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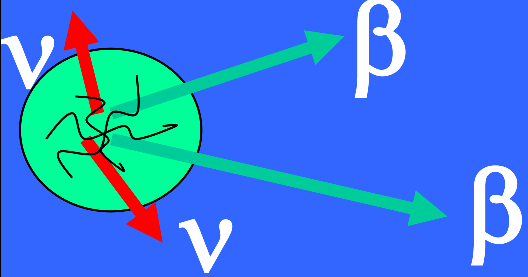
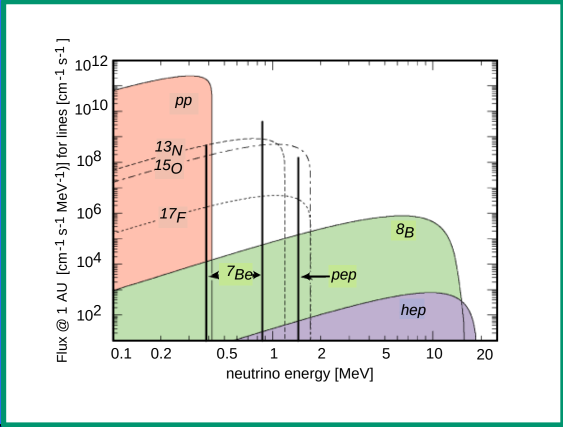
D. Frekers

Charge-exchange reactions
GT-transitions, ββ-decay
and
things beyond





"COLLECTIVE MOTION IN NUCLEI
UNDER EXTREME CONDITIONS"
COMEX5

Outline

- <u>Chargex-reactions (^{3}He,t) & (d,^{2}He)</u>
  - **highlights & features of 2νββ nuclear matrix elements (NME)**

    ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{136}Xe

    fragmentation – smallest/largest NME

university of groningen

- <u>the 0νββ decay nuclear matrix elements</u>

  1st forbidden NME's and 2⁻ states

- <u>solar ν SNU rates and (^{3}He,t) reaction</u>

  ^{71}Ga(^{3}He,t), ^{82}Se(^{3}He,t)

30 min

- <u>the A=96 system</u>

  the ^{96}Zr (β–) → ^{96}Nb Q-value

  and a direct test of 0νββ NME

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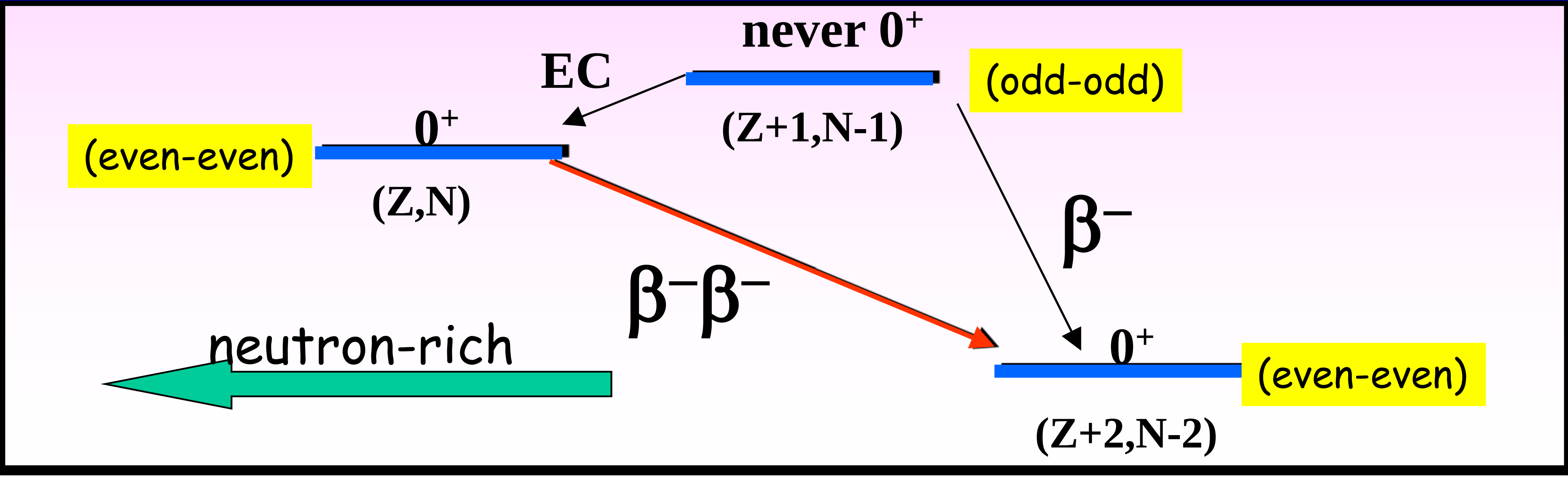
UNIVERSITY OF JYVÄSKYLÄ

$\beta^-\beta^-$ decay



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

$$T_{1/2} \approx 10^{19-21}\, y$$

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

$$T_{1/2} > 10^{24}\, y$$

recall: 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:

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

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

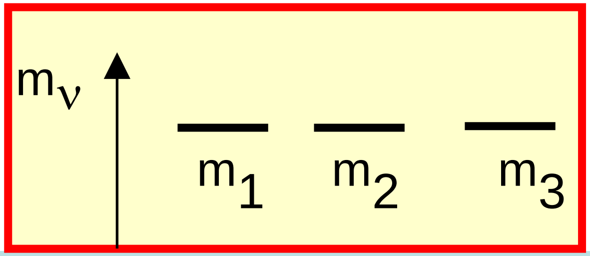
$$\Theta_{13} = 0.11$$

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

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

neutrino-mass-scenarios:

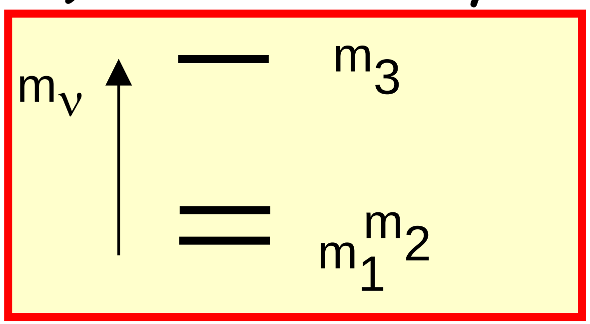
1) degenerate:



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

the best of all cases

2) normal hierarchy:

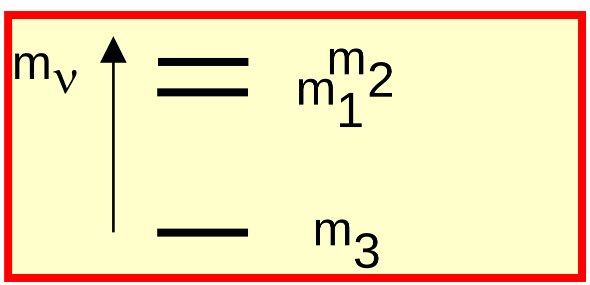


$$|m_{\nu_e}|^2 \propto \Delta m_{sol}^2 \times \left| \frac{3m_1}{\Delta m_{sol}} + e^{-2i(\Phi_2-\Phi_1)} + (<0.5)e^{-2i(\delta-\Phi_1)} \right|^2$$

= ZERO!! for:

$$\Theta_{13} \ \square\ 9^\circ \qquad (\Phi_2 - \Phi_1) = \frac{\pi}{2} \qquad \frac{3m_1}{\Delta m_{sol}} = 1$$

3) inverted hierarchy:



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

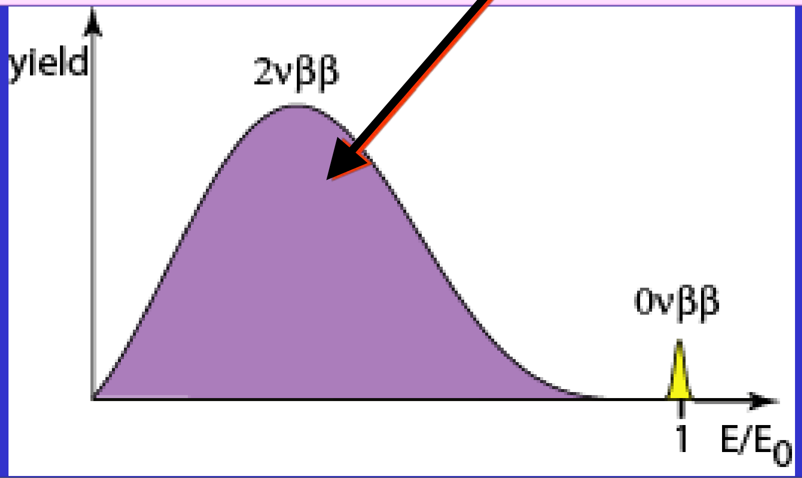
if inverted hierarchy could be established
(LHC, SN-ν, precision-oscillation)
THEN: $|m_{\nu_e}| \approx \Delta m_{atm}$

or neutrino is a Dirac-particle

NME important

$\mathbf{N}_{ucl.}\mathbf{M}_{atrix}\mathbf{E}_{lements}$

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



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

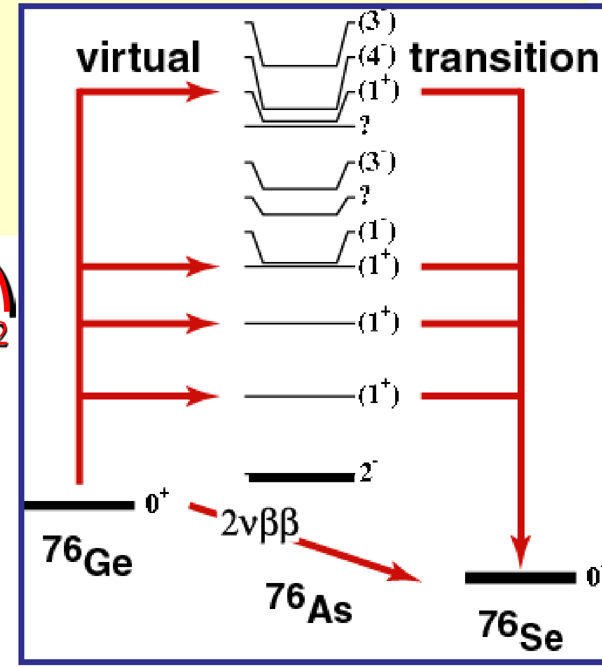
$$G^{2\nu}_{(\beta^-\beta^-)} = \frac{C}{8\pi^7}\left(\frac{G_F\, g_A}{\sqrt{2}}\cos(\theta_C)\right)^4 \left|M^{(2\nu)}_{\mathrm{DGT}}\right|^2 F^2_{(-)}\, f(Q)$$

!!

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

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

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

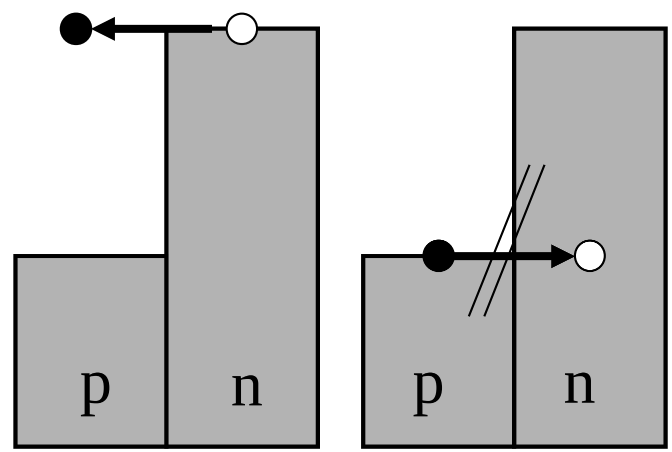


favorable:

1. high Q-value
2. large Z

unfavorable (but cannot be changed):

1. large neutron excess
   (Pauli-blocking)

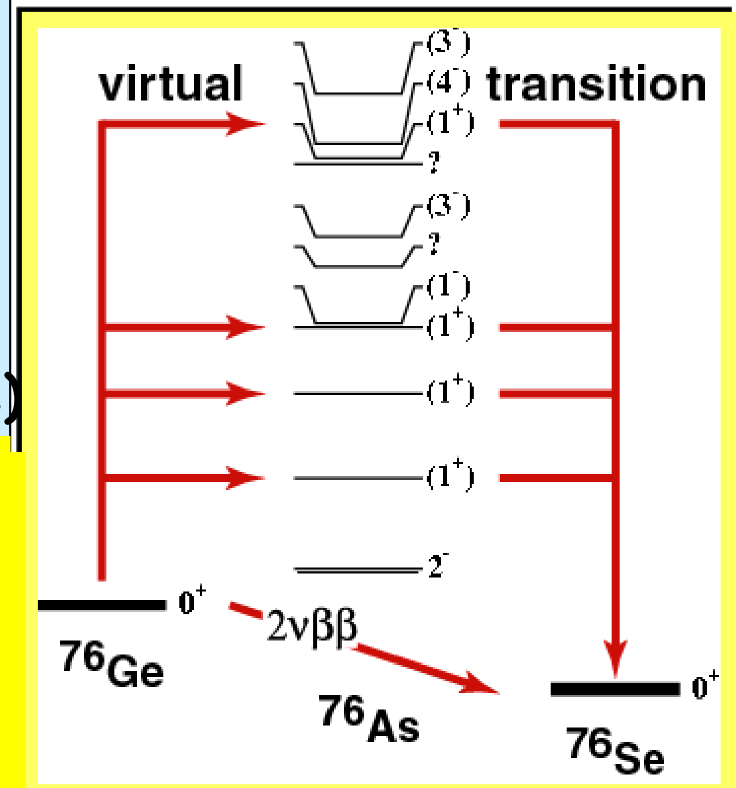


$$M^{(2\nu)}_{DGT} = \sum_m \frac{\langle 0^{(f)}_{g.s.} | \sum_k \sigma_k \tau^-_k | 1^+_m \rangle \langle 1^+_m | \sum_k \sigma_k \tau^-_k | 0^{(i)}_{g.s.} \rangle}{\frac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - E_0}$$

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

to remember:

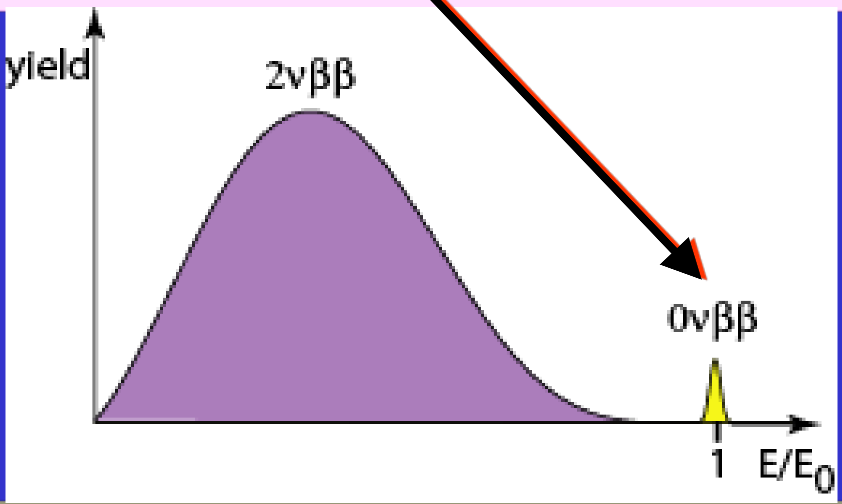
1. 2 sequential & „allowed" β^--decays of „Gamow-Teller" type
2. „1, 2, 3, ... forbidden" decays negligible
3. Fermi–transitions do no contribute (because of different isospin-multiplets)



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

Nucl. M atrix E lements

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



neutrino is a virtual particle

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

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

degree of forbiddeness is lifted

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

!!

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

theory $\approx$ 10 !!

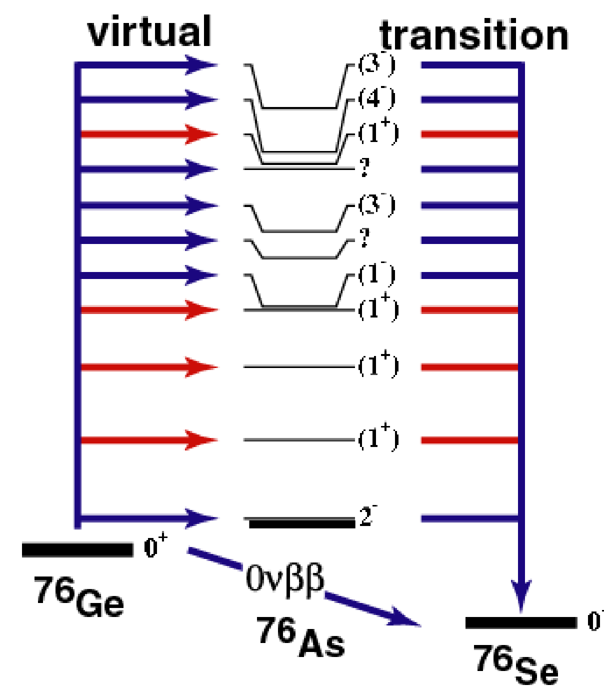
largely independent of (A,Z)
(except near magic nuclei)

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

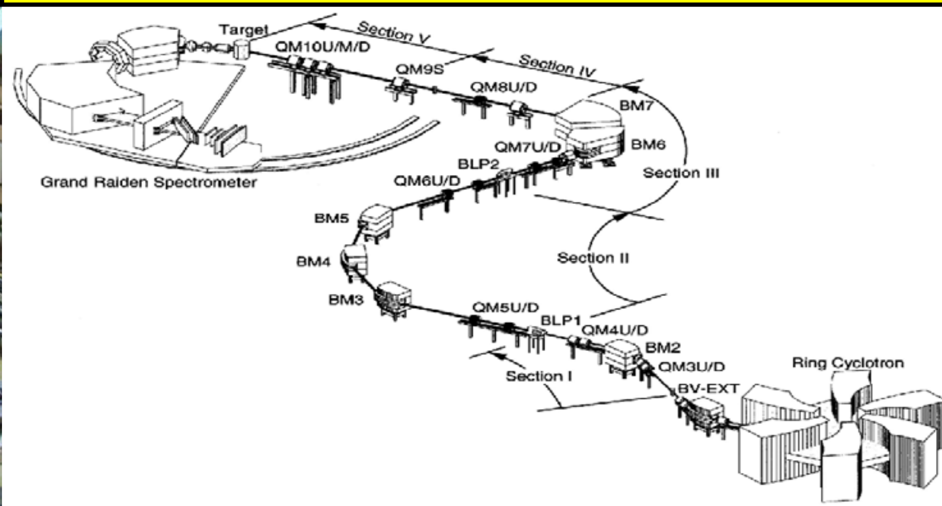
NOT (easily) accessible via charge-exchange reactions

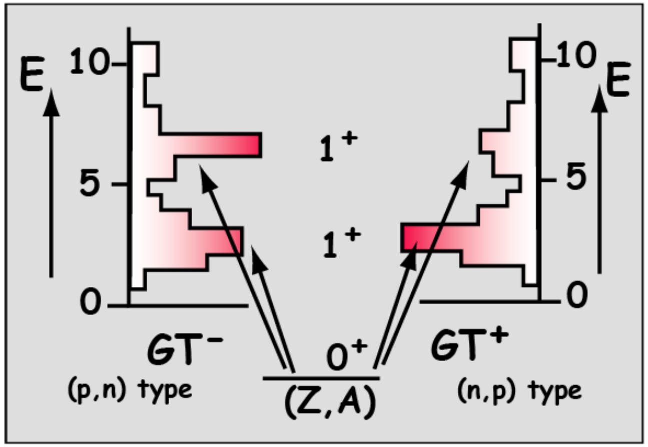


Charge-exchange reactions

Grand Raiden Magnetic Spectrometer

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





Q: what is the connection between „weak στ 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)

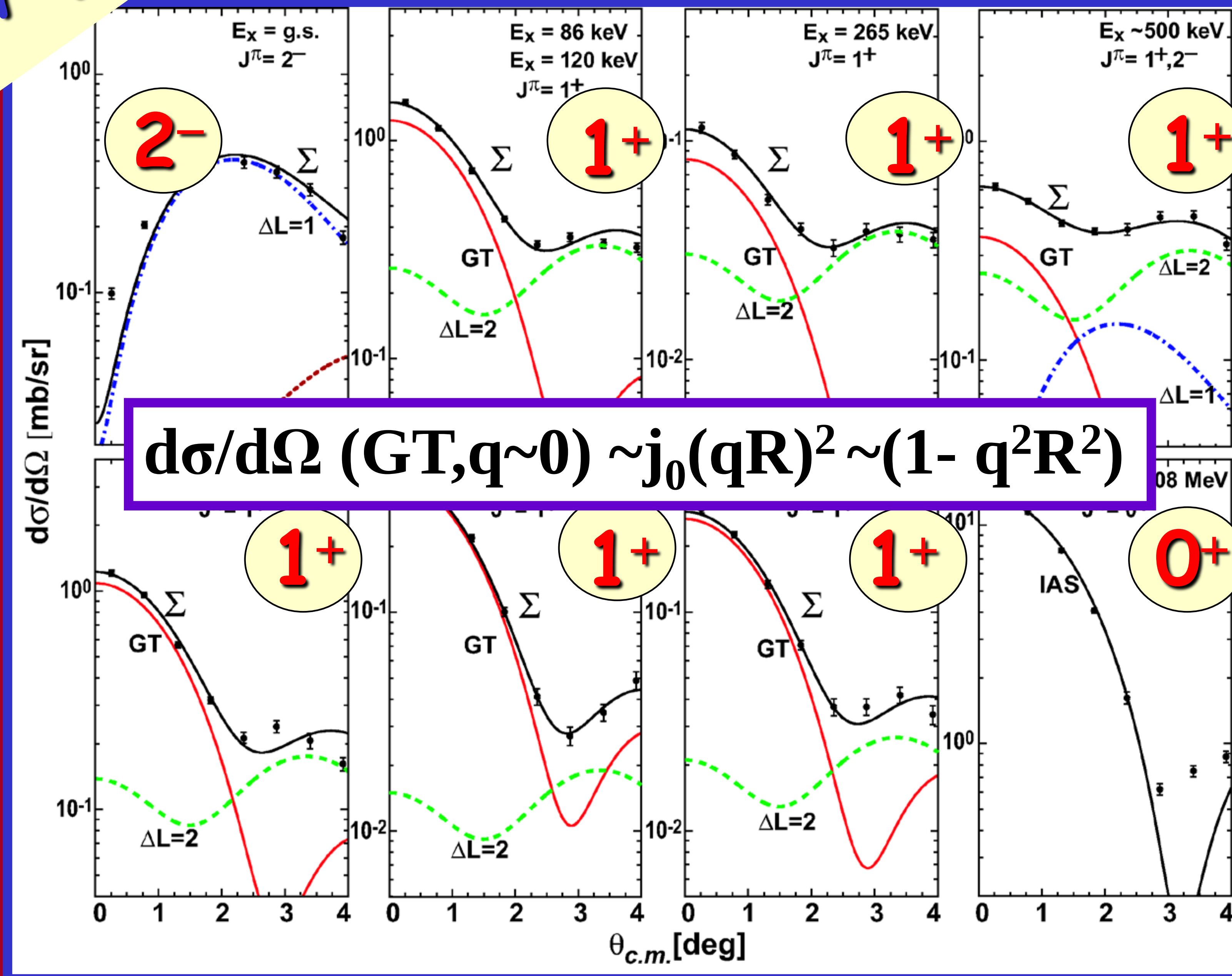
$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{\mu}{\pi\hbar}\right]^2 \frac{k_f}{k_i} N_d \, |V_{\sigma\tau}|^2 \, |\langle f \,|\, \sigma\tau \,|\, i \rangle|^2$$

$q = 0!!$

largest at 100 - 200 MeV/A

examples

$^{76}Ge-^{76}As$

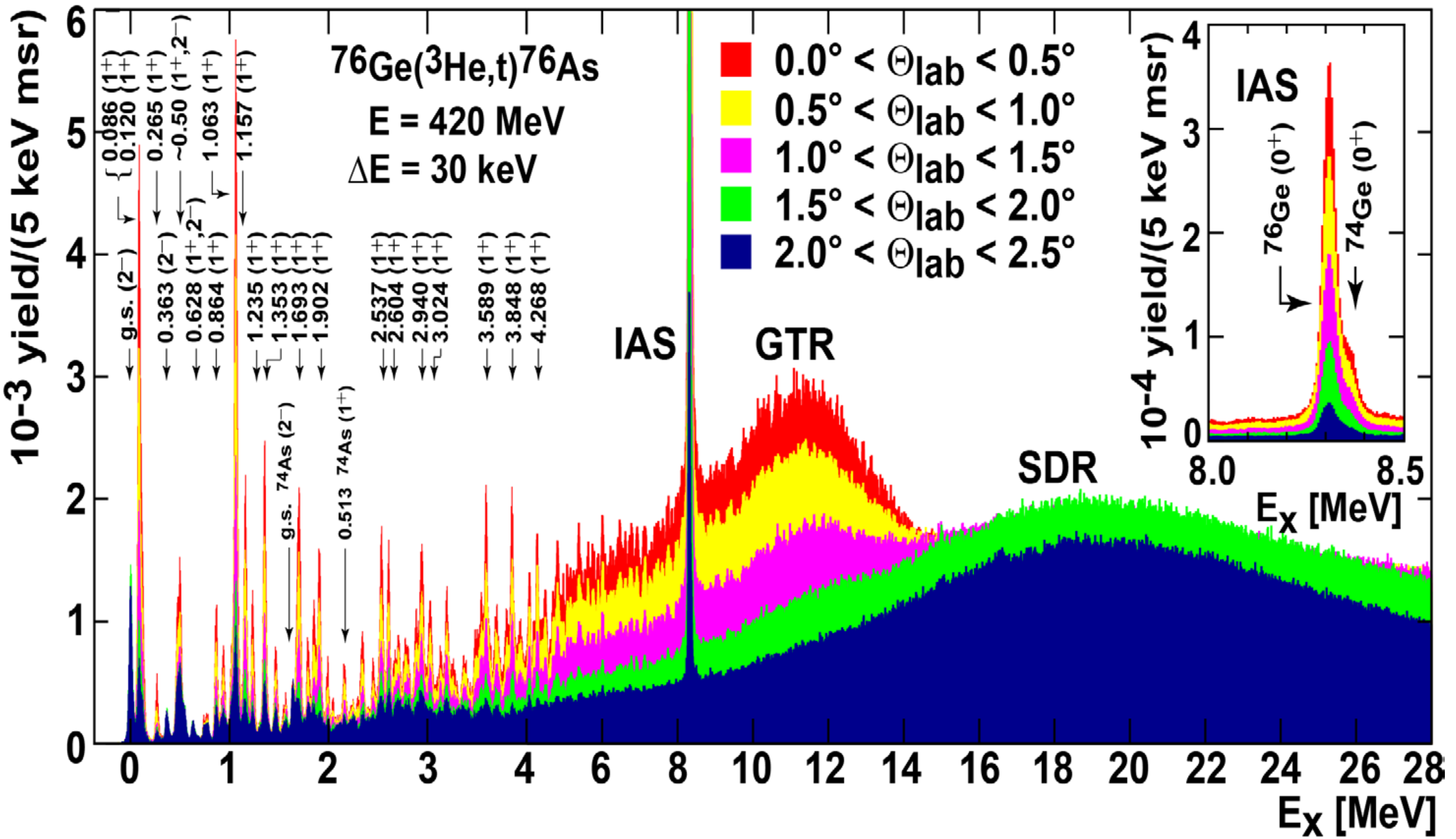


$$d\sigma/d\Omega\ (GT, q\sim 0) \sim j_0(qR)^2 \sim (1 - q^2R^2)$$

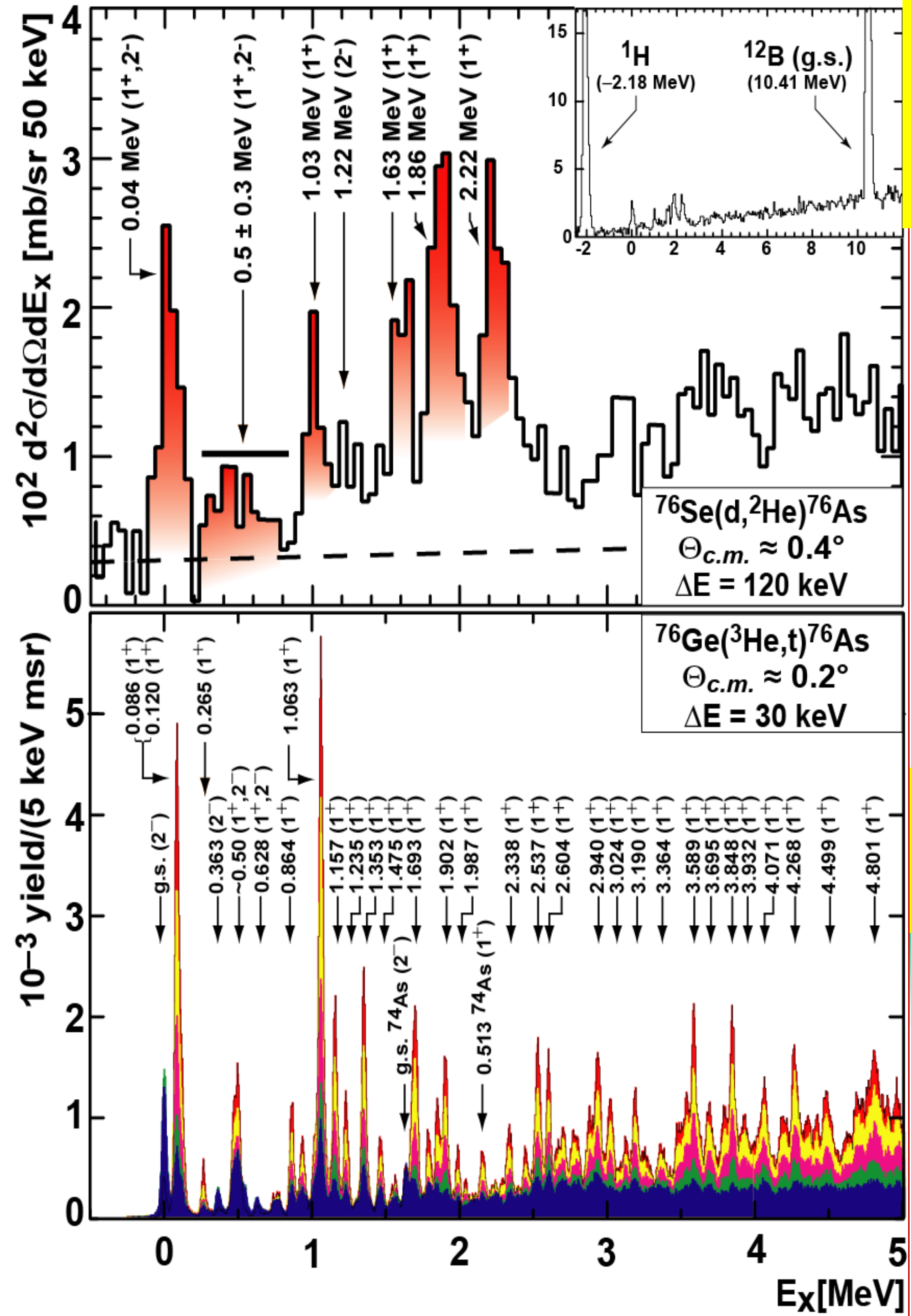
^{76}Ge

N-Z=10

Resolution is the key !!!

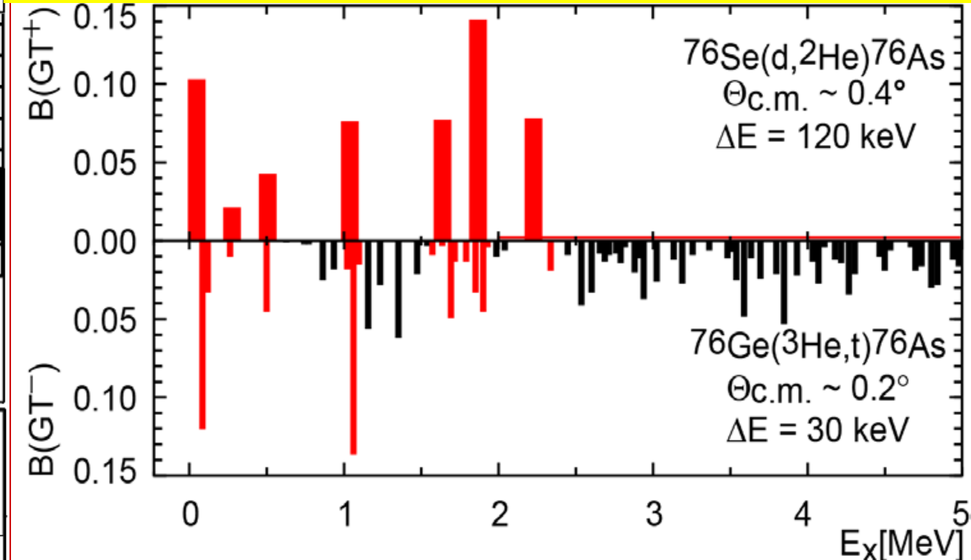


almost 70 !! resolved single states up to 5 MeV identified as GT 1+ transitions !!!

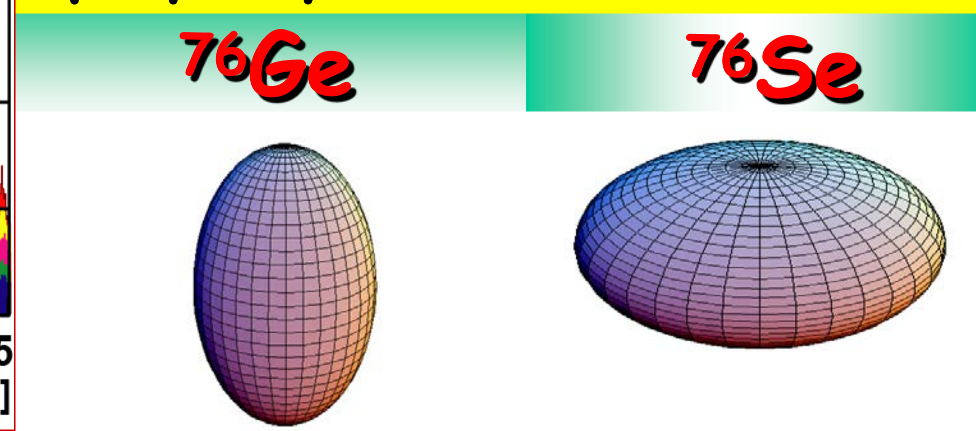


~ 70 !! single states up to 5 MeV !!!

???? anti-correlation ????

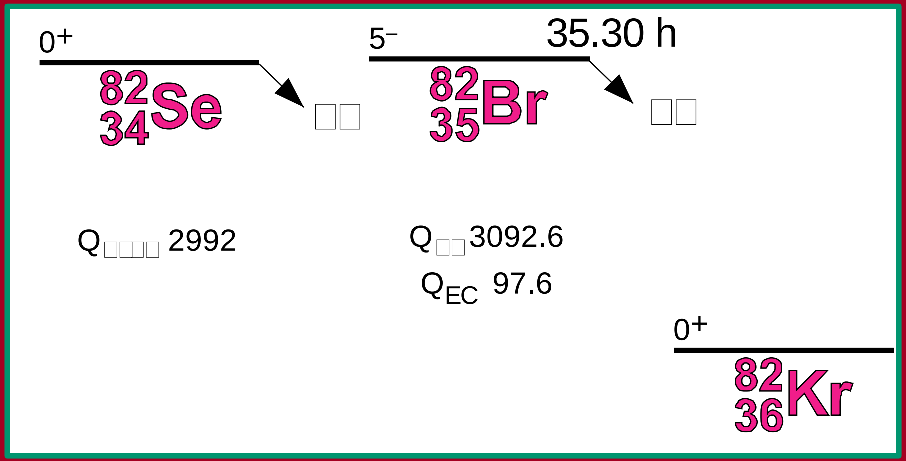


is the anti-correlation a property of deformation ??



^{82}Se

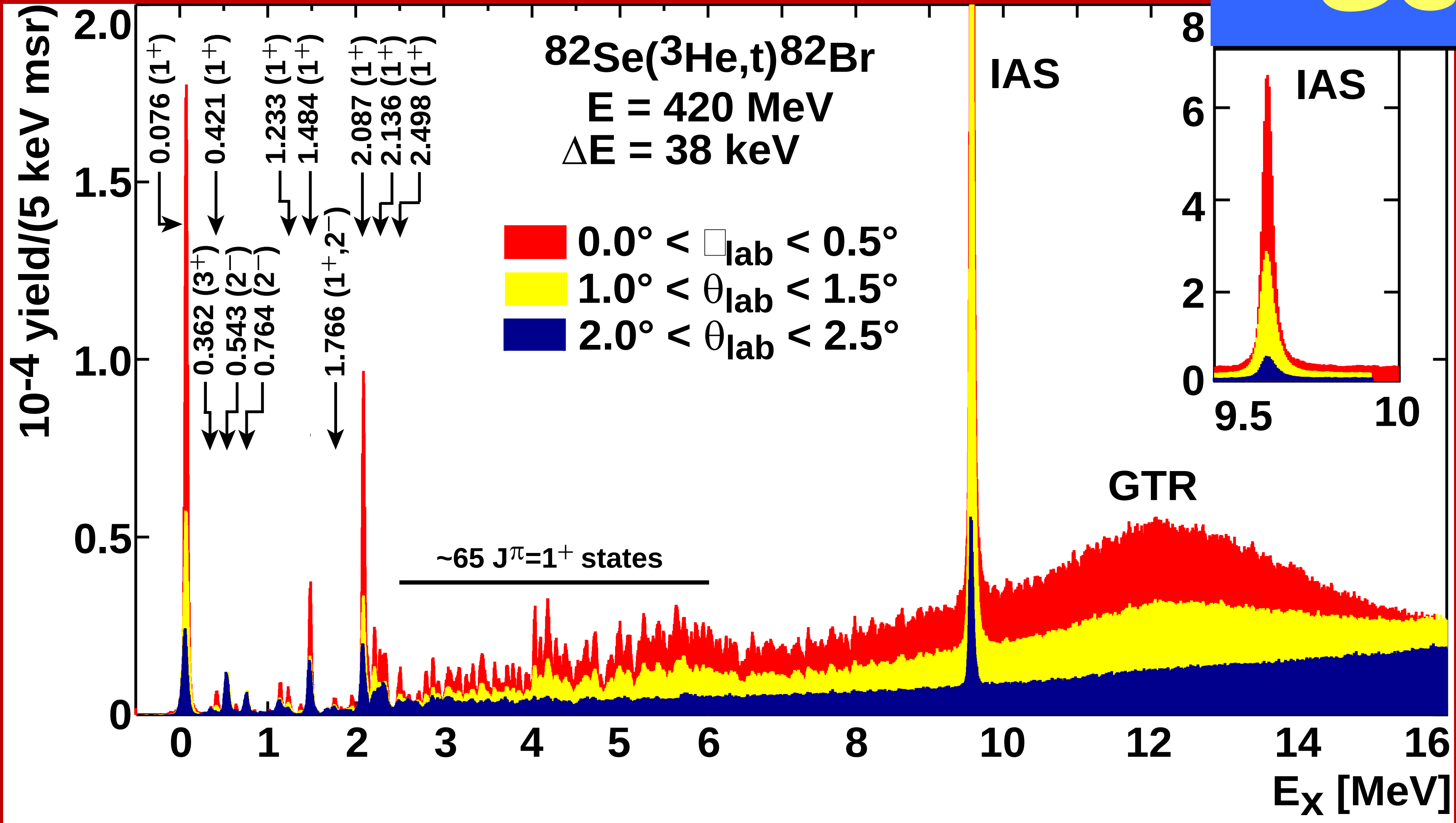
N-Z=14



Resolution is the key !!!

possibly useful for solar neutrino detection

^{82}Se



3 isolated GT transition below 2 MeV- fragmentation recedes to GT resonance

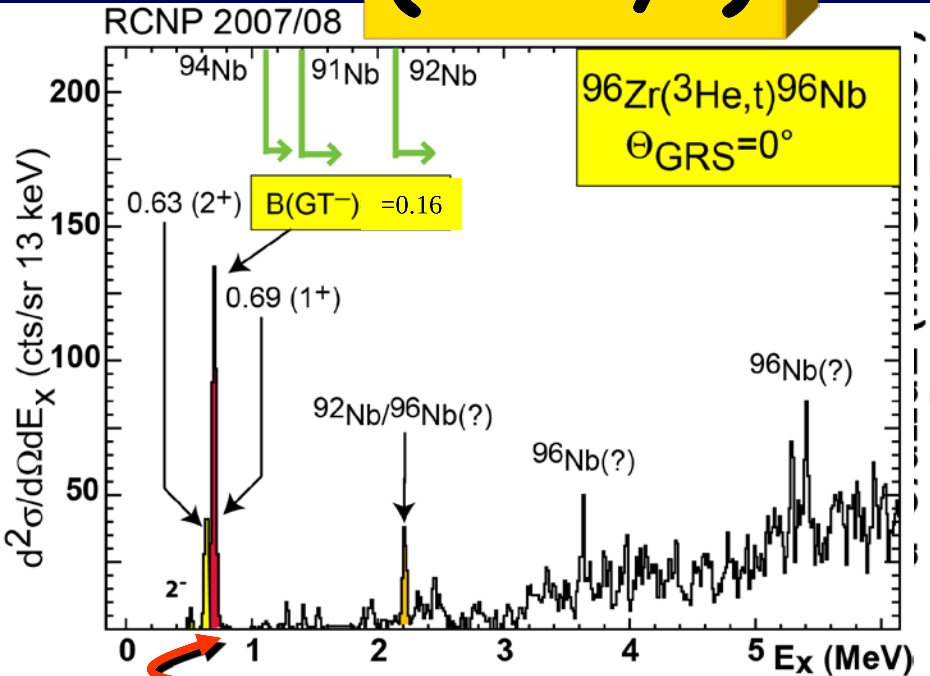
^{96}Zr

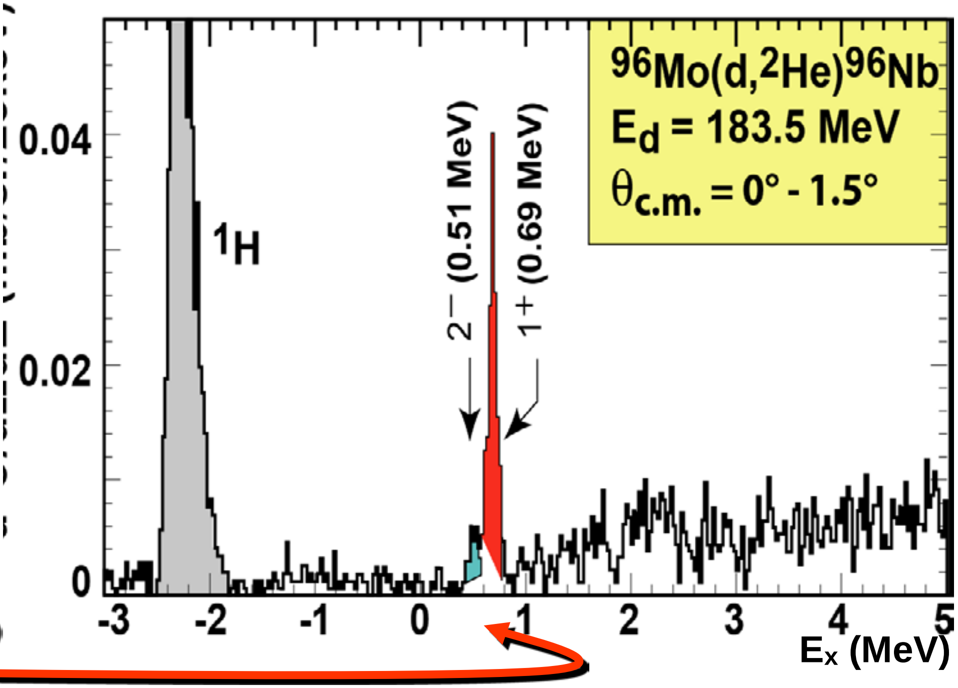
N-Z=16

Remember: $B(GT)_{tot} = 3(N-Z) \sim 50$!

$B(F) = (N-Z)$

(^{3}He,t)　　　　(d,^{2}He)





B(GT$^-$) = 0.16　　　　**B(GT$^+$) = 0.3**

Fascination: With only 1 state:

$$T_{1/2}^{calc.}(2\nu\beta\beta) = (2.1 \pm 0.4) \cdot 10^{19}\ \text{years}$$

$$T_{1/2}^{exp.}(2\nu\beta\beta = (2.3 \pm 0.2) \cdot 10^{19}\ \text{years}\quad \text{(NEMO3-result)}$$

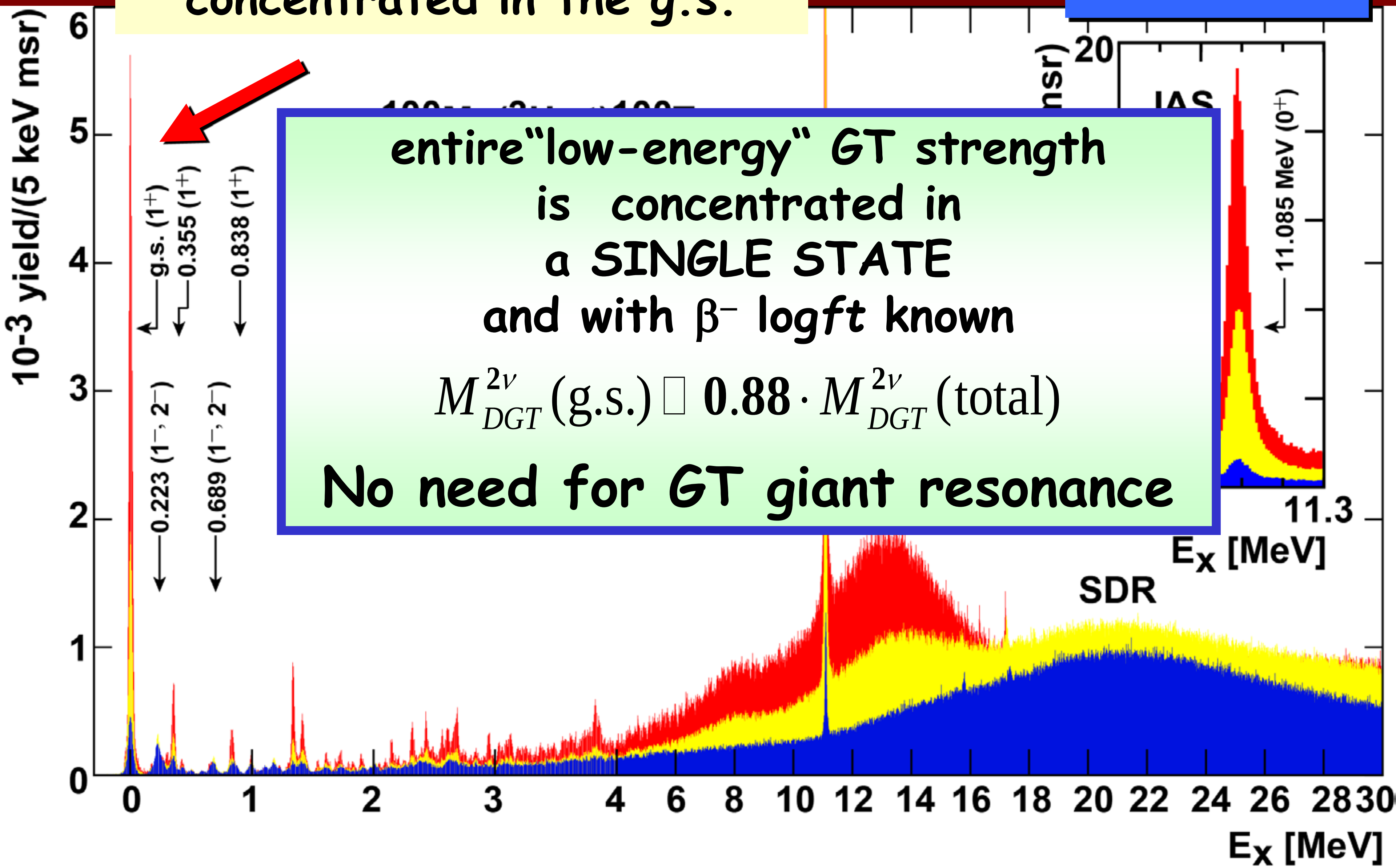
^{100}Mo

$N-Z=16$

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.

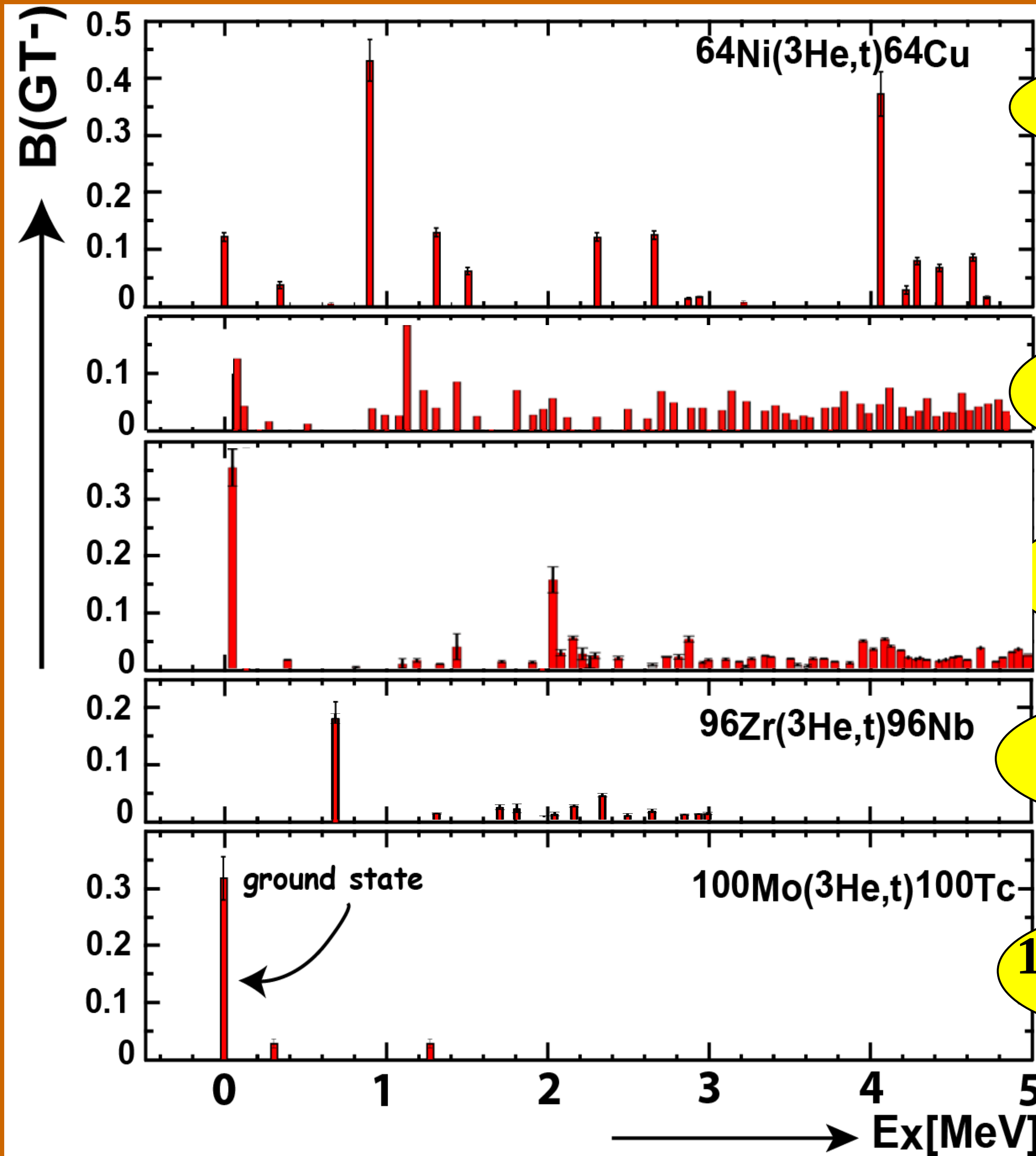
^{100}Mo



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

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

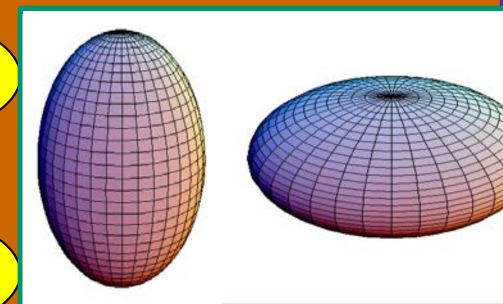
No need for GT giant resonance



^{64}Zn(εε, εβ+)

^{76}Ge(β⁻β⁻)

^{82}Se(β⁻β⁻)



^{96}Zr(β⁻β⁻)

^{100}Mo(β⁻β⁻)

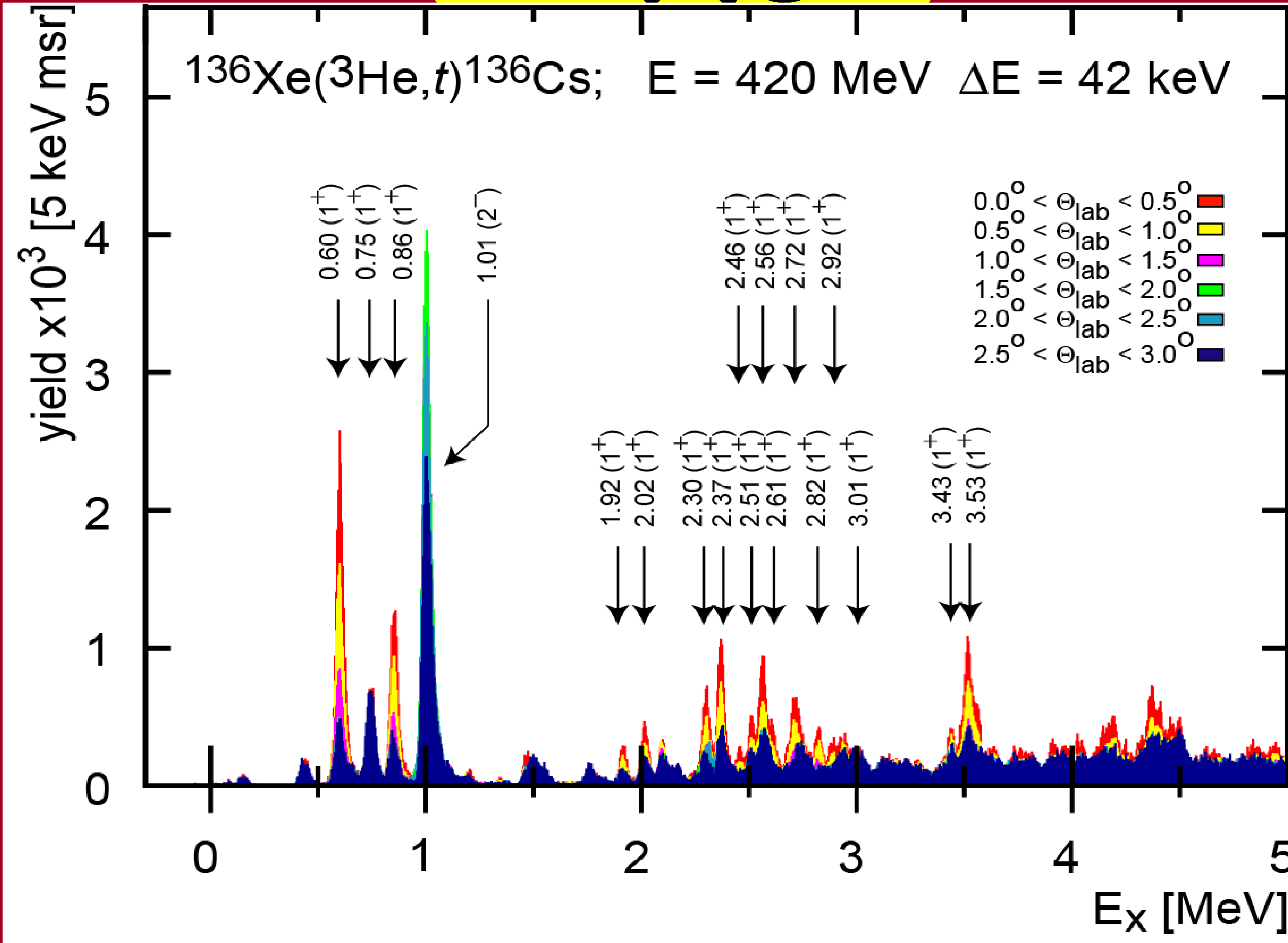
reduced fragmentation of GT strength

^{136}Xe

$N-Z=28$

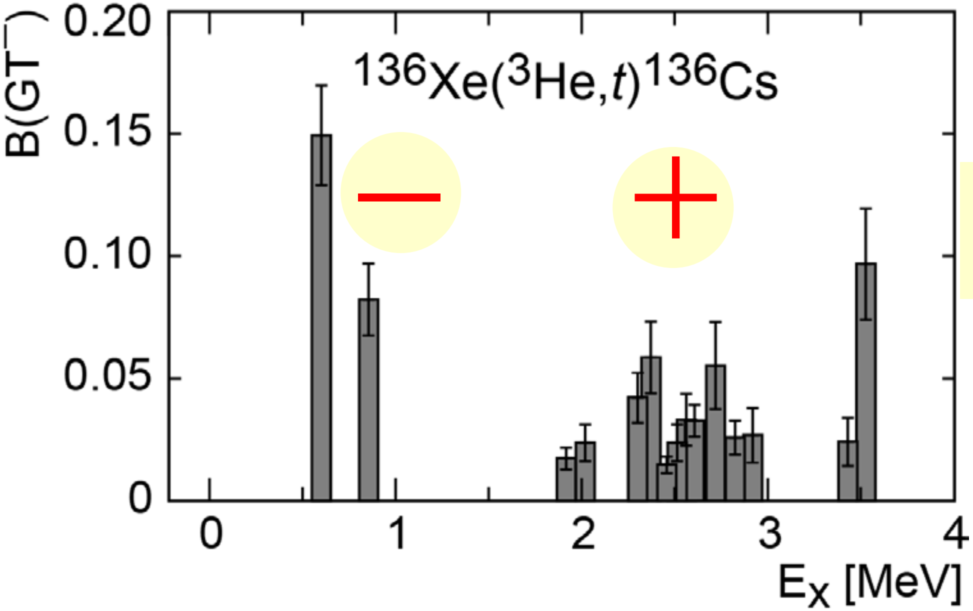
question: why so stable !!!

136Xe



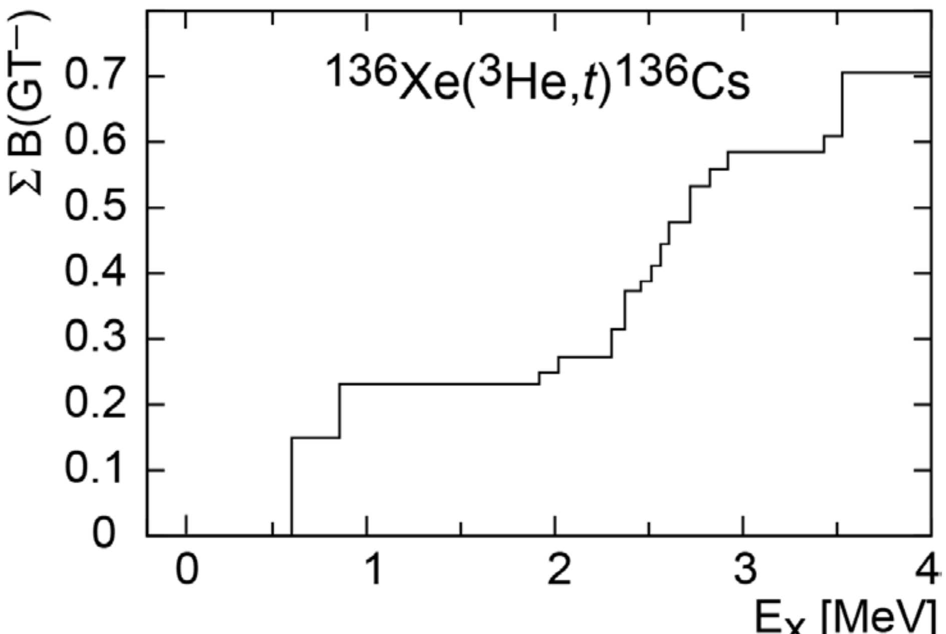
136Xe(3He,t)136Cs; E = 420 MeV ΔE = 42 keV
yield x10^3 [5 keV msr]
Ex [MeV]
0.60 (1+)
0.75 (1+)
0.86 (1+)
1.01 (2-)
2.46 (1+)
2.56 (1+)
2.72 (1+)
2.92 (1+)
1.92 (1+)
2.02 (1+)
2.30 (1+)
2.37 (1+)
2.51 (1+)
2.61 (1+)
2.82 (1+)
3.01 (1+)
3.43 (1+)
3.53 (1+)
0.0° < Θlab < 0.5°
0.5° < Θlab < 1.0°
1.0° < Θlab < 1.5°
1.5° < Θlab < 2.0°
2.0° < Θlab < 2.5°
2.5° < Θlab < 3.0°
0
1
2
3
4
5

What's the size of the NME?



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

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



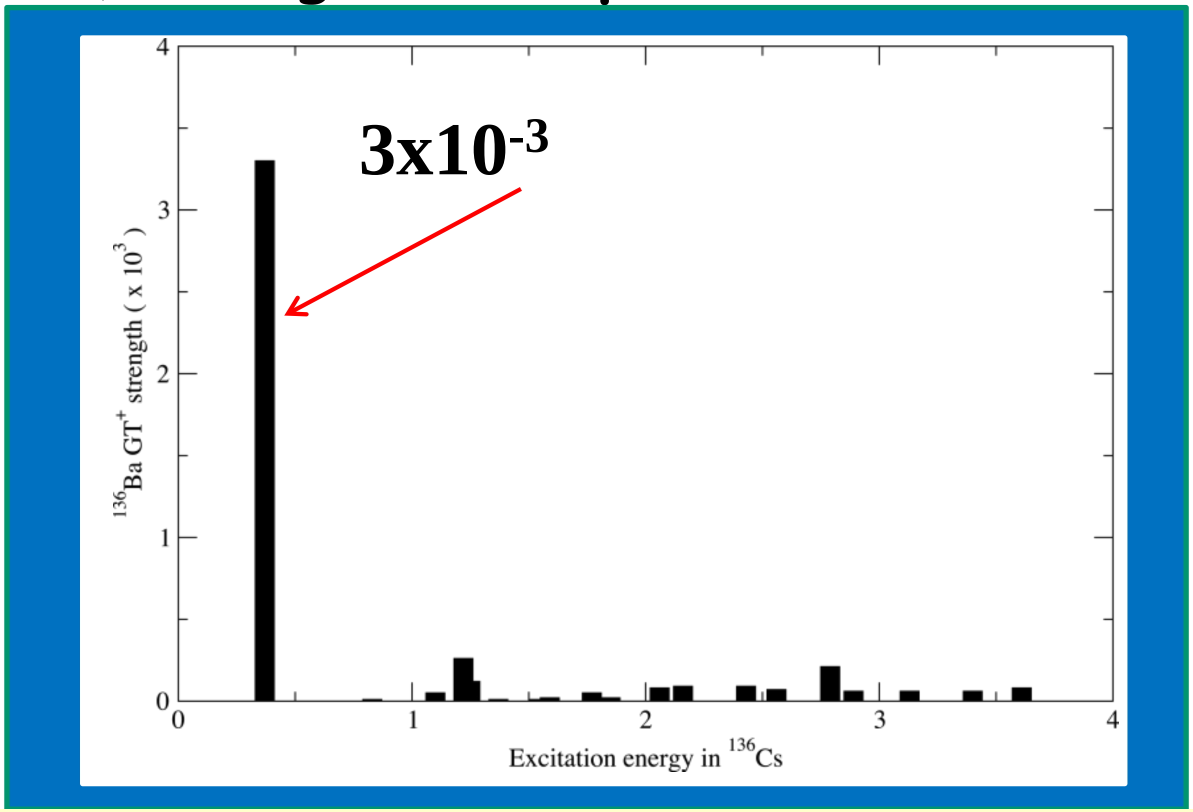
all signs positive —>

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

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

A. Poves (simultaneous to our publication):

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



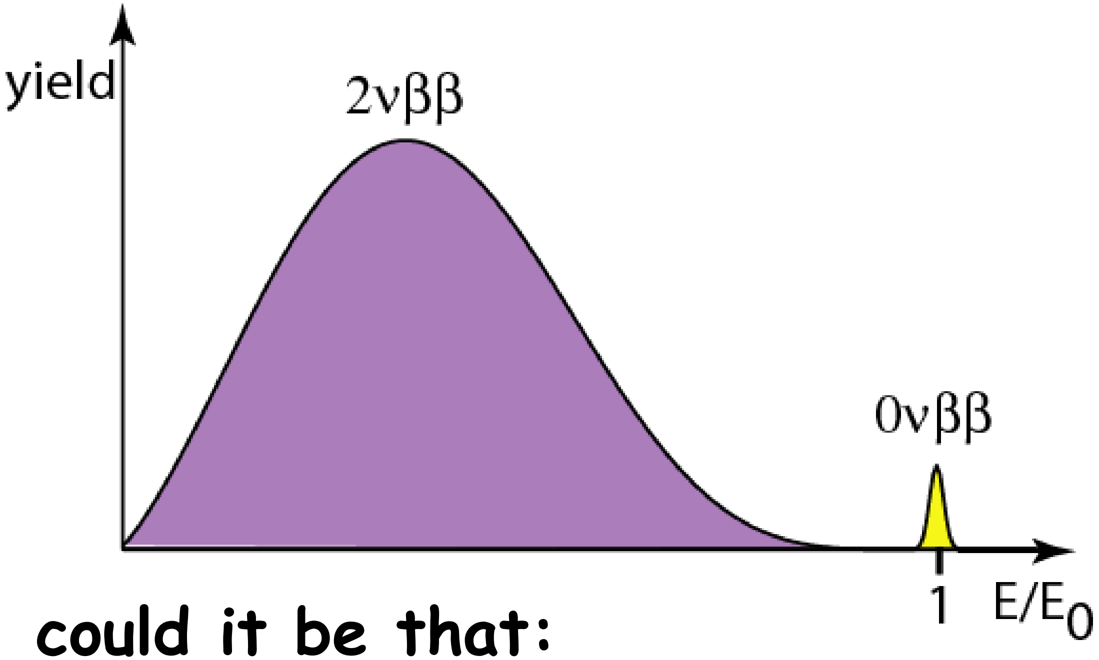
Recall:
^{136}Xe is almost doubly magic!!

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

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

expmt: 2νββ NME is exceptionally small

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

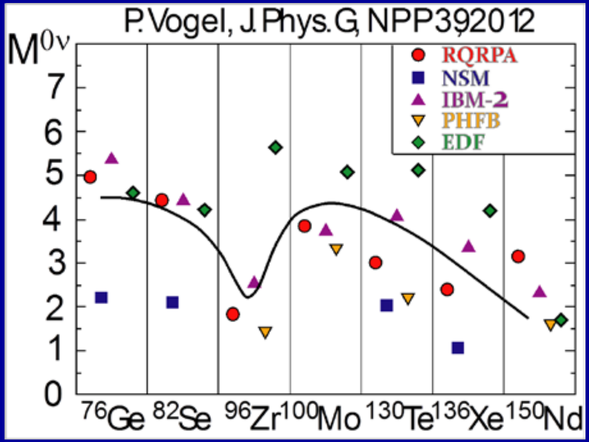


could it be that:

2νββ ME is suppressed AND

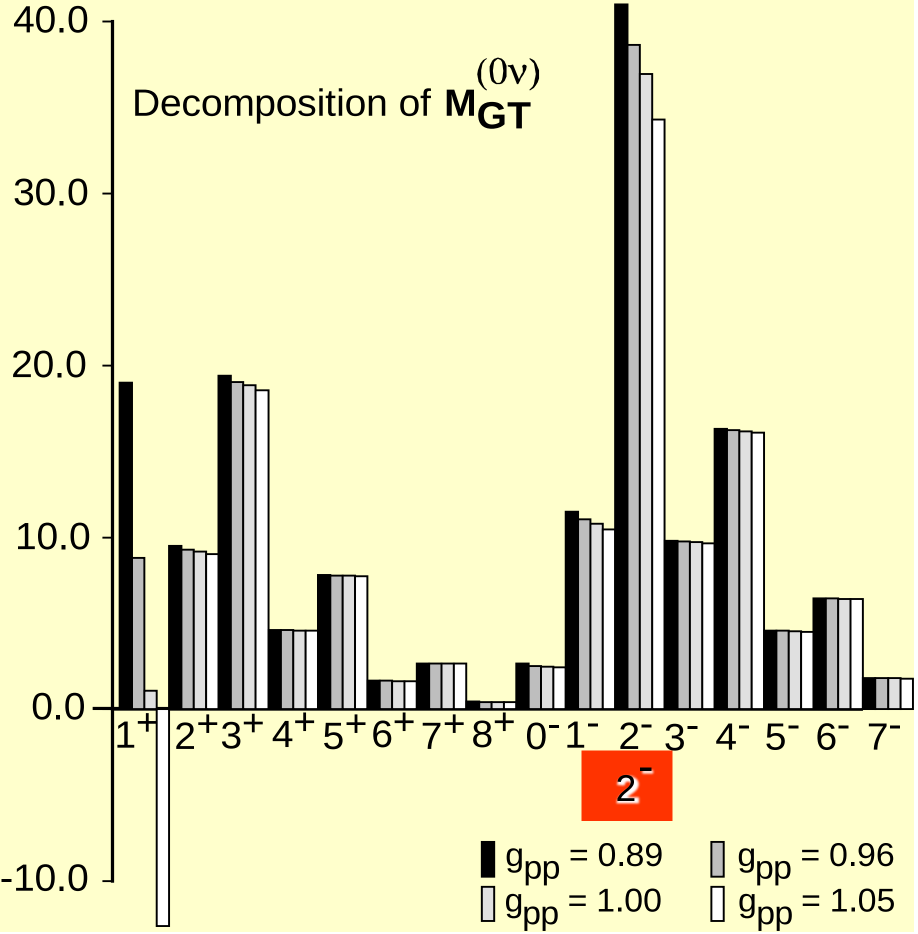
0νββ ME is enhanced ???

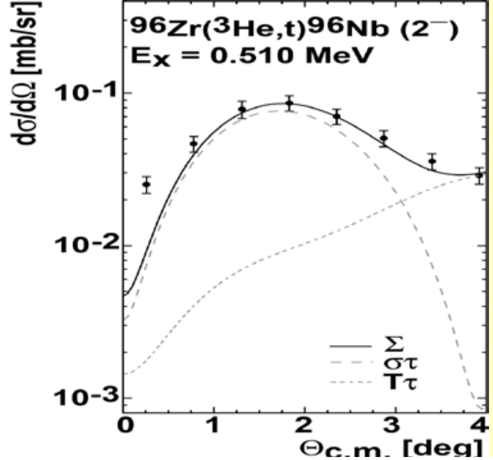
Experiments towards the $0\nu\beta\beta$ NMEs

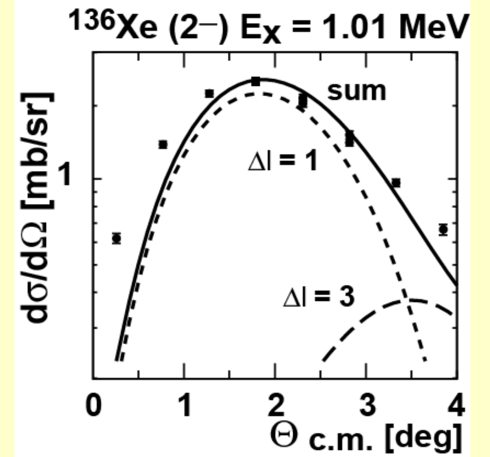


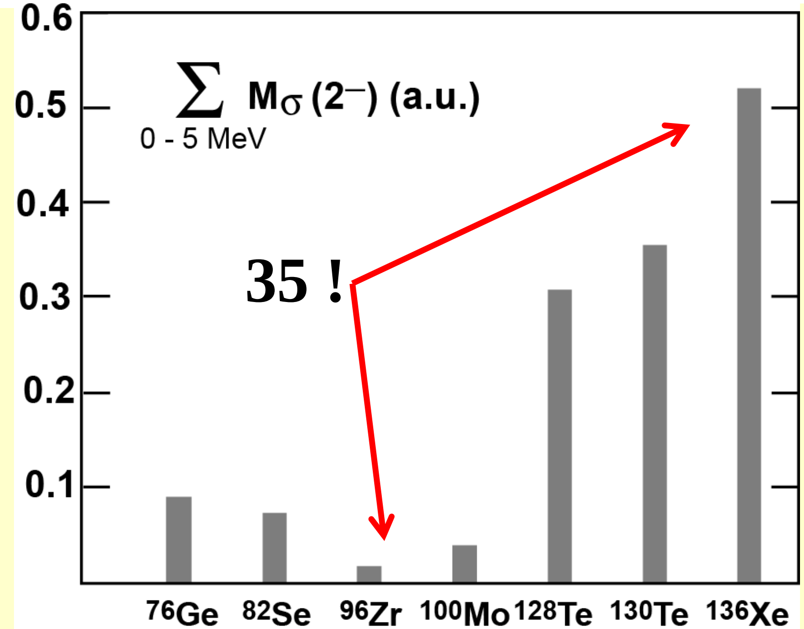
Here:

2^- states and occupation vacancy numbers via chargex reactions









relative 2^- strength to ~ 5 MeV

Theory:

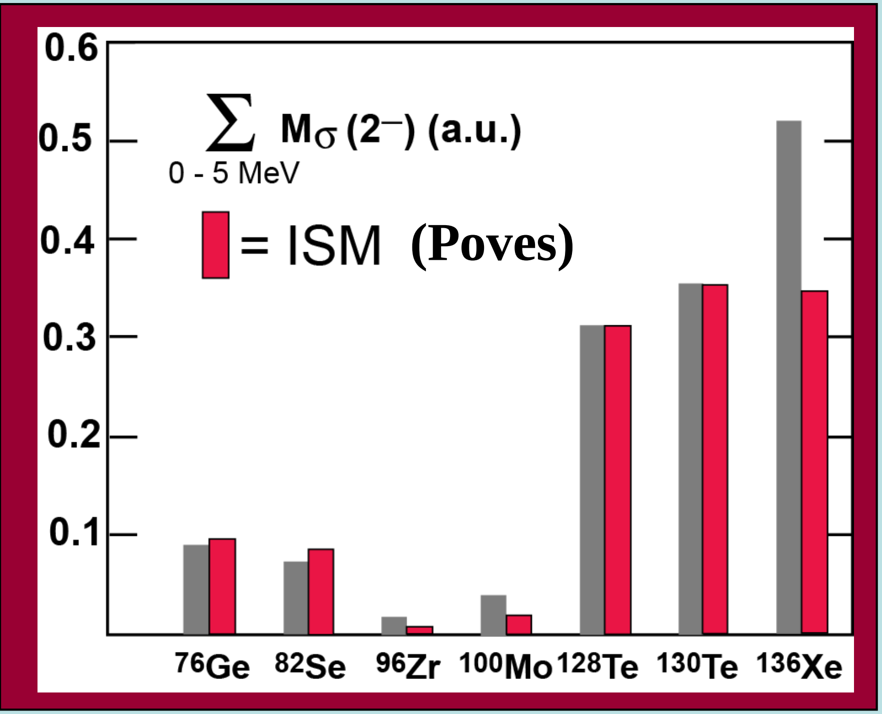
The 2^- strength makes up ~ 20-30% of the 0νββ ME!!

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

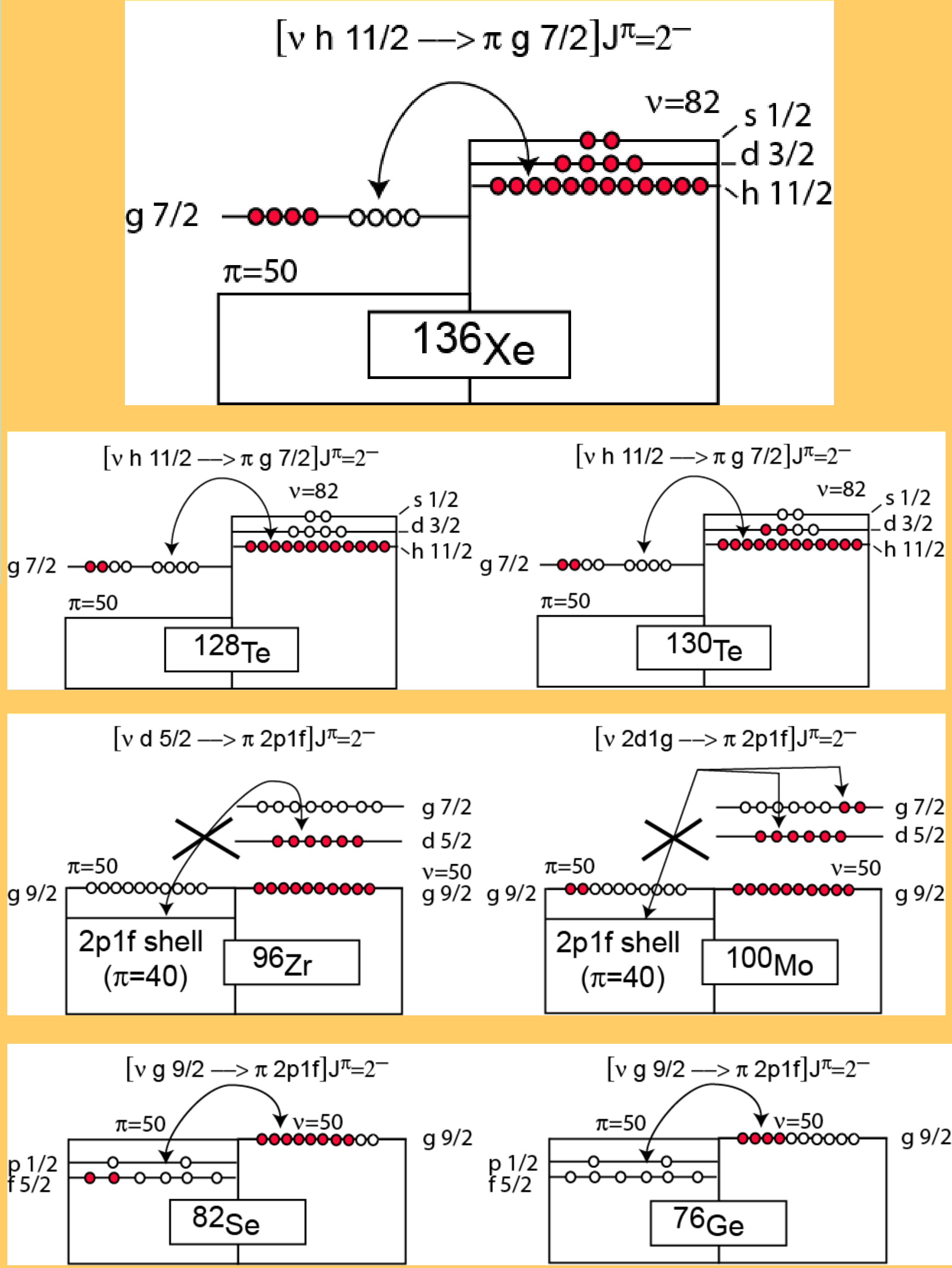
Expmt:

^{136}Xe exhibits largest 2^- strength

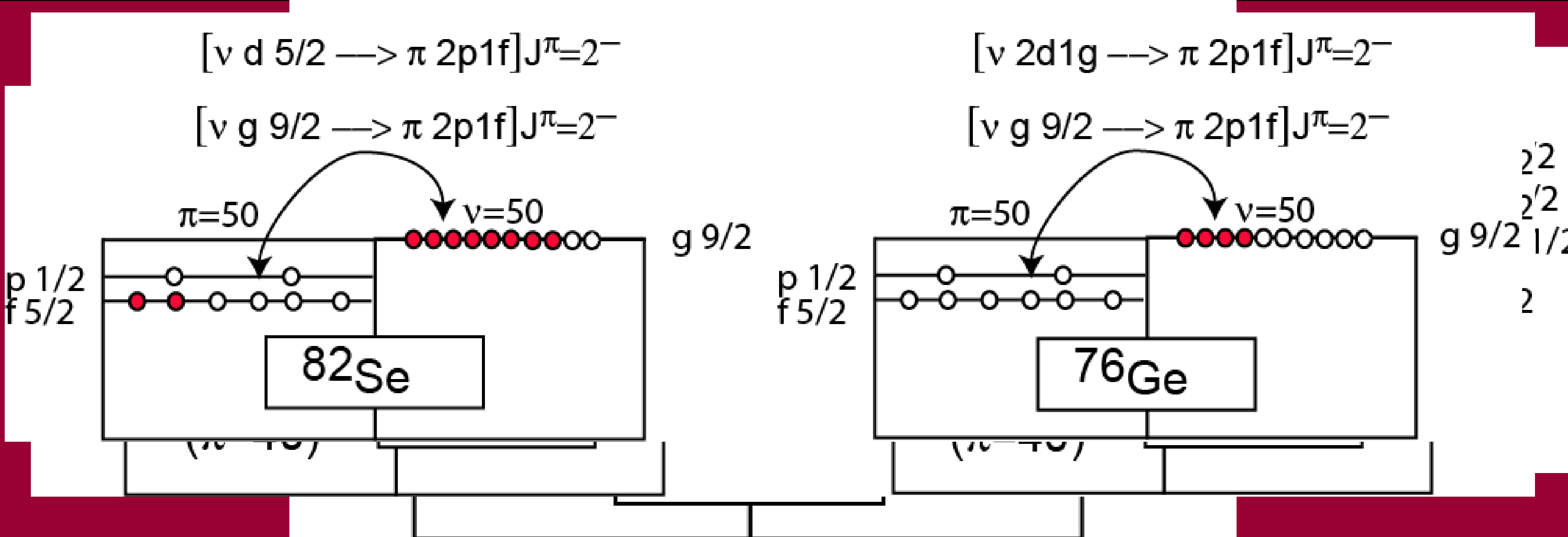
0νββ ME enhanced?!?!

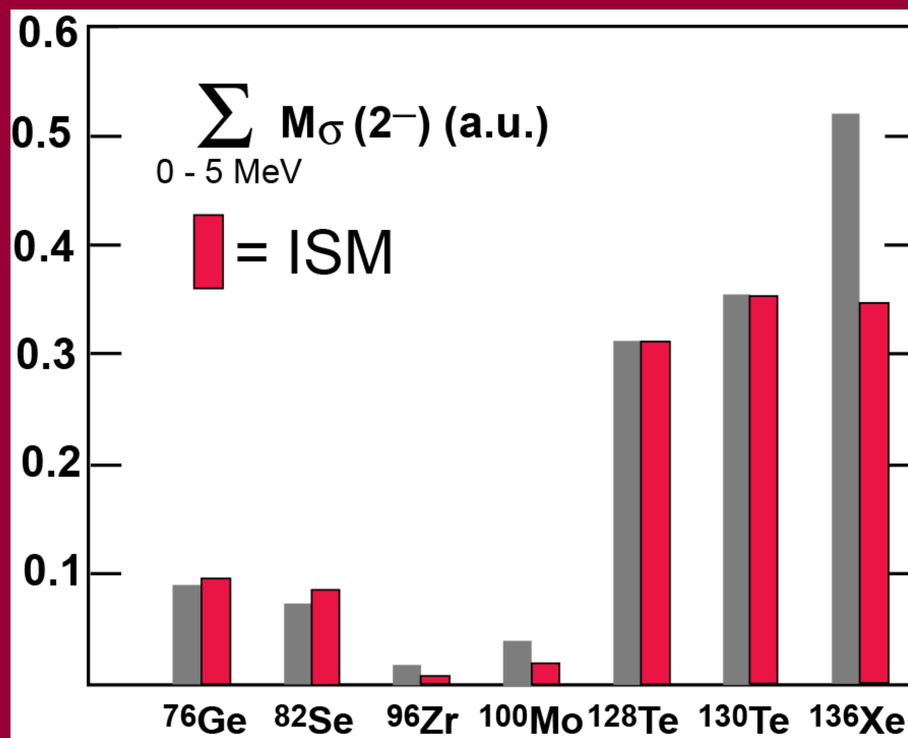


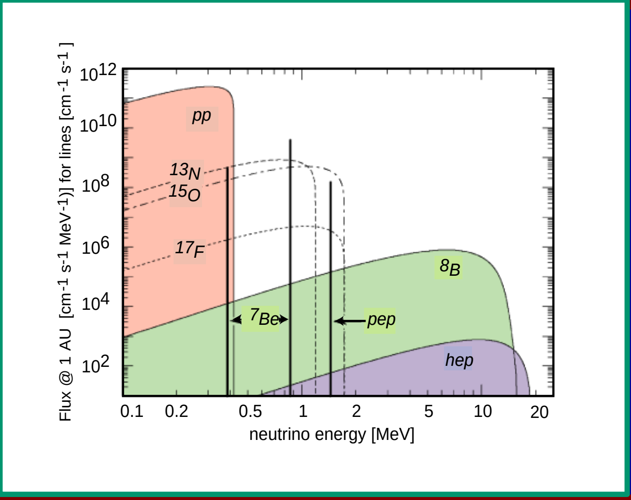
$\sum_{0-5\,MeV} M_\sigma(2^-)$ (a.u.)
= ISM (Poves)
0.6
0.5
0.4
0.3
0.2
0.1
76Ge
82Se
96Zr
100Mo
128Te
130Te
136Xe



[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−
128Te
[ν h 11/2 —> π g 7/2]Jπ=2−
130Te
[ν d 5/2 —> π 2p1f]Jπ=2−
g 7/2
d 5/2
ν=50
g 9/2
π=50
2p1f shell
(π=40)
96Zr
[ν 2d1g —> π 2p1f]Jπ=2−
100Mo
[ν g 9/2 —> π 2p1f]Jπ=2−
p 1/2
f 5/2
82Se
[ν g 9/2 —> π 2p1f]Jπ=2−
76Ge


[ν d 5/2 —> π 2p1f]J$^{\pi}$=2^{-}
[ν g 9/2 —> π 2p1f]J$^{\pi}$=2^{-}
π=50
ν=50
g 9/2
p 1/2
f 5/2
82Se
[ν 2d1g —> π 2p1f]J$^{\pi}$=2^{-}
[ν g 9/2 —> π 2p1f]J$^{\pi}$=2^{-}
π=50
ν=50
g 9/2
p 1/2
f 5/2
76Ge

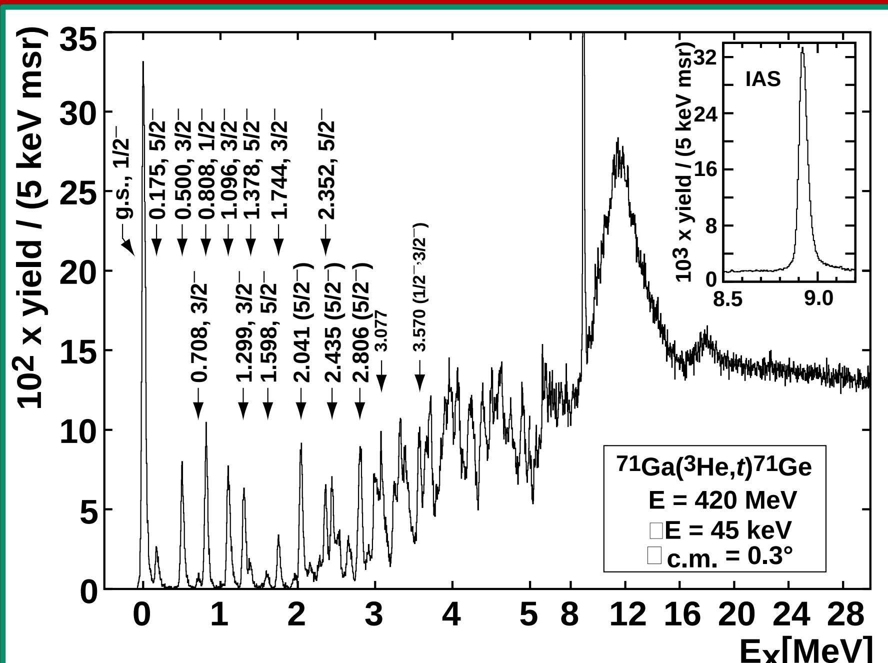

$\sum_{0 - 5 MeV}$ Mσ (2^{-}) (a.u.)
= ISM
0.6
0.5
0.4
0.3
0.2
0.1
76Ge
82Se
96Zr
100Mo
128Te
130Te
136Xe

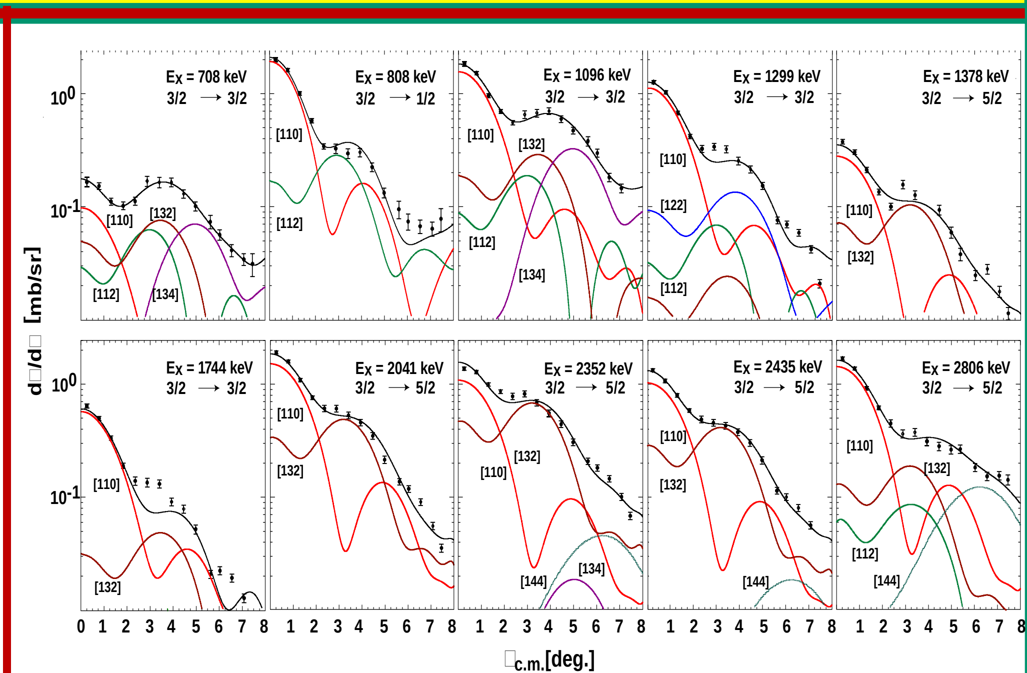


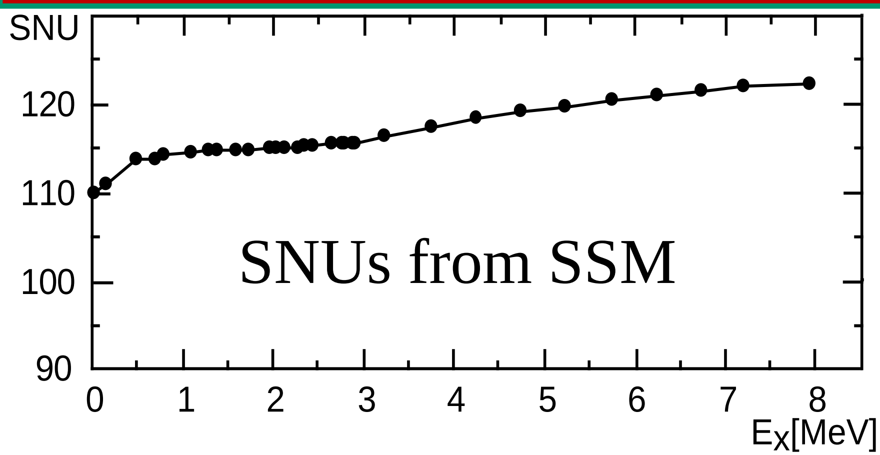
solar neutrino rates via (^{3}He,t)

$^{71}Ga(\nu_{\odot},e^{-})$ SNUs from $^{71}Ga(^{3}He,t)^{71}Ge$ charge-ex reaction

$^{71}Ga(\nu_{\odot},e^{-})$ SNUs from (^{3}He,t) charge-exchange reaction







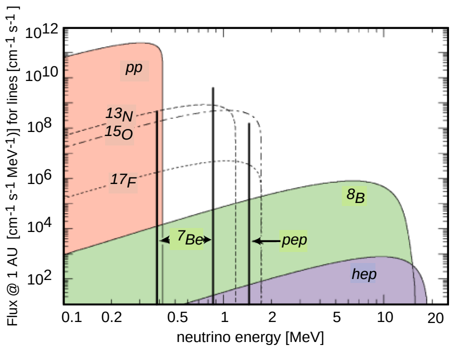
$^{71}Ga(\nu_{\odot},e^{-})$

$$R = 122.4 \pm 3.4(\text{stat}) \pm 1.1(\text{sys})$$

stat. err. mostly due to CNO ν's

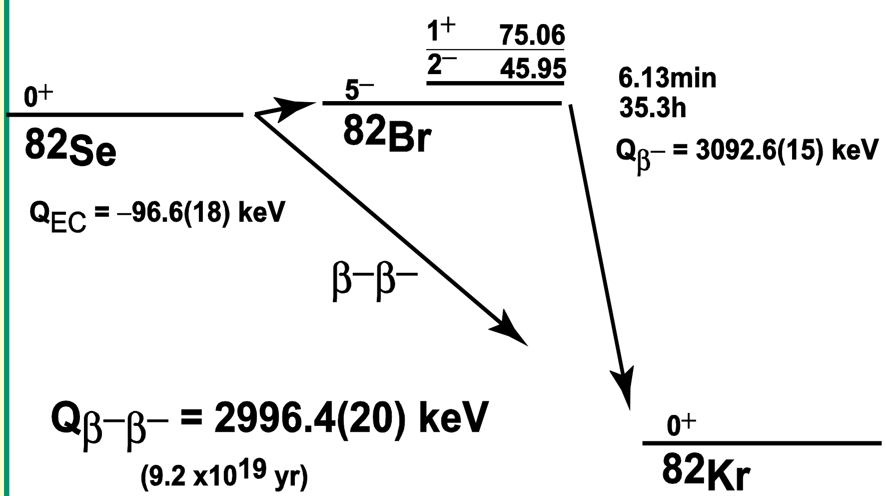
prev'ly: 132 ± 18

DF et al, PRC91,2015



solar neutrino rates via (^{3}He,t)

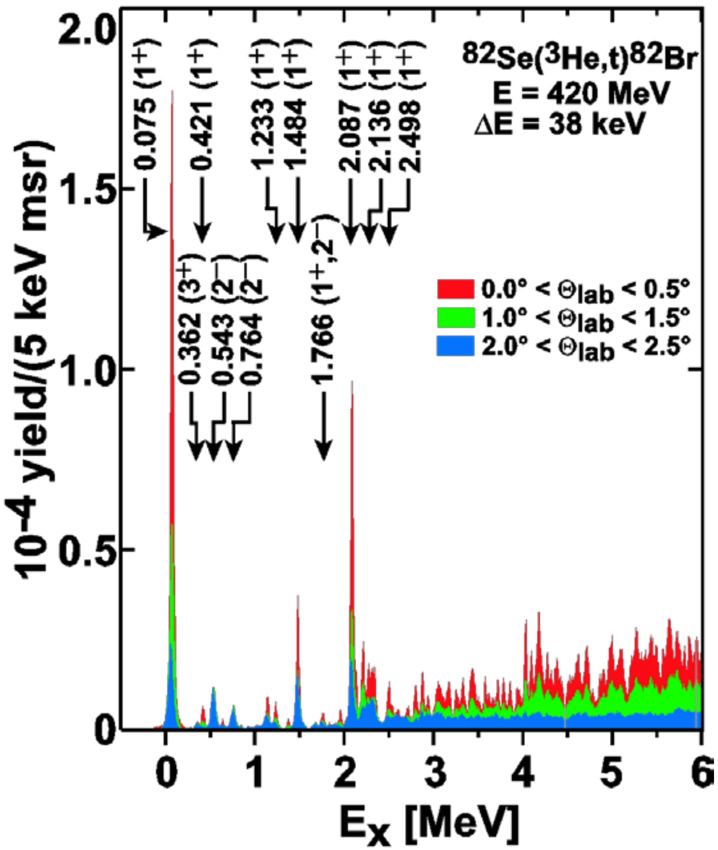
^{82}Se($\nu_\odot$,e$^-$) SNUs from ^{82}Se(^{3}He,t)^{82}Br charge-ex reaction

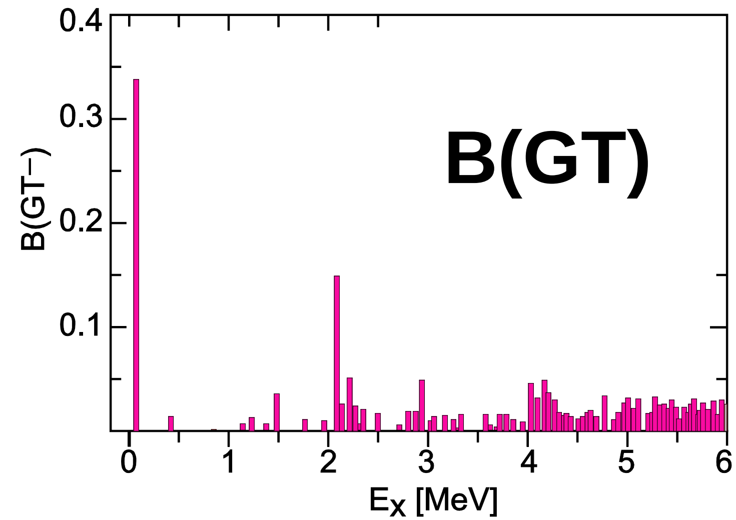


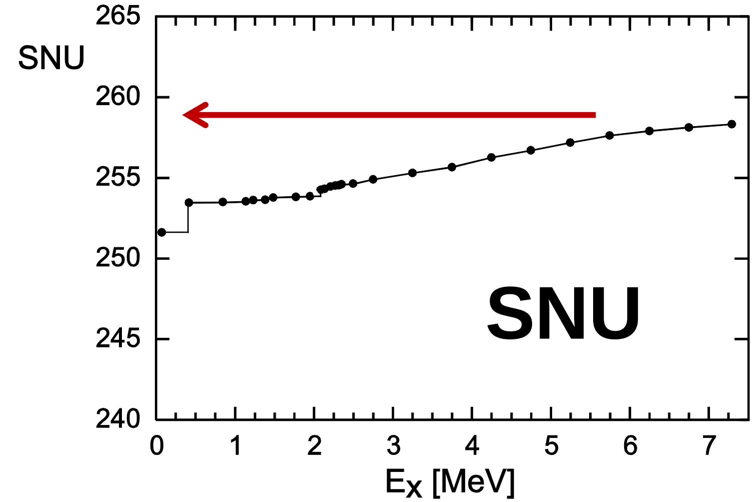
Advantages:

- low threshold
- enhanced sensitivity to pp-neutrinos
- short life-time against β-decay (35h)
- pp-ν's in „real time“
- γ-emission, easy to detect

$^{82}Se(^3He,t)$ spectrum







Total rate:	258 SNU
Population of 1st 1+ state:	97%
pp ν fraction:	76%

preliminary

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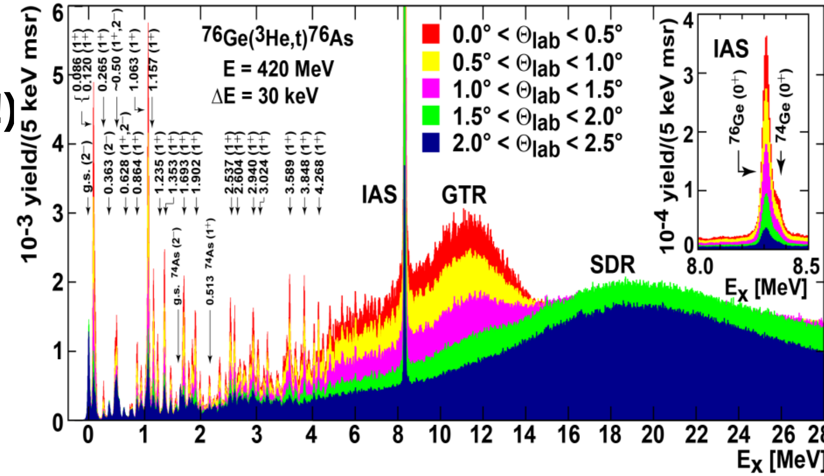
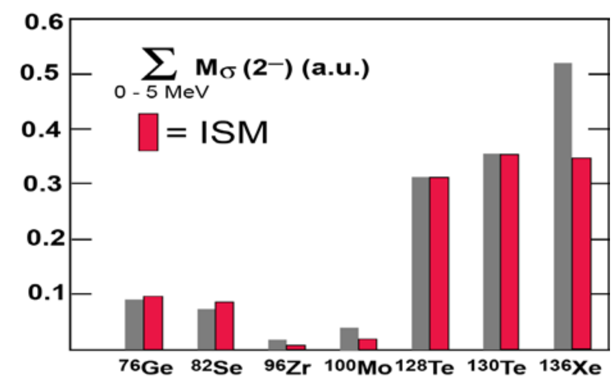
Future perspectives of chargex-reactions

- **ββ-decay and nuclear matrix elements**
  - **Resolution is key issue (RCNP gives the lead!)**
  - **need 20 - 30 keV for <u>(^{3}He,t) & (d,^{2}He)</u>**
  - **Need to explore proportionality between chargex x-section and $\Delta L \neq 0$ transitions (e.g. 2^- states) in weak interaction (resol'n is key)**



- **ν-physics and chargex-reactions**
  - **Hadronic chargex and weak-interaction x-sections are fortuitously connected -- exploit this!!**
  - **solar neutrinos, SN-neutrinos, element synthesis**



- **Need to address quenching issue <u>urgently!!</u>**
  - **Chargex in inverse kinematics plays a pivotal role (BUT need resolution)**

- **EOS and chargex-reaction**
  - **IAS and GT resonance data needed and useful BUT: theories need to converge on their relevance**

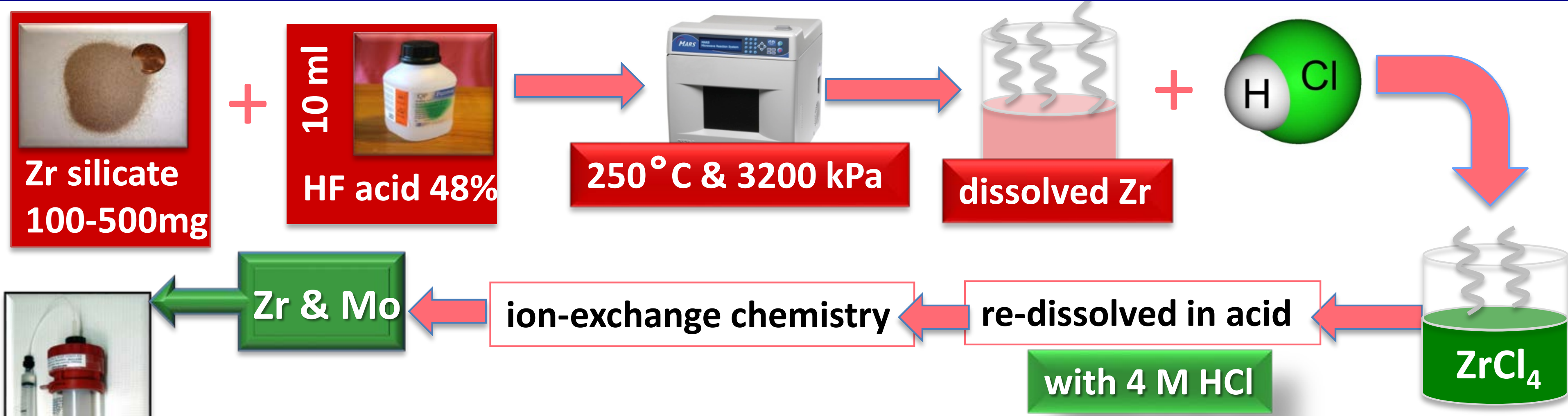
^{71}Ga($\nu_{\odot}$,e$^-$)

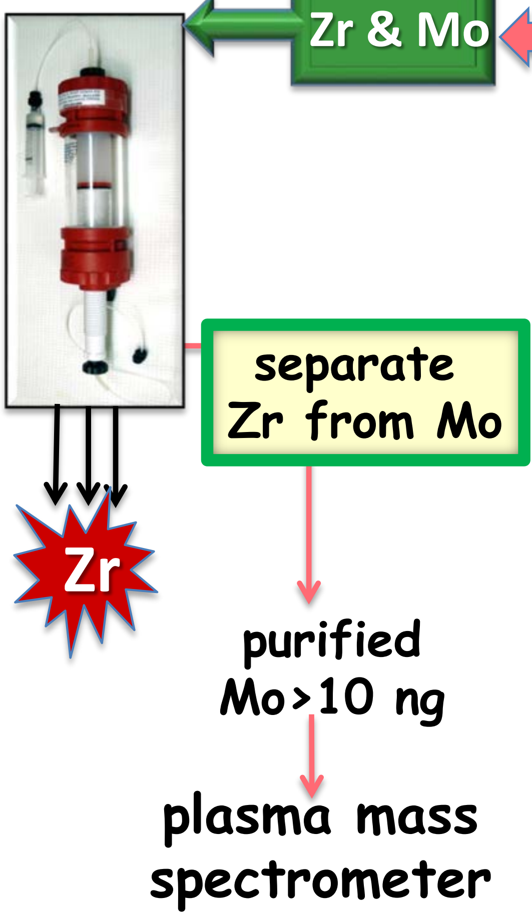
$R = 122.4 \pm 3.4 \pm 1.1$ SNU

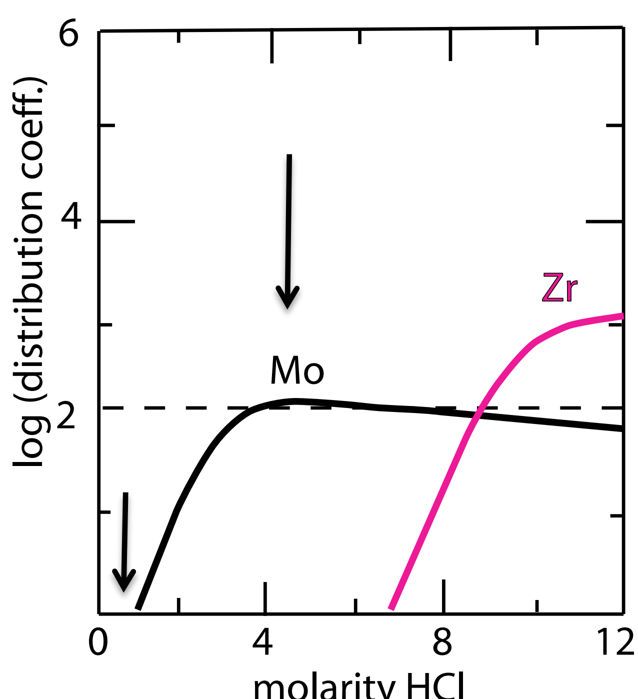
^{82}Se($\nu_{\odot}$,e$^-$)

$R = 258.4$ SNU

Isobar separation method (U of Calgary)







$(\Delta^{96}Mo/^{95}Mo)=0.01\%$

measurable limit
$T^{\beta}_{1/2} \lesssim 15 \times 10^{19}$ y