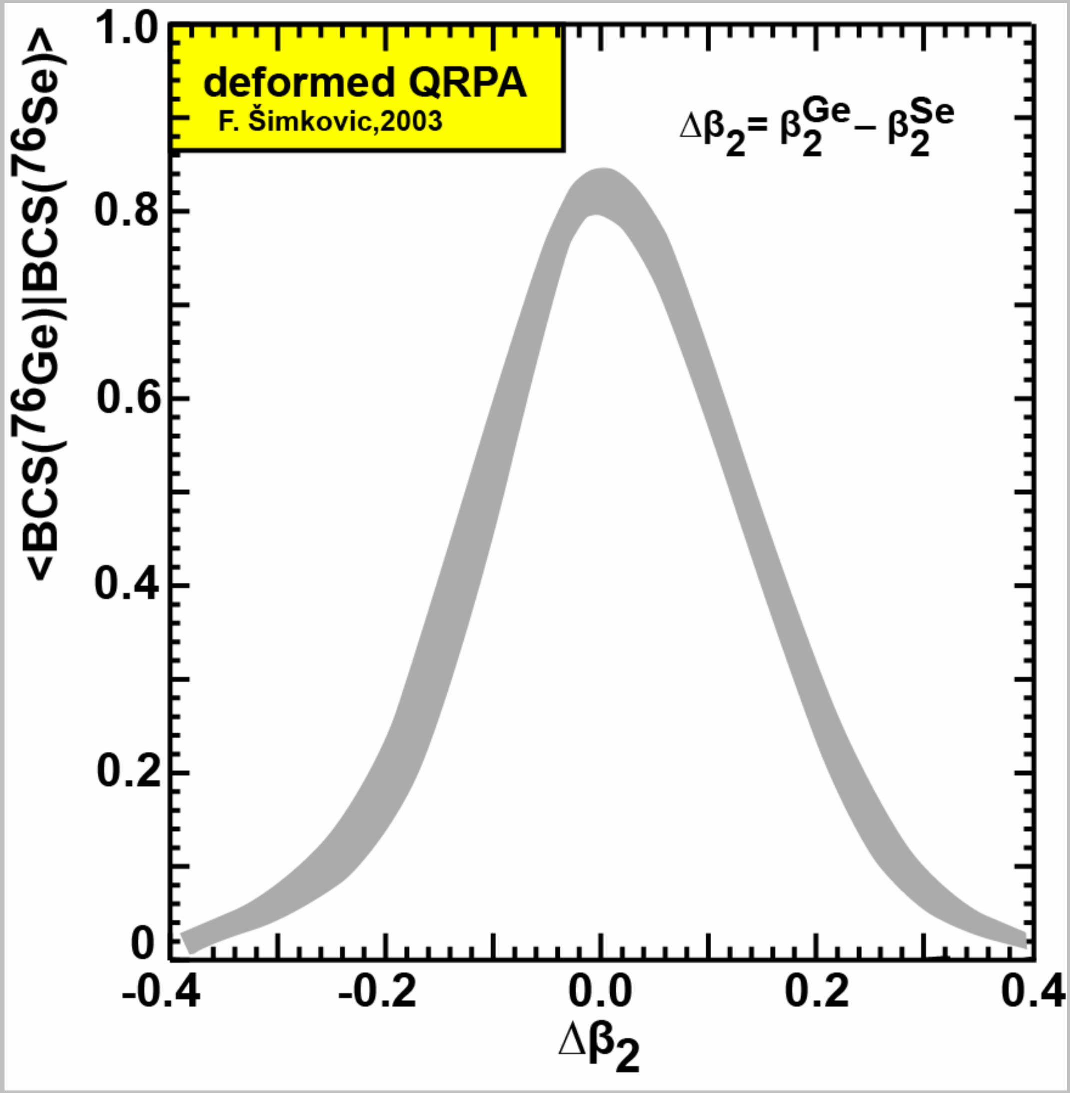


about 70 !! individual levels
up to 5 MeV !!!
???? anticorrelation ????



an effect of the difference of deformation ??

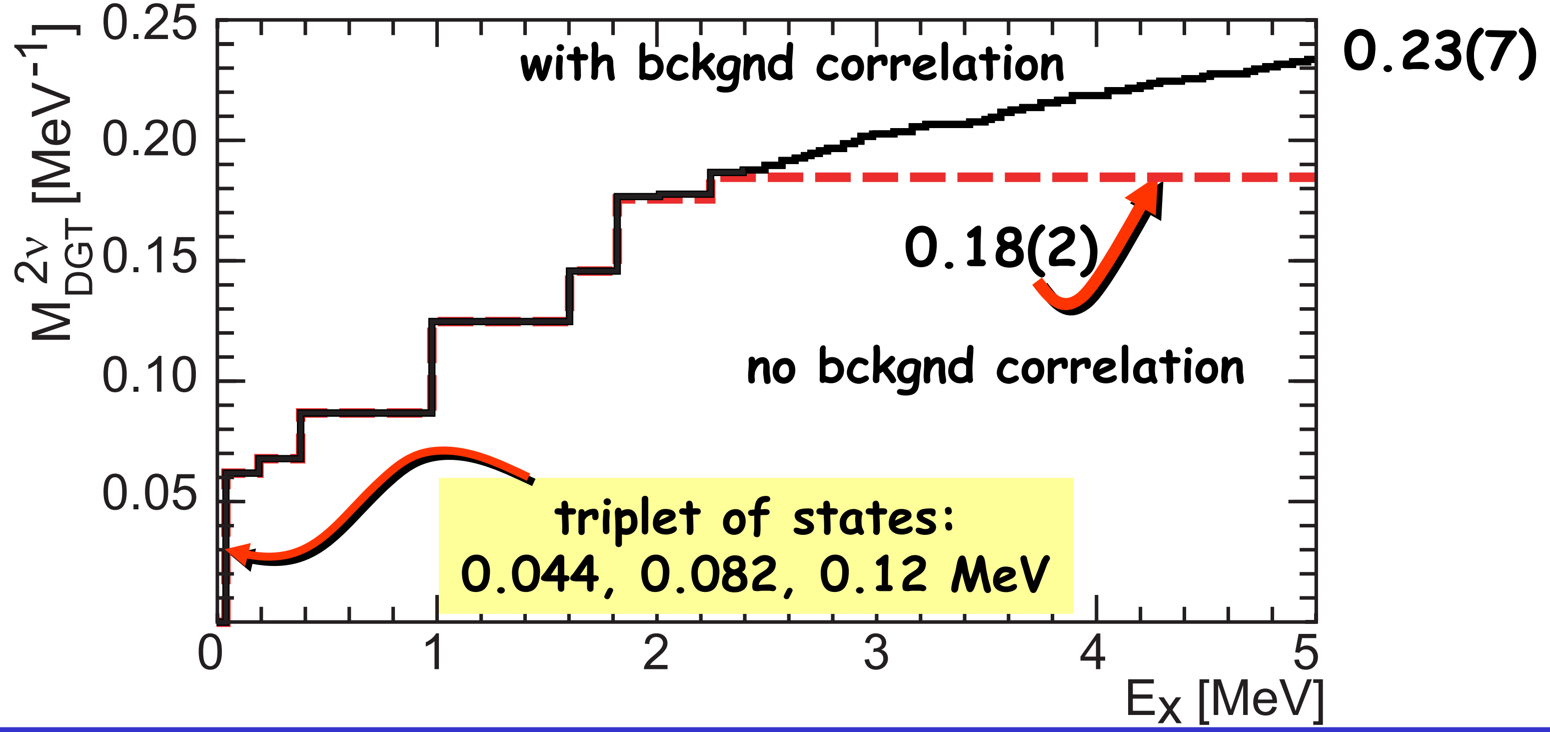
^{76}Ge	^{76}Se
moderately oblate/ prolate (β_2 ~ 0.1)	oblate (β_2 ~ −0.2)



taken from F. Simkovic et al.
(cf also P. Sarriguren et al., PRC67,44313 (2003))

Intrinsic deformation seems to affect the $2\nu\beta\beta$-ME, however, it is the difference of deformation between mother and daughter and not their absolute values which counts.

Exp'lly the deformation seems to manifest itself in a state-by-state mismatch, rather than an overall reduction of B(GT)'s.



Low-E part of M_{DGT} makes up ~100(+)% of $2\nu\beta\beta$-ME

$M_{DGT} = 0.12 + 0.01\ MeV^{-1}$

$T_{1/2} = (2.1 + 0.1) \times 10^{21}$ yr

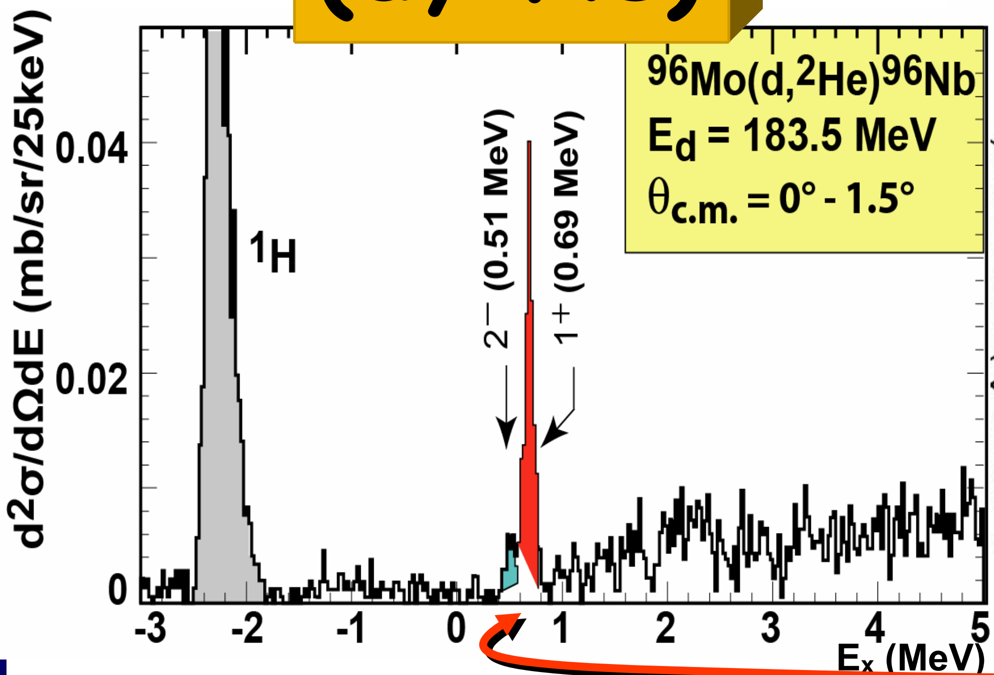
No need for GT giant resonance contribution

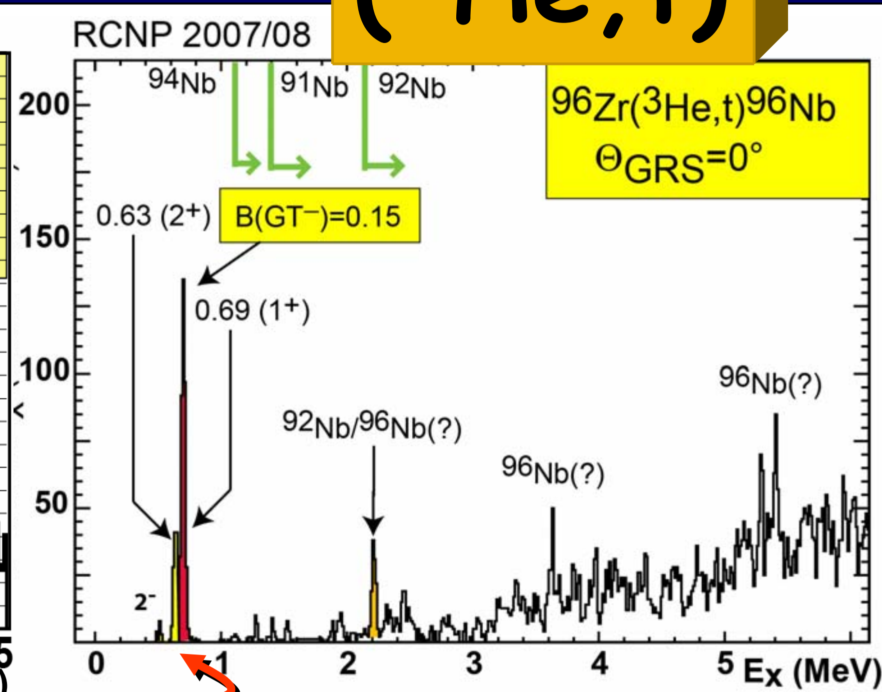
(note: 0.06 MeV^{-1} are due to low-E triplet, which may not be correlated!!)

^{96}Zr

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

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





$B(GT^+)$ = 0.3

$B(GT^-)$ = 0.15

Fascination: With this 1 level only:

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

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

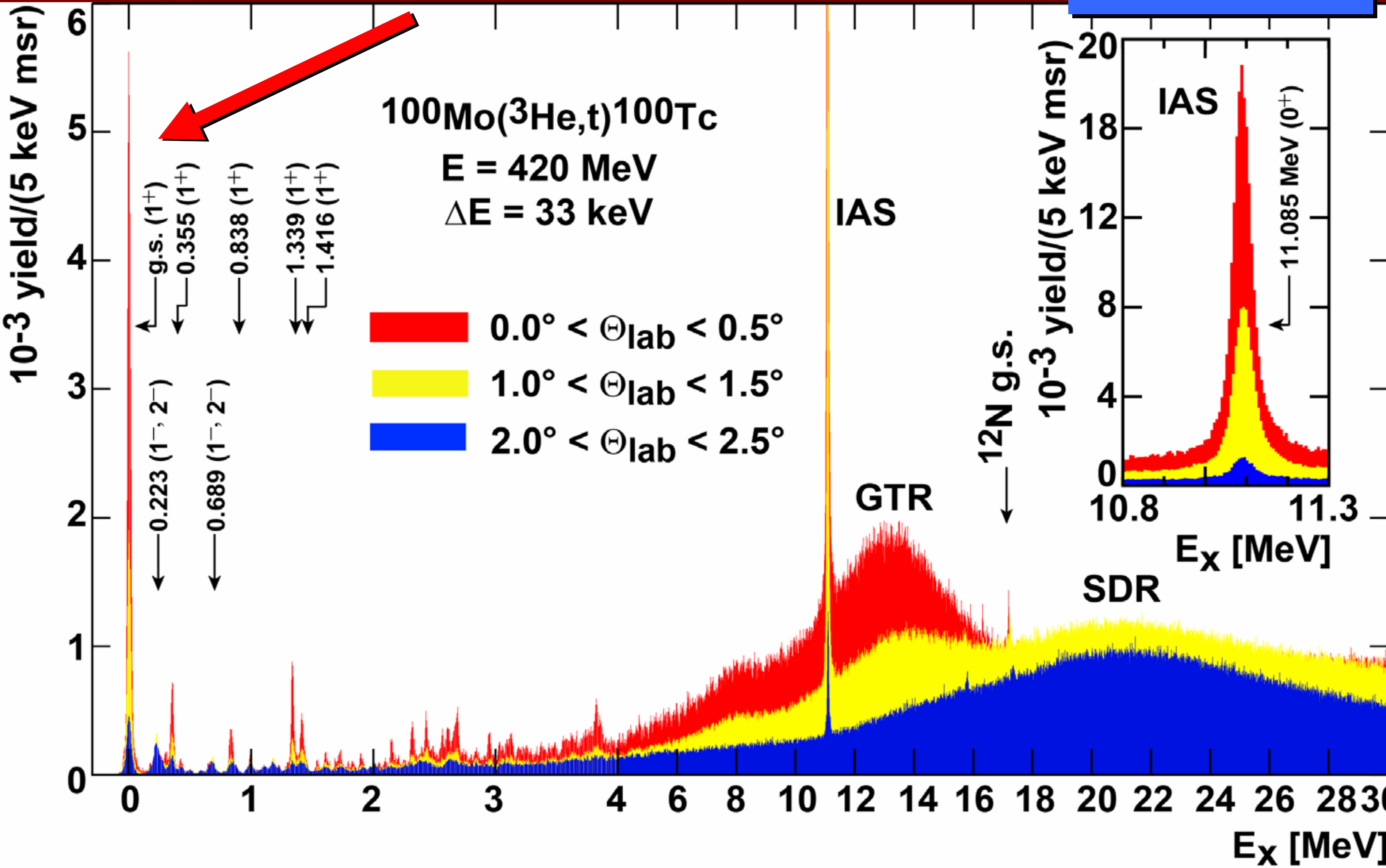
^{100}Mo

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

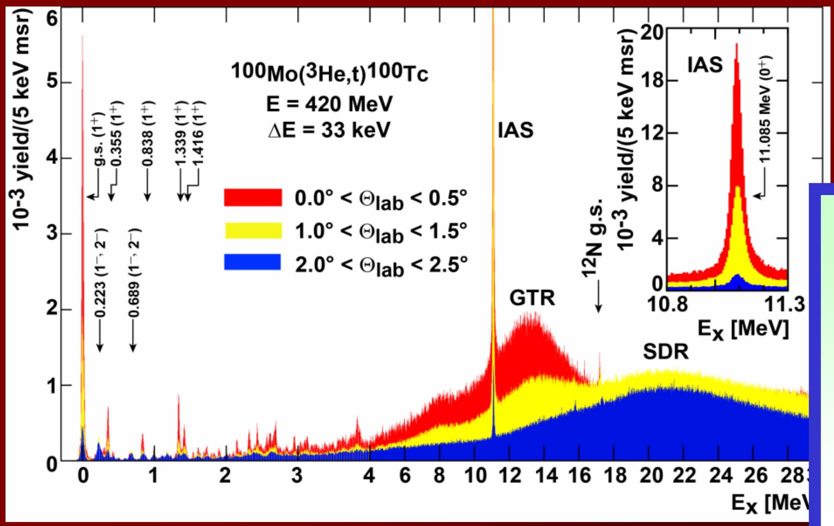
SN-neutrino detector
SN-neutrino temperature

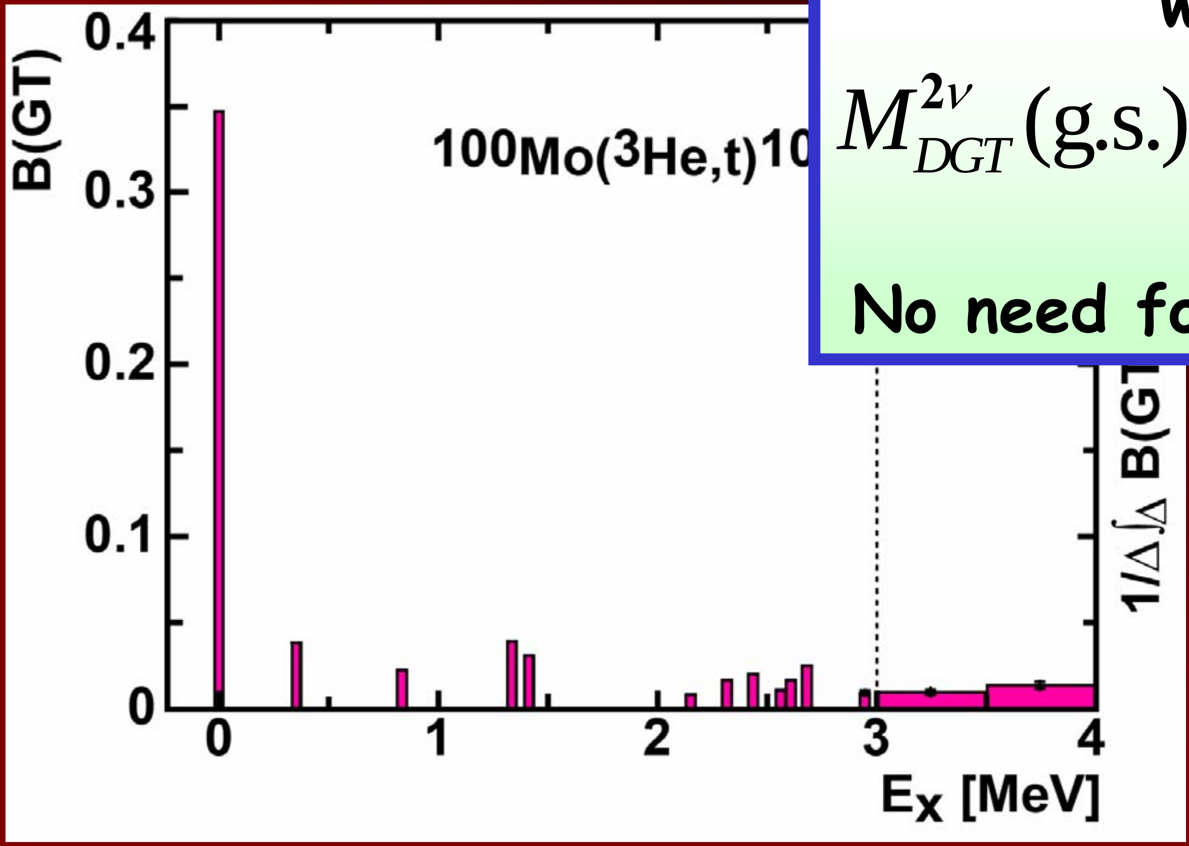
almost entire GT strength concentrated in ground-state

^{100}Mo



^{100}Mo

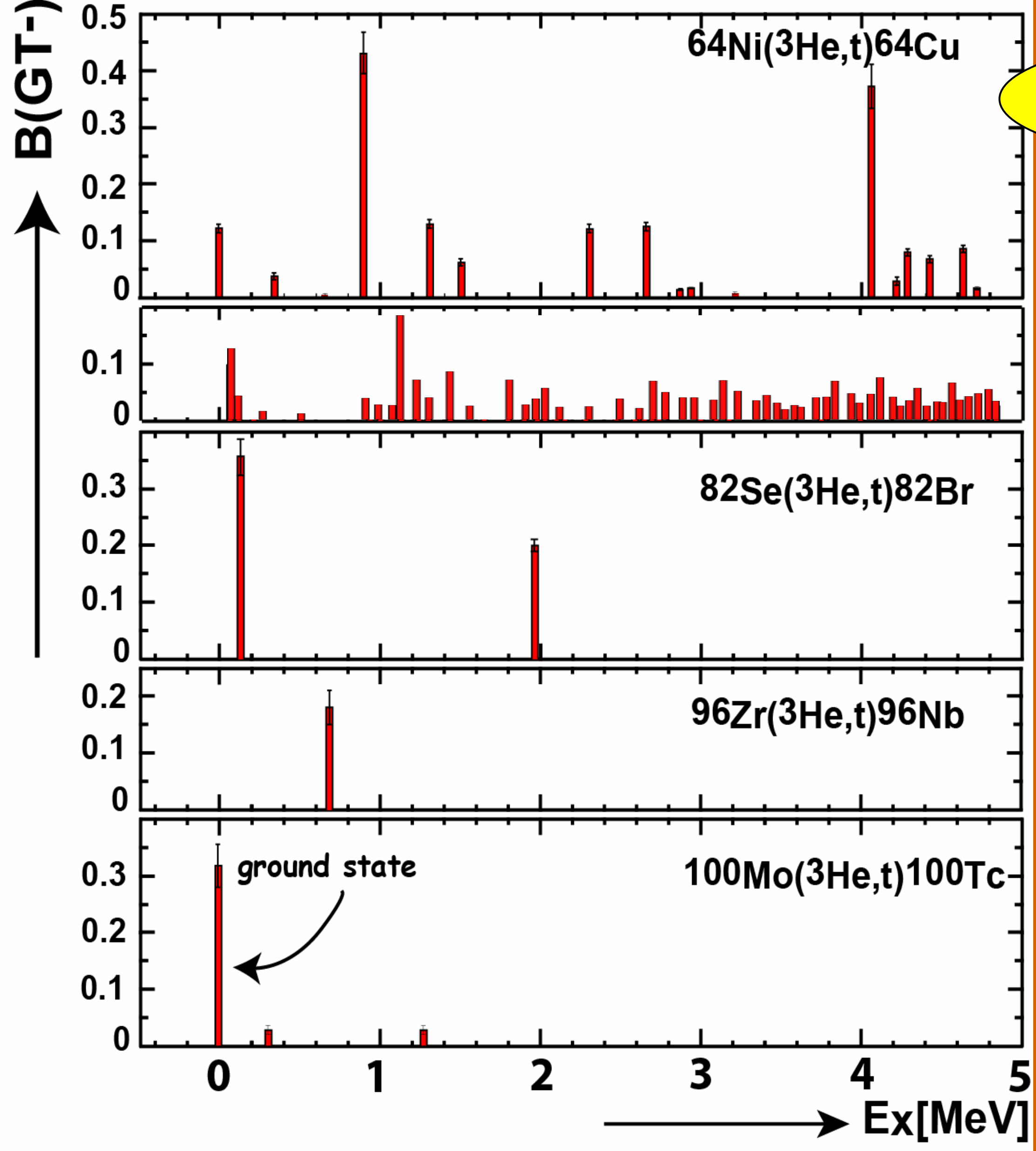




entire low-energy GT-strength is concentrated in ONE single state only (i.e. the g.s.) with β^- log*ft*

$$M^{2\nu}_{DGT}(\text{g.s.}) \sim \mathbf{0.88} \cdot M^{2\nu}_{DGT}(\text{total})$$

No need for GT giant resonance



^{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

$^{128,130}Te$

^{128}Te - ^{130}Te

$$T_{1/2}^{2\nu} = 7.0^{\pm 0.9(\text{stat})}_{\pm 1.1(\text{sys})} \times 10^{20}\,\text{yr}$$

^{130}Te

$$T_{1/2}^{2\nu} = (1.9 \pm 0.4) \times 10^{24}\,\text{yr}$$

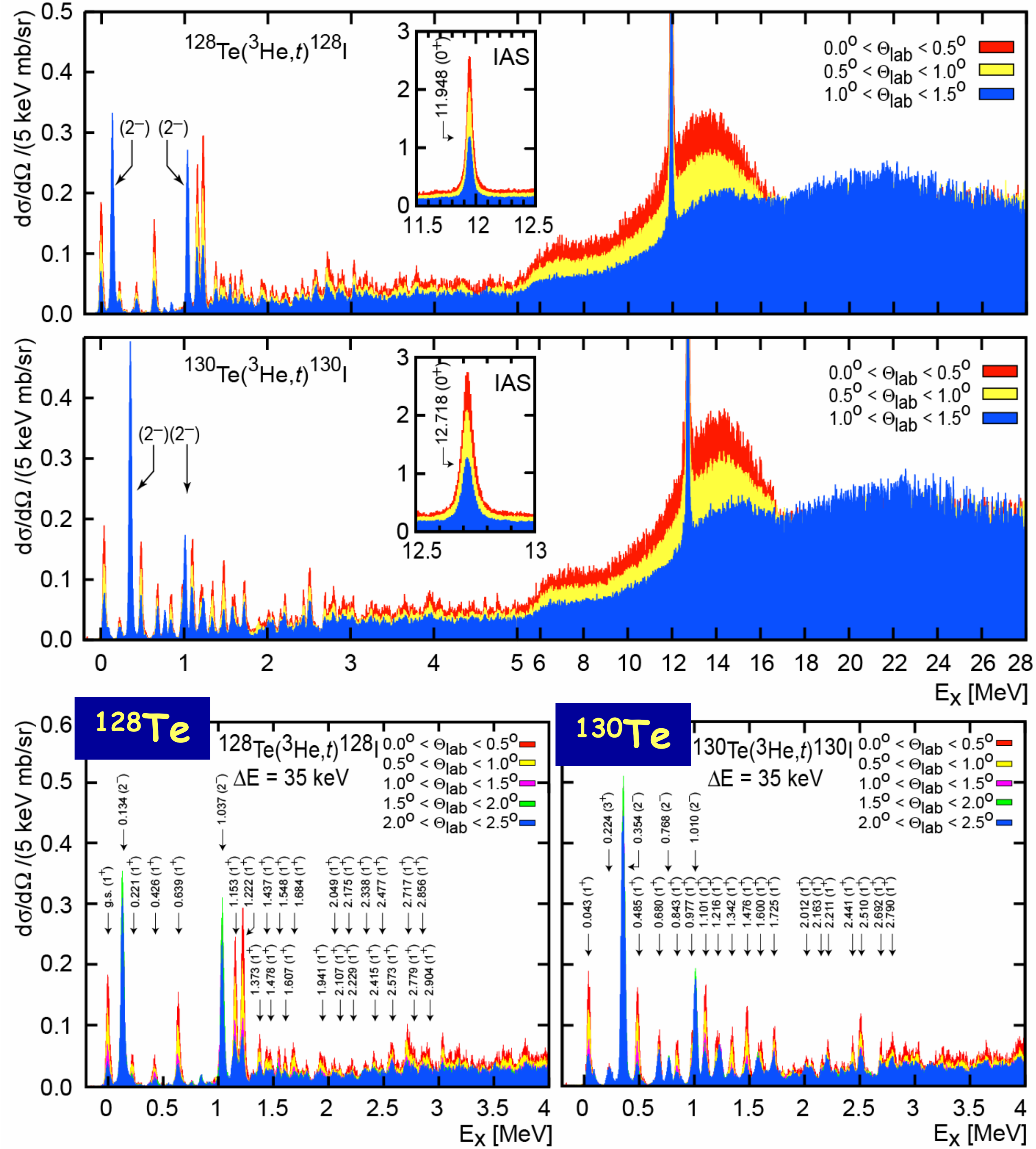
^{128}Te

from geochem. ratio

$$R\left(\frac{^{128}\text{Xe}}{^{130}\text{Xe}}\right) = (3.52 \pm 1.1) \times 10^{-4}$$

$$M_{\text{DGT}}^{2\nu}(^{128}\text{Te}) \sim 1.4 \cdot M_{\text{DGT}}^{2\nu}(^{130}\text{Te})$$

→ decay of ^{128}Te is accelerated by factor 2 !!



128Te

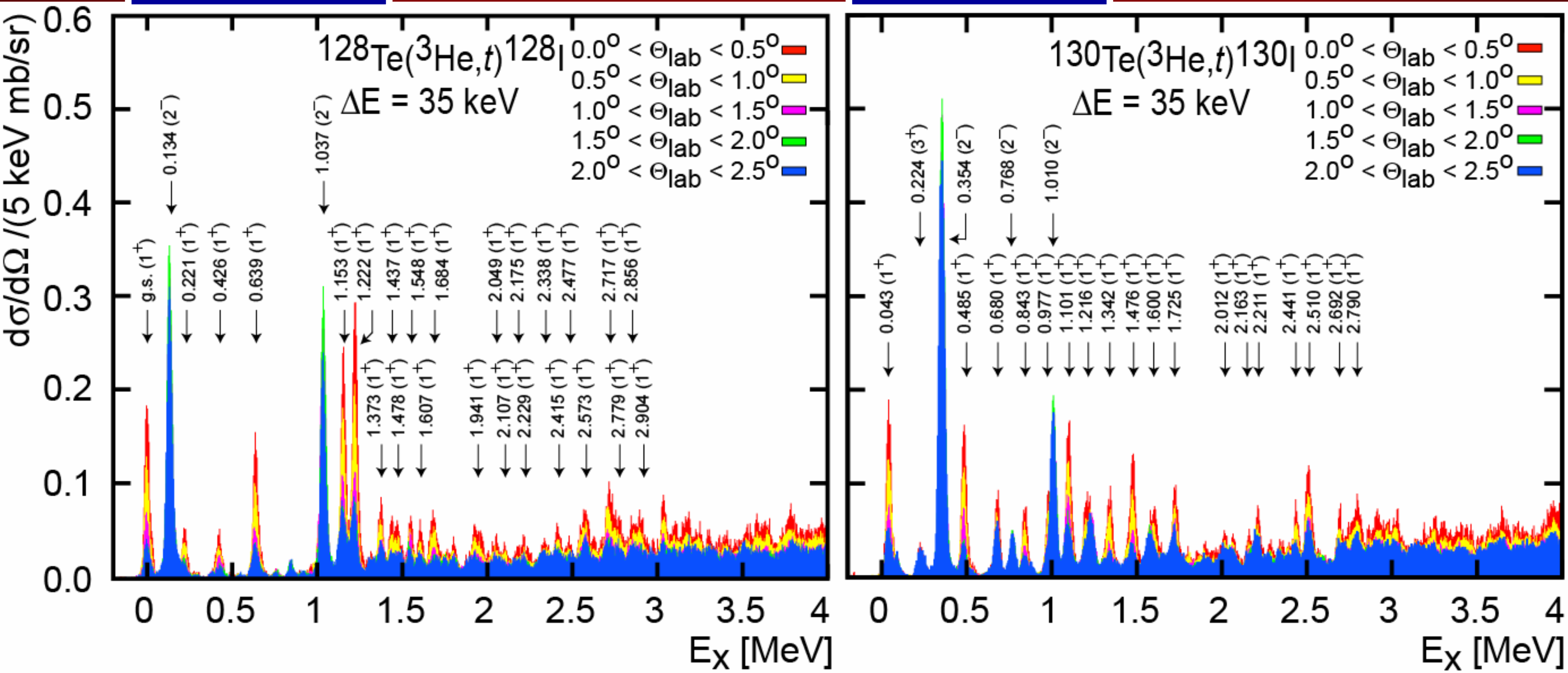
130Te

qualitatively equal

&

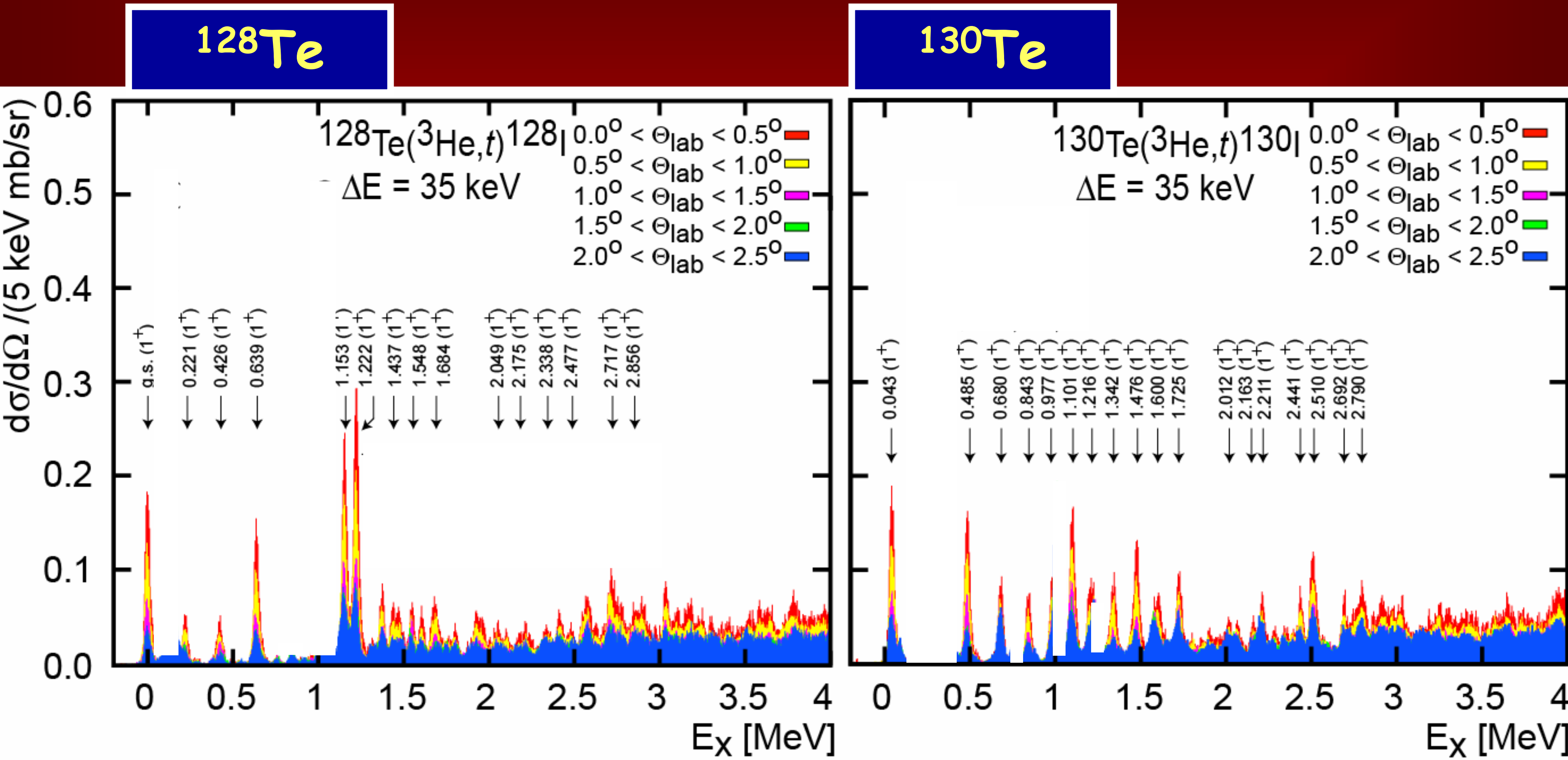
moderately fragmented

^{128}Te ^{130}Te



adding a neutron pair:

1. **little change at low energies**
2. **state at 1.2 MeV tends to dilute**



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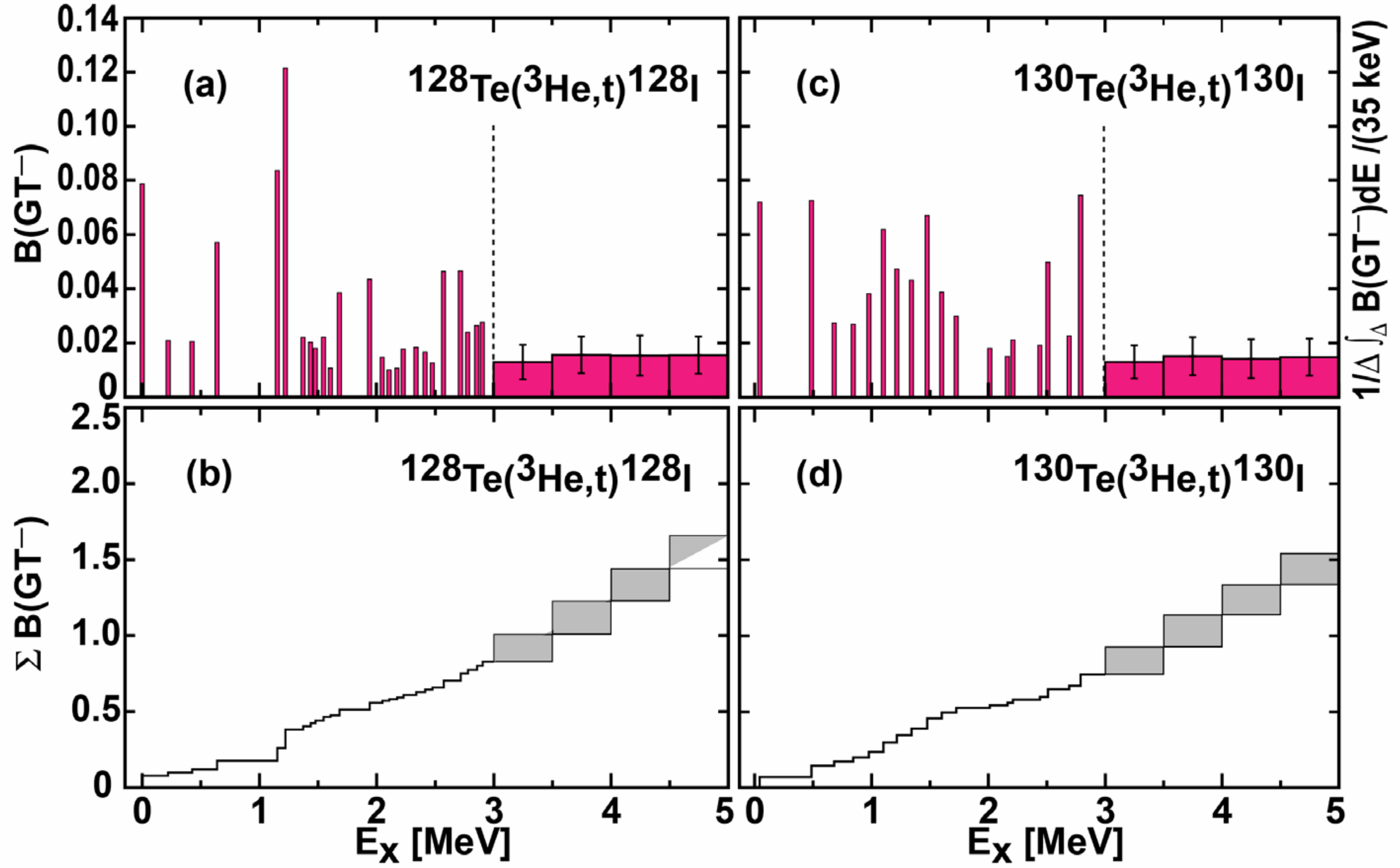
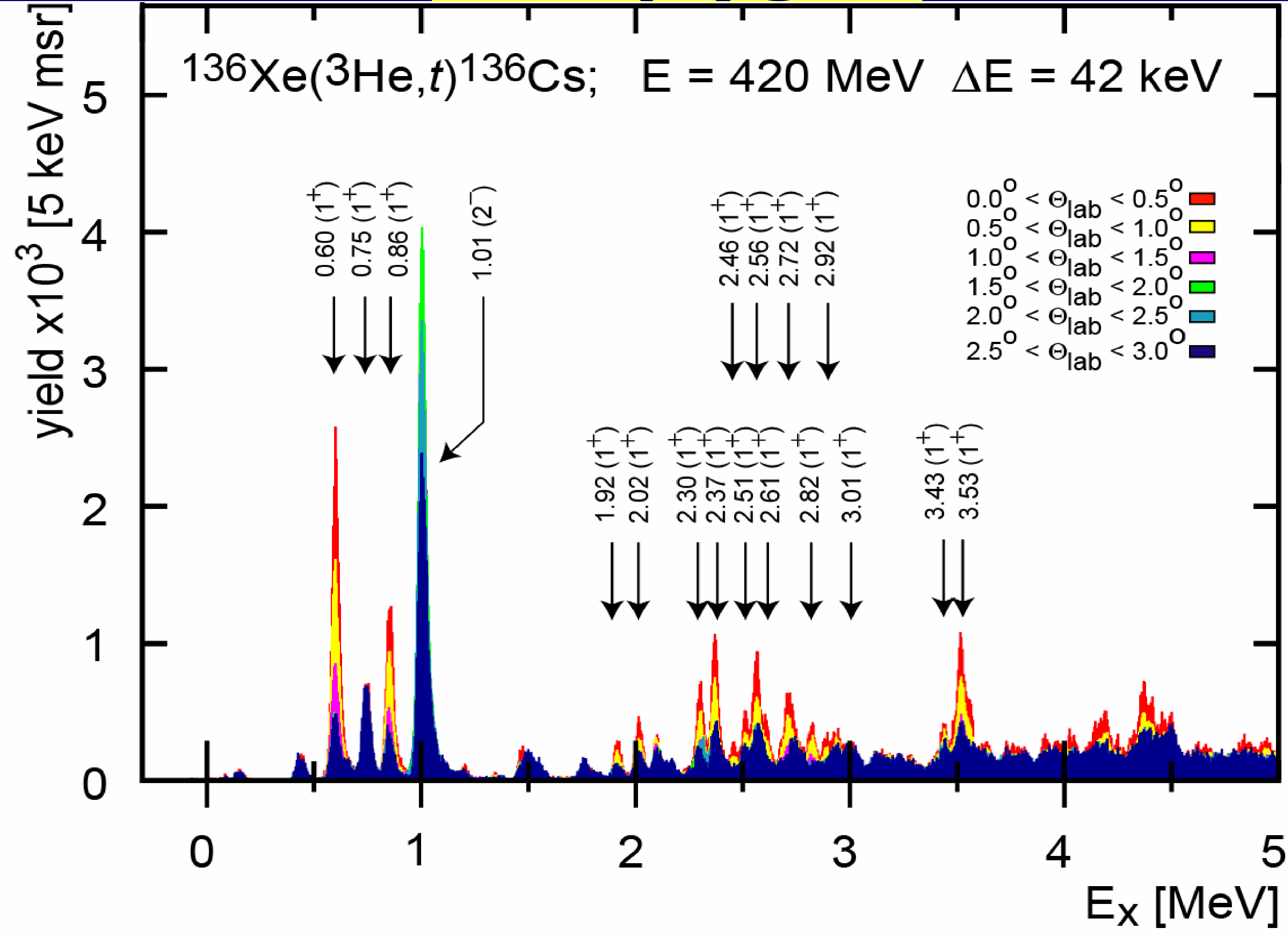


^{128}Te

^{130}Te

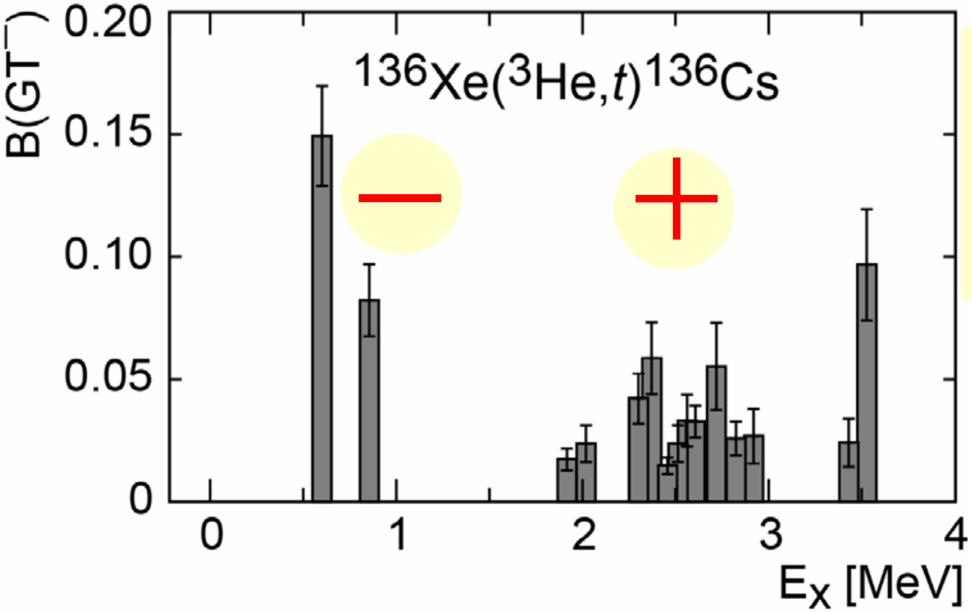
(slightly more fragmented)

136Xe



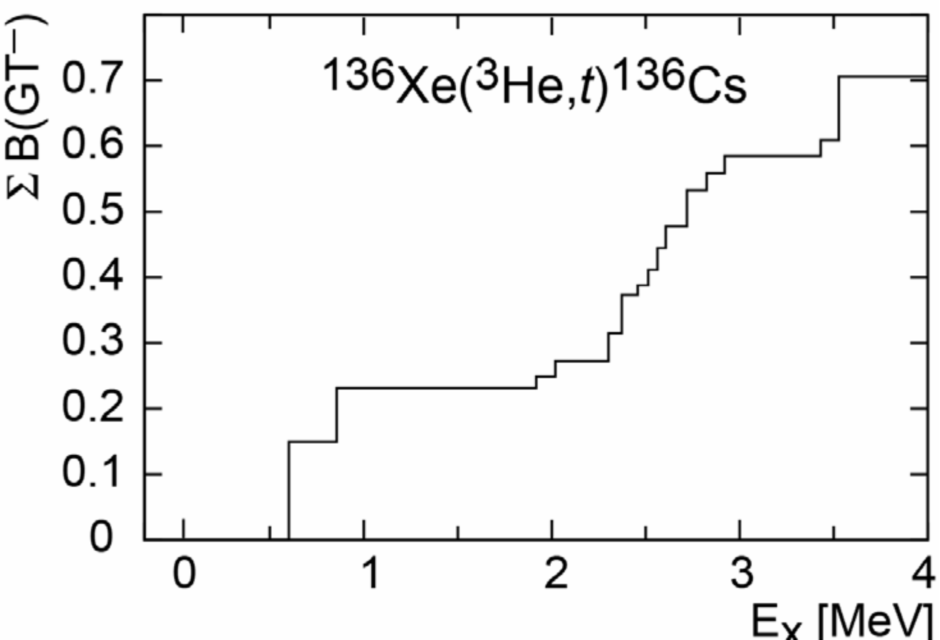
136Xe(3He,t)136Cs; E = 420 MeV ΔE = 42 keV
yield x10^3 [5 keV msr]
Ex [MeV]
0.60 (1+)
0.75 (1+)
0.86 (1+)
1.01 (2-)
2.46 (1+)
2.56 (1+)
2.72 (1+)
2.92 (1+)
1.92 (1+)
2.02 (1+)
2.30 (1+)
2.37 (1+)
2.51 (1+)
2.61 (1+)
2.82 (1+)
3.01 (1+)
3.43 (1+)
3.53 (1+)
0.0° < Θlab < 0.5°
0.5° < Θlab < 1.0°
1.0° < Θlab < 1.5°
1.5° < Θlab < 2.0°
2.0° < Θlab < 2.5°
2.5° < Θlab < 3.0°

How big is the matrix element?



$$T^{2\nu}_{1/2} = 2.11^{\pm 0.04(stat)}_{\pm 0.21(sys)} \cdot 10^{21}\,yr$$

$$M^{(2\nu)}_{DGT} \sim 0.019\ MeV^{-1}$$



scenario-1

all positive sig

$B_m(GT^+) \approx$ … $_m(GT^-)$

Unlikely … Puppe-PRC-2011)

scen

s… 1) = - sign (clst-2)

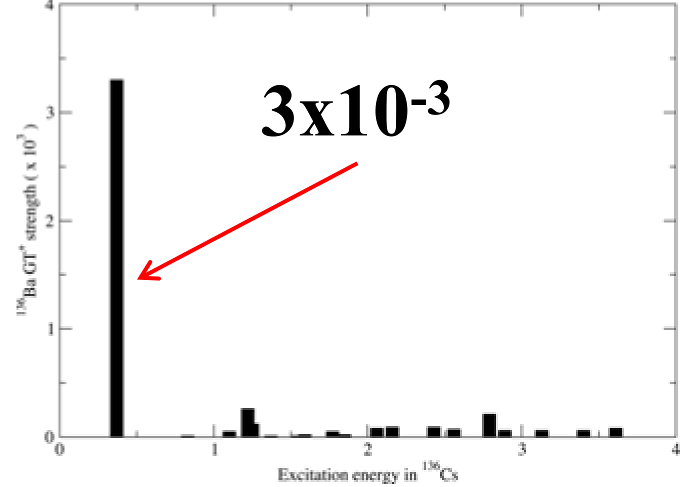
(in our paper Puppe-PRC-2011)

BUT

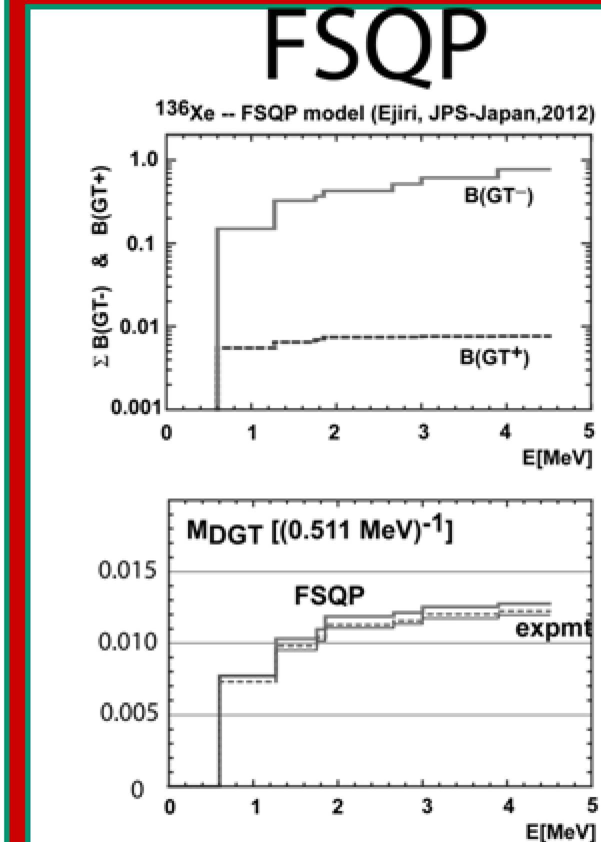
A. Poves:

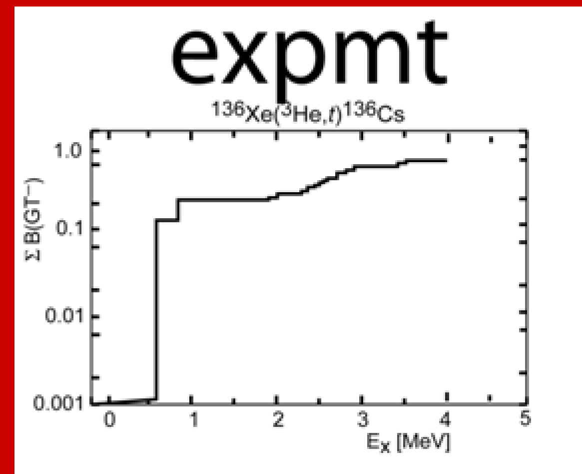
NO cancellation !!

There is no B(GT$^+$) strength, except for the lowest-E 1$^+$ state



H. Ejiri:





Shell model and the FSQP DO provide an explanation for the pathologically long half-life

Conclusion

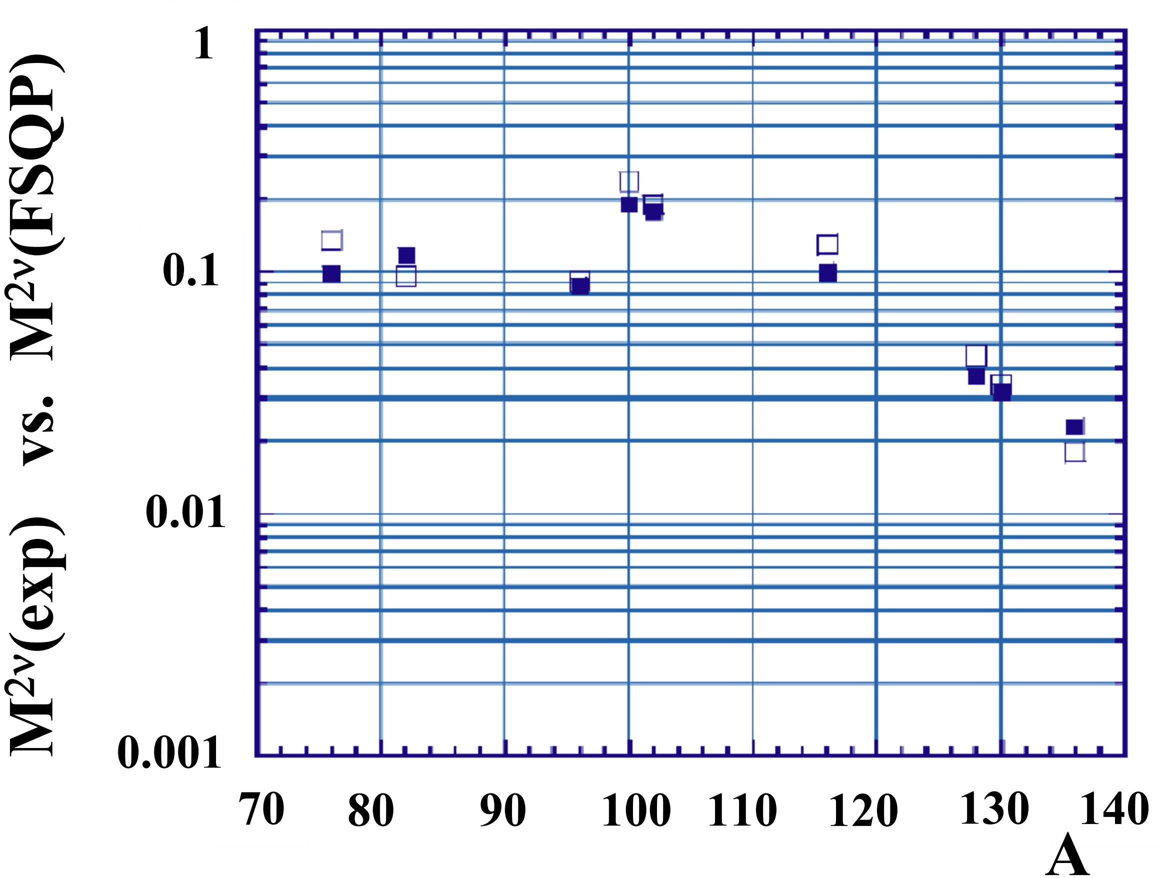
1 Chargex reactions are a powerful tool to determine the $2\nu\beta\beta$ NME
$(d,{}^2He)$ $(t,{}^3He)$ → „GT^+ leg“ & $({}^3He,t)$ → „GT^- leg“
high resolution is essential.

2 The difference between the intrinsic deformation of mother and daughter nucleus seems to cause „state-by-state mismatch“ of B(GT)'s ---------→ How big is the effect on the $0\nu\beta\beta$ NME ??

3 In all cases the **low energy part** of the GT distribution seems to be most relevant for the 2ν decay
even „Single-State-Dominance“ for ^{96}Zr und ^{100}Mo

Would this be true for the $0\nu\beta\beta$ decay as well ?

4 There is an increased urgency to improve theoretical models



$M^{2\nu}(exp)$ vs. $M^{2\nu}(FSQP)$
1
0.1
0.01
0.001
70
80
90
100
110
120
130
140
A

TRIUMF

Westfälische
Wilhelms-Universität
Münster

The SAGE and GALLEX neutrino problem

Remember:

1) SAGE and GALLEX were the two solar neutrino detectors for low-energy (pp) neutrinos !!

2) detection material 60t Ga

3) reaction: $^{71}Ga\ (\nu_e, e^-)^{71}Ge$ (Q=232 keV)

4) signature: $^{71}Ge \xrightarrow{EC} {}^{71}Ge + \text{x-ray}$

HWZ: 11.4d

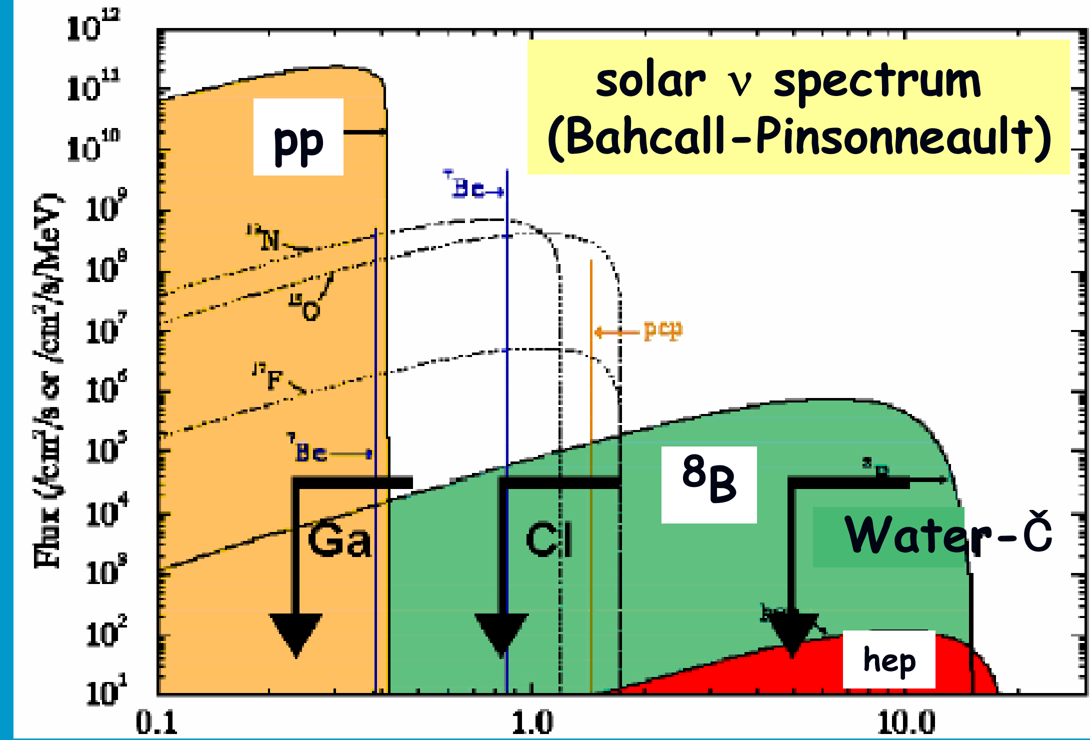
SAGE / GALLEX

$^{71}Ga\ (\nu_e, e^-)^{71}Ge$

(Q=232 keV)

Expected rate: ~ 132 SNU

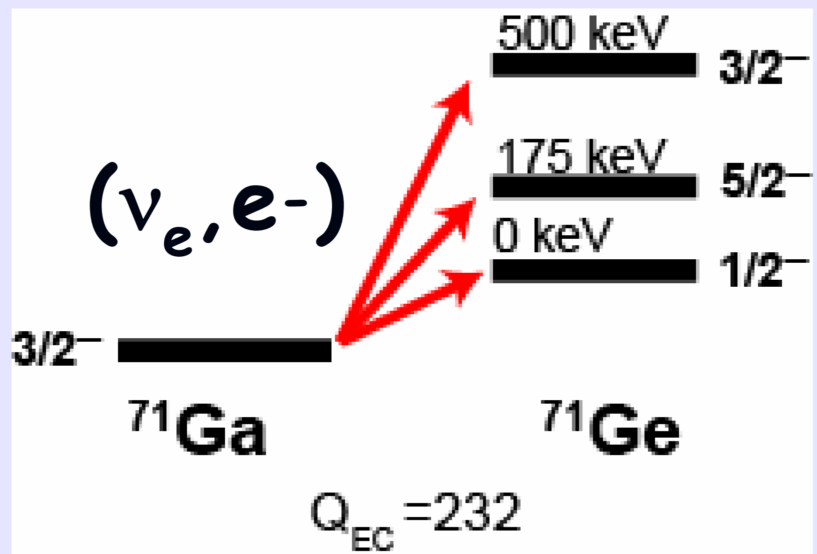
SAGE: 65.4 ± 3.0 SNU
GALLEX: 73.4 ± 7.2 SNU



Calibration with ^{51}Cr (^{37}Ar) ν-source

51Cr

E_ν	transition	BR
747.3 keV	K-EC → ^{51}V g.s.	81.6 %
752.1 keV	L-EC → ^{51}V g.s.	8.5 %
427.1 keV	K-EC → $^{51}V^*$ (320)	8.95 %
432.0 keV	L-EC → $^{51}V^*$ (320)	0.9 %



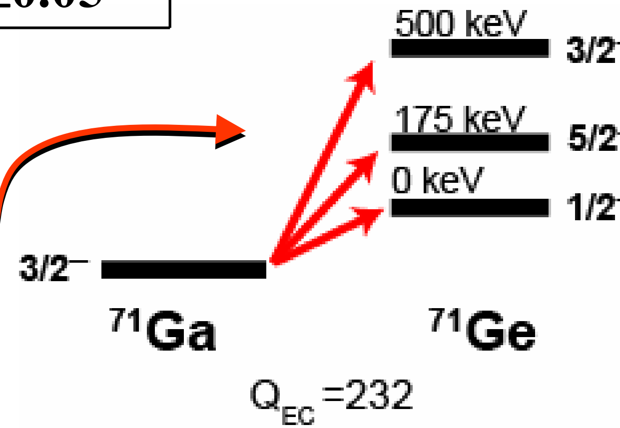
Results of calibration
meas'd evts/ # exp'd evts

experiment	source	ratio
GALLEX	^{51}Cr	0.882±0.078
SAGE	^{51}Cr	0.95± 0.12
SAGE	^{37}Ar	0.79±0.10
average	^{37}Ar, ^{51}Cr	0.87±0.05

Bahcall, Phys. Rev. C56, 3391 (1997):

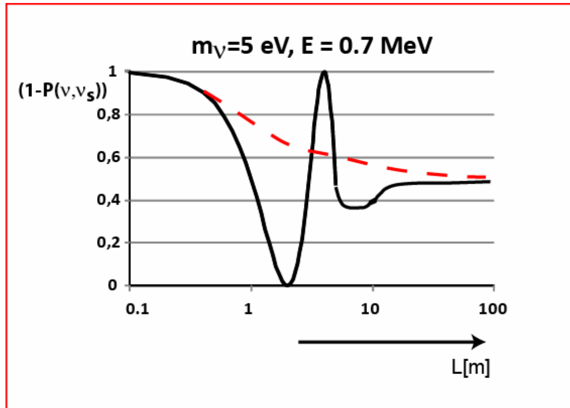
$$\sigma\left({}^{51}\mathrm{Cr}\right)=\sigma_0({}^{51}\mathrm{Cr})\left[1+0.67\frac{B_1(GT)}{B_0(GT)}+0.22\frac{B_2(GT)}{B_0(GT)}\right]$$

Bahcall: 5.1



Possible solutions:

1. efficiencies of detectors — denied √
2. neutrino x-section — may be √
3. sterile neutrinos with small L/E, i.e. L_{osc}~ cm – m & m_ν ~ eV–10 eV — who knows √

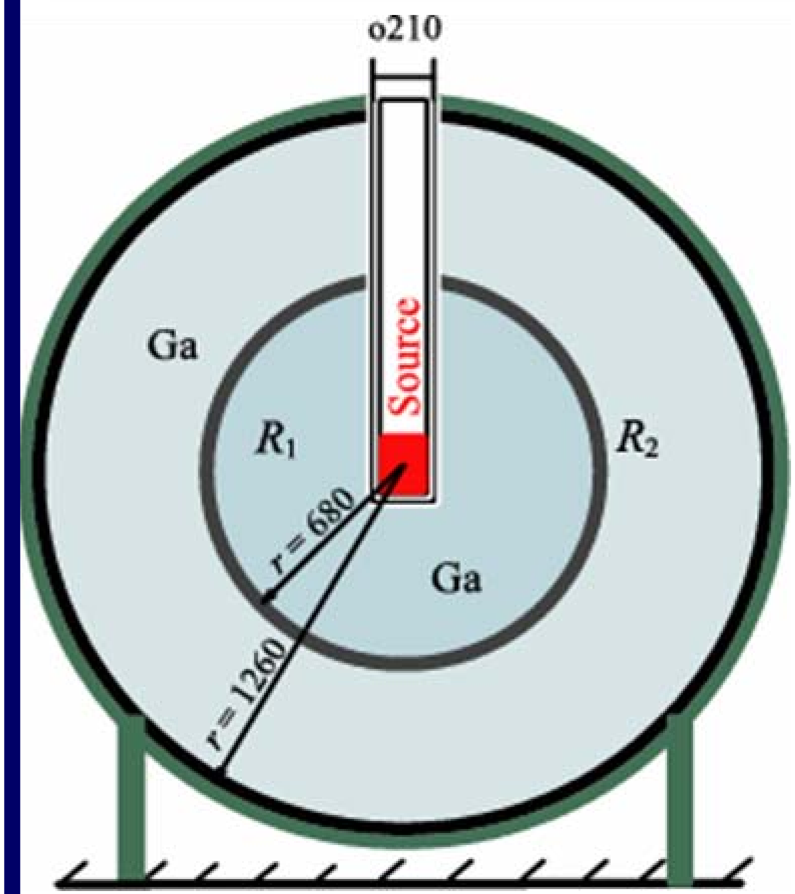


Gallium experiments with artificial neutrino sources as a tool for investigation of transition to sterile states

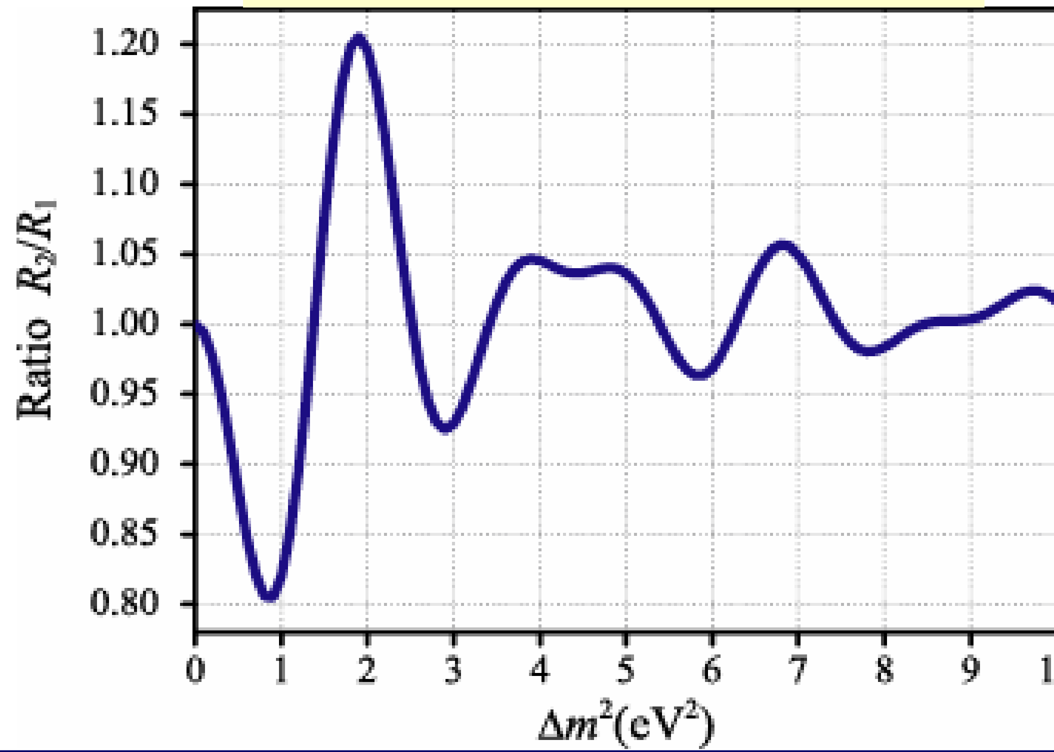
V. N. Gavrin,* V. V. Gorbachev,* E. P. Veretenkin,* and B. T. Cleveland†

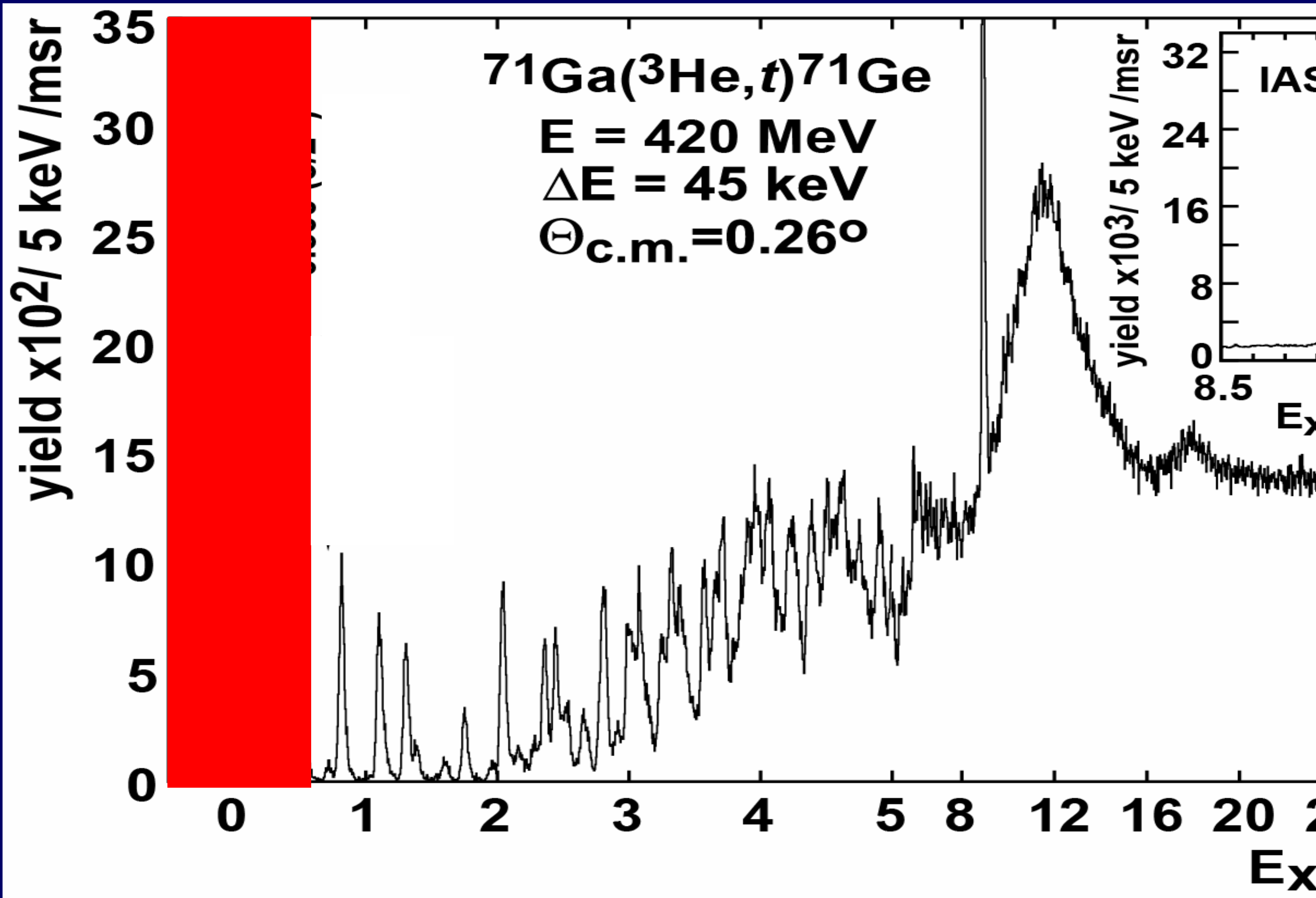
20 July 2010

We propose to place a very intense source of ^{51}Cr at the center of a 50–tonne target of gallium metal that is divided into two concentric spherical zones and to measure the neutrino capture rate in each zone. This experiment can set limits on transitions from active to sterile neutrinos with $\Delta m^2 \approx 1$ eV^2 with a sensitivity to disappearance of electron neutrinos of a few percent.



ratio: $\dfrac{\text{\# event outer circle}}{\text{\# event inner circle}}$





$^{71}Ga(^3He,t)^{71}Ge$
E = 420 MeV
ΔE = 45 keV
$\Theta_{c.m.}$=0.26°
yield x10²/ 5 keV /msr
35
30
25
20
15
10
5
0
0
1
2
3
4
5
8
12
16
20
Ex
yield x10³/ 5 keV /msr
32
24
16
8
0
8.5
IAS
Ex

Checking the neutrino x-section

2) The ft-value of ^{71}Ge (EC)

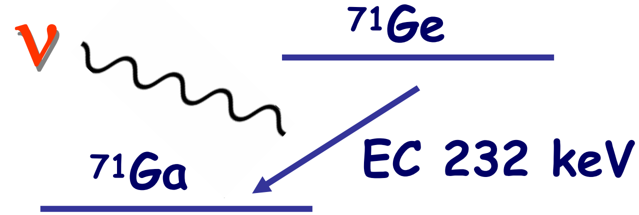
$$\sigma(^{51}\mathrm{Cr}) = \sigma_0(^{51}\mathrm{Cr})\left[1 + 0.67\frac{B_1(GT)}{B_0(GT)} + 0.22\frac{B_2(GT)}{B_0(GT)}\right]$$

$$\sigma_0(^{51}\mathrm{Cr}) = F(\mathrm{atom})\ \frac{1}{ft}$$

$$ft \propto Q_{EC}^2 \cdot t$$

!

Problem:
how to measure the EC Q-value ?



In 1/10^4 cases the EC decay is accompanied by a photon (int'nl bremsstrahlung, IB-EC)

1) **the end-point spectrum is sensitive to the neutrino mass → of course!!**

2) **end-point energy determines the Q-value (Q_{EC})**

BUT:

nobody really knows how the end-point spectrum looks like – esp'lly near Q_{EC} – (E(K_α) ~ 8–10 keV).

Q: Are atomic excit'ns / de-excit'ns decoupled from IB??
and what are these excitations in case of IB-EC

Conditions for IB detection

1. Need extremely strong sources
   (~ 10^{10} – 10^{11} Bq) (thru (n,γ) activation)
2. Extreme activity of K-shell X-rays precludes use of internal source (i.e. activation of detector)
3. Extreme pile-up components to deal with
4. Unknown background conditions after activation
5. Need precise knowledge of efficiencies

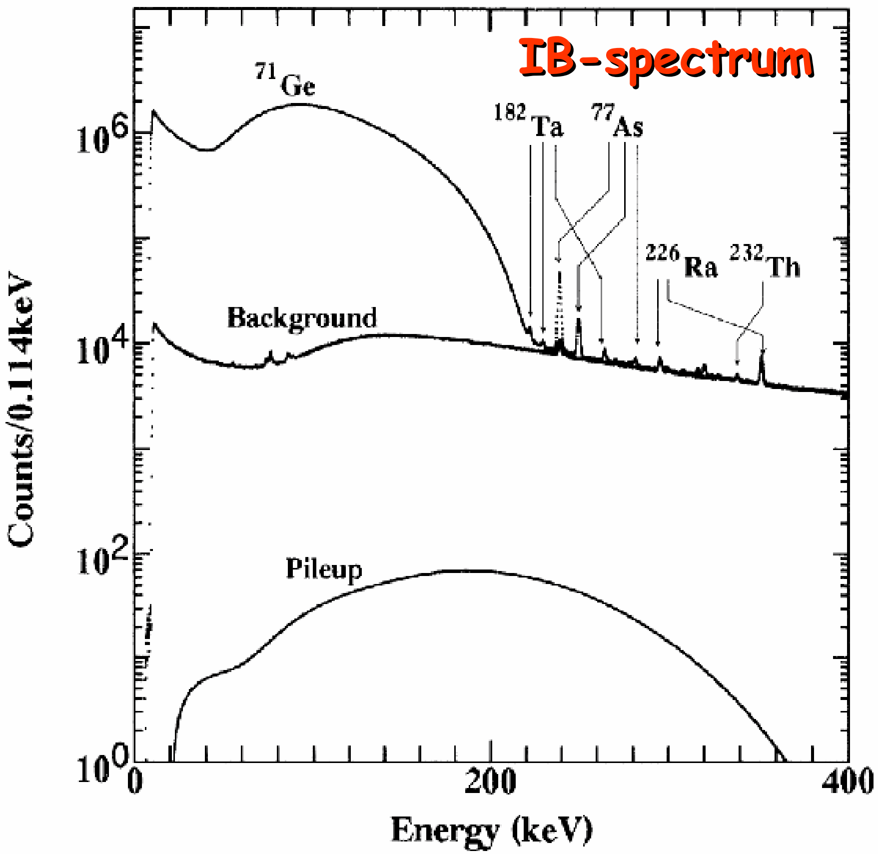
Corollary:

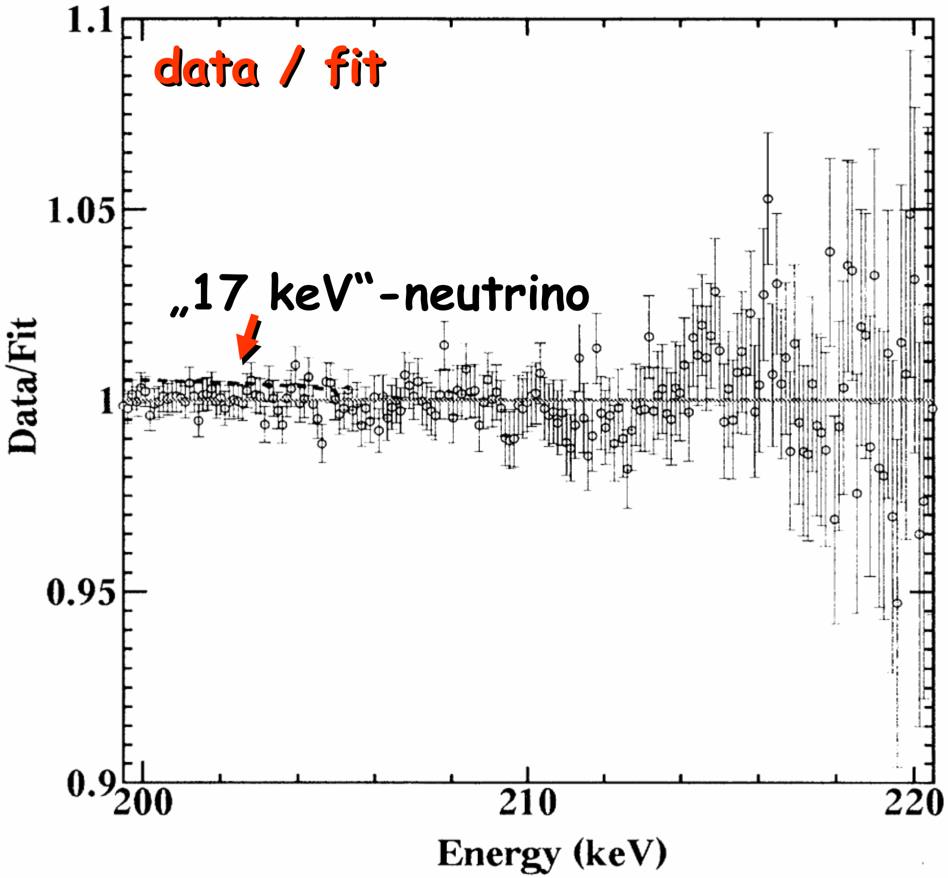
None of the IB-EC experiments on ^{71}Ge were intended for an exact meas'nt of the Q-value

Saraf et al., PR91, 1216 **(1953)**
Blisi et al., Nuov. Cim. 11, 290 **(1955)**
Žlimen et al., PRL 67, 560 **(1991)** ✓
DiGrigorio et al., PRC47, 2916 **(1993)**
Lee et al., PRC51, 2779 **(1995)**

„17 keV"-neutrino

Example:
Lee et al., PRC51, 2779 (1995)

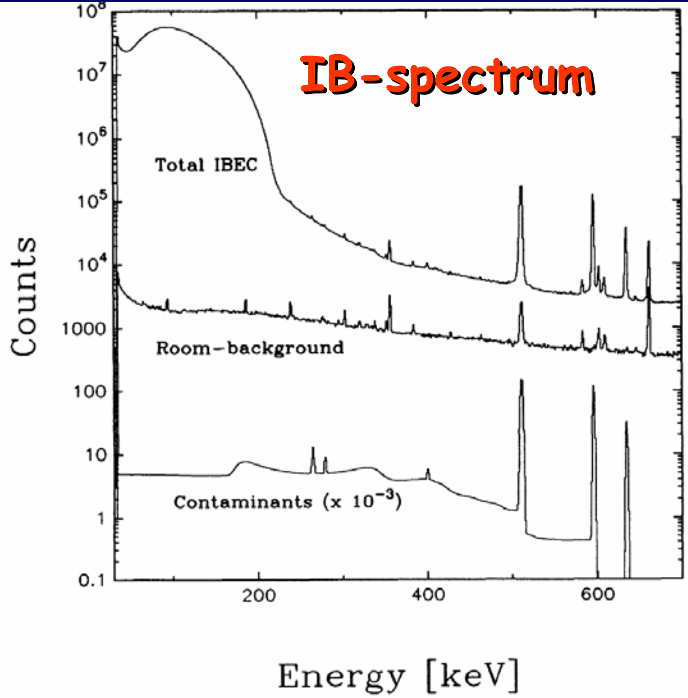


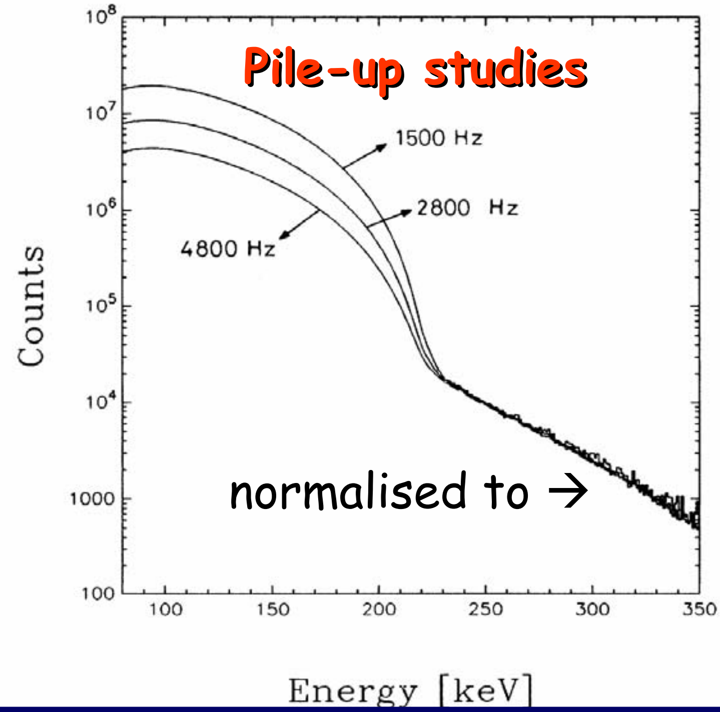


Quoted:
Q_{EC}=232.65 ± 0.15 keV

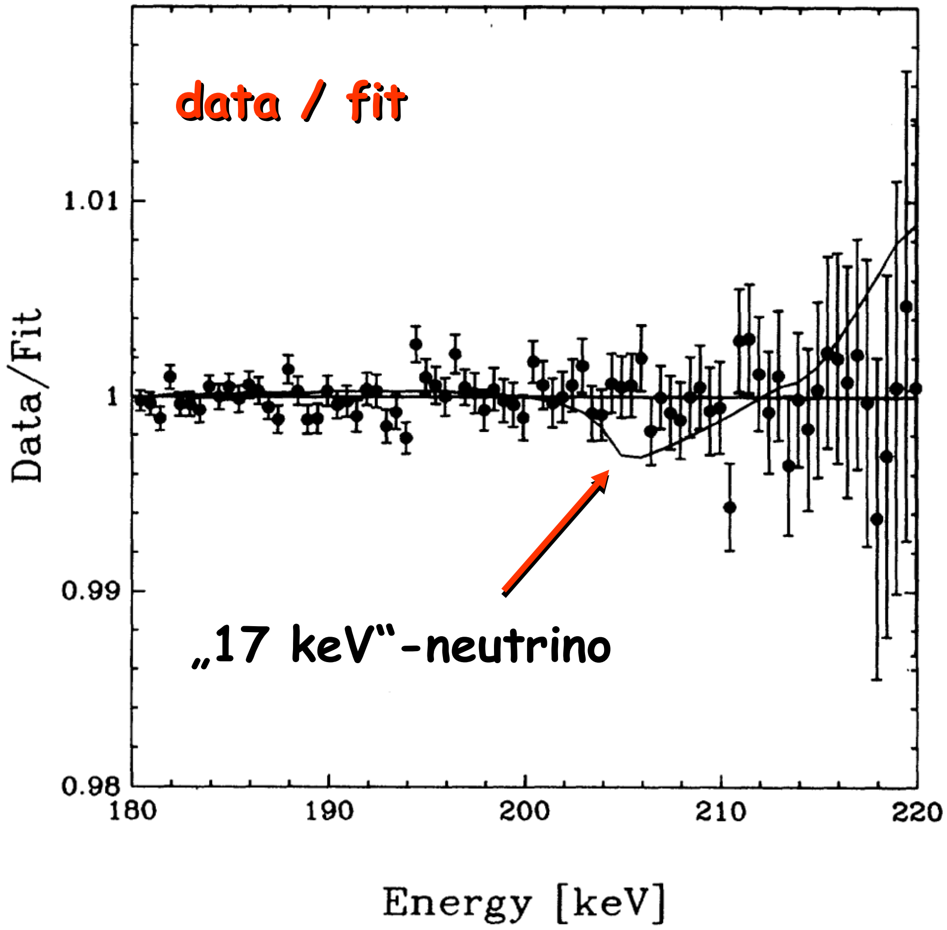
Example:

DiGrigorio et al., PRC 47, 2916 (1993)

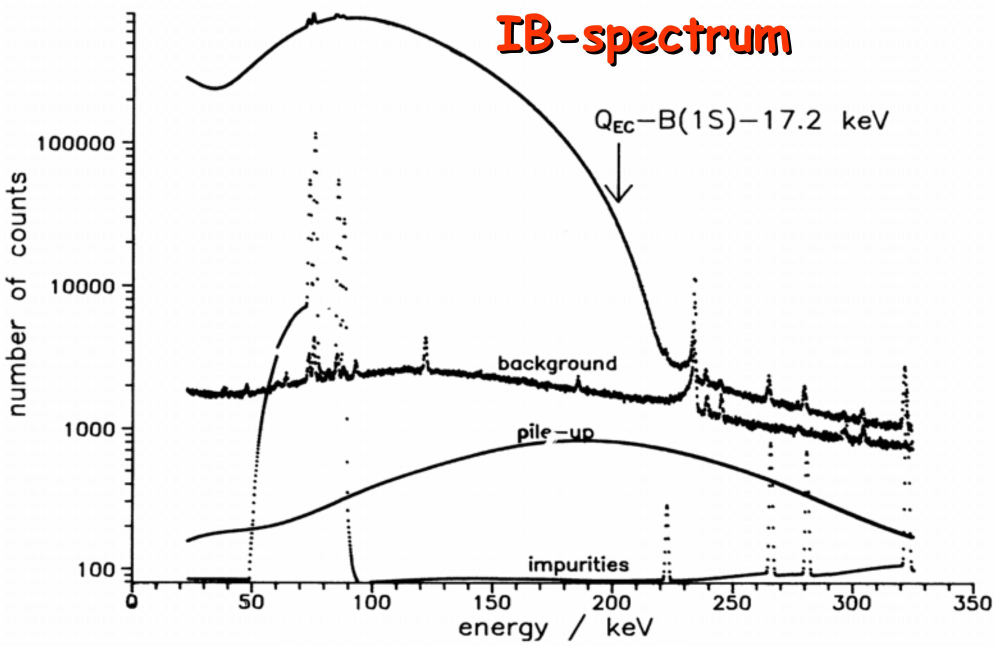


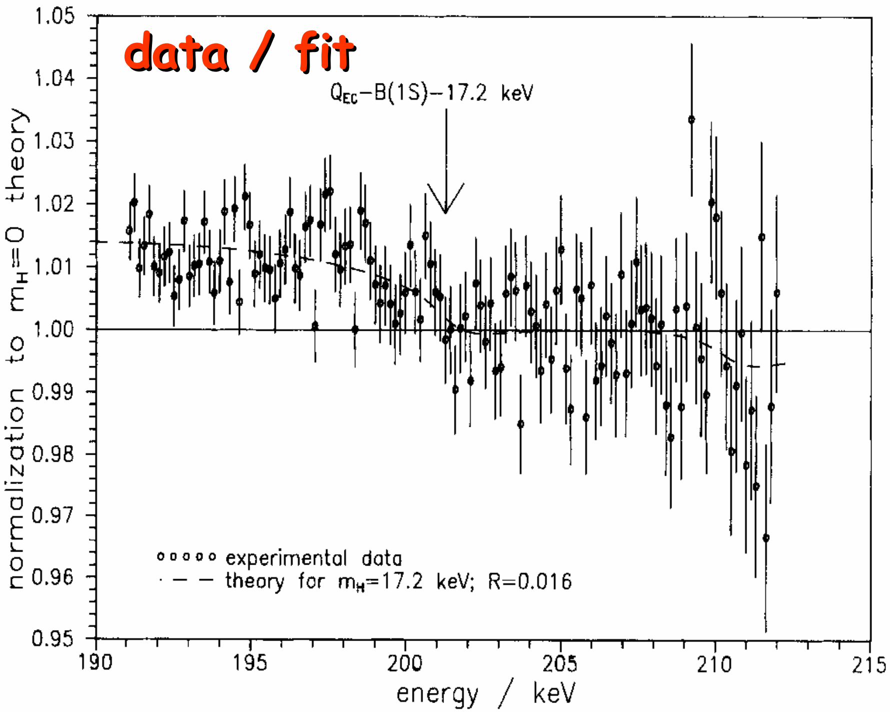


Quoted:
$Q_{EC}=232.1 \pm 0.1$ keV



Example:
Žlimen et al., PRL67, 560 (1991)





Quoted:
Q_{EC}=229.0 ± 0.5 keV, $m_{H\nu}$=17.2 keV
B(1S) = 10.367 keV (of daughter!!)

^{71}Ga/^{71}Ge Q-value measurement expmt (TITAN setup)

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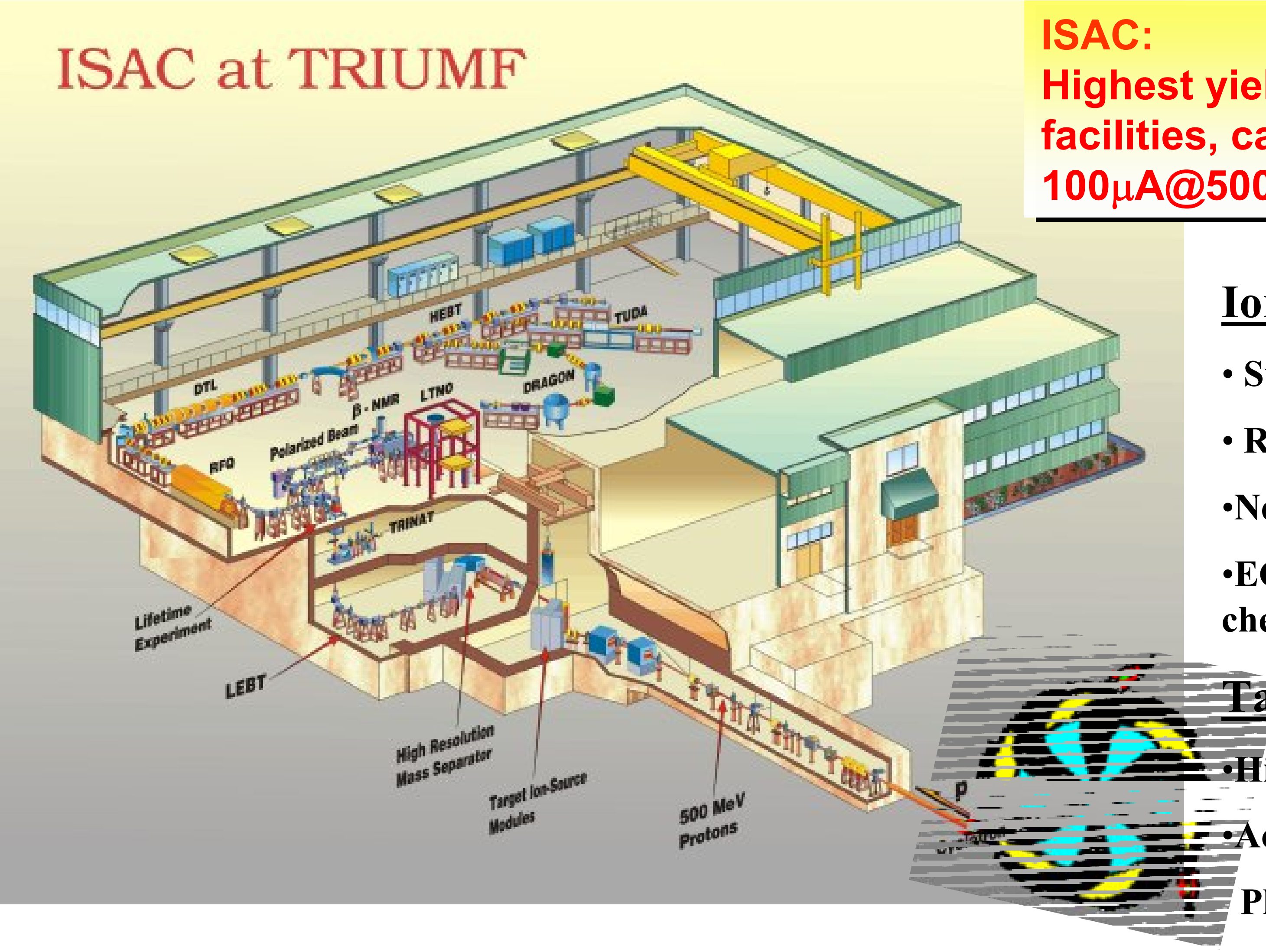
Production of radioactive isotopes @ ISAC/TRIUMF



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

Ion-sources:

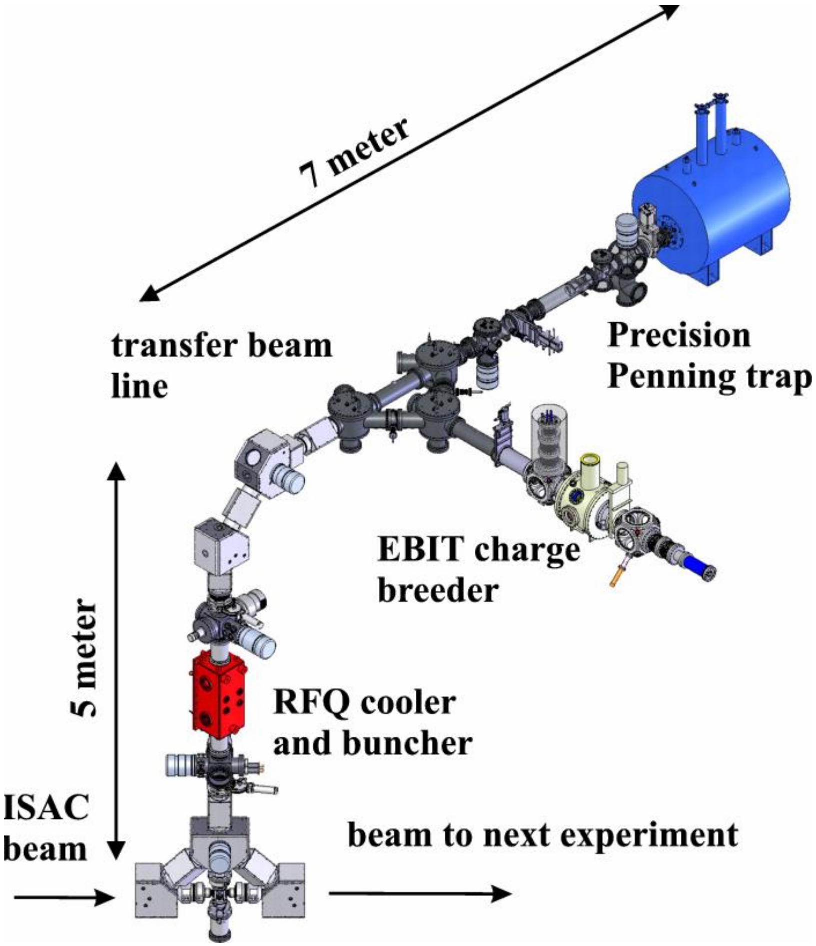
- Surface ☑
- Resonant-Laser source☑
- Negative, off-line test ☑
- ECR, on-line tests and checks ☑

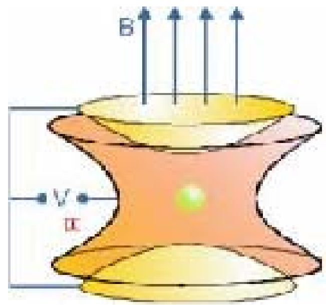
Targets:

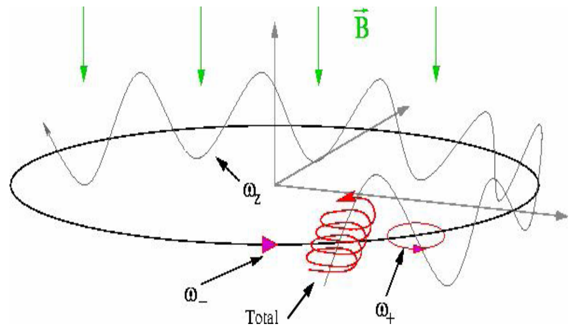
- High power targets ☑
- Actinide targets:

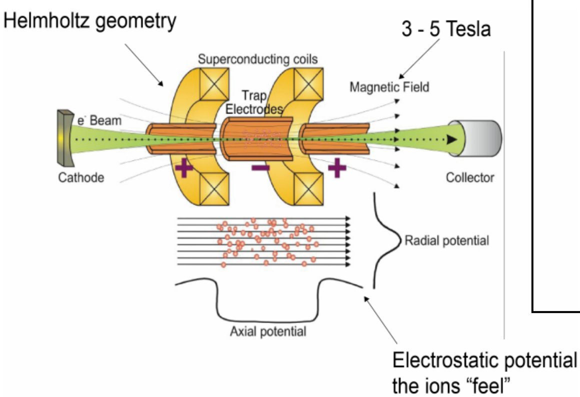
  Plan to run tests 2012

TITAN-TRIUMF's Ion Trap for Atomic & Nuclear science









$$\nu_c = \frac{1}{2\pi}\frac{q}{m}\cdot B$$

$$\frac{\delta m}{m} \approx \frac{m}{q\cdot B\cdot T_{RF}\sqrt{N}}$$

1. radioactive beam provided by ISAC
2. transfer to EBIT (charge breeding - to highly-charged ions)
3. transfer to Penning trap (frequency meas'mnt via TOF)

^{71}Ga/^{71}Ge Q-value measurement expmt (TITAN MPET and EBIT)

Issues:

1) need ^{71}Ga beam AND radioactive ^{71}Ge beam (~ 10^7–10^8 p/s) by spallation with 500 MeV (30μA) p-beam on Ta target.

2) separation of ^{71}Ga / ^{71}Ge by laser-ionization /surface ionization

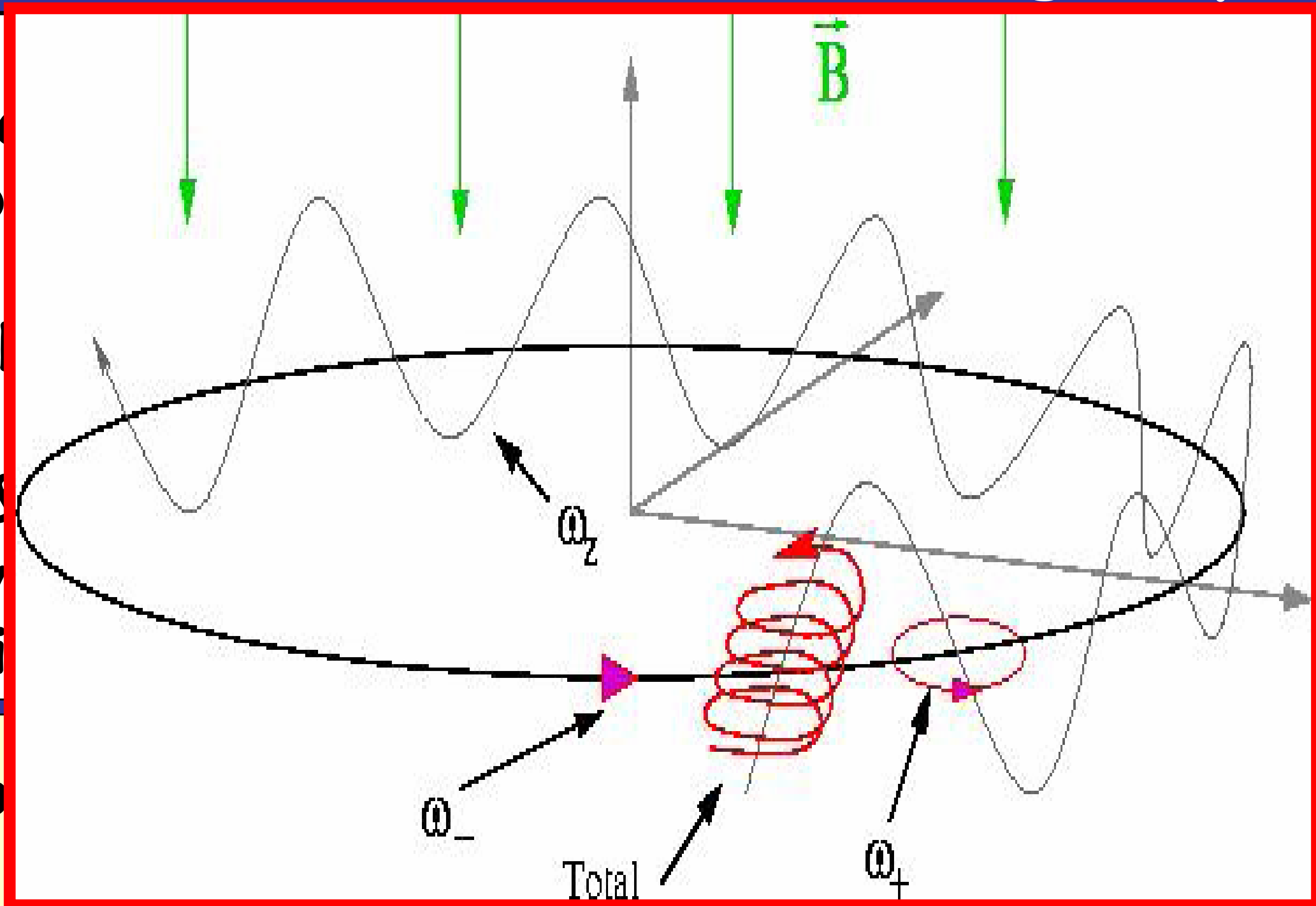
3) transport beam to mass measurment setup (30m)

4) Increase charge-state by charge-breeding ions to Ne-like charge-states
   - beam-1 → pure ^{71}Ga charge-state 21^+
   - beam-2 → pure ^{71}Ge beam for charge-state 22^+ eliminates effectively ^{71}Ga

Scheme ensures:
high isobaric purity !!! & high precision $\Delta m/m \sim 1/q$

Principle of mass measurements with Penning trap

1) single ion inje
2) confinement b
   E-field
3) excitation wit
   frequency
4) trap opening &
   kinetic energy
   → time-of-fli



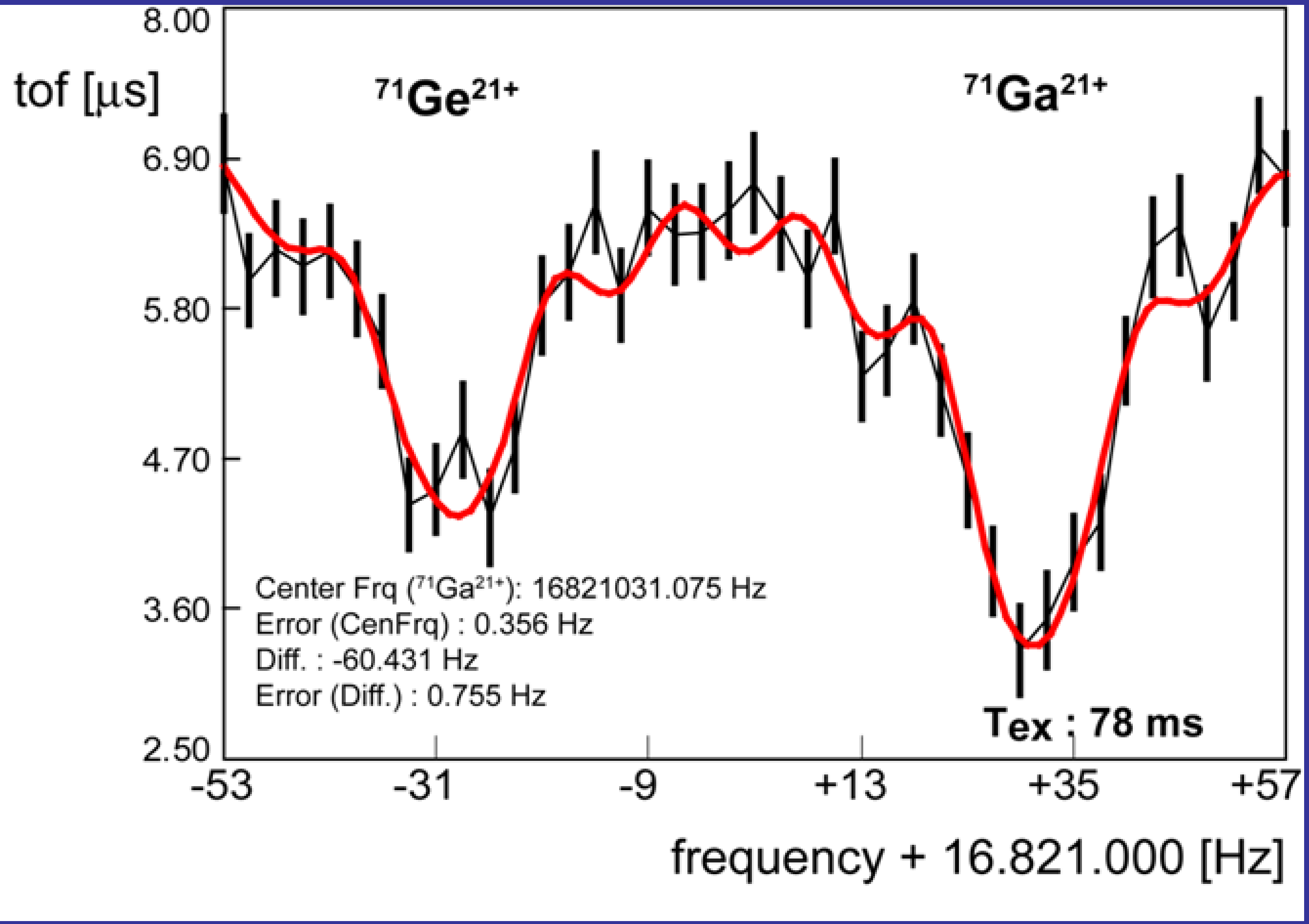
cyclotro

precision: $\frac{\delta m}{m} \approx \frac{m}{q \cdot B \cdot T_{RF}\sqrt{N}}$

depends on
charge state !!

mass: $m_1 = \frac{q_1}{q_2} \cdot \frac{\nu_2}{\nu_1} \cdot m_2$

both ion species, laser-ionized, charge-bred 21+, excitation time 78 ms



We observe that the mass difference between ^{71}Ge and ^{71}Ga is close to the literature value

(surprising)

Q_{EC} = 234.0 +/- 1.0 keV

Conclusion about the SAGE/GALLEX problem:

nuclear physics aspect of ν x-section has been investigated with high precision

1) **Contribution from excited states: 7.2±2% (5.1% →Bahcall) amplifies the discrepancy**

2) **Q_{EC} - value is close to the Bahcall value (he was lucky), new value only reduces contribution from excited states to 6.5%**

The observed SAGE/GALLEX discrepancy

is NOT due to any

unknowns in Nuclear Physics

Gallium experiments with artificial neutrino sources as a tool for investigation of transition to sterile states

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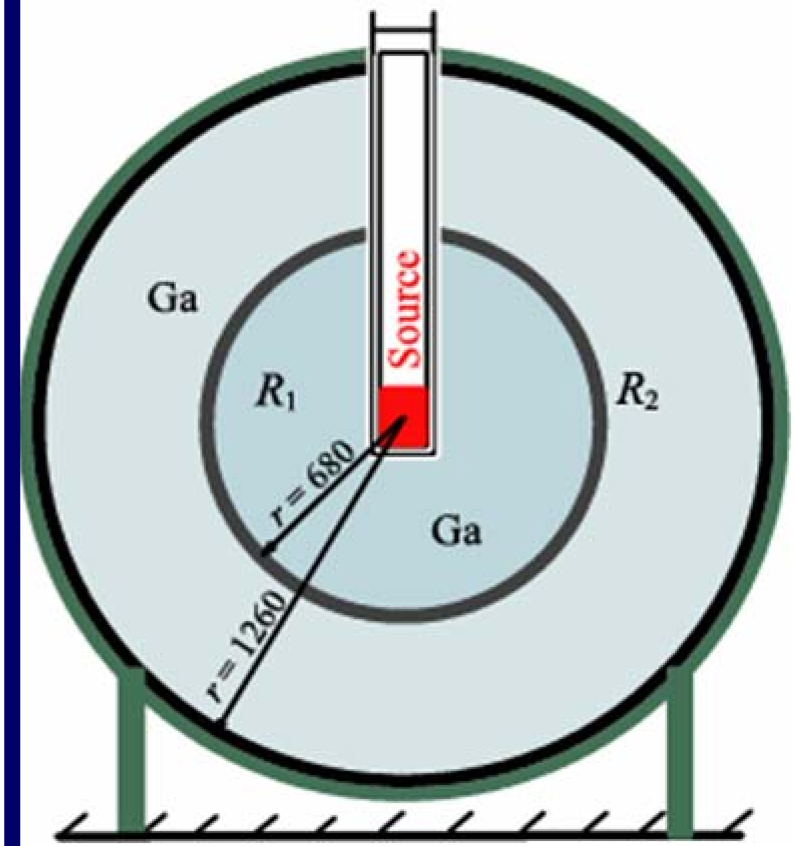

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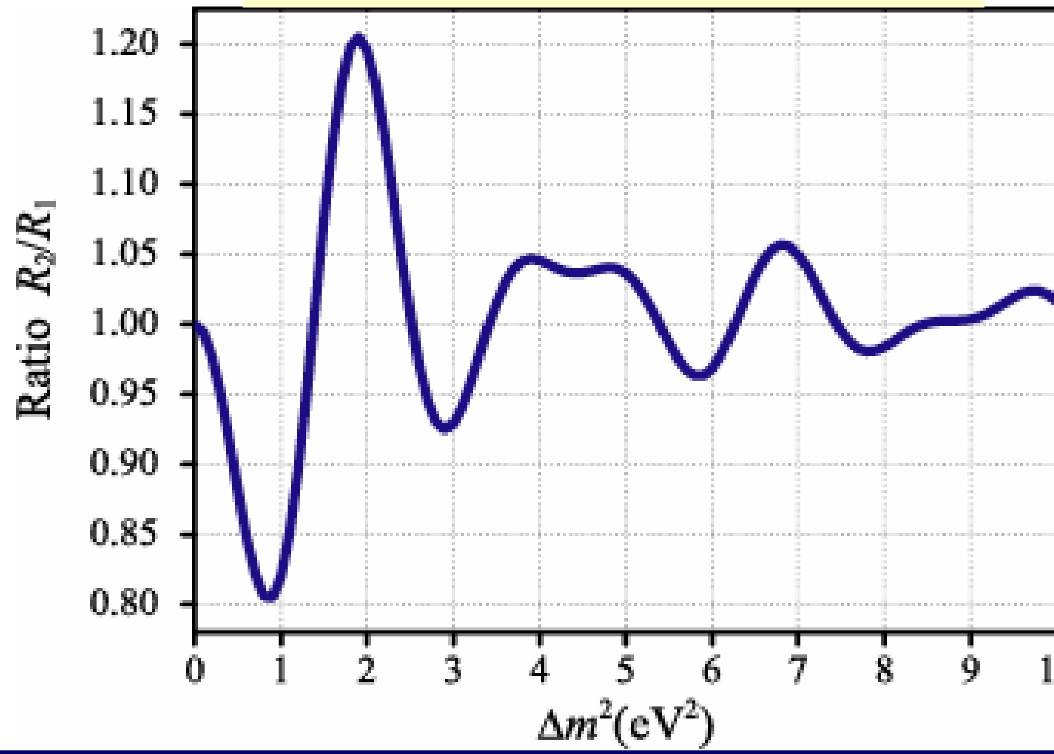
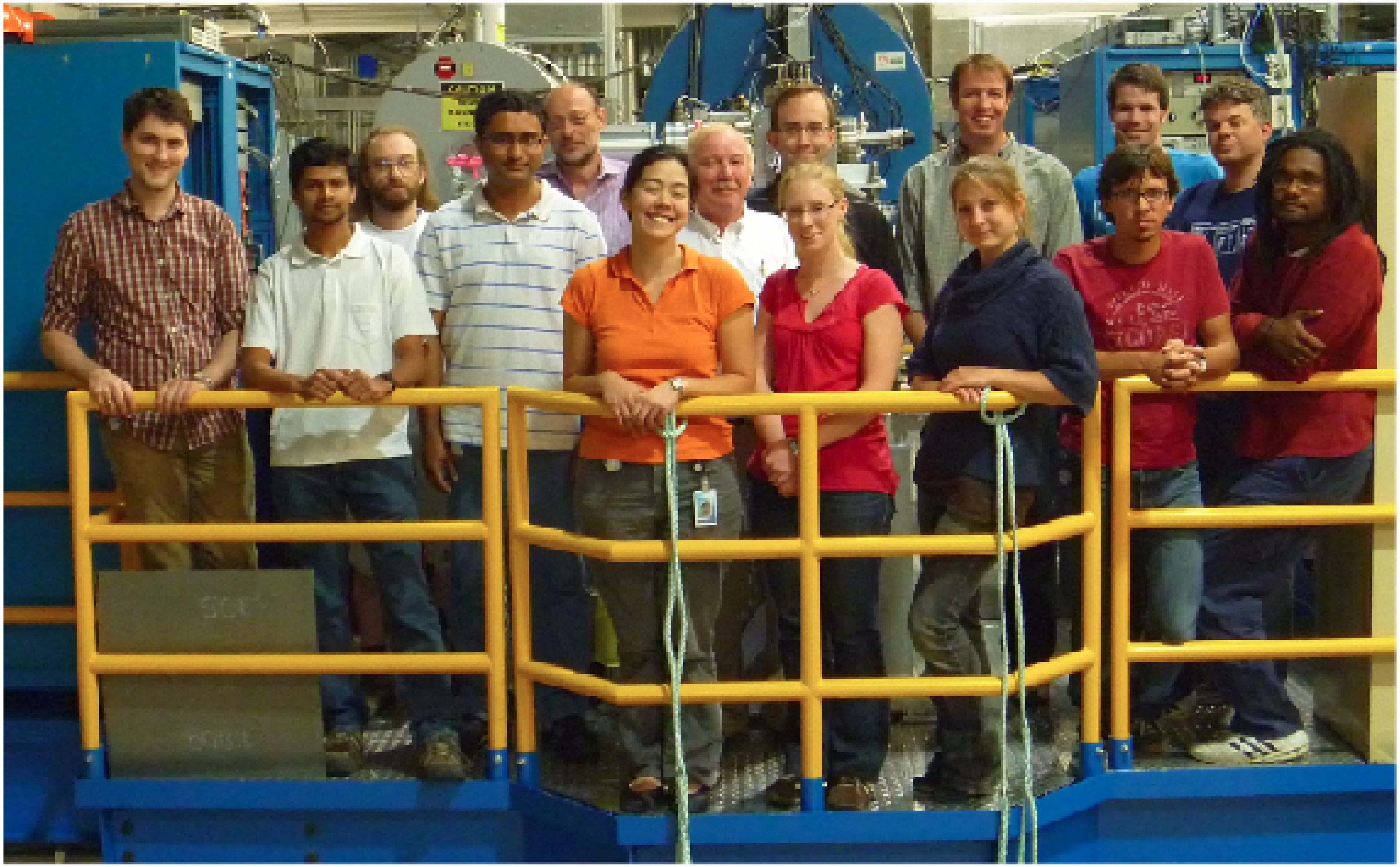


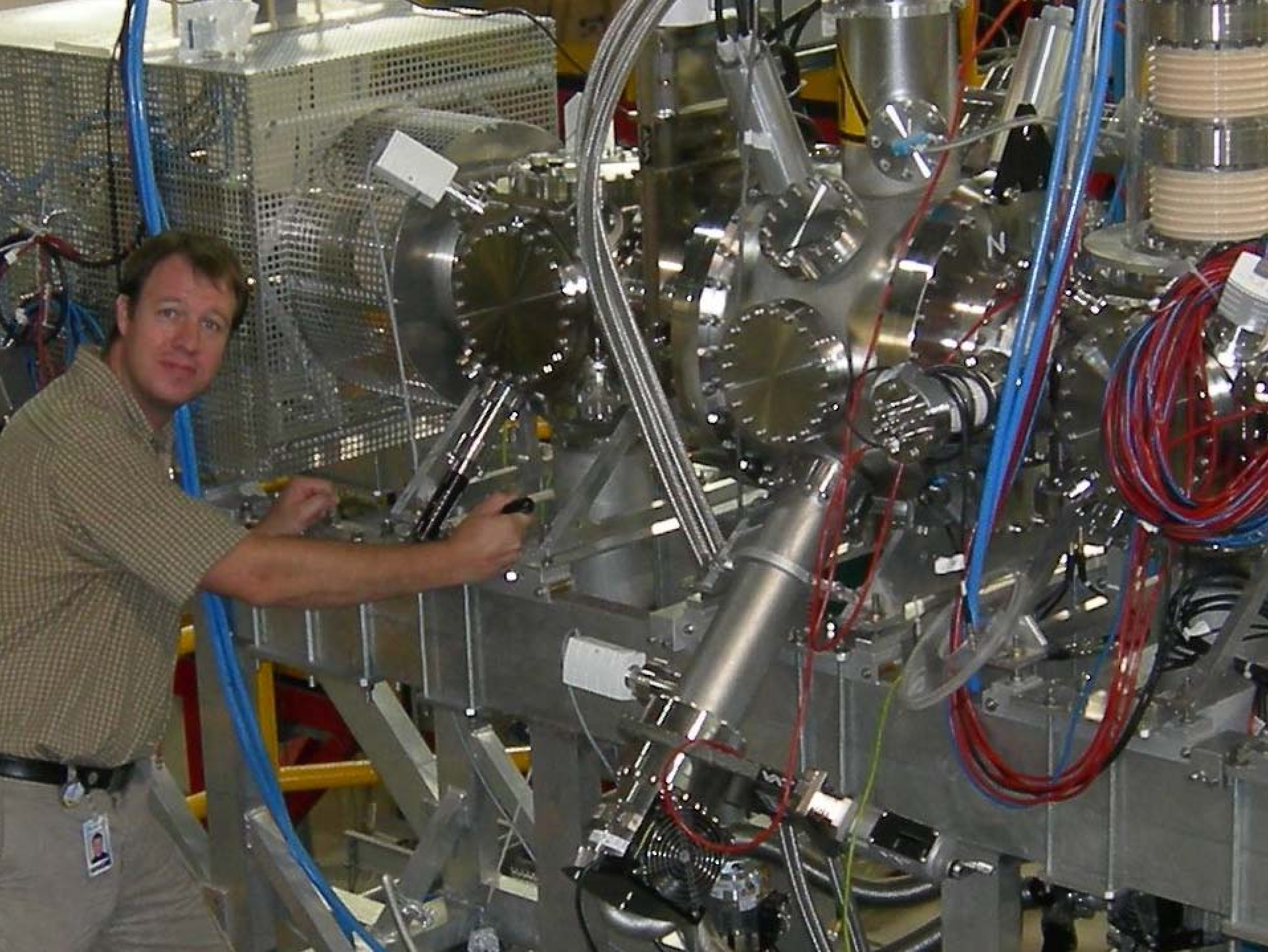
Acknowledgements

Many thanks to the TITAN group at TRIUMF



Many thnx to

RCNP - group



- **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

^{48}Ca

Resolution is the issue !!!!