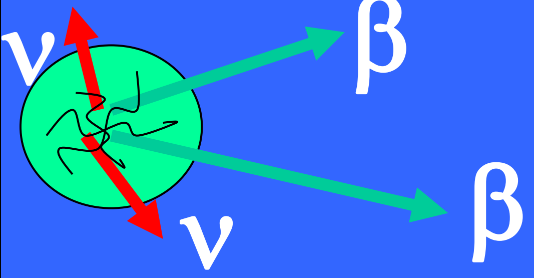
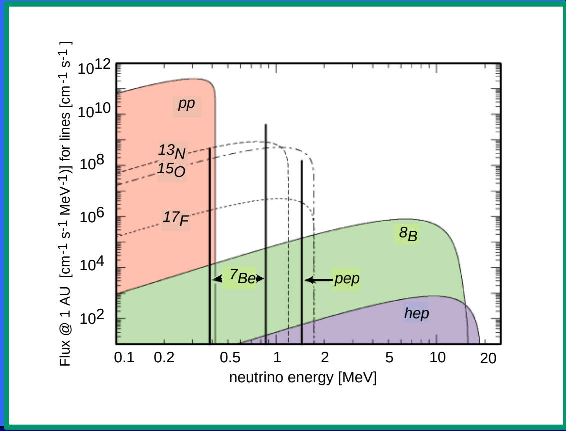
Westfälische
Wilhelms-Universität
Münster

D. Frekers

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





NUMEN2015

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)

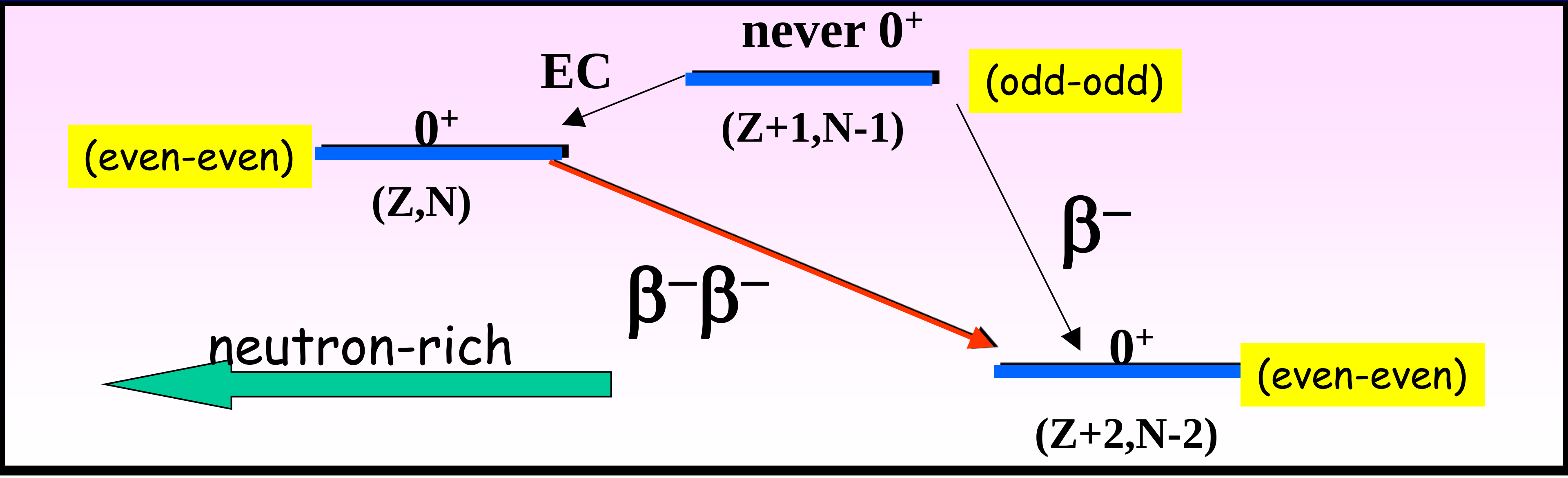
- **the A=96 system**

  the ^{96}Zr (β–) → ^{96}Nb Q-value

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

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

$\beta^-\beta^-$ 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:

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

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

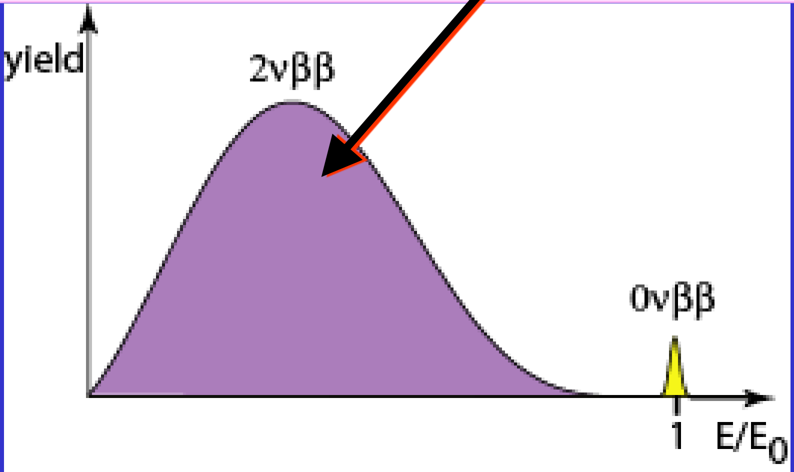
$0\nu\beta^-\beta^-$ decay:

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

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

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

2νβ⁻β⁻ decay

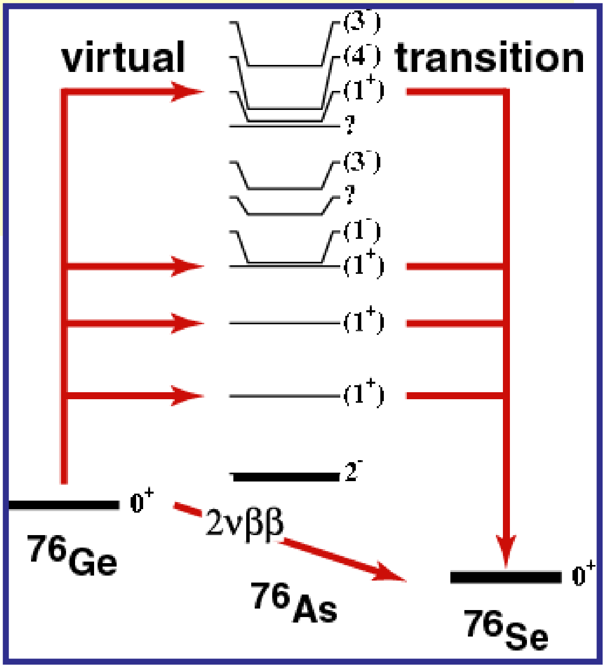


q-transfer like in ordinary
β-decay
(q ~ 0.01 fm^{-1} ~ 2 MeV/c)
i.e. only allowed transitions possible

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

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

extracted from half-life

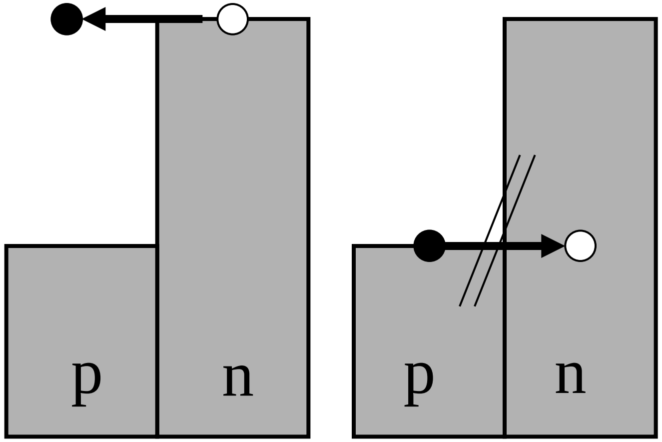


favorable:

1. high Q-value
2. large Z

unfavorable (but cannot be changed):

1. large neutron excess (Pauli-blocking)



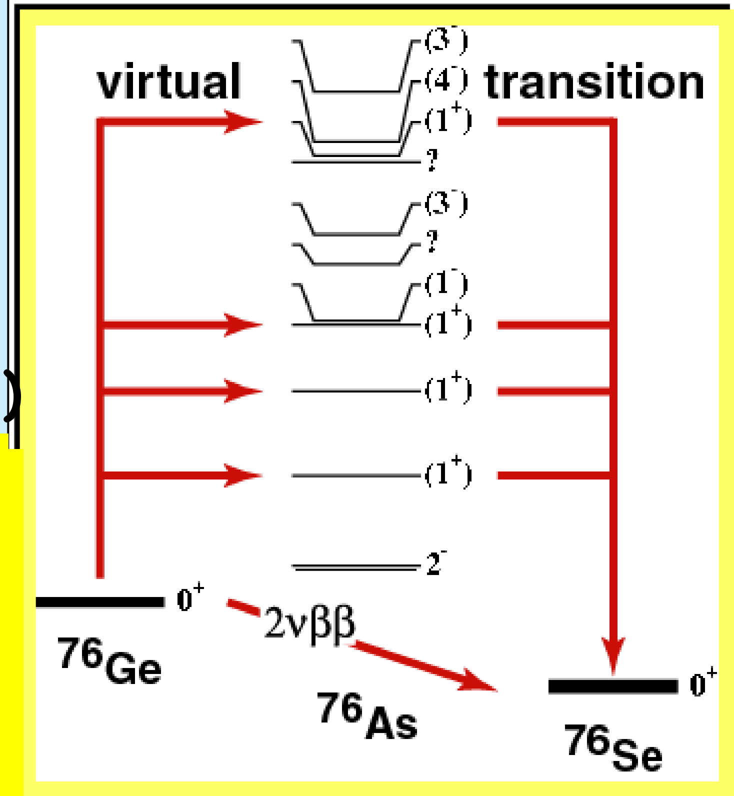
$$M^{(2\nu)}_{\mathrm{DGT}} = \sum_m \frac{\left\langle 0^{(f)}_{g.s.} \middle| \sum_k \sigma_k \tau_k^- \middle| 1^+_m \right\rangle \left\langle 1^+_m \middle| \sum_k \sigma_k \tau_k^- \middle| 0^{(i)}_{g.s.} \right\rangle}{\frac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - E_0}$$

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

to remember:

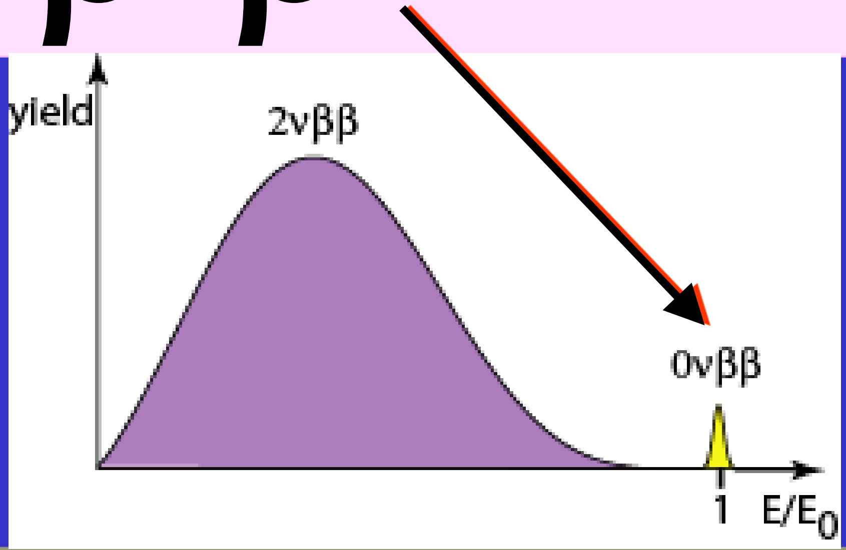
1. 2 sequential & „allowed“ β^--decays of „Gamow-Teller“ type
2. „1, 2, 3, ... forbidden“ decays negligible
3. Fermi–transitions do no contribute (because of different isospin-multiplets)

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



Nucl. Matrix Elements

$0\nu\beta^-\beta^-$ 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 forbiddeness is lifted

!!

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

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

mass of Majorana-ν !

to remember:

1. „higher-fold forbidden" transitions possible
2. Fermi-transitions im
3. „Pauli-blockin d
4. large Q important

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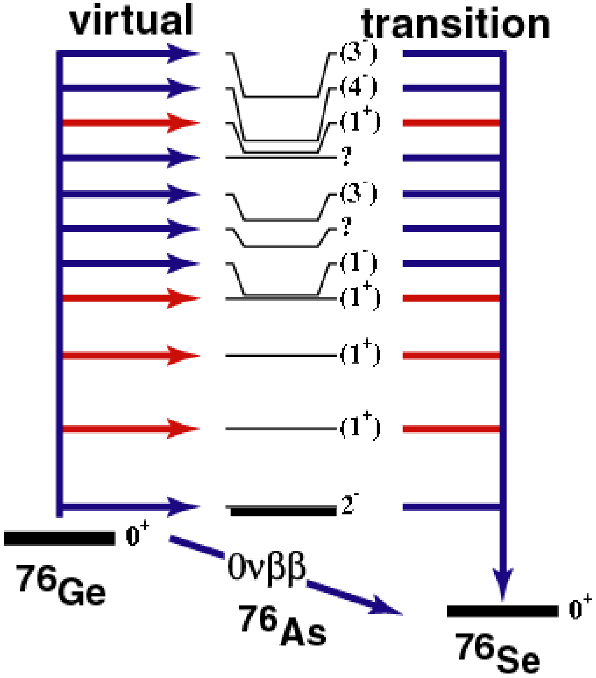
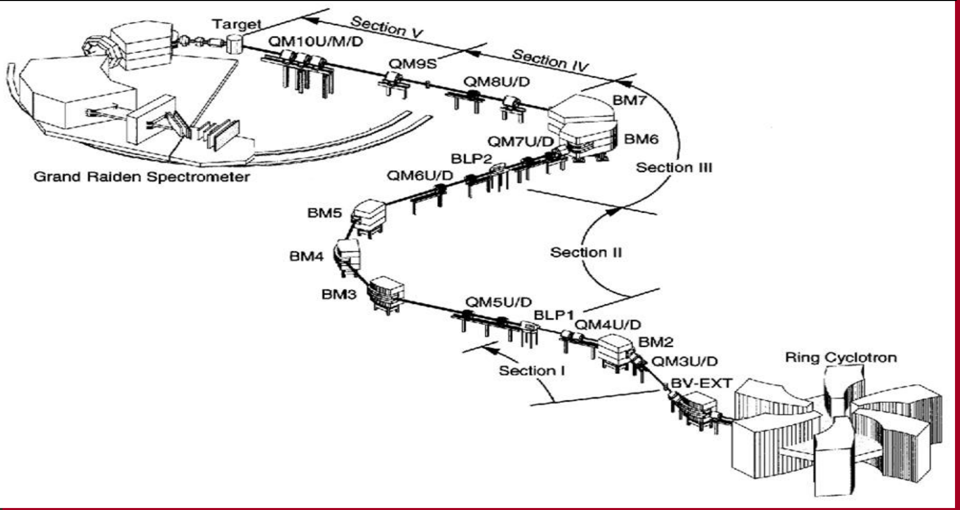
N accessible via
ch exchange reactions

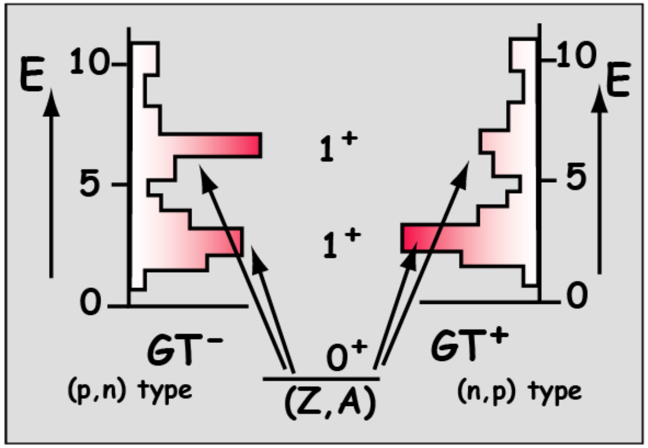


Charge-exchange reactions

Grand Raiden
Magnetic Spectrometer

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





Q: what is the connection between „weak στ operator“ and the hadronic reaction

A: dominance of the Vστ 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)

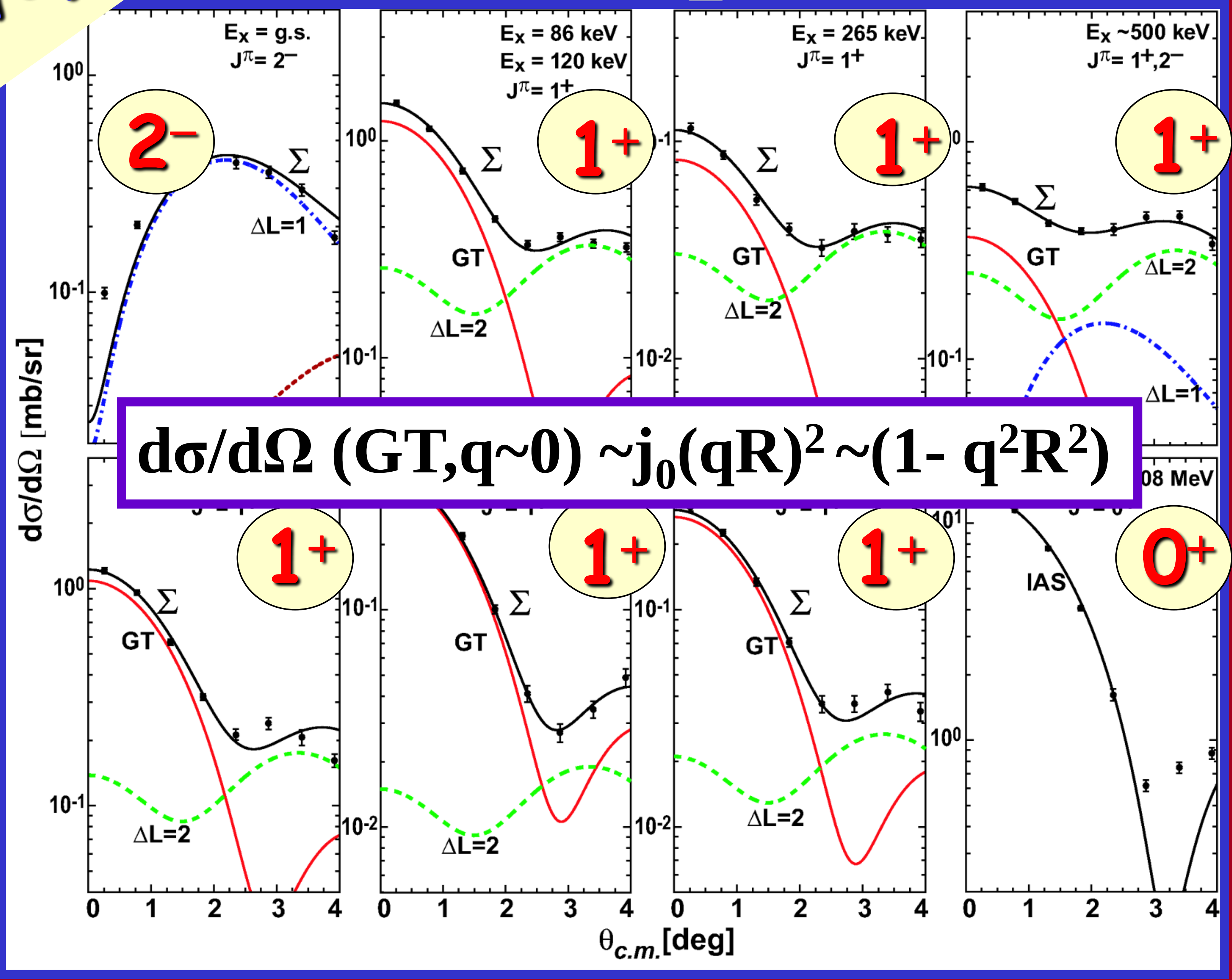
$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{\mu}{\pi\hbar}\right]^2 \frac{k_f}{k_i} N_D \, |V_{\sigma\tau}|^2 \, |\langle f \,|\, \sigma\tau \,|\, i \rangle|^2$$

$$q = 0!!$$

largest at 100 - 200 MeV/A

examples

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

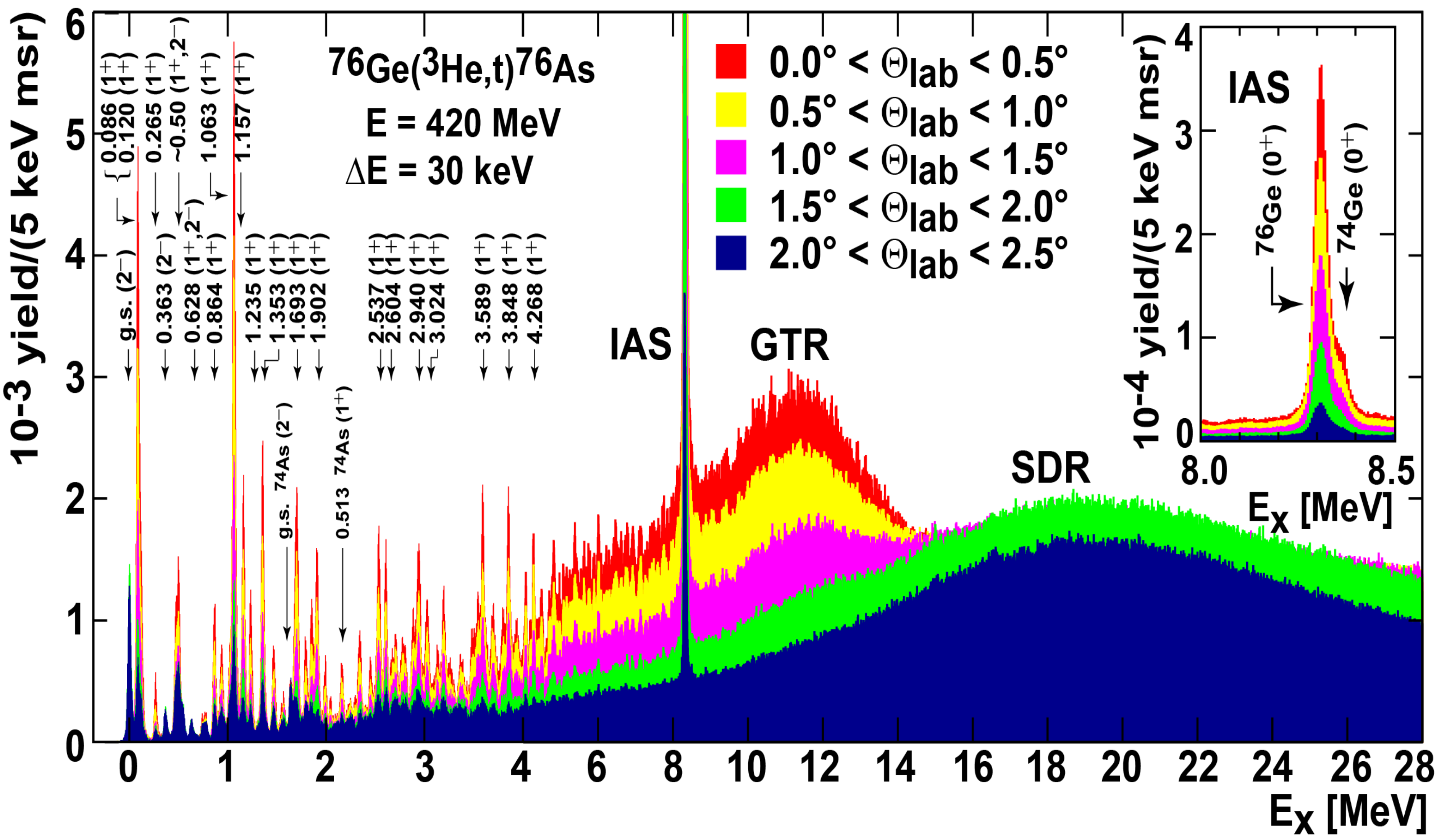


$$d\sigma/d\Omega\ (GT, q\sim0) \sim j_0(qR)^2 \sim (1- q^2R^2)$$

^{76}Ge

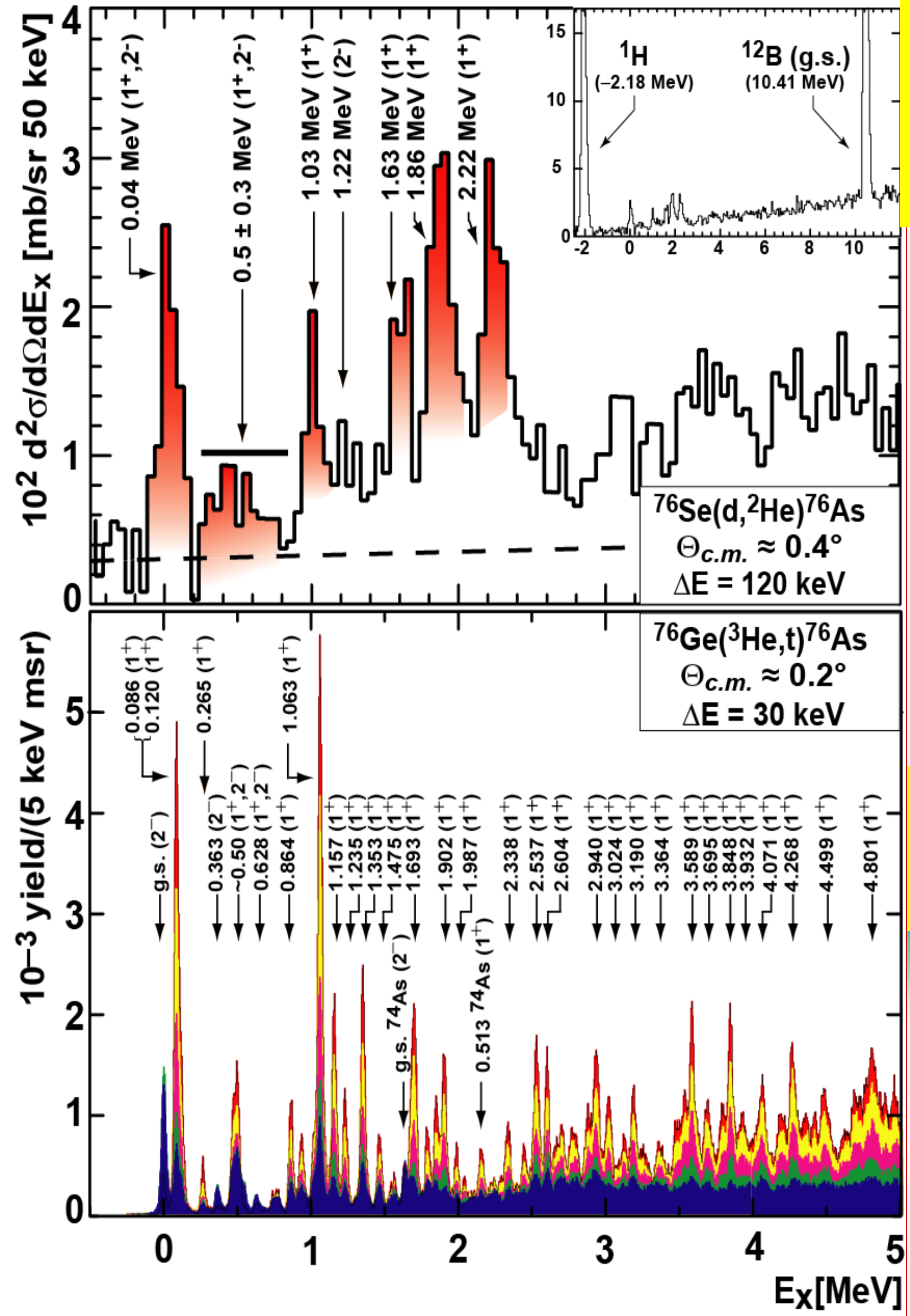
$N-Z=10$

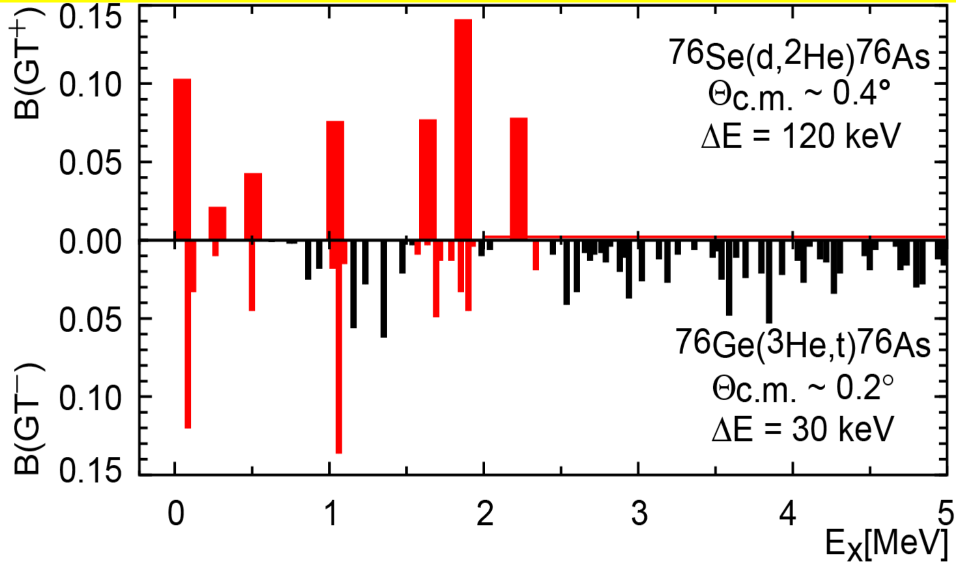
Resolution is the key !!!



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

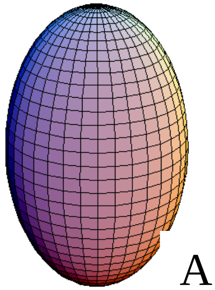
~ 70 !! single states
up to 5 MeV !!!
???? anti-correlation ????



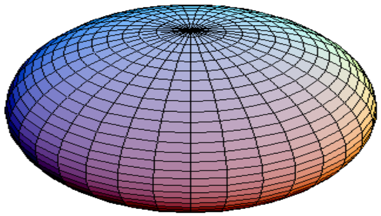


is the anti-correlation a property of deformation ??

^{76}Ge

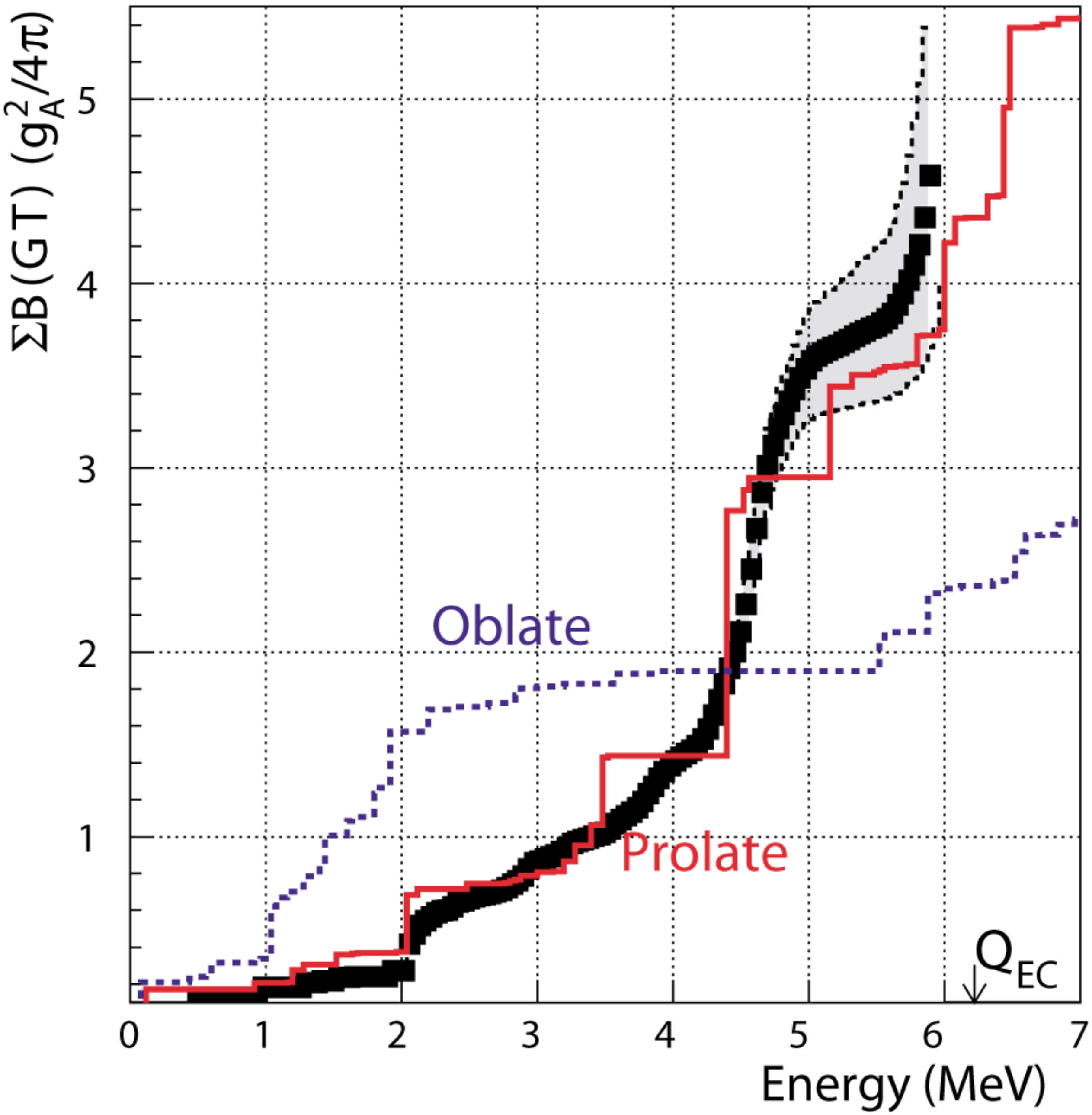


^{76}Se



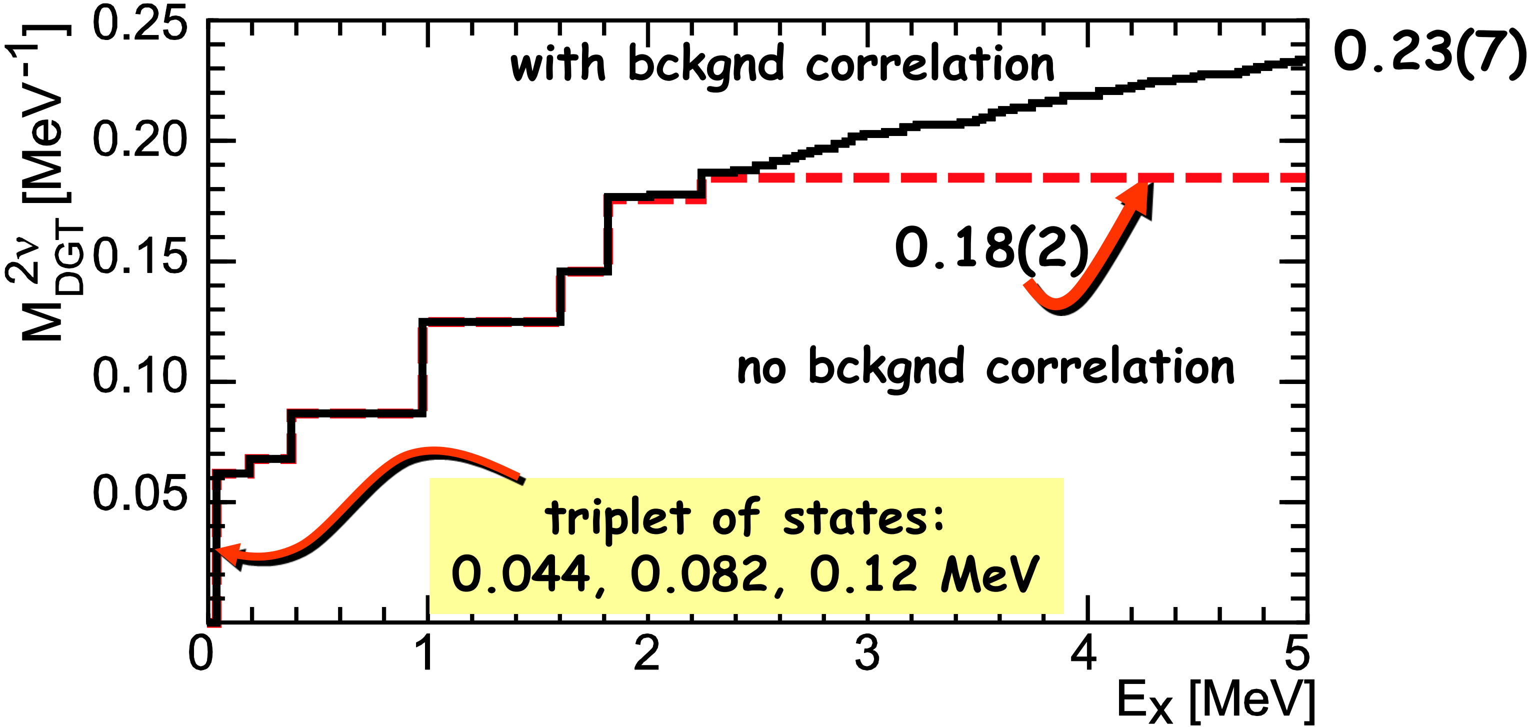
A. Faessler et al. PRC70 (2004)

E. Nacher, et al. PRL **92, 232501 (2004).**



76-Sr

prolate
or
oblate



Low-E part of M_{DGT} makes up ~100(+)% of $2\nu\beta\beta$-ME

M_{DGT} = 0.12 + 0. 01 MeV^{-1}

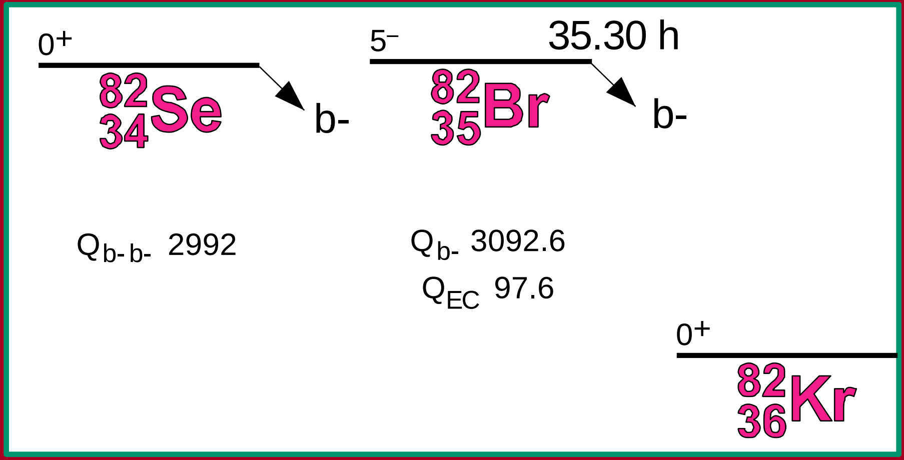
$T_{1/2}$ = (2.1 + 0.1) x 10^{21} yr

No need for GT giant resonance contribution

(note: 0.06 MeV^{-1} are due to low-E triplet, which may not be correlated!!)

^{82}Se

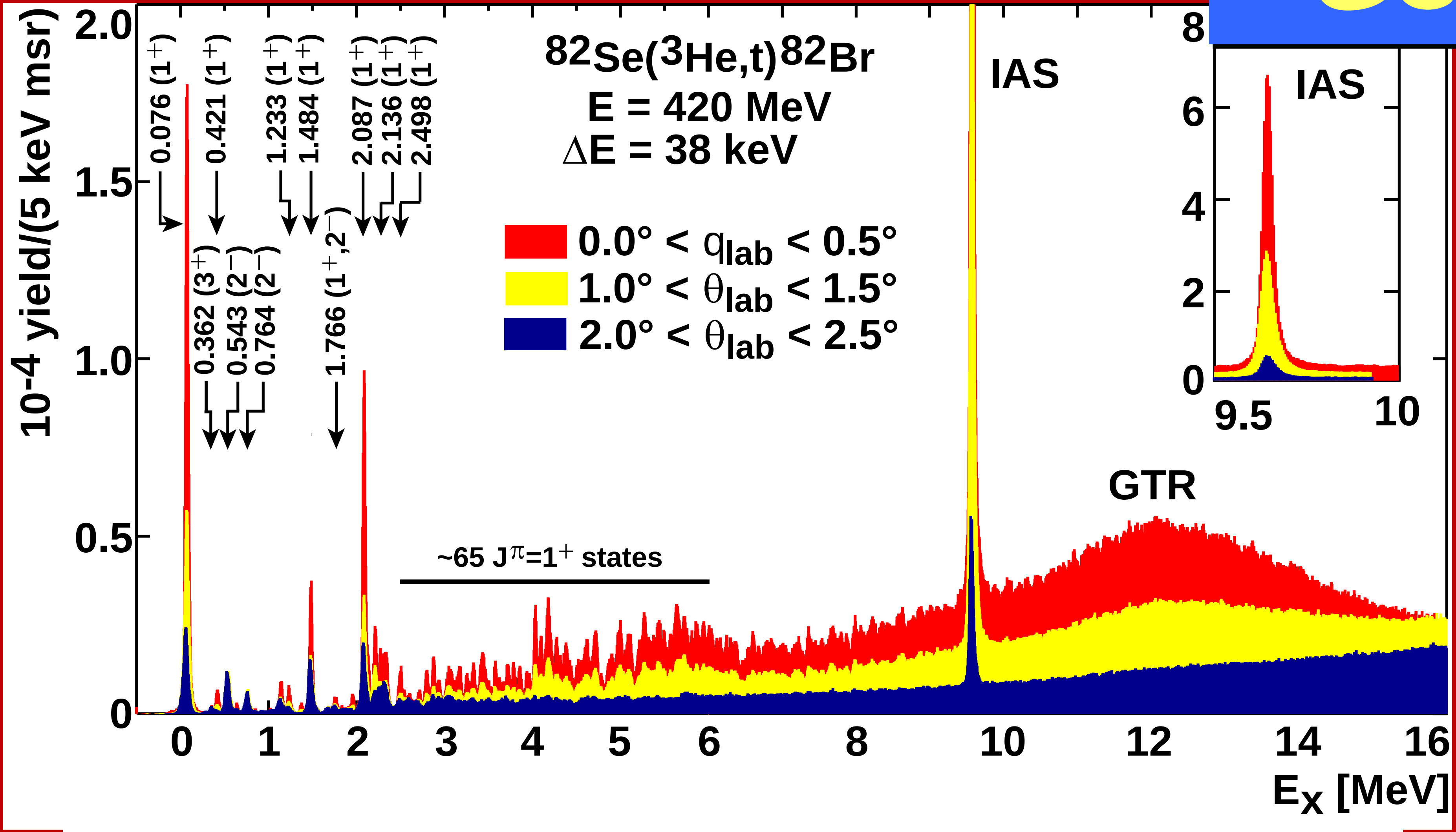
N-Z=14



Resolution is the key !!!

possibly useful for solar neutrino detection

^{82}Se



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

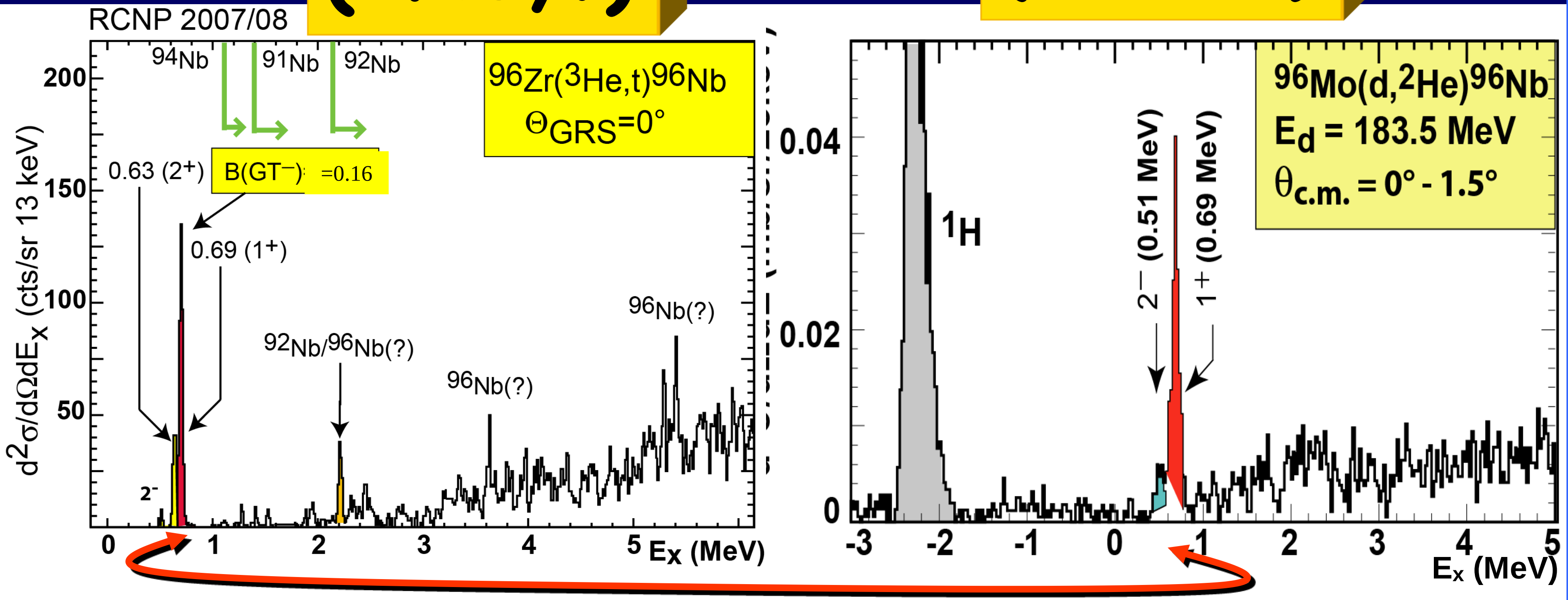
^{96}Zr

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:

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

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

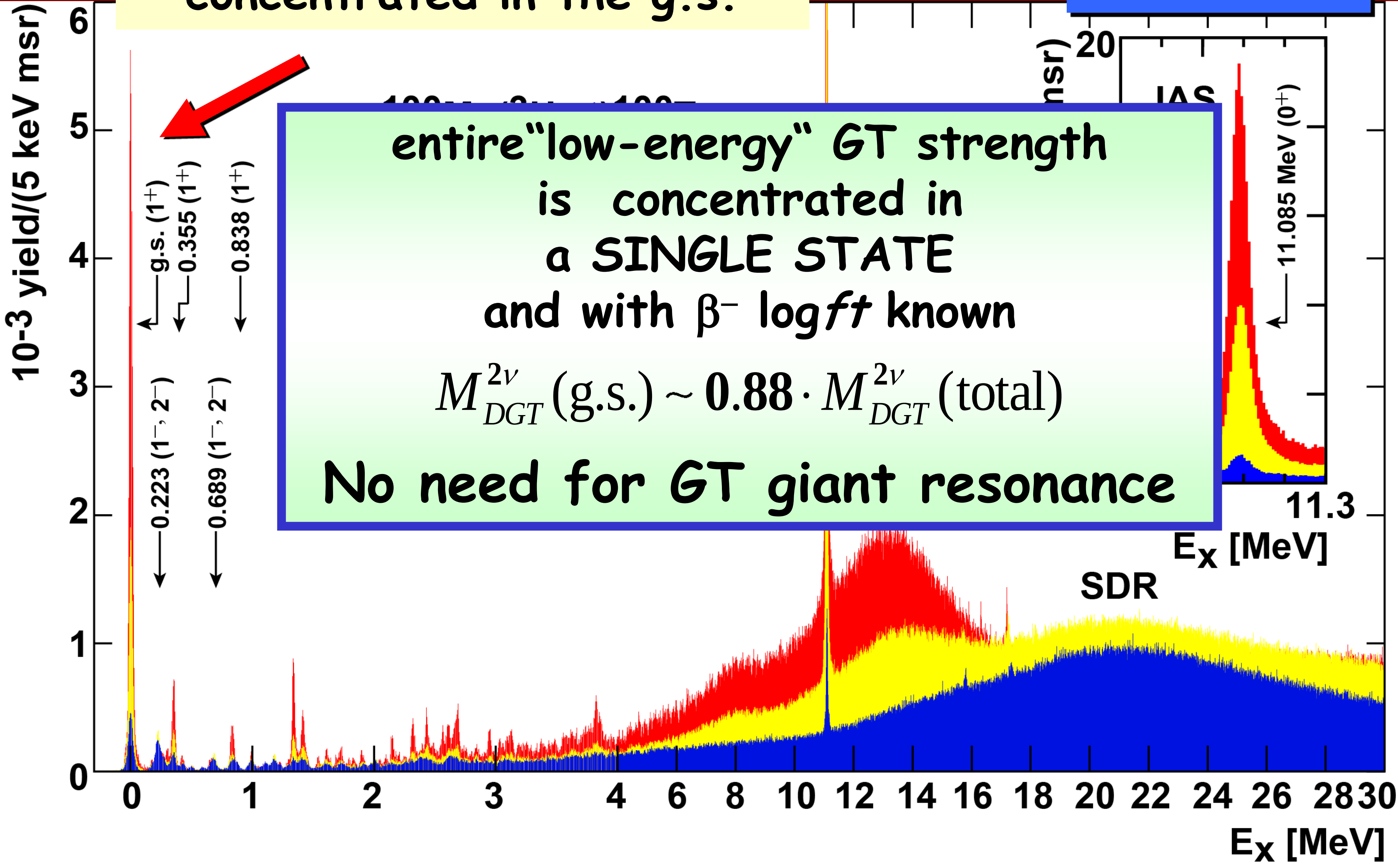
^{100}Mo

$N-Z=16$

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

^{100}Mo

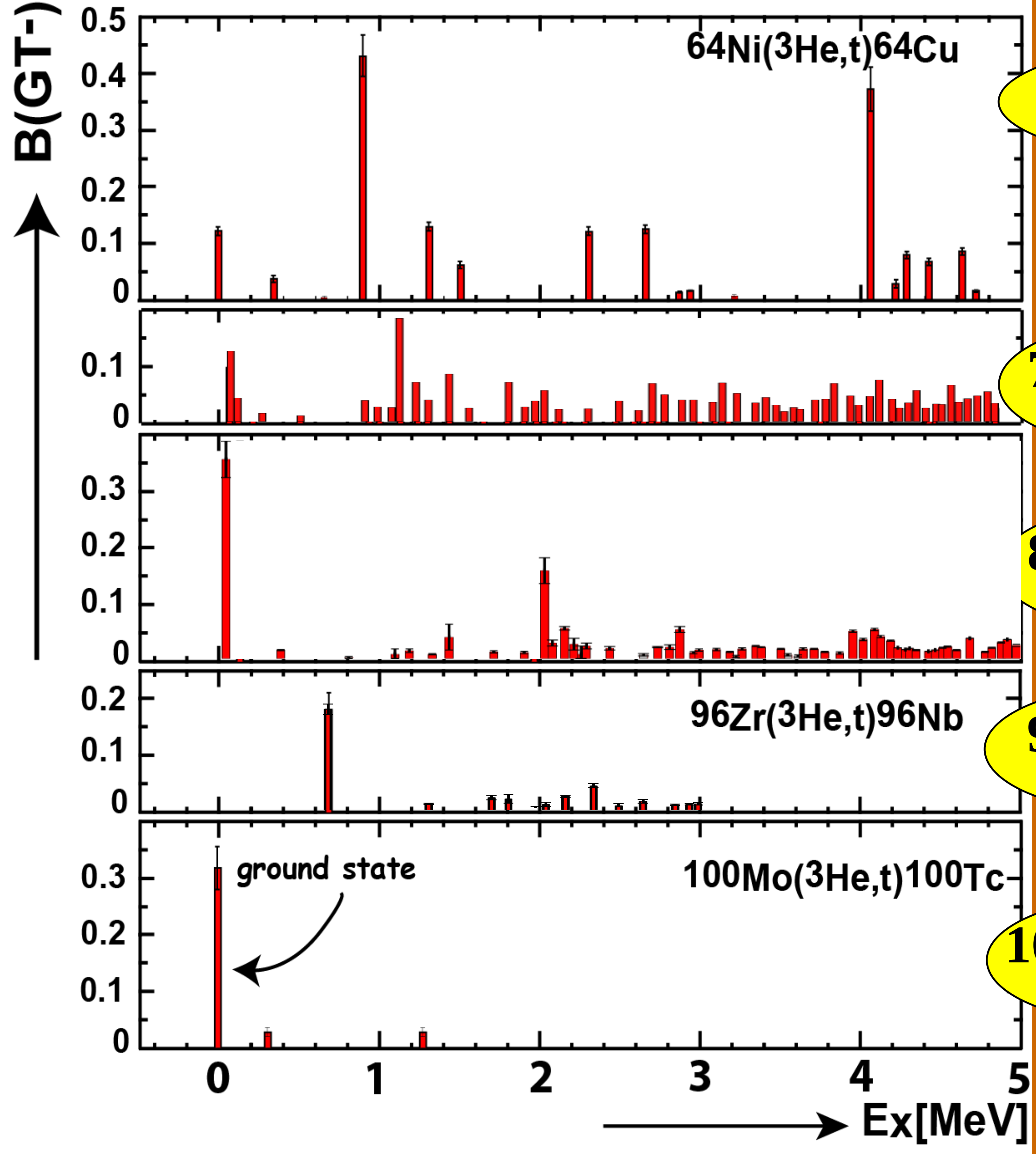
HERE: almost the entire low-E GT strength is concentrated in the g.s.



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

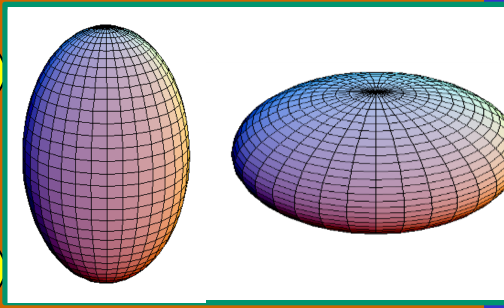
$$M^{2\nu}_{DGT}(\text{g.s.}) \sim \mathbf{0.88} \cdot M^{2\nu}_{DGT}(\text{total})$$

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⁻)

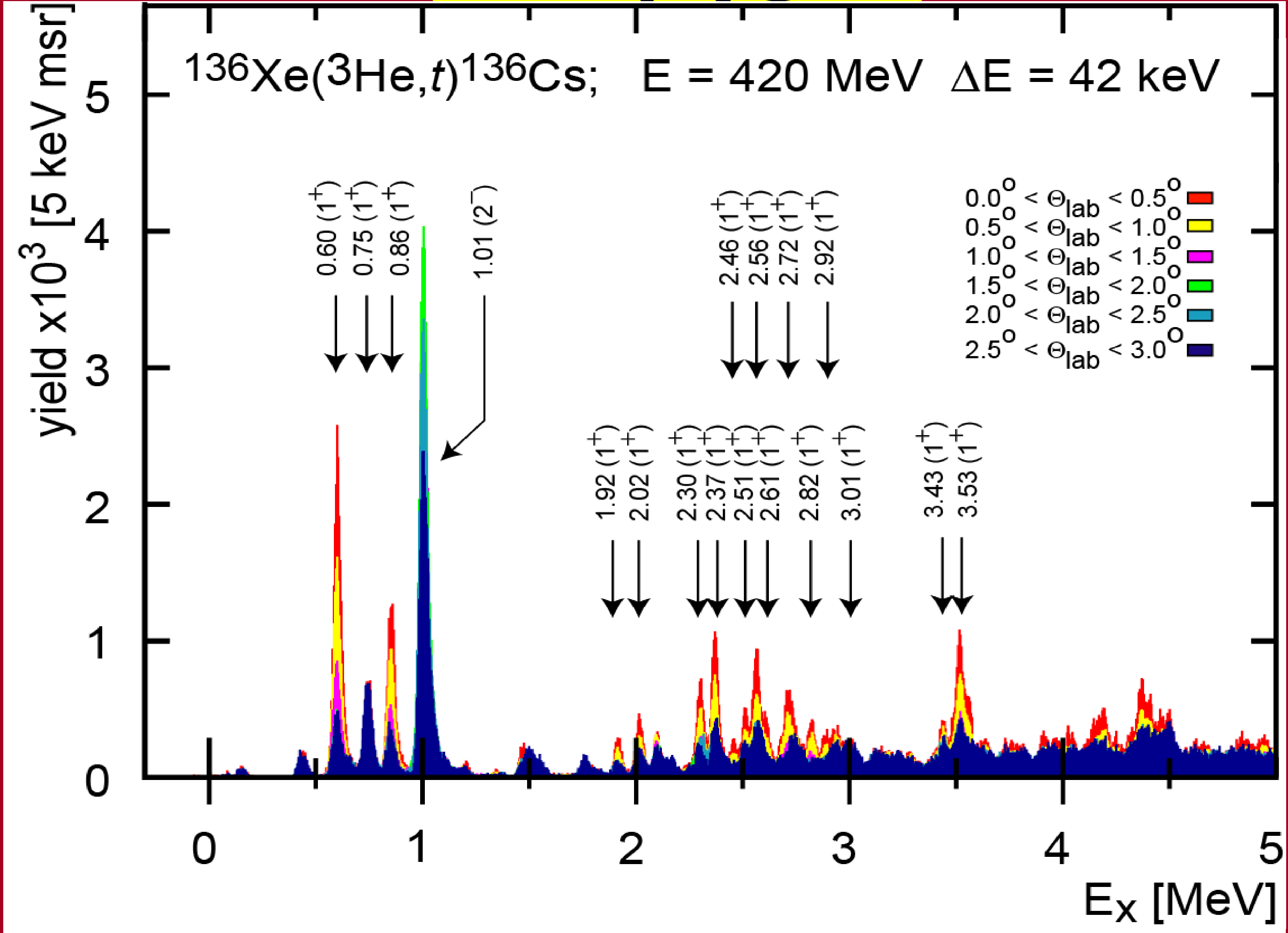
reduced fragmentation of GT strength

^{136}Xe

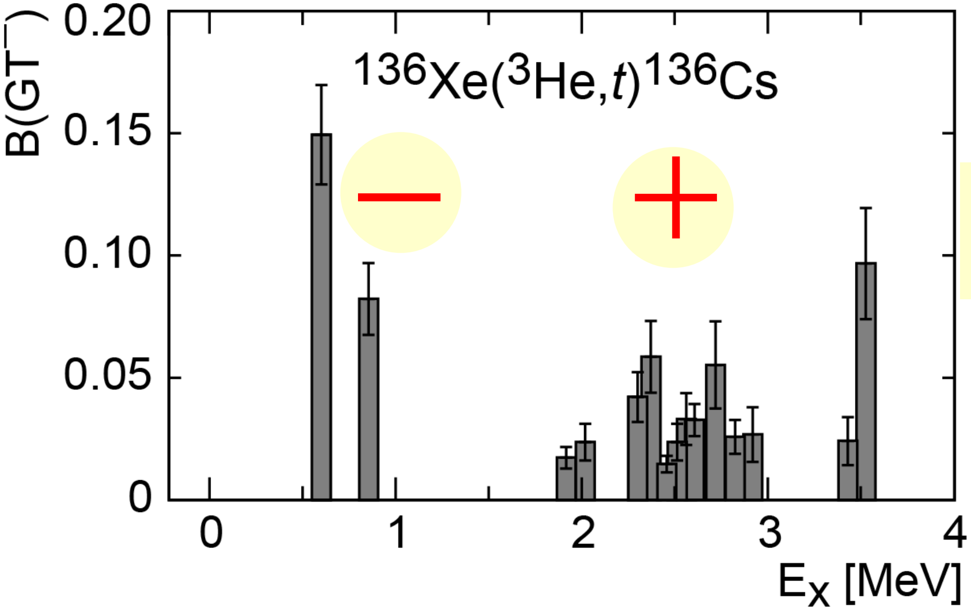
$N-Z=28$

question: why so stable !!!

136Xe

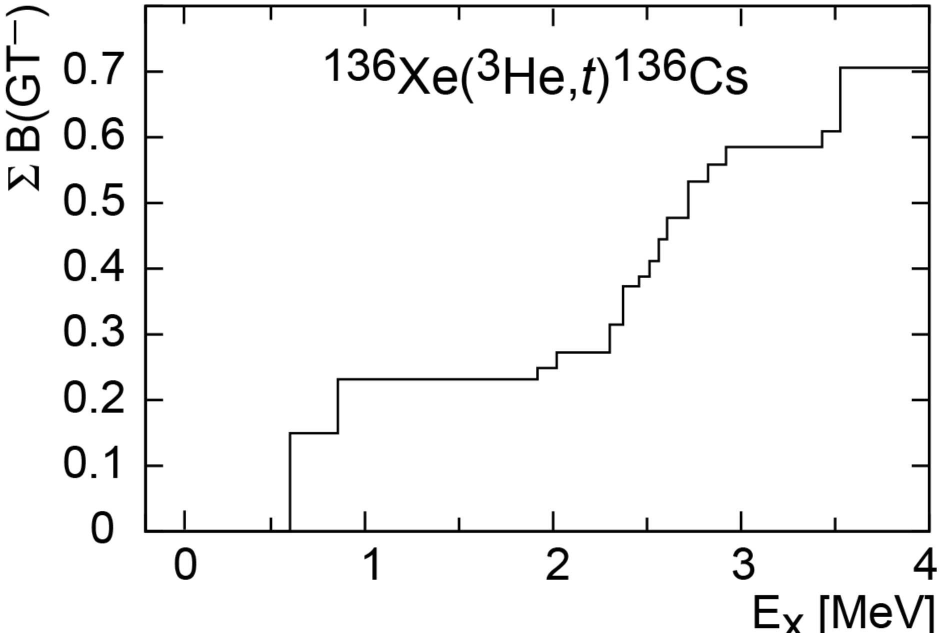

136Xe(3He,t)136Cs; E = 420 MeV ΔE = 42 keV
yield x10³ [5 keV msr]
0
1
2
3
4
5
Ex [MeV]
0.60 (1+)
0.75 (1+)
0.86 (1+)
1.01 (2−)
2.46 (1+)
2.56 (1+)
2.72 (1+)
2.92 (1+)
1.92 (1+)
2.02 (1+)
2.30 (1+)
2.37 (1+)
2.51 (1+)
2.61 (1+)
2.82 (1+)
3.01 (1+)
3.43 (1+)
3.53 (1+)
0.0° < Θlab < 0.5° 🟥
0.5° < Θlab < 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?



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

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



all signs positive —>

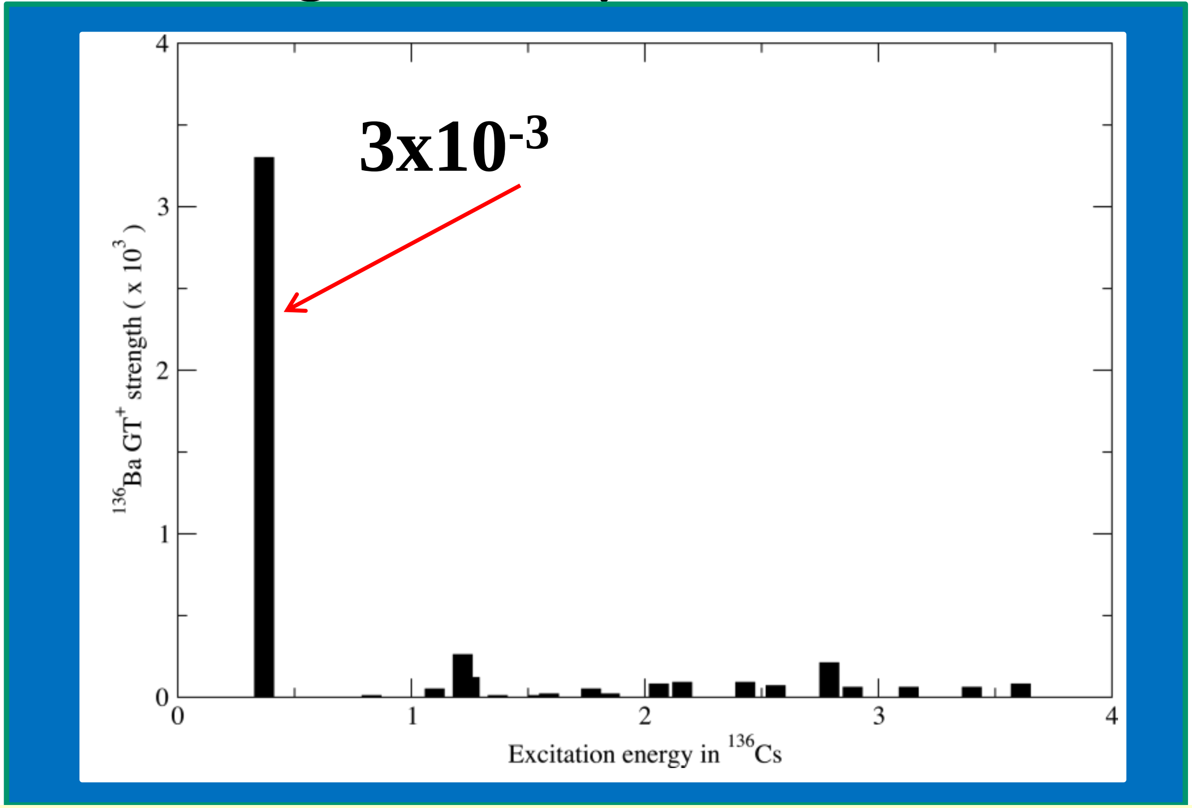
$$\mathrm{B_m}\ \ GT^{+}\ \approx 10^{-2}\cdot \mathrm{B_m}\ \ GT^{-}$$

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

A. Poves (simultaneous to our publication):

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

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

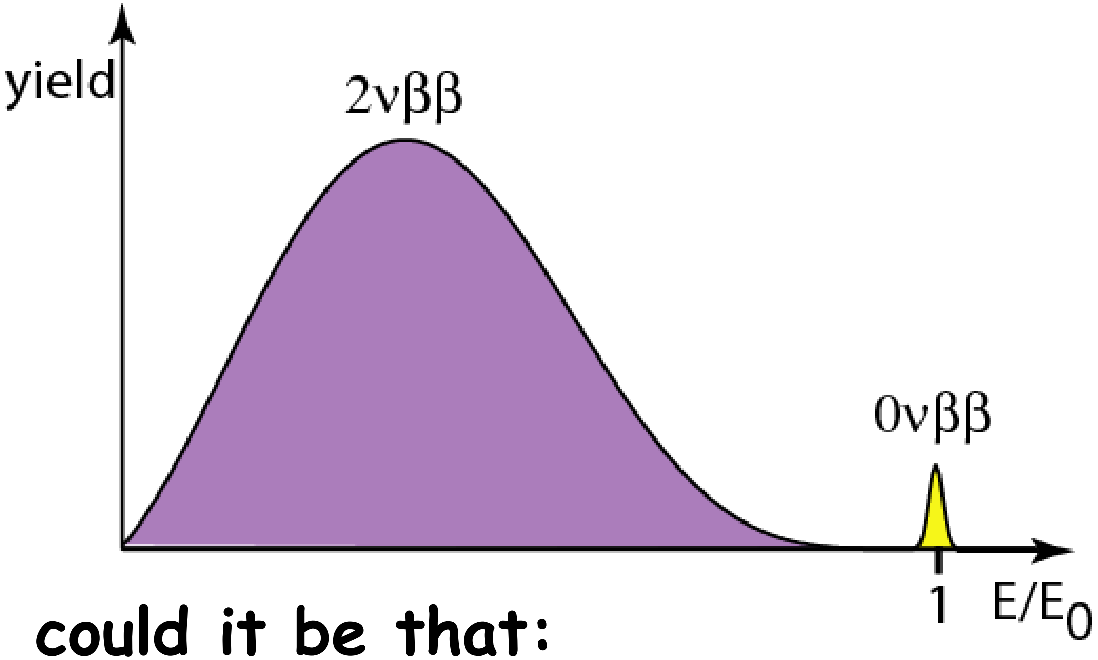


Shell model provides explanation for the deemed „pathologically" long half-life of ^{136}Xe.
Expt'l test: ^{136}Ba(d,^{2}He)^{136}Cs

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

expmt: 2νββ NME is exceptionally small

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



could it be that:

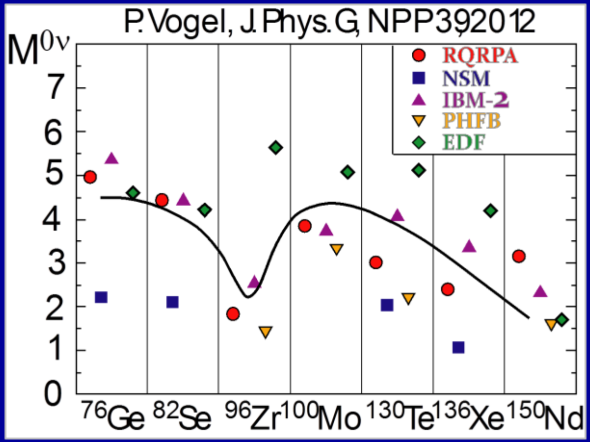
2νββ ME is suppressed AND

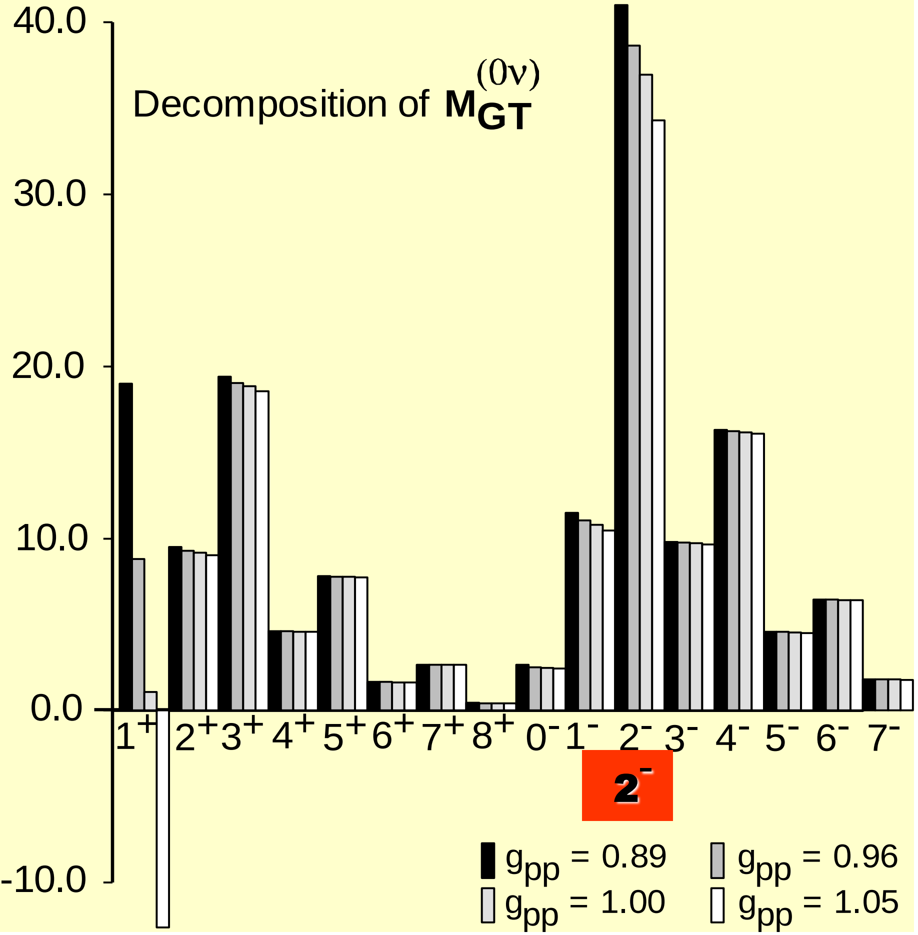
0νββ ME is enhanced ???

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

Here:

2^- states and occupation vacancy numbers via chargex reactions

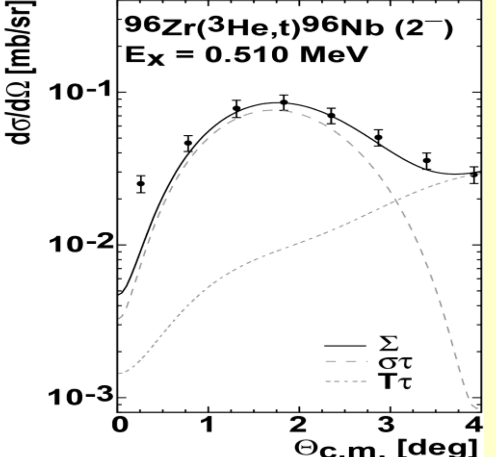


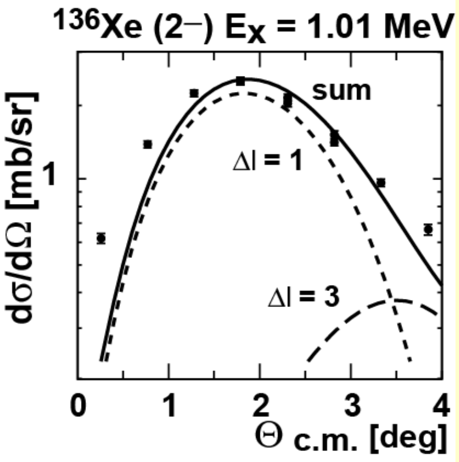


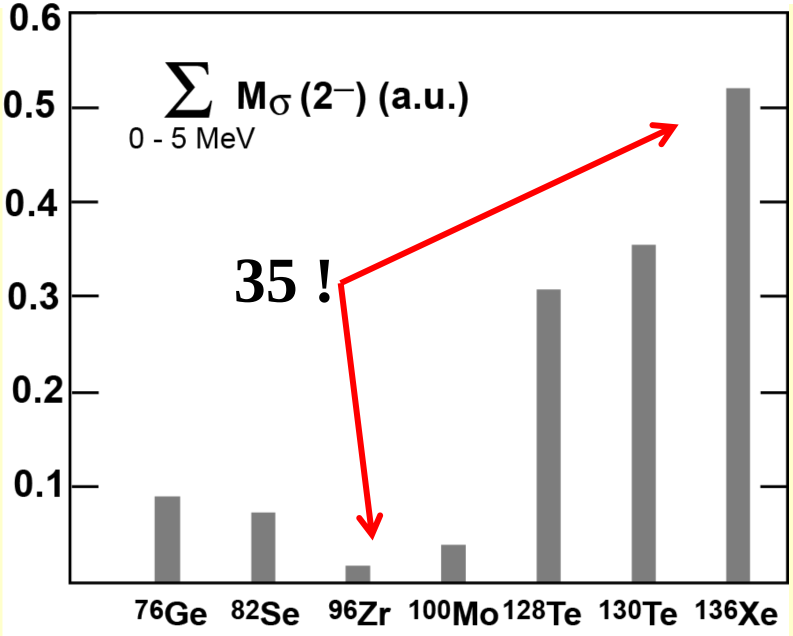
Theory:

The 2^- strength makes up ~ 20-30% of the $0\nu\beta\beta$ ME!!

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





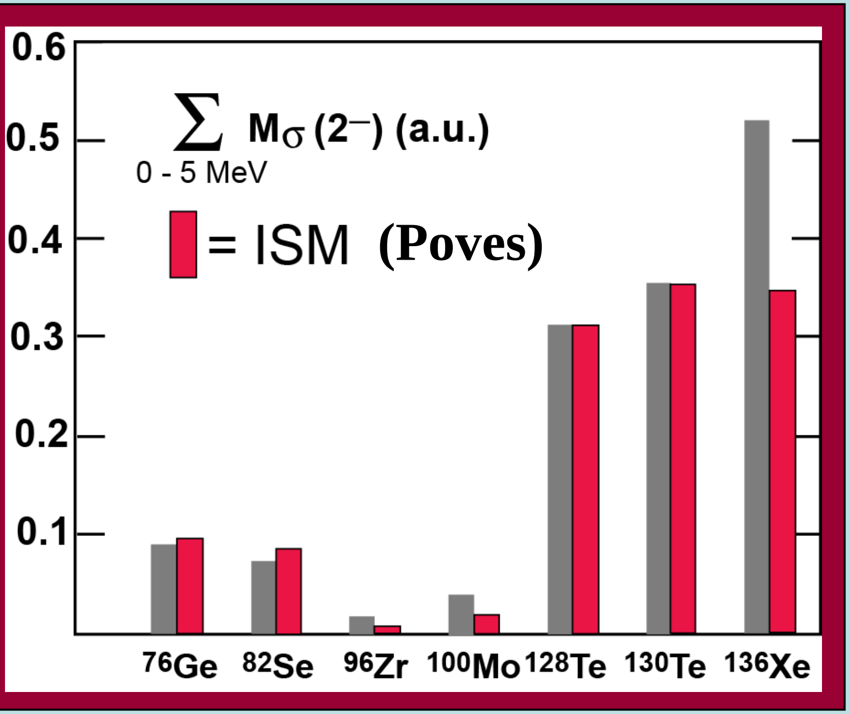


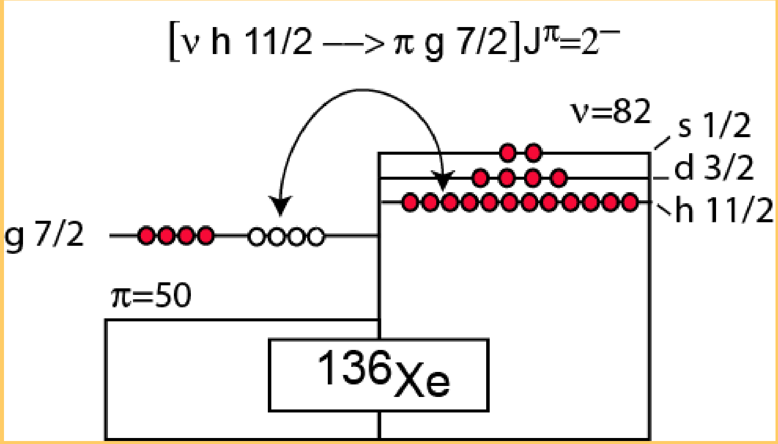
relative 2^- strength to ~ 5 MeV

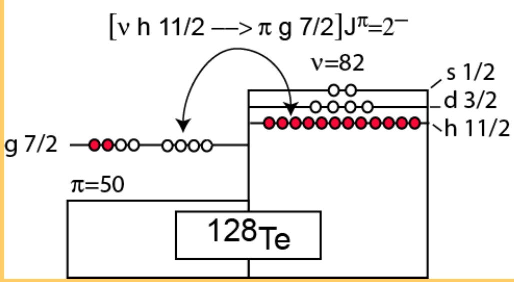
Expmt:

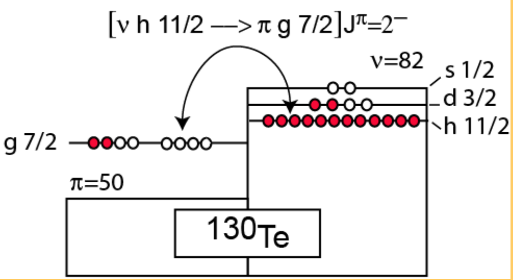
^{136}Xe exhibits largest 2^- strength

$0\nu\beta\beta$ ME enhanced?!?!




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


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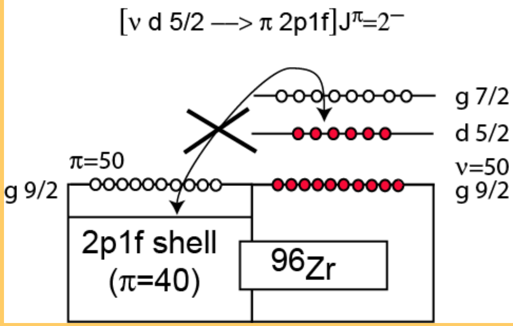
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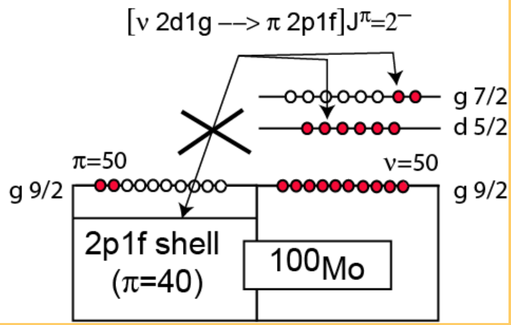
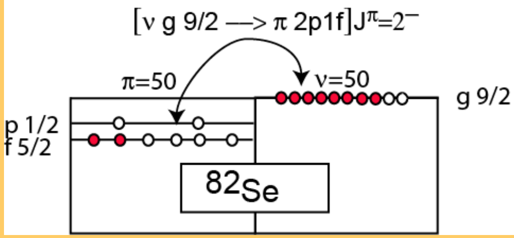

$[\nu\ 2d1g \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$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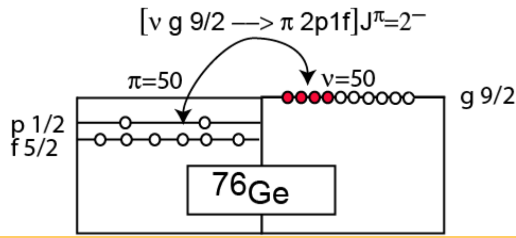
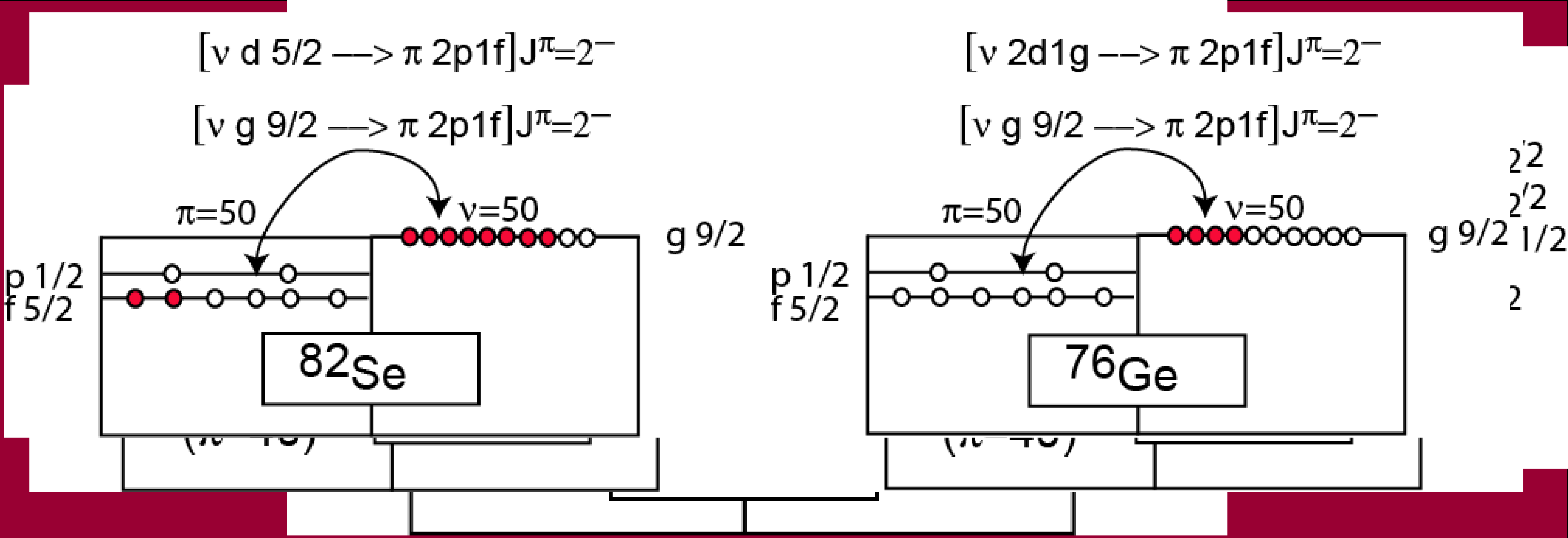
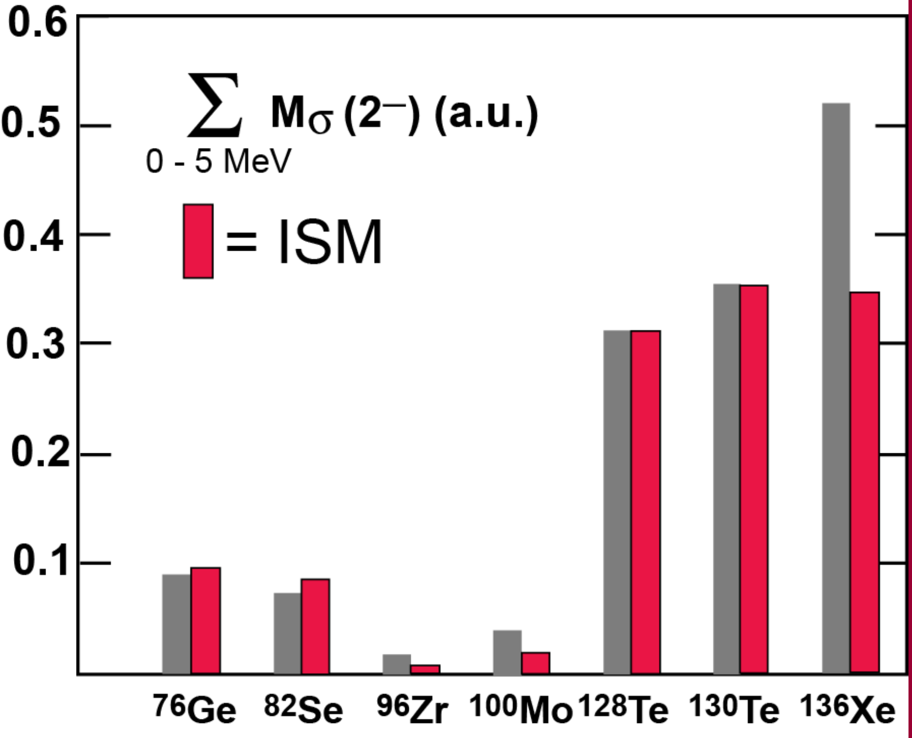
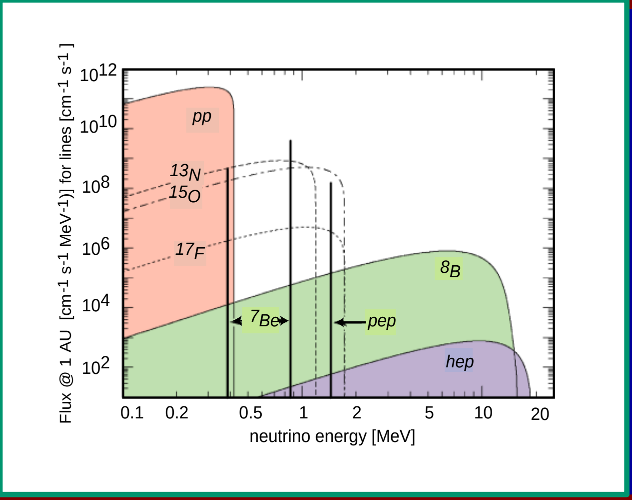

$[\nu\ g\ 9/2 \longrightarrow \pi\ 2p1f]J^{\pi}=2^{-}$


[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

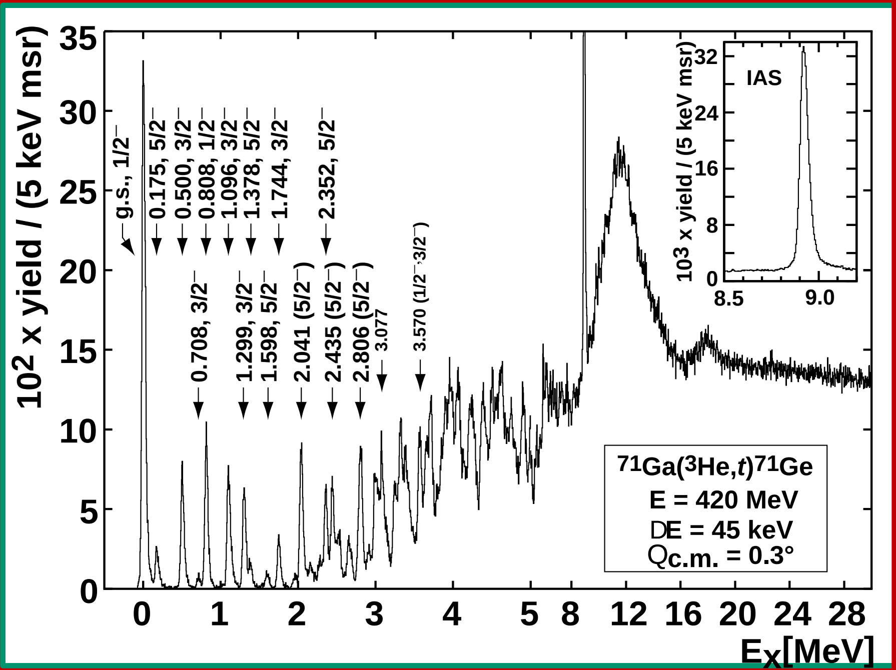

$\sum_{0-5\ \mathrm{MeV}} M_\sigma(2^-)$ (a.u.)
🟥 = ISM
0.6
0.5
0.4
0.3
0.2
0.1
76Ge
82Se
96Zr
100Mo
128Te
130Te
136Xe

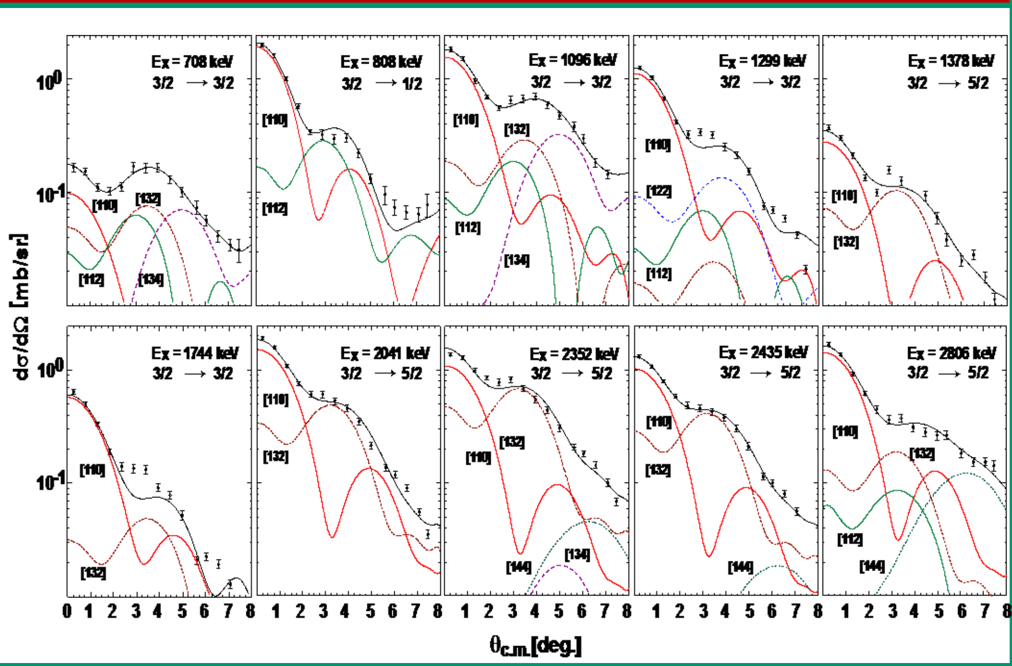


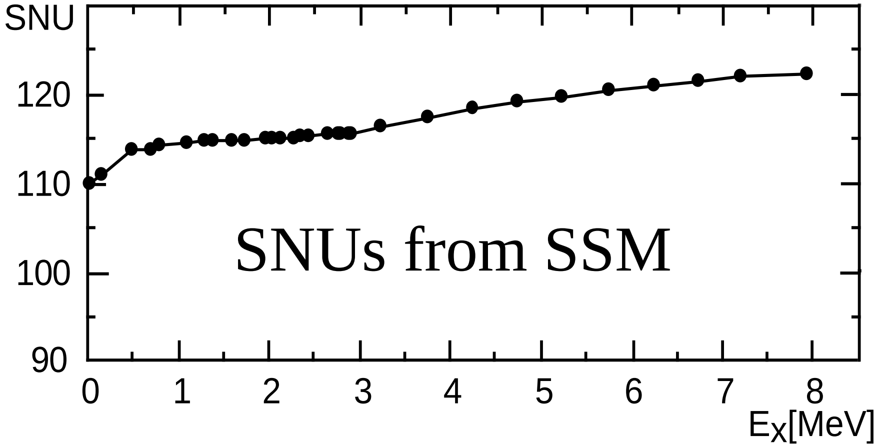
solar neutrino rates via (^{3}He,t)

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

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







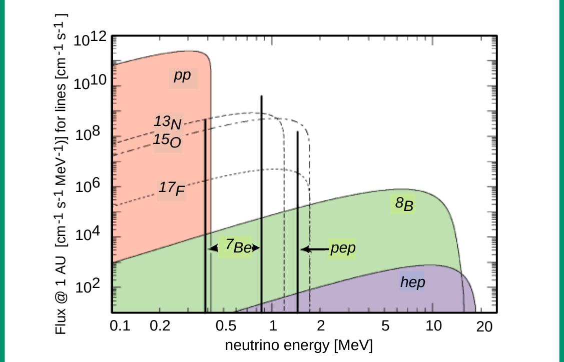
^{71}Ga($\nu_\odot$,e$^-$)

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

stat. err. mostly due to CNO ν's

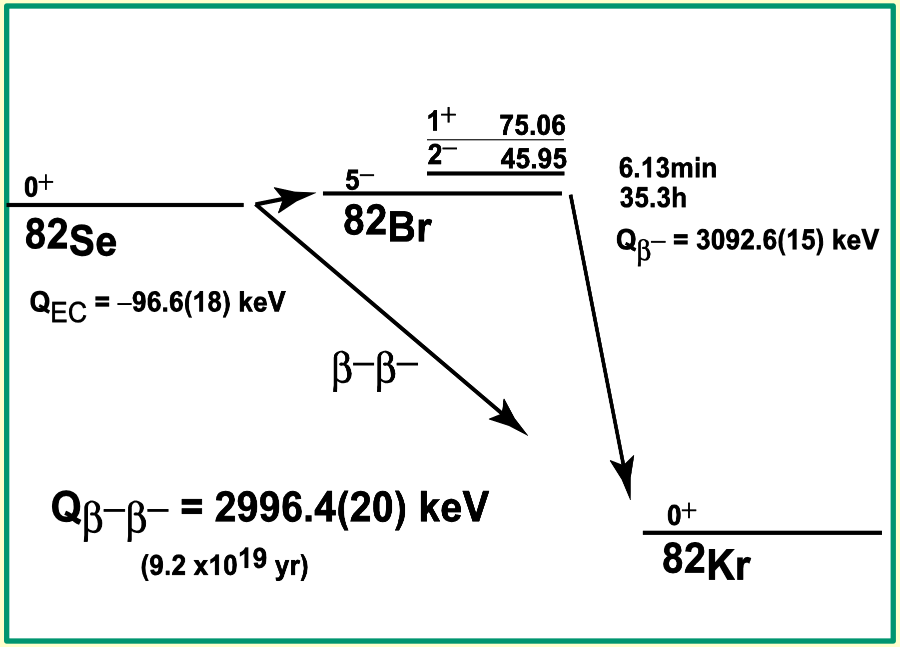
prev'ly:132 ± 18

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



1^+ 75.06

2^- 45.95

0^+

5^-

82Se

82Br

6.13min

35.3h

Q_{β^-} = 3092.6(15) keV

Q_{EC} = –96.6(18) keV

$\beta^-\beta^-$

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

(9.2×10^{19} yr)

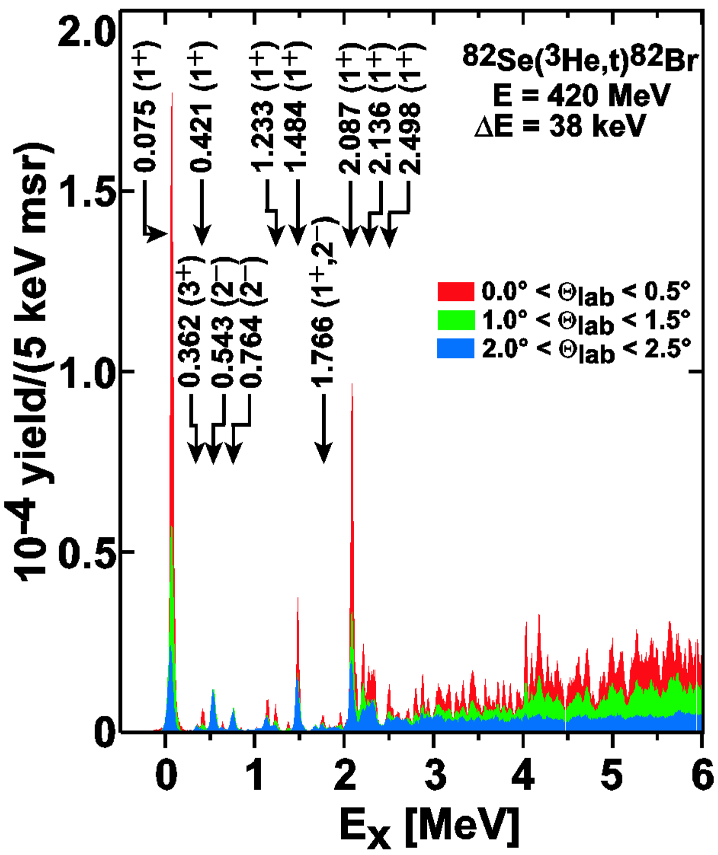
0^+

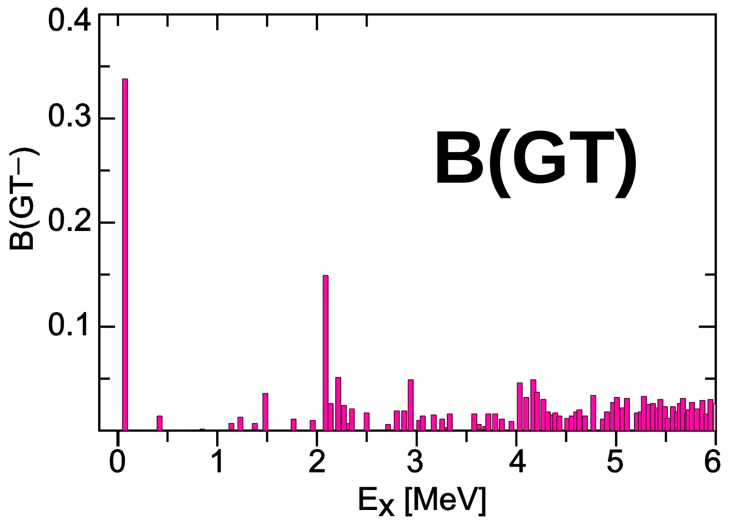
82Kr

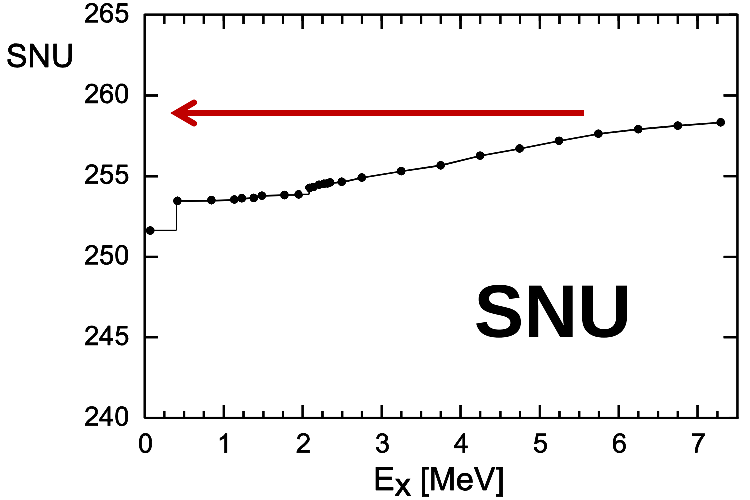
Advantages:

- ➢ 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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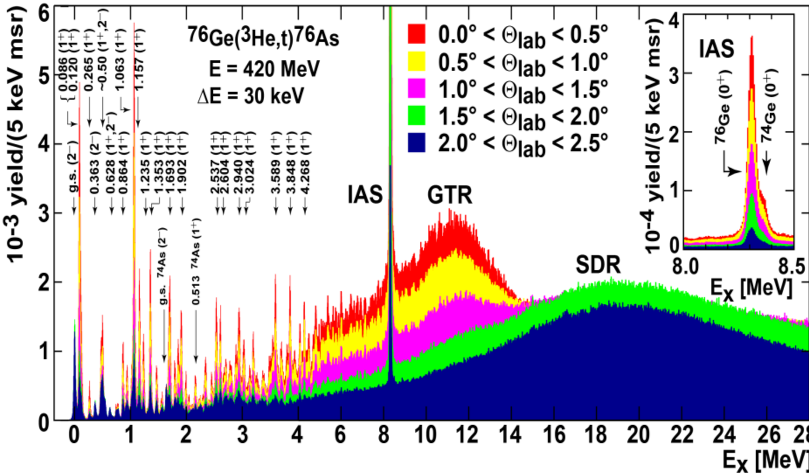
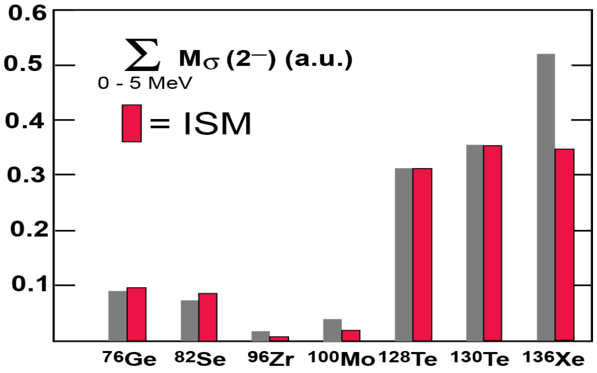
MÜNSTER

Future perspectives of chargex-reactions

- **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 0νββ decay and the quenching issue <u>urgently!!</u>**
  - New ideas to tackle the problem needed
  - DCX could play a pivotal role for ββ decay
  - DCX reaction could also shed light on the quenching of g_A

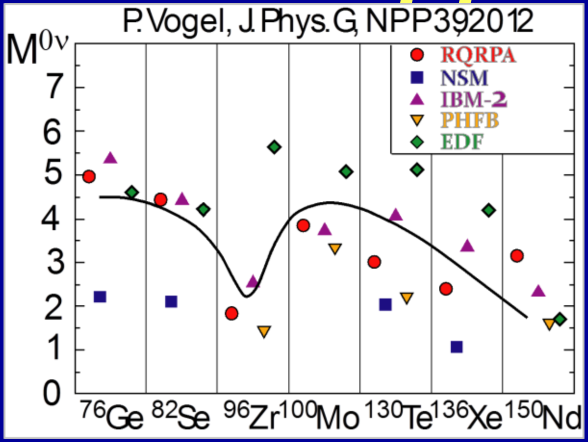
^{71}Ga($\nu_\odot$,e^-)

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

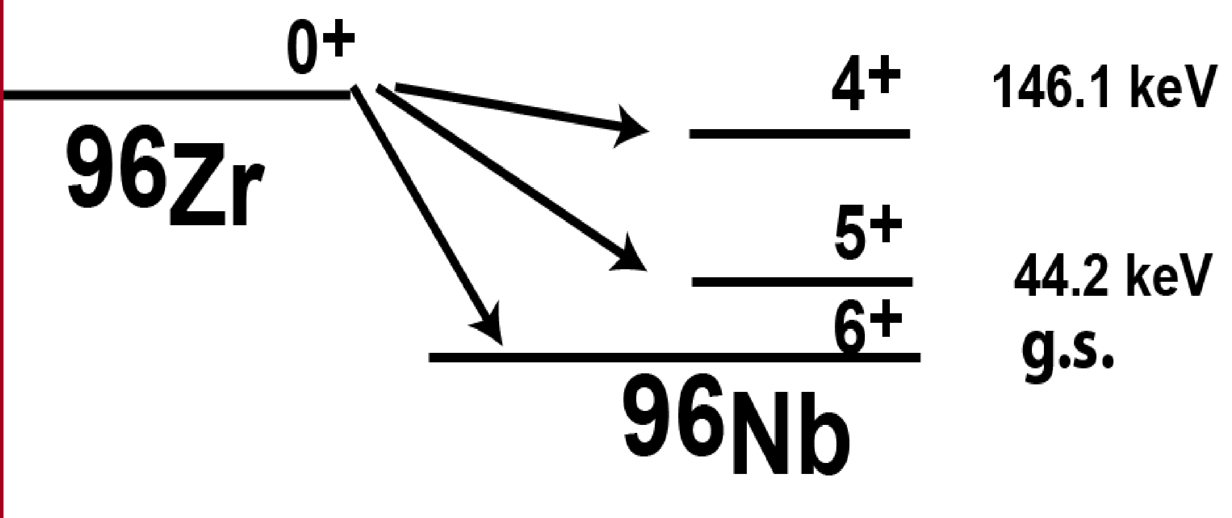
^{82}Se($\nu_\odot$,e^-)

$R = 258.4$ SNU

experiments towards the 0νββ NMEs


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

the A=96 system in ββ decay



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

two conflicting half-lives:

NEMO-3: $T^{2\nu\beta\beta}_{1/2} = (2.3\pm0.2)\times10^{19}\,\mathrm{y}$

geo-chem: $T_{1/2} = (0.94\pm0.32)\times10^{19}\,\mathrm{y}$ ①

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

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

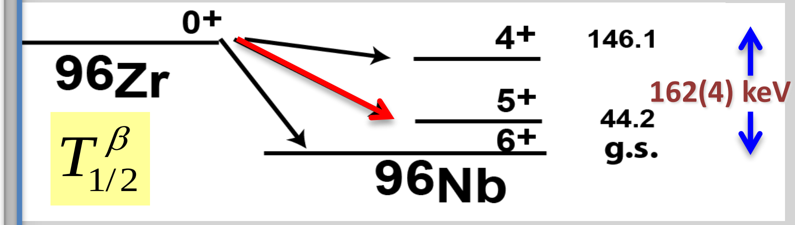
expected $T^{\beta}_{1/2} = (1.6\pm0.9)\times10^{19}\,\mathrm{y}$

experiment $T^{\beta}_{1/2} > 2.6\times10^{19}\,\mathrm{y}$ ②

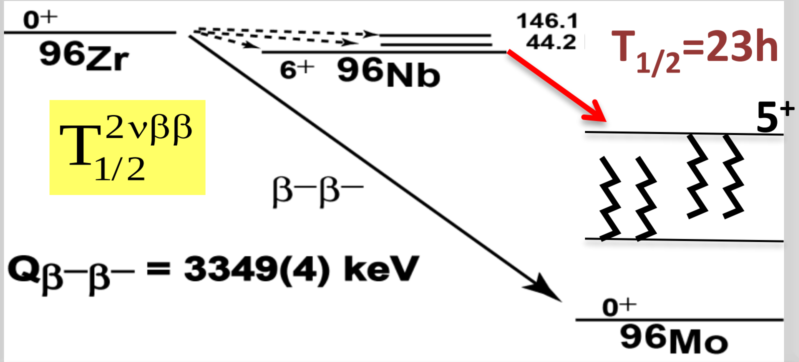
pred. (QRPA) $T^{\beta}_{1/2} = 24\times10^{19}\,\mathrm{y}$ ③

BUT

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



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

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

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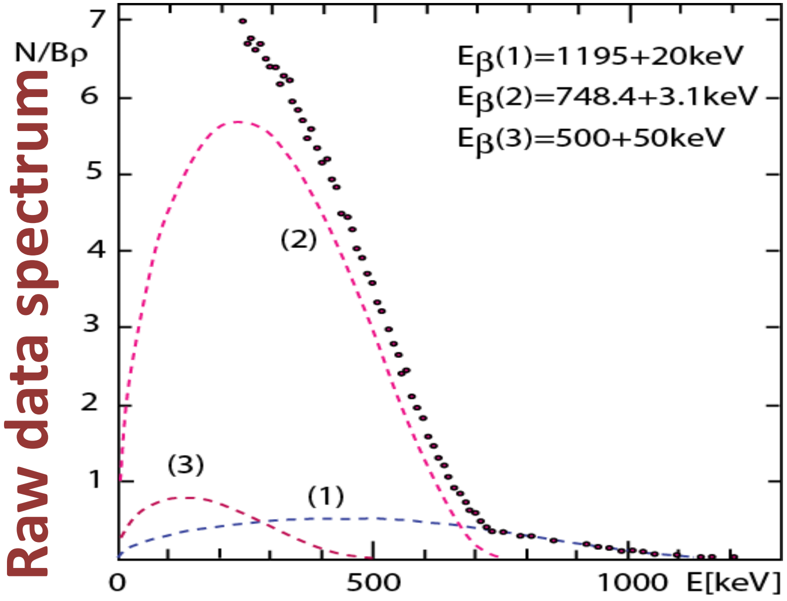
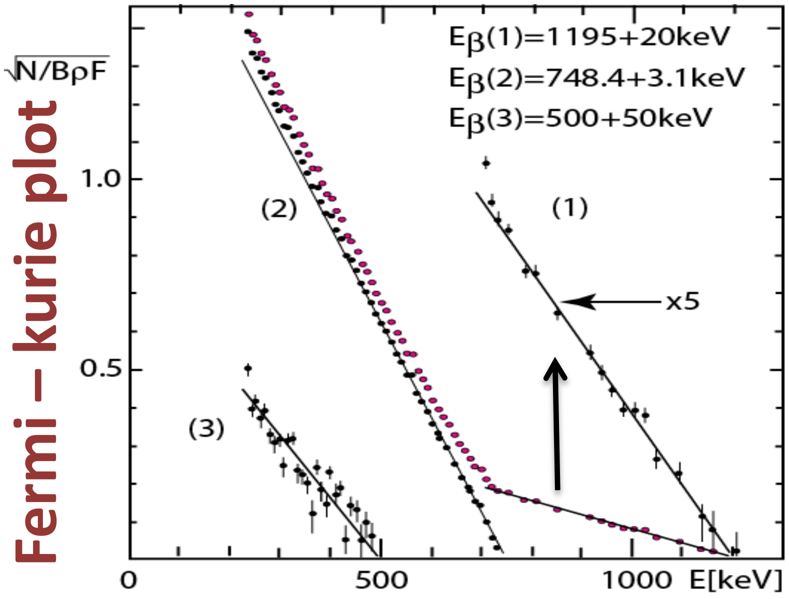
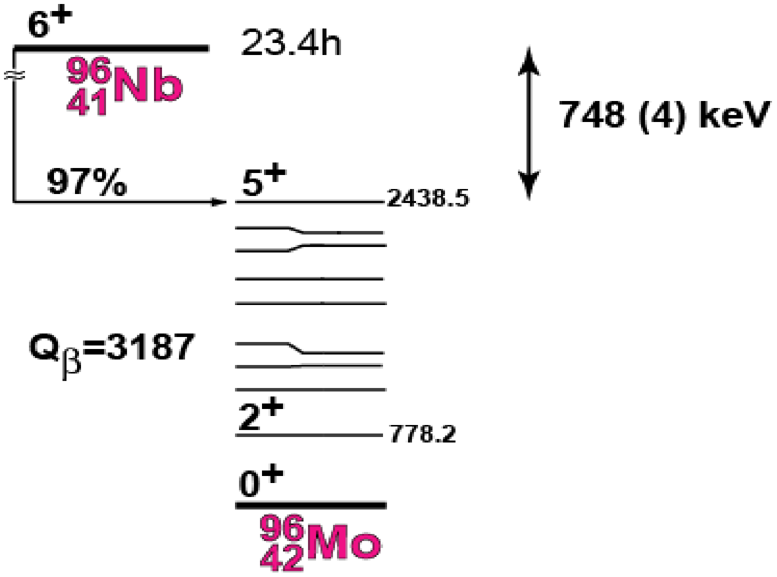
The only ^{96}Nb mass: deduced from β^- decay end point energy {Antman et al. NPA 110 1968}





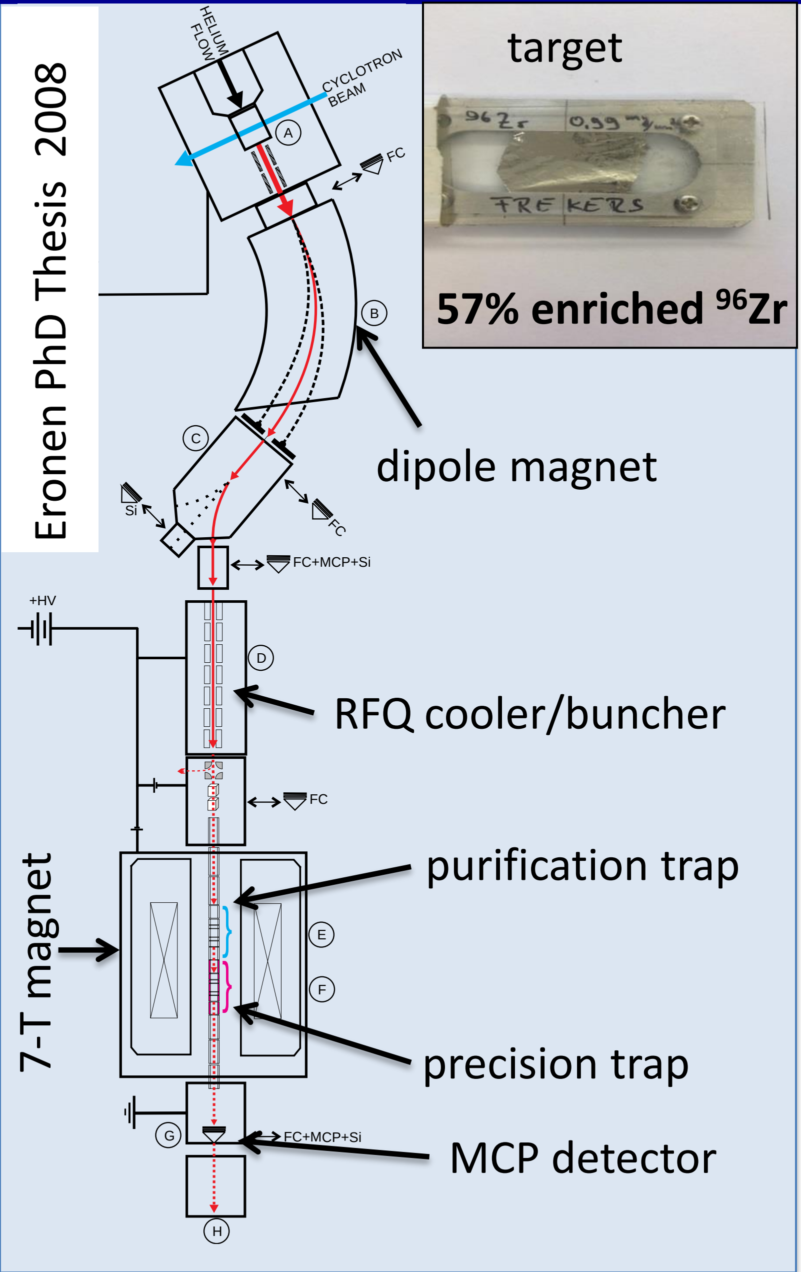


the 1195 keV is NOT a ^{xx}Nb long-lived isomer!!

the 500 keV transition does NOT exist.
→ fit depends on 2 transitions, which don't exist!!

→ Q-value is in doubt !!

IGISOL/JYFLTRAP mass measm'nts



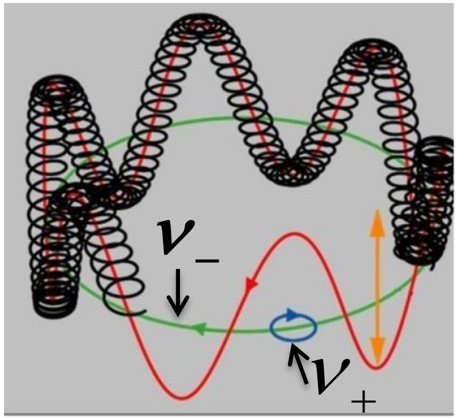
57% enriched ^{96}Zr

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

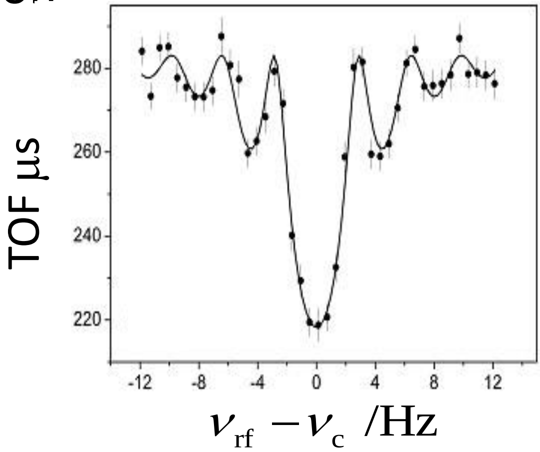
- ➢ performing accurate mass measurements via cyclotron frequency

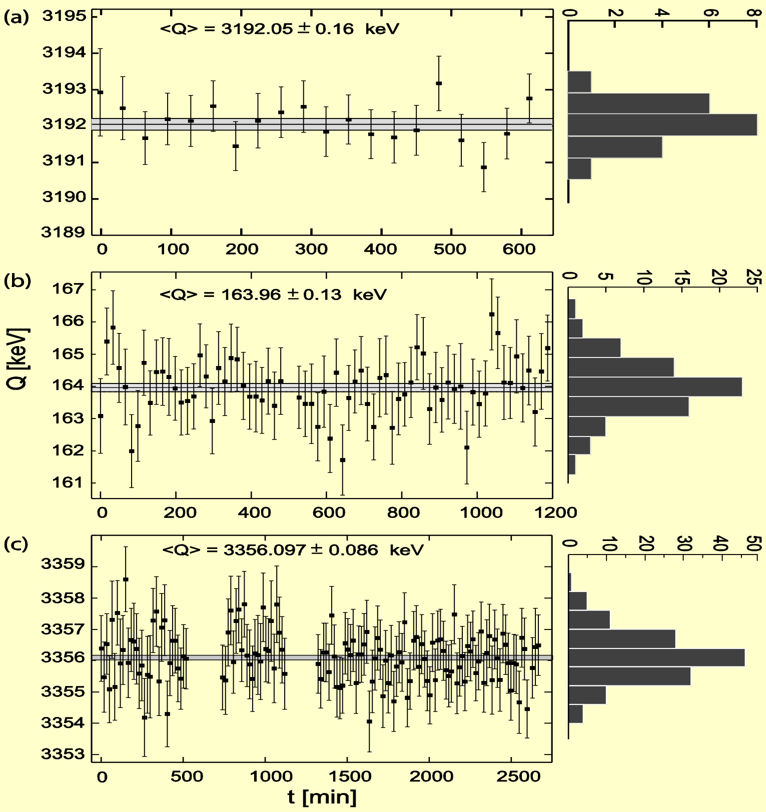
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}\cdot \mathrm{B}$$

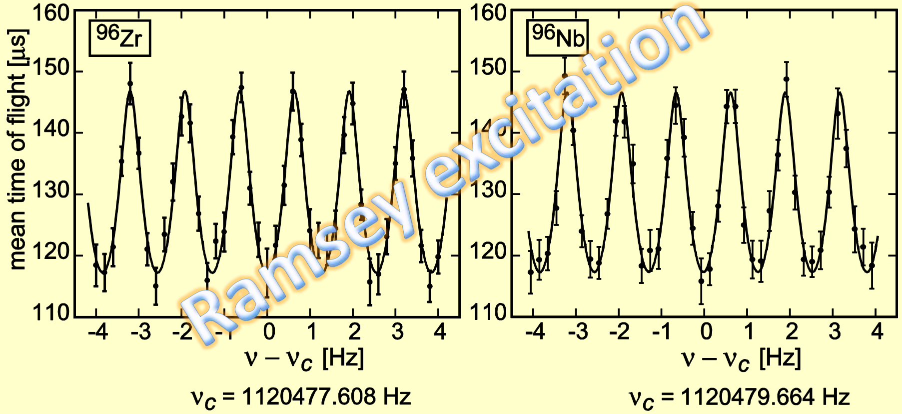
$$\nu_c = \nu_- + \nu_+$$

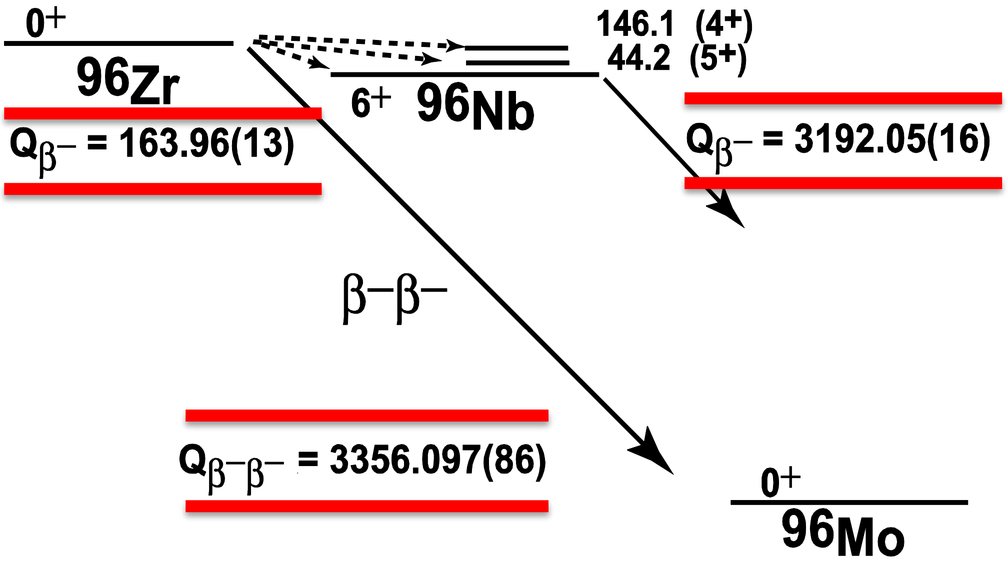


- ➢ frequency determination done by **TOF-ICR** technique









0^+

^{96}Zr

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

146.1 (4^+)

44.2 (5^+)

6^+ ^{96}Nb

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

$\beta^-\beta^-$

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

0^+

^{96}Mo

96Zr

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

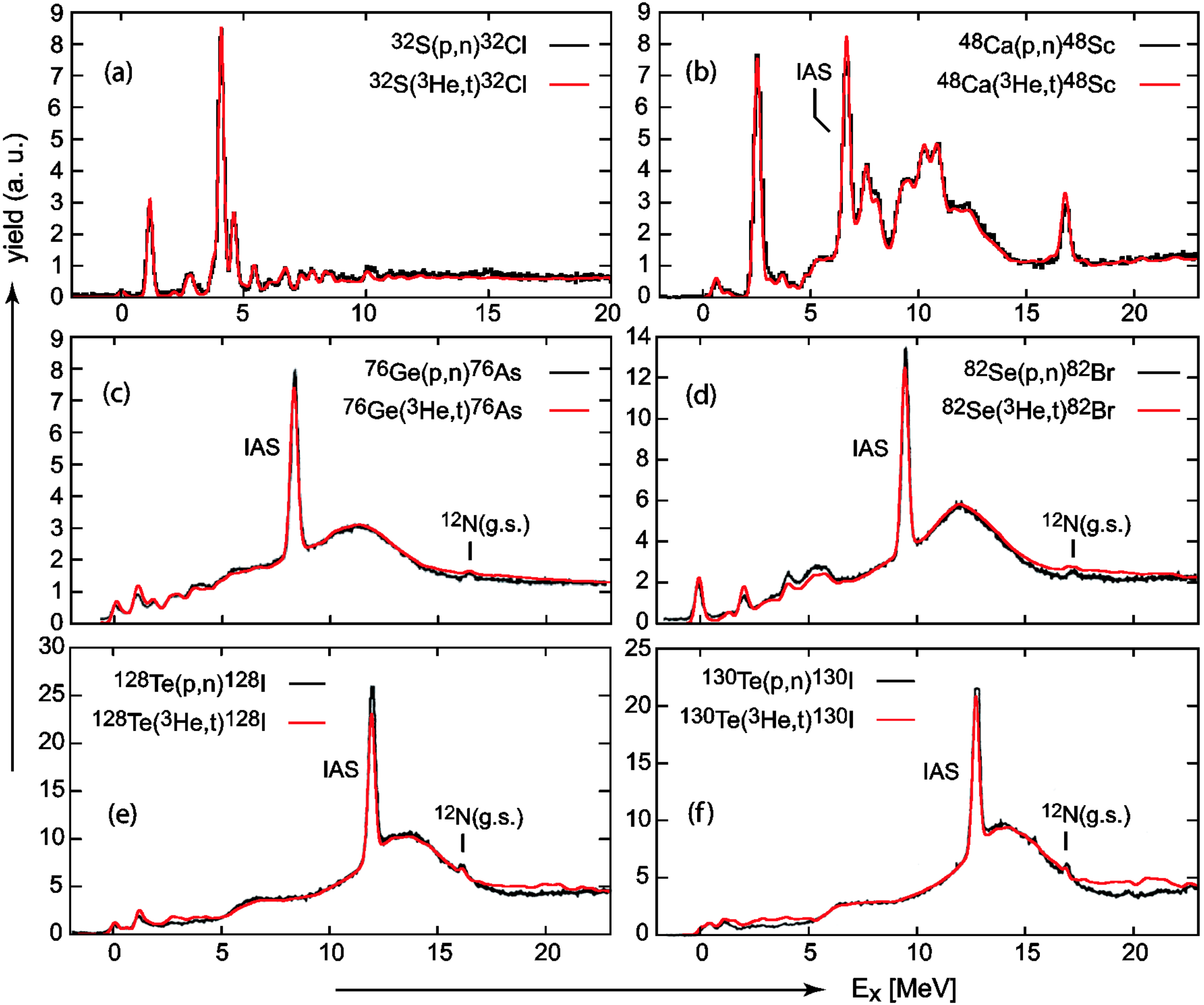
7.1 keV higher than AME2012

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

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

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

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


(a)
$^{32}S(p,n)^{32}Cl$
$^{32}S(^3He,t)^{32}Cl$
(b)
IAS
$^{48}Ca(p,n)^{48}Sc$
$^{48}Ca(^3He,t)^{48}Sc$
(c)
$^{76}Ge(p,n)^{76}As$
$^{76}Ge(^3He,t)^{76}As$
IAS
^{12}N(g.s.)
(d)
$^{82}Se(p,n)^{82}Br$
$^{82}Se(^3He,t)^{82}Br$
IAS
^{12}N(g.s.)
(e)
$^{128}Te(p,n)^{128}I$
$^{128}Te(^3He,t)^{128}I$
IAS
^{12}N(g.s.)
(f)
$^{130}Te(p,n)^{130}I$
$^{130}Te(^3He,t)^{130}I$
IAS
^{12}N(g.s.)
yield (a. u.)
E_x [MeV]
0
5
10
15
20
0
1
2
3
4
5
6
7
8
9
12
14
25
30