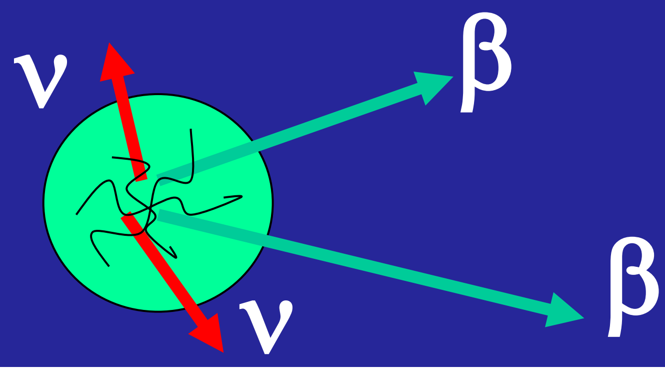
Westfälische Wilhelms-Universität Münster

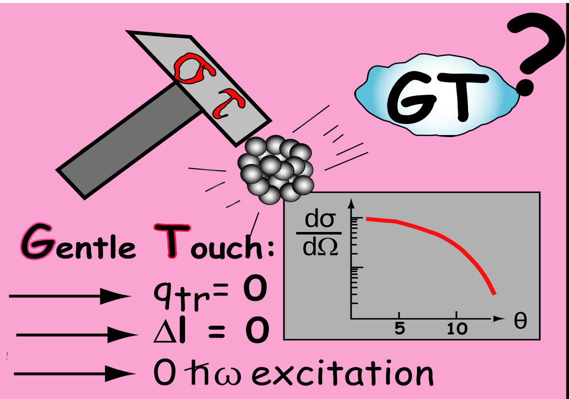
D. Frekers

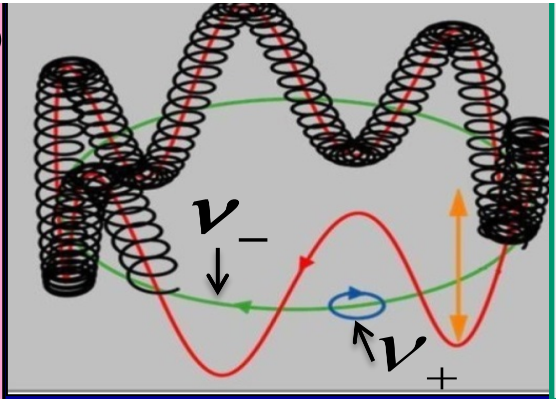
Novel approaches to the nuclear physics of ββ-decay:

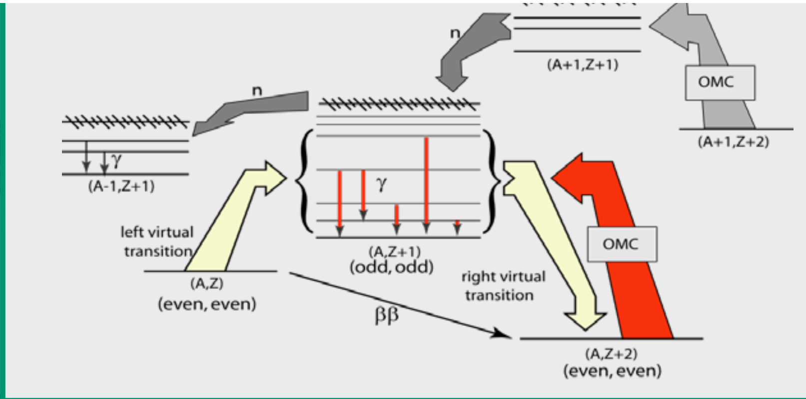
chargex reactions, mass-measurements, μ-capture



CNNP Catania 2017







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)

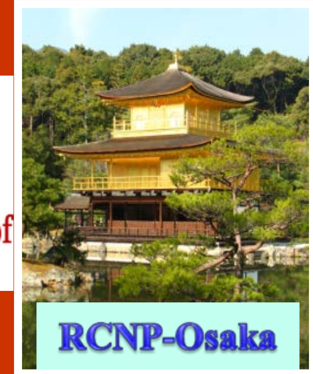
4. Mass measurements
   - 0νββ NME
   - ^{96}Zr is a „golden" case

(PRL116, Feb-2016)

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

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

university of groningen



JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

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General features

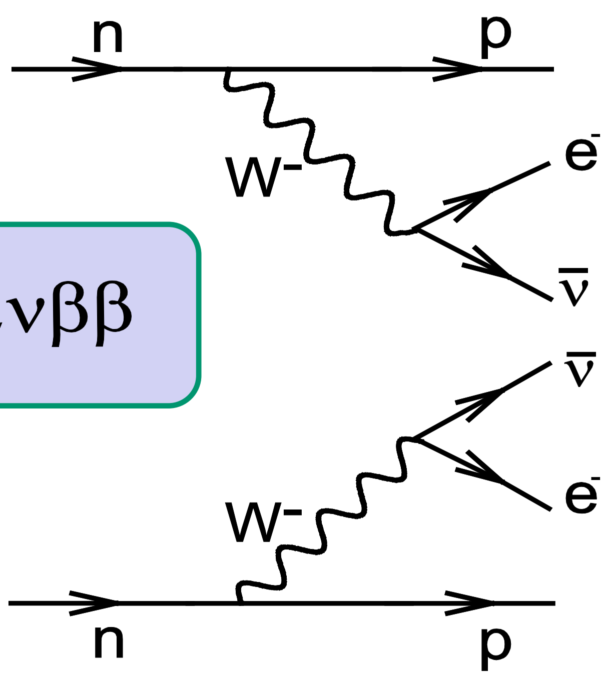
(2νββ / 0νββ decay)

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

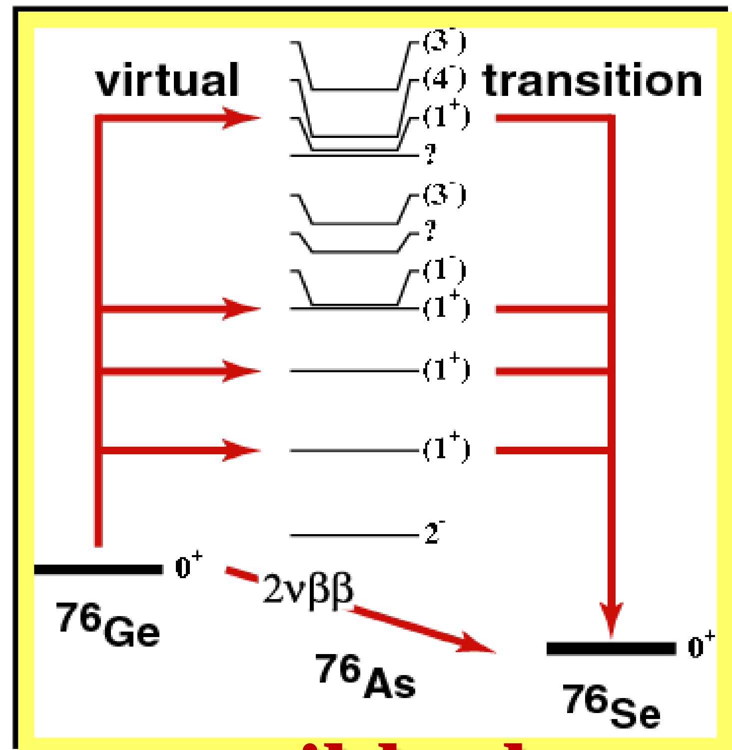
$$= G^{2\nu}(Q,Z) \quad g_A^4 \quad \left|M^{(2\nu)}_{DGT}\right|^2$$

!

2νββ



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



accessible thru charge-ex reaction

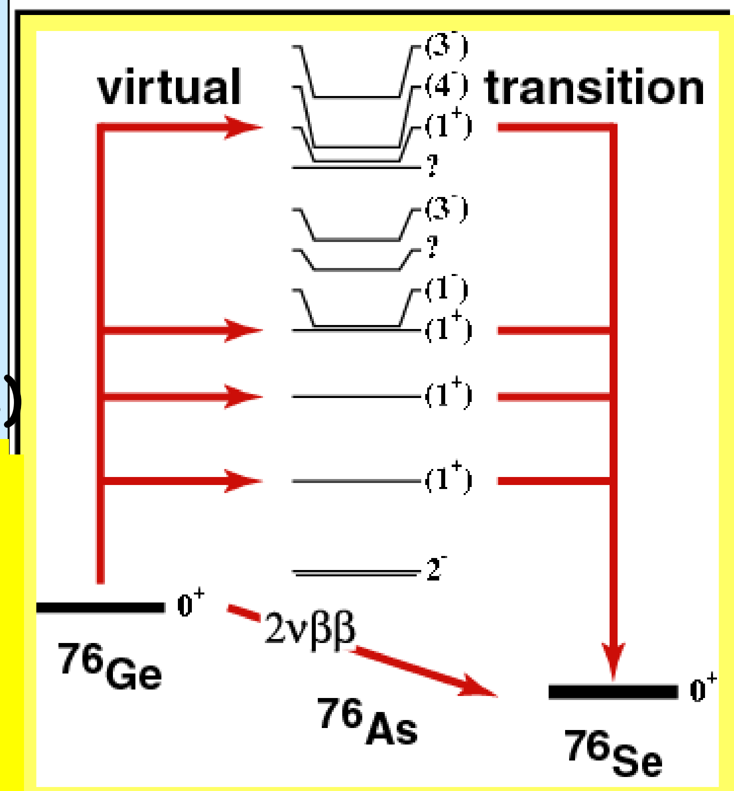
$$M_{\mathrm{DGT}}^{(2\nu)} = \sum_m \frac{\left\langle 0_{g.s.}^{(f)} \left| \sum_k \sigma_k \tau_k^- \right| 1_m^+ \right\rangle \left\langle 1_m^+ \left| \sum_k \sigma_k \tau_k^- \right| 0_{g.s.}^{(i)} \right\rangle}{\tfrac{1}{2} Q_{\beta\beta}(0_{g.s.}^{(f)}) + E(1_m^+) - E_0}$$

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

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))

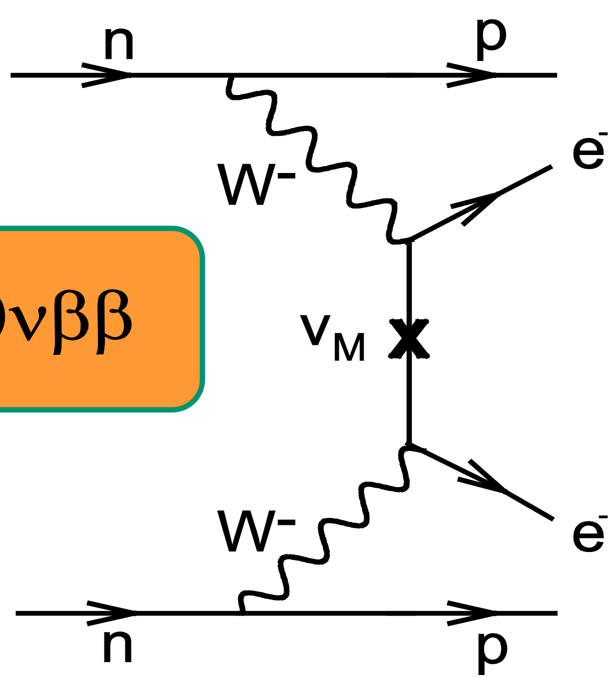


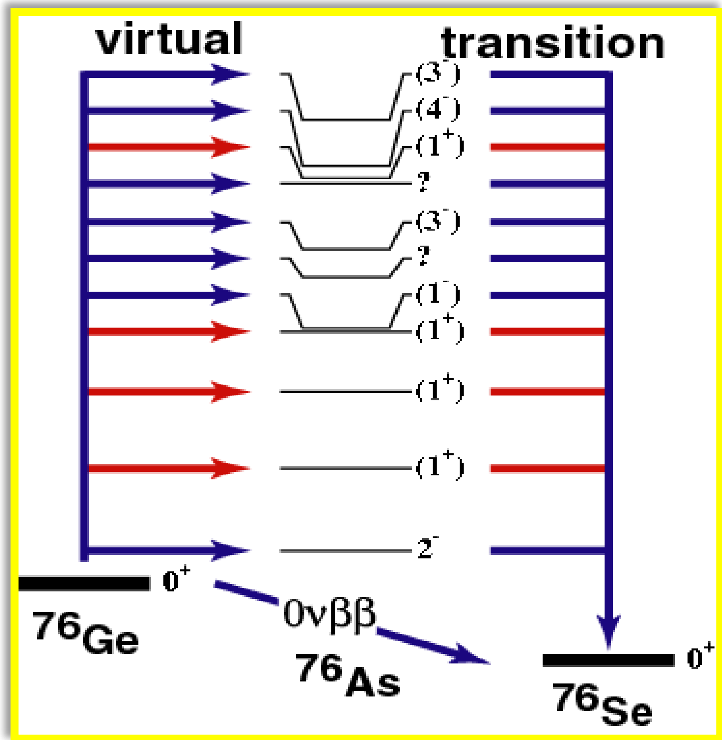
$$G^{0\nu}_{(\beta^-\beta^-)} = G^{0\nu}(Q,Z)\, g_A^4 \left| M^{(0\nu)}_{DGT} - \left(\frac{g_V}{g_A}\right)^2 M^{(0\nu)}_{DF} \right|^2 \left| m_{\nu_e} \right|^2$$

!

Majorana-ν !

0νββ

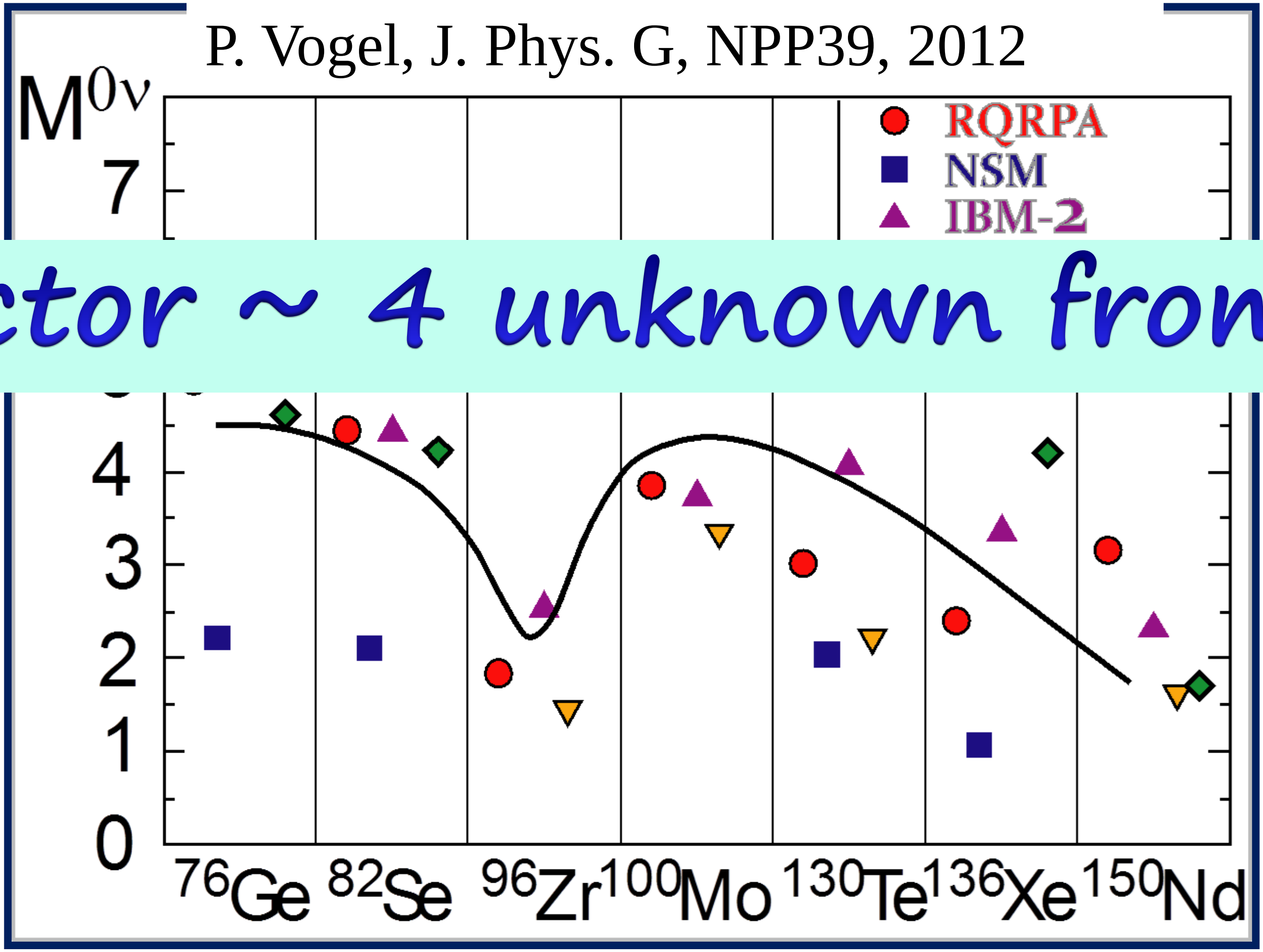




$q_{tr} \sim 0.5\ \mathrm{fm}^{-1}$!!

NOT accessible thru charge-ex reaction

The situation of the Nuclear Matrix Elemets for neutrinoless ββ decay



+ factor ~ 4 unknown from g_A^4.

-2-

Charge-exchange reactions

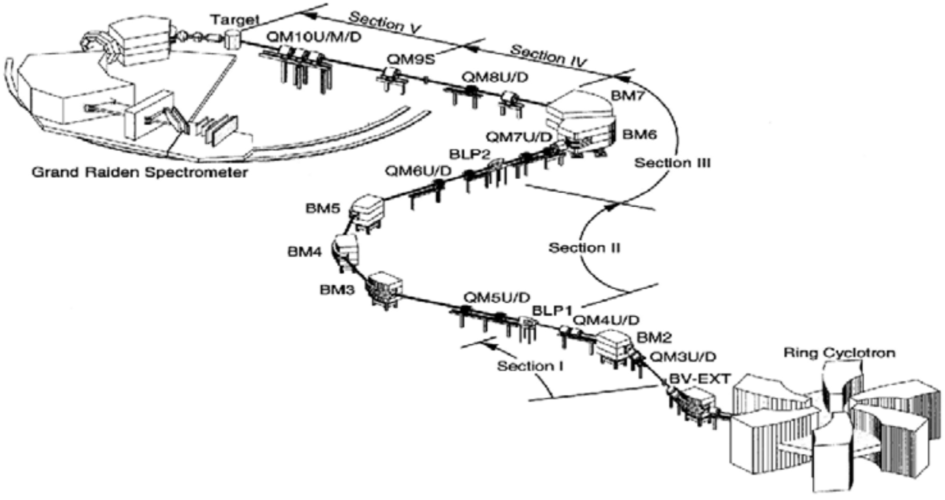
GT-part

(2νββ decay)

Charge-exchange reactions

Grand Raiden Magnetic Spectrometer

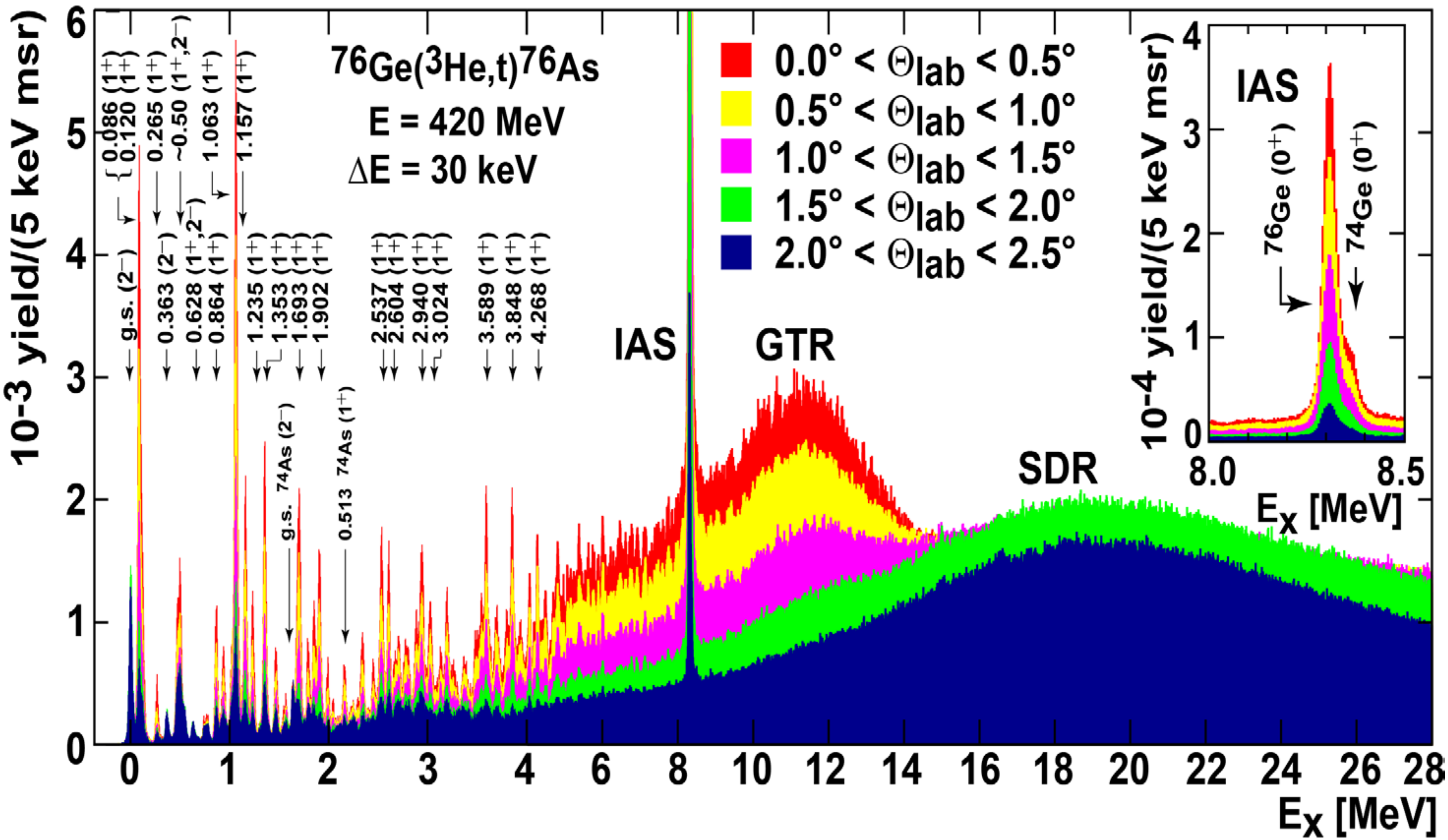
$\Delta E/E \sim 5 \times 10^{-5}$ ~ 25 keV
at 420 MeV (^3He)



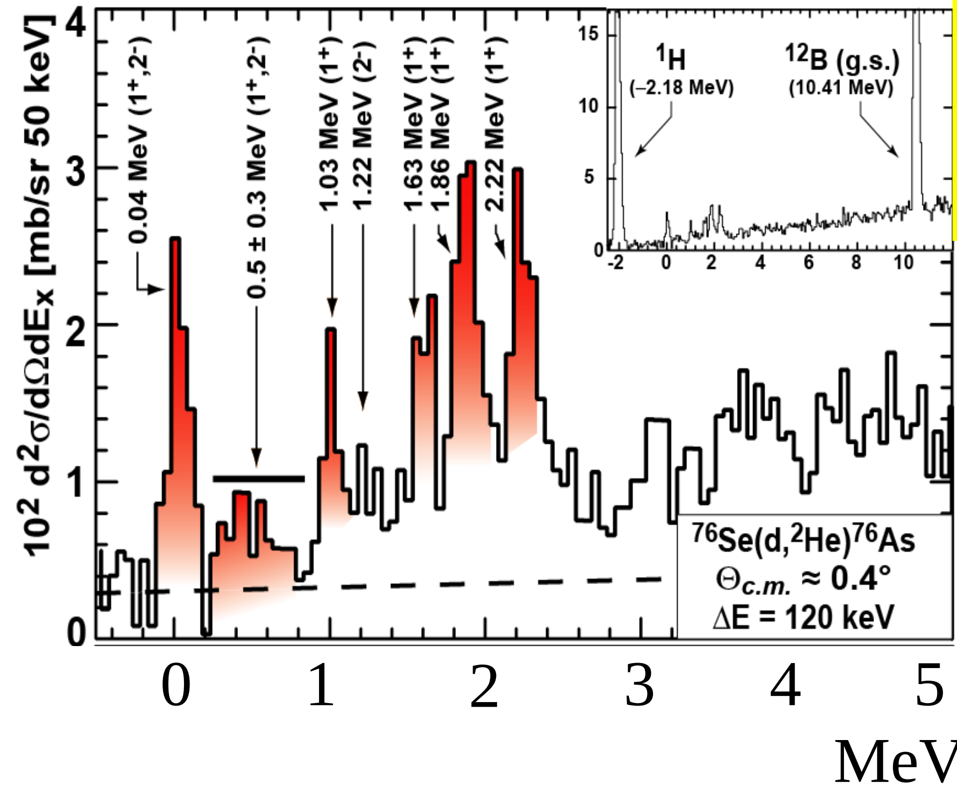
^{76}Ge

N-Z=10

Resolution is the key !!!



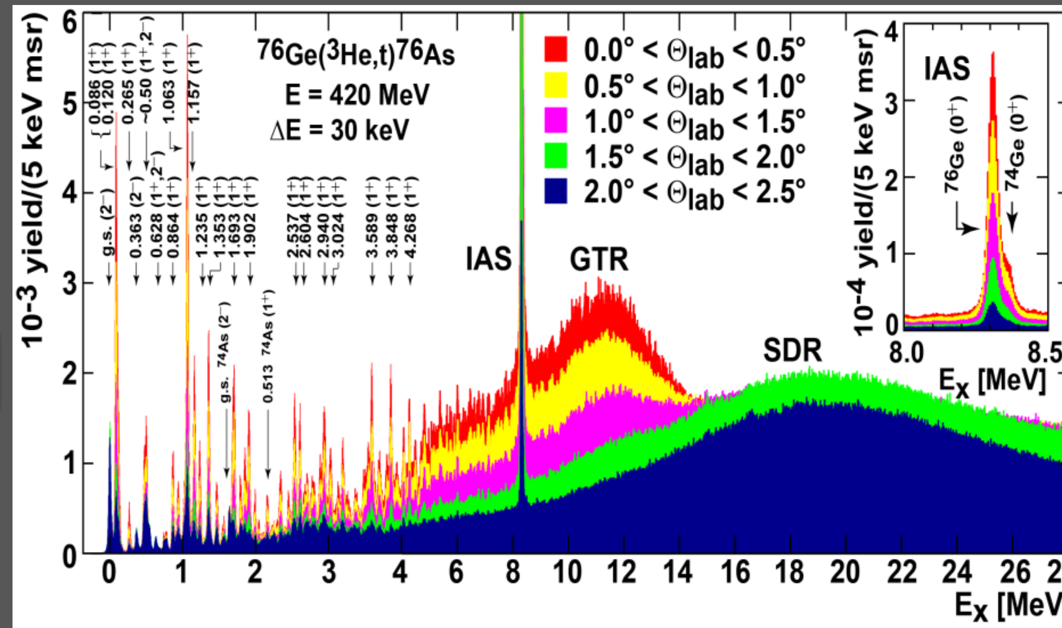
almost 70 !! resolved single states up to 5 MeV identified as GT 1+ transitions !!!



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

a surprise:

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



no need for

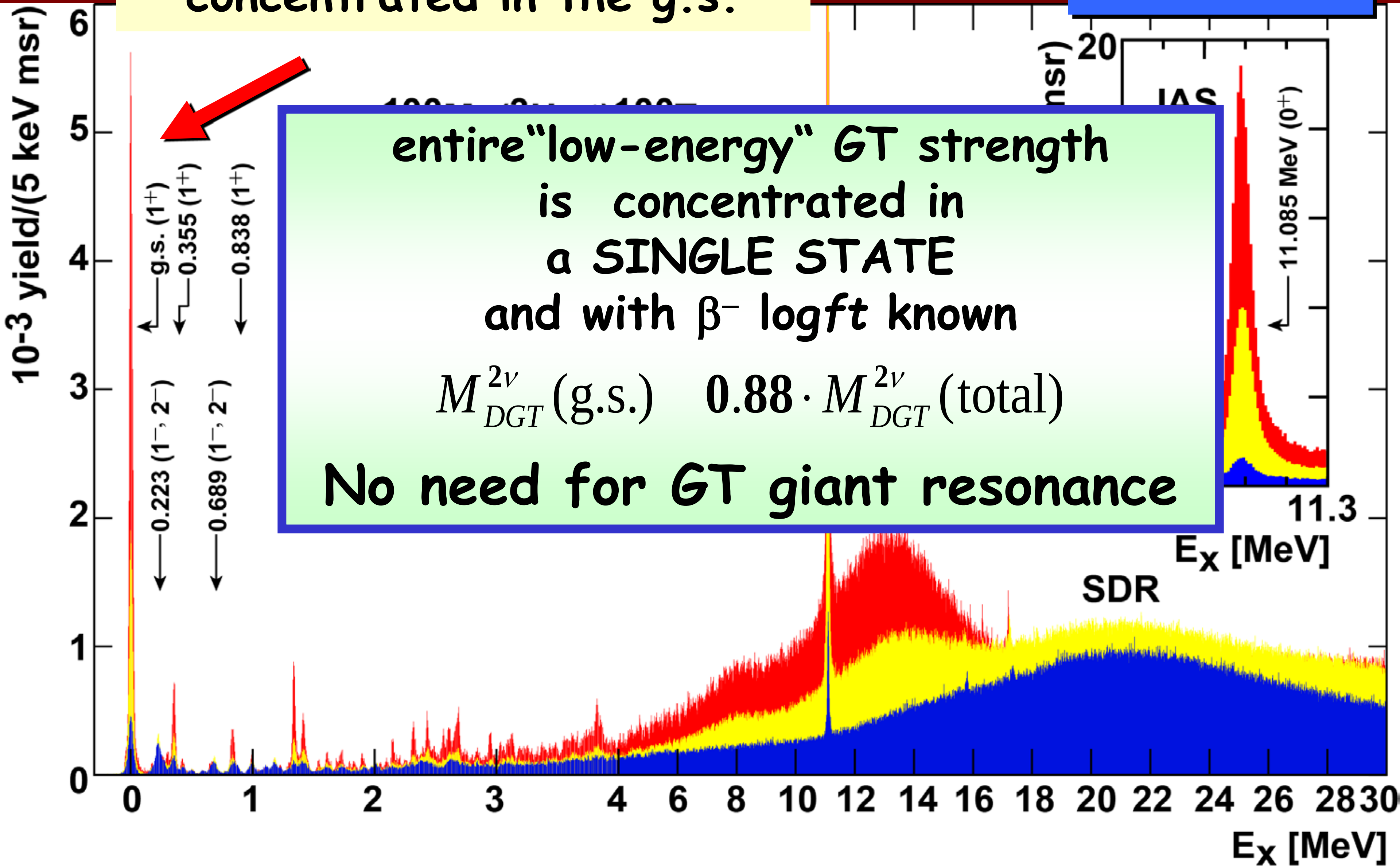
GT giant resonance contribution

^{100}Mo

N-Z=16

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

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

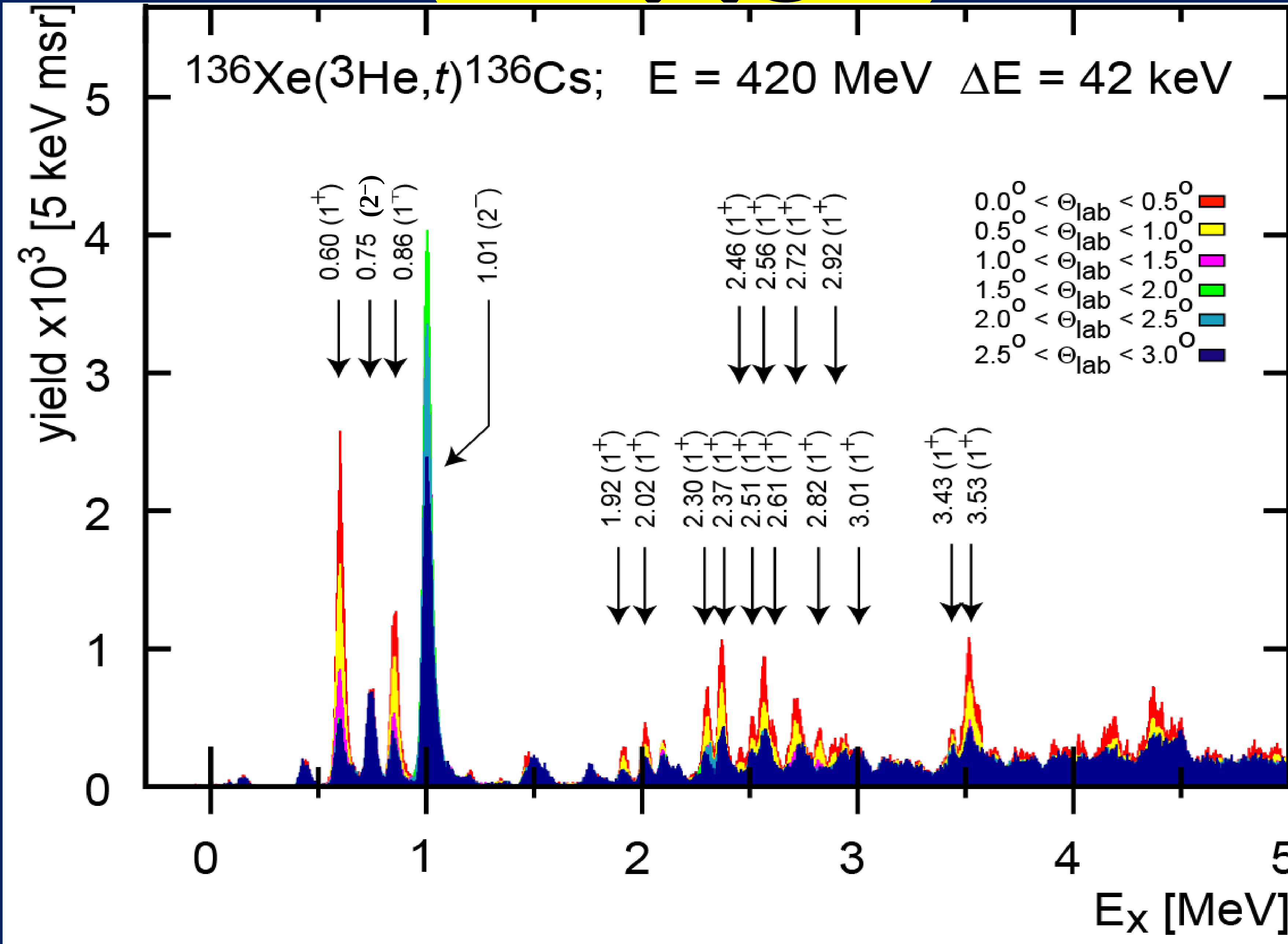
No need for GT giant resonance

^{136}Xe

$N-Z=28$

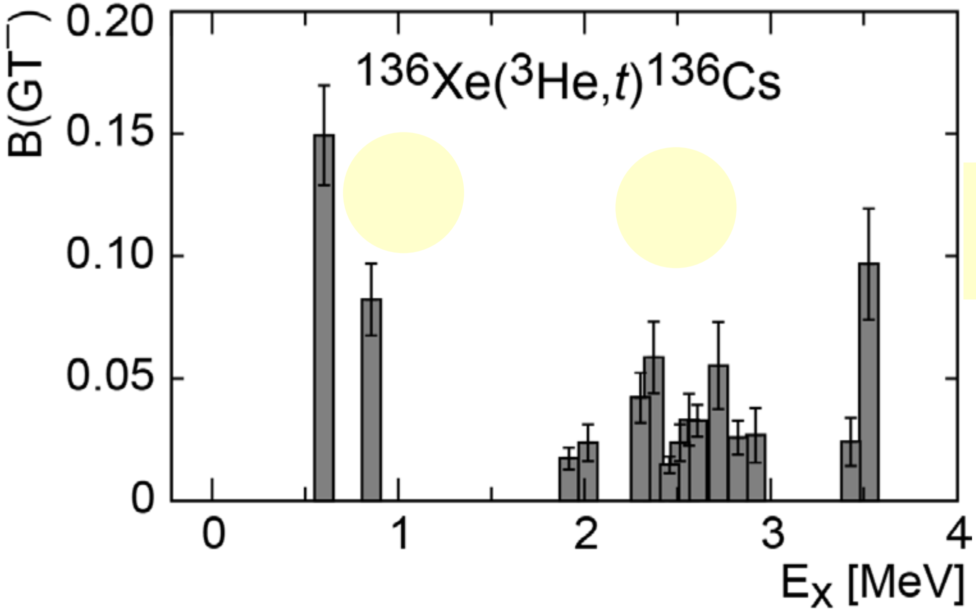
question: why so stable !!!

136Xe



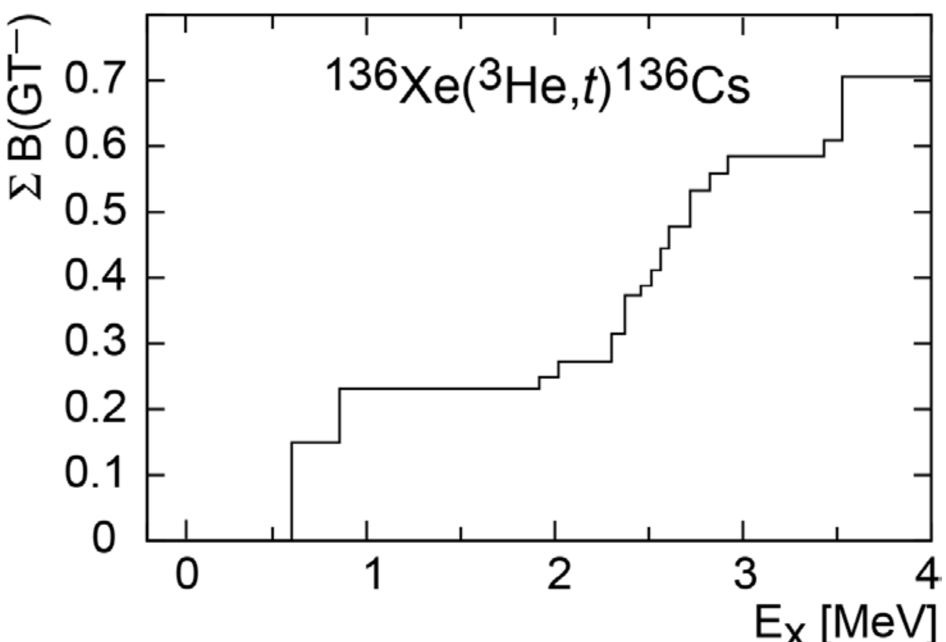
$^{136}Xe(^3He,t)^{136}Cs$; E = 420 MeV ΔE = 42 keV
yield x10^3 [5 keV msr]
Ex [MeV]
0.60 (1+)
0.75 (2−)
0.86 (1+)
1.01 (2−)
1.92 (1+)
2.02 (1+)
2.30 (1+)
2.37 (1+)
2.46 (1+)
2.51 (1+)
2.56 (1+)
2.61 (1+)
2.72 (1+)
2.82 (1+)
2.92 (1+)
3.01 (1+)
3.43 (1+)
3.53 (1+)
0.0° < Θlab < 0.5°
0.5° < Θlab < 1.0°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



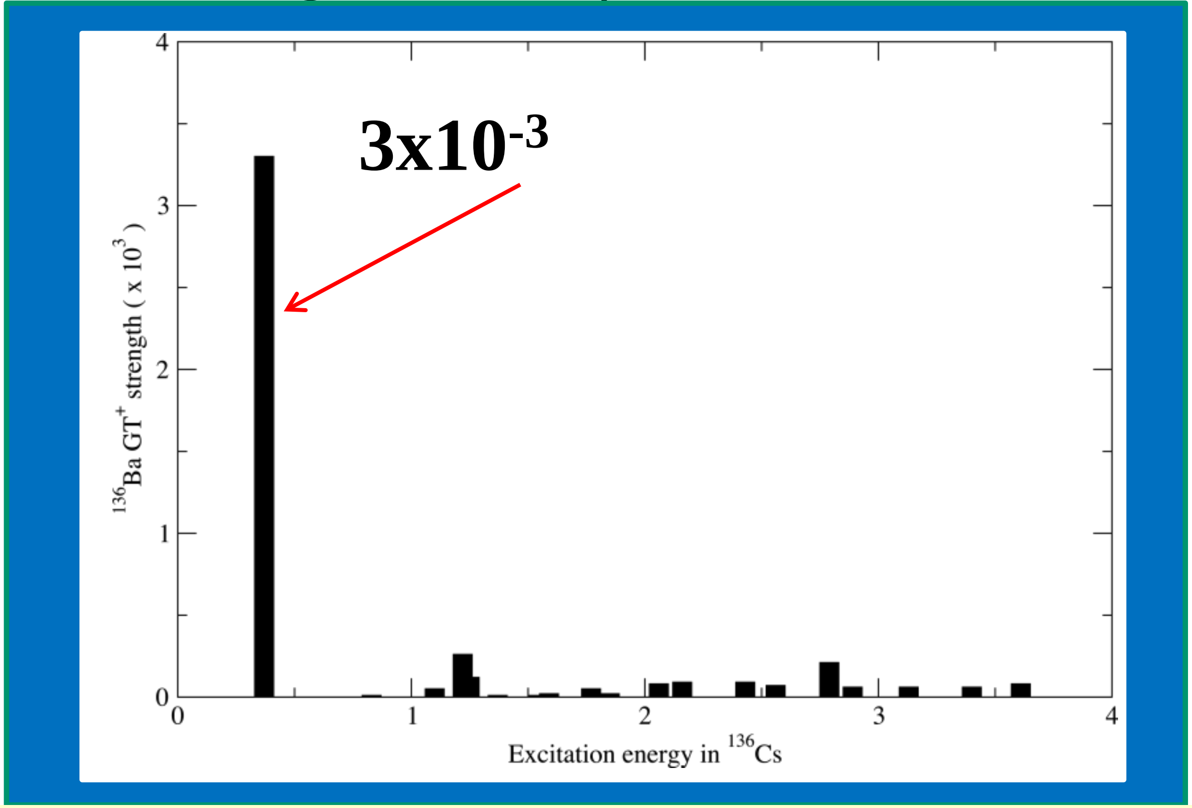
$$T^{2n}_{1/2} = 2.2\times 10^{21}\,\mathrm{yr}$$

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



A. Poves (simultaneous to our publication):

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



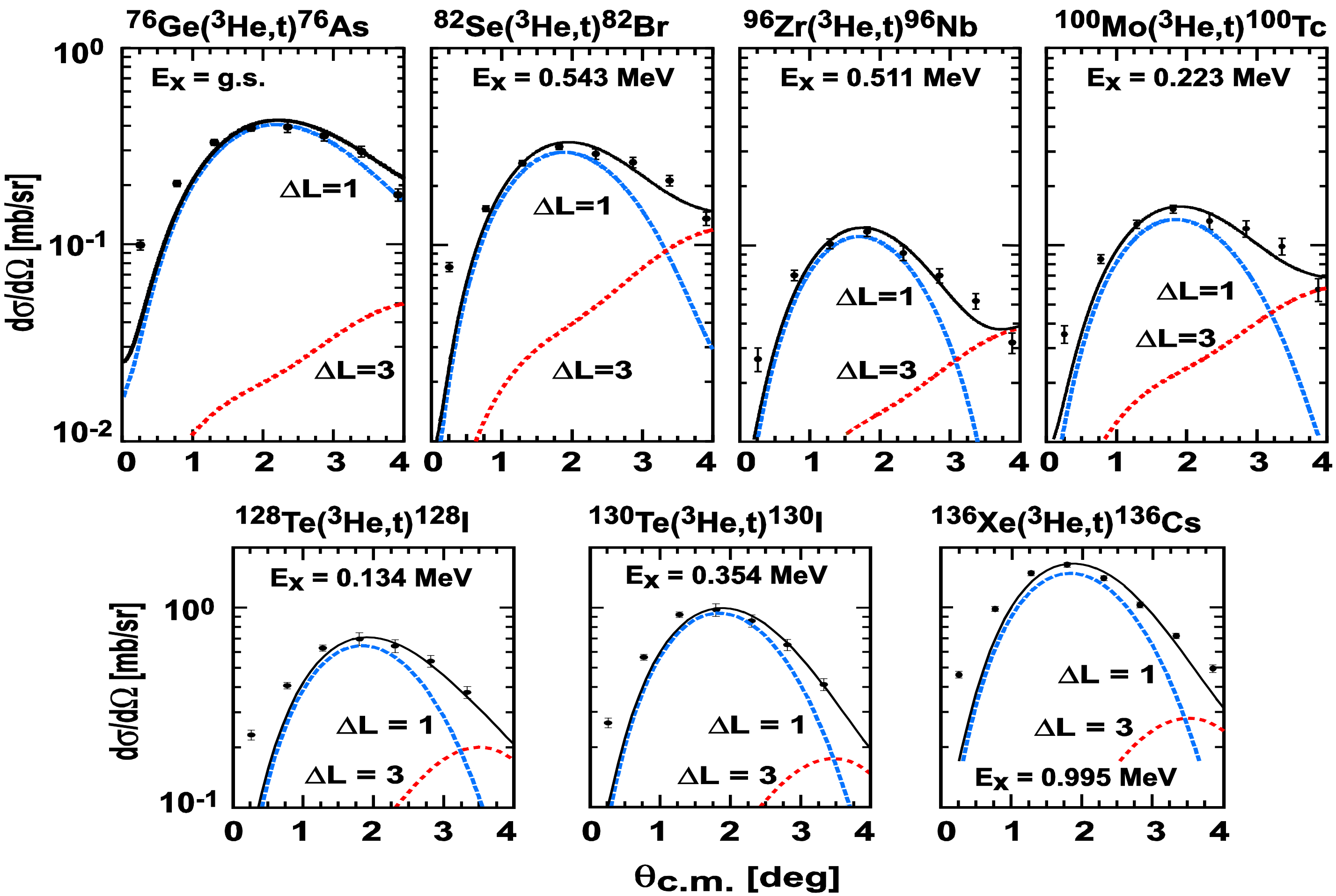
Recall:
^{136}Xe is almost doubly magic!!

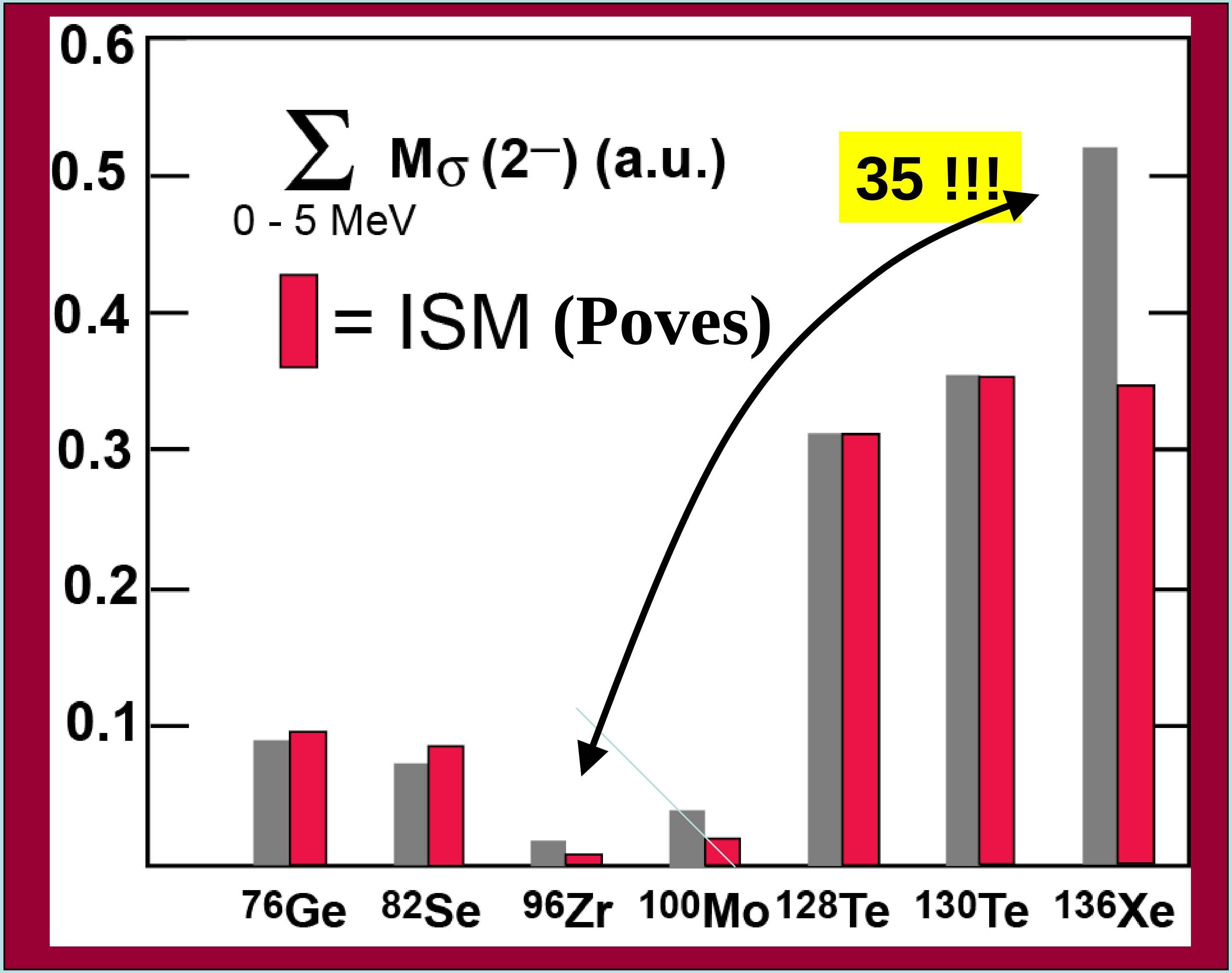
Shell model provides conclusive explanation for the deemed „pathologically“ long half-life of ^{136}Xe.
Expt‘l test: $^{136}Ba(d,^2He)^{136}Cs$

-3-
Charge-exchange reactions
spin-dipole part
(0νββ decay)

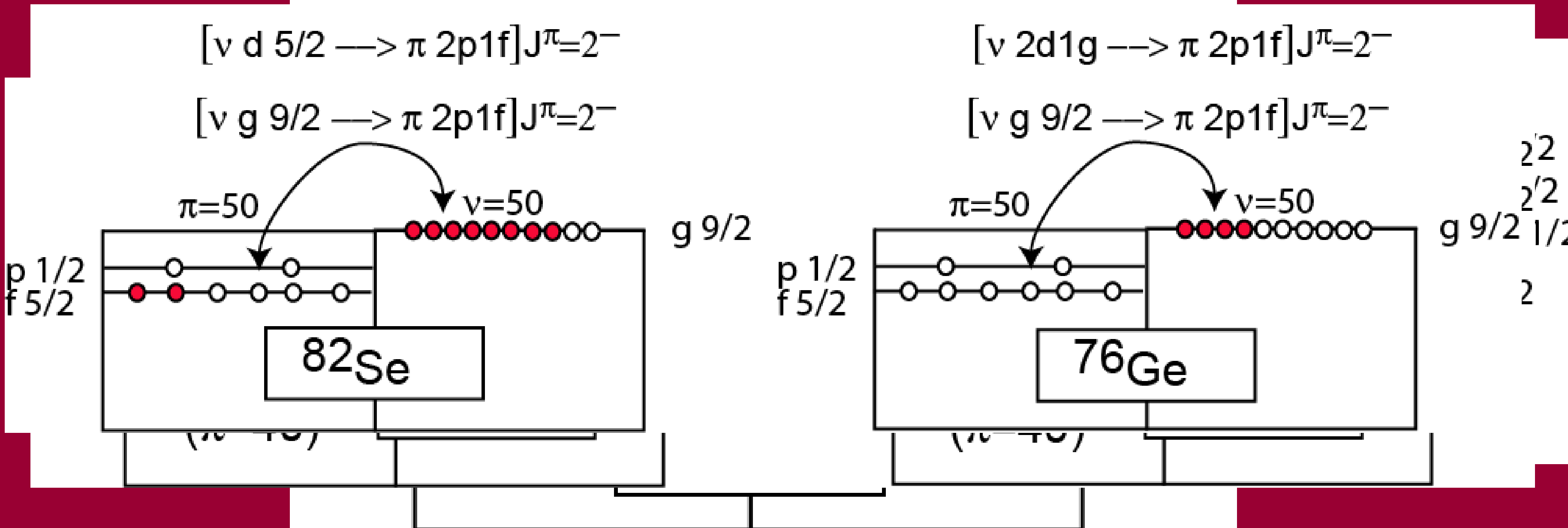
Charge-exchange reaction towards the 0νββ NME's

Here: 2^- states via chargex reactions

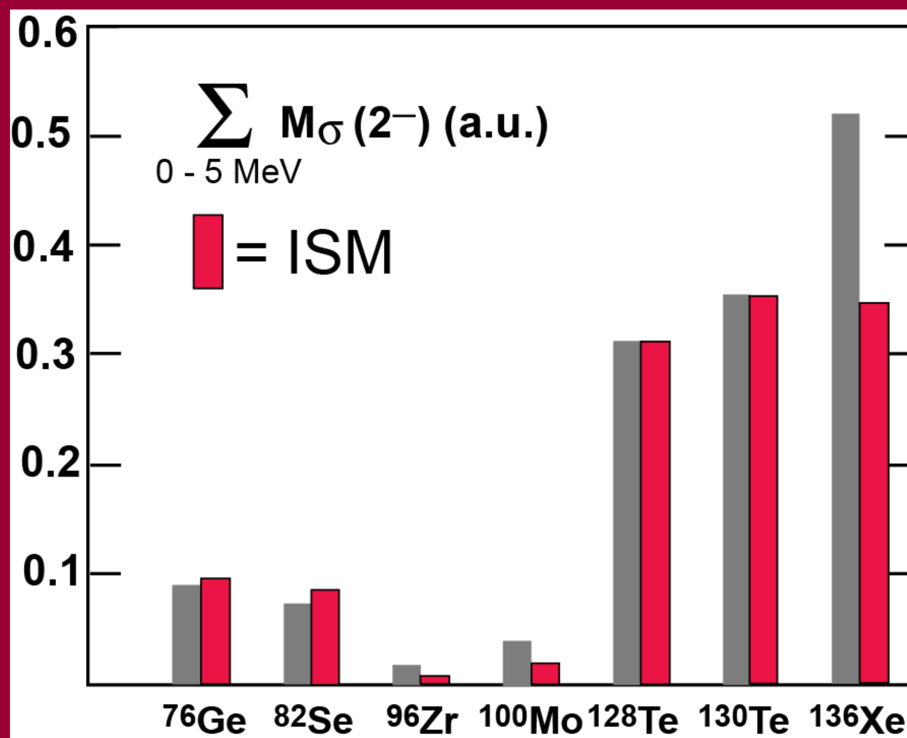




0.6
0.5
0.4
0.3
0.2
0.1
Σ Mσ (2⁻) (a.u.)
0 - 5 MeV
= ISM (Poves)
35 !!!
76Ge
82Se
96Zr
100Mo
128Te
130Te
136Xe



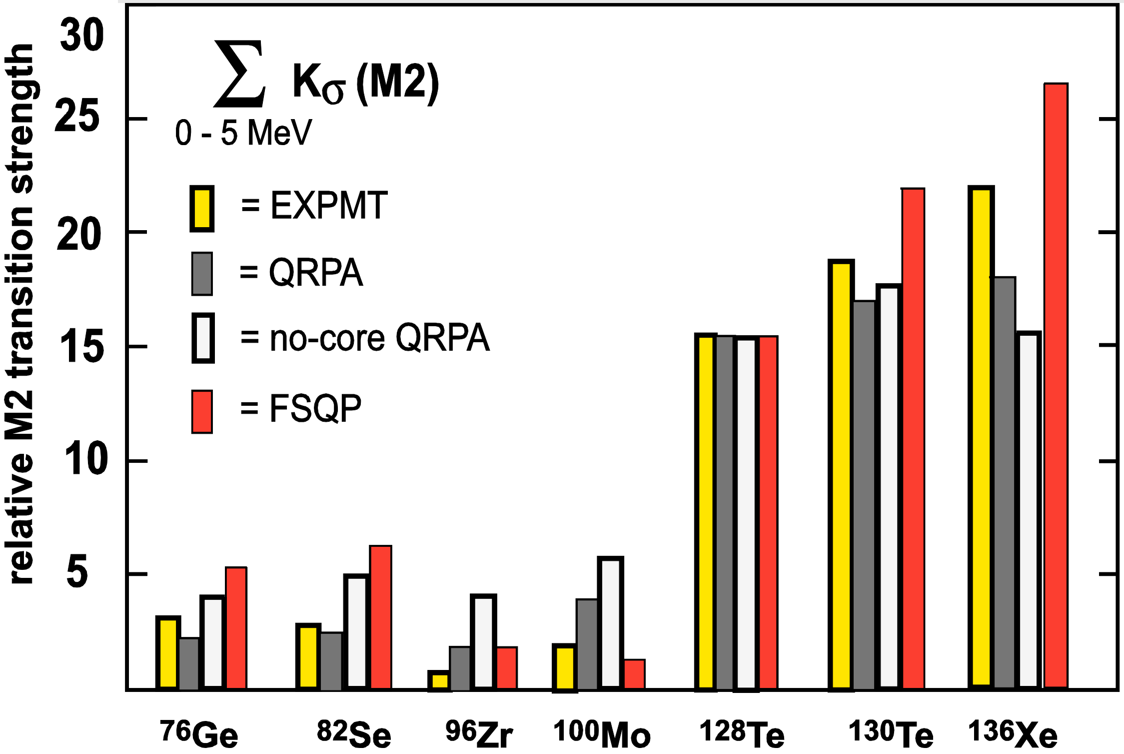
[ν d 5/2 —> π 2p1f]Jπ=2⁻
[ν g 9/2 —> π 2p1f]Jπ=2⁻
π=50
ν=50
g 9/2
p 1/2
f 5/2
82Se
[ν 2d1g —> π 2p1f]Jπ=2⁻
[ν g 9/2 —> π 2p1f]Jπ=2⁻
π=50
ν=50
g 9/2
p 1/2
f 5/2
76Ge



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

Low-energy spin-dipole (2^-) strength to test nuclear wave function for $0\nu\beta\beta$ decay NME's

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



forbidden in the extreme shell model

MODELS

QRPA
→ reasonable description

no-core QRPA
→ washes out shell structures

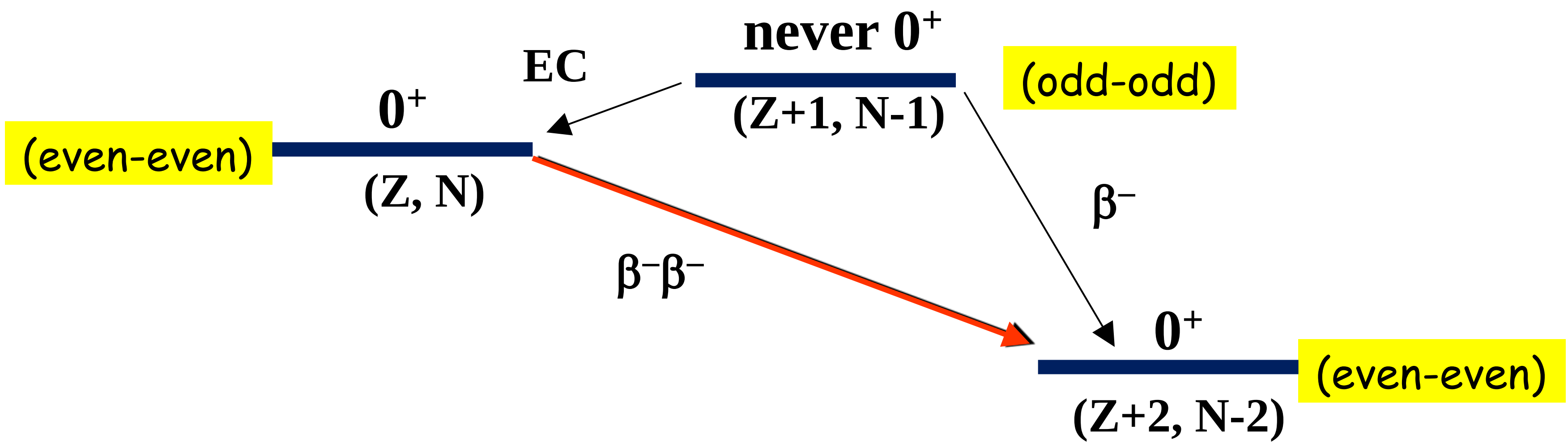
FSQP
→ semi-microscopic model, excellent description of data

-4-

Mass measurements and 0νββ NMEs

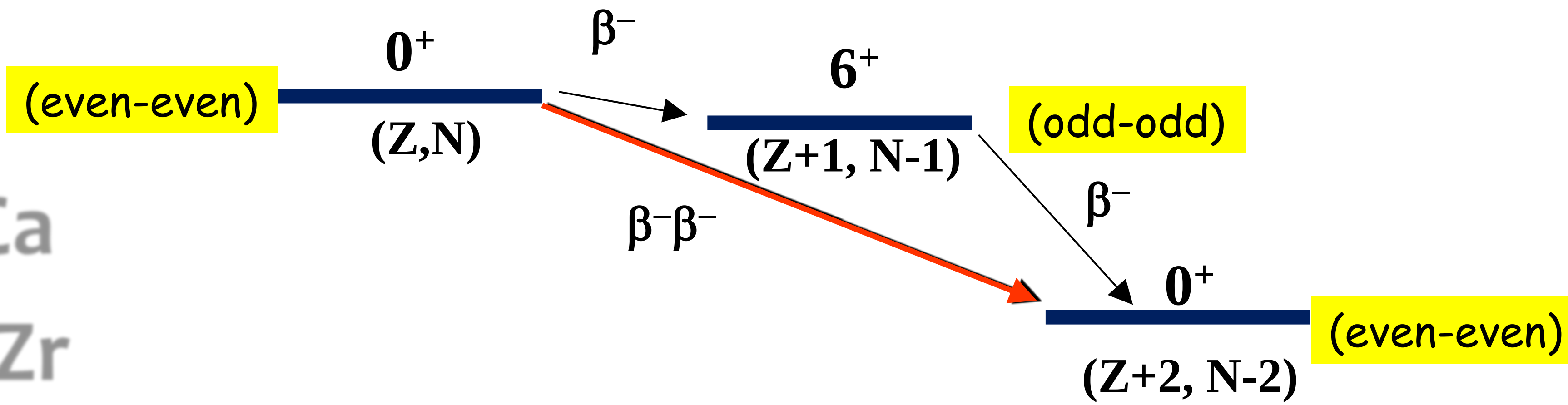
^{96}Zr

$\beta^-\beta^-$



β β

$\beta^-\beta^-$ decay



^{48}Ca

^{96}Zr

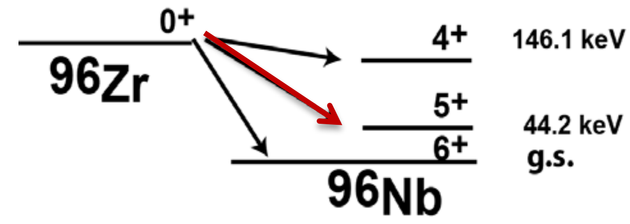
1. ^{48}Ca

   ^{96}Zr

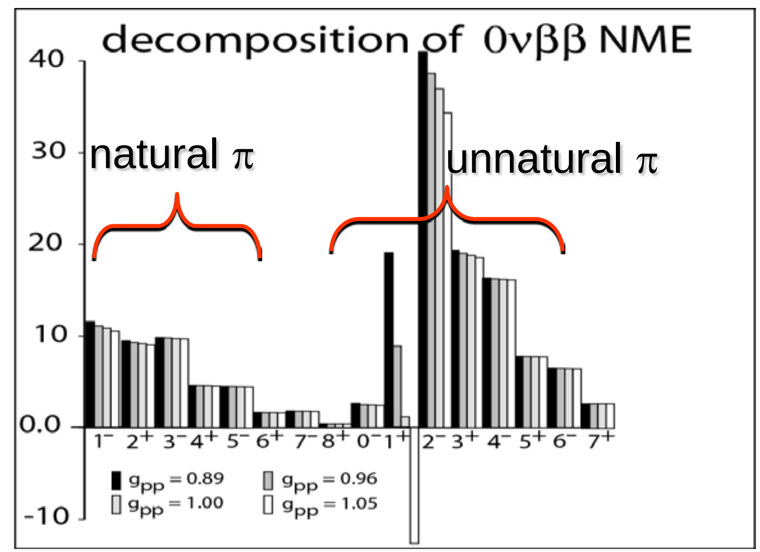
} β β

Idea

- Q-value →
  single **β**-decay



- single **β**-decay
- →
- 4-fold forbidden
  β-decay NME
- **0νββ**-decay NME for the
  same nucleus!!



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

two conflicting half-lives:

$$T_{1/2}^{2\nu\beta\beta} = (2.3 \pm 0.2) \times 10^{19}\,\mathrm{y}$$
$$T_{1/2} = (0.94 \pm 0.32) \times 10^{19}\,\mathrm{y}$$

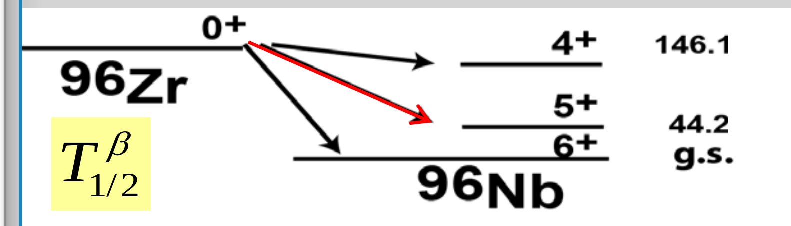
can this difference be reconciled ?
yes, if single β competes with ββ decay

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

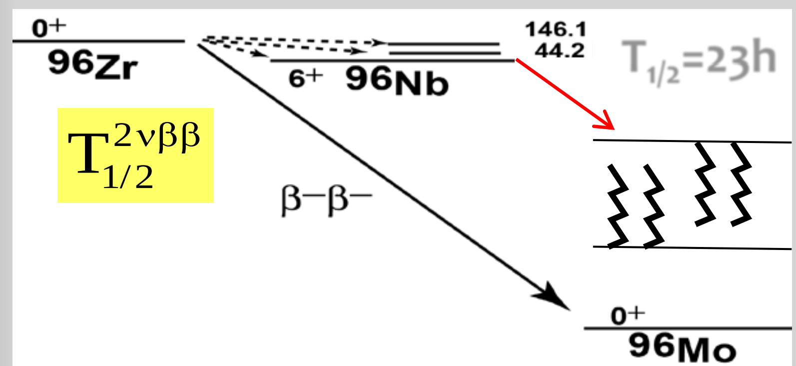
$$T_{1/2}^{\beta} = (1.6 \pm 0.9) \times 10^{19}\,\mathrm{y}$$
$$T_{1/2}^{\beta} > 2.6 \times 10^{19}\,\mathrm{y}$$
$$T_{1/2}^{\beta} = 24 \times 10^{19}\,\mathrm{y}$$

BUT

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

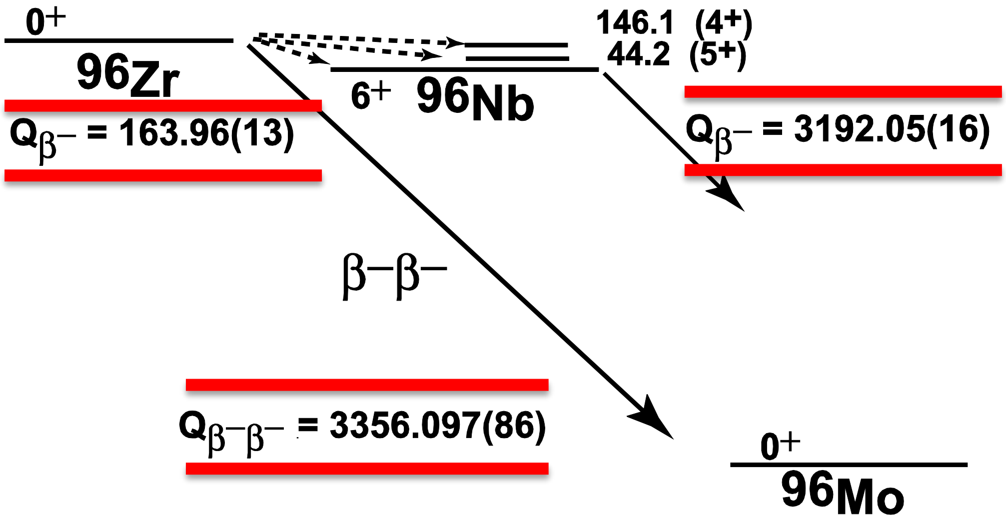


0⁺ → 6⁺ 6-fold non-unique (unobservably long)
0⁺ → 5⁺ 4-fold unique (possible)
0⁺ → 4⁺ 4-fold non-unique (no phase space)



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

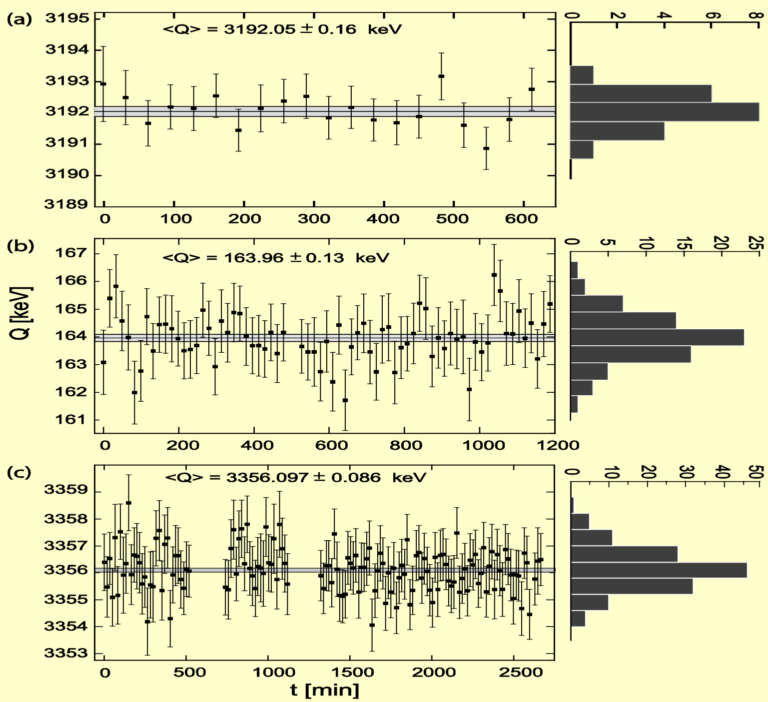
Results



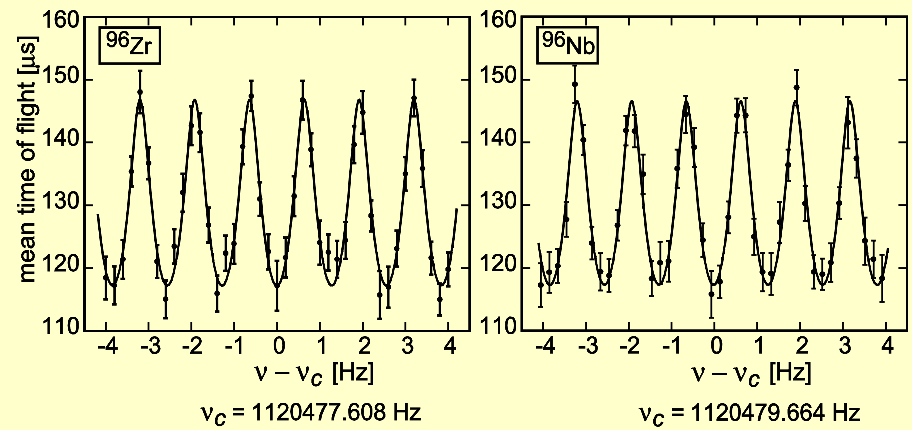
96Zr

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

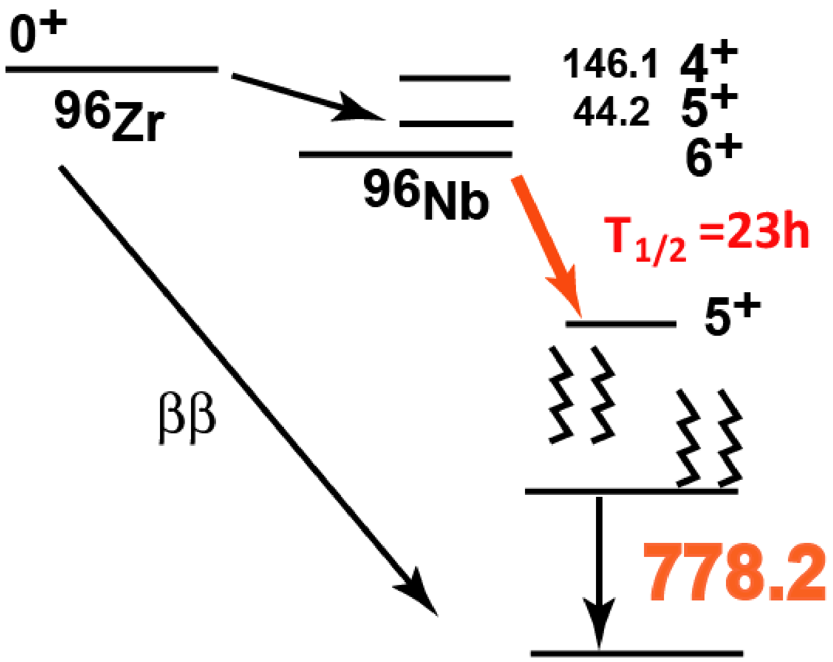
$$Q_{\beta} = 163.96 \pm 0.13 \text{ keV} \quad !!$$



Ramsey excitation



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



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

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

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

Important side effect:

single β decay depends on g_A^2

$2\nu/0\nu\beta\beta$ decay depends on g_A^4

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

-5-
Muon capture and $0\nu\beta\beta$ NMEs

Motivations

- μ-cap features momentum transfers similar to 0νββ decay (q_{tr} ~0.5fm^{-1} ~100MeV/c)
- μ-cap processes to 1^+ states in A(μ$^-$,ν)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 (~5%) is most relevant for 0νββ decay
- level scheme of final odd-odd nucleus is extremely!! poorly known

The muon capture and g_A in weak decays

<u>Title</u>

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

M. Alanssari,[1] I. H. Hashim,[2] L. Jokiniemi,[3] H. Ejiri,[4] E. Ideguchi,[4] A. Sato,[4] J. Suhonen,[3] and D. Frekers[1]

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[2]Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

[3]University of Jyvaskyla, Department of Physics, FI-40014, Finland

[4]Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

The amazing muon

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

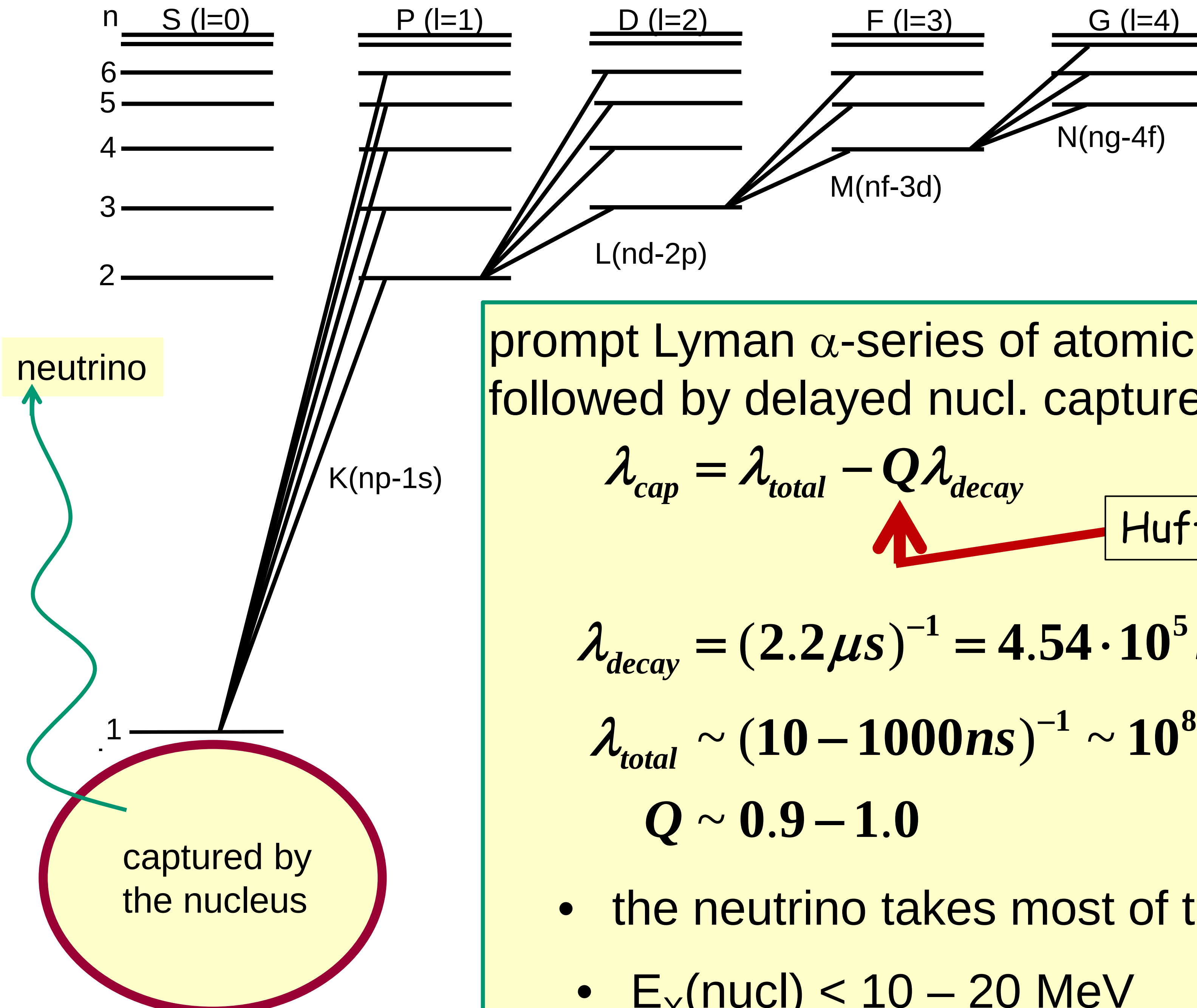
Production: $p + A \to X + \pi^-$

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

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

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

$$G_F = 1{,}16637(2) \cdot 10^{-5} GeV^{-2}$$



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

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

Huff-factor

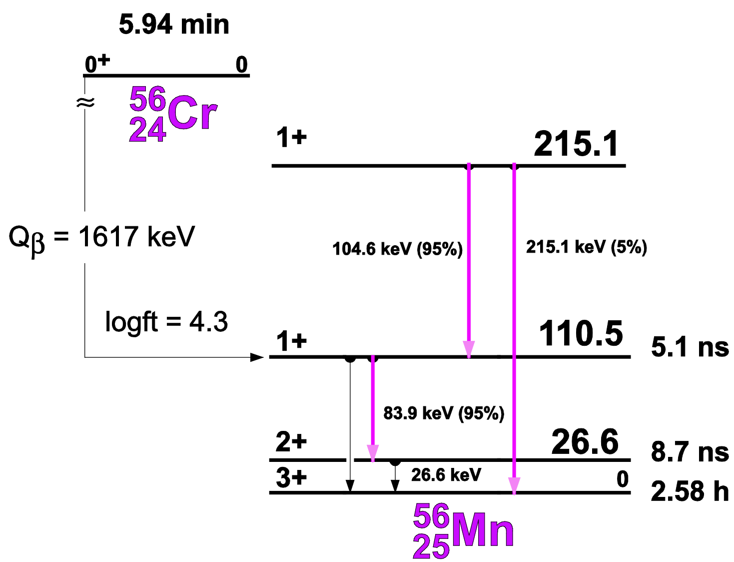
$$\lambda_{decay} = (2.2\mu s)^{-1} = 4.54 \cdot 10^{5} s^{-1}$$

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

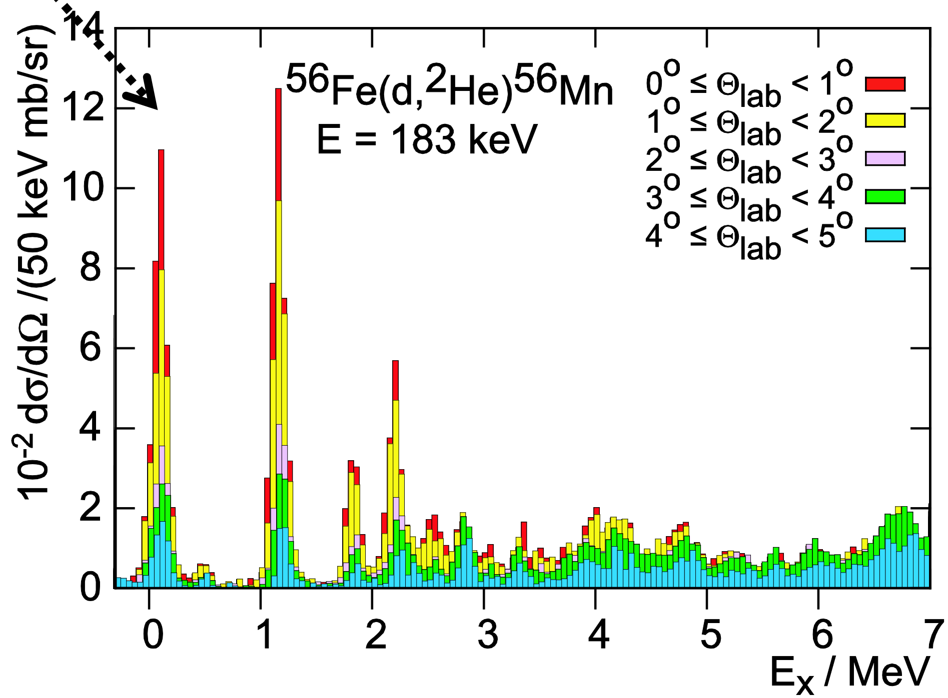
$$Q \sim 0.9 - 1.0$$

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

The issue of g_A queching

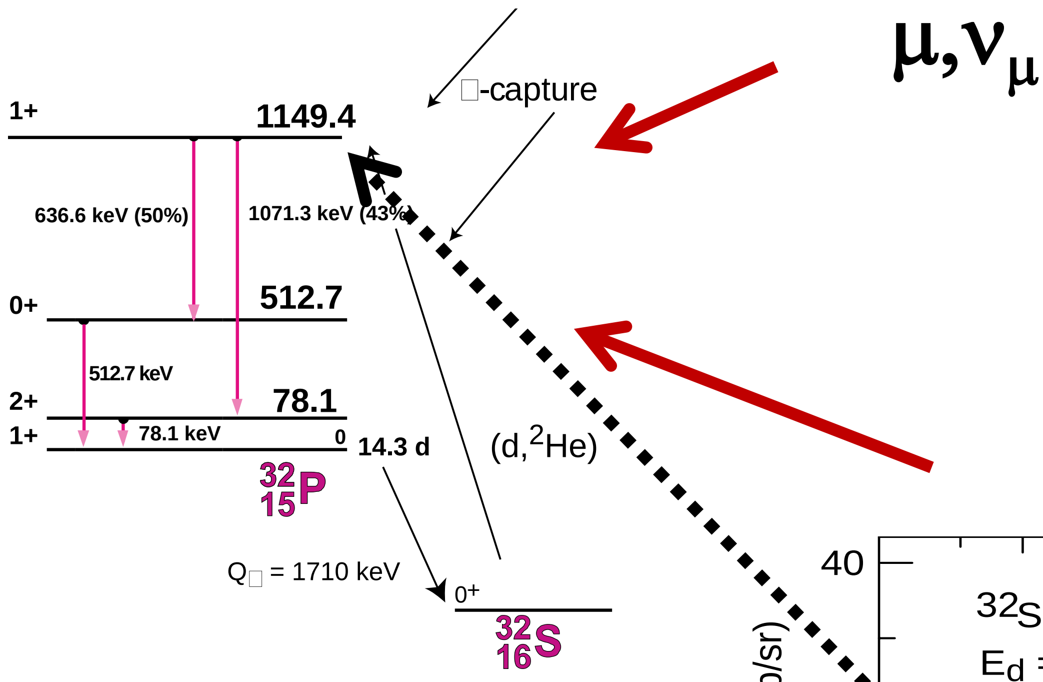


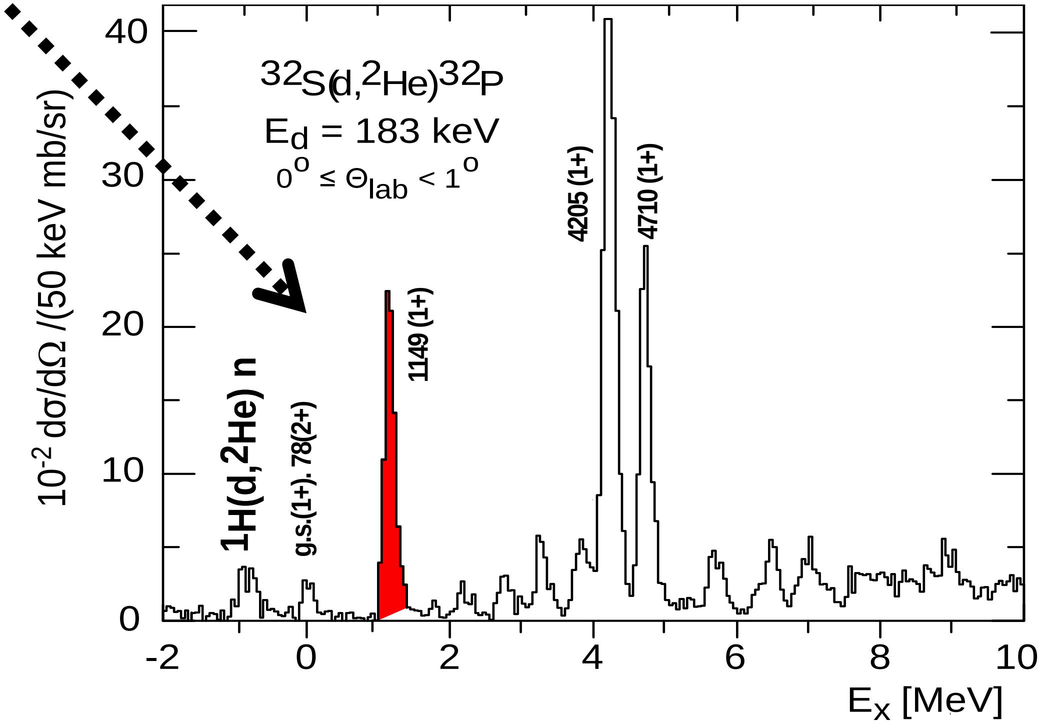
μ, ν_μ



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

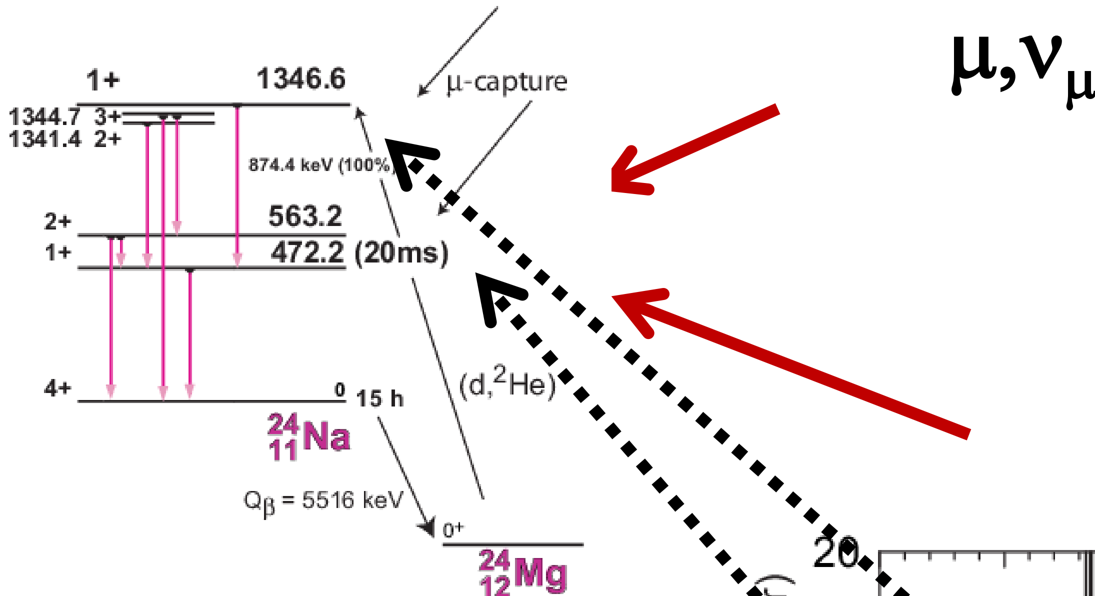
The issue of g_A queching

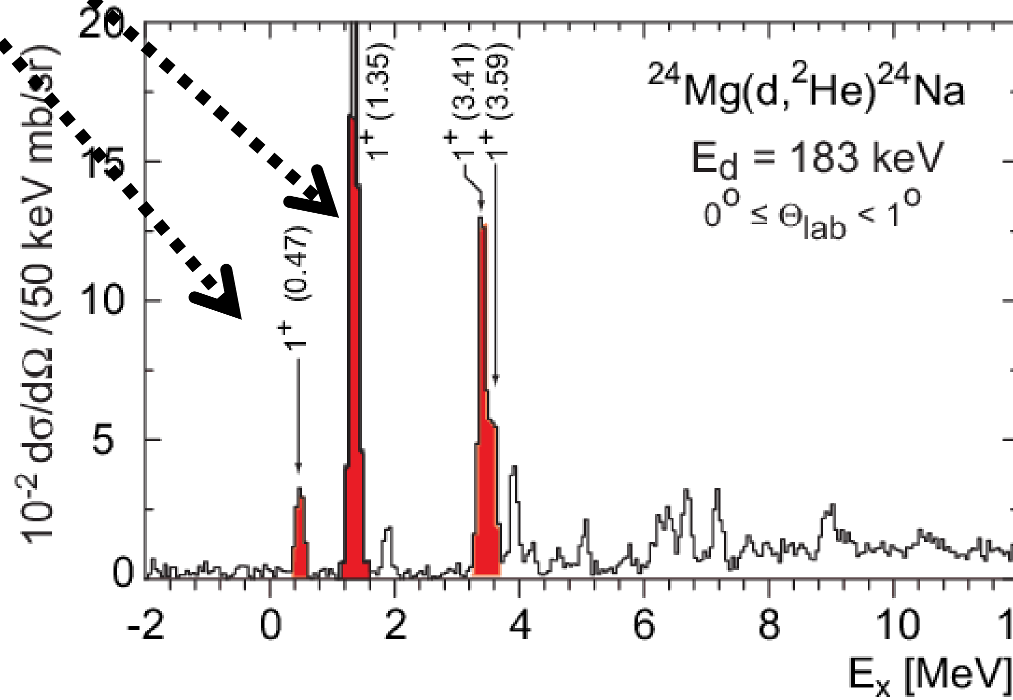




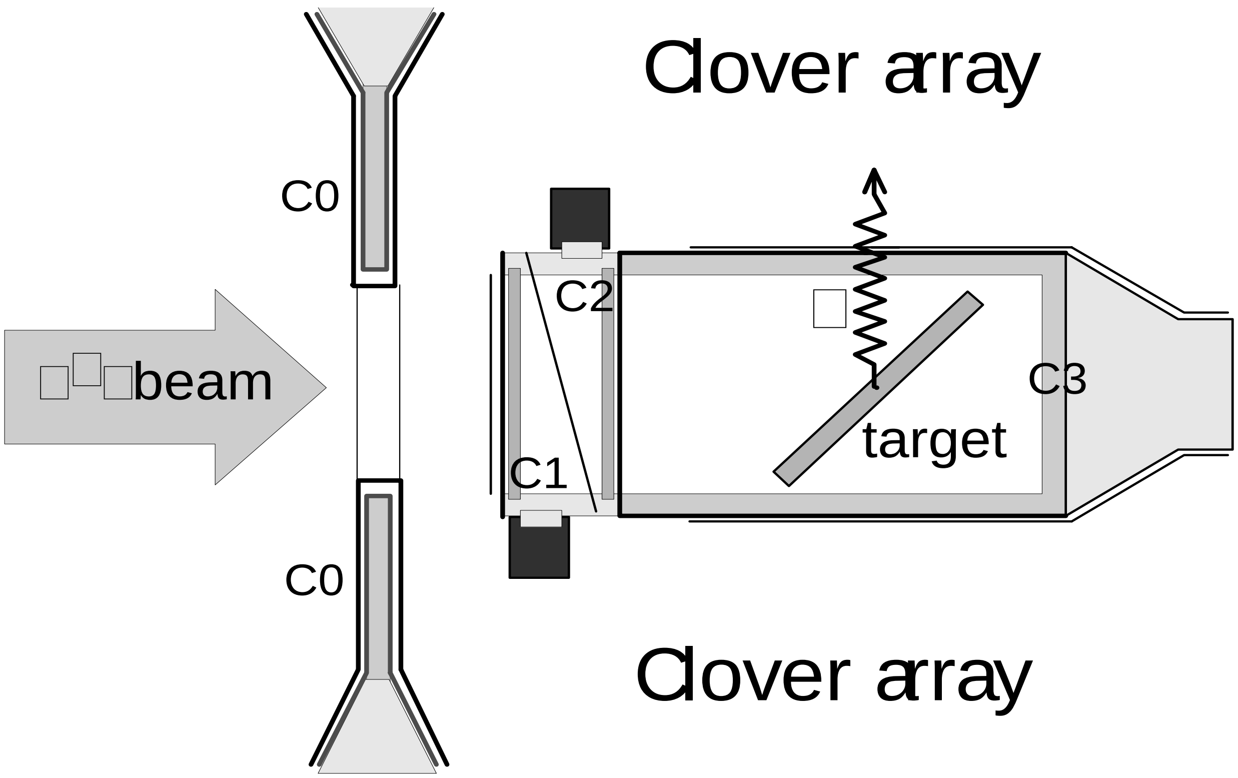
Example:
Compare transition strength in μ-cap and (d,²He) charge-ex

The issue of g_A queching



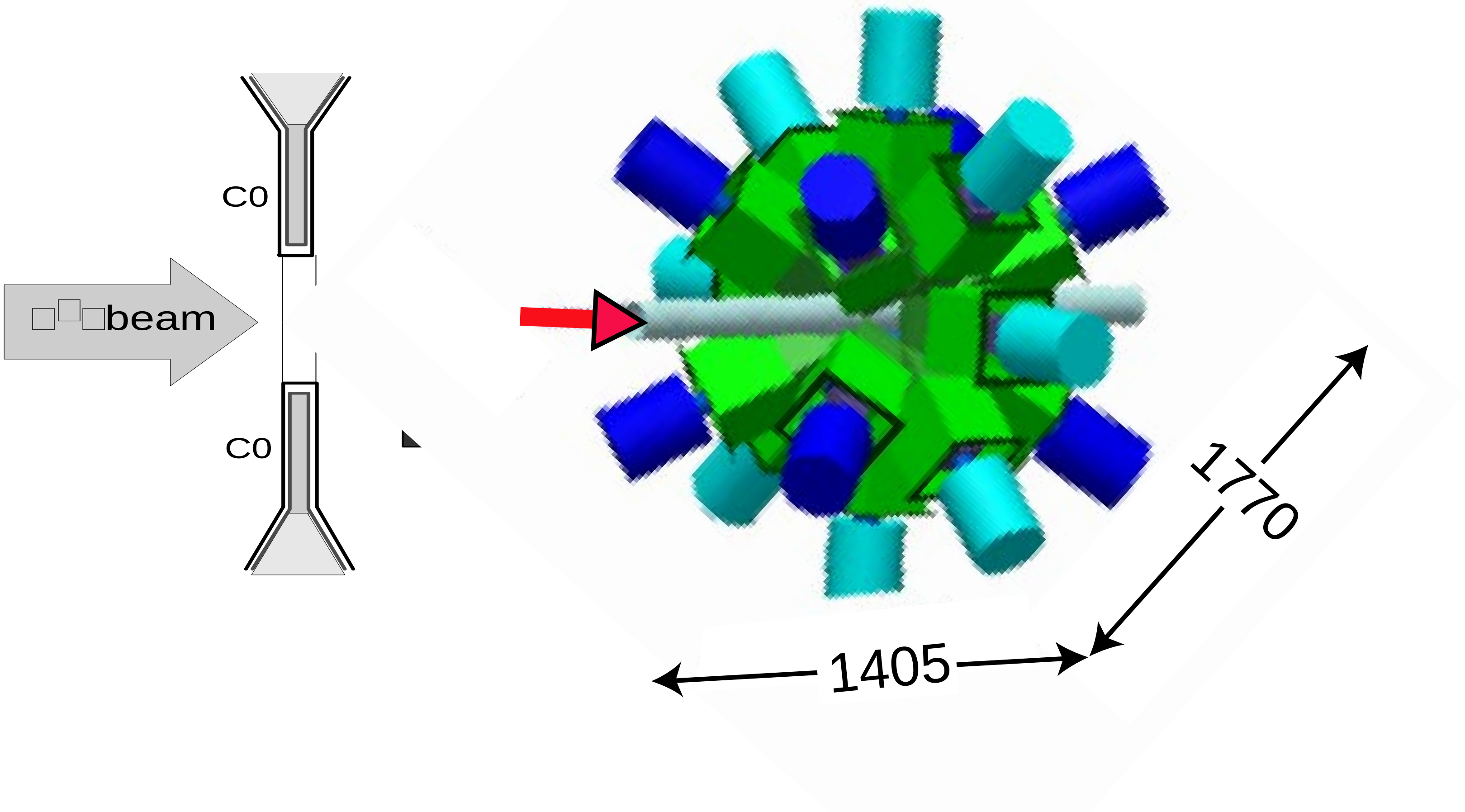


Example:
Compare transition strength in μ-cap and (d,^{2}He) charge-ex



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

μ−


beam
C0
C0
1770
1405

The issue of g_A queching

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

μ

What is this ????

$\pi \quad -1$

→
→
→

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)