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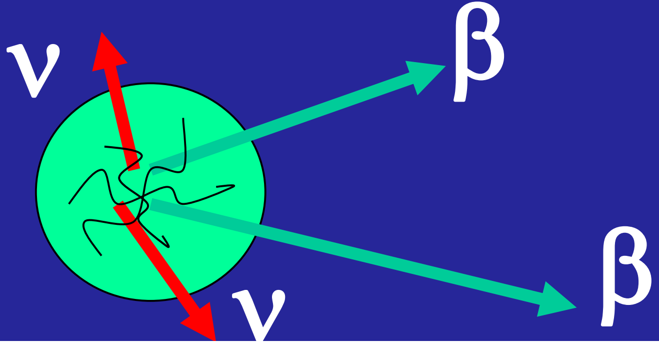
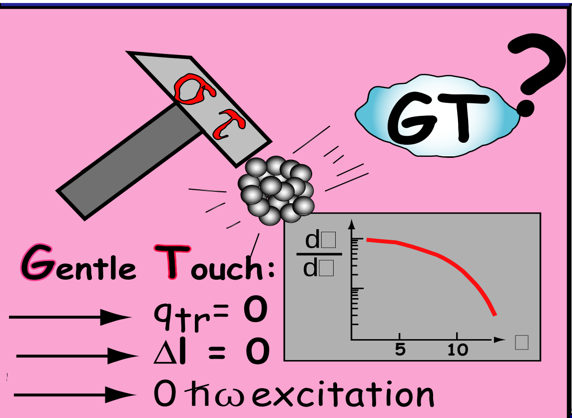
D. Frekers

Novel approaches to the nuclear physics of ββ-decay:

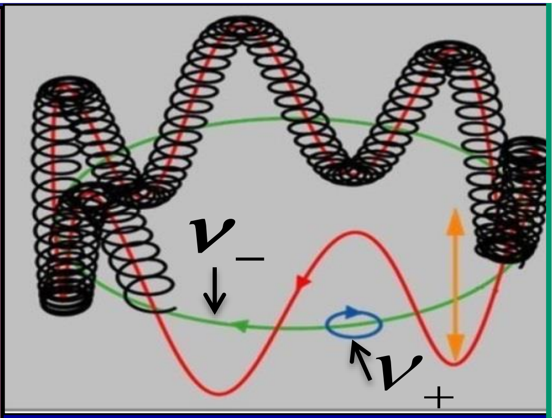
chargex reactions, mass-measurements, μ-capture

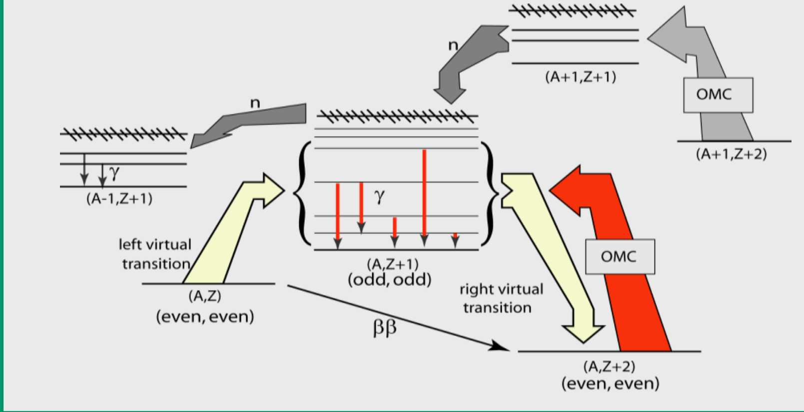


INT- 2018



Gentle Touch:
→ $q_{tr} = 0$
→ $\Delta l = 0$
→ $0\,\hbar\omega$ excitation





Where do we stand in ββ decay when putting together the pieces of the puzzle?

1. **General features**

2. **Chargex-reactions (^{3}He,t) & (d,^{2}He)**
   - ➢ perfect for 2νββ NME's

3. **Chargex-reactions**
   - ➢ limited for 0νββ NME's
     (here: 2^- states and nuclear wave function)

4. **Mass measurements**
   - ➢ 0νββ NME
   - ➢ ^{96}Zr is a „golden" case

(PRL116, Feb-2016)

$$^{96}\mathrm{Zr}\ (\beta^-)\ \xrightarrow[4u]{}\ ^{96}\mathrm{Nb},\ \text{and } g_A$$

5. **Muon capture projects starting (MuSIC)**
   - ➢ a high-q transfer phenomenon !!
     gives handle on **g_A quenching**

university of groningen

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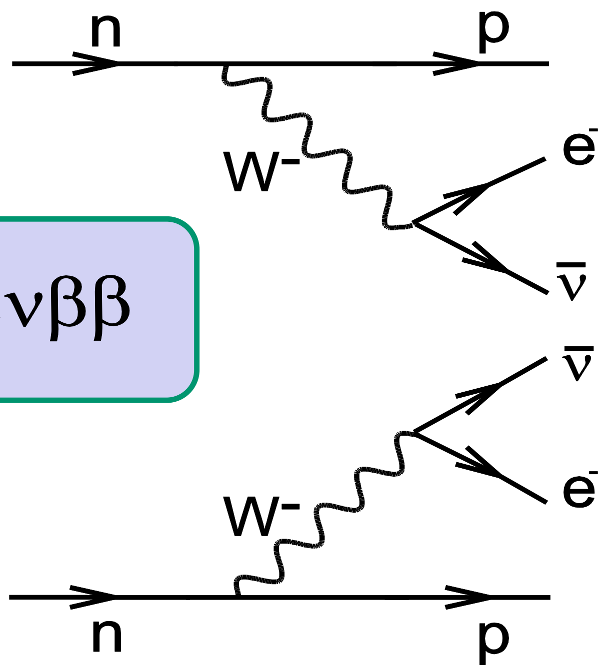
General features
(2νββ / 0νββ decay)

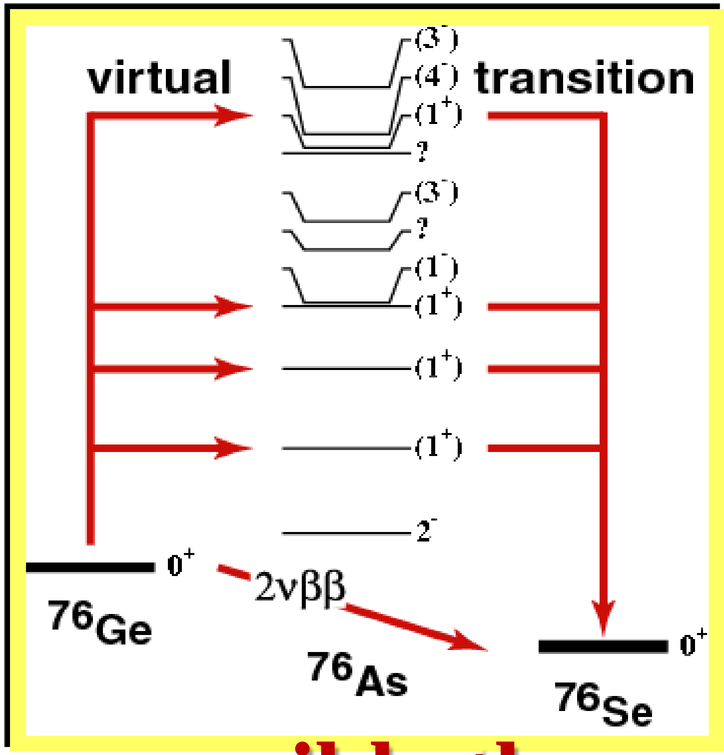
$$\Gamma^{2\nu}_{(\beta^-\beta^-)} = \frac{C}{8\pi^7}\left(\frac{G_F\, \overset{\swarrow\,!}{g_A}}{\sqrt{2}}\cos(\Theta_C)\right)^4 \left|M^{(2\nu)}_{DGT}\right|^2 F^{2}_{(-)}\, f(Q)$$

$$= G^{2\nu}(Q,Z) \quad g_A^4 \quad \left|M^{(2\nu)}_{DGT}\right|^2$$

2νββ



$q_{tr} \sim 0.01\ \mathrm{fm}^{-1}$



accessible thru charge-ex reaction

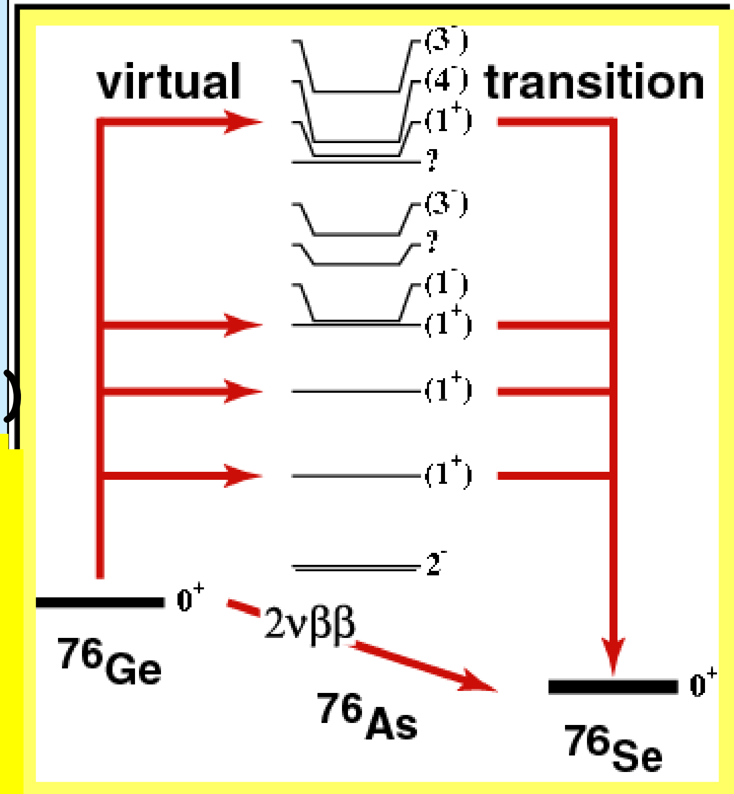
$$M^{(2\nu)}_{\mathrm{DGT}} = \sum_m \frac{\left\langle 0^{(f)}_{g.s.} \middle| \sum_k \sigma_k \tau_k^- \middle| 1^+_m \right\rangle \left\langle 1^+_m \middle| \sum_k \sigma_k \tau_k^- \middle| 0^{(i)}_{g.s.} \right\rangle}{\frac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - E_0}$$

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

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))

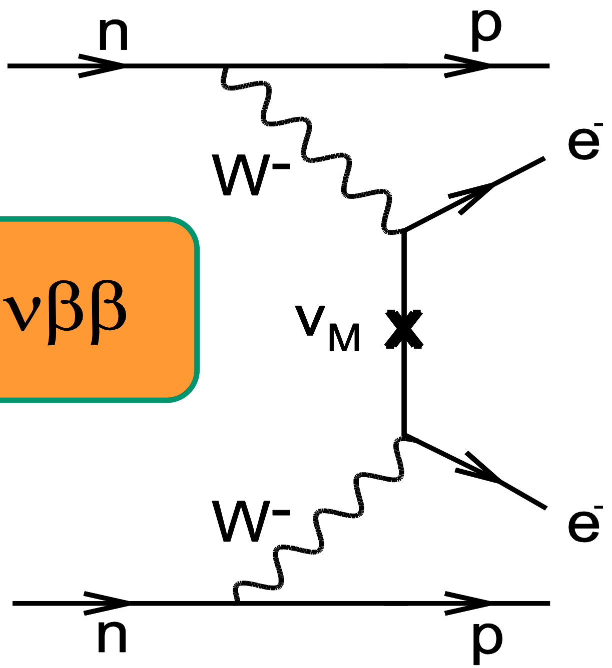


$$G^{0\nu}_{(\beta^-\beta^-)} = G^{0\nu}(Q,Z)\, g_A^4 \left| M^{(0\nu)}_{DGT} - \left(\frac{g_V}{g_A}\right)^2 M^{(0\nu)}_{DF} \right|^2 \left| m_{\nu_e} \right|^2$$

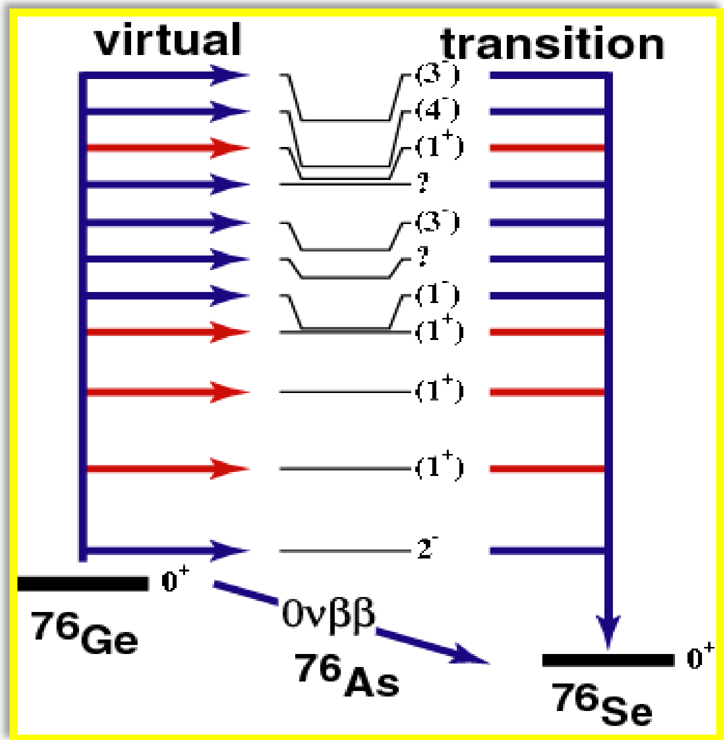
!

Majorana-ν !

0νββ



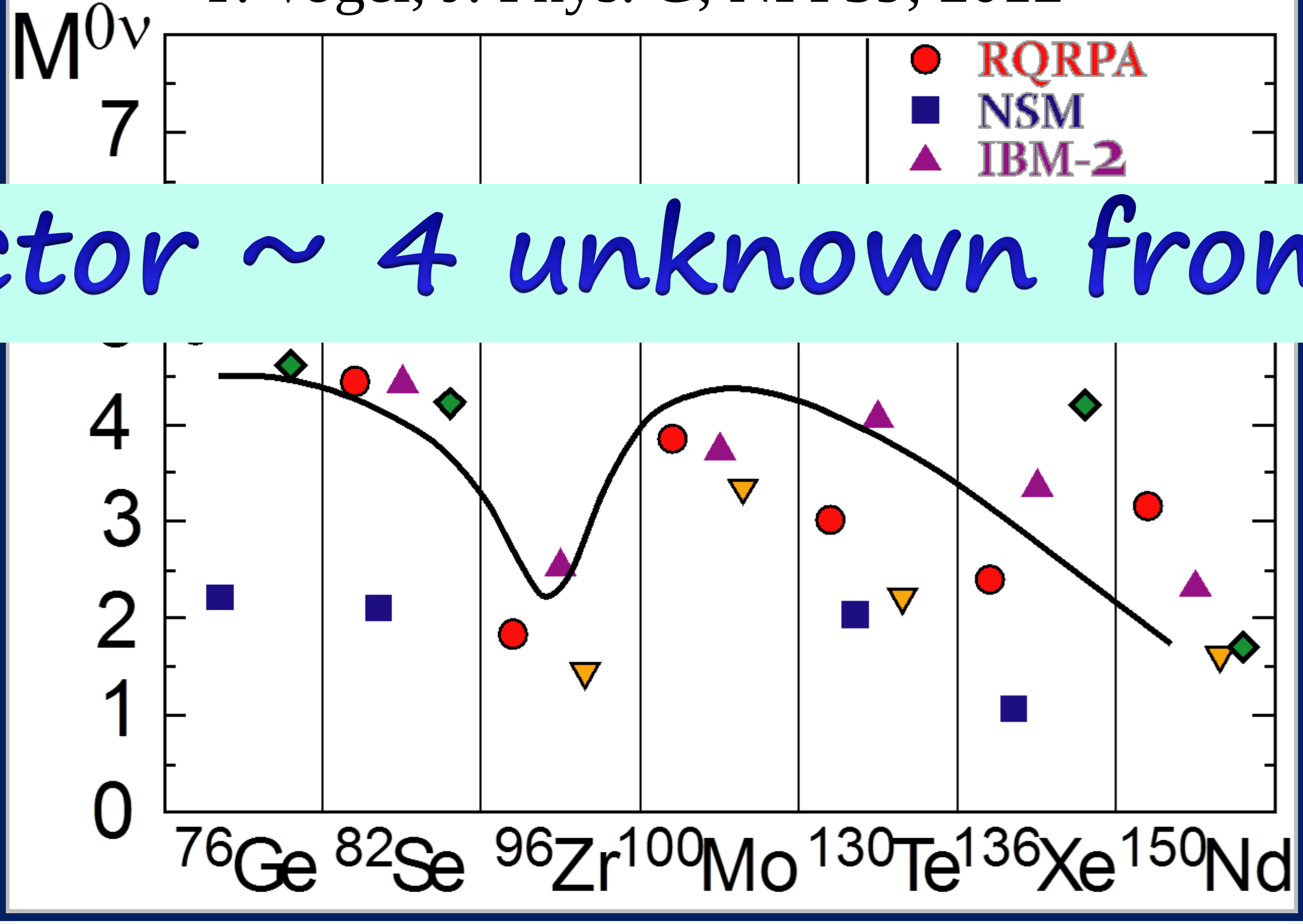
$q_{tr} \sim 0.5\ \mathrm{fm}^{-1}$!!



NOT accessible thru charge-ex reaction

The situation of the Nuclear Matrix Elemets for neutrinoless ββ decay

P. Vogel, J. Phys. G, NPP39, 2012



+ factor ~ 4 unknown from g_A^4.

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Charge-exchange reactions

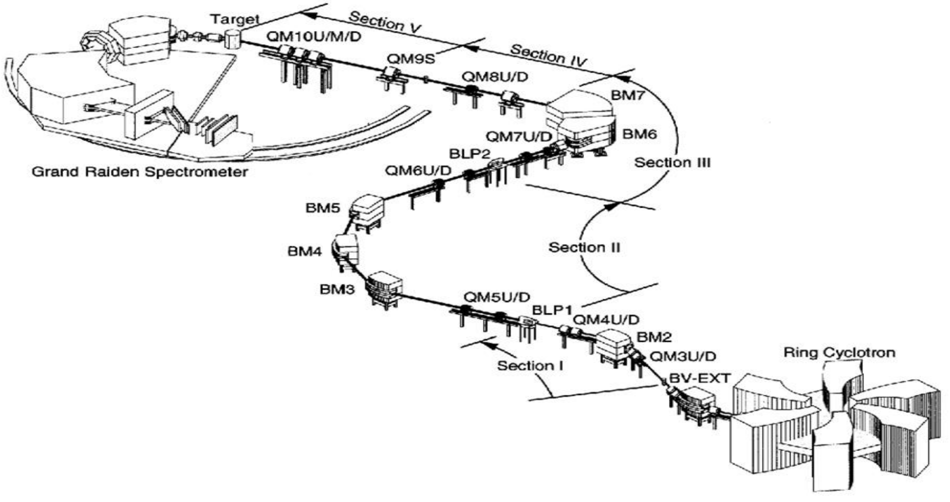
GT-part

(2$\nu\beta\beta$ decay)

Charge-exchange reactions

Grand Raiden Magnetic Spectrometer

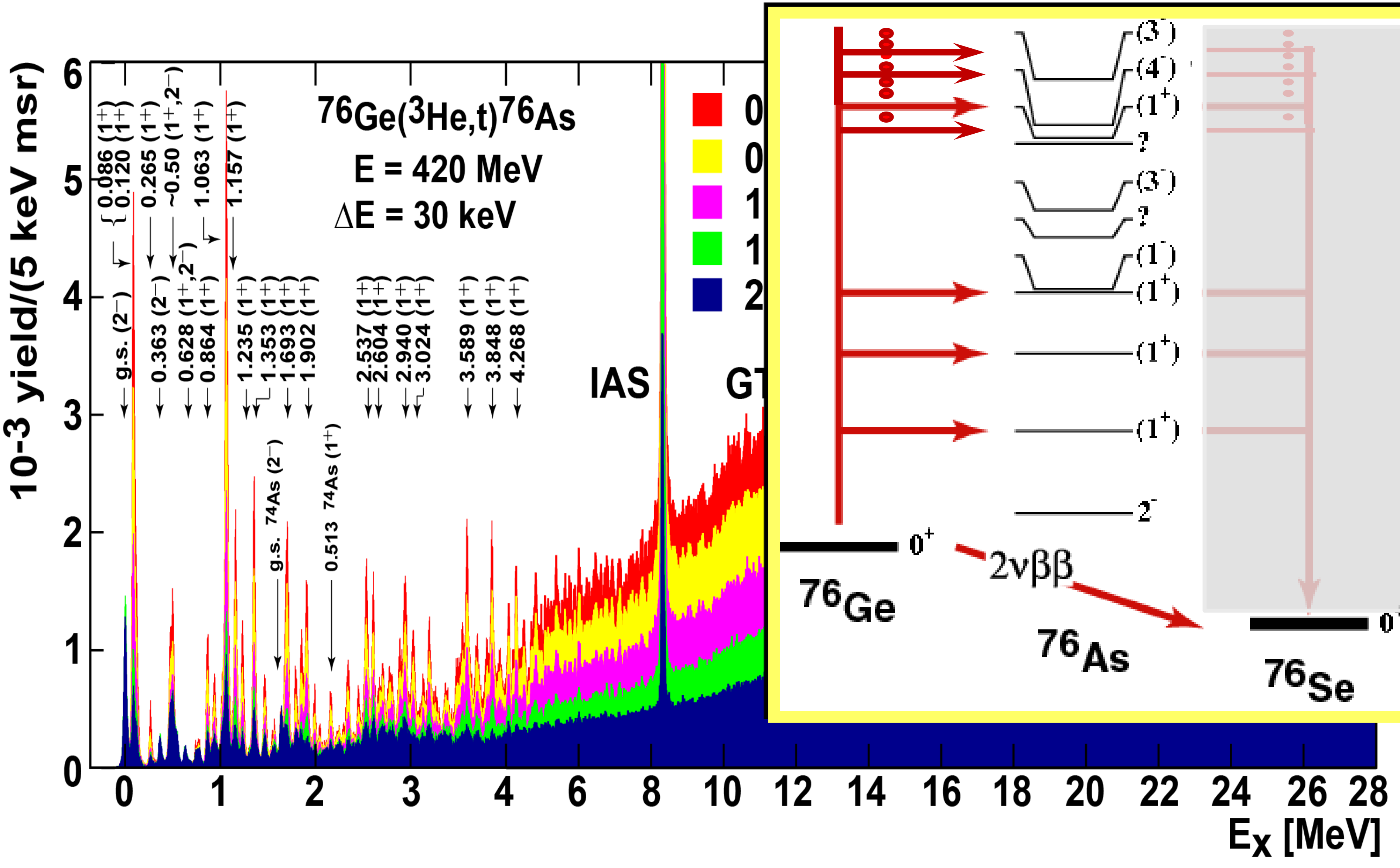
$\Delta E/E \sim 5 \times 10^{-5}$ ~ 25 keV
at 420 MeV (^{3}He)



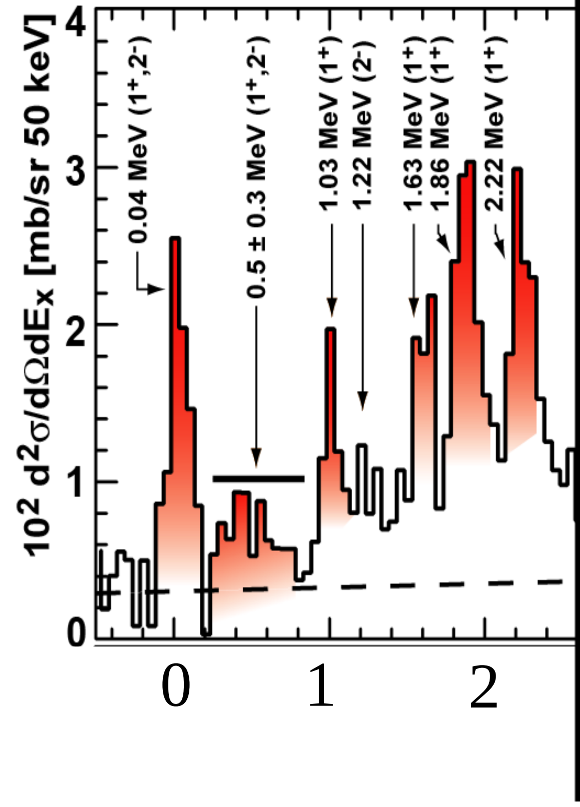
^{76}Ge

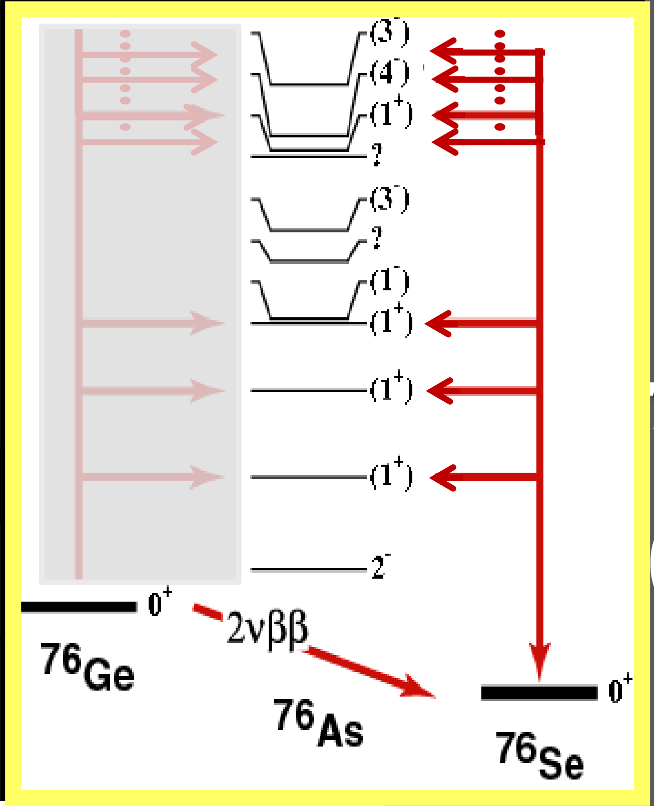
$N-Z=10$

Resolution is the key !!!

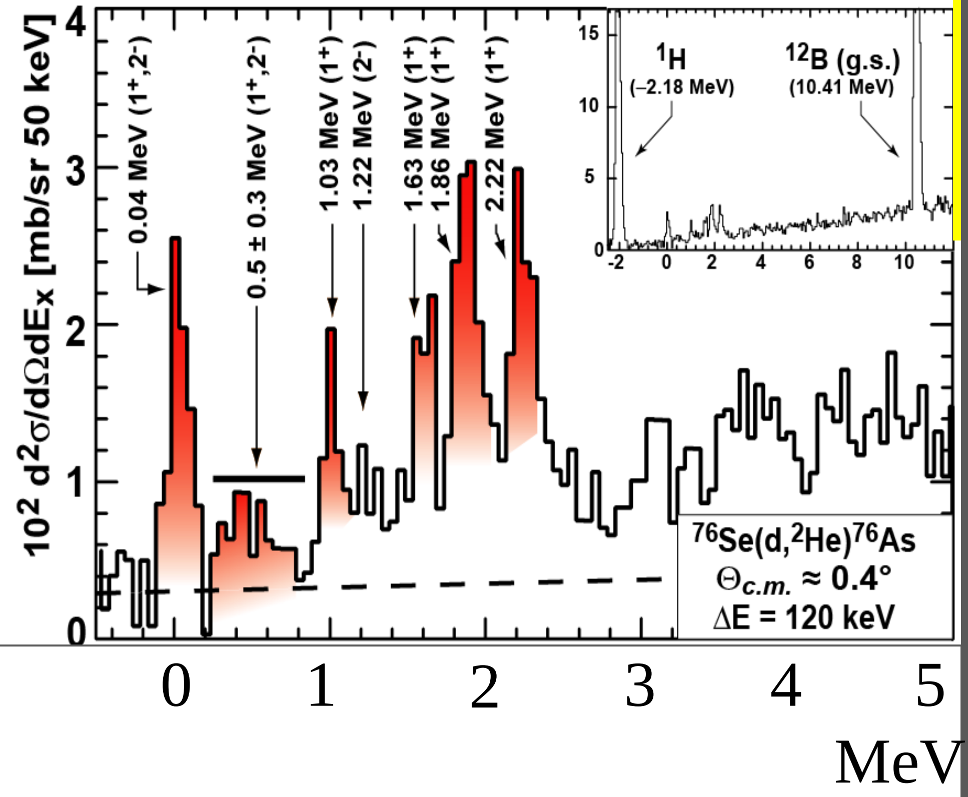


almost 70 !! resolved single states up to 5 MeV identified as GT 1+ transitions !!!



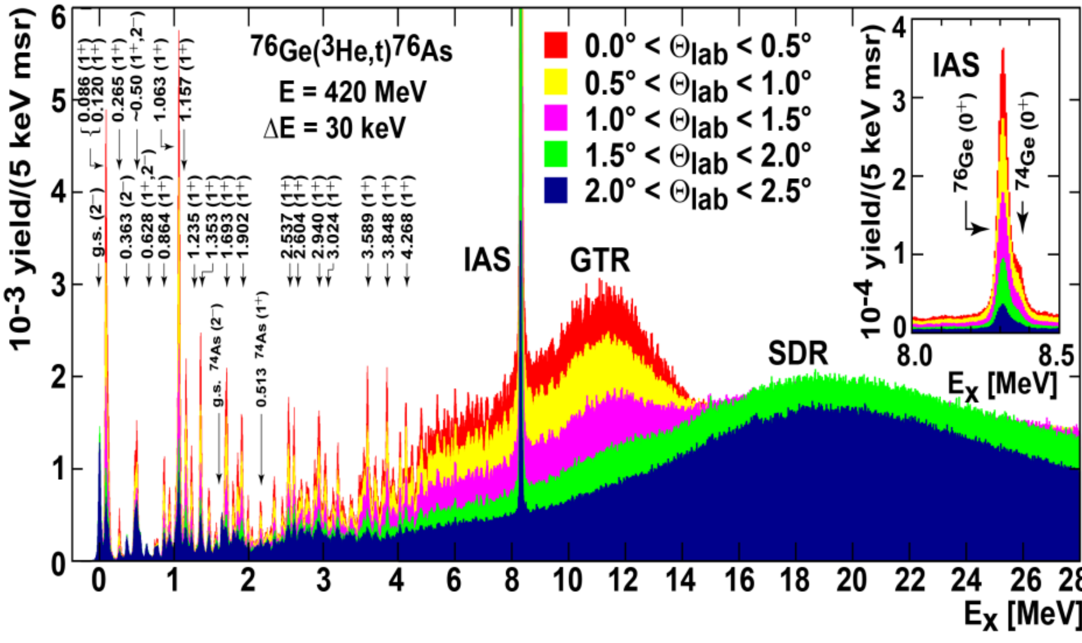


the other leg (BGT^{+}): ^{76}Se(d,^{2}He)^{76}As (ΔE = 120 keV)



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

a surprise:



low-E part of NME makes up ~100% of total $2\nu\beta\beta$-ME (given by $T_{1/2}^{2\nu\beta\beta} = 1.4 \times 10^{21}$yr)

no need for GT giant resonance contribution

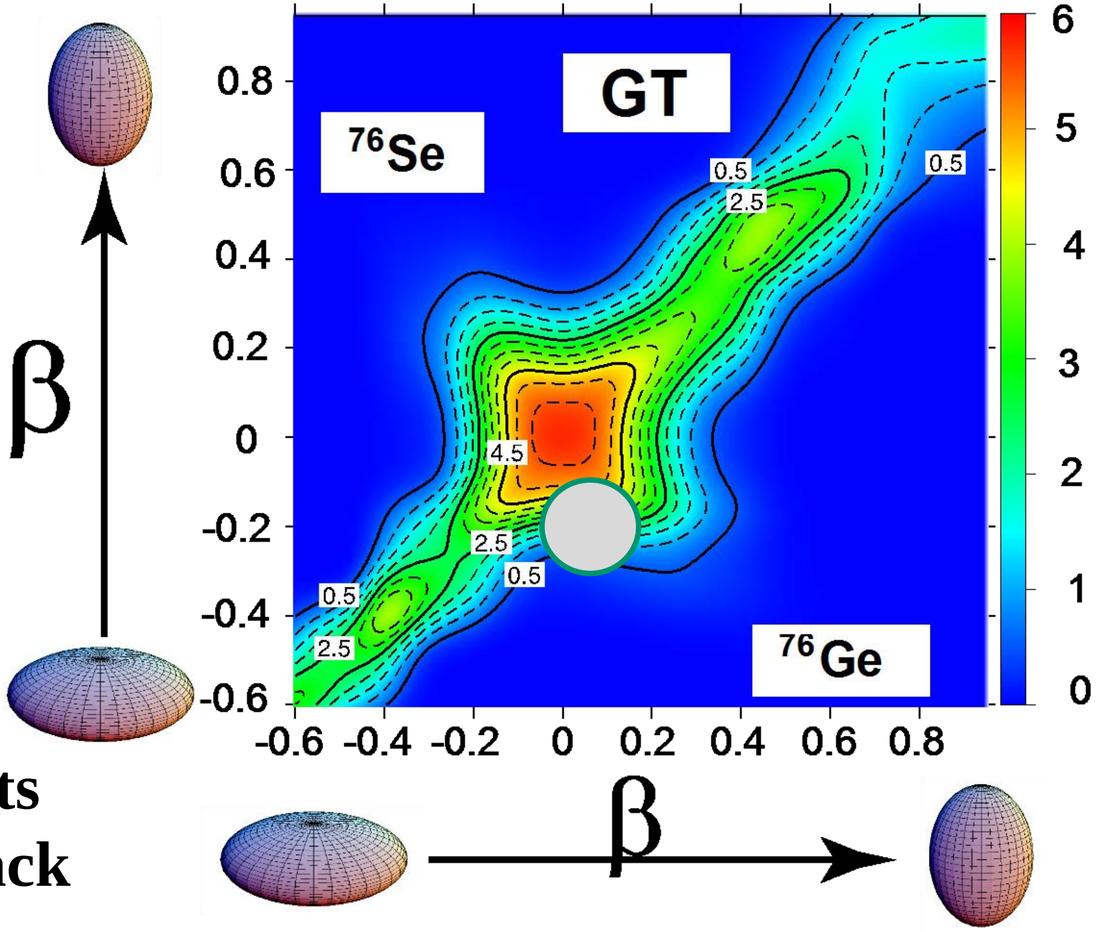
Nuclear matrix elements and deformation

^{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 manifest 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)

^{100}Mo

N-Z=16

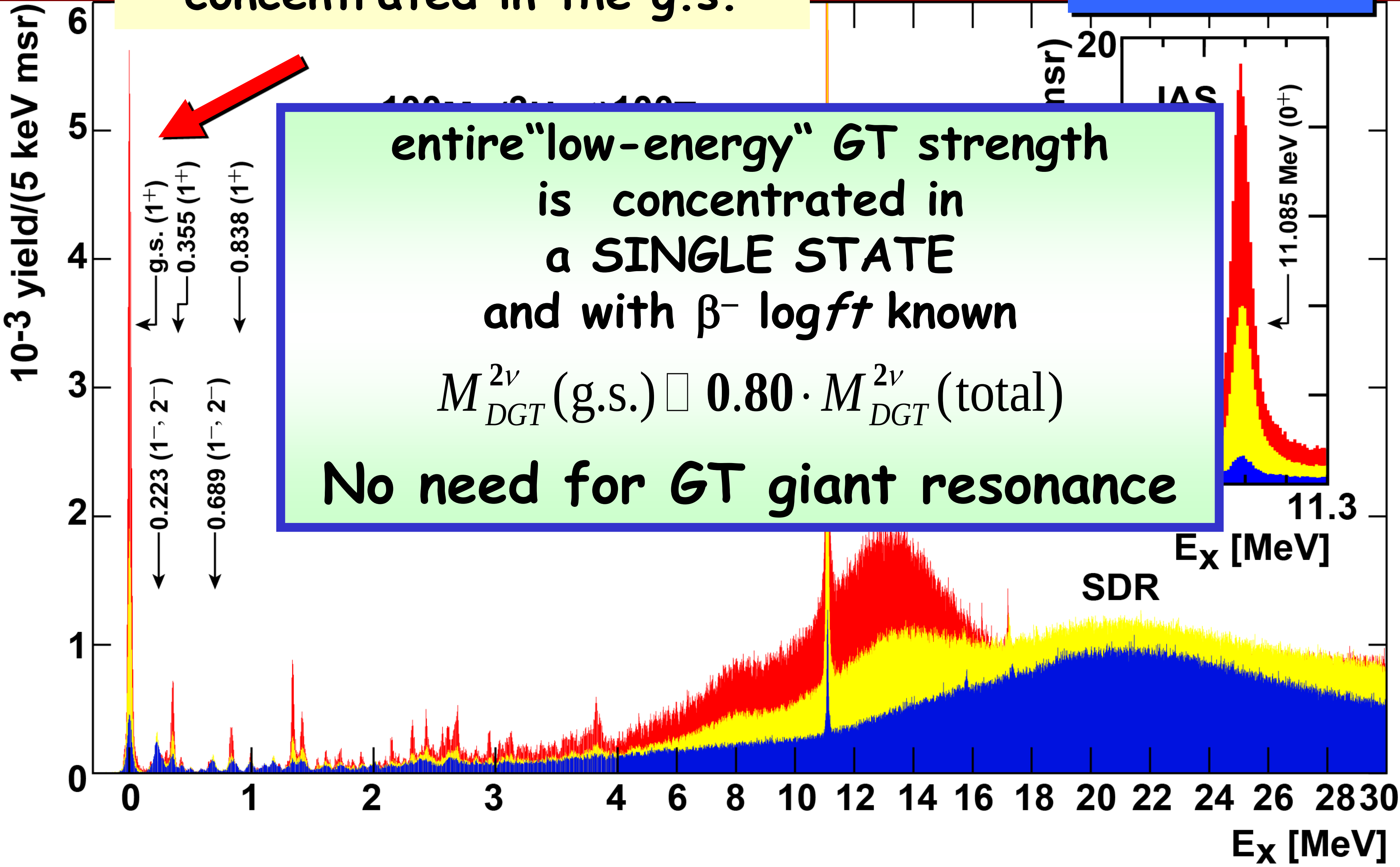
$T_{1/2}^{2\nu\beta\beta} = 6.9 \times 10^{18}$ yr

has the largest NME

(NME ~ 0.24/MeV)

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

$$M^{2\nu}_{DGT}(\mathrm{g.s.}) \approx \mathbf{0.80} \cdot M^{2\nu}_{DGT}(\mathrm{total})$$

No need for GT giant resonance

^{136}Xe

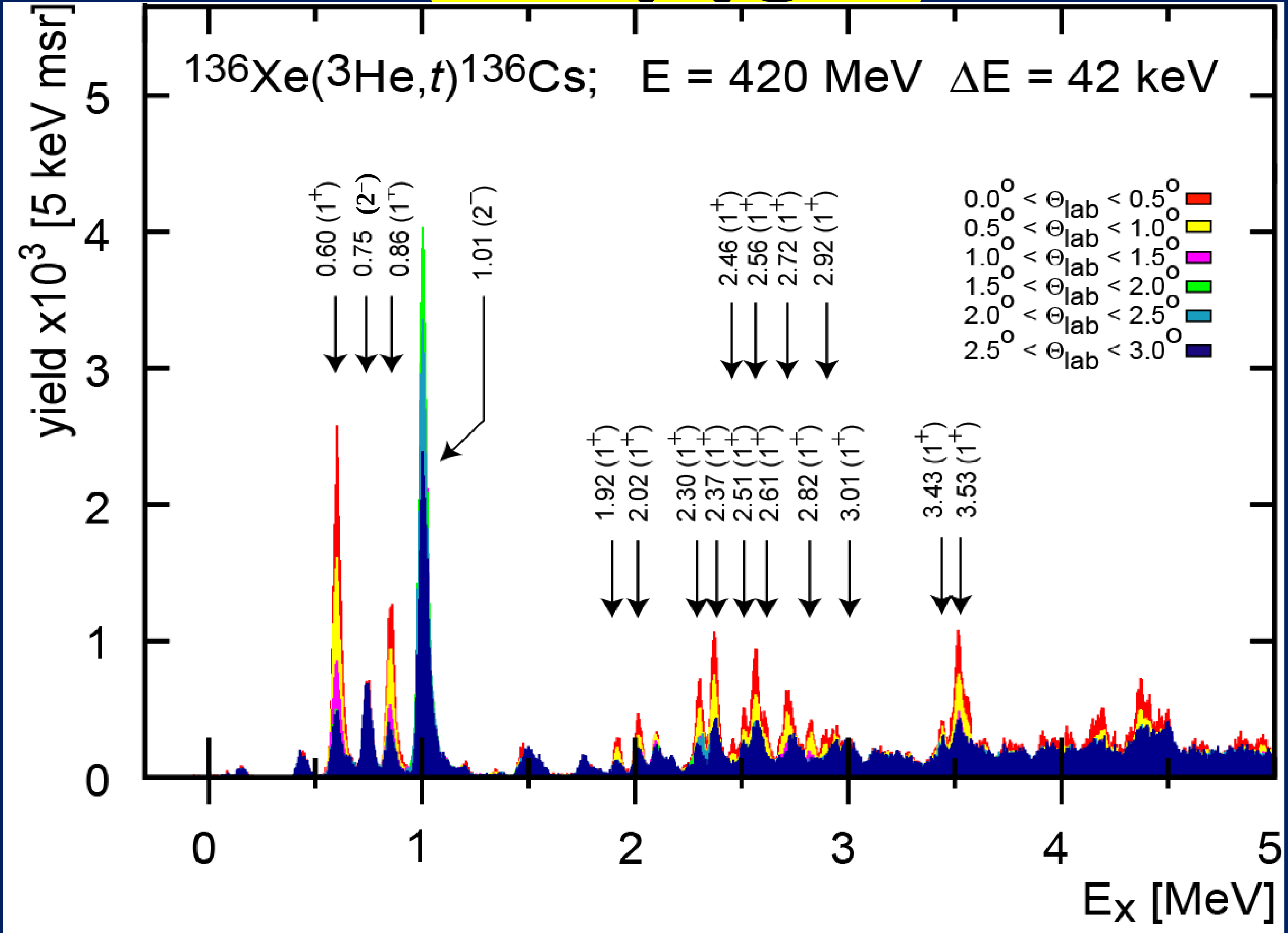
$T_{1/2}^{2\nu\beta\beta} = 2.2 \times 10^{21}$ yr

has the smallest NME

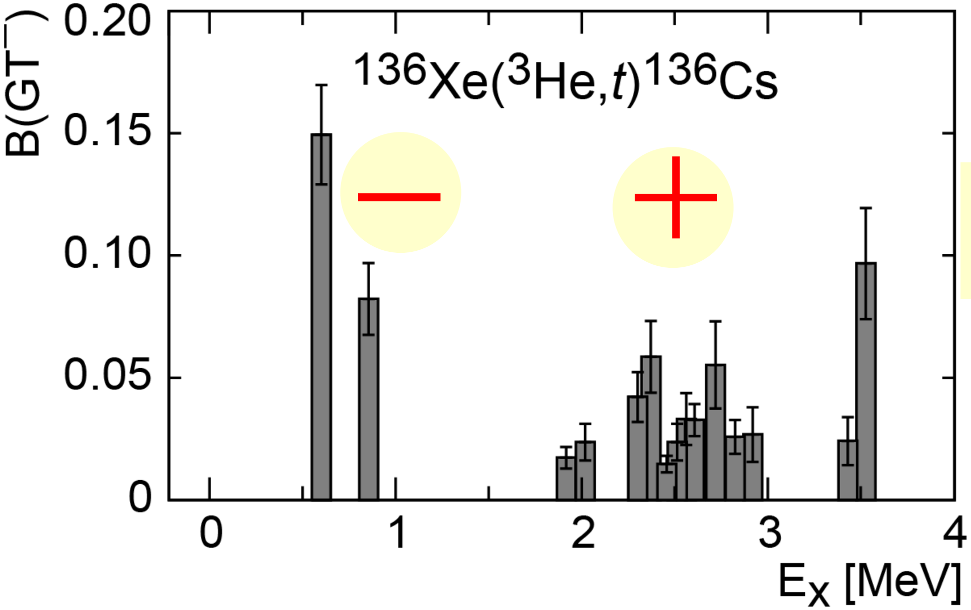
question: why so stable !!!

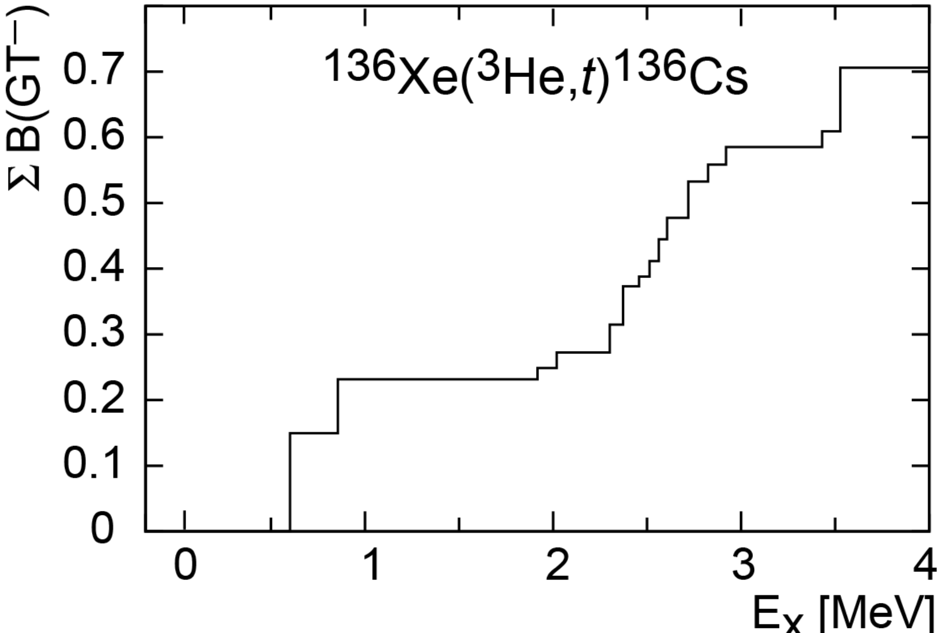
(lives 300 times longer than ^{100}Mo)

^{136}Xe


^{136}Xe(^{3}He,t)^{136}Cs; E = 420 MeV ΔE = 42 keV
yield x10^3 [5 keV msr]
E_x [MeV]
0
1
2
3
4
5
0.60 (1^+)
0.75 (2^-)
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^+)
$0.0^o < \Theta_{lab} < 0.5^o$ 🟥
$0.5^o < \Theta_{lab} < 1.0^o$ 🟨
$1.0^o < \Theta_{lab} < 1.5^o$ 🟪
$1.5^o < \Theta_{lab} < 2.0^o$ 🟩
$2.0^o < \Theta_{lab} < 2.5^o$ 🟦
$2.5^o < \Theta_{lab} < 3.0^o$ 🟦

What's the size of the NME?





$$T^{2n}_{1/2} = 2.2\times10^{21}\,\mathrm{yr}$$

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

all signs positive —>

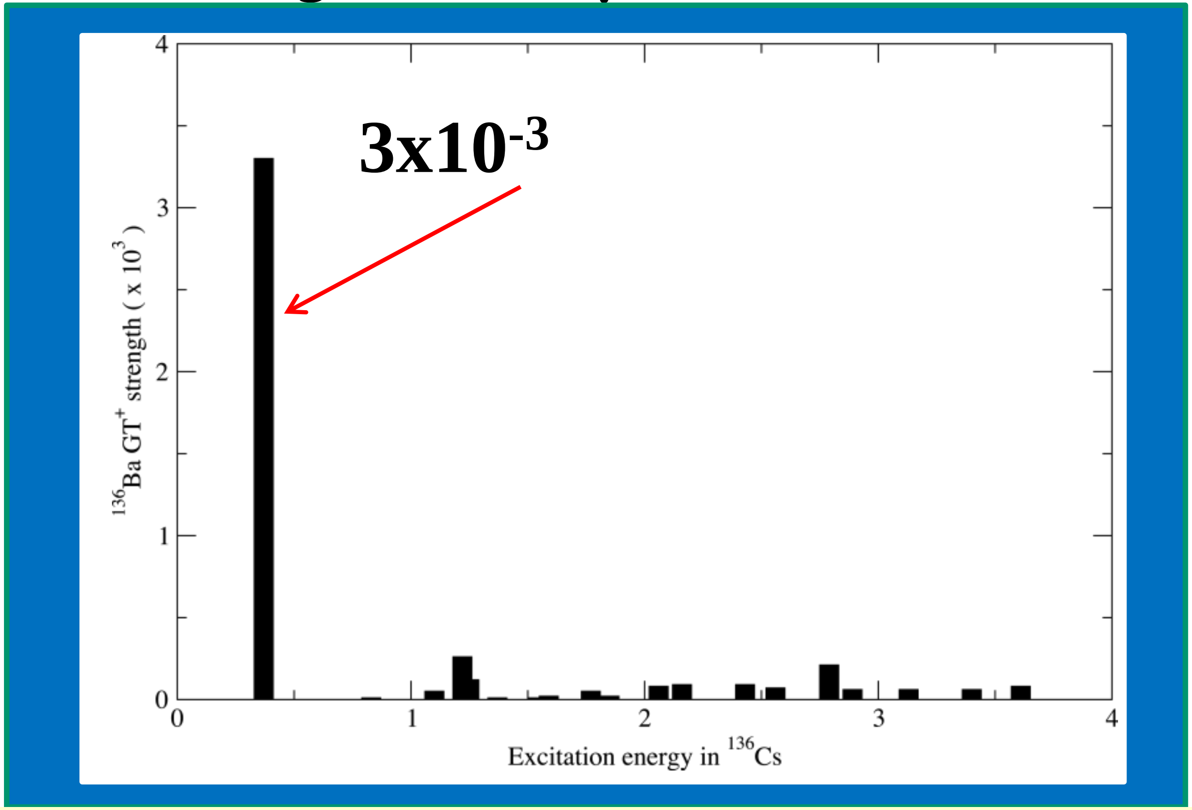
$$B_m\left(GT^{+}\right) \text{»}\ 10^{-2}\times B_m\left(GT^{-}\right)$$

$$B_m\left(GT^{+}\right) \text{»}\ 10^{-3}\ !!!!$$

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

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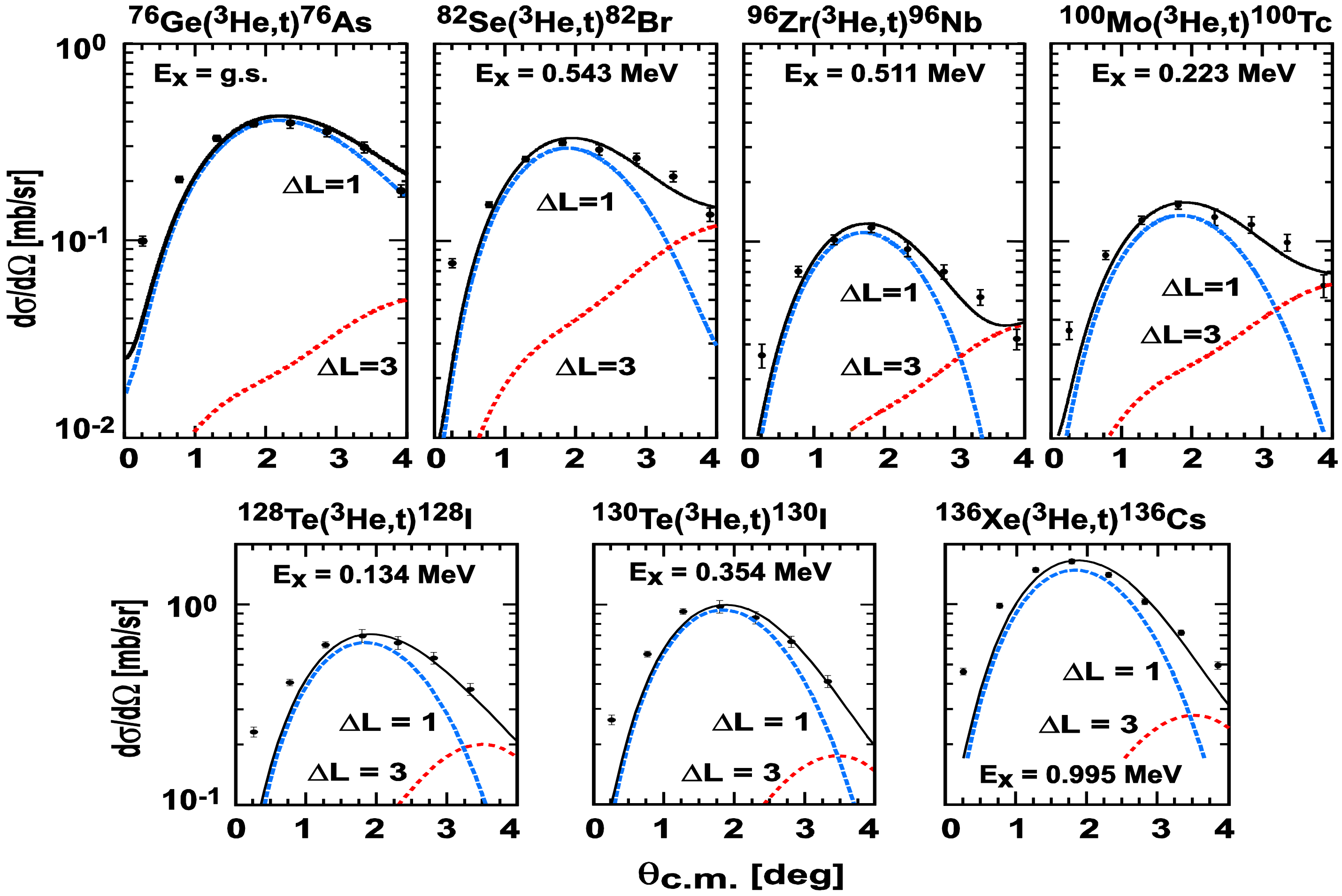
Charge-exchange reactions

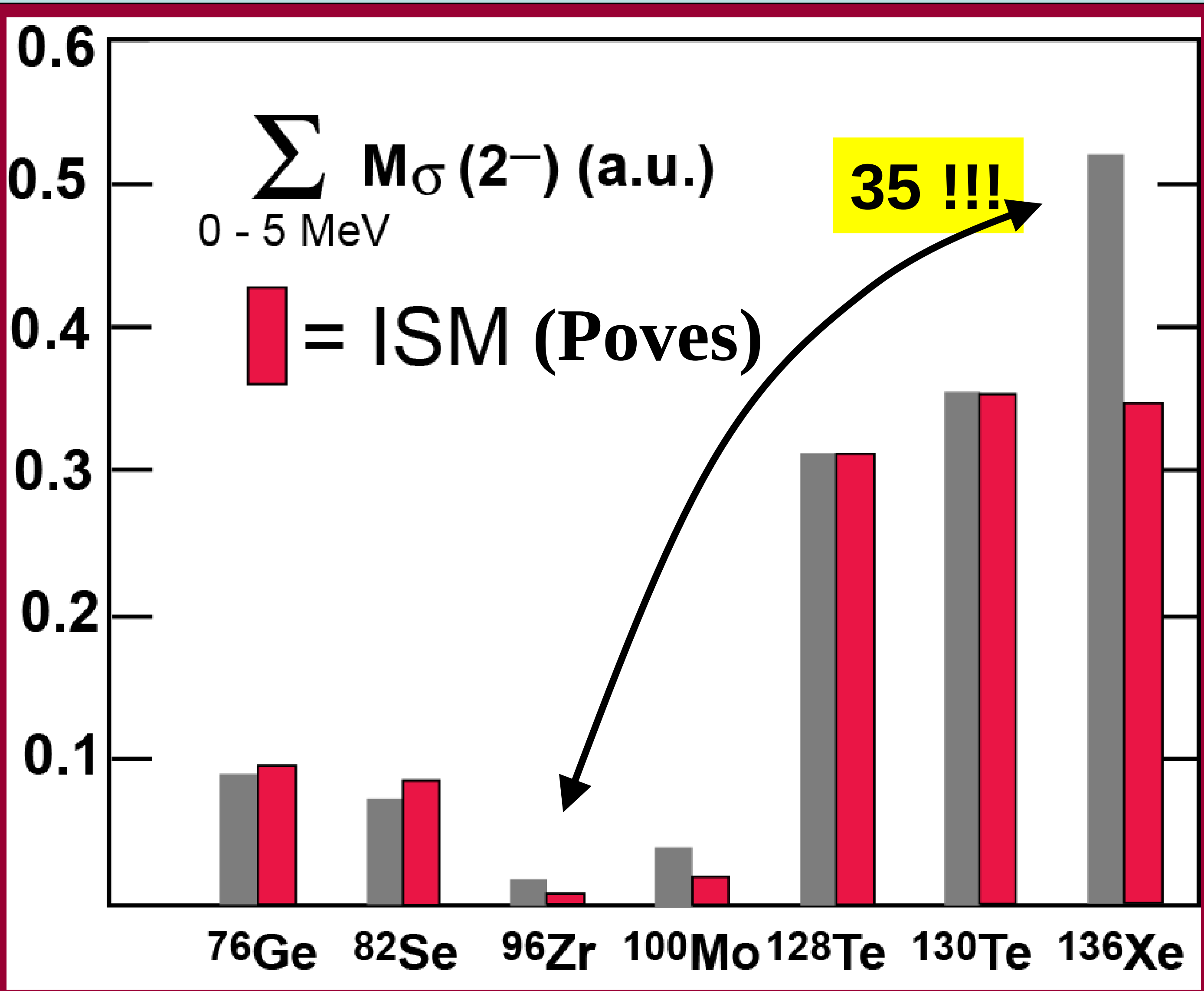
spin-dipole part

(0νββ decay)

Charge-exchange reaction towards the 0νββ NME's

Here: 2^- states via chargex reactions

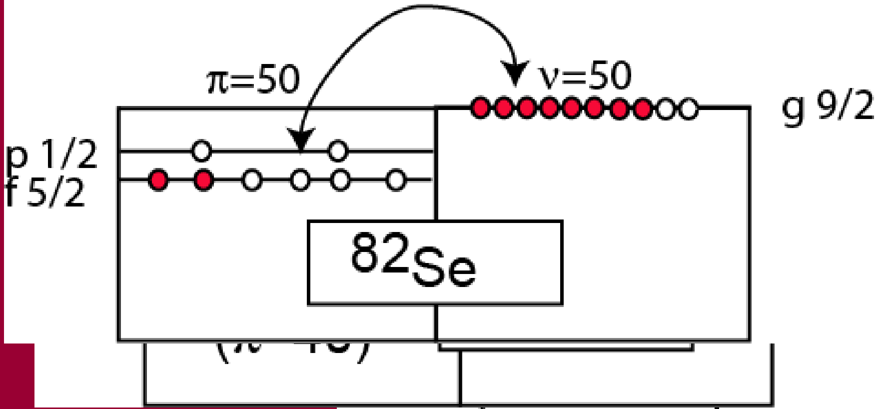



$\sum_{0 - 5\ \mathrm{MeV}} M_\sigma(2^-)$ (a.u.)
🟥 = ISM (Poves)
0.6
0.5
0.4
0.3
0.2
0.1
^{76}Ge
^{82}Se
^{96}Zr
^{100}Mo
^{128}Te
^{130}Te
^{136}Xe

35 !!!

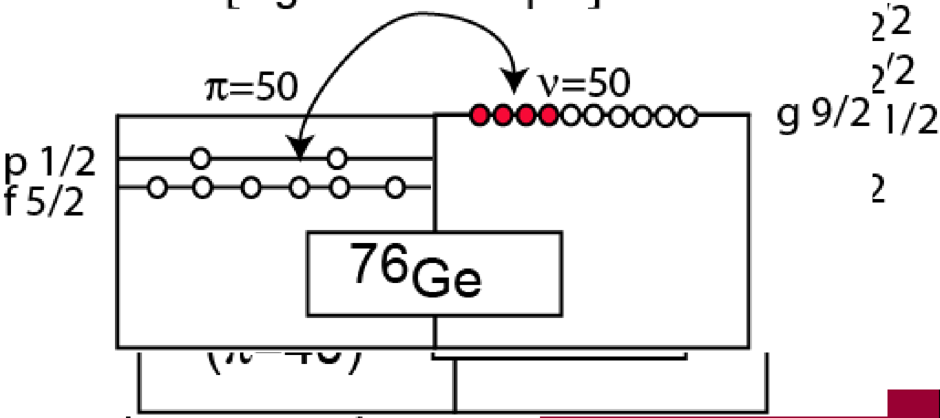
$[\nu\ d\,5/2 \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$

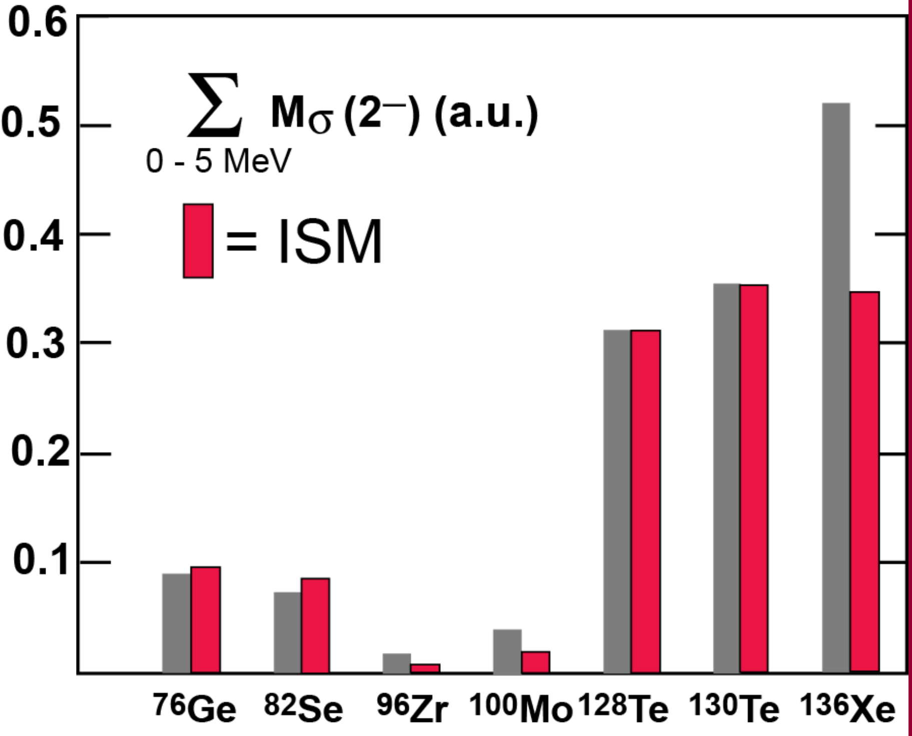
$[\nu\ g\,9/2 \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$



$[\nu\ 2d1g \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$

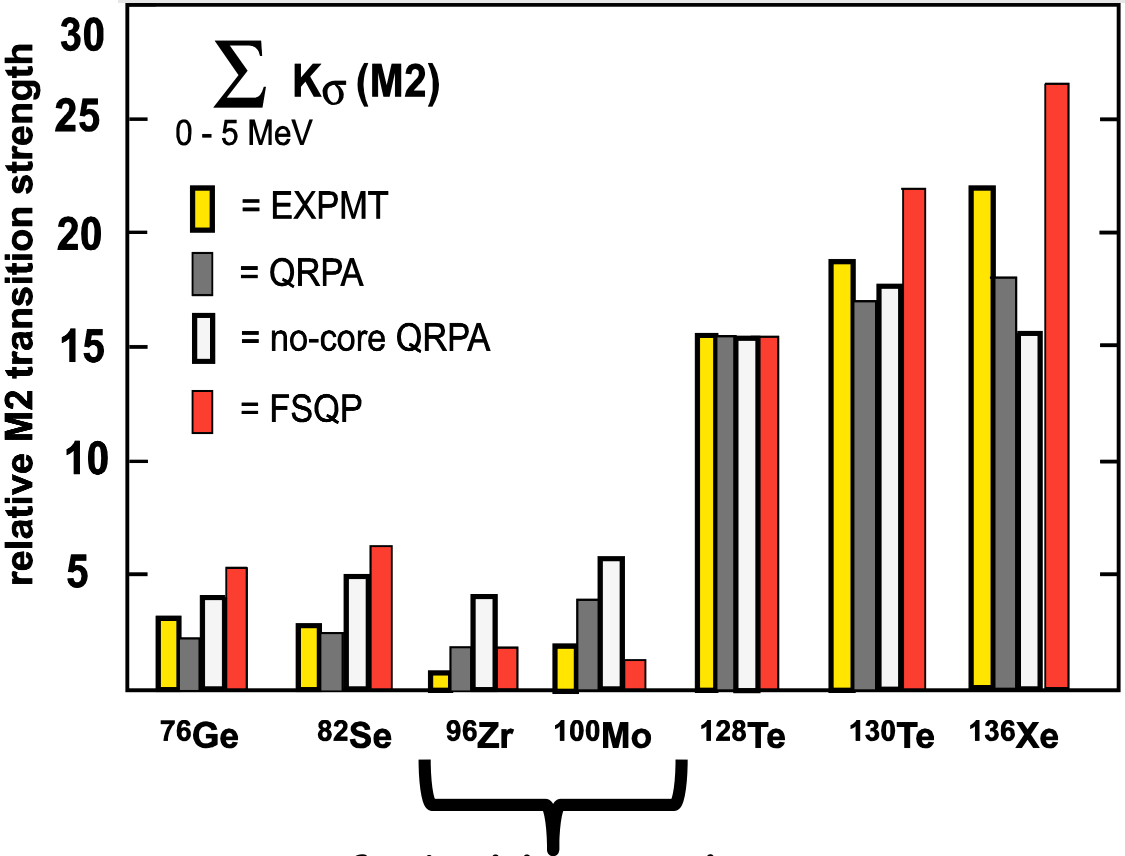
$[\nu\ g\,9/2 \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$





Low-energy spin-dipole (2⁻) strength to test nuclear wave function for 0νββ decay NME's

$$\left.\frac{d\sigma^{\mathrm{SD}}}{d\Omega}\right|_{q_{\max}} = \left[\frac{\mu}{\pi\hbar^2}\right]^2 \frac{k_f}{k_i} N_D^{\sigma\tau} \left|\frac{J_{\sigma\tau}^{q_{\max}}}{r_0 A^{1/3}}\right|^2 K_\sigma(M2).$$



forbidden in the extreme shell model

MODELS

QRPA

→ reasonable description

no-core QRPA

→ washes out shell structures

FSQP

→ semi-microscopic model, excellent description of data

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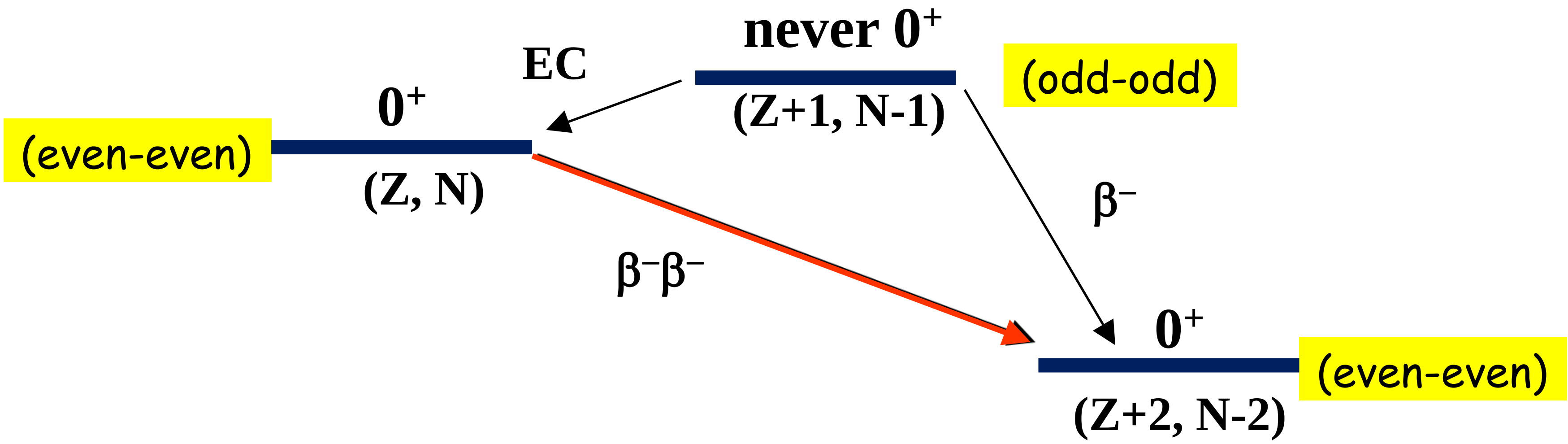
Mass measurements and 0νββ NMEs ^{96}Zr

$\beta^-\beta^-$ decay



never 0^+

(odd-odd)

EC

0^+

(even-even)

(Z+1, N-1)

(Z, N)

β^-

$\beta^-\beta^-$

0^+

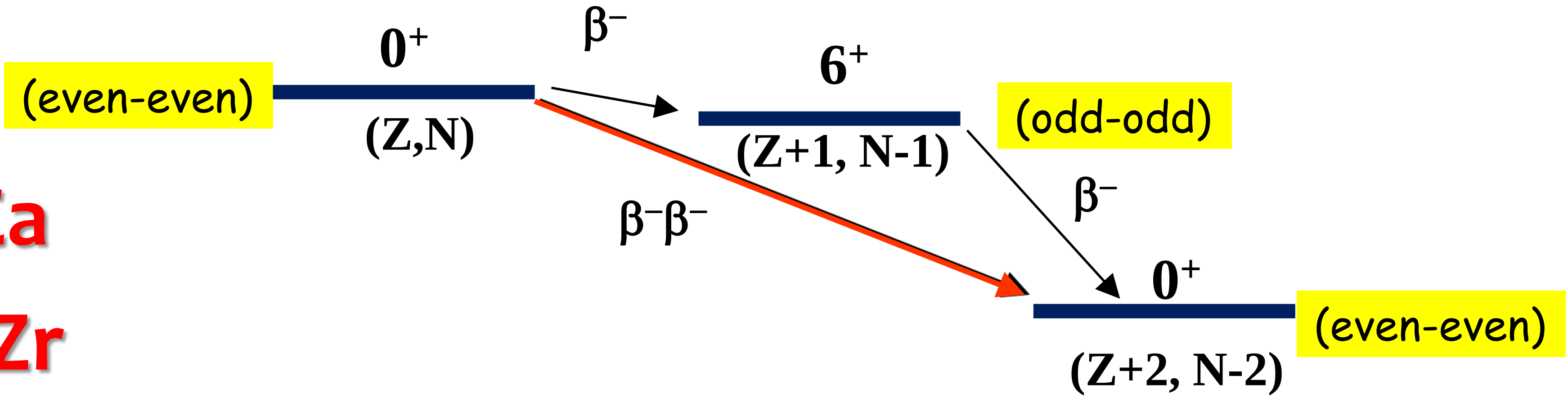
(even-even)

(Z+2, N-2)

1. ^{48}Ca
2. ^{150}Nd
3. ^{96}Zr
1. ^{100}Mo
2. ^{82}Se
3. ^{116}Cd
7. ^{130}Te
8. ^{136}Xe
9. ^{124}Sn
10. ^{76}Ge
11. ^{110}Pd

The β-β- decay candidates with highest Q-value

$\beta^-\beta^-$ decay



^{48}Ca

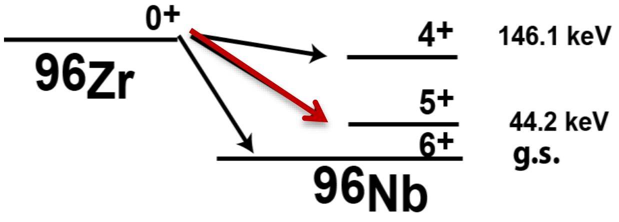
^{96}Zr

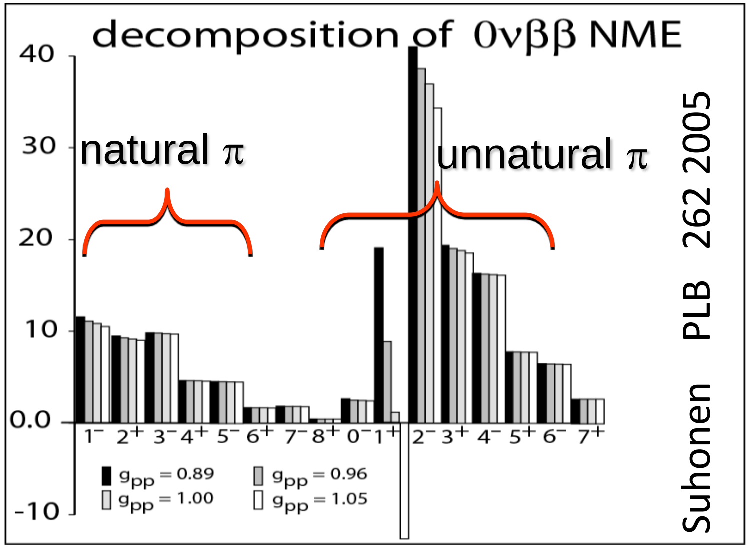
1. ^{48}Ca
2. ^{150}Nd
3. ^{96}Zr
1. ^{100}Mo
2. ^{82}Se
3. ^{116}Cd
7. ^{130}Te
8. ^{136}Xe
9. ^{124}Sn
10. ^{76}Ge
11. ^{110}Pd

The β-β- decay candidates with highest Q-value

Idea

- measure **Q-value** for ^{96}Zr $\longrightarrow$ ^{96}Nb **single β-decay** by precision mass measurement
- measure the **single β-decay** rate
- → 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!!**





Suhonen PLB 262 2005

Competition between β & ββ decay of ^{96}Zr

two conflicting half-lives:

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

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

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

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

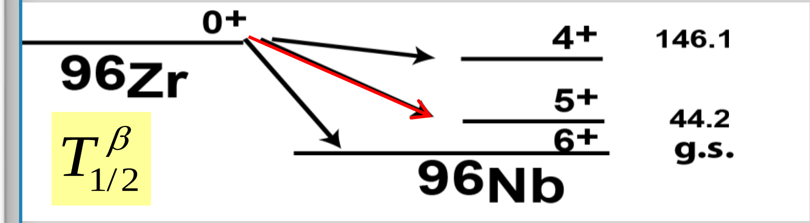
expected $T_{1/2}^{\beta} = (1.6 \pm 0.9) \times 10^{19}\,\mathrm{y}$

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

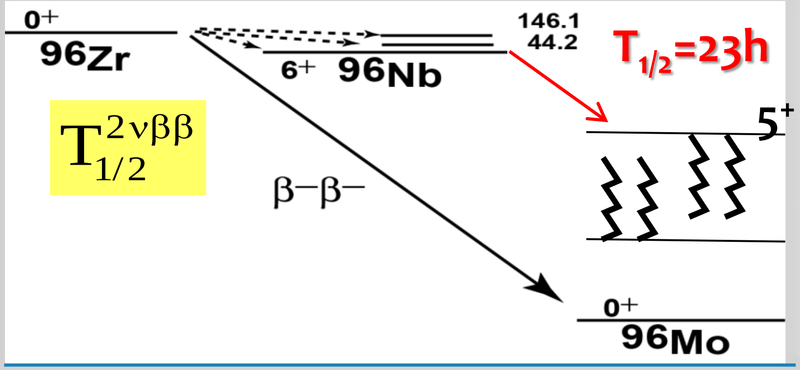
pred. (QRPA) $T_{1/2}^{\beta} = 24 \times 10^{19}\,\mathrm{y}$ ③

BUT

$$(T_{1/2}^{\beta})^{-1} \propto 0(Q^{13})\, g_A^2 \left\langle M_{\beta}^{4u} \right\rangle^2$$



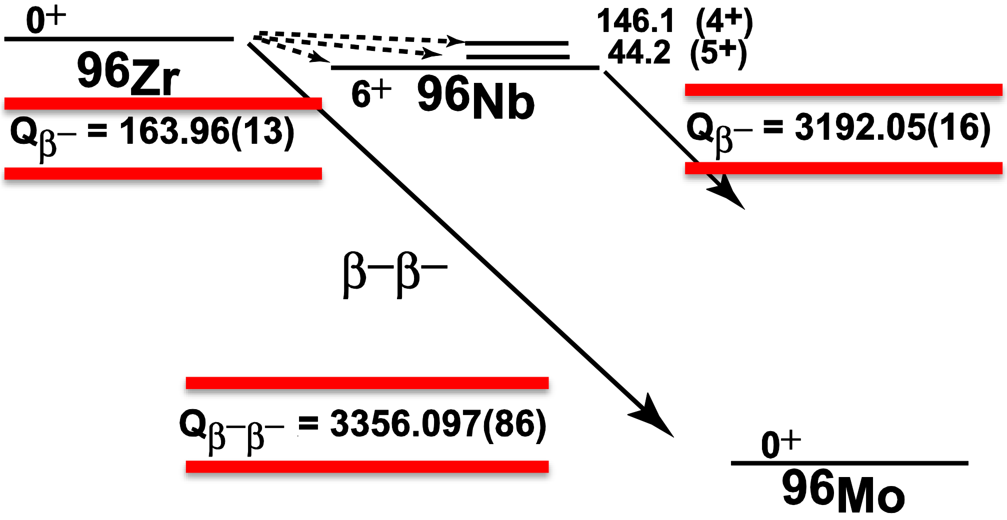
0⁺ → 6⁺ 6-fold non-unique (unobservably long)
0⁺ → 5⁺ 4-fold unique (possible)
0⁺ → 4⁺ 4-fold non-unique (no phase space)



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

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

Results



0^+

^{96}Zr

$Q_{\beta^-} = 163.96(13)$

6^+ ^{96}Nb

146.1 (4^+)

44.2 (5^+)

$Q_{\beta^-} = 3192.05(16)$

$\beta^-\beta^-$

$Q_{\beta^-\beta^-} = 3356.097(86)$

0^+

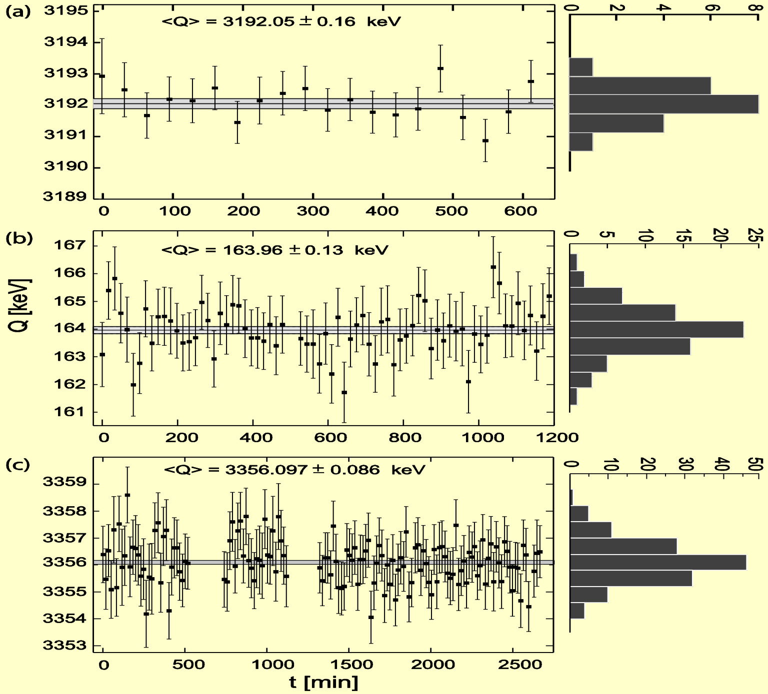
^{96}Mo

^{96}Zr

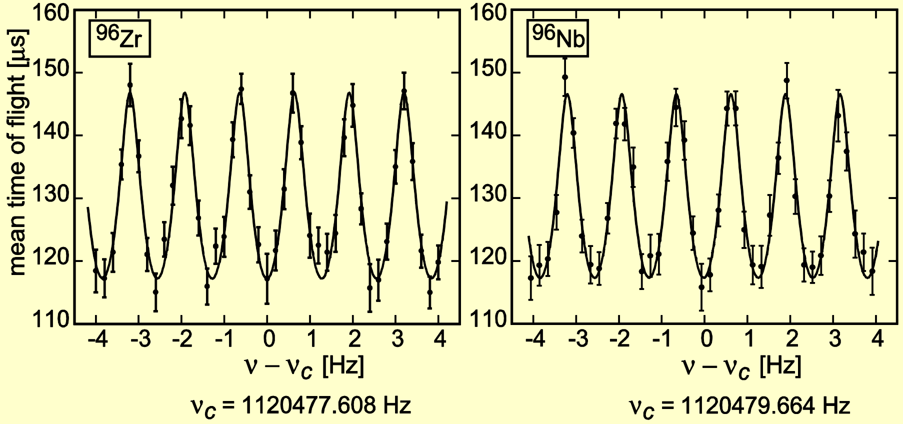
$$Q_{\beta\beta} = 3356.097 \pm 0.086 \text{ keV}$$

7.1 keV higher than AME2012

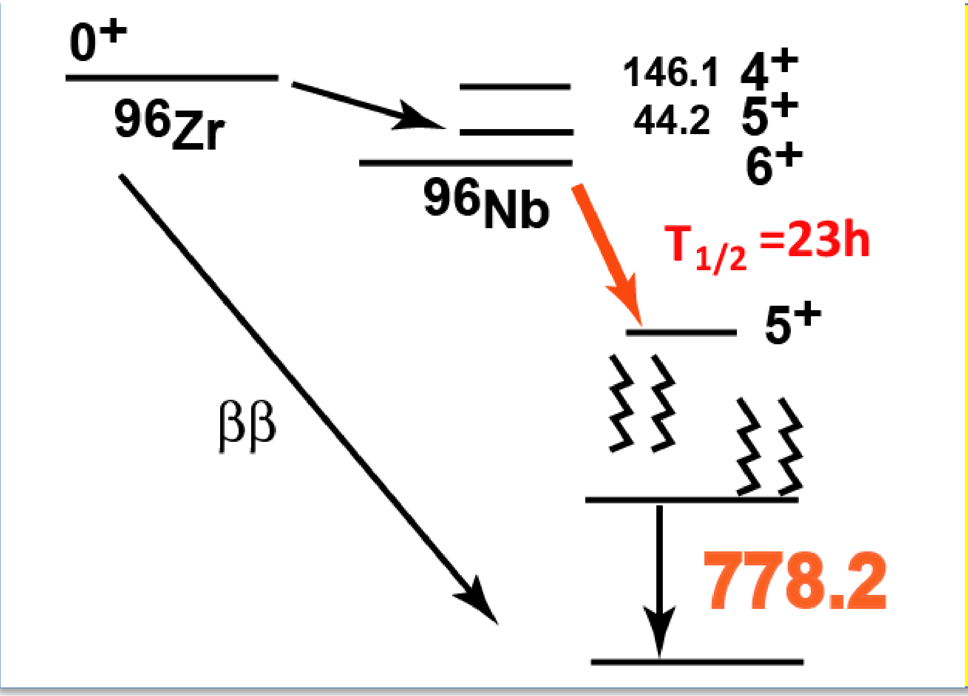
$$Q_{\beta} = 163.96 \pm 0.13 \text{ keV}$$!!



Ramsey excitation



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



$$T_{1/2}(\text{QRPA}) = \frac{24}{g_A^2} \times 10^{19}\ \text{yr}$$

$$T_{1/2}(\text{SM}) = \frac{11}{g_A^2} \times 10^{19}\ \text{yr}$$

$$T_{1/2}(\exp) > 2.3 \times 10^{19}\ \text{yr}$$

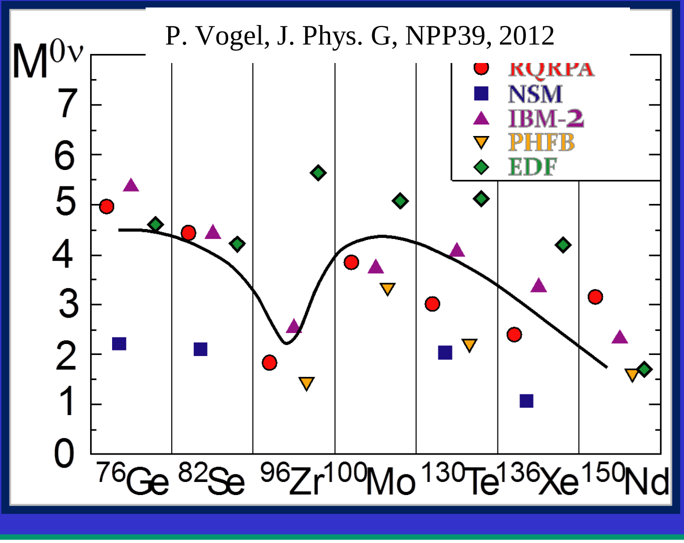
Important side effect:

single β decay depends on g_A^2
2ν/0νββ decay depends on g_A^4

A measurements of single β decay gives expmtl handle on the quenching of g_A

$0\nu\beta\beta$ NMEs

1. what about getting the $0\nu\beta\beta$ NMEs ?
2. what about how to test the models ?
3. what are the expmtl tools?


P. Vogel, J. Phys. G, NPP39, 2012

- investigate „higher-order forbidden“ matrix elements of $\sigma\tau$ – type

  $(0^+ \rightarrow 2^-;\quad 0^+ \rightarrow 3^+; \ldots\ldots\ )$ → limited possibilities, not promising

- are there nuclei, where β and $\beta\beta$ decay are in competition ?

  → YES! ^{48}Ca and ^{96}Zr

- can muon-nuclear physics help?

  → YES μ-capture a potentially powerful tool

Muon capture and $0\nu\beta\beta$ NMEs

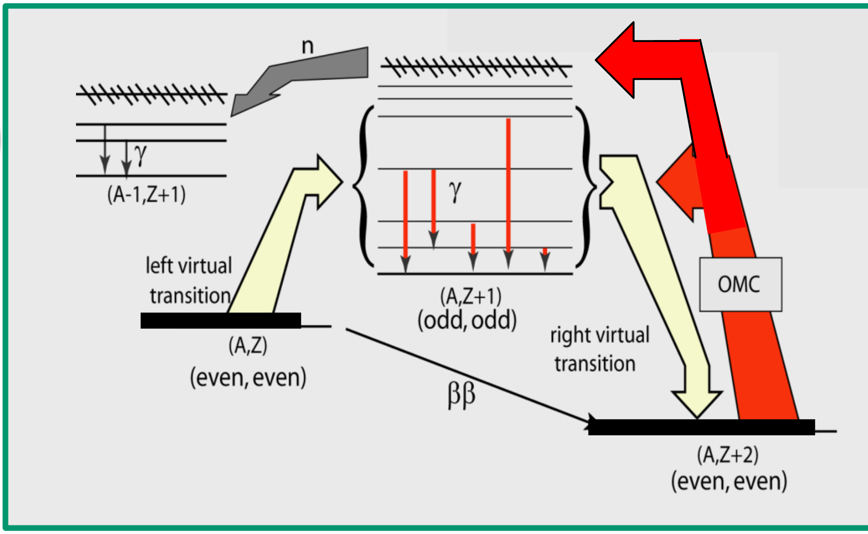
$^{56}\mathrm{Fe}$ $^{32}\mathrm{S}$ $^{24}\mathrm{Mg}$

Motivations

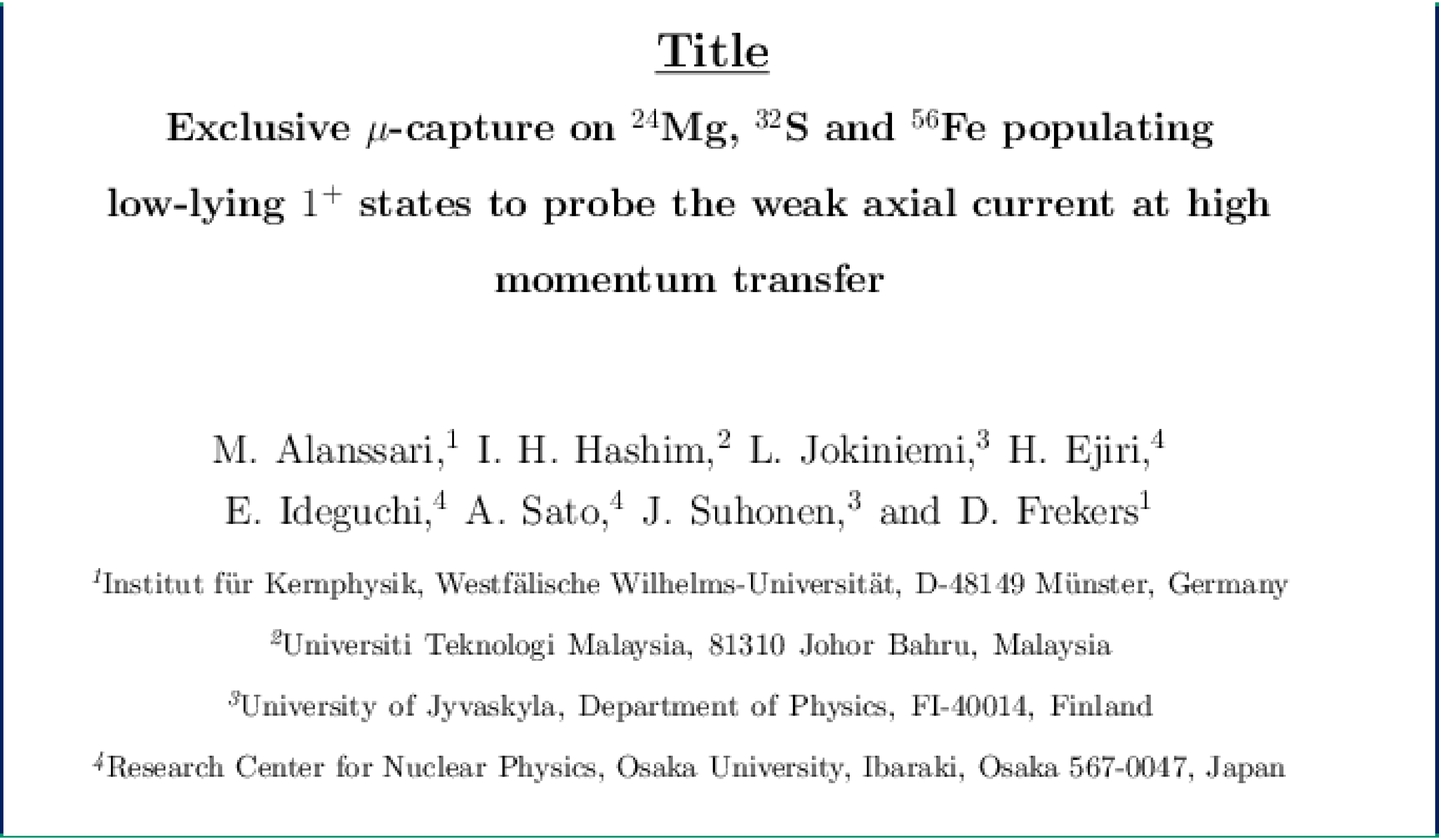
- μ-cap features momentum transfers similar to $0\nu\beta\beta$ decay (q_{tr} ~0.5fm^{-1} ~100MeV/c)
- μ-cap processes to 1^+ states in **$A(\mu^-,\nu)B$** may be compared with charge-ex reactions of (n,p) type.
- μ-cap may give access to g_A quenching issue

However

- only the 0n-channel (~10%) is relevant for $0\nu\beta\beta$ decay
- level scheme of final odd-odd nucleus is extremely poorly known



The muon capture and g_A in weak decays



Title

Exclusive μ-capture on ^{24}Mg, ^{32}S and ^{56}Fe populating low-lying 1^+ states to probe the weak axial current at high momentum transfer

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The amazing muon

There has not been any other elementary particle so „successful" in advancing our knowledge in so many different areas of physics.

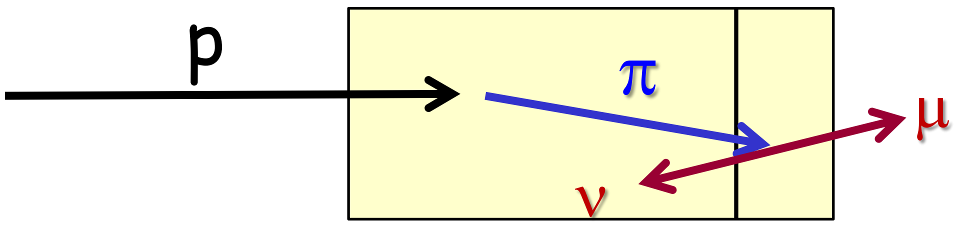
Production: $p + A \rightarrow X + \pi^-$

$(26\text{ns}) \quad \hookrightarrow \mu^- + \bar{\nu}_\mu$

$(2.2\mu\text{s}) \quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

$E_{\text{proton}} \sim 500$ MeV

Surface muons: produced from stopped (usually negative) pions at end of target



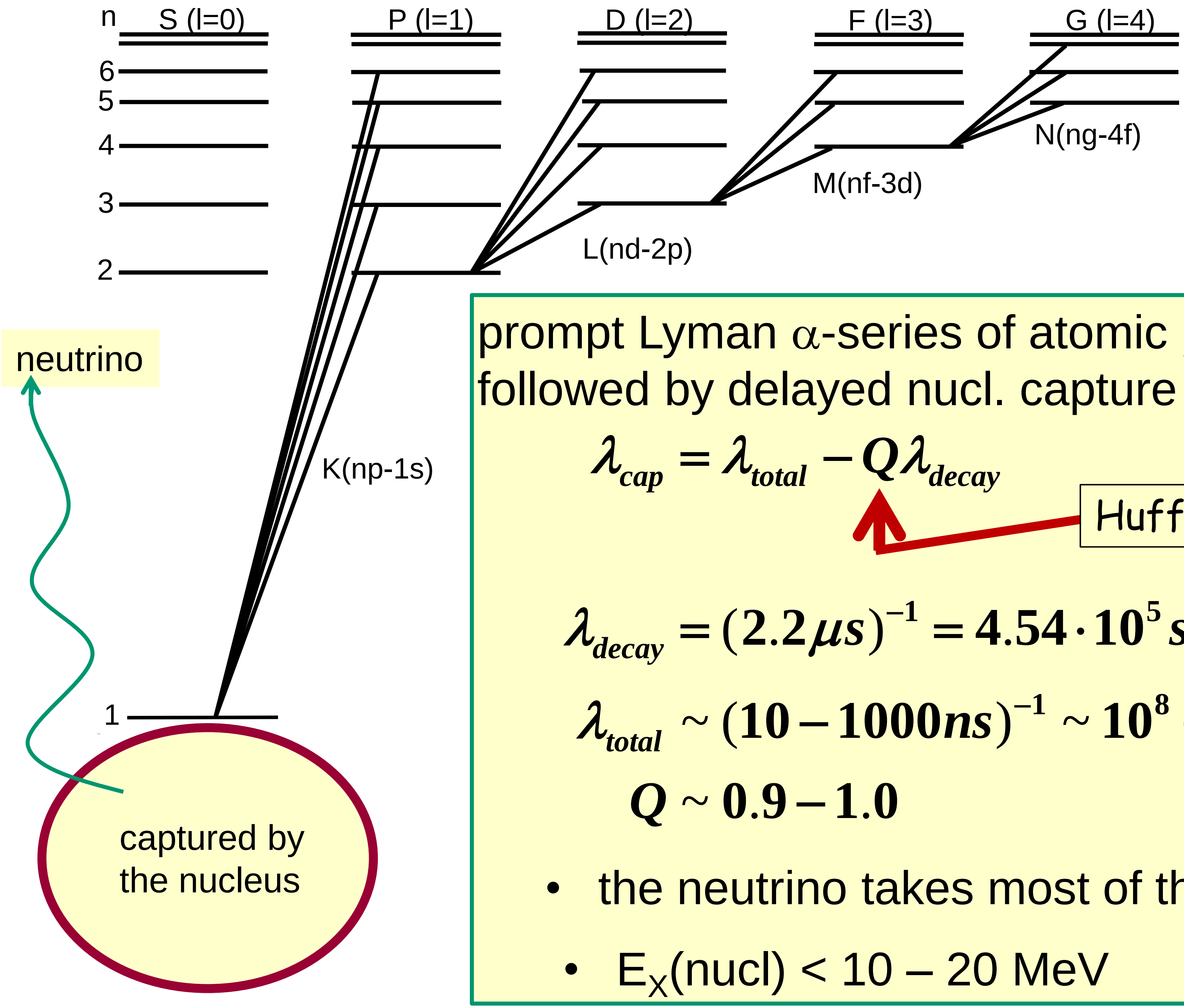
$E_\mu \sim 4.1$ MeV

$q_\mu \sim 30$ MeV/c

Life-time: $\Gamma_\mu = \frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1-\varepsilon) = (2{,}196981(2)\ \mu\text{sec})^{-1} \quad (\varepsilon \approx 10^{-3})$

$G_F = 1{,}16637(2) \cdot 10^{-5} GeV^{-2} \qquad m_\mu = 105.6583745\left(24\right)\ MeV$

Muonium: $\mu^+ + e^-$ **an exotic hydrogen** I ~ 13.6 eV



prompt Lyman α-series of atomic μ-capture followed by delayed nucl. capture

$$\lambda_{cap} = \lambda_{total} - Q\lambda_{decay}$$

Huff-factor

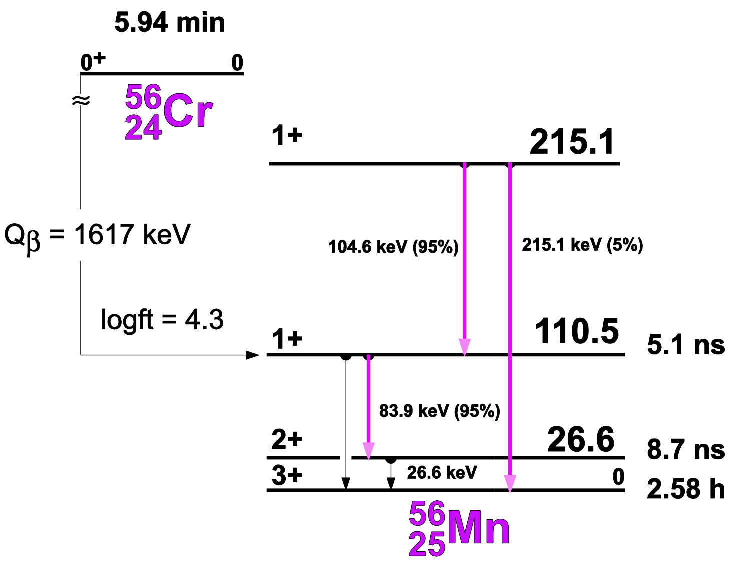
$$\lambda_{decay} = (2.2\mu s)^{-1} = 4.54 \cdot 10^{5} s^{-1}$$

$$\lambda_{total} \sim (10 - 1000 ns)^{-1} \sim 10^{8} - 10^{6} s^{-1}$$

$$Q \sim 0.9 - 1.0$$

- the neutrino takes most of the energy
- E_X(nucl) < 10 – 20 MeV

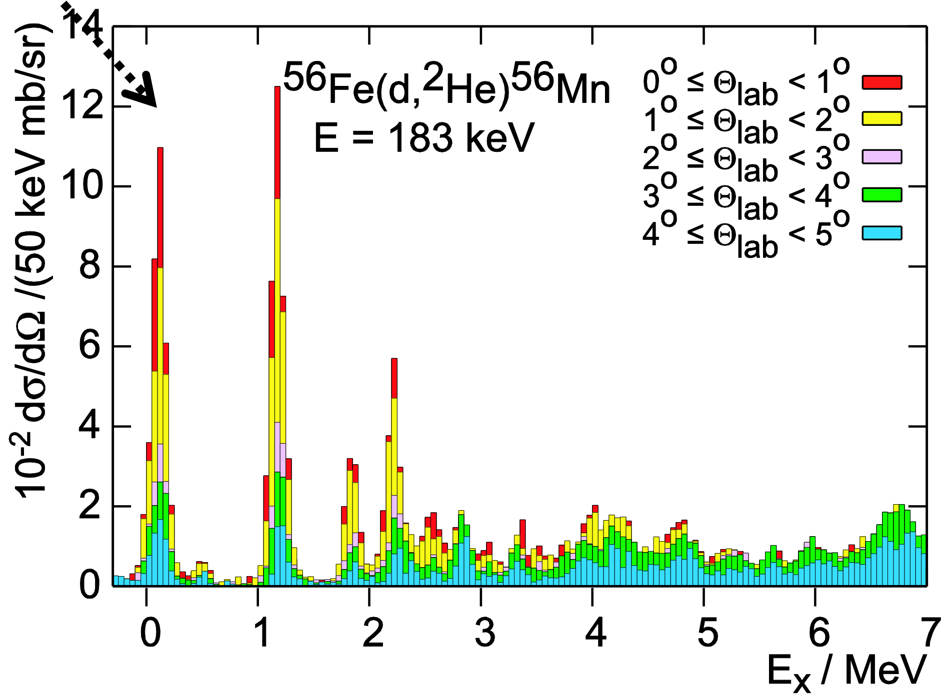
The issue of g_A queching



^{56}Fe(μ,ν_μ)^{56}Mn, (0 n)

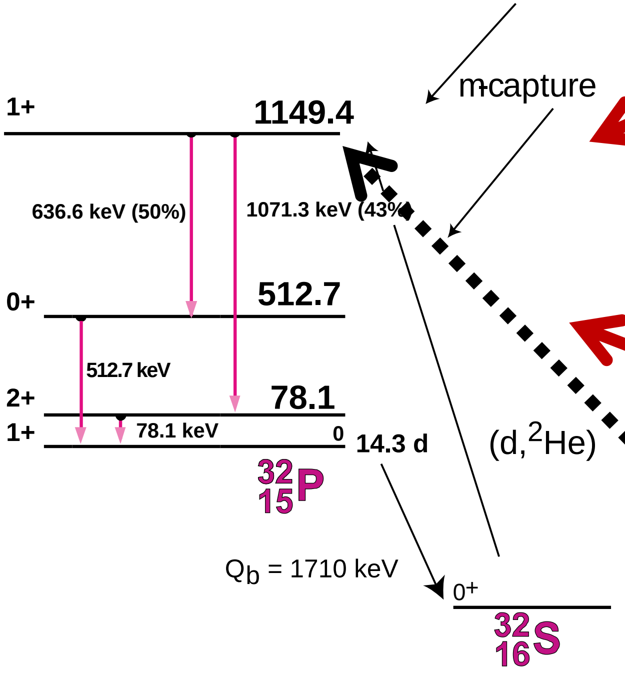
^{56}Fe(d,^{2}He)^{56}Mn

**Example:
Compare transition strength in μ-cap and (d,^{2}He) charge-ex**

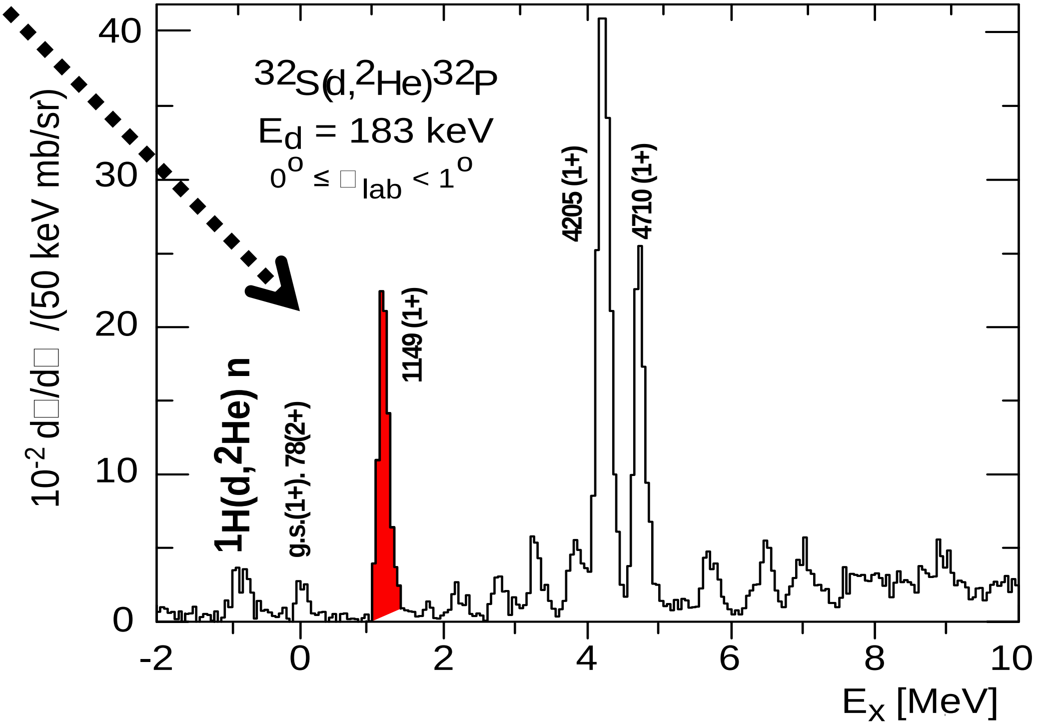


The issue of g_A queching

$^{32}S(\mu,\nu_{\mu})^{32}P$, (0 n)



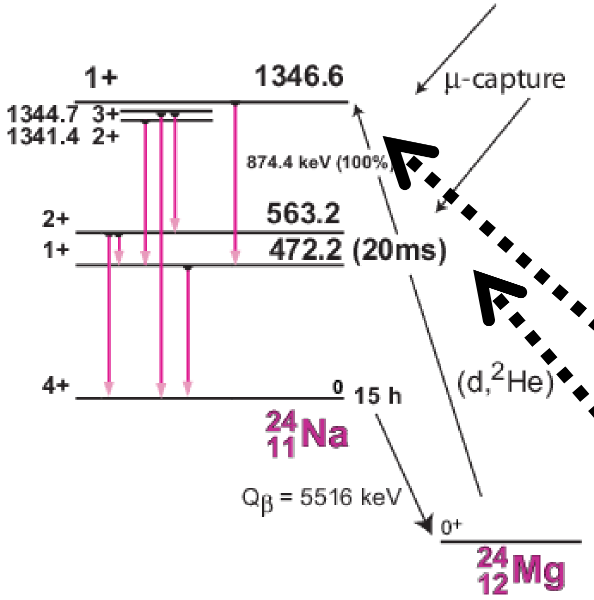
$^{32}S(d,^2He)^{32}P$



Example:

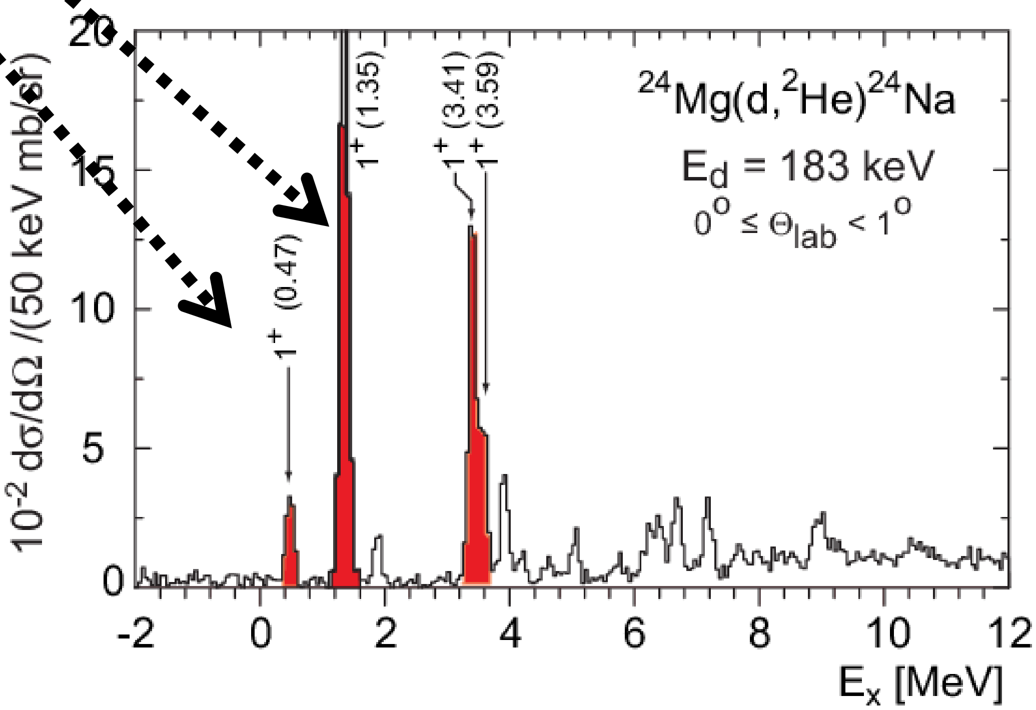
Compare transition strength in μ-cap and (d,²He) charge-ex

The issue of g_A queching



^{24}Mg(μ,ν_μ)^{24}Na, (0 n)

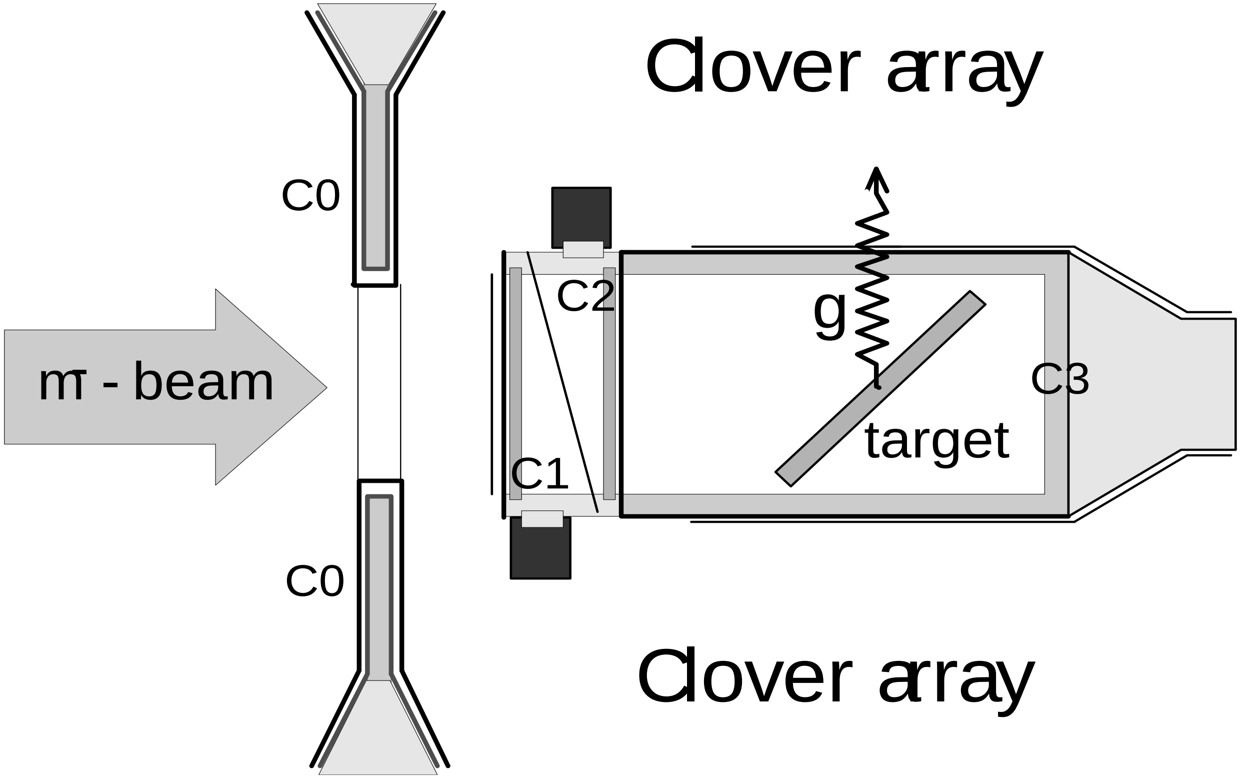
^{24}Mg(d,^{2}He)^{24}Na



Example:

Compare transition strength in μ-cap and (d,^{2}He) charge-ex

Schematics of set-up

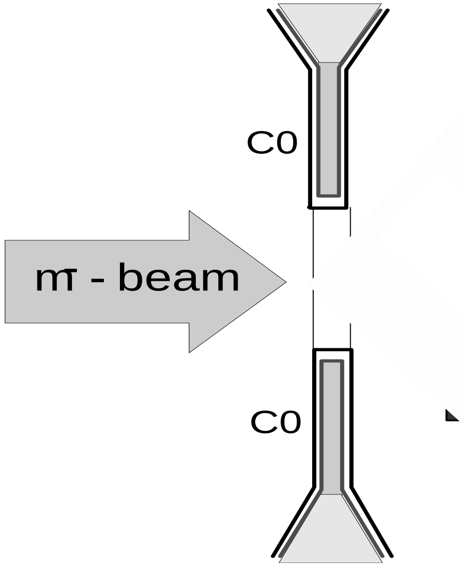


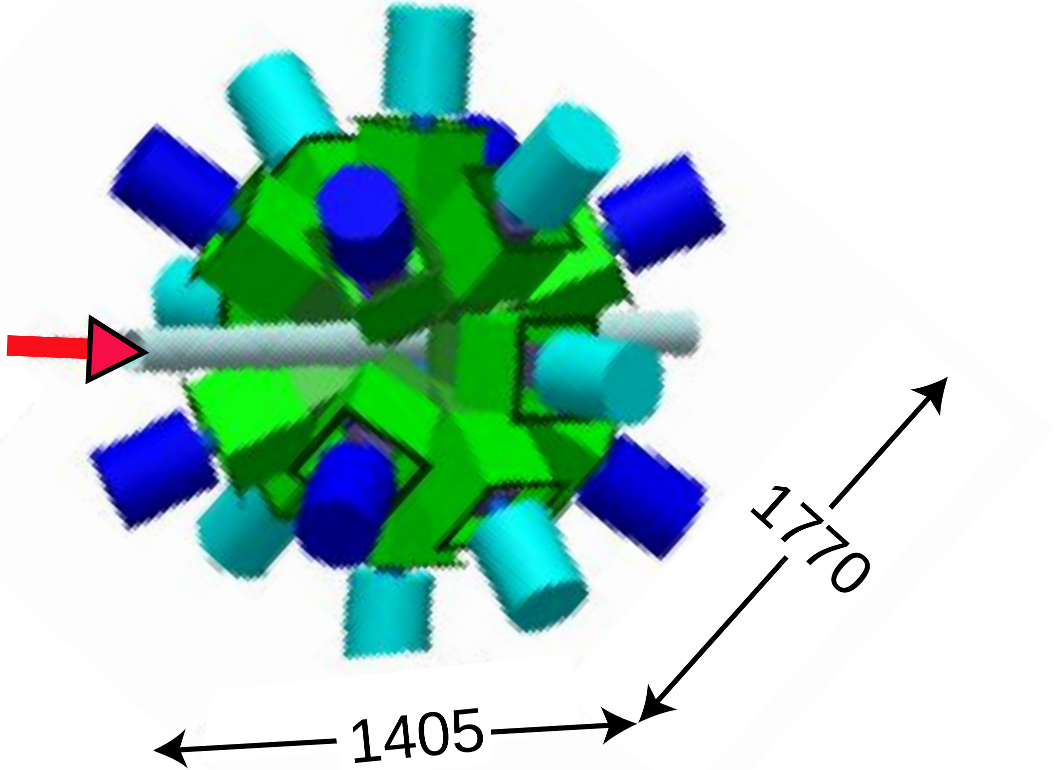
$$\mu_{stop} = \overline{C0} \wedge C1 \wedge C2 \wedge \overline{C3}$$

# of μ–stop = 8 – 25 x 10^3 with 20 – 30 MeV/c

target can be used for solids and gas

Schematics of set-up muon beam line facility “MuSIC” + “CAGRA” at RCNP Osaka





CAGRA = Clover Array Gamma RAy spectrometer

MuSIC = MUon Science Innovative muon beam Channel

The issue of g_A queching

But: Hold your horses !!!
things are a bit more complicated

there is a pseudo-scalar coupling effective in μ-capture with a constant g_P (also badly known !!)

What is this ????

Inside the nucleus the muon can decay back into a virtual pion (lots of energy available!!), and the pion generates a final state imprinting it with the parity of the pion. ($P(\pi) = -1$)

The effect depends on how many protons there are.

^{24}Mg → 12 protons
^{32}S → 16 protons
^{56}Fe → 26 protons

Conclusion

- **Charge-ex reactions:**
  - useful tool for $2\nu\beta\beta$ decay NME's.
- **Spin-dipole excitation via charge-ex:**
  - used for first time, low-E spin-dipole strength mirrors ground-state properties
- **Precision mass measurement:**
  - ^{96}Zr is a golden case for testing 0ν–NME's and getting experimental handle on g_A
- **μ-cap:**
  - maybe the only viable tool to study weak response at high momentum transfer and to fix the g_A problem by comparing with (d,^{2}He)