D. Frekers

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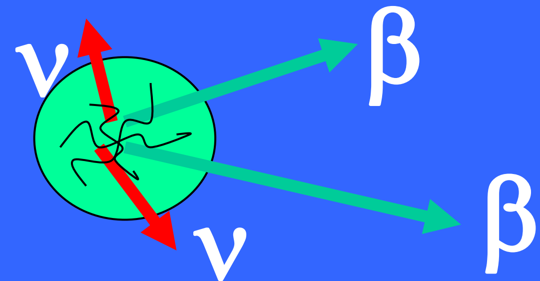
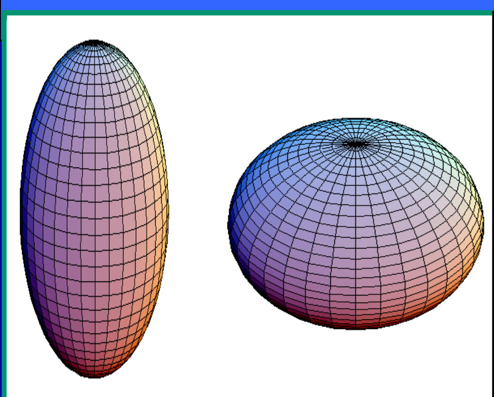
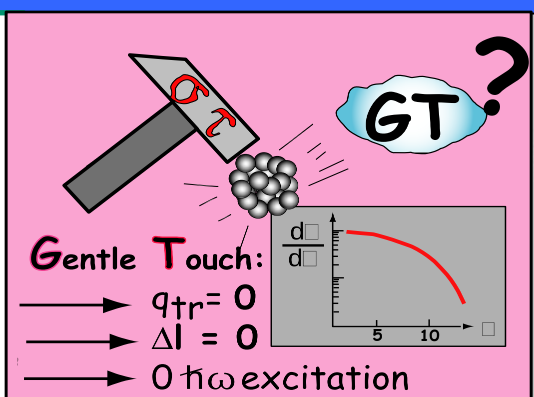
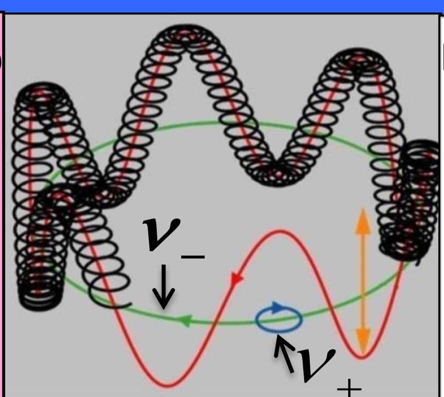
Putting together the pieces of the puzzle in ββ-decay

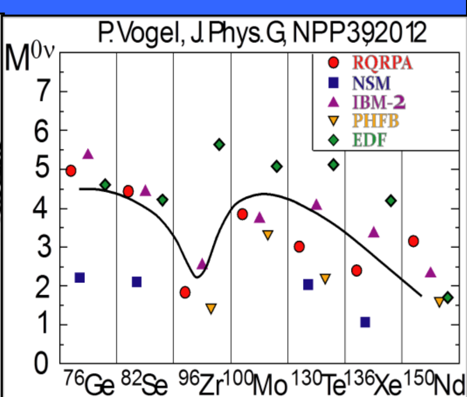


TRIUMF May-2016









The pieces of the puzzle

- **Chargex-reactions (^{3}He,t) & (d,^{2}He)**
  - $2\nu\beta\beta$ nuclear matrix elements
  - **Q:** is it relevant for $0\nu\beta\beta$–decay?
  - **A:** yes! **(i.e. nucl. shape)**

- **Chargex-reactions**
  - $0\nu\beta\beta$ nuclear matrix element
  - **Q:** is it possible?
  - **A:** yes! **(NME's & 2$^-$ states, occupation #'s)**

- **Mass measurements**
  - $0\nu\beta\beta$ nuclear matrix element
  - **Q:** what is the connection?
  - **A:** ^{96}Zr is a „golden" case

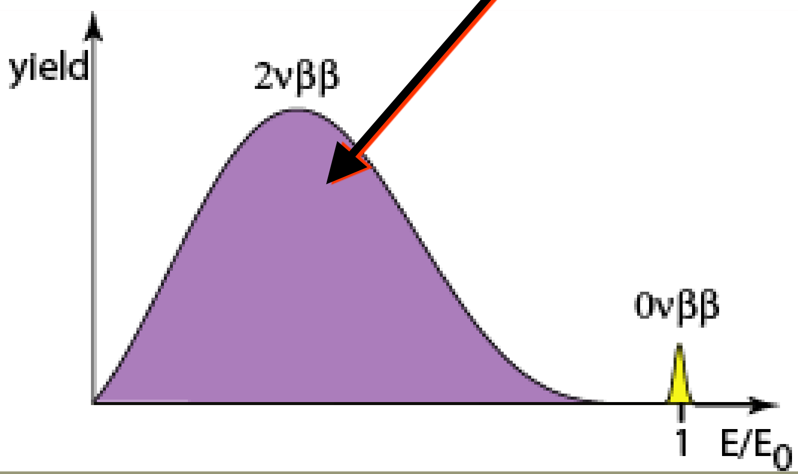
^{96}Zr (β^-) $\xrightarrow{4u}$ ^{96}Nb, and g_A

(PRL116, Feb-2016)

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Nucl.**M**atrix**E**lements

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



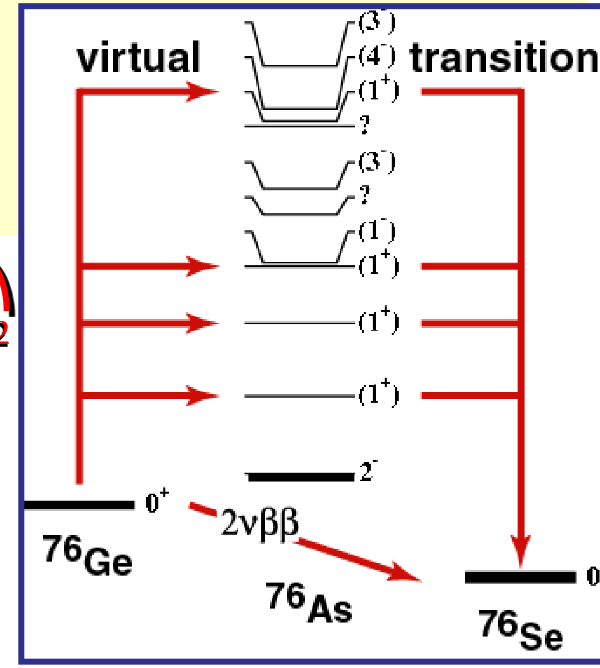
q-transfer like in ordinary β-decay
(q ~ 0.01 fm^{-1} ~ 2 MeV/c)
i.e. only allowed transitions possible

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

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

$\propto Q^{11} \cdot Z^2$

exp $\approx 10^{-3}$ MeV^{-2}
extracted from half-life

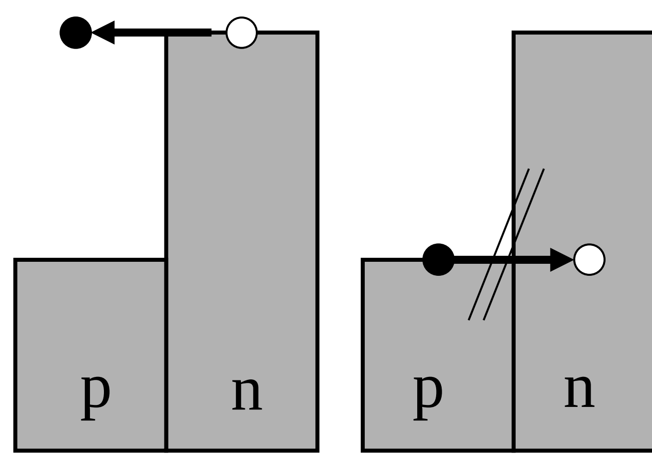


favorable:

1. high Q-value
2. large Z

unfavorable (but cannot be changed):

1. large neutron excess
   (Pauli-blocking)



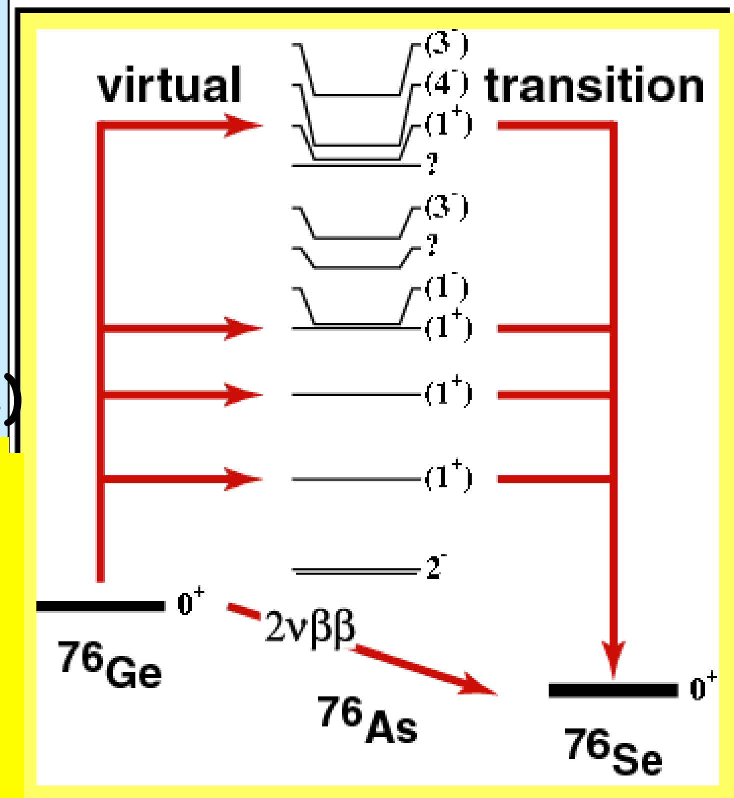
$$M^{(2\nu)}_{\mathrm{DGT}} = \sum_m \frac{\langle 0^{(f)}_{g.s.} | \sum_k \sigma_k \tau^-_k | 1^+_m \rangle \langle 1^+_m | \sum_k \sigma_k \tau^-_k | 0^{(i)}_{g.s.} \rangle}{\tfrac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - E_0}$$

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

to remember:

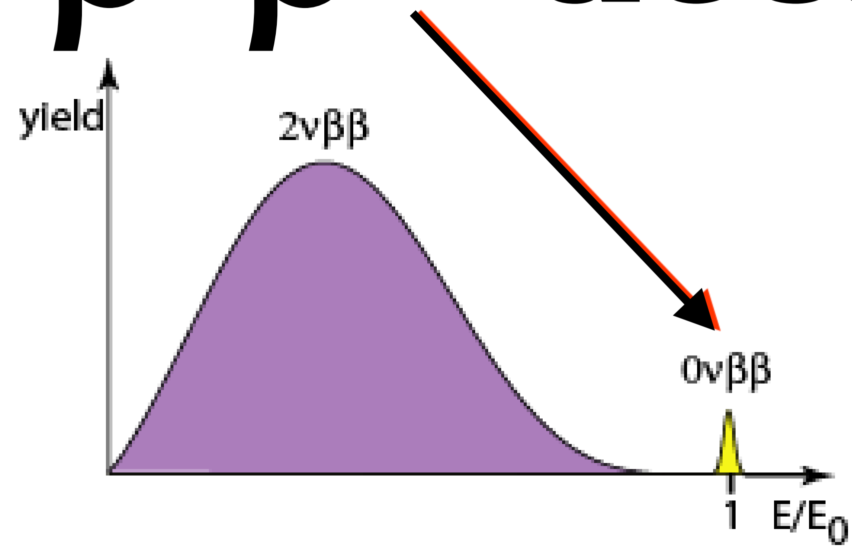
1. 2 sequential & „allowed" β^--decays of „Gamow-Teller" type
2. „1, 2, 3, ... forbidden" decays negligible
3. Fermi–transitions do no contribute (because of different isospin-multiplets)

Can be determined via charge-exchange reactions in the (n,p) and (p,n) direction (e.g. (d,^{2}He) or (^{3}He,t))



Nucl.**M**atrix**E**lements

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



neutrino is a virtual particle

$q \sim 0.5 fm^{-1}$ (~ 100 MeV/c)

(due to Heisenberg $\Delta q \cdot \Delta x \sim 1$)

degree of forbiddenness is lifted

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

!!

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

$\overset{\text{theory}}{\approx}$ 10 !!

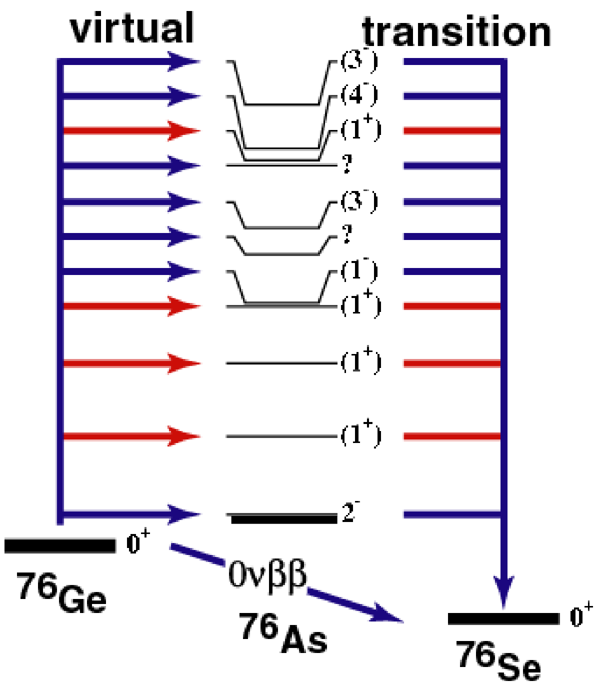
largely independent of (A,Z)
(except near magic nuclei)

mass of Majorana-ν !

to remember:

1. „higher-fold forbidden" transitions possible
2. Fermi-transitions important
3. „Pauli-blocking" largely lifted
4. large Q-value, high Z important

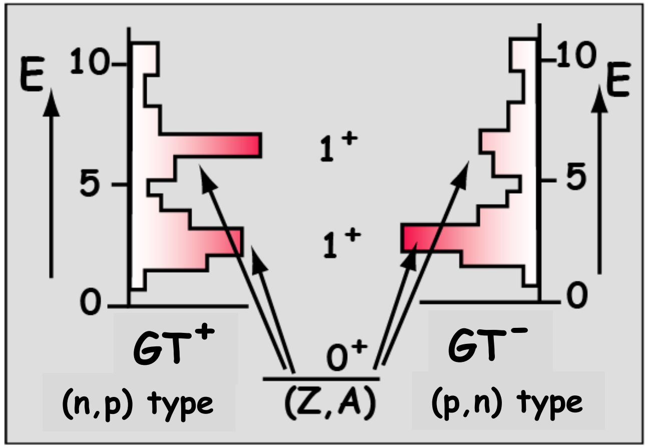
NOT (easily) accessible via charge-exchange reactions



1st piece of puzzle

Charge-exchange reactions

(p,n) type & (n,p) type



Q: what is the connection between „weak $\sigma\tau$ operator" and the hadronic reaction

A: dominance of the $V_{\sigma\tau}$ effective interaction at medium energies

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

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

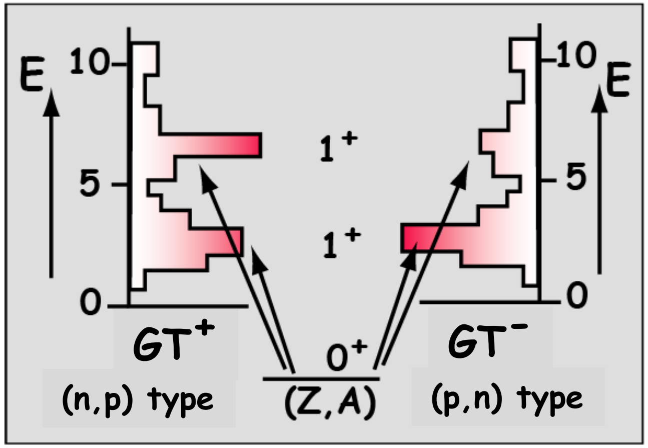
hadronic probes: (n,p), (d,^{2}He), (t,^{3}He)

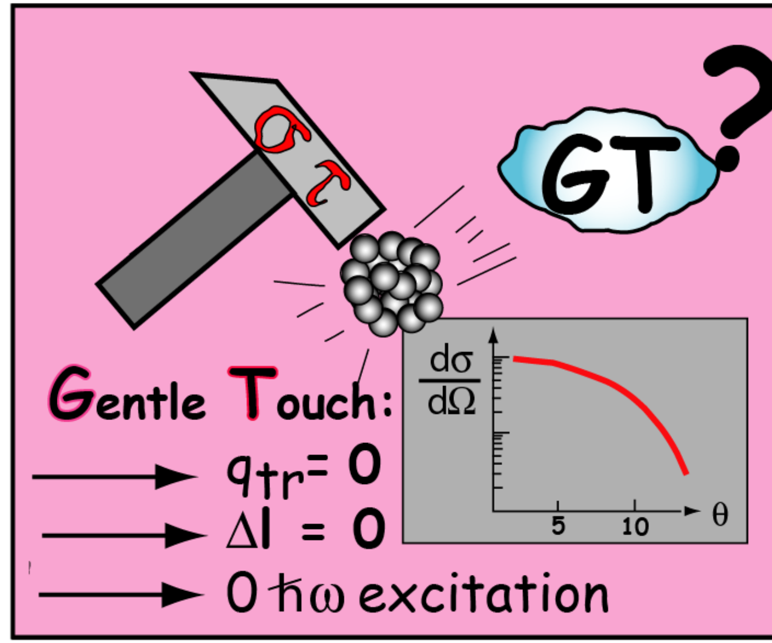
or (p,n), (^{3}He,t)

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

$q = 0!!$

largest at 100 - 200 MeV/A





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

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

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

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

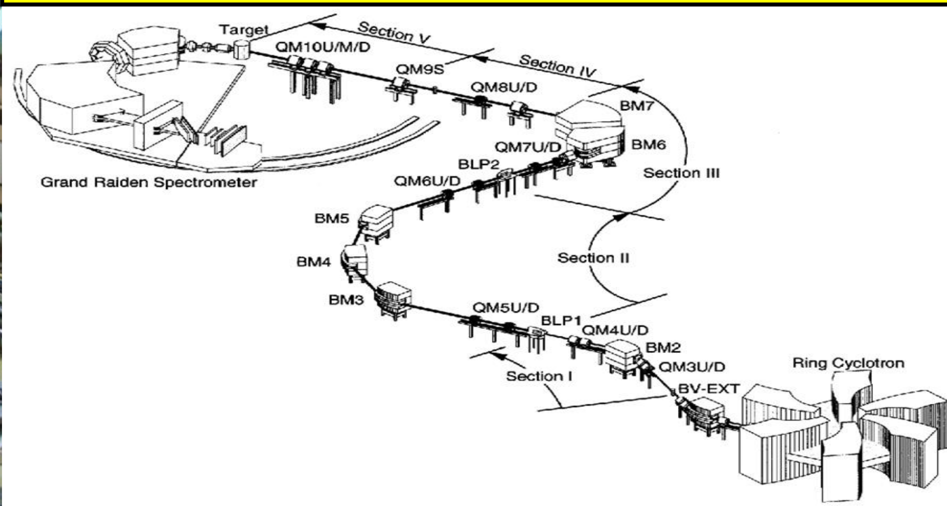
$$q = 0!!$$

largest at 100 - 200 MeV/A

Charge-exchange reactions

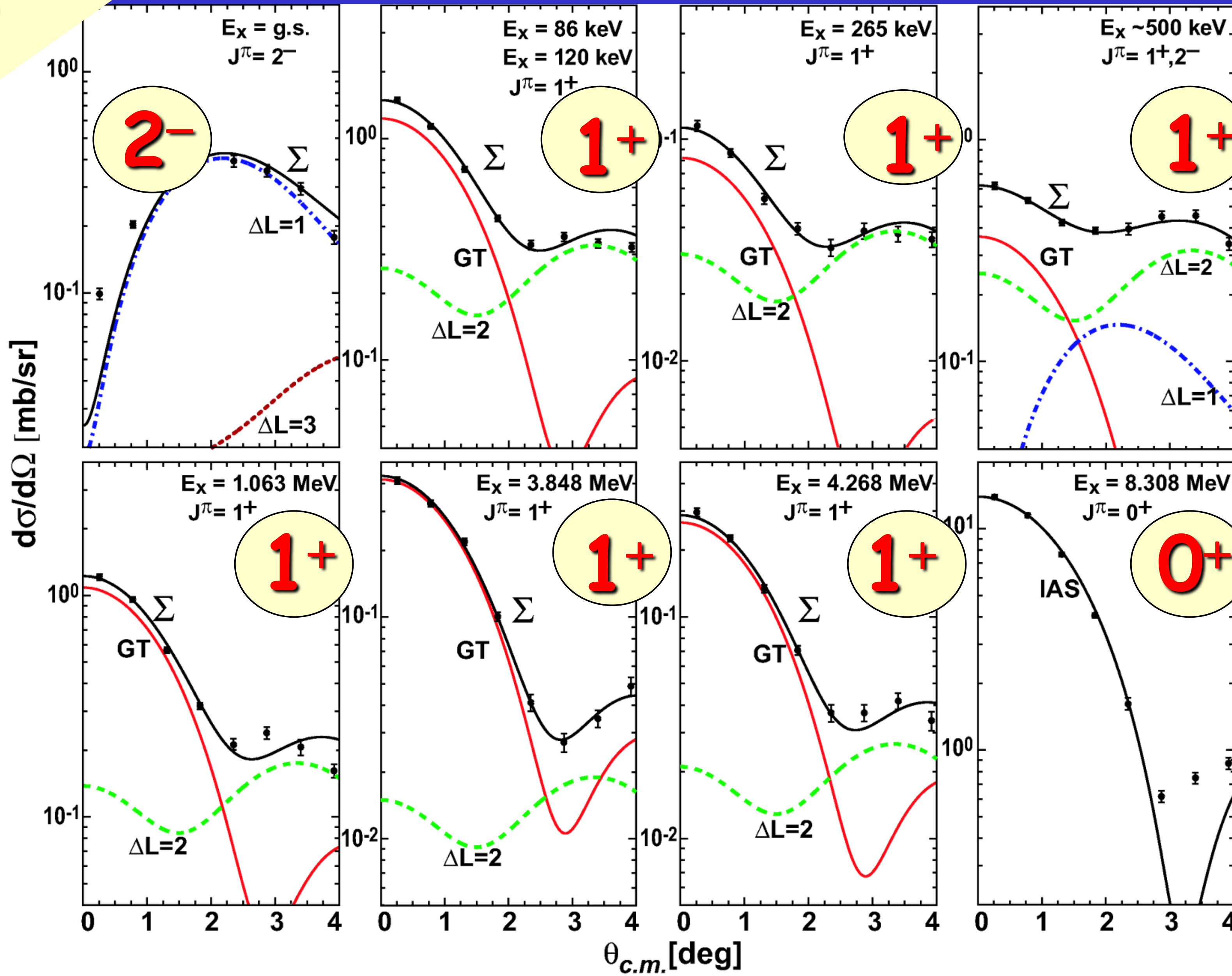
Grand Raiden
Magnetic Spectrometer

$\Delta E/E \sim 5 \times 10^{-5}$ ~ 25 keV
at 420 MeV (^{3}He)



76Ge-76As

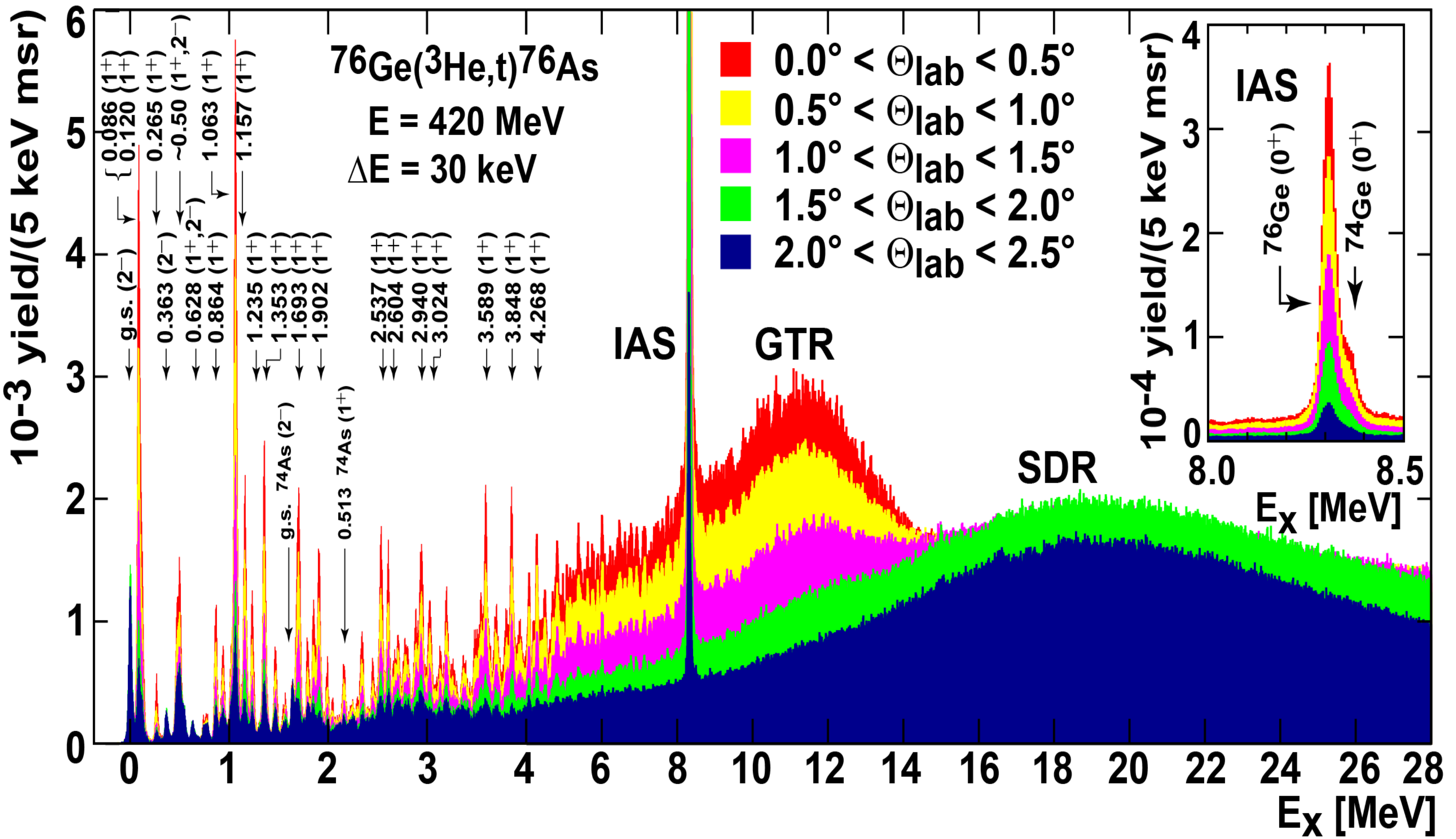
examples



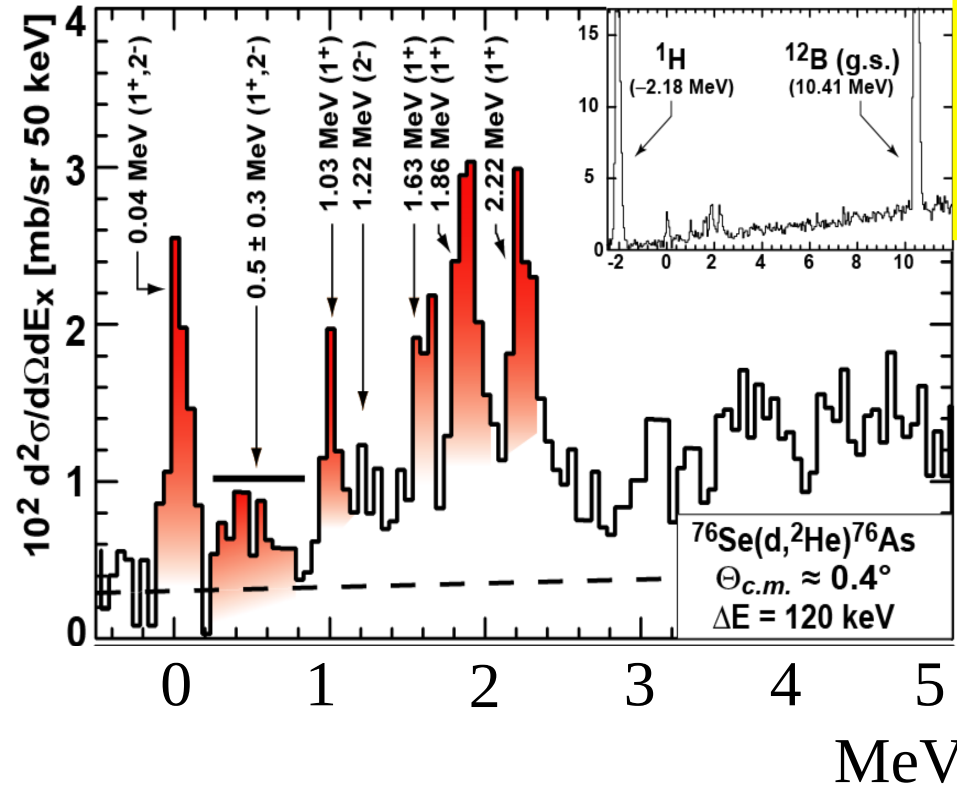
^{76}Ge

$N-Z=10$

Resolution is the key !!!



almost 70 !! resolved single states up to 5 MeV identified as GT 1+ transitions !!!



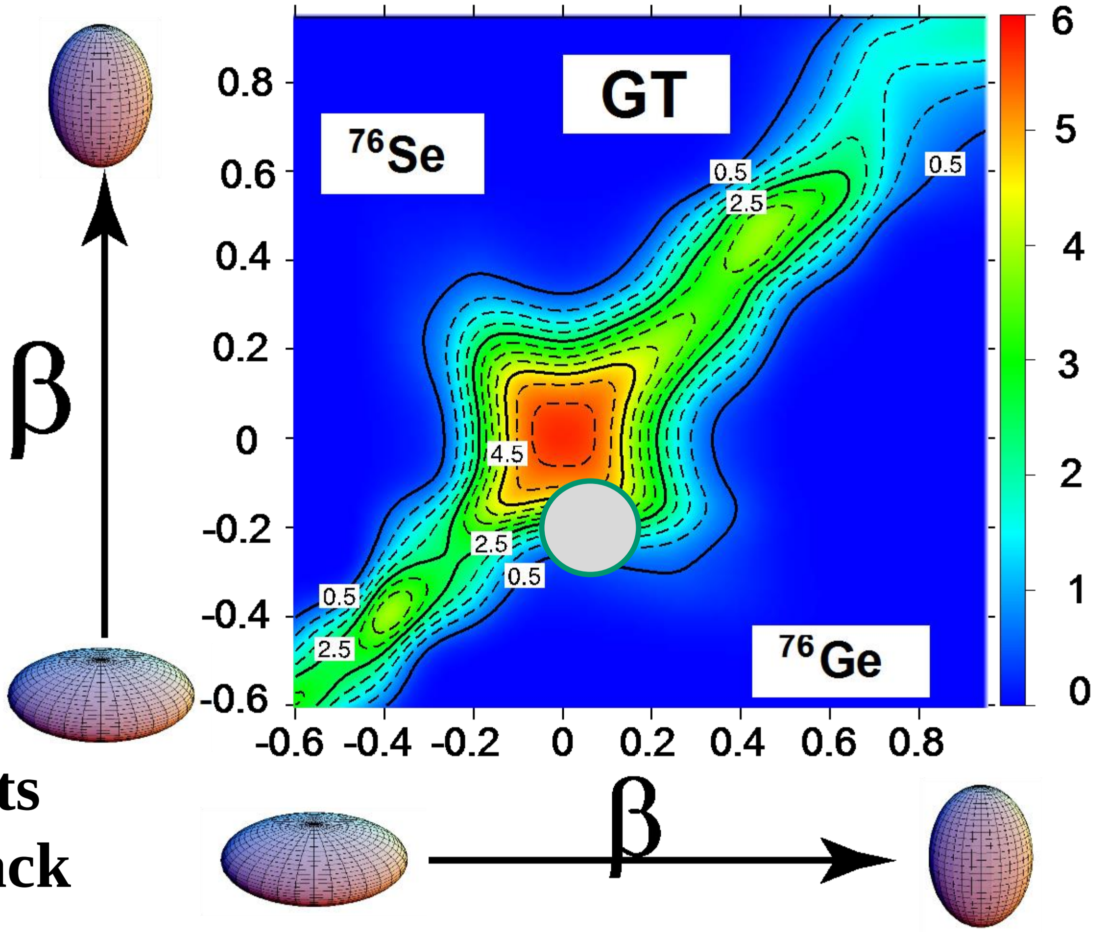
the other leg (B_{GT^+}): $^{76}Se(d,^{2}He)^{76}As$ (ΔE = 120 keV)

Nuclear matrix elements and deformation

^{76}Ge: β ~ + 0.1
^{76}Se : β ~ – 0.2

reduction of the NME due to deformation is theoretically confirmed

but

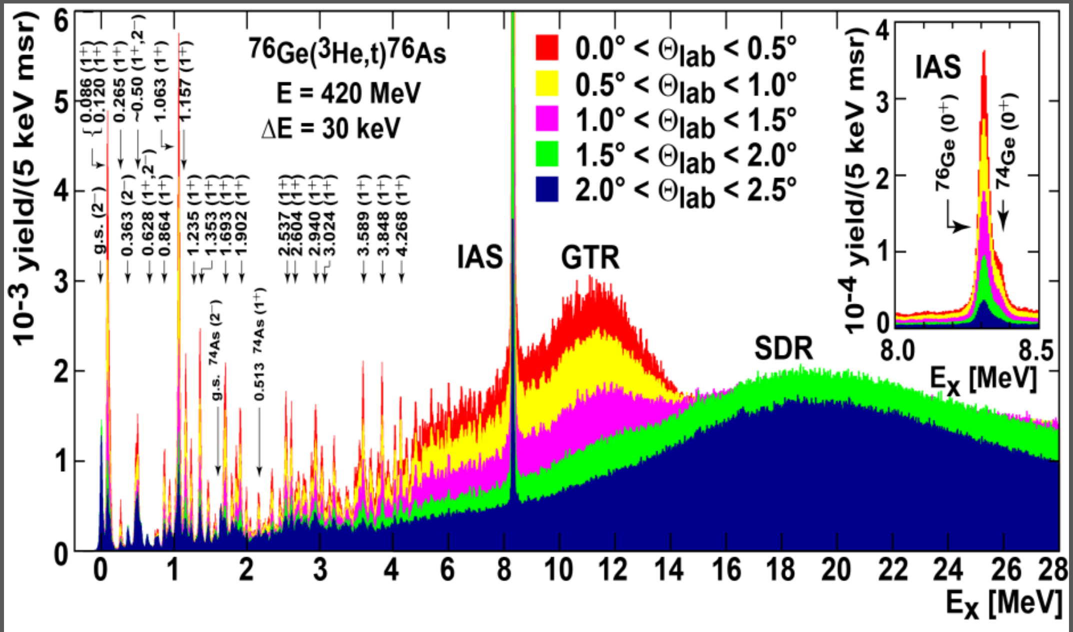


expm'lly it seems to manifests itself (in 2νββ decay) by a lack of correlation between the two different B(GT) „legs", rather than a reduction of individual strength

From: T. R. Rodriguez, et al, PRL105 (2010)

another surprise:

low-E part of NME makes up ~100% of total 2νββ-ME



no need for
GT giant resonance contribution

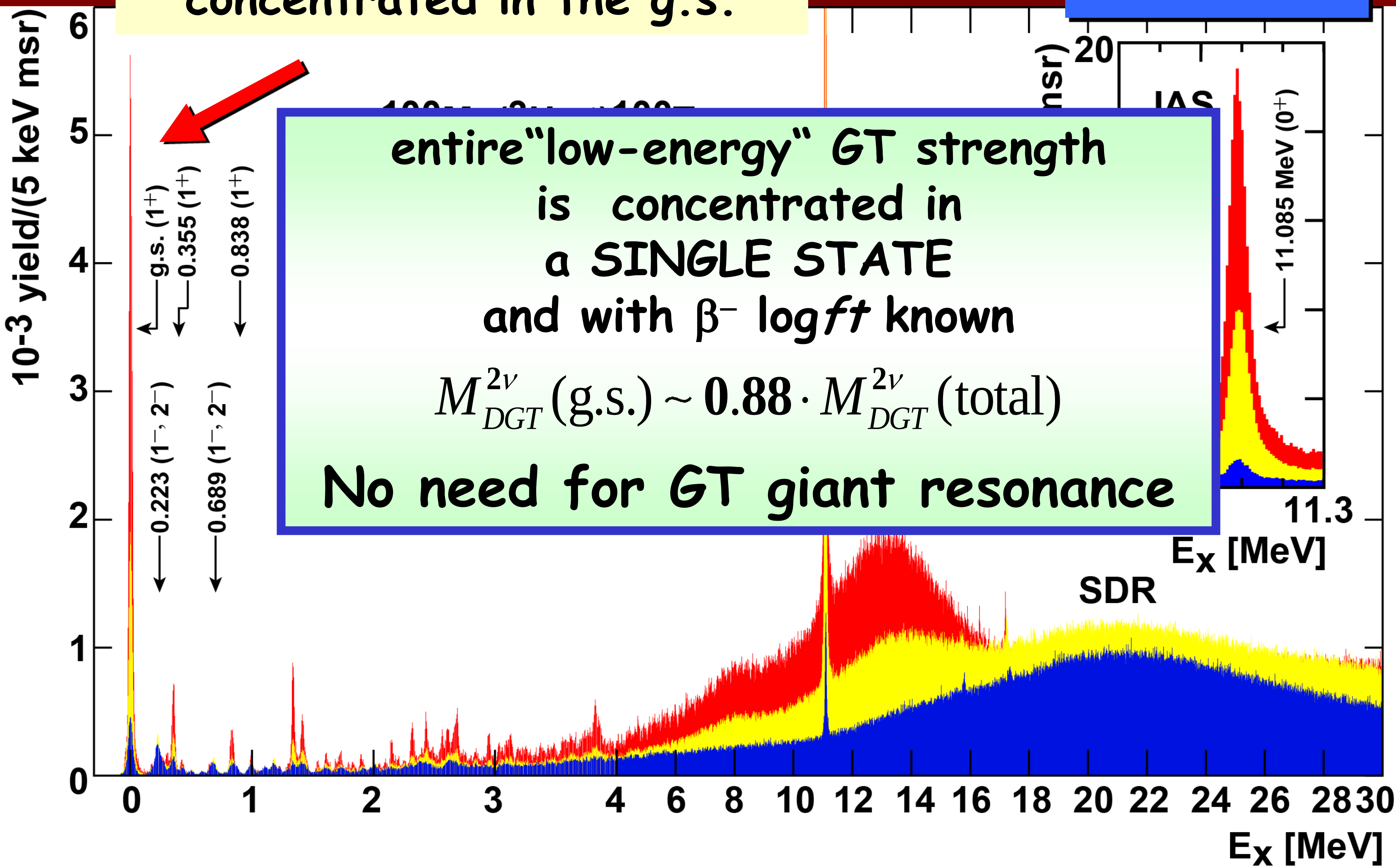
^{100}Mo

N-Z=16

also useful as SN neutrino detector (sensitive to ν temperature in SN)

HERE: almost the entire low-E GT strength is concentrated in the g.s.

^{100}Mo



entire "low-energy" GT strength is concentrated in a SINGLE STATE and with β⁻ log*ft* known

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

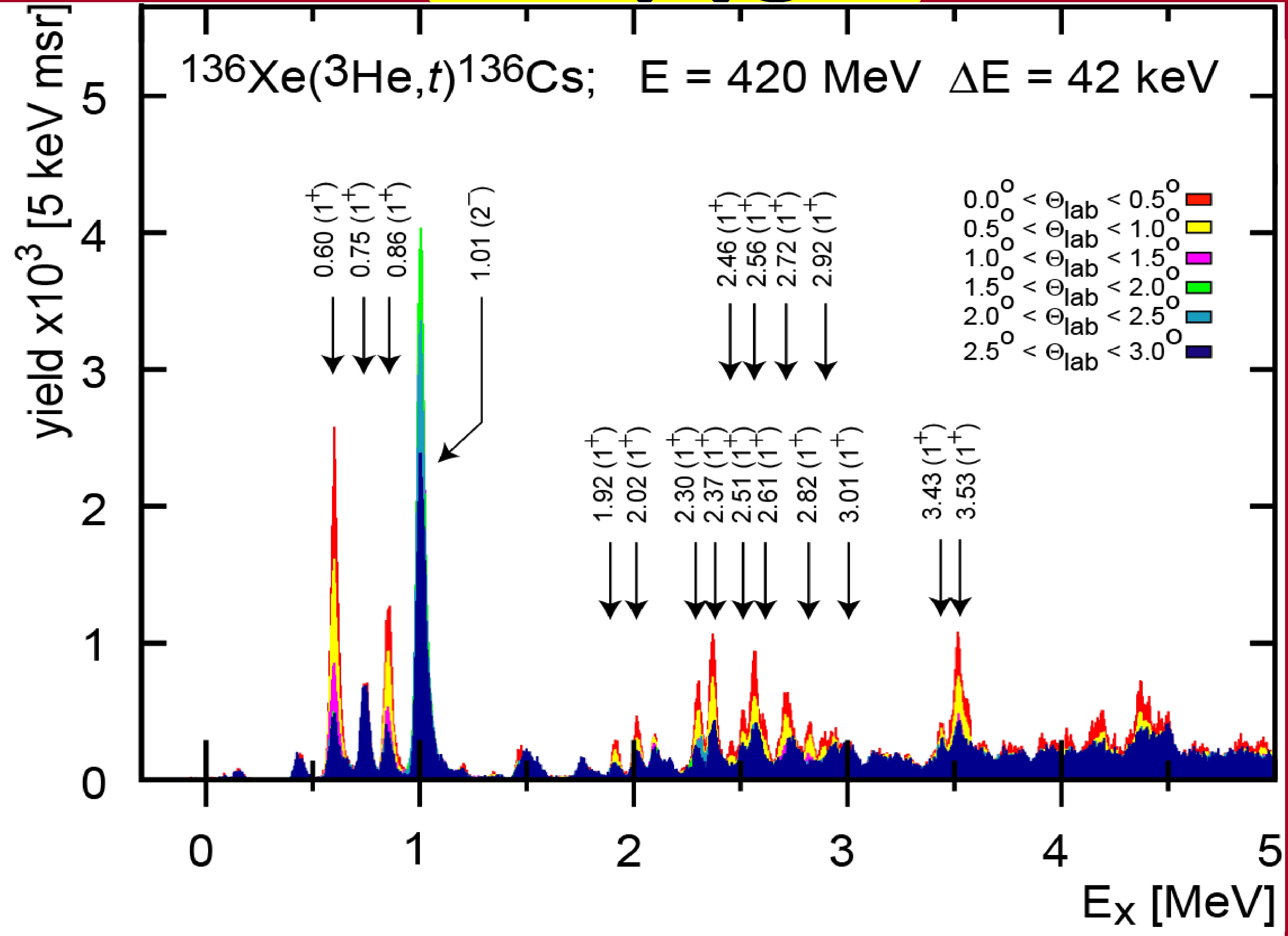
No need for GT giant resonance

^{136}Xe

N-Z=28

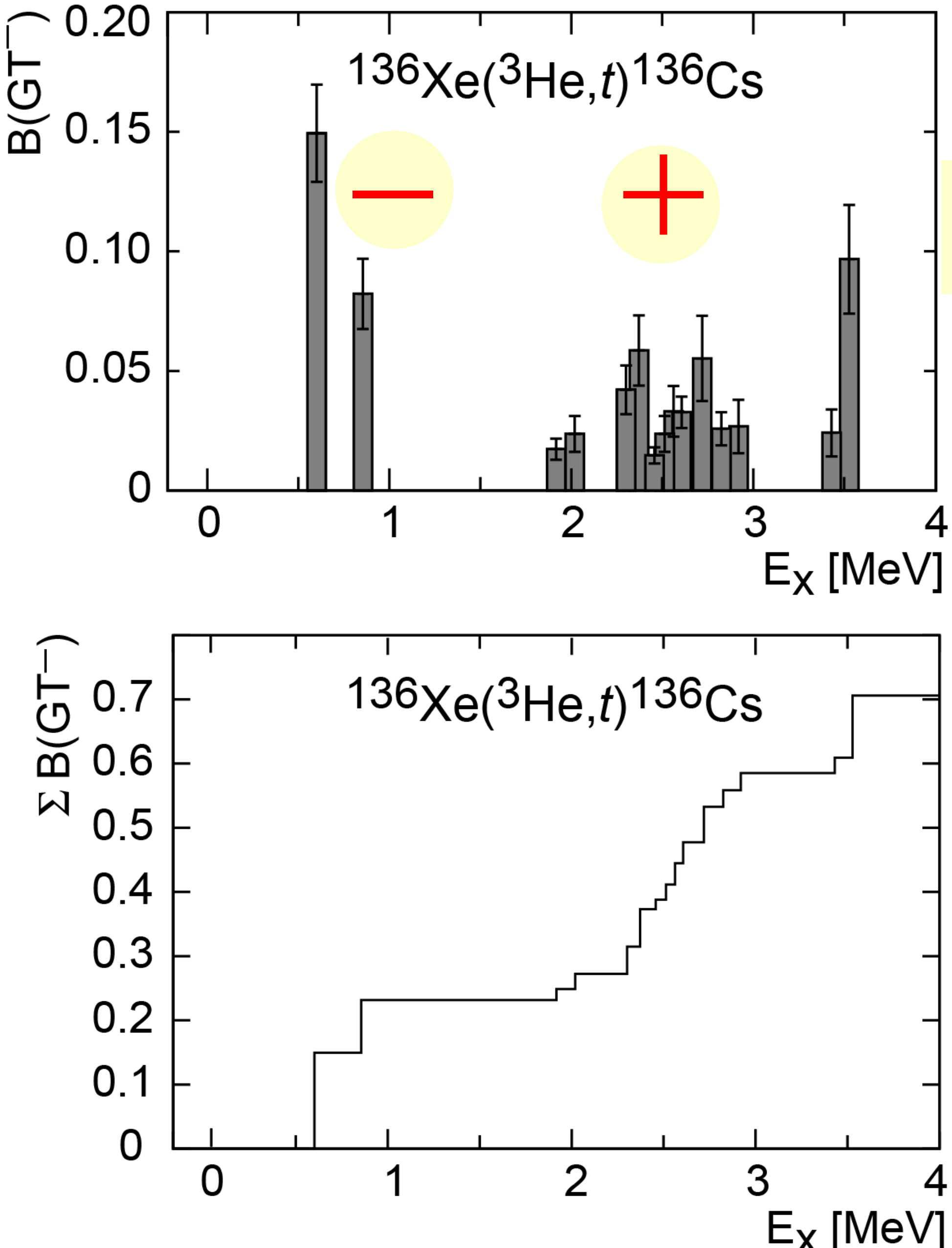
question: why so stable !!!

136Xe



$^{136}Xe(^3He,t)^{136}Cs$; 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°

What's the size of the NME?



$$T^{2\nu}_{1/2} = 2.2 \cdot 10^{21}\,\mathrm{yr}$$

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

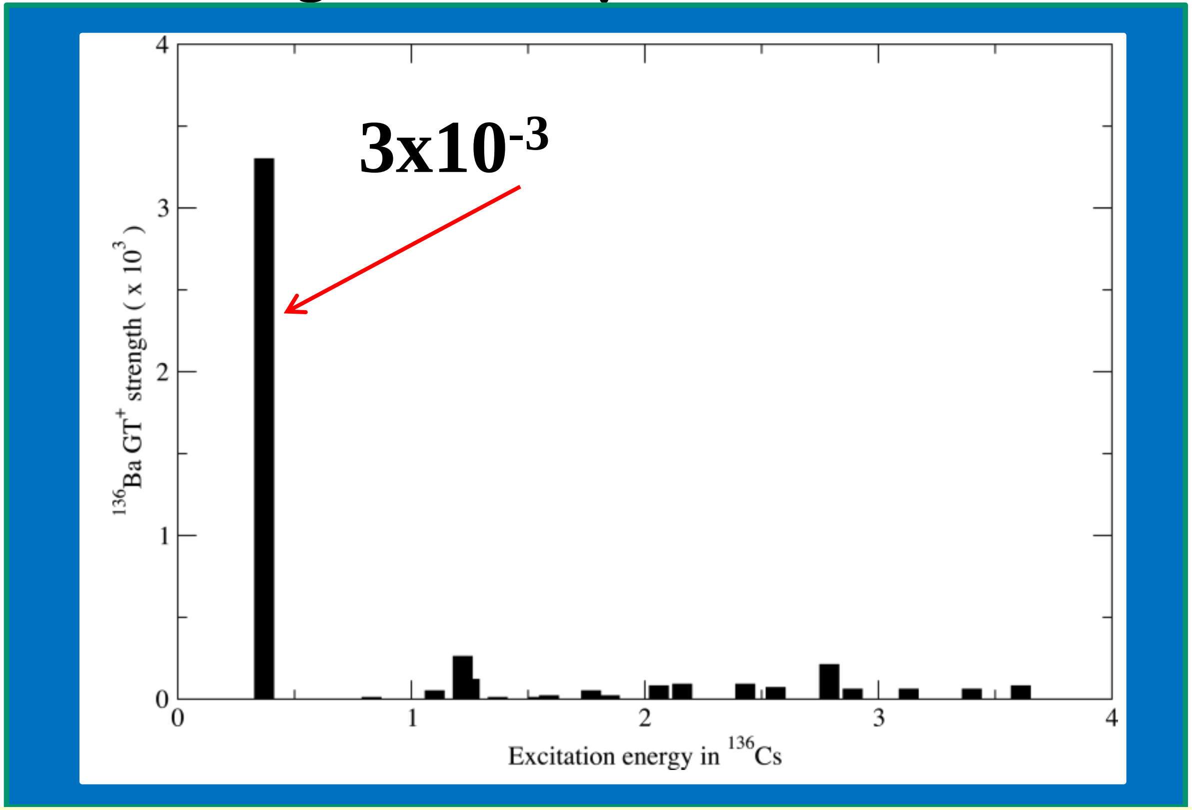
all signs positive —>

$$B_m\ GT^+ \approx 10^{-2} \cdot B_m\ GT^-$$

$$B_m\ GT^+ \approx 10^{-3}\ !!!!$$

A. Poves (simultaneous to our publication):

there is no B(GT$^+$) strength, except for lowest 1$^+$ state



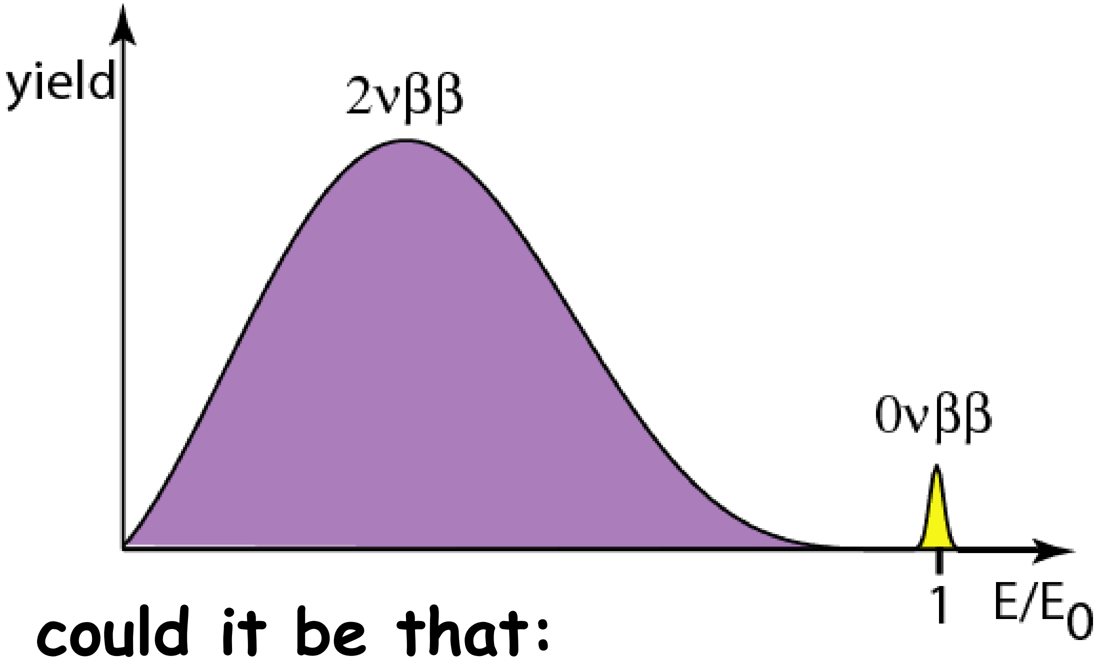
Recall:
^{136}Xe is almost doubly magic!!

Shell model provides conclusive explanation for the deemed „pathologically" long half-life of ^{136}Xe.
Expt'l test: ^{136}Ba(d,^{2}He)^{136}Cs

$$^{136}\mathrm{Xe} \xrightarrow{\beta^-\beta^-} {}^{136}\mathrm{Ba}$$

expmt: 2νββ NME is exceptionally small

question: how does the ME scale in the case of 0νββ decay?



could it be that:

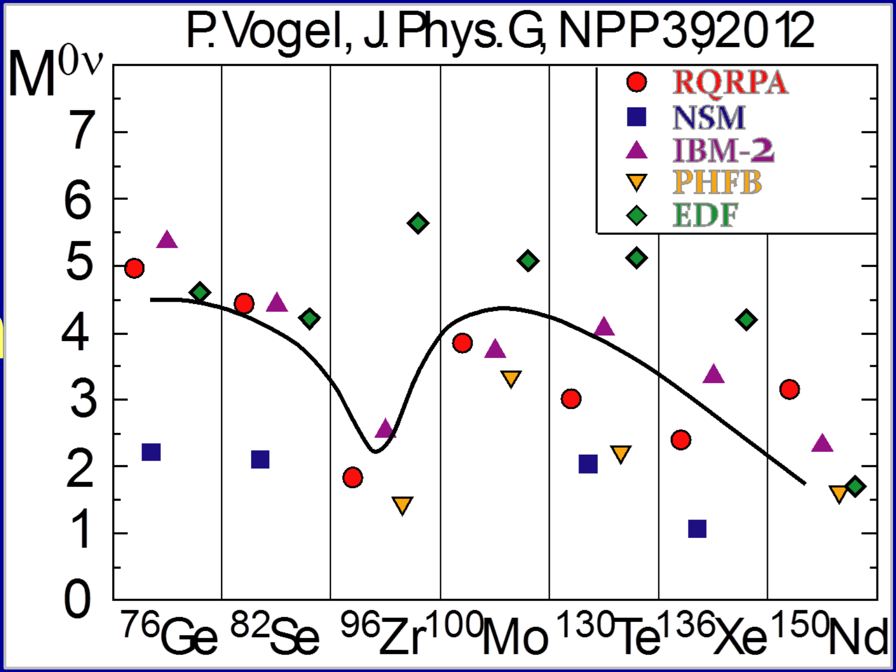
2νββ ME is suppressed AND

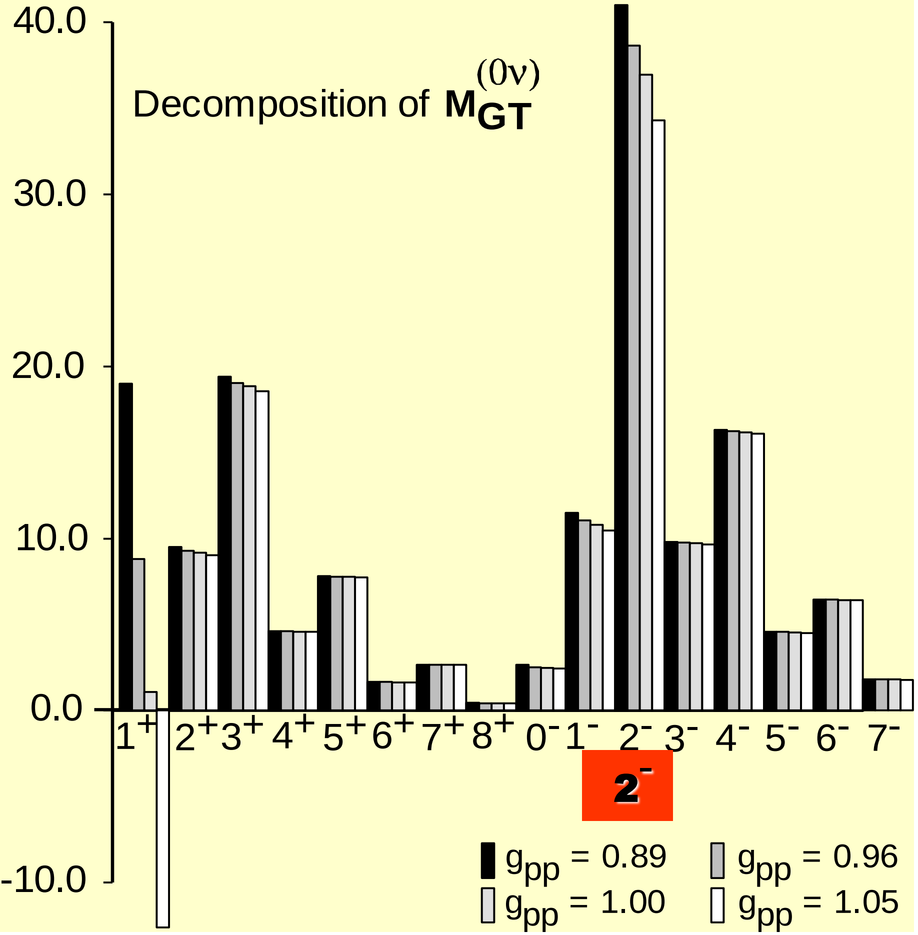
0νββ ME is enhanced ???

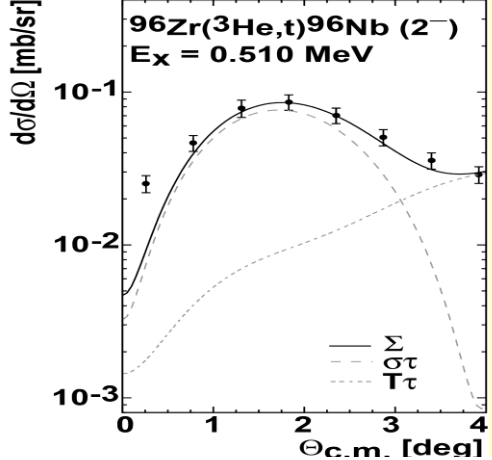
2nd piece of puzzle

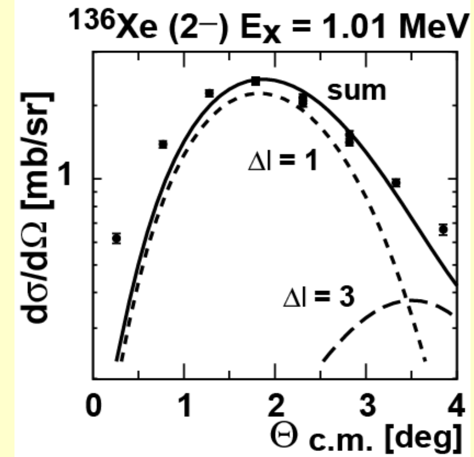
Charge-exchange reaction towards the $0\nu\beta\beta$ NMEs ???

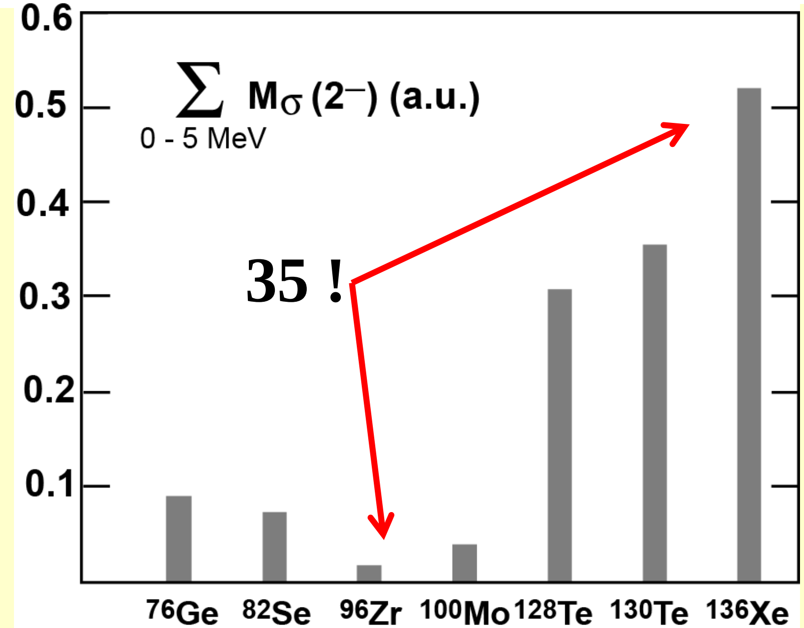
Here:
2^- states and occupation vacancy numbers via chargex reactions











relative 2⁻ strength to ~ 5 MeV

<u>Theory:</u>

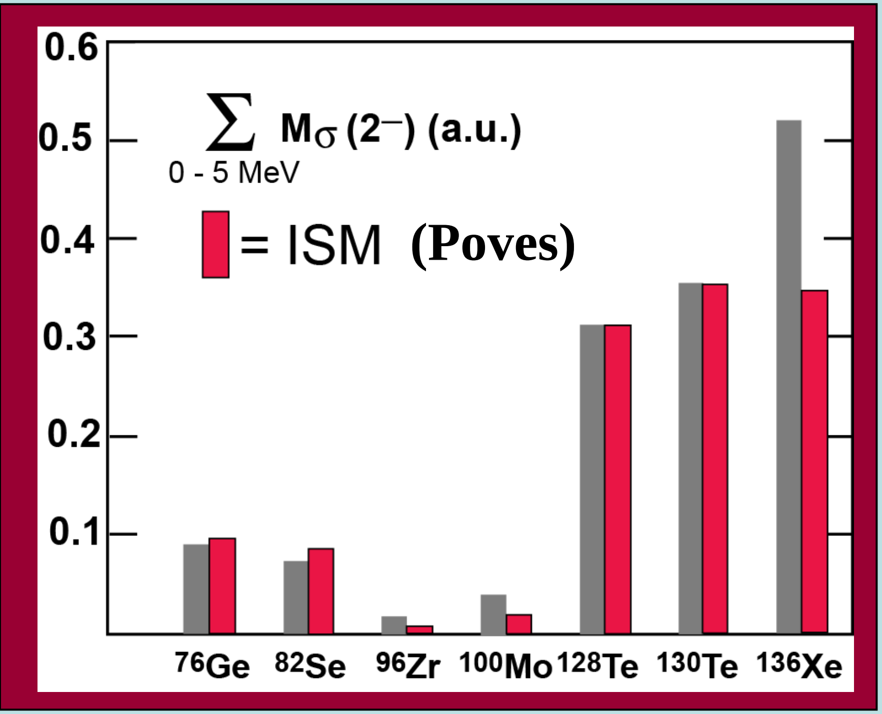
The 2⁻ strength makes up ~ 20-30% of the 0νββ ME!!

J. Suhonen, Phys. Lett B607, 87 (2005)

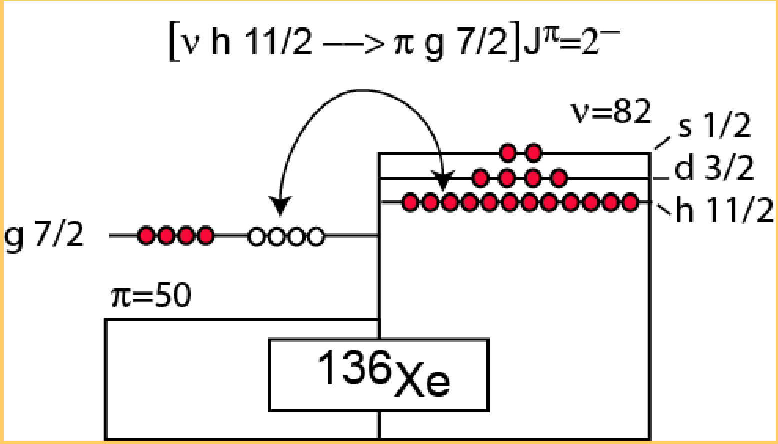
<u>Expmt:</u>

^{136}Xe exhibits largest 2⁻ strength

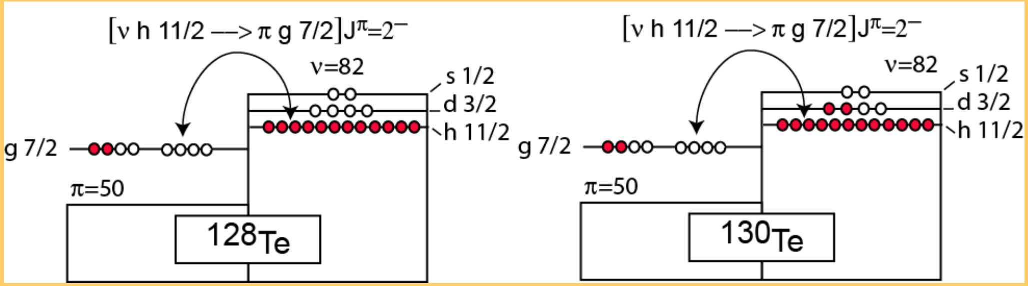
0νββ ME enhanced?!?!



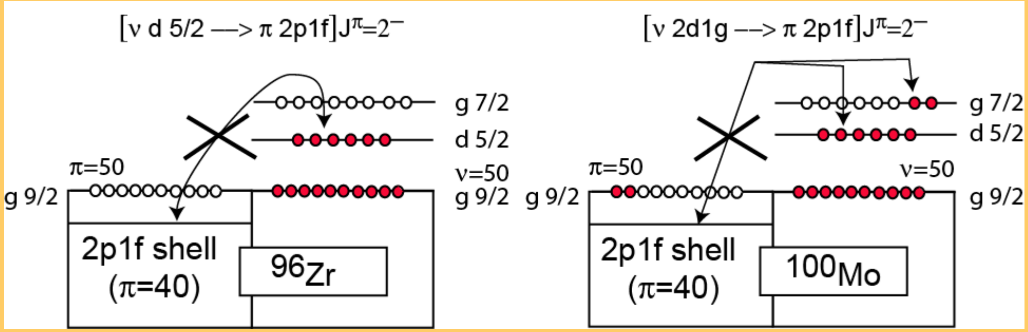
0.6
0.5
0.4
0.3
0.2
0.1
∑ Mσ (2⁻) (a.u.)
0 - 5 MeV
= ISM (Poves)
76Ge
82Se
96Zr
100Mo
128Te
130Te
136Xe



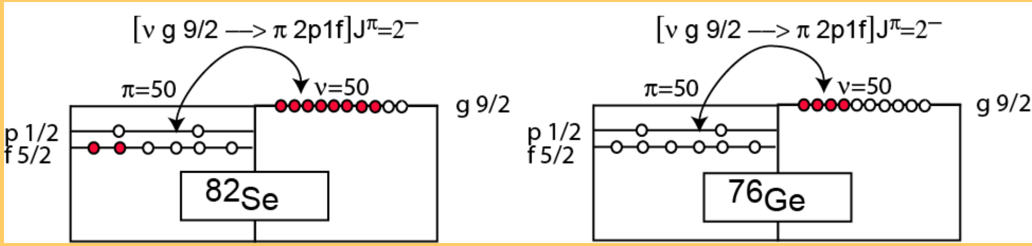
[ν h 11/2 —> π g 7/2]Jπ=2⁻
ν=82
s 1/2
d 3/2
h 11/2
g 7/2
π=50
136Xe



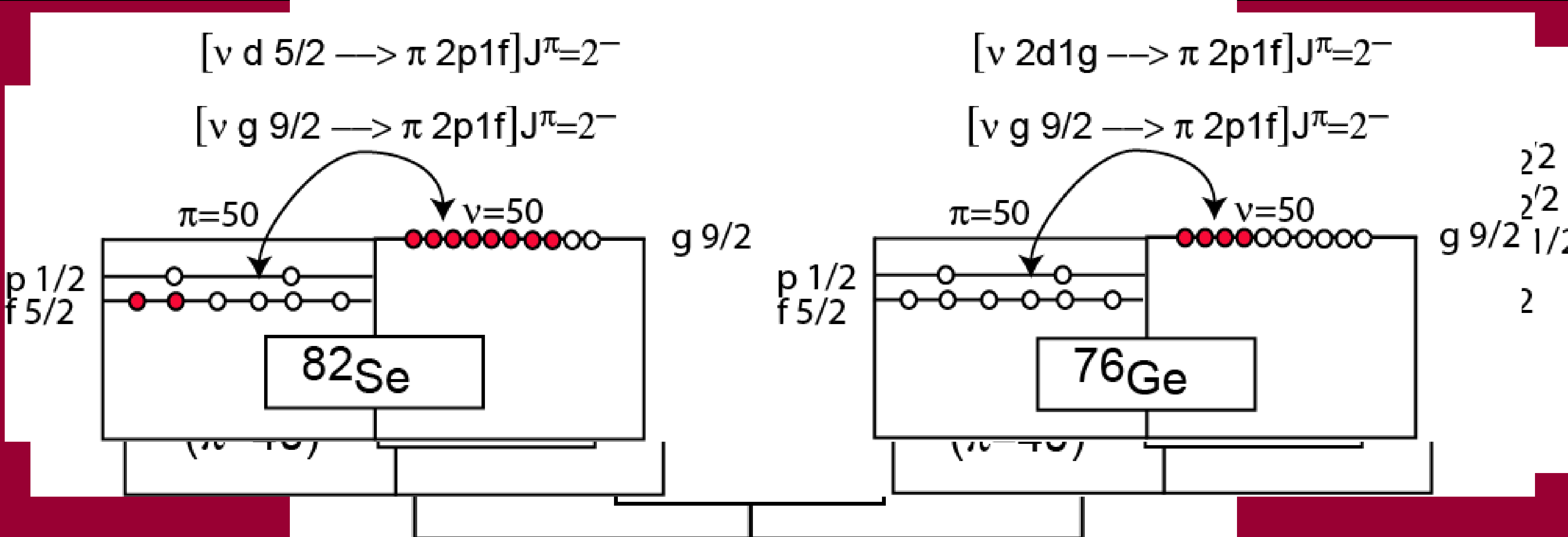
[ν h 11/2 —> π g 7/2]Jπ=2⁻
ν=82
s 1/2
d 3/2
h 11/2
g 7/2
π=50
128Te
[ν h 11/2 —> π g 7/2]Jπ=2⁻
ν=82
s 1/2
d 3/2
h 11/2
g 7/2
π=50
130Te

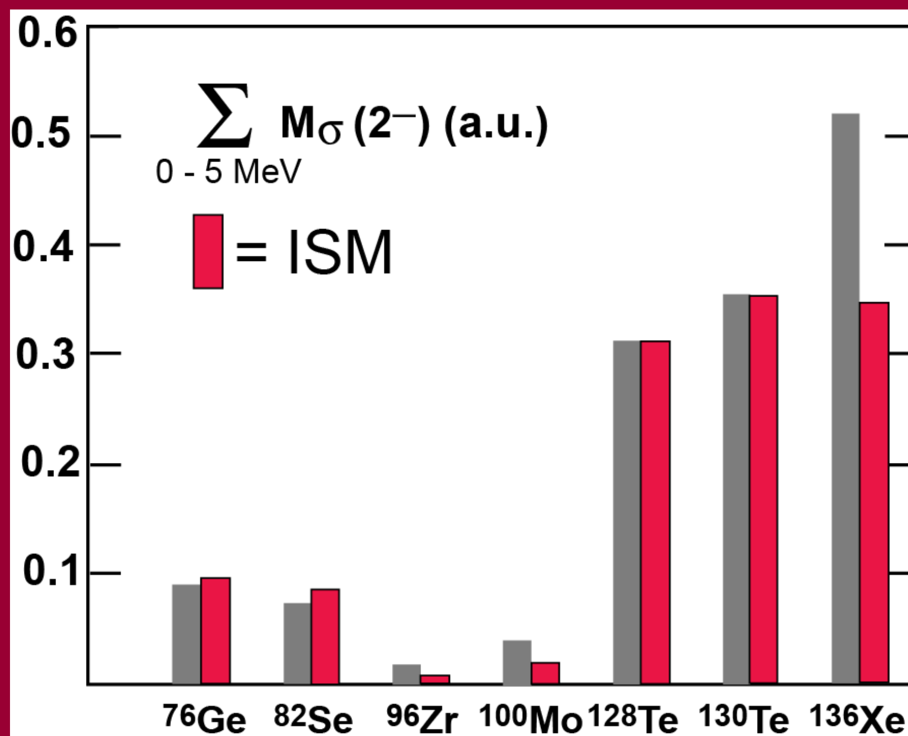


[ν d 5/2 —> π 2p1f]Jπ=2⁻
g 7/2
d 5/2
ν=50
g 9/2
π=50
g 9/2
2p1f shell
(π=40)
96Zr
[ν 2d1g —> π 2p1f]Jπ=2⁻
g 7/2
d 5/2
π=50
ν=50
g 9/2
g 9/2
2p1f shell
(π=40)
100Mo



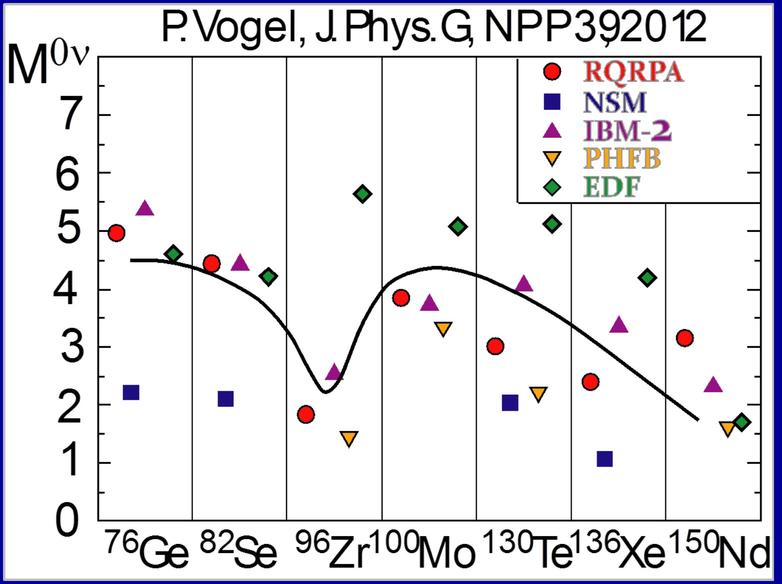
[ν g 9/2 —> π 2p1f]Jπ=2⁻
π=50
ν=50
g 9/2
p 1/2
f 5/2
82Se
[ν g 9/2 —> π 2p1f]Jπ=2⁻
π=50
ν=50
g 9/2
p 1/2
f 5/2
76Ge

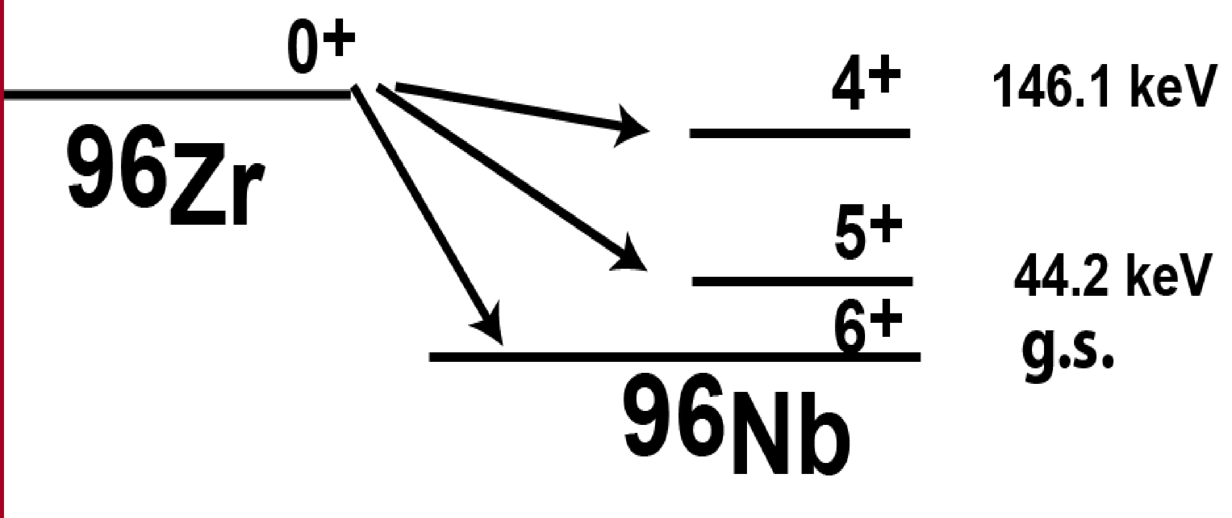

[ν d 5/2 —> π 2p1f]J^π=2^−
[ν g 9/2 —> π 2p1f]J^π=2^−
π=50
ν=50
g 9/2
p 1/2
f 5/2
82Se
[ν 2d1g —> π 2p1f]J^π=2^−
[ν g 9/2 —> π 2p1f]J^π=2^−
π=50
ν=50
g 9/2
p 1/2
f 5/2
76Ge


Σ Mσ (2−) (a.u.)
0 - 5 MeV
= ISM
0.6
0.5
0.4
0.3
0.2
0.1
76Ge
82Se
96Zr
100Mo
128Te
130Te
136Xe

3rd piece of puzzle

The A=96 system and the $0\nu/2\nu$ $\beta\beta$ NMEs





Single β & ββ decay in ^{96}Zr

two conflicting half-lives:

NEMO-3: $T_{1/2}^{2\nu\beta\beta} = (2.3 \pm 0.2) \times 10^{19}\,y$

geo-chem: $T_{1/2} = (0.94 \pm 0.32) \times 10^{19}\,y$ (1)

Q: can this difference be reconciled ?
A: yes, if single β competes with ββ decay

$$\left(T_{1/2}\right)^{-1} = \left(T_{1/2}^{2\nu\beta\beta}\right)^{-1} + \left(T_{1/2}^{\beta}\right)^{-1}$$

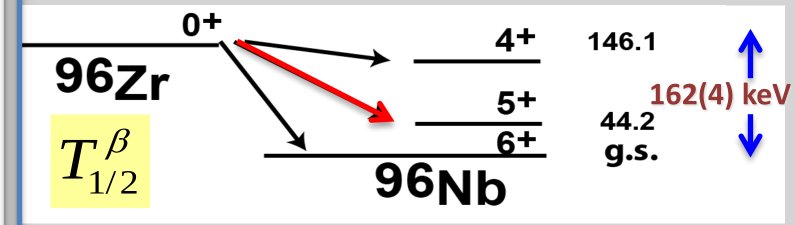
expected $T_{1/2}^{\beta} = (1.6 \pm 0.9) \times 10^{19}\,y$

experiment $T_{1/2}^{\beta} > 2.6 \times 10^{19}\,y$ (2)

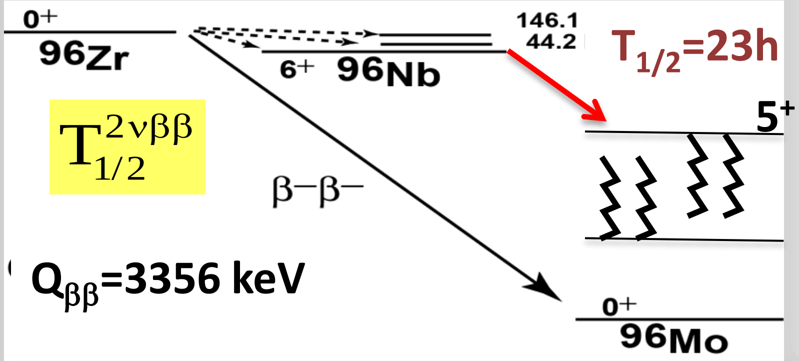
pred. (QRPA) $T_{1/2}^{\beta} = 24 \times 10^{19}\,y$ (3)

BUT

$$(T_{1/2}^{\beta})^{-1} \propto o(Q^{13}) \left\langle M_{\beta}^{4u} \right\rangle^2$$



$0^+ \rightarrow 6^+$ 6-fold non-unique (unobservably long)
$0^+ \rightarrow 5^+$ 4-fold unique (possible)
$0^+ \rightarrow 4^+$ 4-fold non-unique (no phase space)



Q-value → M_{β}^{4u} → $(T_{1/2}^{0\nu\beta\beta})^{-1} \propto Q^5 \left|M_{\beta\beta}^{0\nu}\right|^2 \left\langle m_{\beta\beta} \right\rangle^2$

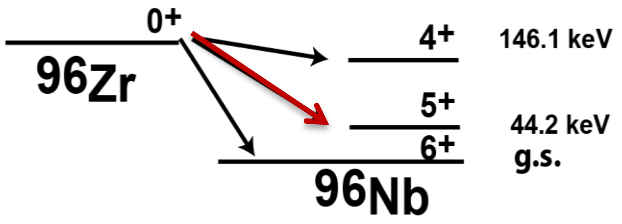
(1) *Wieser, PRC64,2001,* (2) *Barabash, JPG-NPP22, 1996* (3) *Heiskanen, JPG3,2007*

Idea

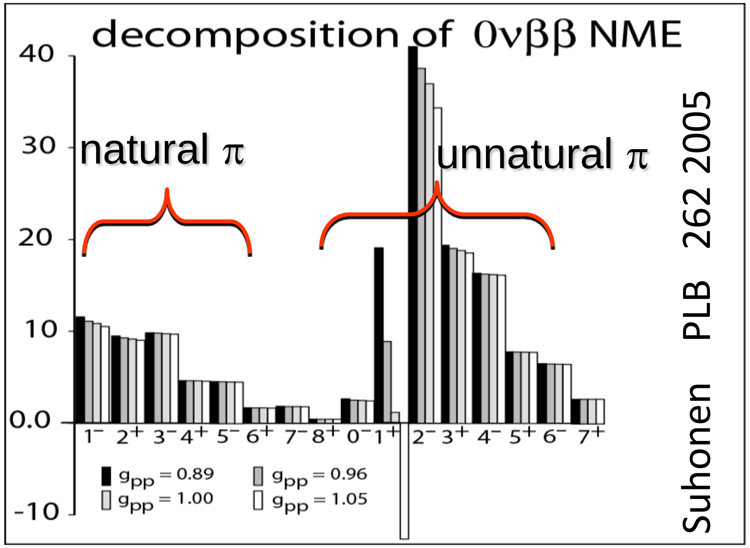
- (i) measure **Q-value** for $^{96}Zr \longrightarrow {}^{96}Nb$ **single β-decay** by precision mass measurement and

  (ii) measure the **single β-decay** rate

  (iii) → ft-value

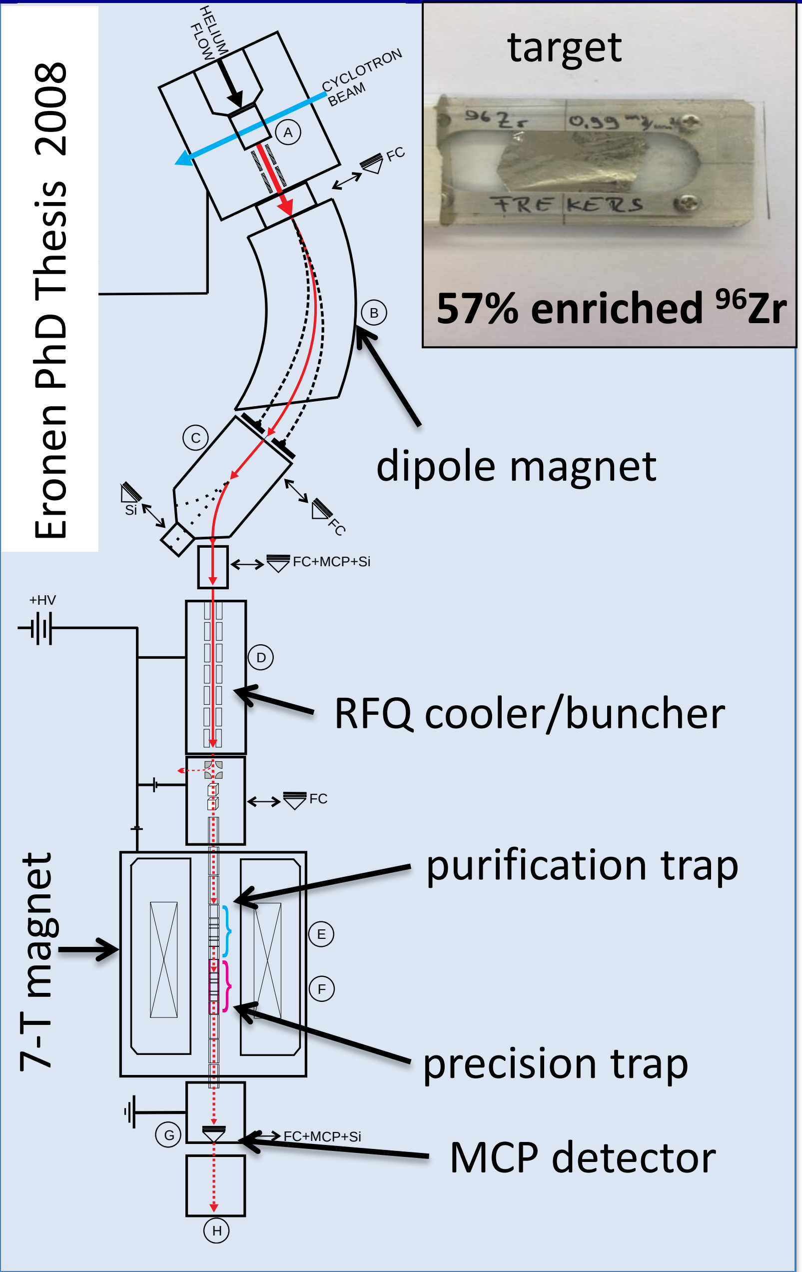


- determine the ^{96}Zr **4-fold forbidden β-decay NME** and confront with theory



- confront with same theories aimed at calculating **0νββ-decay NME for the same nucleus!!**

IGISOL/JYFLTRAP mass measm'nts



target

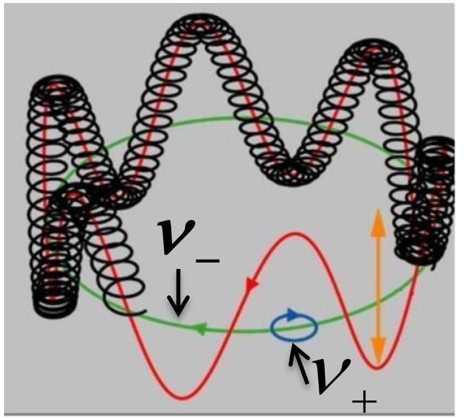
57% enriched ^{96}Zr

^{96}Zr (p, n)^{96}Nb reaction for production of ^{96}Nb

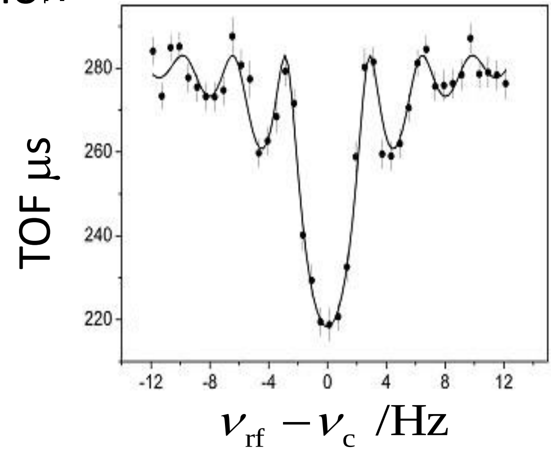
- performing accurate mass measurements via cyclotron frequency

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

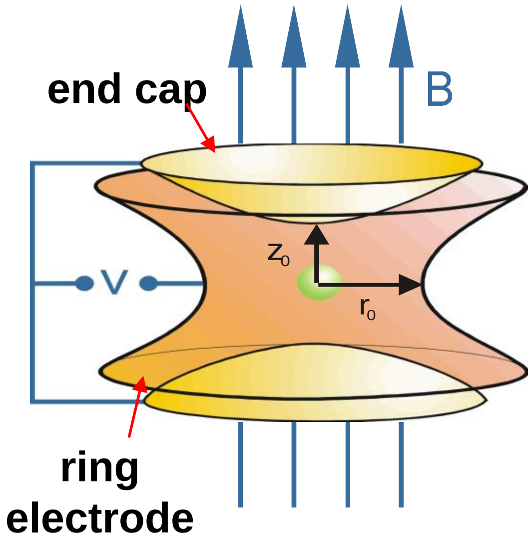
$$\nu_\mathrm{c} = \nu_- + \nu_+$$



- frequency determination done by **TOF-ICR** technique

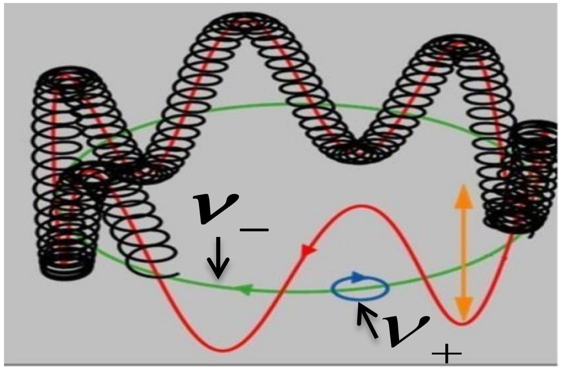


ion motion in a Penning Trap



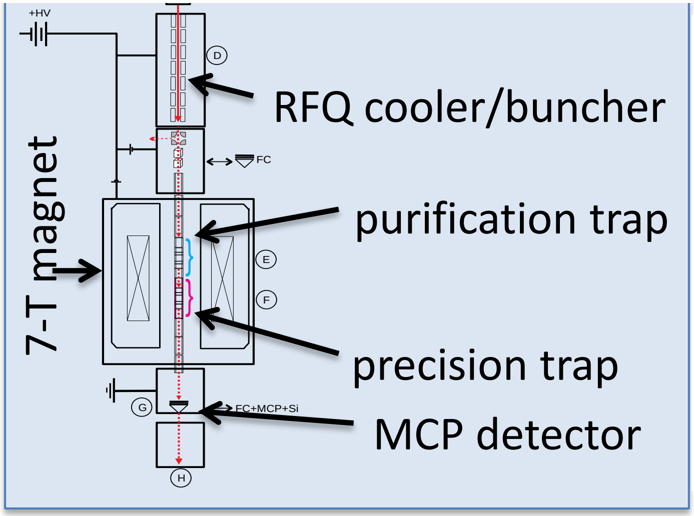
a superposition of 3 harmonic motions:

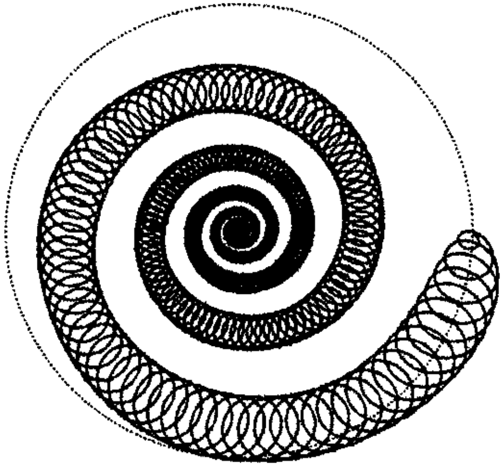
1) axial motion (ν_z)
2) magnetron motion (ν_-)
3) reduced cyclotron motion (ν_+)



typical freq's: $\nu_- \approx 1$ kHz,
$\nu_+ \approx 1$ MHz
cycl. freq.: $\nu_c = \nu_- + \nu_+$

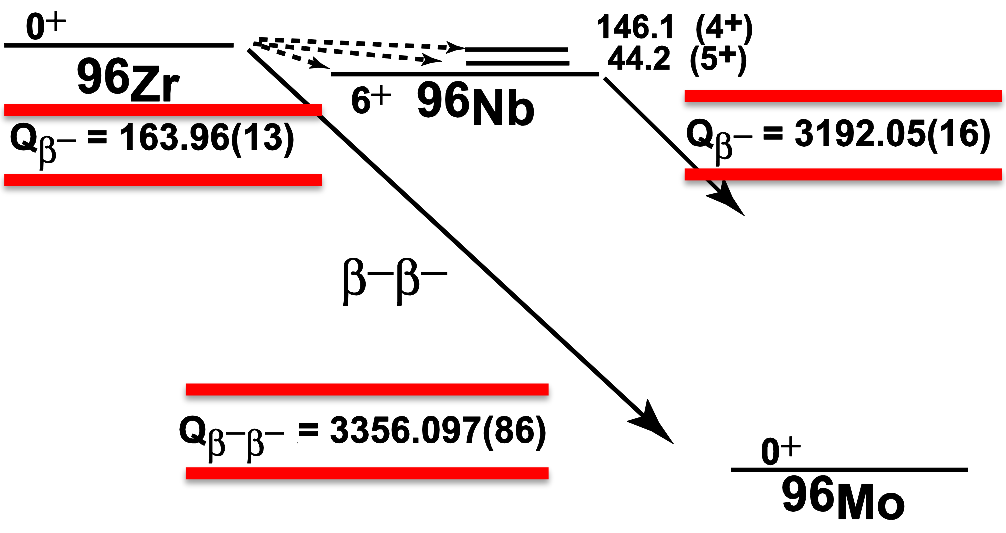
principle of isobar separation in purification trap





excitation of ion of interest with cyc. freq. causes collisional cooling of this species
(purification: > 500/1)

Results



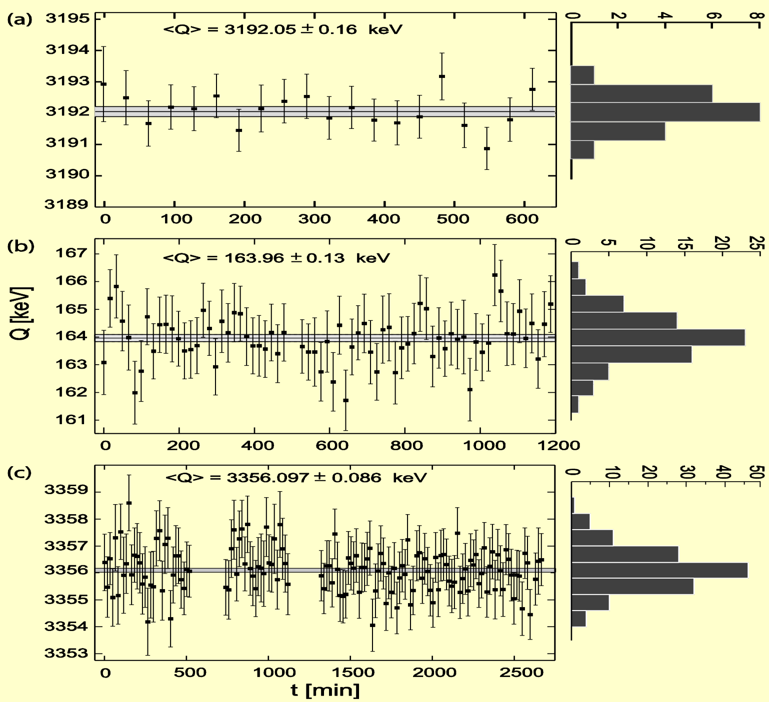
^{96}Zr

$$Q_{\beta\beta} = 3356.097 \pm 0.086 \text{ keV}$$

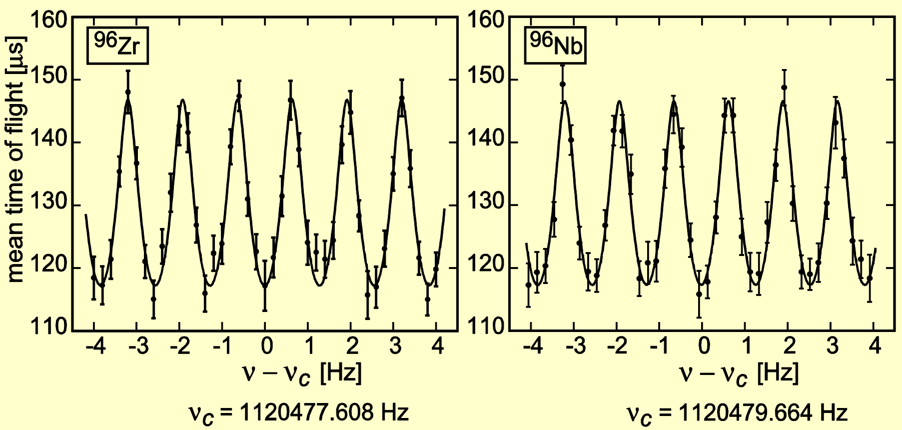
7.1 keV higher than AME2012

$$Q_{\beta} = 163.96 \pm 0.13 \text{ keV}$$

!!



Ramsey excitation



Next: need $T_{1/2}$ of single β decay

$$T_{1/2}(\mathrm{QRPA}) = 24\times10^{19}\ \mathrm{yr} \quad (g_A = 1)$$

$$T_{1/2}(\mathrm{SM}) = \frac{11}{g_A^2}\times10^{19}\ \mathrm{yr} \quad (g_A^2 = 0.75....1.6)$$

$$T_{1/2}(\mathrm{exp}) > 2.3\times10^{19}\ \mathrm{yr}$$

Important side effect:

single β decay depends on g_A^2

2ν/0νββ decay depends on g_A^4

A measurements of single β decay would give for the first time an expmtl handle on the quenching of the axial vector coupling constant

$T_{1/2}$ of ^{96}Zr decay

Geochemical method (zircon sample)

accumulation of decay daughter over geological time

- **Pros**: can provide longer $T_{1/2}$
- **Cons**: - measure only total decay
  - systematics from ^{95}Mo (n,γ) reaction
    n-sources: ^{238}U sf , cosmics
    BUT: zircon contains Gd (i.e. ^{157}Gd(n,γ))
  - needs chemical isobar separation (A=96)

age of sample:	1.822(±0.003) ×10^9 y
	dated by U-Pb technique
origin:	Capel Australia
advantage:	Mo is embedded in zircon attice with infinite retention time

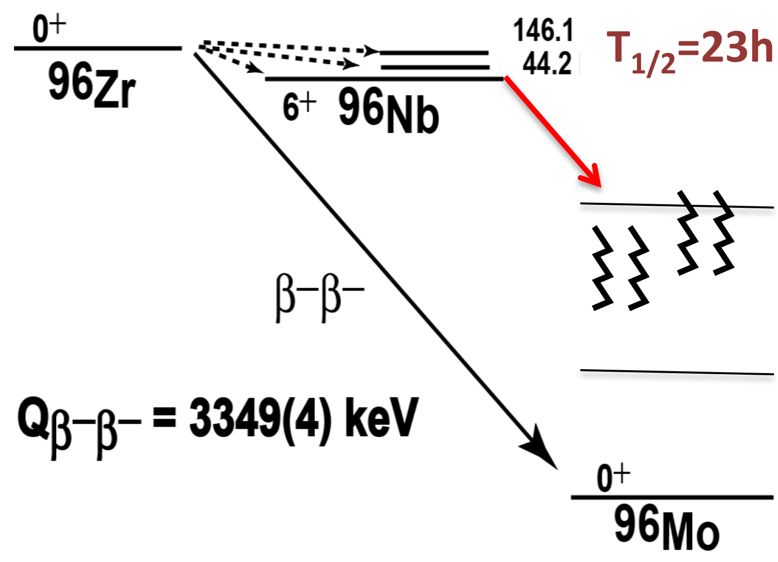
geo. $T_{1/2}$ calculation

- # of ^{96}Mo excess atoms in sample
- # of ^{96}Zr atoms in sample
- age of the sample

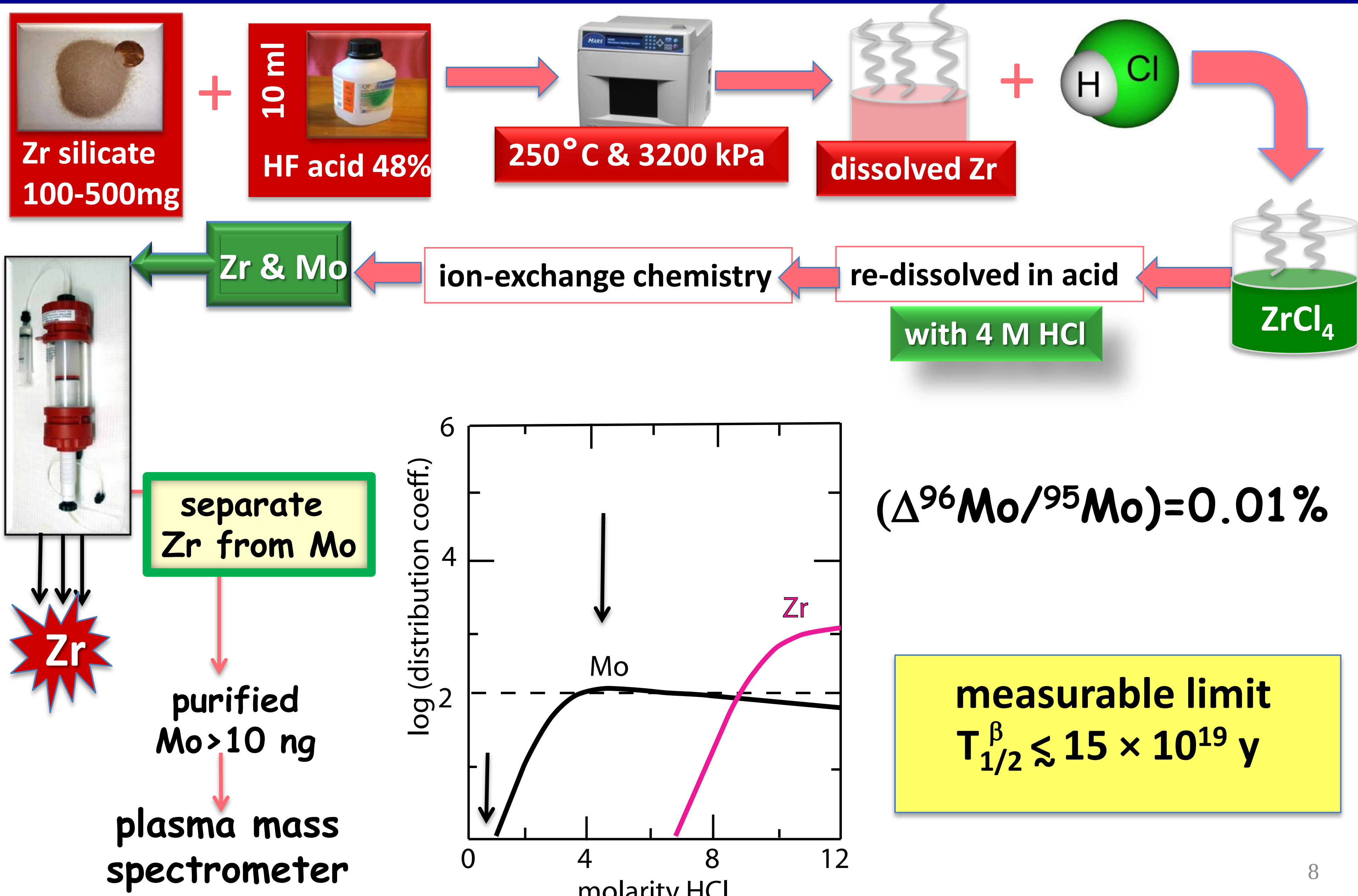
Counting-rates method

measures the decay rate

- **Pros**: measure partial decays
- **Cons**: - extremely low counting rates
  - background and time limited



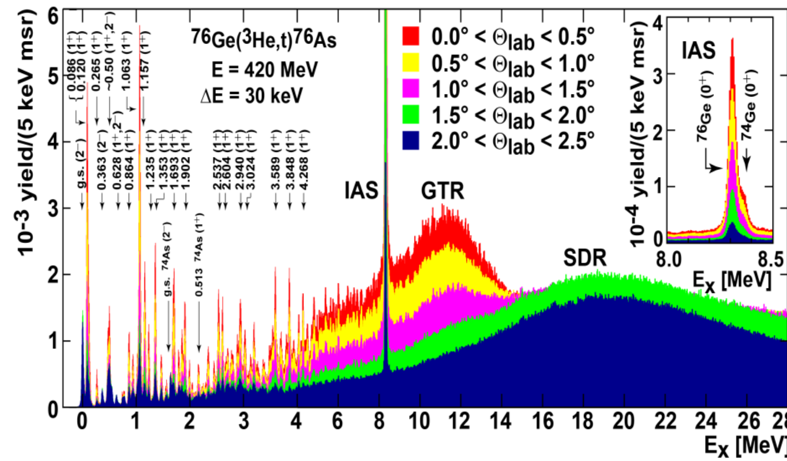
Isobar separation method (U of Calgary)



These and more pieces to the puzzle

- **chargex-reactions for 2νββ decay**

  Hadronic chargex and weak-interaction x-sections are fortuitously connected -- exploit this!!



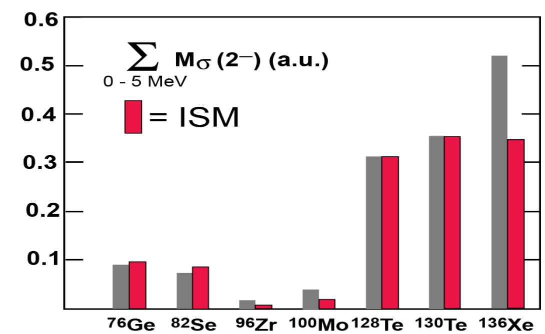
- **0νββ-decay and chargex-reaction**

  useful but limited

  e.g. 2^- states (resol'n is key)

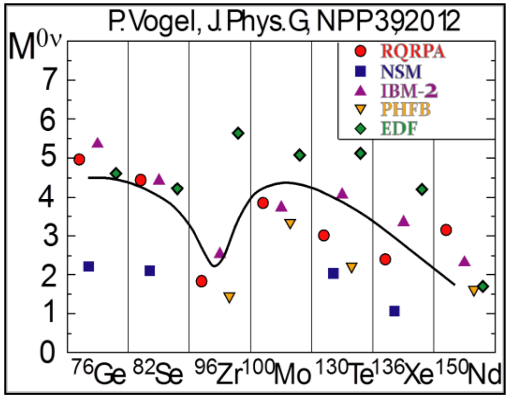
- **mass measurements for ββ-decay NME**

  the potential still needs to be exploited



- **single β decay half-life for ^{96}Zr (and ^{48}Ca)**
- **ground-state properties of intermediate odd-odd nuclei (TRIUMF, TITAN-EC)**
- **need to address quenching issue <u>urgently!!</u>**
- **need relevant spectroscopic information**

  (but theory needs to tell what is relevant)



- **theory needs to converge !!**
- **………**