DF

European Supernova Collaboration

D. Frekers
University Münster

Westfälische Wilhelms-Universität Münster

FACETS OF (d,^{2}He) CHARGE-EXCHANGE REACTIONS:
from few-body physics to astrophysics to double beta decay

astrophysics !

double-beta decay

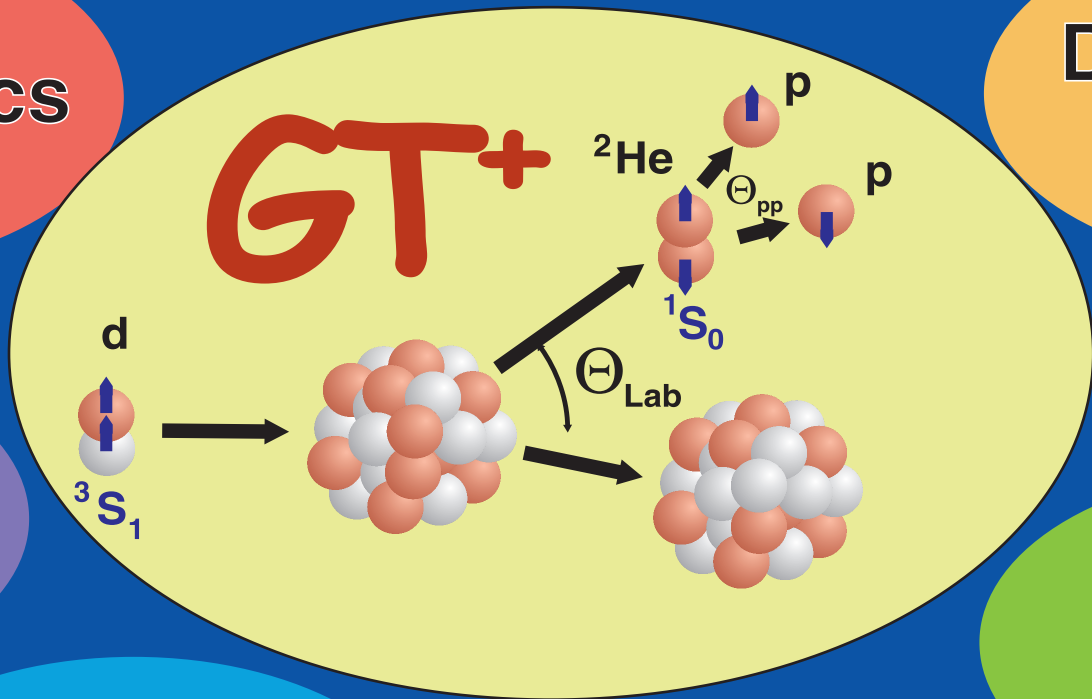
NN-studies

halo nuclei

stretched states

(d,^{2}He) research potential

- Astrophysics
- Double beta decay
- Isospin symmetry
- Few-body (a_{nn})



- Quantum entanglement
- Halo nuclei

The (d,^{2}He) reaction

1)- reaction mechanism forces a spin-flip and an isospin-flip !
$\Delta S=1$, $\Delta T=1$ perfect GT filter

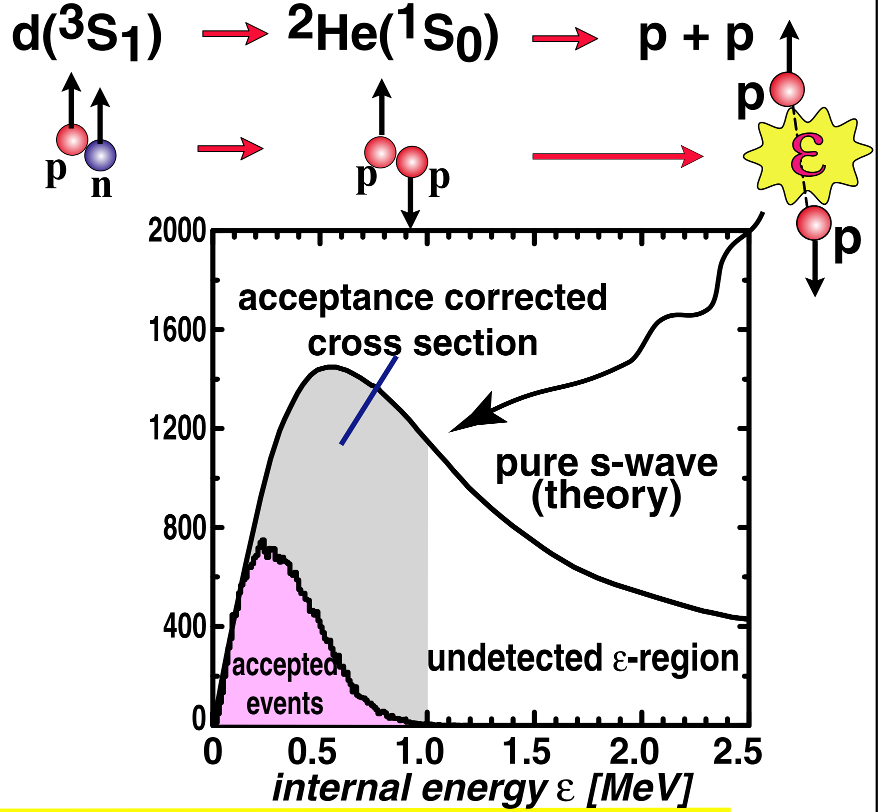
2)- coincident detection of two protons from ^{2}He decay
➡ background-free spectra
but need large accptnc spectrometer

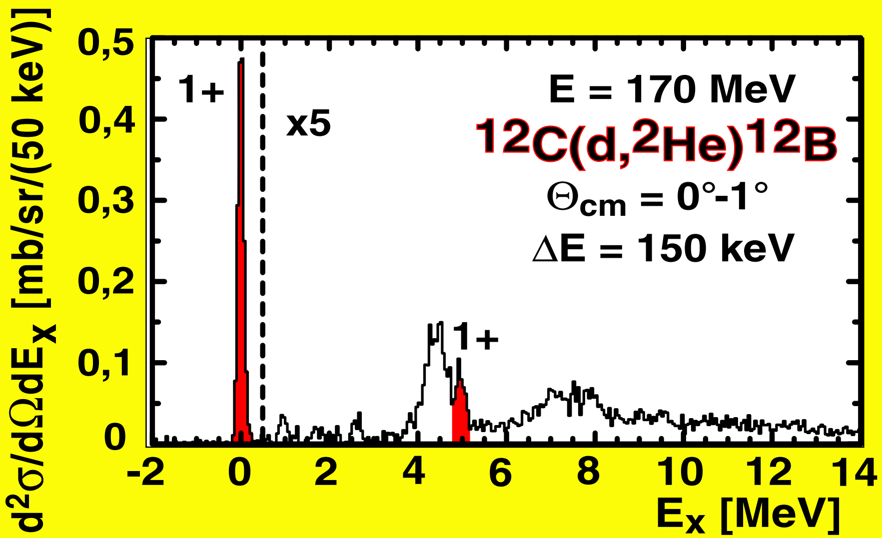
3)- contributions from higher p-p partial waves? Dont'worry!!

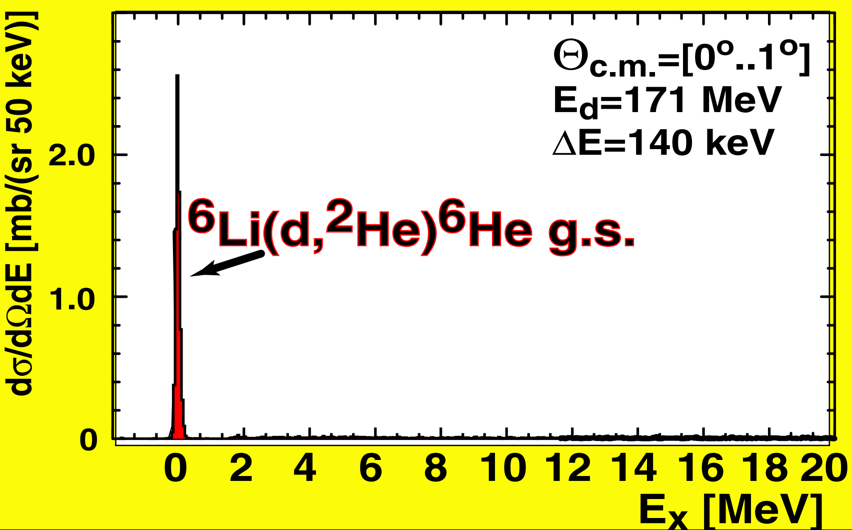
Alternatives:

(n,p) resolution?? Fermi transition
(t,^{3}He) triton beam?? Fermi transition
(HI,HI) resolution?? reaction mechanism??

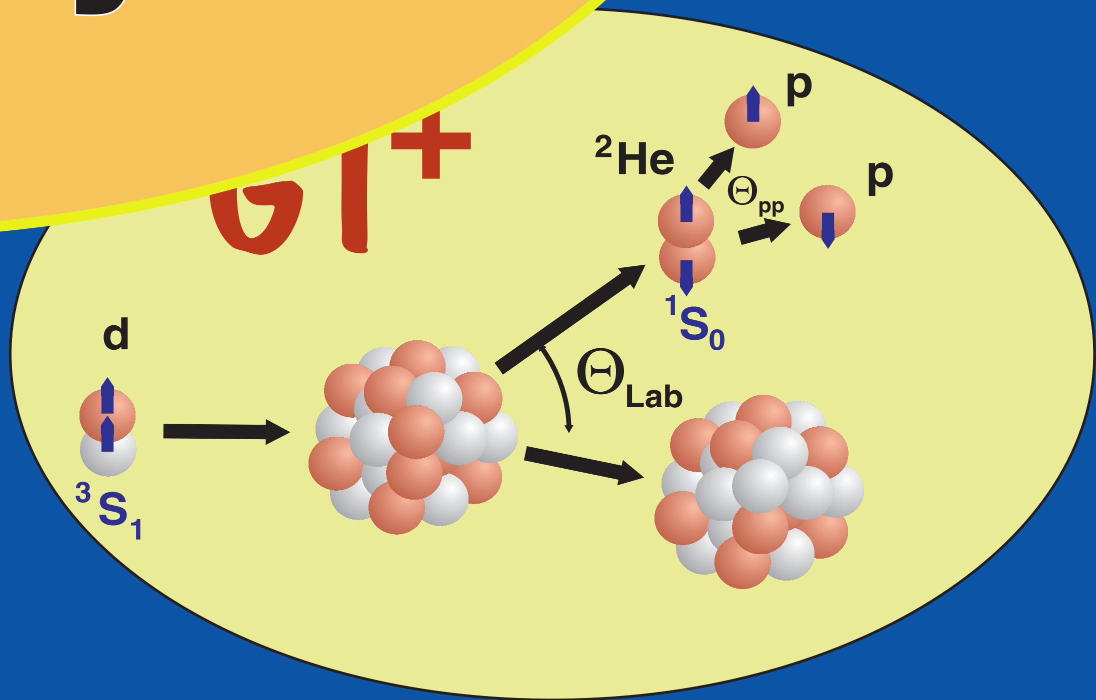
S=1, T=0 → S=0, T=1



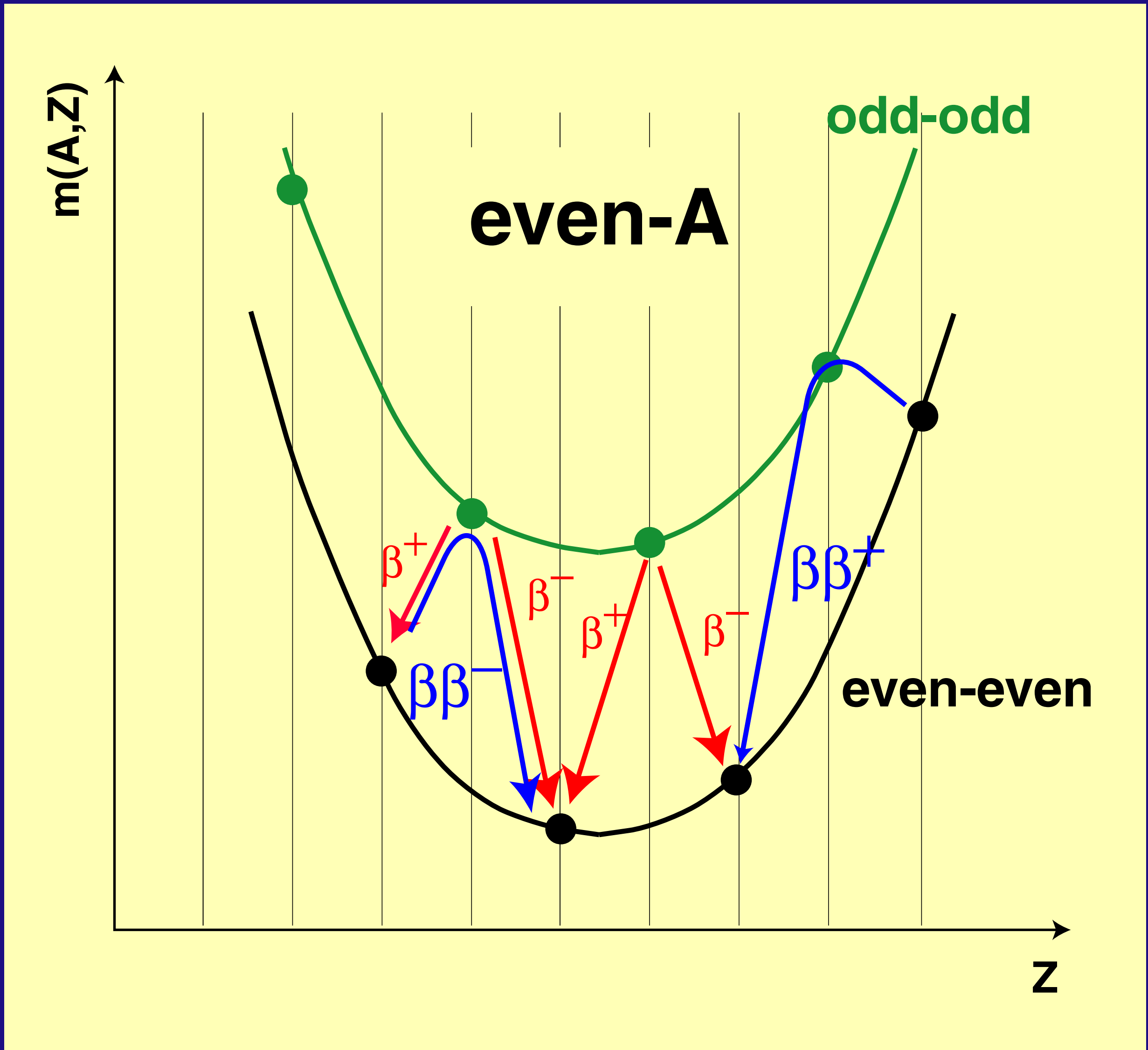


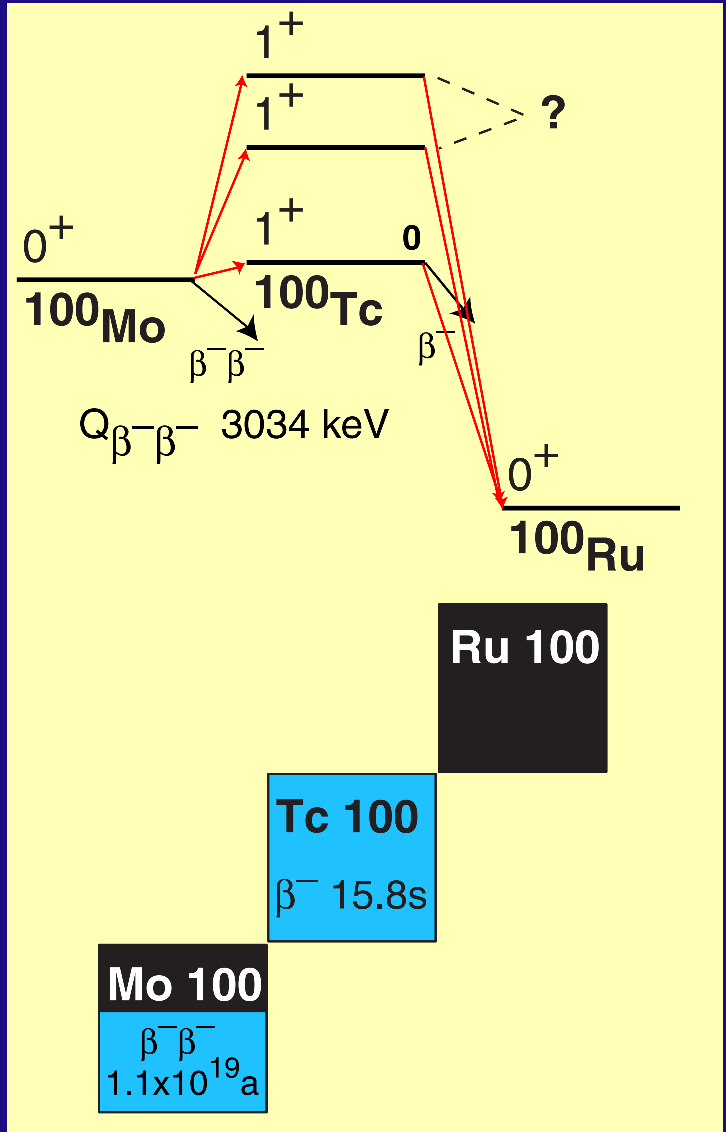


Double beta decay



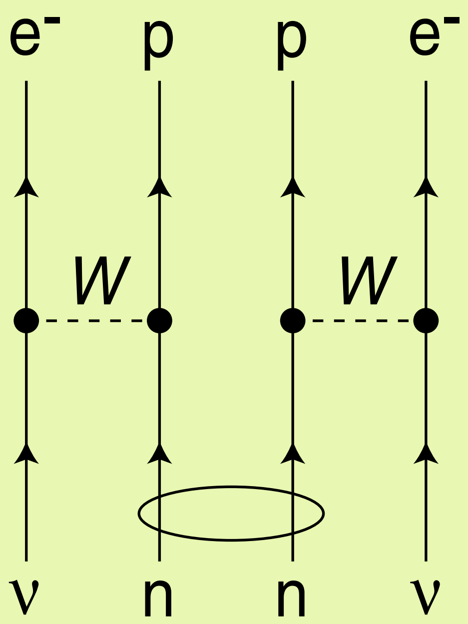
Nuclear double beta decay





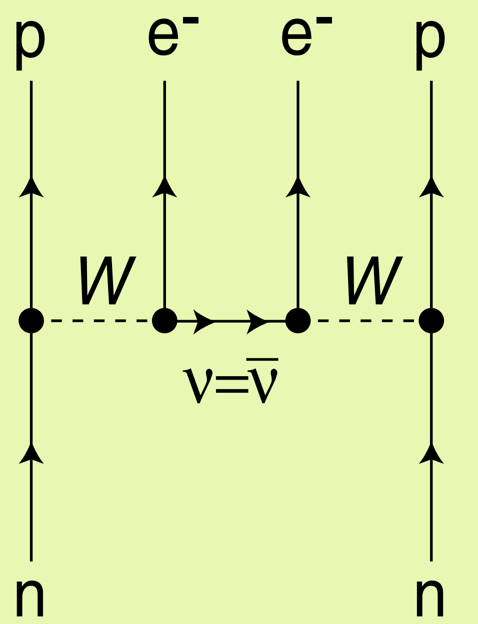
Important ββ decay modes

(2νββ)



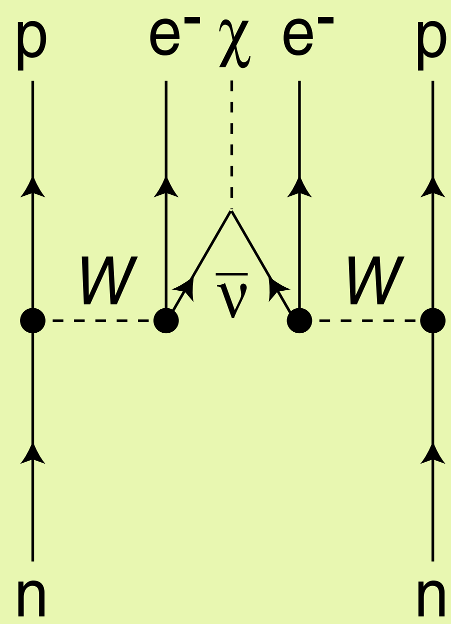
Dirac-Decay

(0νββ)



Majorana-Decay

(0νχββ)



Majoron-Decay

0νββ-decay: half-life & neutrino mass

$$\left[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G^{0\nu}(E_0, Z)\left|M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu}\right|^2 \langle m_\nu \rangle^2$$

measure! — look up — nuclear structure — ν mass

$$M_{GT}^{0\nu} = \langle f \left| \sum_{lk} \sigma_l \cdot \sigma_k \tau_l^+ \tau_k^+ H(r_{lk}, \overline{A}) \right| i \rangle$$

$$M_F^{0\nu} = \langle f \left| \sum_{lk} \tau_l^+ \tau_k^+ H(r_{lk}, \overline{A}) \right| i \rangle$$

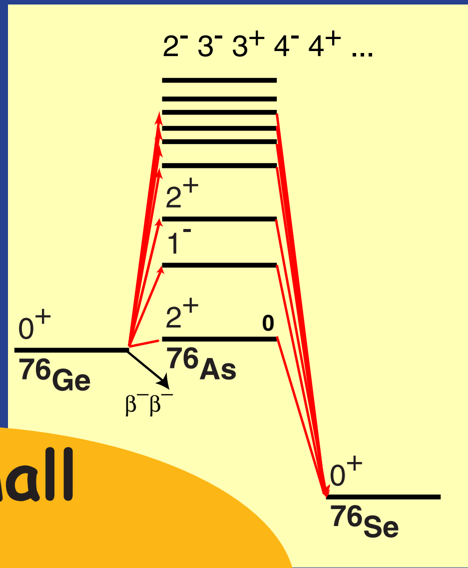
Neutrino potential (ν's don't escape from nucleus)

$0\nu\beta\beta$-decay: half-life & neutrino mass

$$M_{GT}^{0\nu} = \langle f | \sum_{lk} \sigma_l \cdot \sigma_k \tau_l^+ \tau_k^+ H(r_{lk}, \overline{A}) | i \rangle$$

$$M_{F}^{0\nu} = \langle f | \sum_{lk} \tau_l^+ \tau_k^+ H(r_{lk}, \overline{A}) | i \rangle$$

Neutrino potential



r_{lk} small → q large ($0.5\ fm^{-1}$)

- Expand expression with H(r,A)
- Many higher multipoles contribute!

$$[t_{1/2}^{(0\nu)}]^{-1} = G^{(0\nu)} \, | M_{GT}^{(0\nu)} |^2 \, \langle m_\nu \rangle^2$$ + Fermi contribution

$$= G^{(0\nu)} \left| \sum_m \frac{\langle 0_{g.s.}^{(f)} || O_{\sigma\tau^-}(r,S,L) || J_m^\pi \rangle \langle J_m^\pi || O_{\sigma\tau^-}(r,S,L) || 0_{g.s.}^{(i)} \rangle}{1/2\, Q_{\beta\beta}(0_{g.s.}^{(f)}) + E(J_m^\pi) - E_0} \right|^2 \langle m_\nu \rangle^2$$

+ Fermi contribution

Easier case:

$2\nu\beta\beta$

Half-lives & Matrix elements

Half life:

$$[t^{(2\nu)}_{1/2}]^{-1} = G^{(2\nu)} \, | M^{(2\nu)}_{DGT} |^2$$

Phase space + coupling constants: $G \sim Q^{-11}$

ββ matrix element:

$$M_{DGT} = \sum_m \frac{\langle 0^{(f)}_{g.s.} || \sigma\tau^- || 1^+_m \rangle \langle 1^+_m || \sigma\tau^- || 0^{(i)}_{g.s.} \rangle}{1/2\, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - M_i}$$

All 1^+ levels must be considered!

Approximation:

$$M_{DGT} \cong \frac{M_S \, M_{S'}}{\Delta_S}$$

M_S: Single beta decay matrix elements

Δ_S: Energy denominator

holds if
- only one strong 1+ intermediate state
- further excited states weak or E_x high

Measurement of $M_{DGT}^{(2\nu)}$ thru hadronic probes

$$M_{DGT} = \sum_m \frac{\langle 0^{(f)}_{g.s.} \| \sigma\tau^- \| 1^+_m \rangle \langle 1^+_m \| \sigma\tau^- \| 0^{(i)}_{g.s.} \rangle}{1/2\, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - M_i}$$

$$= \sum_m \frac{M_m^{GT+} \; M_m^{GT-}}{1/2\, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - M_i}$$

Measure B(GT+) through (n,p)-type reactions

Measure B(GT-) through (p,n)-type reactions

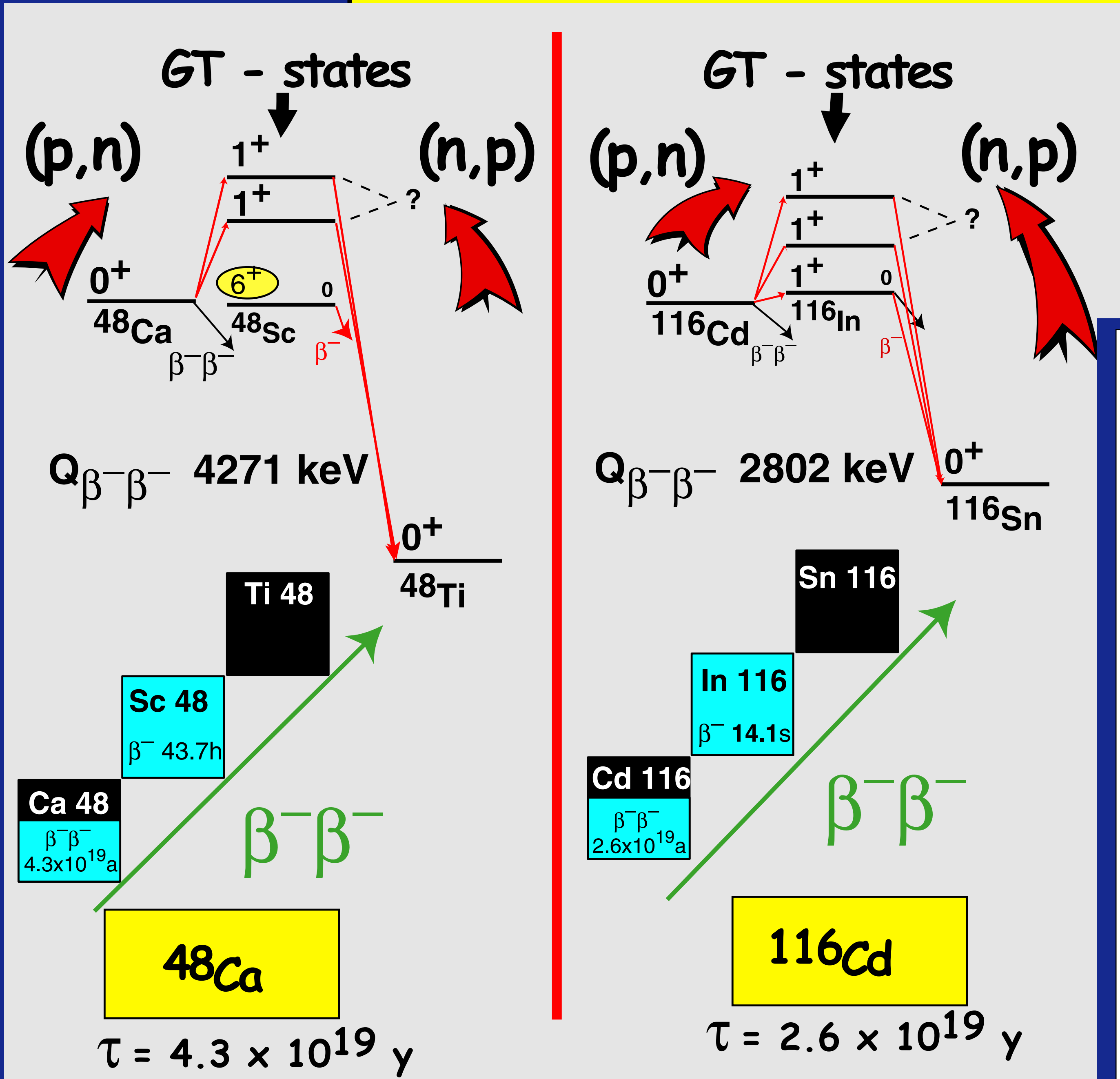
$$B(GT) = \frac{1}{2J_i + 1} \, | \, M(GT) \, |^2$$

$$B(GT) = \hat{\sigma}(GT) \, \frac{d\sigma(q=0)}{d\Omega}$$

forward angles

- Phase cannot be measured
- Simple relation σ <-> B(GT)
- Little model dependence

The 2ν double-β decay



τ from counting experiments and as 2nd order weak process ($\beta^- \rightarrow \beta^-$) !!!

Half life:

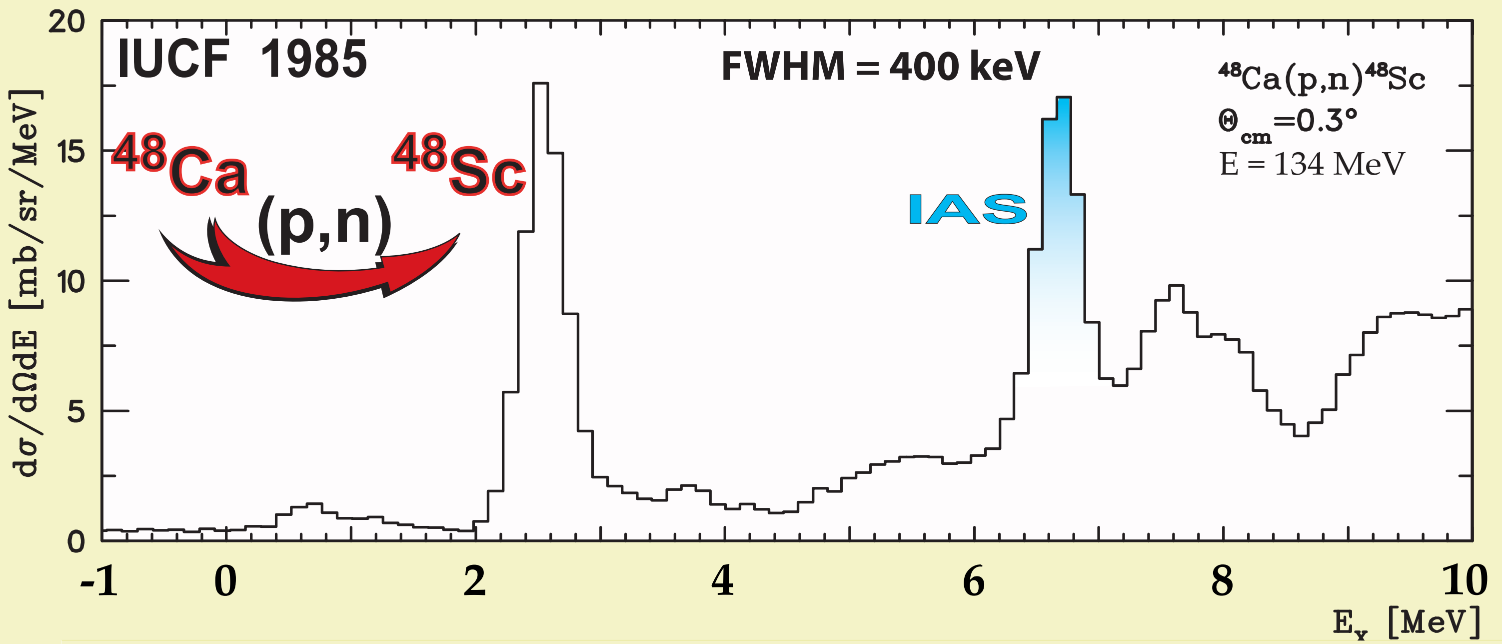
$$[t_{1/2}]^{-1} = G^{(2\nu)} \, | M_{DGT} |^2$$

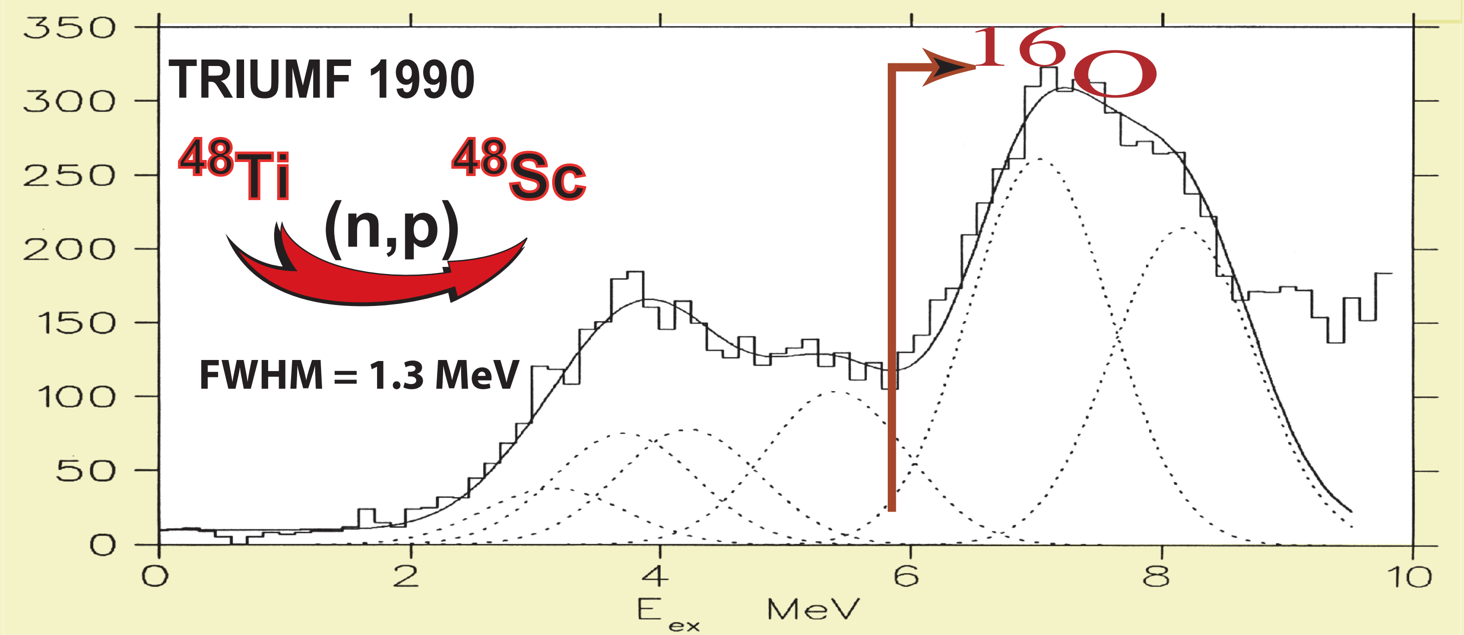
$$M_{DGT} = \sum_m \frac{<0^{(f)}_{g.s.} || \sigma\tau^- || 1^+_m > <1^+_m || \sigma\tau^- || 0^{(i)}_{g.s.}>}{1/2 \, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - E_0}$$

$$G^{(2\nu)} \sim (Q_{\beta\beta})^{11}$$

matrix elements available thru (p,n) and (n,p) type reactions

^{48}Ca - ^{48}Sc - ^{48}Ti



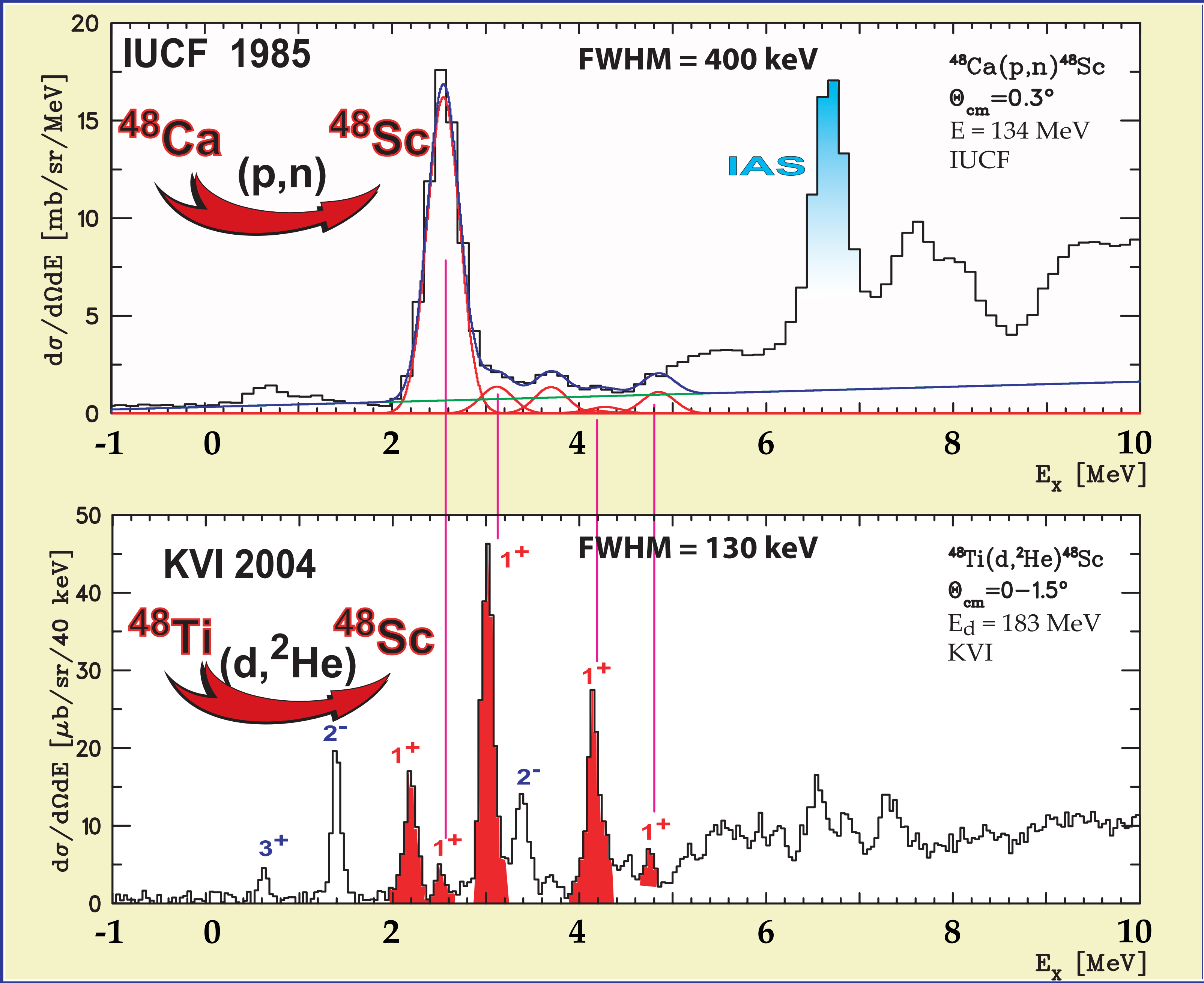


(p,n)

(n,p)

How to connect these states ??

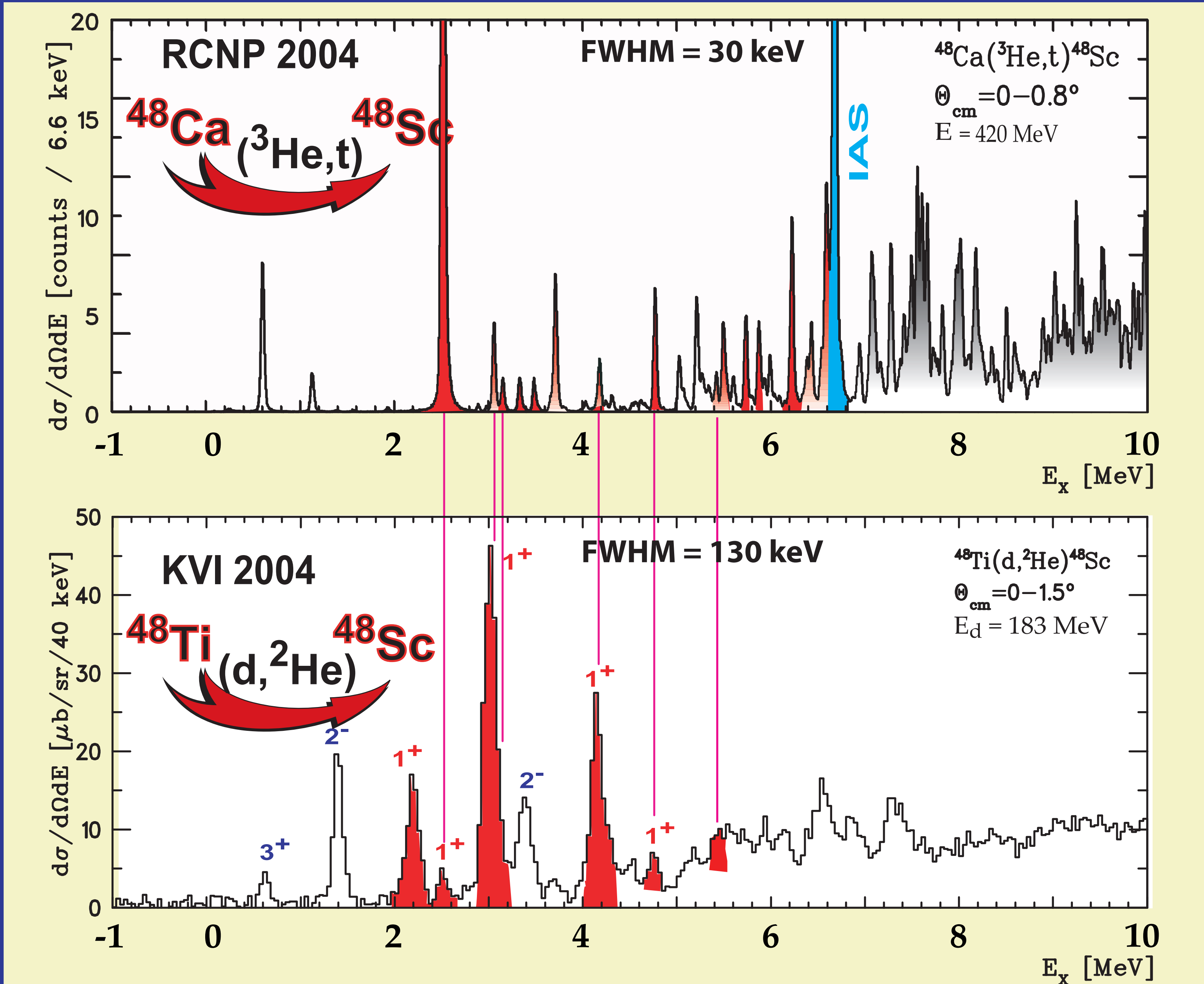
^{48}Ca - ^{48}Sc - ^{48}Ti



(p,n)

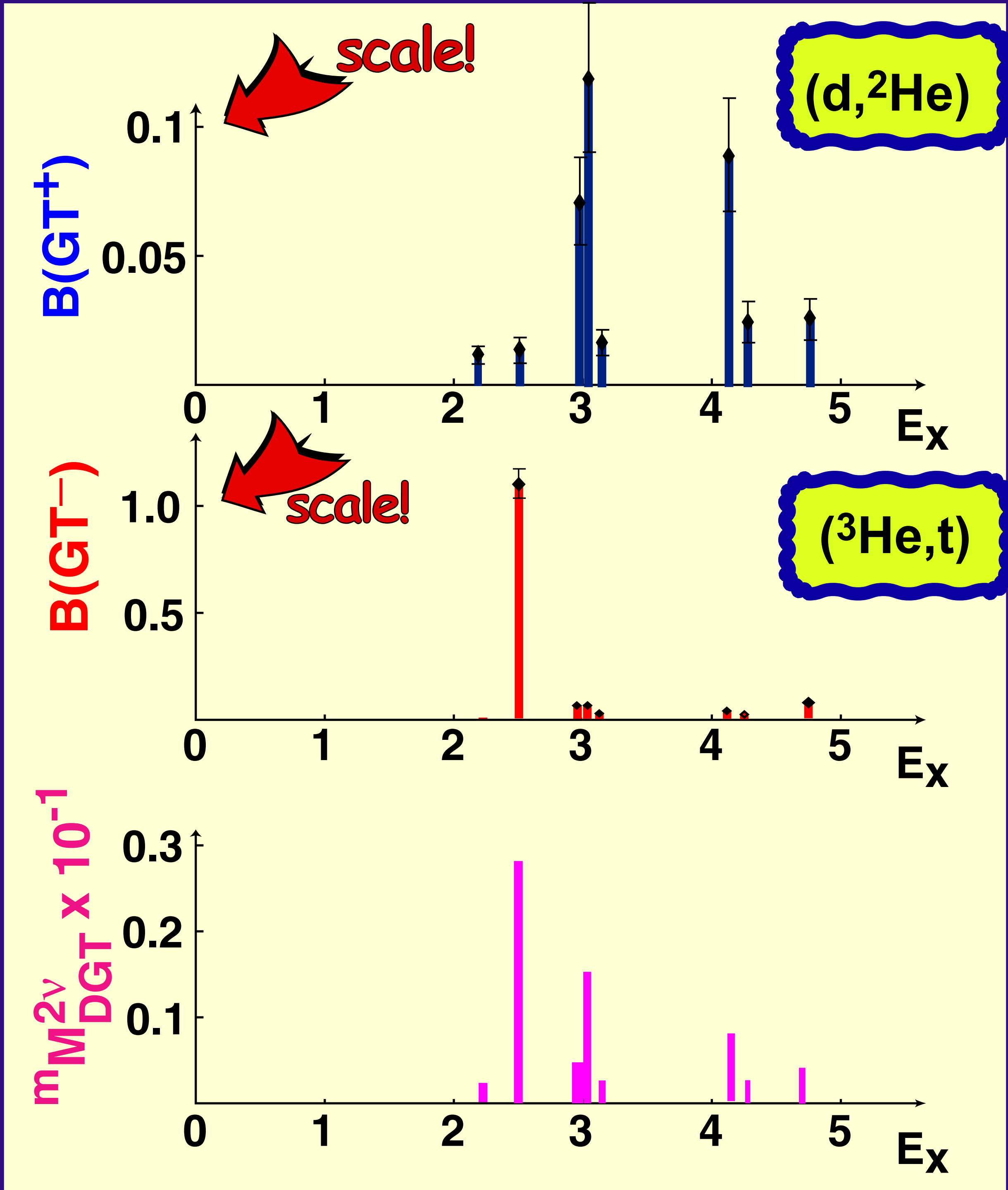
(d,^{2}He)

^{48}Ca - ^{48}Sc - ^{48}Ti



(^{3}He,t)

(d,^{2}He)



Experimental matrix elements

$$M_{DGT} = \sum_m {}^m M_{DGT}/E_m$$

$$= 0.074 \pm 0.0155$$

all positive

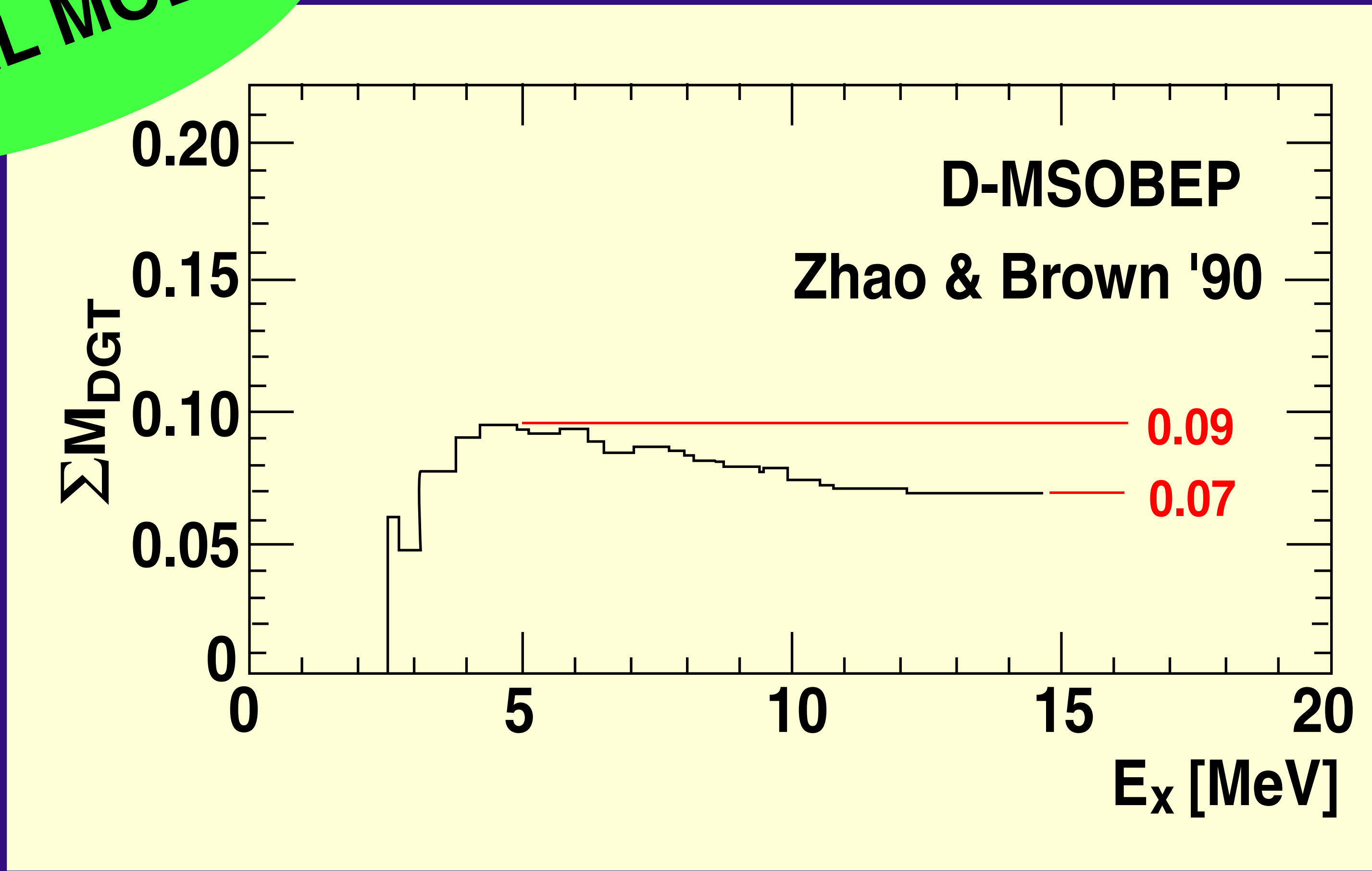
$T_{1/2} =$
$(1.66 \pm 0.31) \times 10^{19}$ yr

Compare to counting exp't:

$T_{1/2} =$
$(4.3 \pm 2.5) \times 10^{19}$ yr

Higher lying states (E_x > 5 MeV)

SHELL MODEL



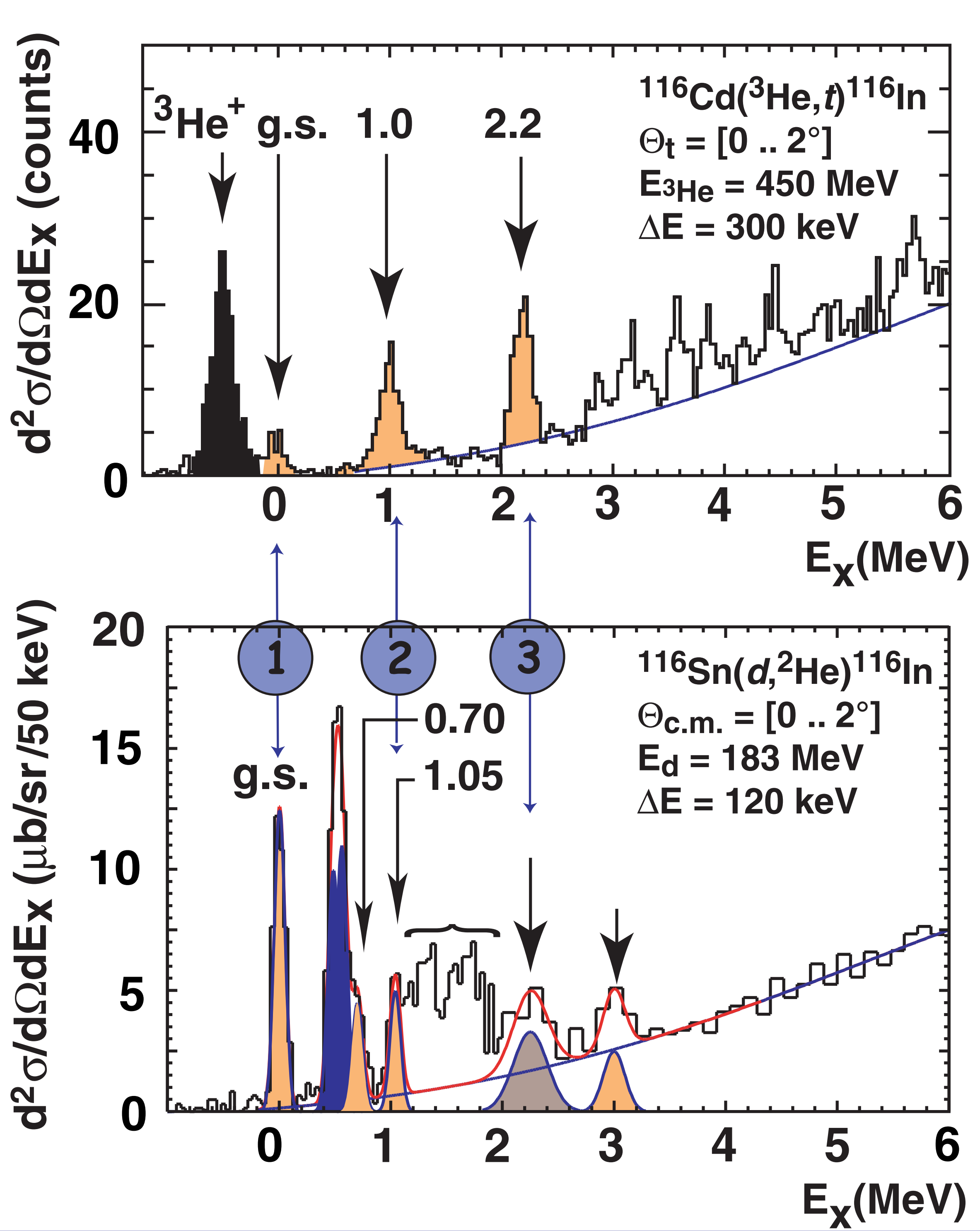
Reduction of matrix element by ~ 25%

$T_{1/2}$ = 3.1×10^{19} yr

^{116}Cd 2νββ decay

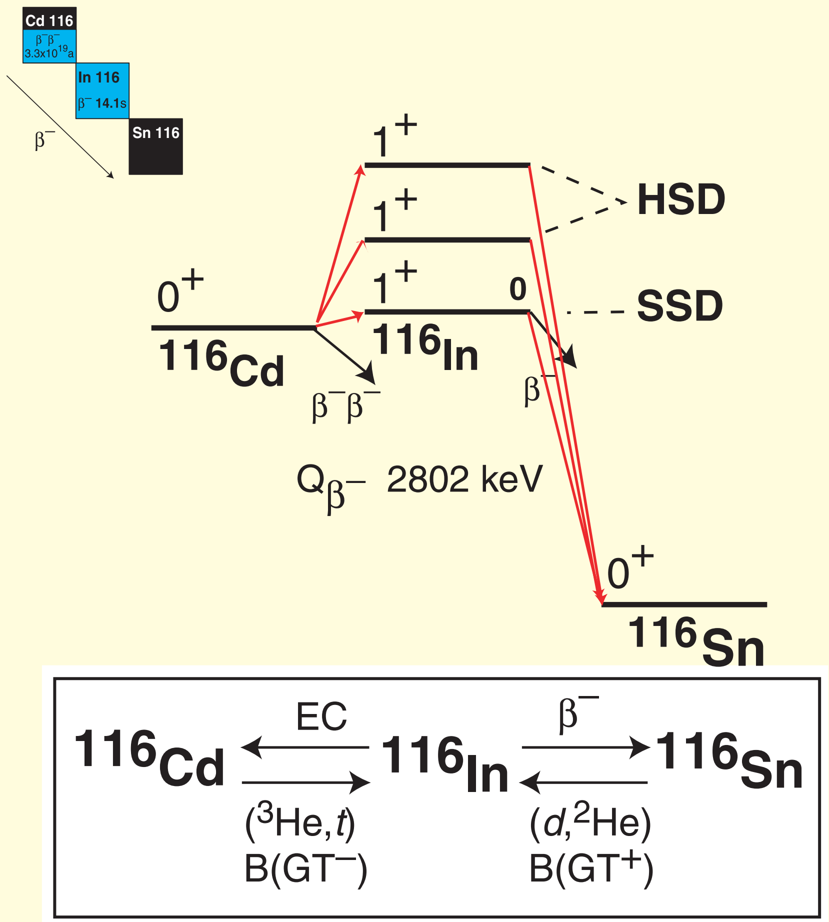
	$B(GT^-)$	$B(GT^+)$	M^m_{DGT}	running sum ΣM_{DGT}
1	0.032	0.256	0.025	0.025
2	0.12	0.11	0.020	0.045
3	0.17	0.07	0.013	0.058

Matrix element from counting experiment:
ΣM_{DGT} = 0.064 ± 0.007



Single state dominance and its oddeties

the conjecture



the oddety

Case	B(GT⁻)	B(GT⁺)	M(DGT)	$T_{1/2}^{(2\nu)}$ [10^{19} y]
direct	–	–	0.06	3.3
(^{3}He,t)/ β⁻	0.032	0.256	0.025	22
EC/ β⁻	0.47	0.256	0.09	1.5
theory	1.165	0.065	0.07	2.4
(^{3}He, t)/(d,^{2}He)	0.061*	1.09*	0.05	4.0

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Study of Gamow-Teller transitions to intermediate states in ββ-decay

Westfälische
Wilhelms-Universität
Münster

Status:

Finished: ^{48}Ca, ^{116}Cd

Proposed for 2004: ^{76}Ge, ^{96}Zr, ^{100}Mo, ^{150}Nd

2005-2007: ^{82}Se, $^{128,130}Te$, ^{136}Xe

double beta decay -- Majorana neutrino and atomic/nuclear state degeneracy

2ν ββ decay rate:

Q dependence : Q^{10} (ordinary phase space)
Z dependence: high-Z quenching (Coulomb effect)
nuclear strucure: GT-quenching, Pauli-blocking at high A (N-Z large)
state mismatch (re: ^{48}Ca!!)

0ν ββ decay rate:

above arguments are weakened
but: ~ m_ν^2

theory: needs the 2ν ββ decay for calcultating the 0ν variant

experiment: needs to detect sum energy of the 2 electrons !

are there other double beta decay variants ??

$\beta^+\beta^+$ decay
β^+EC decay
ECEC decay

2ν $\beta^+\beta^+$ decay rate:

Q dependence : $(Q - 4m_oc^2)^{10}$ (ordinary phase space)
energy penalty!!!

Z dependence: high-Z enhancement (Coulomb effect)

nuclear strucure: much reduced Pauli-blocking at high A (N-Z small)

2ν or 0ν experiment: very ! low isotopic abundances
vanishing decay rates
4 gamma's plus two beta's

β^+EC case: not much different
except energy penalty is only $2m_oc^2$

hopeless

ECEC decay

2ν ECEC decay rate:

Q dependence : moderate (ordinary phase space)
no energy penalty!!!

Z dependence: $\sim (\alpha Z)^6$ electron density!!

nuclear strucure: much reduced Pauli-blocking at high A
(N-Z small)

hopeless can never detect the X-rays (Auger-electrons)
estimated lifetime ~ 10^{30-32} y

0ν ECEC decay rates: need an extra photon to carry away energy
(0νγ ECEC--X-ray)
$\sim (\alpha/Q)^2$ i.e. need low Q !!
$\sim (\alpha Z)^6$ electron density
no phase space factor
estimated lifetime ~ 10^{30-32} y

however: there is a resonant enhancement if the Q-value matches the atomic excitation

$\beta^+\beta^+$ decay nuclei(6)

transition	Q-value	final states in daughter	isotopic abundance
$^{78}Kr \rightarrow {}^{78}Se$	2.868	many	0.35%
$^{96}Ru \rightarrow {}^{96}Mo$	2.725	many	5.52%
$^{106}Cd \rightarrow {}^{106}Pd$	2.770	many	1.25%
$^{124}Xe \rightarrow {}^{124}Te$	2.865	many	0.10%
$^{130}Ba \rightarrow {}^{130}Xe$	2.610	many	0.11%
$^{136}Ce \rightarrow {}^{136}Ba$	2.400	many	0.20%

energy penalty $\beta^+\beta^+$: $4m_oc^2$ = 2.044 MeV
energy penalty β^+ EC : $2m_oc^2$ = 1.022 MeV
energy penalty EC EC: none

decay rate $\Gamma(\beta^+\beta^+) \sim (Q - 4m_oc^2)^{10}$

β+EC decay nuclei (13)

transition	Q-value	final states in daughter	isotopic abundance
$^{58}Ni \rightarrow ^{58}Fe$	1.924	g.s. , 0.810 (2+) ,1.674 (2+)	68.08%
$^{64}Zn \rightarrow ^{64}Ni$	1.097	g.s.	48.60%
$^{74}Se \rightarrow ^{74}Ge$	1.209	g.s. , 0.595 (2+) , 1.204 (2+)	0.89%
$^{84}Sr \rightarrow ^{84}Kr$	1.789	g.s. , 0.881 (2+)	0.56%
$^{92}Mo \rightarrow ^{92}Zr$	1.649	g.s., 0.934 (2+) , 1.382 (0+) , 1.495 (4+)	14.84%
$^{112}Sn \rightarrow ^{112}Cd$	1.923	many	0.97%
$^{120}Te \rightarrow ^{120}Sn$	1.703	g.s. ,1.171 (2+)	0.09%
$^{144}Sm \rightarrow ^{144}Nd$	1.781	g.s. ,0.696 (3-) ,1.314 (4+) ,1.510 (3-) ,1.561 (2+)	3.10%
$^{150}Gd \rightarrow ^{150}Sm$	1.290	many	α-decay 10^6y
$^{156}Dy \rightarrow ^{156}Gd$	2.010	many	0.06%
$^{162}Er \rightarrow ^{162}Dy$	1.845	many	0.14%
$^{168}Yb \rightarrow ^{168}Er$	1.422	many	0.13%
$^{174}Hf \rightarrow ^{174}Yb$	1.102	many	0.16%

energy penalty β^+ EC : $2m_oc^2$ = 1.022 MeV

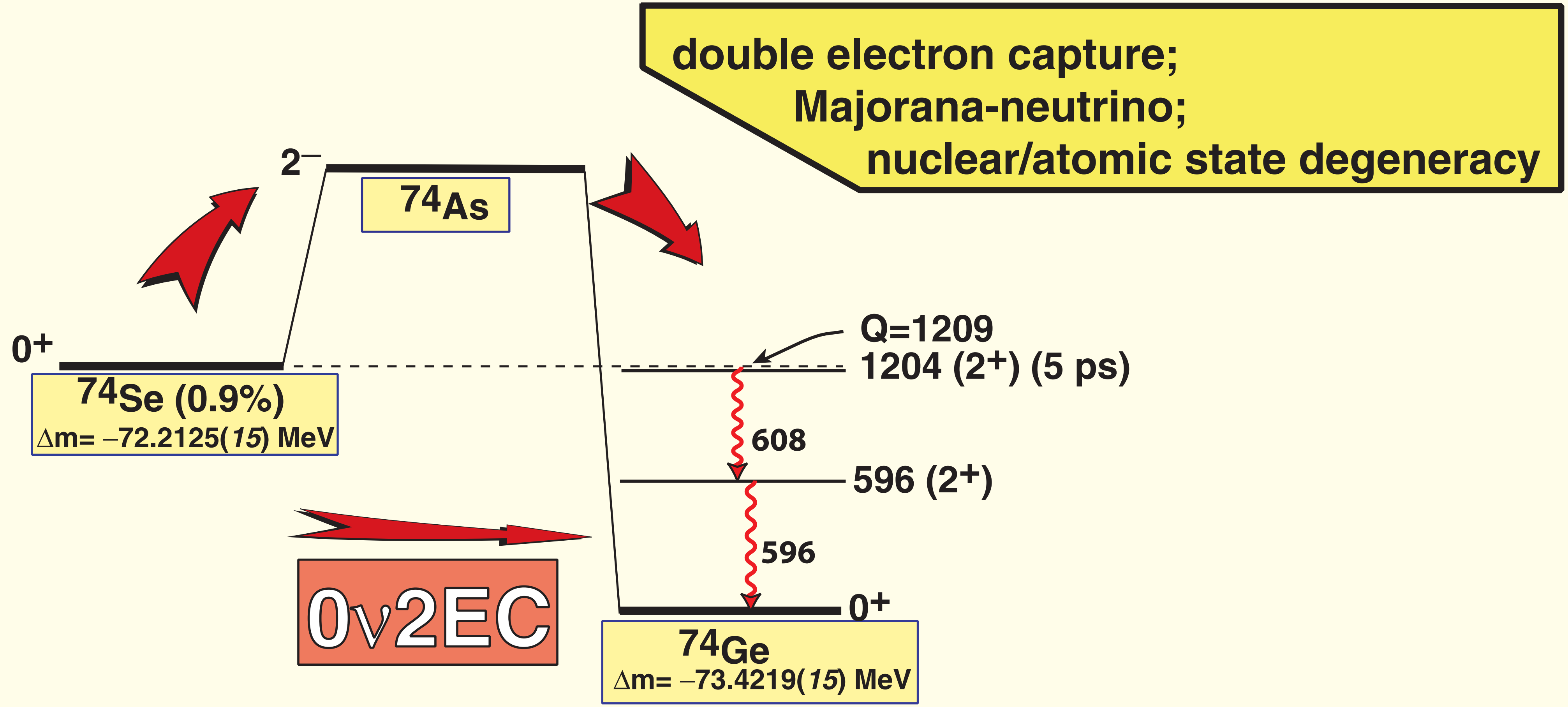
energy penalty EC EC: none -- decay rate Γ(ECEC) ~ $(\alpha Z)^6$

ECEC decay nuclei (12)

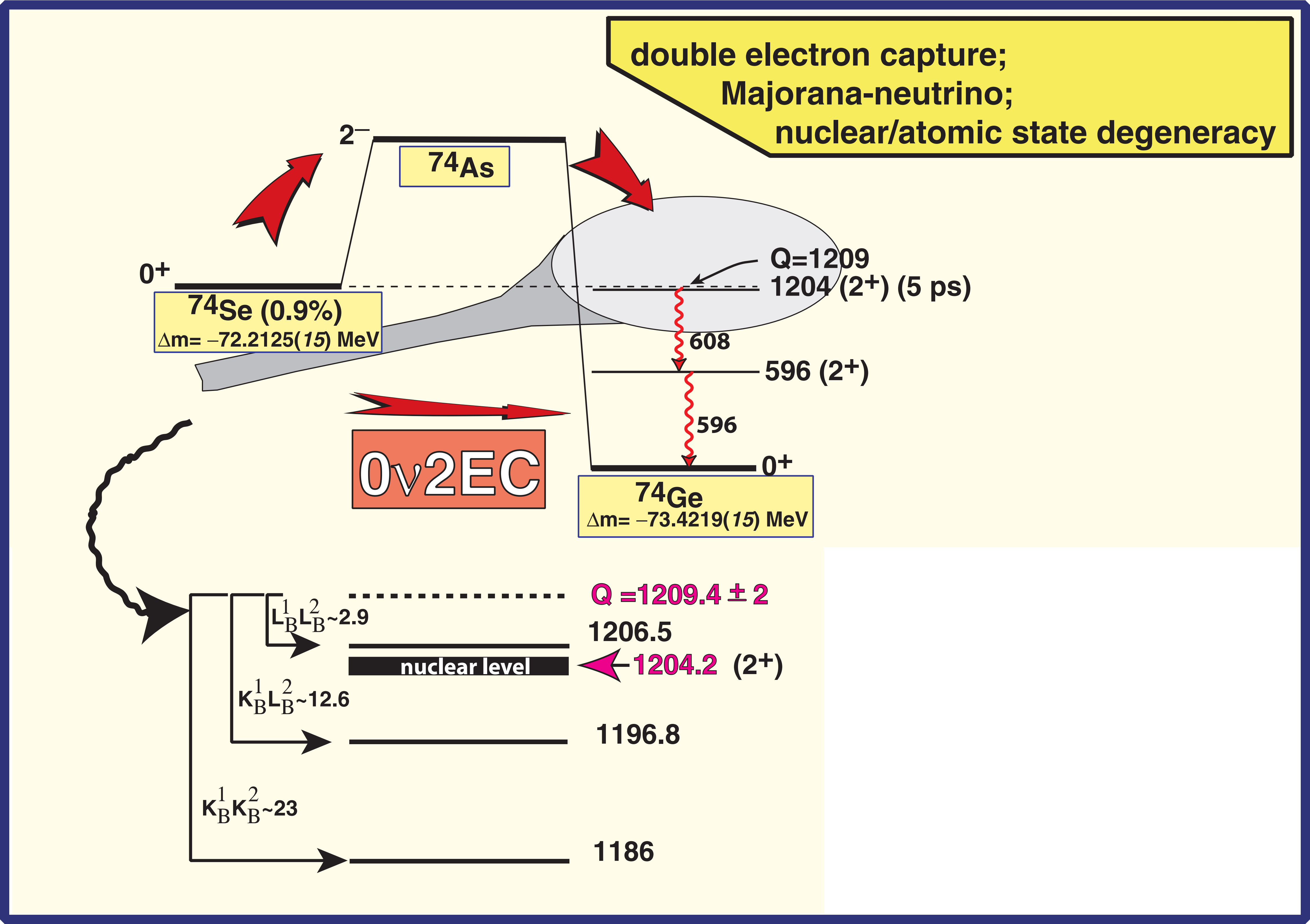
transition	Q-value	final states in daughter	isotopic abundance
$^{36}Ar \rightarrow ^{36}S$	0.434	g.s. (0+)	0.34%
$^{40}Ca \rightarrow ^{40}Ar$	0.193	g.s. (0+)	96.94%
$^{54}Fe \rightarrow ^{54}Cr$	0.681	g.s. (0+)	5.80%
$^{108}Cd \rightarrow ^{108}Pd$	0.259	g.s. (0+)	0.89%
$^{126}Xe \rightarrow ^{126}Te$	0.897	g.s. (0+) . 0.666 (2+)	0.09%
$^{132}Ba \rightarrow ^{132}Xe$	0.841	g.s. (0+) . 0.668 (2+)	0.10%
$^{138}Ce \rightarrow ^{138}Ba$	0.693	g.s. (0+)	71.70%
$^{152}Gd \rightarrow ^{152}Sm$	0.056	g.s. (0+)	0.20%
$^{158}Dy \rightarrow ^{158}Gd$	0.284	g.s. (0+) . 0.079 (2+) . 0.261 (4+)	0.10%
$^{164}Er \rightarrow ^{164}Dy$	0.024	g.s. (0+)	1.61%
$^{180}W \rightarrow ^{180}Hf$	0.145	g.s. (0+) . 0.093 (2+)	0.13%
$^{196}Hg \rightarrow ^{196}Pt$	0.820	g.s. (0+) . 0.355 (2+) . 0.689 (2+)	0.15%

energy penalty EC EC: none

decay rate $\Gamma \sim (\alpha Z)^6 (\alpha/Q)^2$ (e-density x photon propagator) state degeneracy and the special case of ^{74}Se for a Majorana neutrino signature



double electron capture;
Majorana-neutrino;
nuclear/atomic state degeneracy
2⁻
74As
0+
74Se (0.9%)
Δm= –72.2125(15) MeV
Q=1209
1204 (2+) (5 ps)
608
596 (2+)
596
0+
74Ge
Δm= –73.4219(15) MeV
0ν2EC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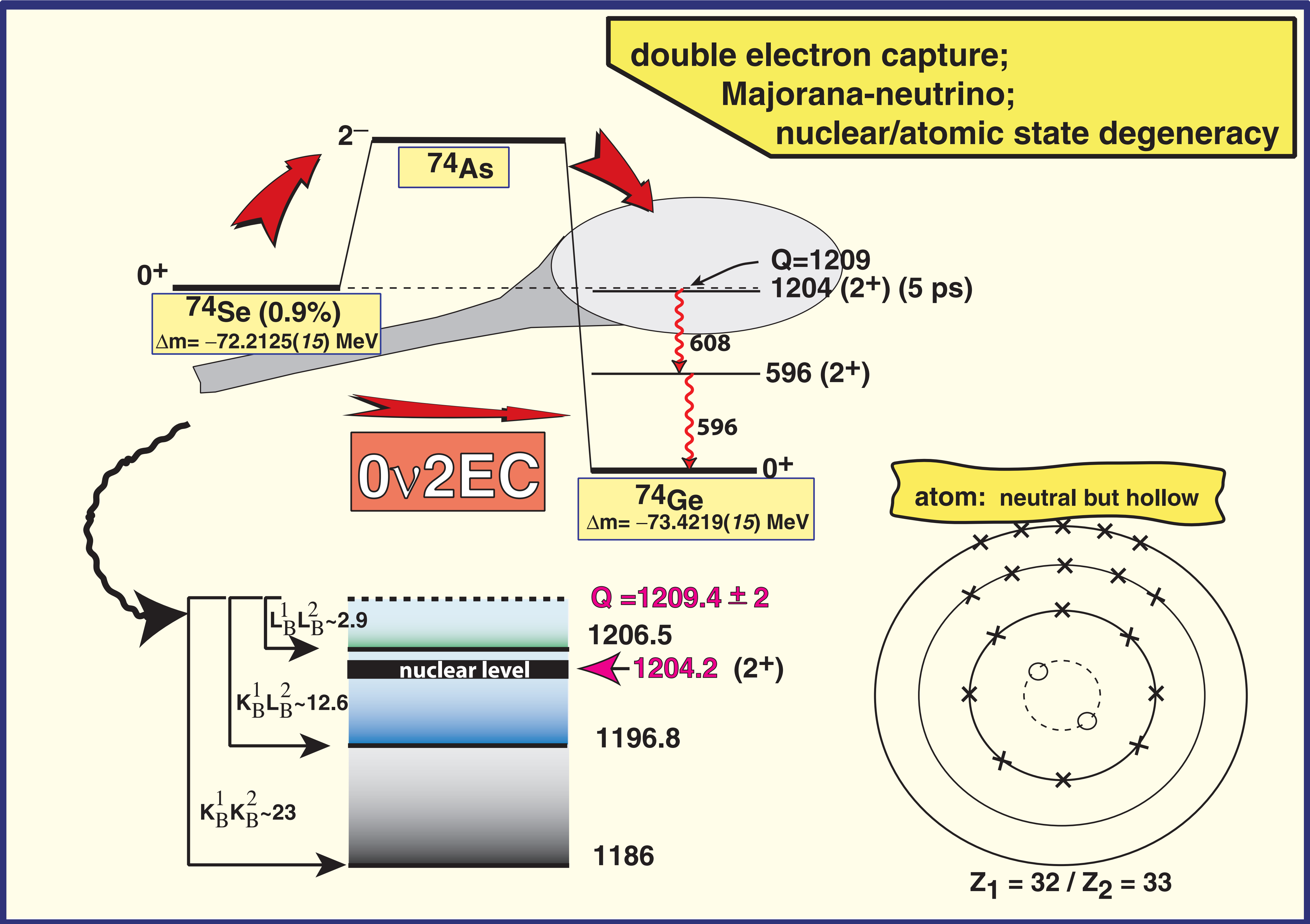
0ν2EC
Q =1209.4 ± 2
1206.5
LBLB~2.9
nuclear level
1204.2 (2+)
KBLB~12.6
1196.8
KBKB~23
1186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Q=1209
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608
596 (2+)
596
0+
74Ge
Δm= −73.4219(15) MeV
0ν2EC
atom: neutral but hollow
Q =1209.4 ± 2
1206.5
nuclear level
1204.2 (2+)
1196.8
1186
L1B L2B ~2.9
K1B L2B ~12.6
K1B K2B ~23
Z1 = 32 / Z2 = 33

^{74}Se and Majorana neutrino signature

estimated lifetime for 0νECEC decay:

10^{20} - 10^{25} y possible

(0.2 - 10^{4} cts/day/kmol) x $|m_{\nu}(eV)|^{2}$)

need desperately theory support !!

(present calculations from S. Wycech to be refined)

The case of ^{48}Ca

$T_{1/2} \sim G \sim Q^{-11}$

48Ca

Q = 4.27 MeV
$T_{1/2}$ = 4.3×10^{19} yr

116Cd

Q = 2.80 MeV
$T_{1/2}$ = 3.8×10^{19} yr

NUCLEAR STRUCTURE

Shell-model calculations (Caurier&Poves, 1990)