WESTFÄLISCHE
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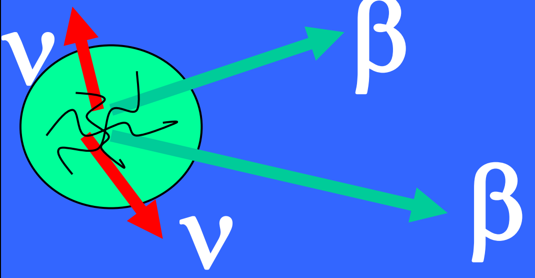
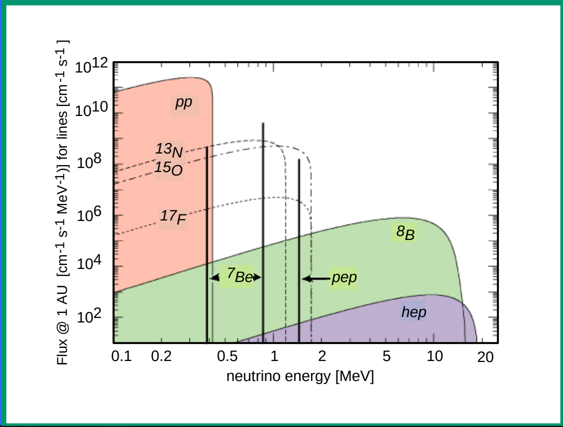
MÜNSTER

D. Frekers

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





HST15

INTERNATIONAL SYMPOSIUM ON
HIGH-RESOLUTION SPECTROSCOPY & TENSOR INTERACTIONS

Outline

- **Chargex-reactions (^{3}He,t) & (d,^{2}He)**
  - highlights & features of $2\nu\beta\beta$ nuclear matrix elements (NME)

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

    fragmentation – smallest/largest NME

university of groningen

- **the $0\nu\beta\beta$ decay nuclear matrix elements**

  1st forbidden NME's and 2^{-} states

- **solar ν SNU rates and (^{3}He,t) reaction**

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

- **the A=96 system**

  the ^{96}Zr ($\beta-$) → ^{96}Nb Q-value

  and a direct test of $0\nu\beta\beta$ NME

JYVÄSKYLÄN YLIOPISTO
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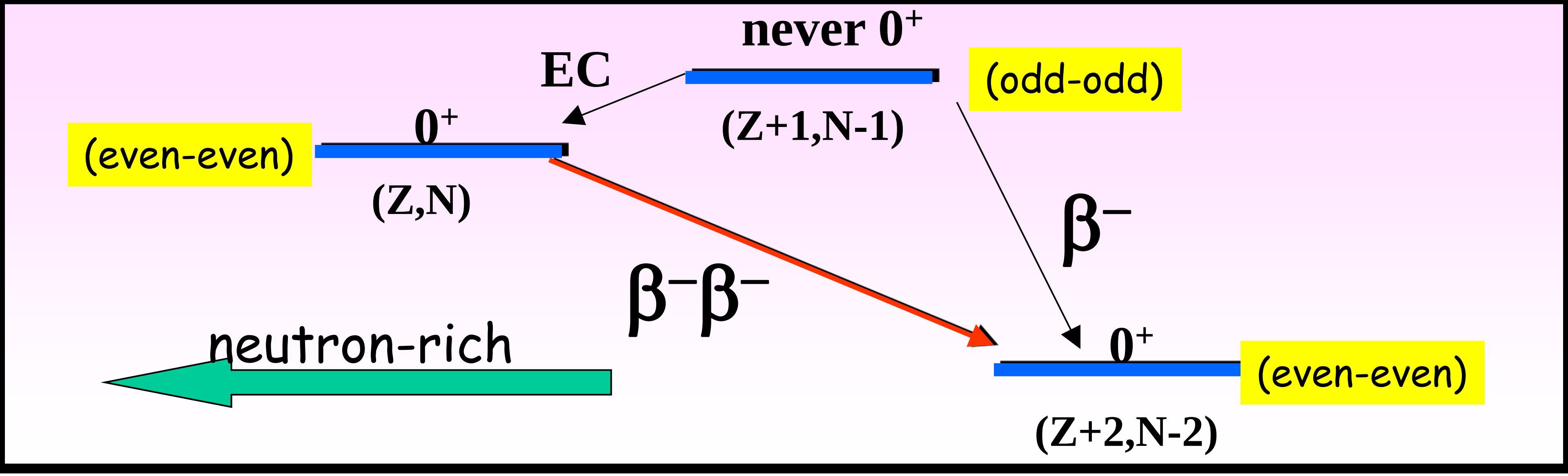
$\beta^-\beta^-$ decay



never 0^+

EC

(odd-odd)

0^+

(even-even)

(Z+1,N-1)

(Z,N)

β^-

$\beta^-\beta^-$

neutron-rich

0^+

(even-even)

(Z+2,N-2)

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

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

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

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

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

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

recall: neutrino mass problem

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

$\boldsymbol{U = V \cdot \mathrm{diag}(e^{-i\Phi_1}, e^{-i\Phi_2}, 1)}$ ⟵ **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:

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

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

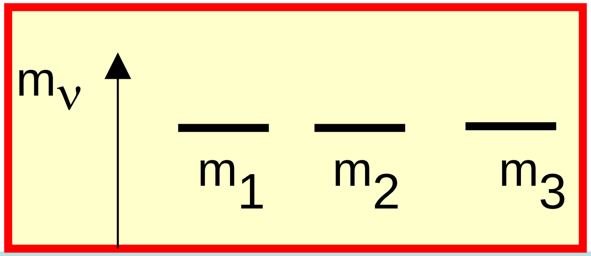
$$\Theta_{13} = 0.11$$

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

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

neutrino-mass-scenarios:

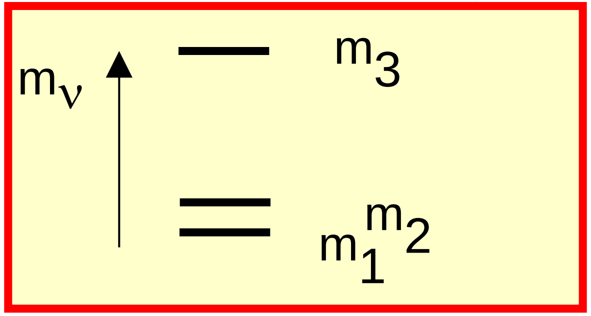
1) degenerate:



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

the best of all cases

2) normal hierarchy:

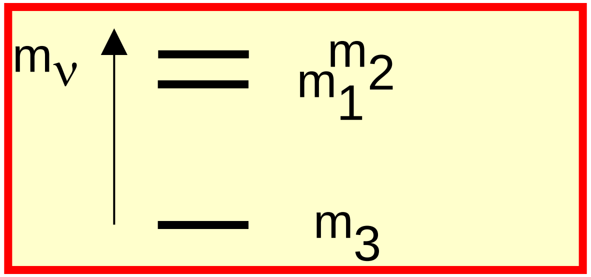


$$\left|m_{\nu_e}\right|^2 \propto \Delta m^2_{sol} \times \left|\frac{3m_1}{\Delta m_{sol}} + e^{-2i(\Phi_2-\Phi_1)} + (<0.5)e^{-2i(\delta-\Phi_1)}\right|^2$$

= ZERO!! for:

$$\Theta_{13} \sim 9° \quad (\Phi_2-\Phi_1) = \frac{\pi}{2} \quad \frac{3m_1}{\Delta m_{sol}} = 1$$

3) inverted hierarchy:



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

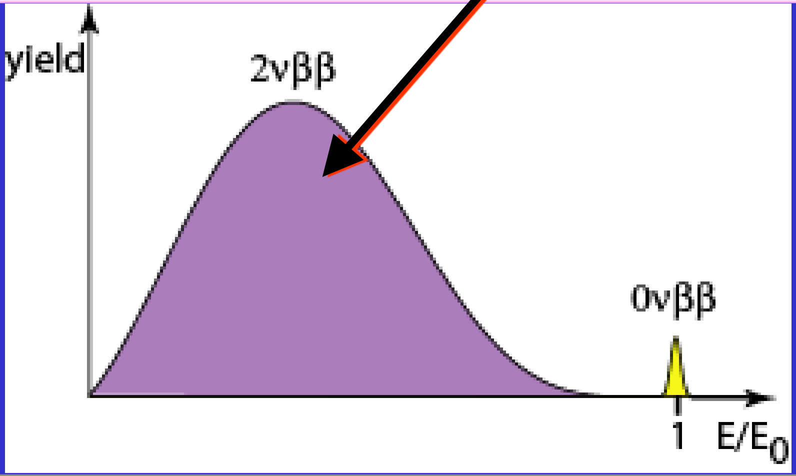
if inverted hierarchy could be established
(LHC, SN-ν, precision-oscillation)
THEN: $\left|m_{\nu_e}\right| \approx \Delta m_{atm}$

or neutrino is a Dirac-particle

NME important

Nucl.MatrixElements

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

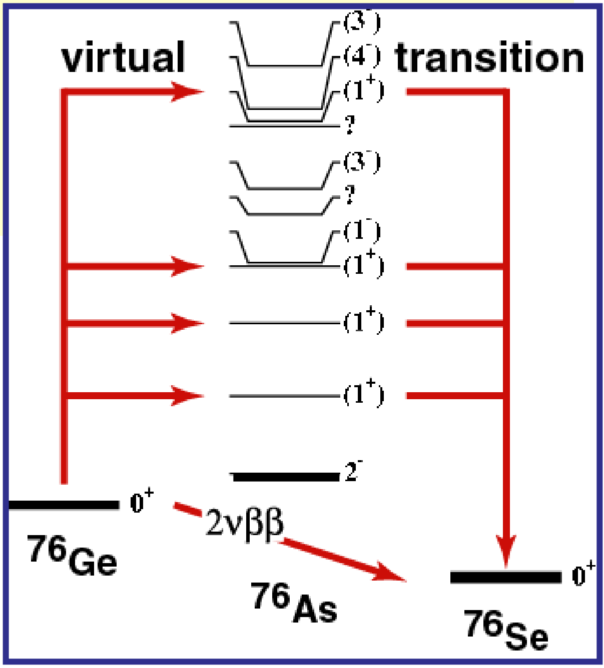


q-transfer like in ordinary
β-decay
(q ~ 0.01 fm^{-1} ~ 2 MeV/c)
i.e. only allowed transitions possible

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

$$= \underbrace{G^{2\nu}(Q,Z)}_{\propto Q^{11}\cdot Z^2}\ \underbrace{\left|M^{(2\nu)}_{\mathrm{DGT}}\right|^2}_{\exp \approx 10^{-3}\ \mathrm{MeV}^{-2}}$$

extracted from half-life

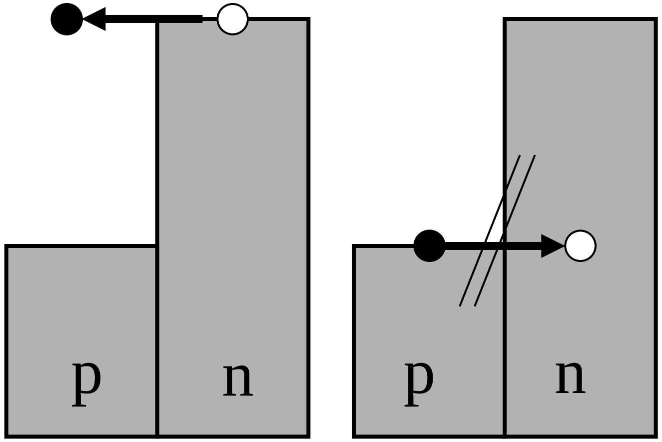


favorable:

1. high Q-value
2. large Z

unfavorable (but cannot be changed):

1. large neutron excess
   (Pauli-blocking)



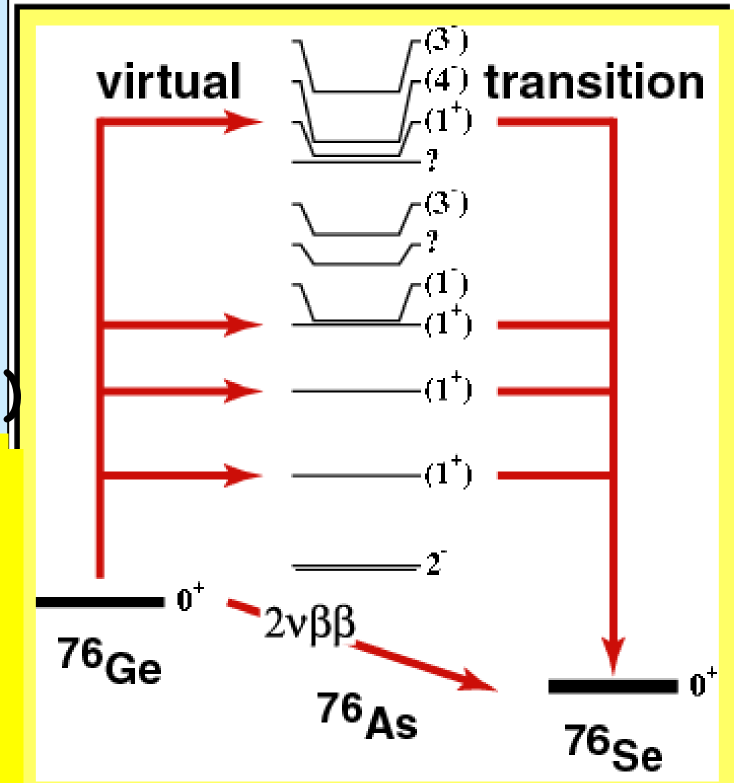
$$M^{(2\nu)}_{\mathrm{DGT}} = \sum_m \frac{\left\langle 0^{(f)}_{g.s.} \middle| \sum_k \sigma_k \tau_k^- \middle| 1_m^+ \right\rangle \left\langle 1_m^+ \middle| \sum_k \sigma_k \tau_k^- \middle| 0^{(i)}_{g.s.} \right\rangle}{\tfrac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1_m^+) - E_0}$$

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

to remember:

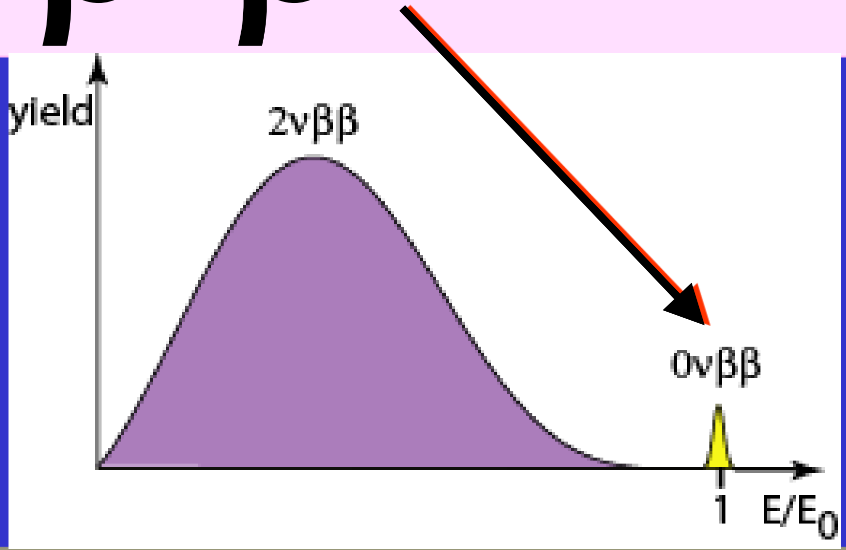
1. 2 sequential & „allowed“ β^--decays of „Gamow-Teller“ type
2. „1, 2, 3, ... forbidden“ decays negligible
3. Fermi–transitions do no contribute (because of different isospin-multiplets)

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. Matrix Elements

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

$$\Gamma^{0\nu}_{(\beta^-\beta^-)} = \underbrace{G^{0\nu}(Q,Z)\, \overset{!!}{g_A^4}}_{\propto Q^5 \cdot Z^4} \underbrace{\left| M^{(0\nu)}_{\mathrm{DGT}} - \left(\frac{g_V}{g_A}\right)^2 M^{(0\nu)}_{\mathrm{DF}}\right|^2}_{\overset{\text{theory}}{\approx}\; 10\;!!} \left|m_{\nu_e}\right|^2$$

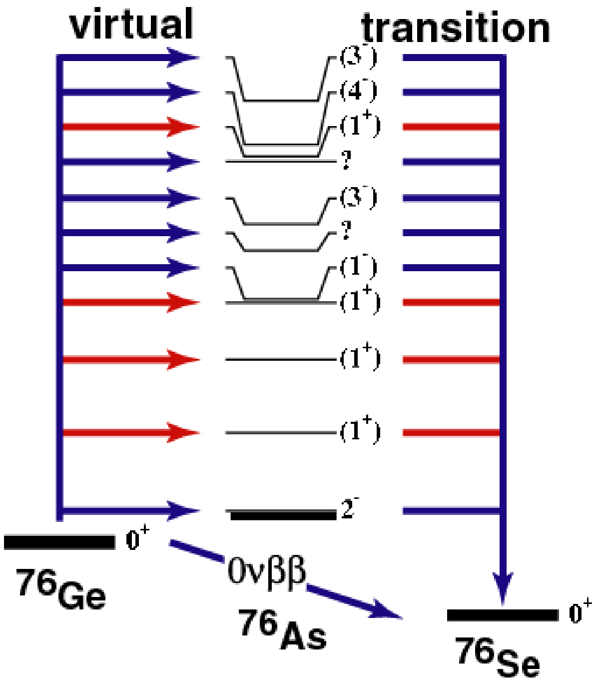
largely independent of (A,Z)
(except near magic nuclei)

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

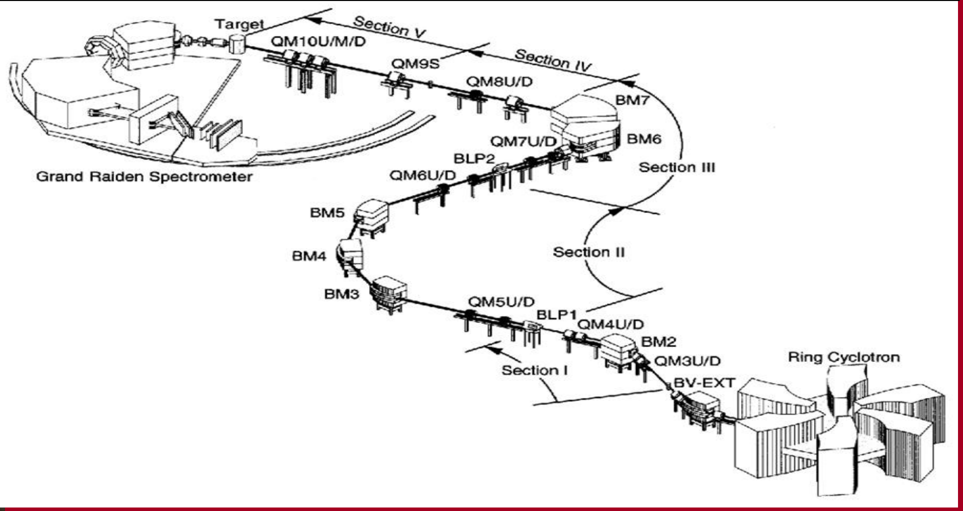
NOT (easily) accessible via charge-exchange reactions

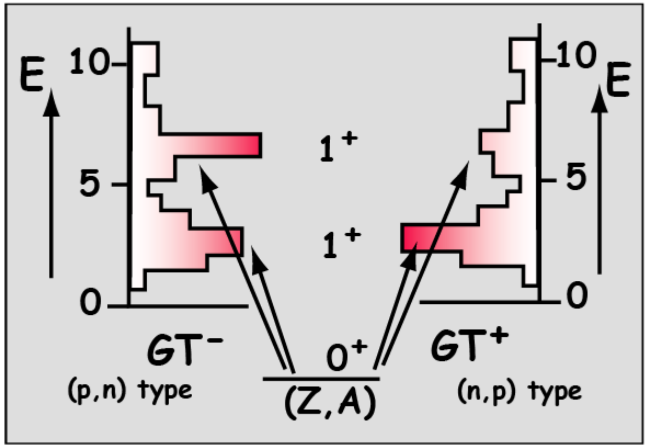


Charge-exchange reactions

Grand Raiden
Magnetic Spectrometer

$\Delta E/E \sim 5\times10^{-5}$ ~ 25 keV
at 420 MeV (^{3}He)





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)

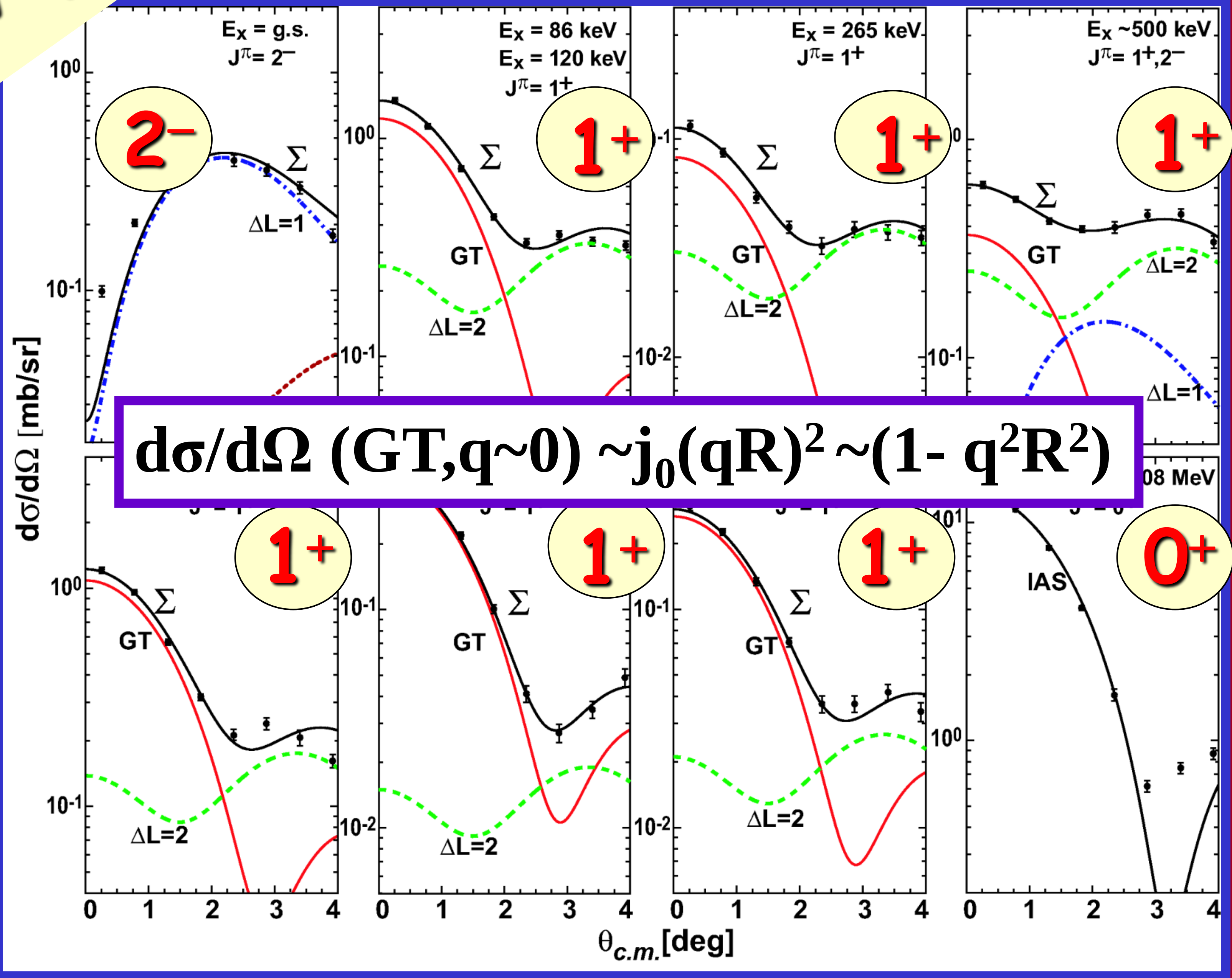
or (p,n), (^{3}He,t)

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{\mu}{\pi\hbar}\right]^2 \frac{k_f}{k_i} N_d \, \underbrace{|V_{\sigma\tau}|^2}_{\text{largest at 100 - 200 MeV/A}} \, |\langle f \,|\, \sigma\tau \,|\, i \rangle|^2$$

$$q = 0!!$$

^{76}Ge-^{76}As

examples

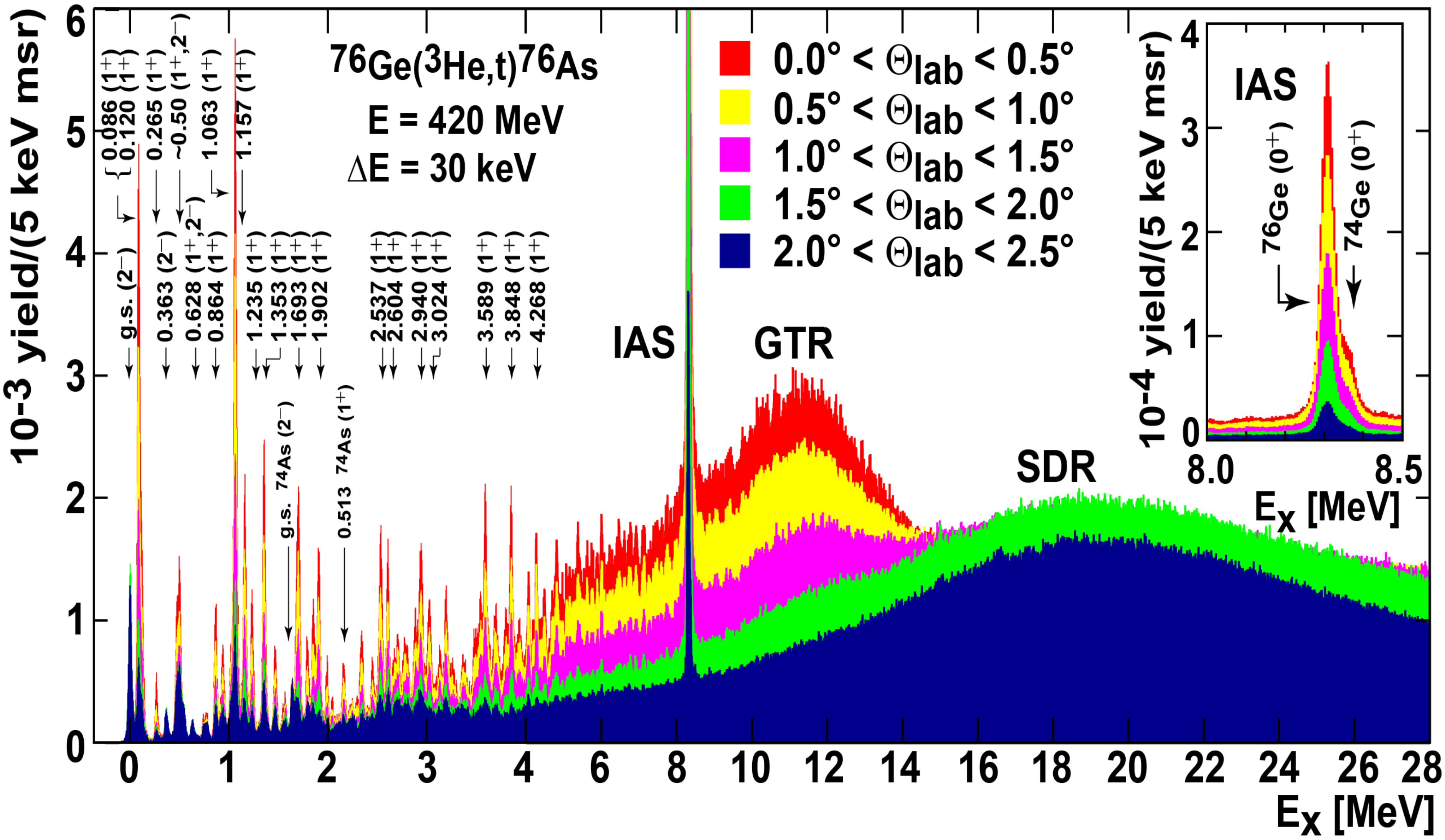


$$d\sigma/d\Omega\ (\mathrm{GT}, q\sim 0) \sim j_0(qR)^2 \sim (1 - q^2R^2)$$

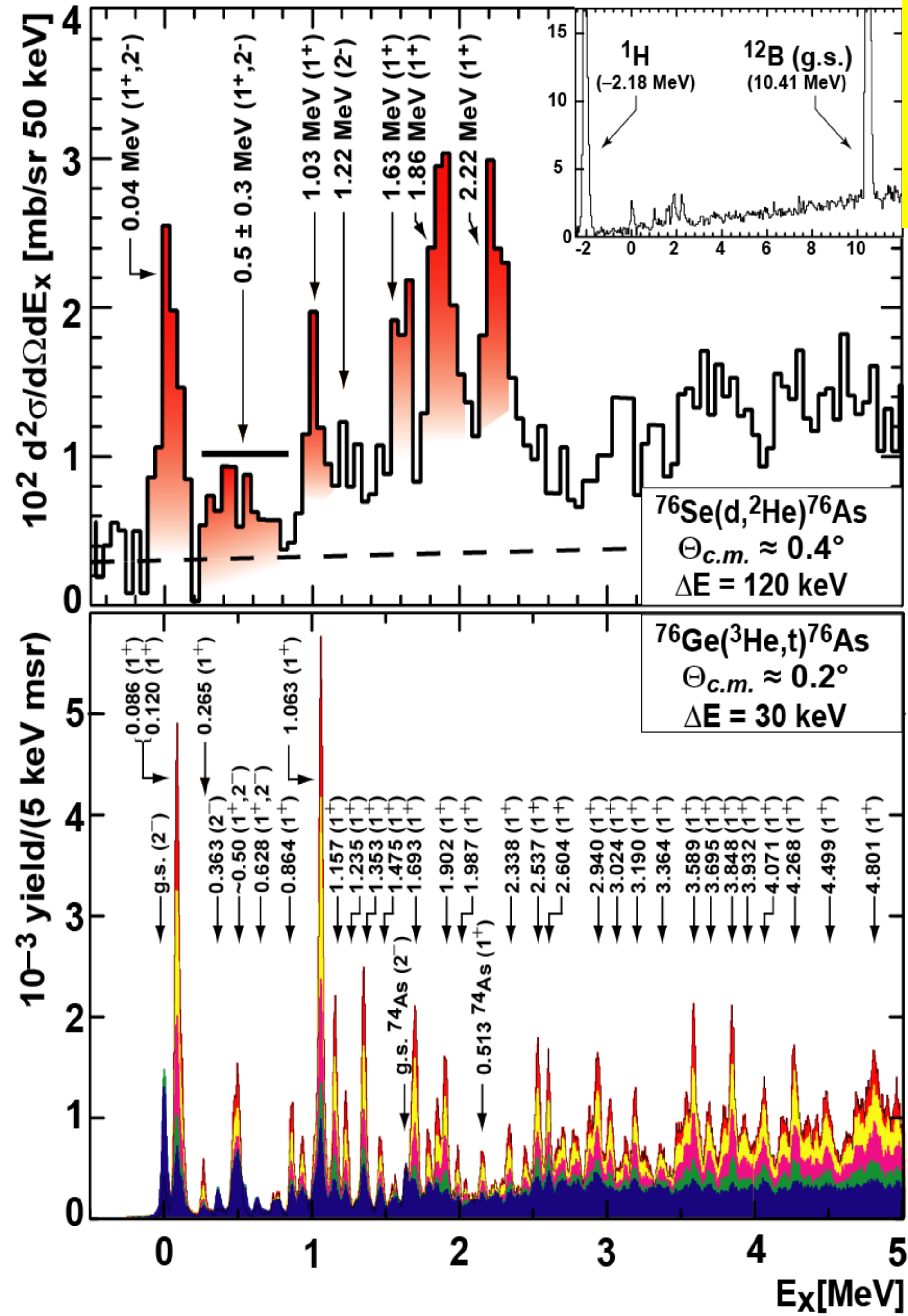
^{76}Ge

N-Z=10

Resolution is the key !!!

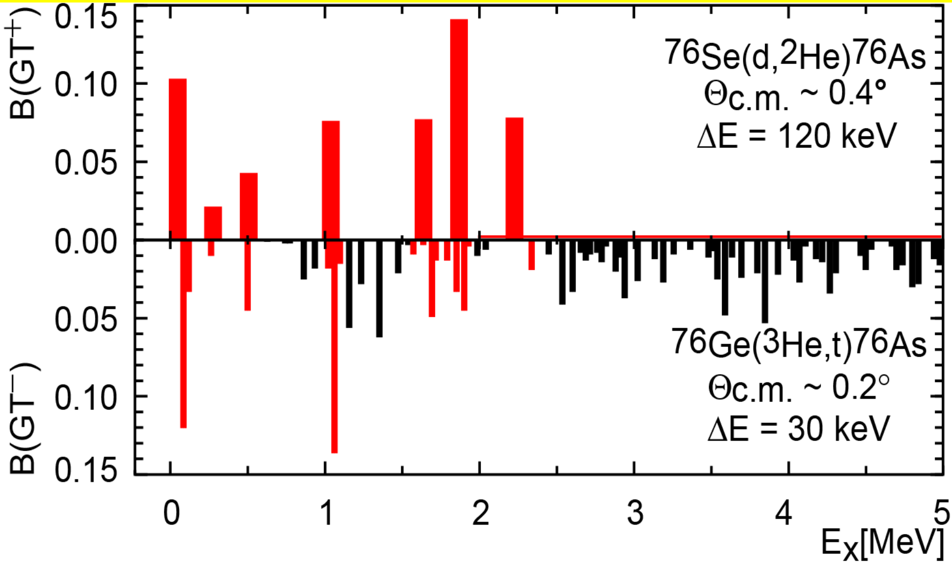


almost 70 !! resolved single states up to 5 MeV identified as GT 1+ transitions !!!



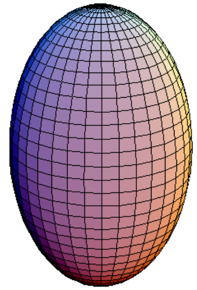
~ 70 !! single states up to 5 MeV !!!

???? anti-correlation ????

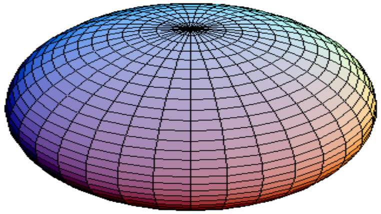


is the anti-correlation a property of deformation ??

^{76}Ge

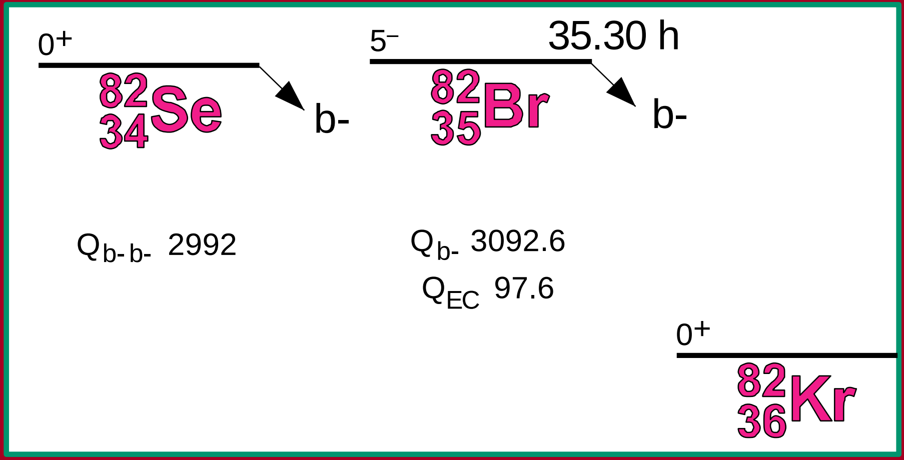


^{76}Se



$^{82}\mathrm{Se}$

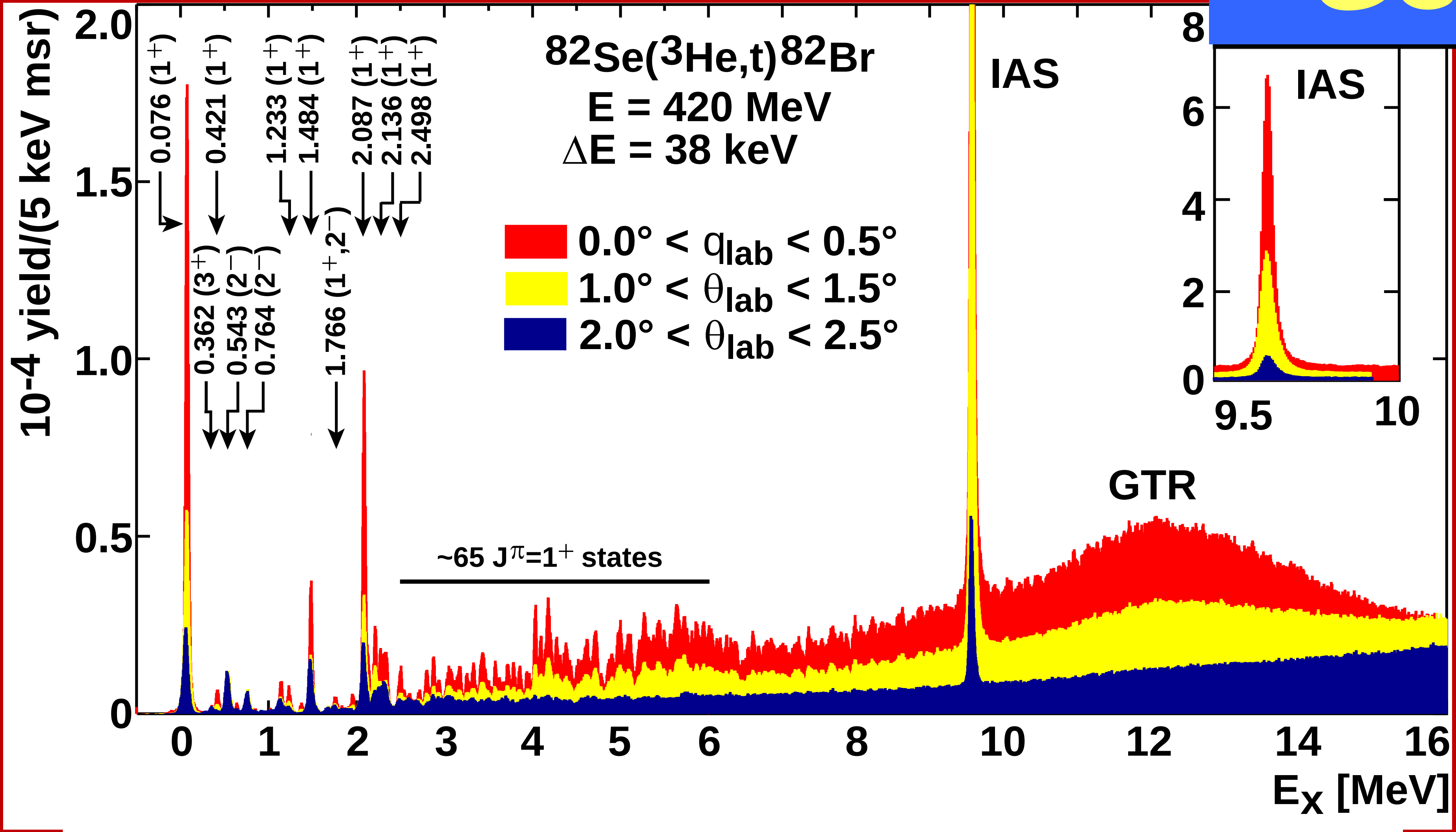
$N-Z=14$



Resolution is the key !!!

possibly useful for solar neutrino detection

^{82}Se



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

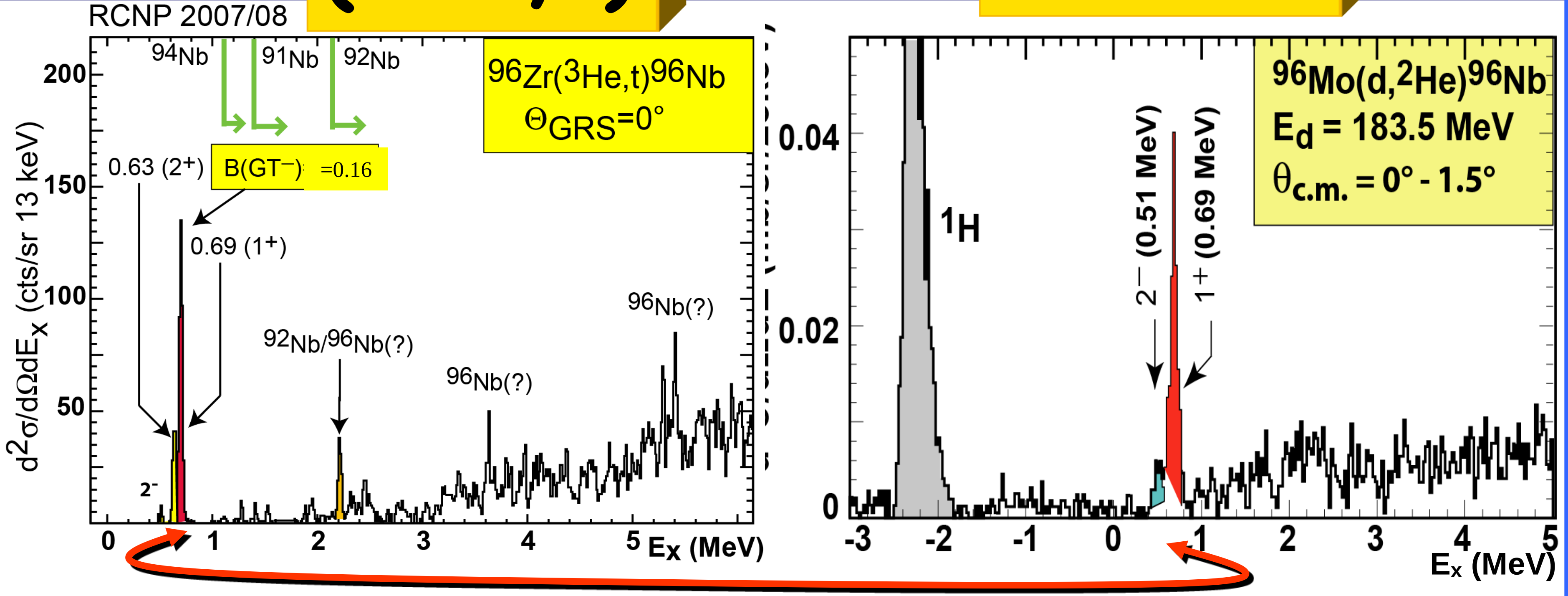
^{96}Zr

N-Z=16

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

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

$(^3He,t)$ $(d,^2He)$



$B(GT^-) = 0.16$

$B(GT^+) = 0.3$

Fascination: With only 1 state:

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

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

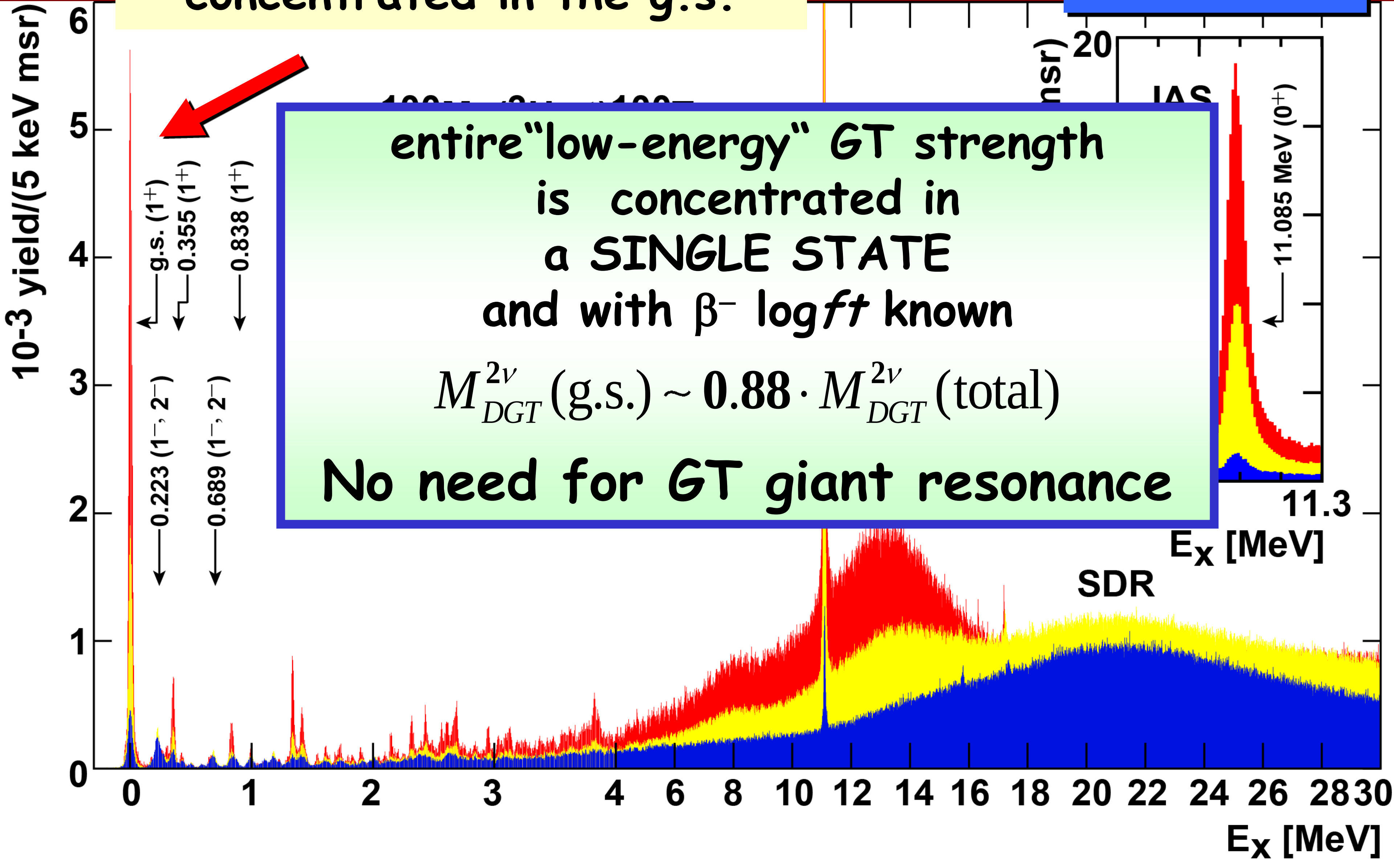
^{100}Mo

$N-Z=16$

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

^{100}Mo

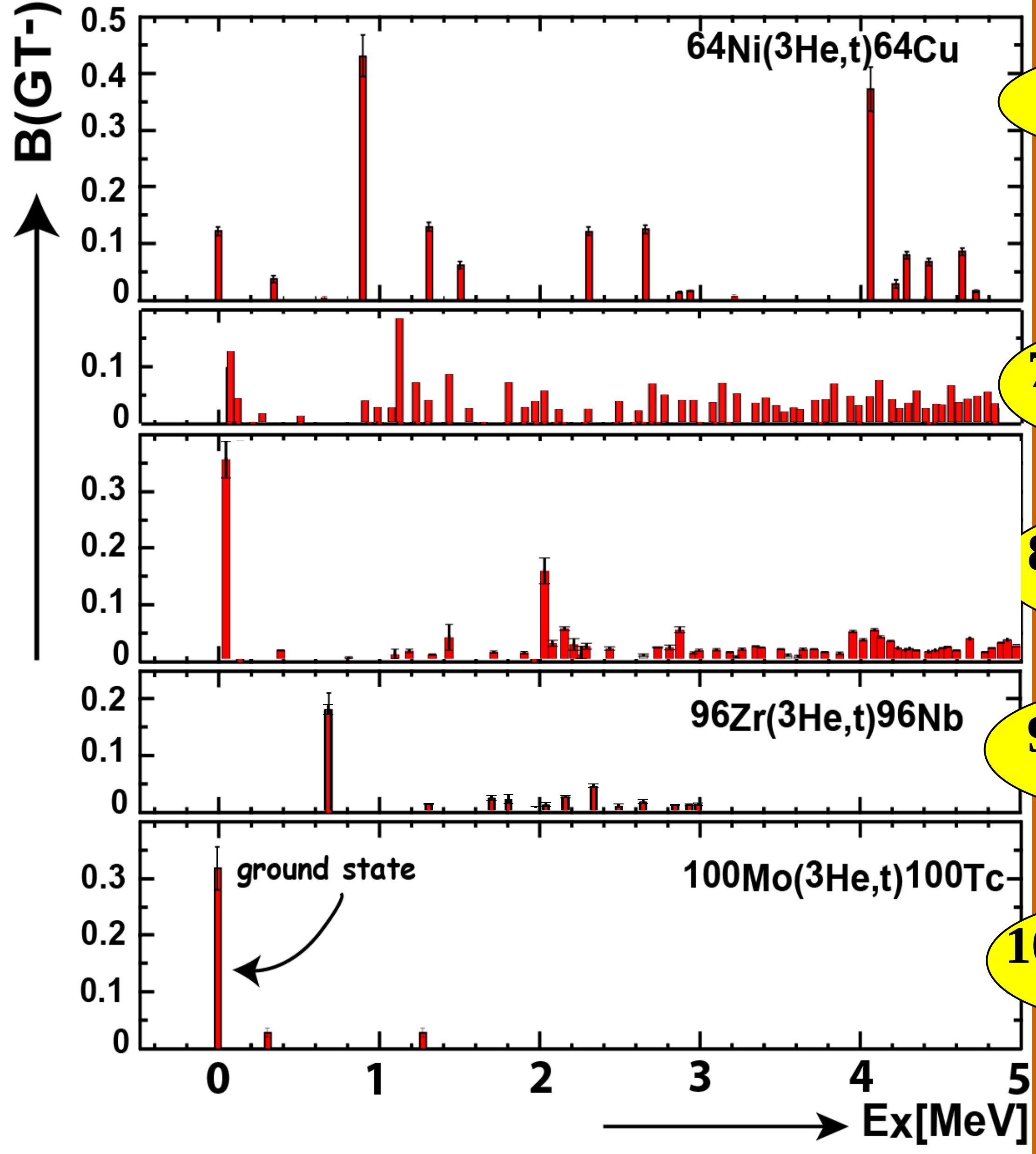
HERE: almost the entire
low-E GT strength is
concentrated in the g.s.



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

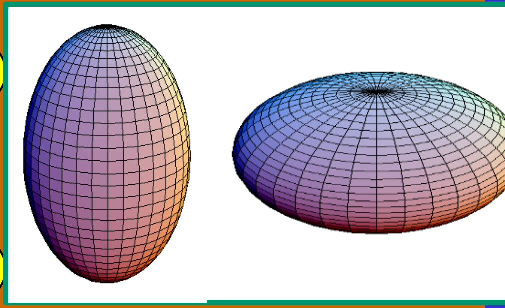
$$M^{2\nu}_{DGT}(\mathrm{g.s.}) \sim \mathbf{0.88}\cdot M^{2\nu}_{DGT}(\mathrm{total})$$

No need for GT giant resonance



^{64}Zn($\varepsilon\varepsilon$, $\varepsilon\beta^+$)

^{76}Ge($\beta^-\beta^-$)



^{82}Se($\beta^-\beta^-$)

^{96}Zr($\beta^-\beta^-$)

^{100}Mo($\beta^-\beta^-$)

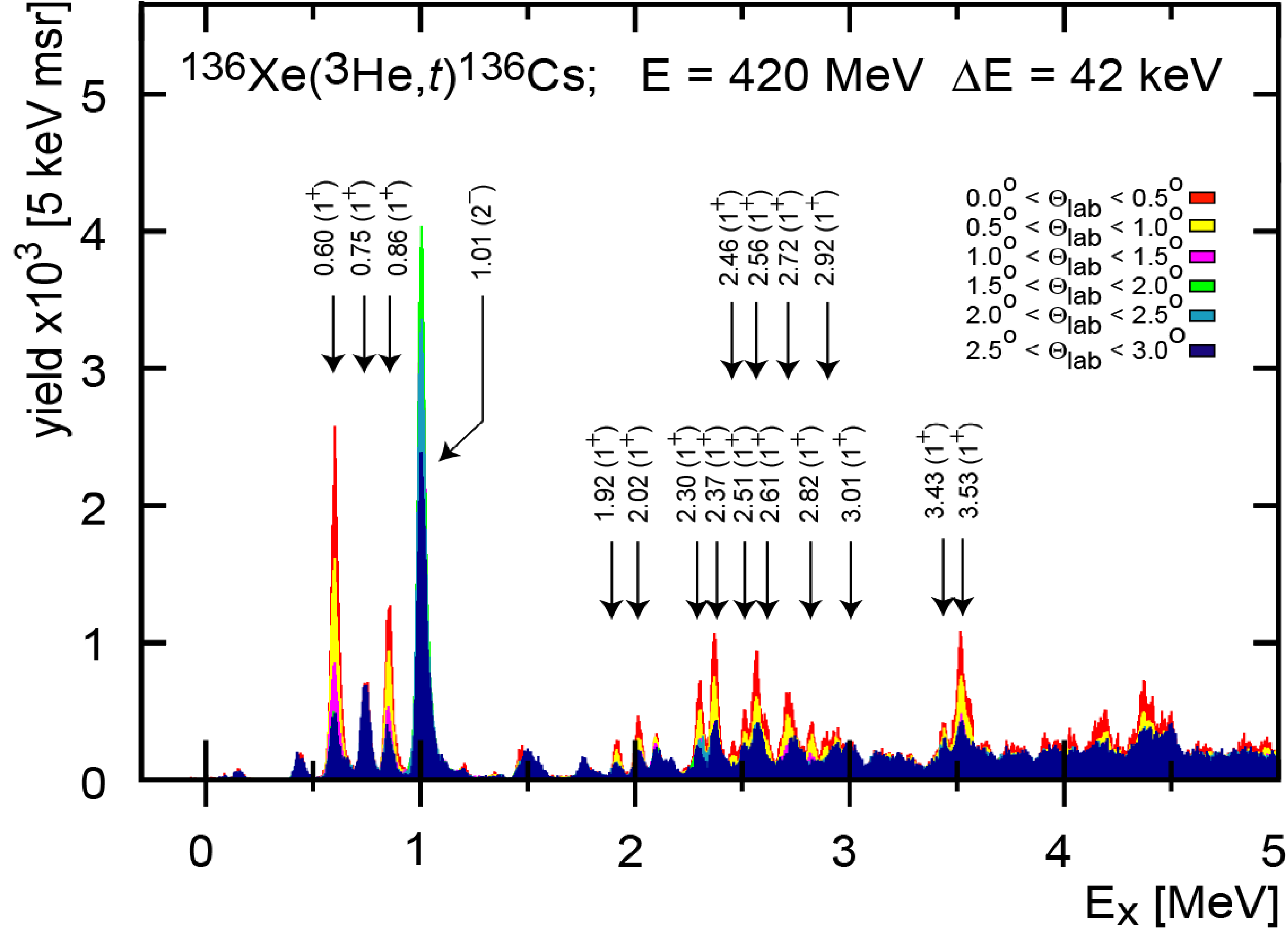
reduced fragmentation of GT strength

^{136}Xe

$N-Z=28$

question: why so stable !!!

136Xe



^{136}Xe(^{3}He,t)^{136}Cs; E = 420 MeV ΔE = 42 keV
yield x10^3 [5 keV msr]
0
1
2
3
4
5
E$_X$ [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° < Θ$_{lab}$ < 0.5° 🟥
0.5° < Θ$_{lab}$ < 1.0° 🟨
1.0° < Θ$_{lab}$ < 1.5° 🟪
1.5° < Θ$_{lab}$ < 2.0° 🟩
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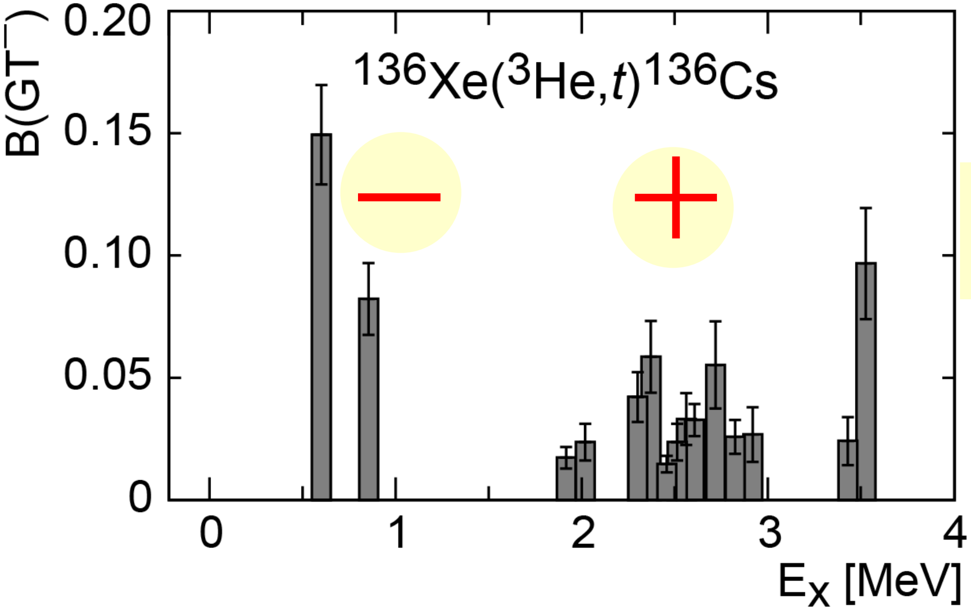
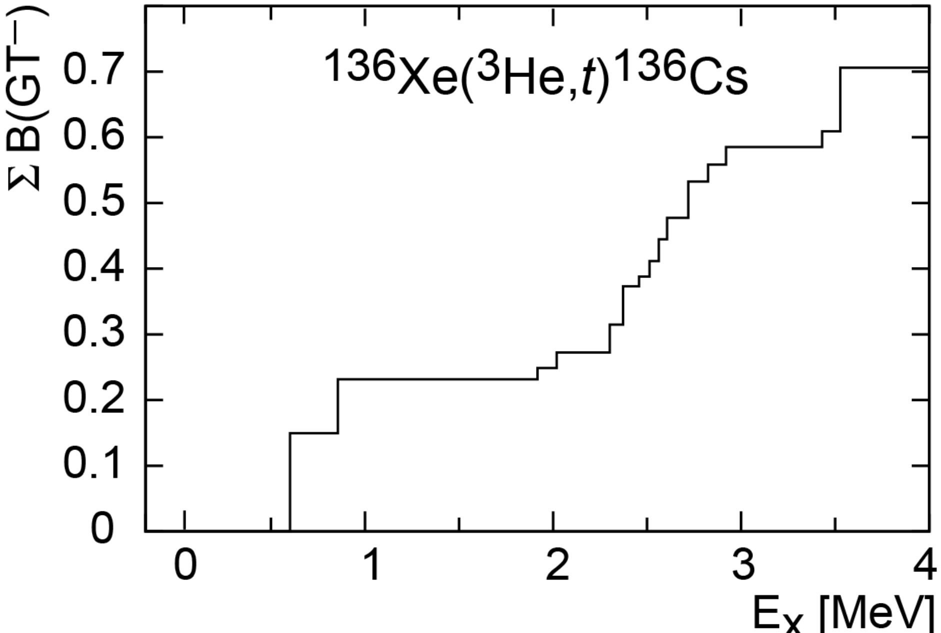
2.5° < Θ$_{lab}$ < 3.0° 🟦

What's the size of the NME?



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

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



all signs positive —>

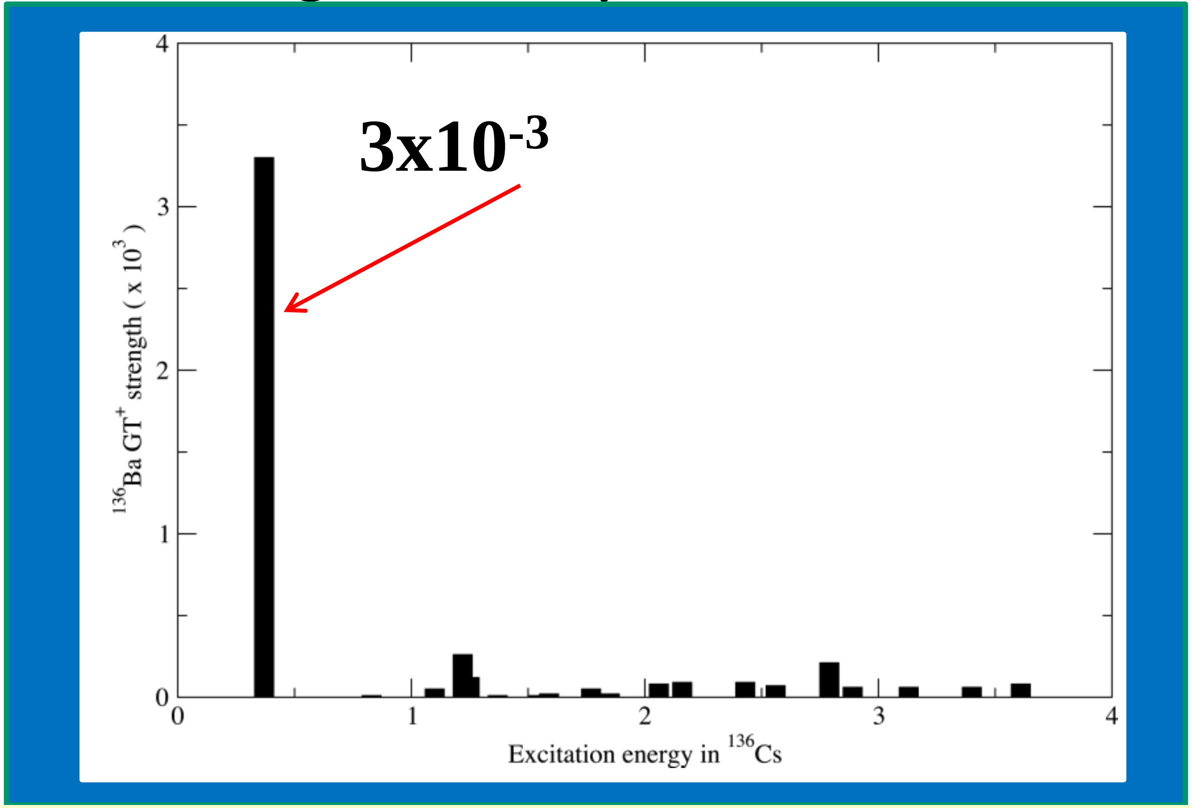
$$\mathrm{B_m}\ \ GT^{+}\ \approx 10^{-2}\cdot \mathrm{B_m}\ \ GT^{-}$$

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

A. Poves (simultaneous to our publication):

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

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

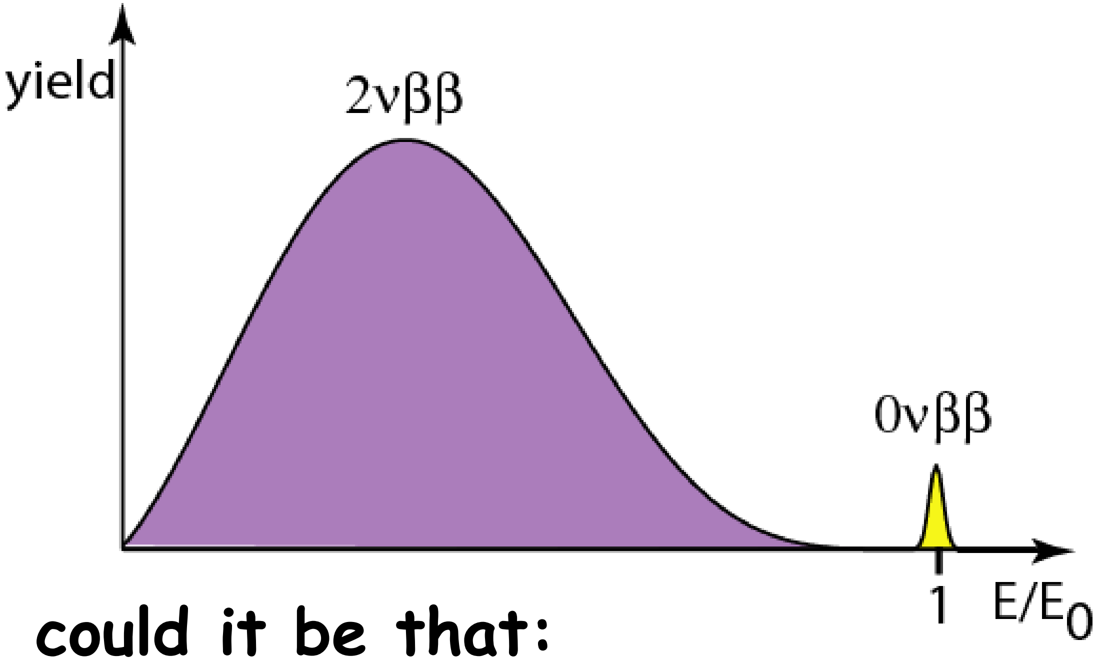


Shell model provides conclusive explanation for the deemed „pathologically“ long half-life of ^{136}Xe.
Expt‘l test: ^{136}Ba(d,^{2}He)^{136}Cs

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

expmt: 2νββ NME is exceptionally small

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



could it be that:

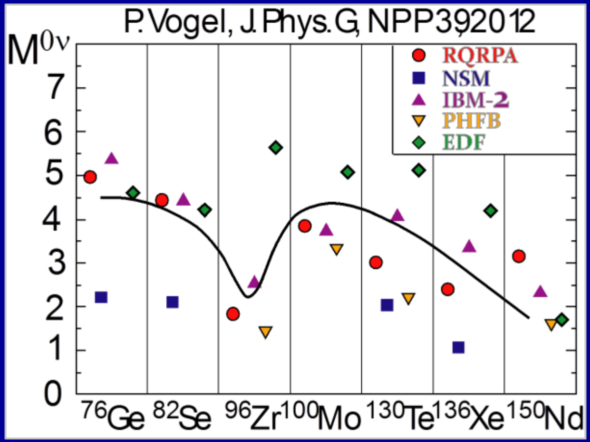
2νββ ME is suppressed AND

0νββ ME is enhanced ???

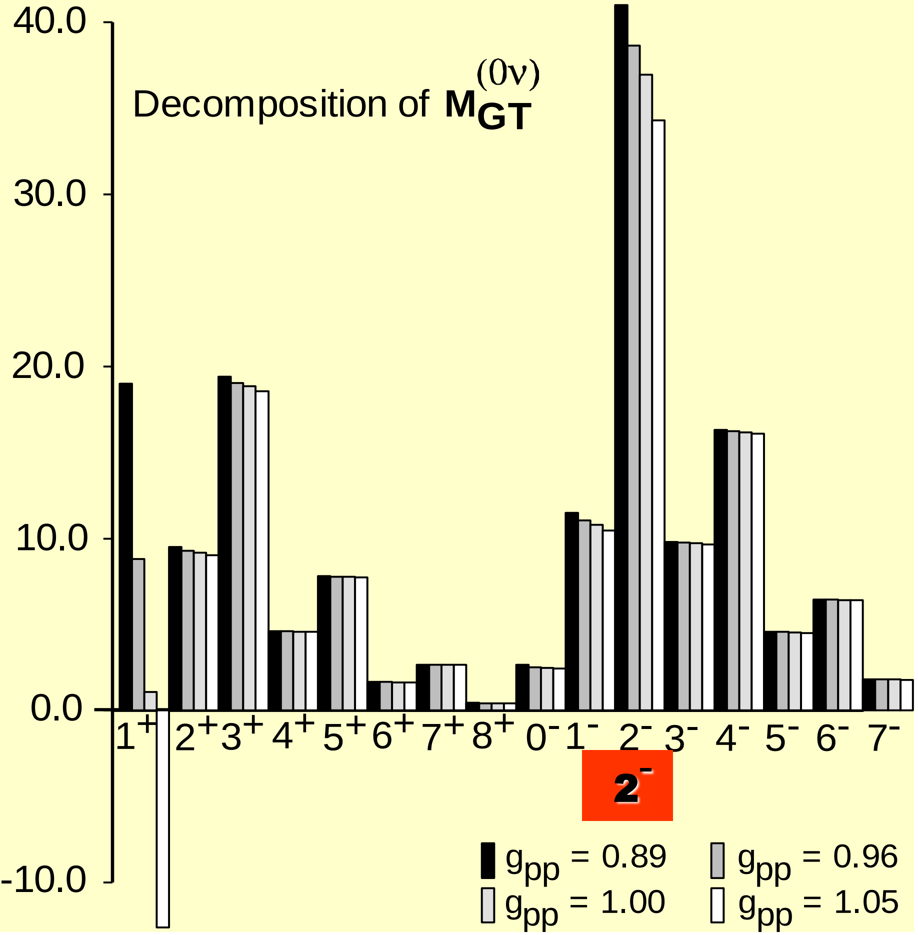
Experiments towards the $0\nu\beta\beta$ NMEs

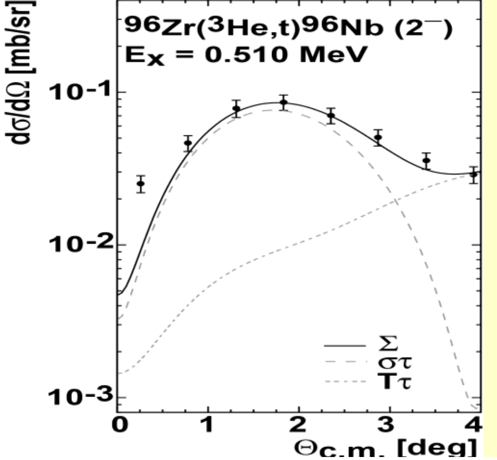
Here:

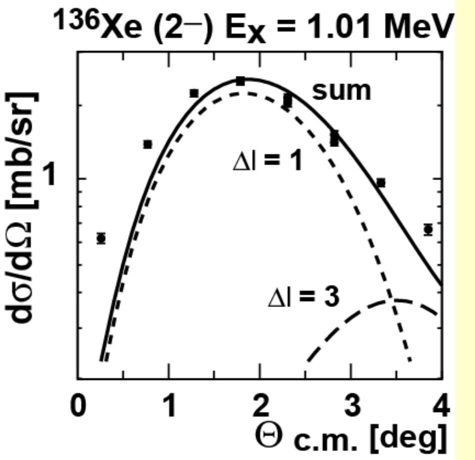
2^- states and occupation vacancy numbers via chargex reactions

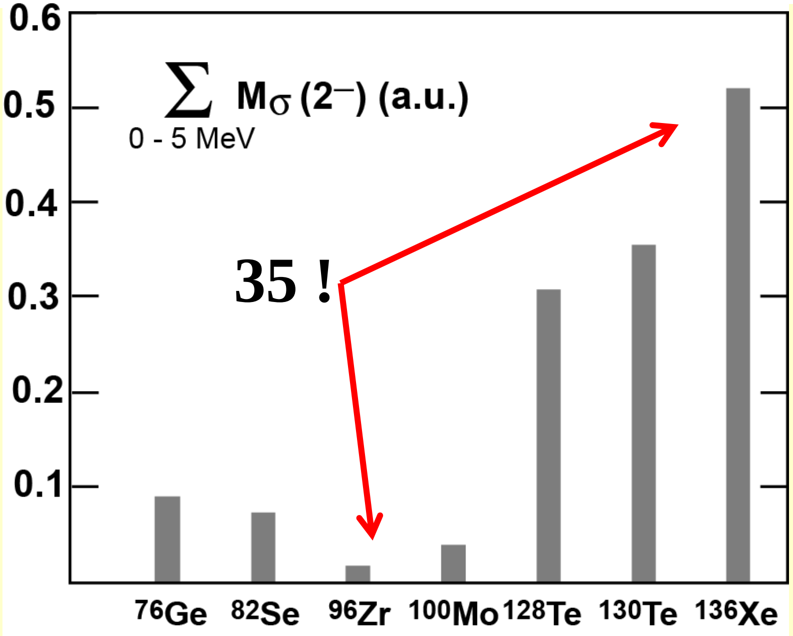


P. Vogel, J. Phys. G, NPP 39 2012









relative 2⁻ strength to ~ 5 MeV

<u>Theory:</u>

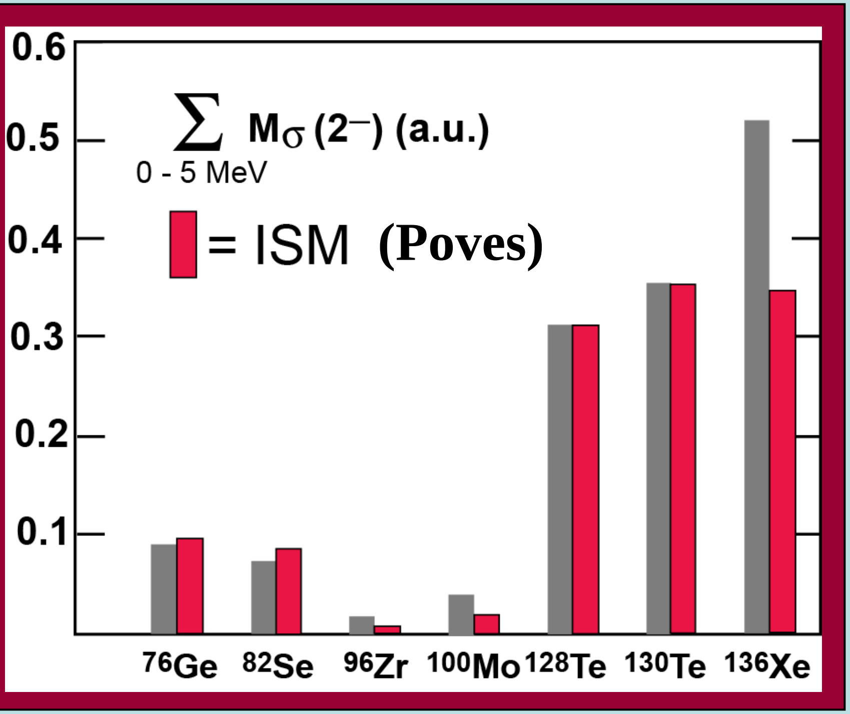
The 2⁻ strength makes up ~ 20-30% of the 0νββ ME!!

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

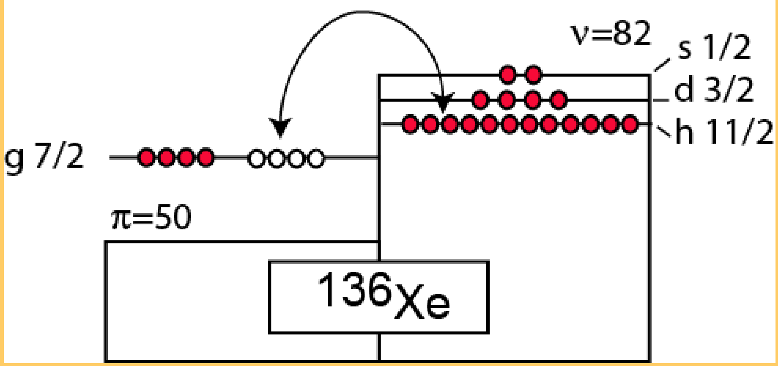
<u>Expmt:</u>

^{136}Xe exhibits largest 2⁻ strength

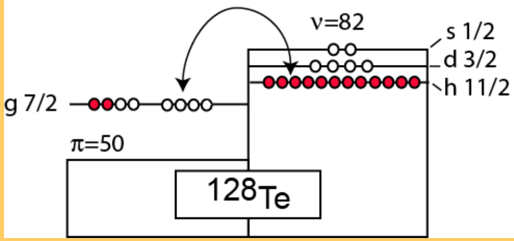
0νββ ME enhanced?!?!



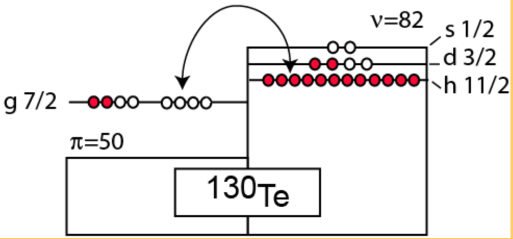
$[\nu\ h\ 11/2 \longrightarrow \pi\ g\ 7/2]J^{\pi}=2^{-}$



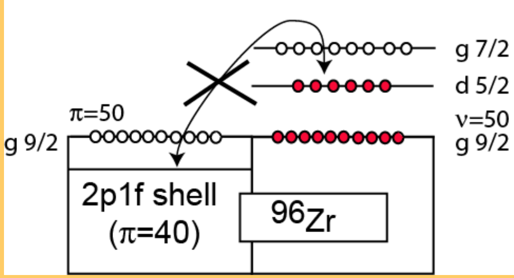
$[\nu\ h\ 11/2 \longrightarrow \pi\ g\ 7/2]J^{\pi}=2^{-}$



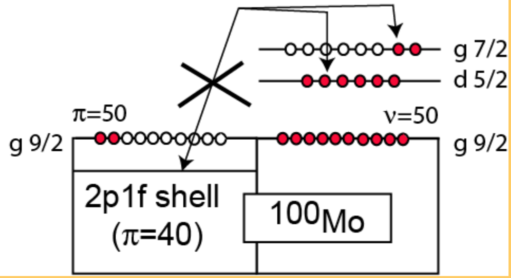
$[\nu\ h\ 11/2 \longrightarrow \pi\ g\ 7/2]J^{\pi}=2^{-}$



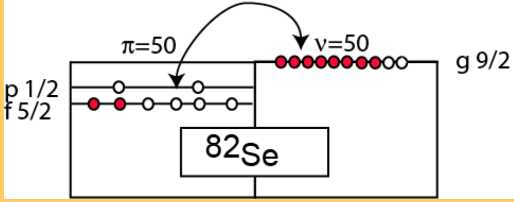
$[\nu\ d\ 5/2 \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$



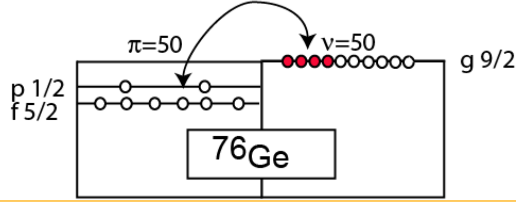
$[\nu\ 2d1g \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$

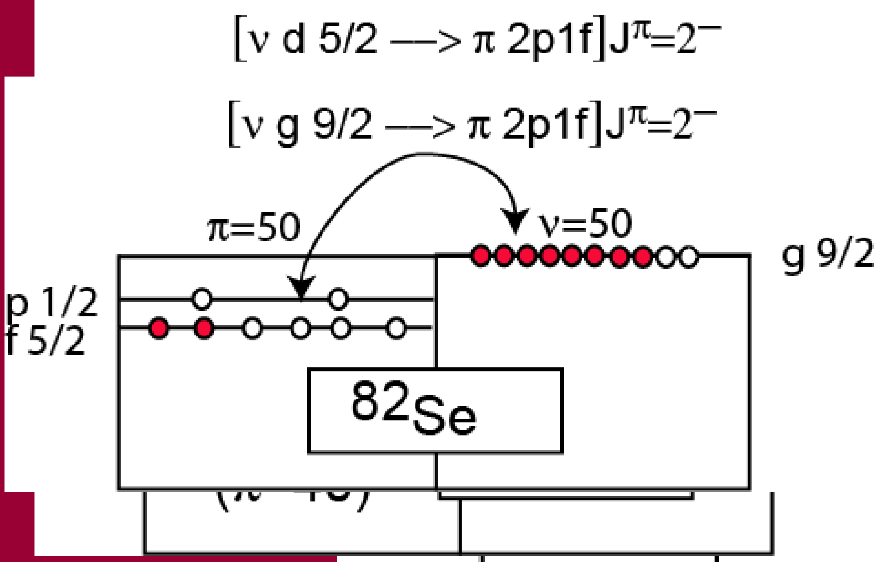


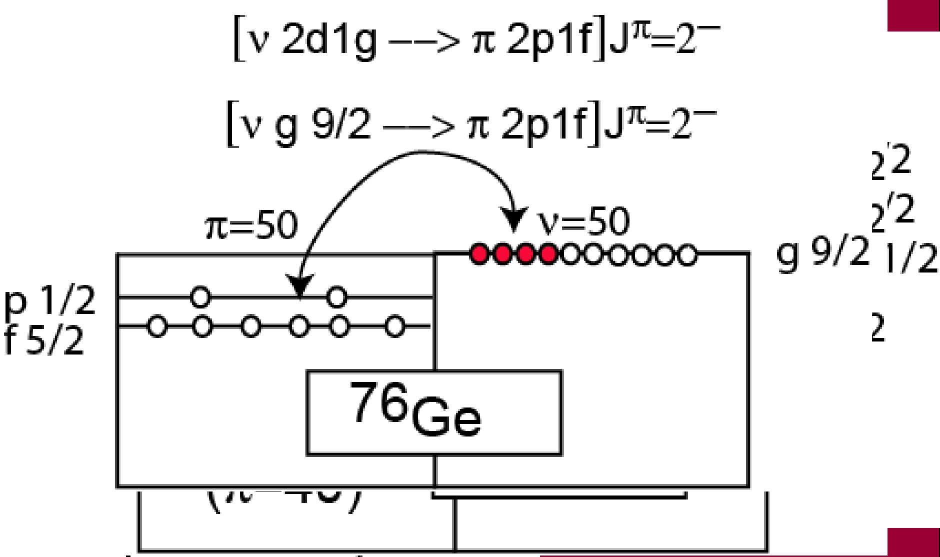
$[\nu\ g\ 9/2 \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$

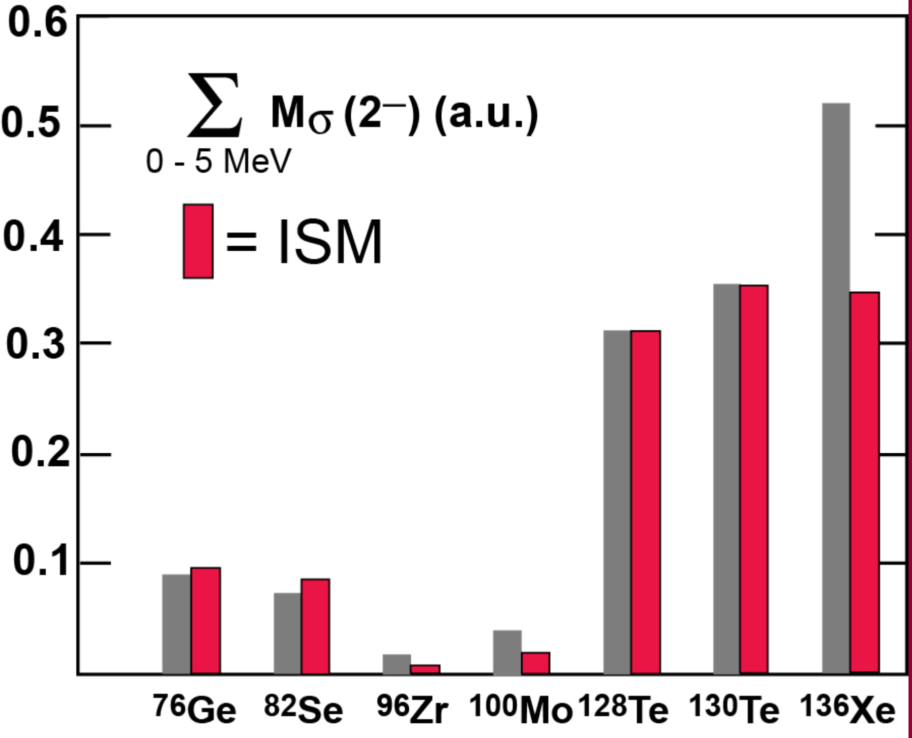


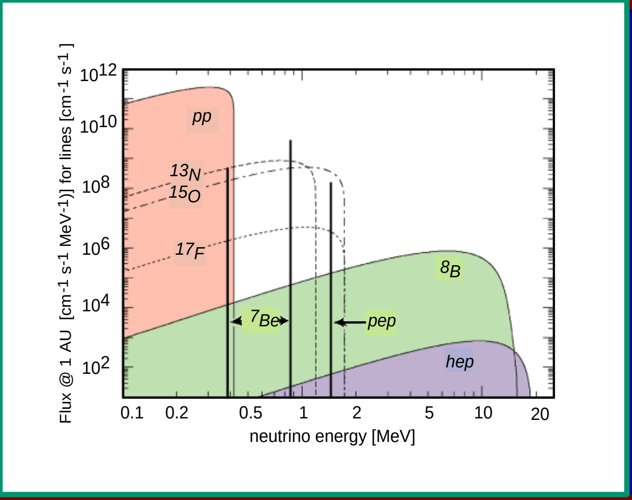
$[\nu\ g\ 9/2 \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$




[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

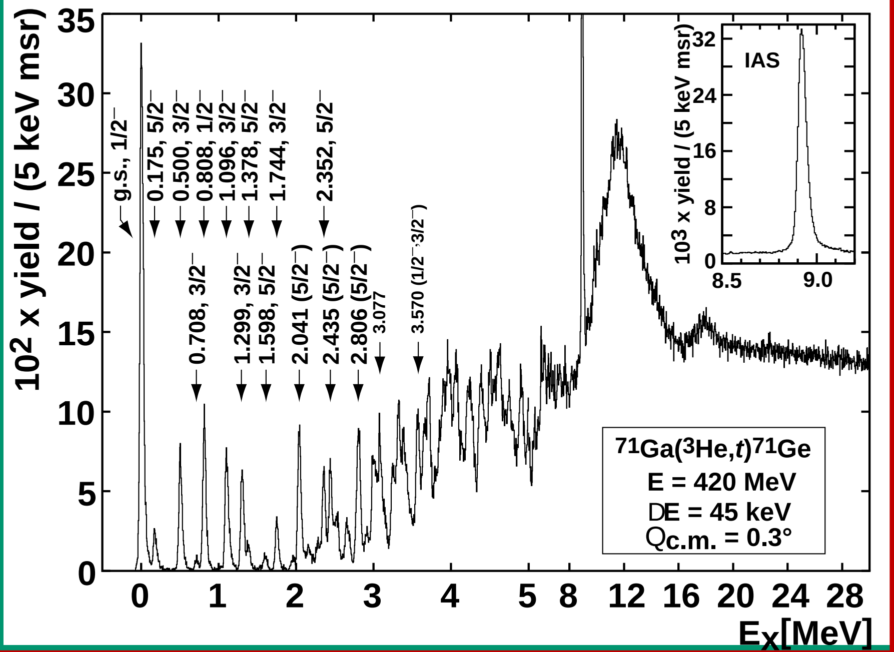

Σ 0 - 5 MeV Mσ (2⁻) (a.u.)
🟥 = ISM
0.6
0.5
0.4
0.3
0.2
0.1
76Ge
82Se
96Zr
100Mo
128Te
130Te
136Xe

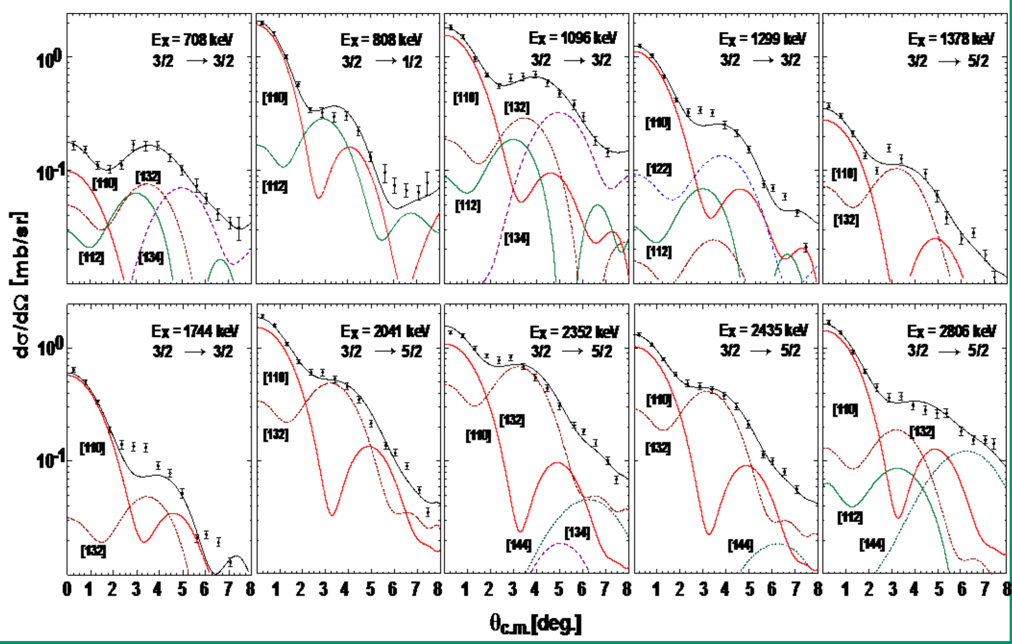


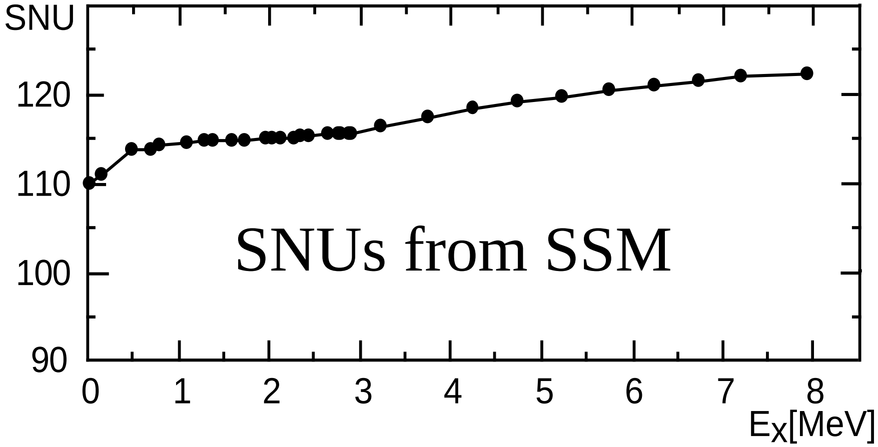
solar neutrino rates via (^{3}He,t)

^{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







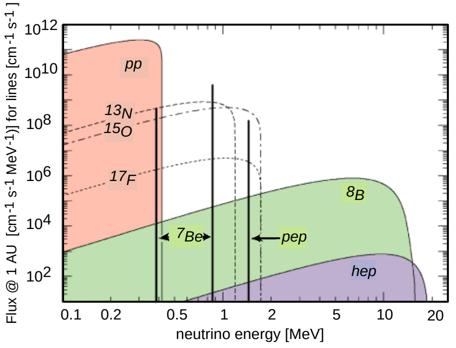
^{71}Ga($\nu_\odot$,e$^-$)

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

stat. err. mostly due to CNO ν's

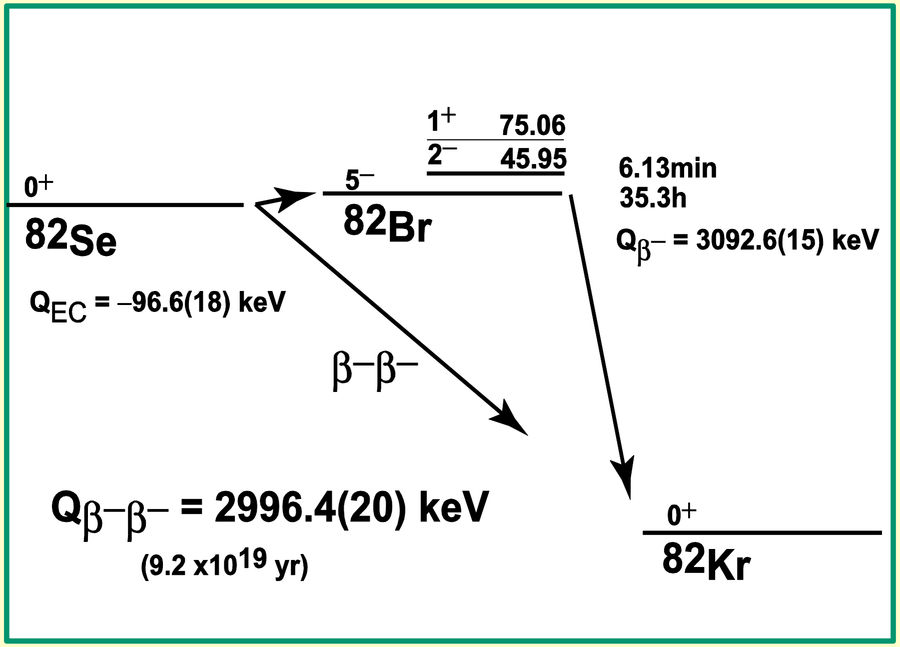
prev'ly:132 ± 18

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



0^+

^{82}Se

Q_{EC} = –96.6(18) keV

$\beta^-\beta^-$

$Q_{\beta^-\beta^-}$ = 2996.4(20) keV

(9.2×10^{19} yr)

1^+ 75.06

2^- 45.95

5^-

^{82}Br

6.13min

35.3h

Q_{β^-} = 3092.6(15) keV

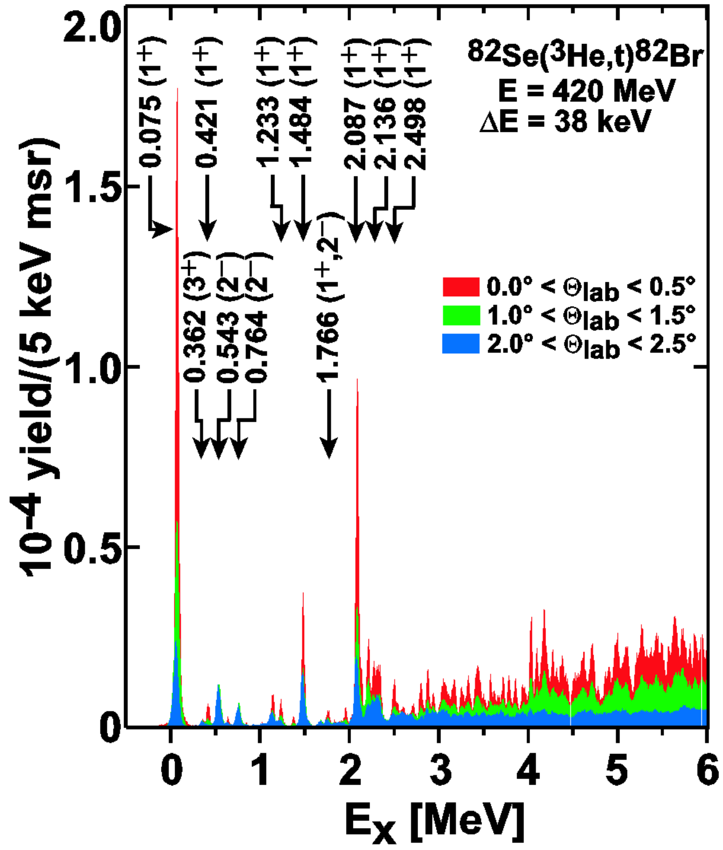
0^+

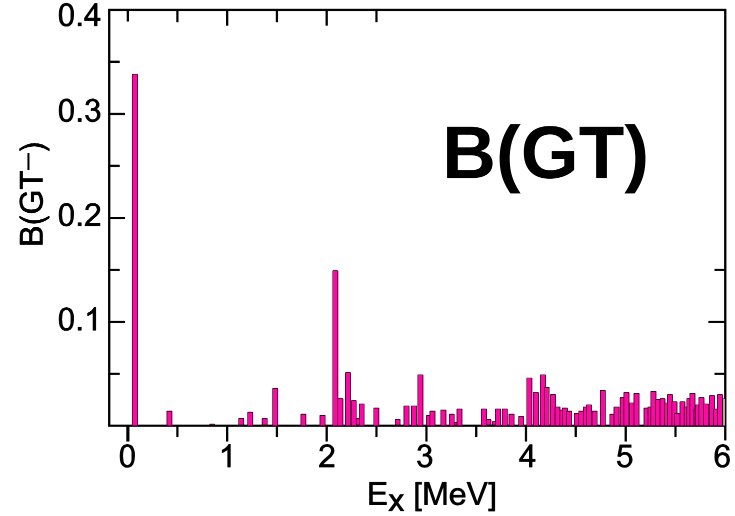
^{82}Kr

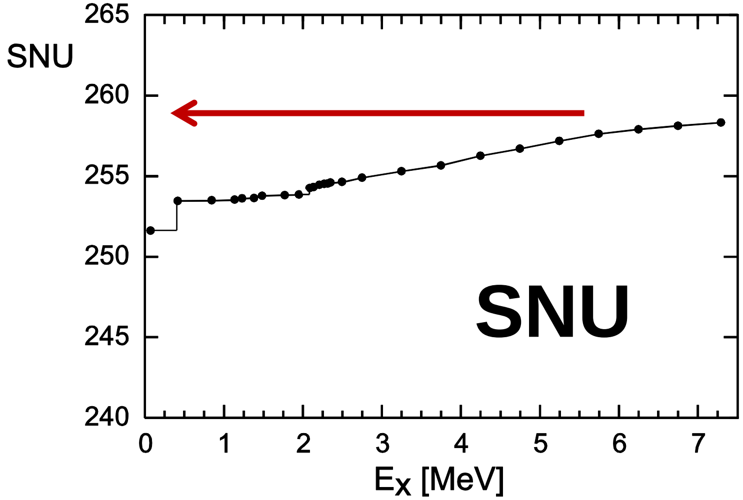
Advantages:

- 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(^{3}He,t) spectrum







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

preliminary

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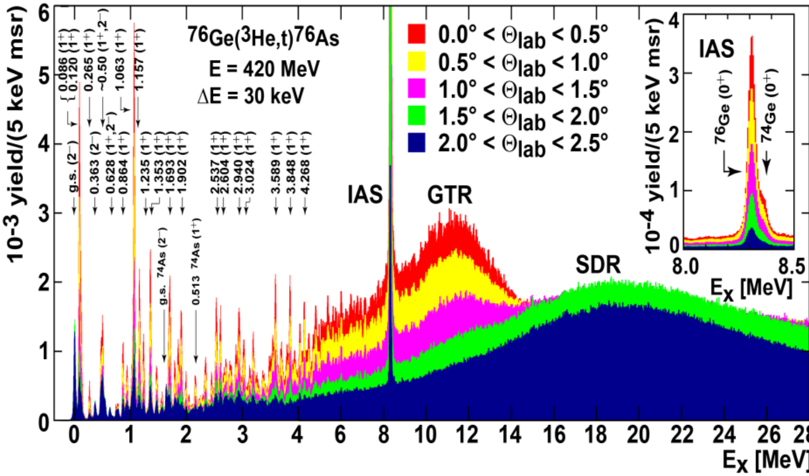
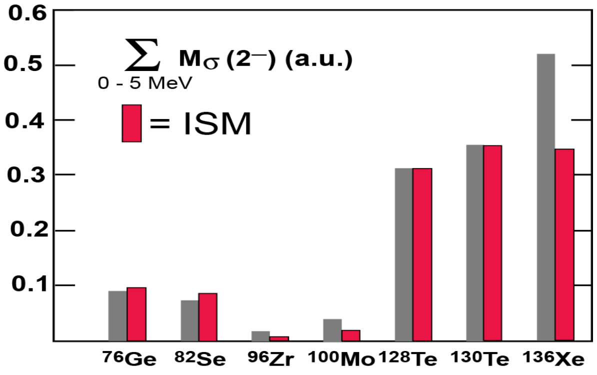
MÜNSTER

Future perspectives of chargex-reactions

- $\beta\beta$-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)

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

$$R = 122.4 \pm 3.4 \pm 1.1\ \mathrm{SNU}$$

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

$$R = 258.4\ \ \mathrm{SNU}$$

- EOS and chargex-reaction
  - IAS and GT resonance data needed and useful

    BUT: theories need to converge on their relevance