Weak interaction procesess in Super-Novae:

New probes using charge-exchange reactions at intermediate energies

1) - using the (d,^{2}He) tool as a Gamow-Teller (GT) probe

2) - astrophysics applications of (d,^{2}He)

→ supernova-dynamics, EC-rates and Y_e

3) - study of halo nuclei → ^{6}He and ^{7}He

4) - $2\nu-\beta\beta$ decay

(why is ^{48}Ca so stable?)

The $(d,{}^2He)$ 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 ^2He decay

➡ background-free spectra

but need large accptnc spectrometer

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

Alternatives:

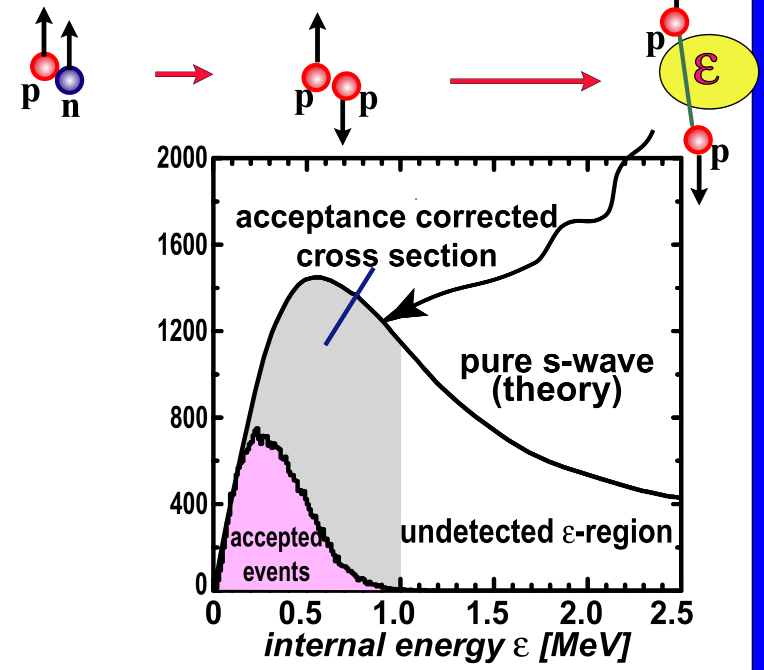
(n,p) resolution?? Fermi transition

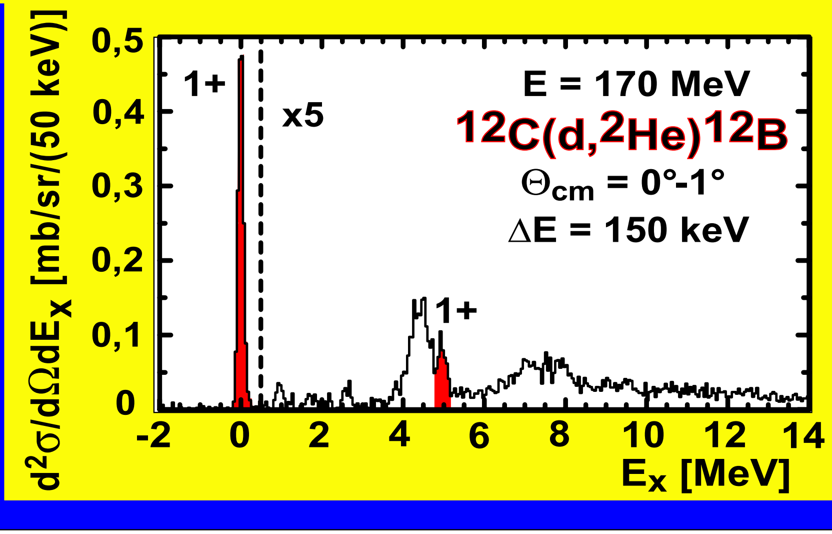
$(t,{}^3He)$ triton beam?? Fermi transition

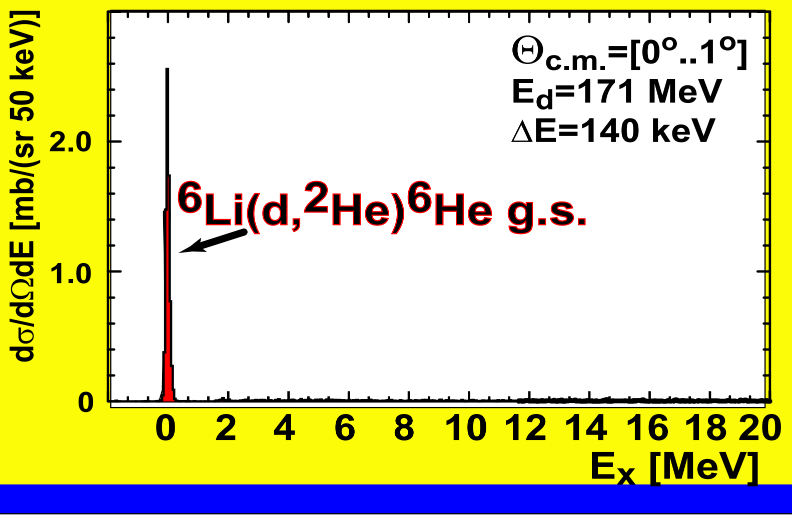
(HI,HI) resolution?? reaction mechanism??

S=1, T=0 → S=0, T=1

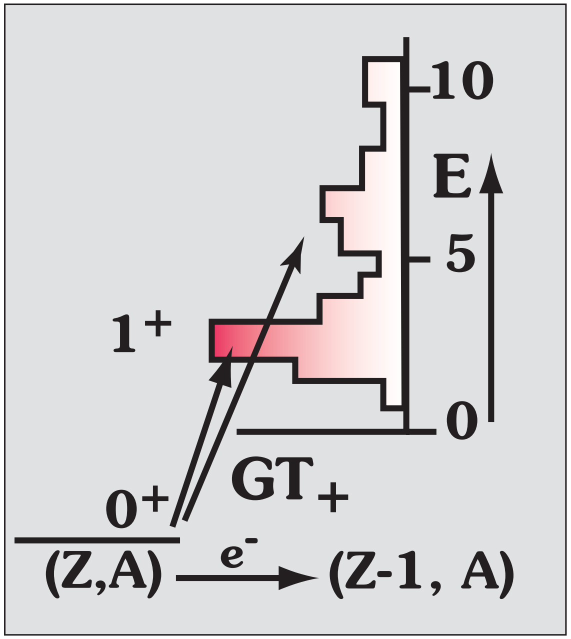
$d(^3S_1) \rightarrow {}^2He(^1S_0) \rightarrow p + p$







GT^+ transitions from nuclei of pf-shell: relevance for astrophysics



H.A. Bethe et al. (1979):

Electron-Capture (EC) from nuclei in pf-shell plays pivotal role in the deleptonization of a massive star prior to core-collapse.

Fuller, Fowler & Newman (FFN) (1982-1985),
M. Aufderheide (1994):

systematic estimates of EC-rates in stellar environments

FFN

-> calculations of GT-centroids only

Langanke, Martinez-Pinedo, Caurier (1999):

$B(GT^+)$-distributions from modern shell-model calculations

some marked deviations from FFN-rates

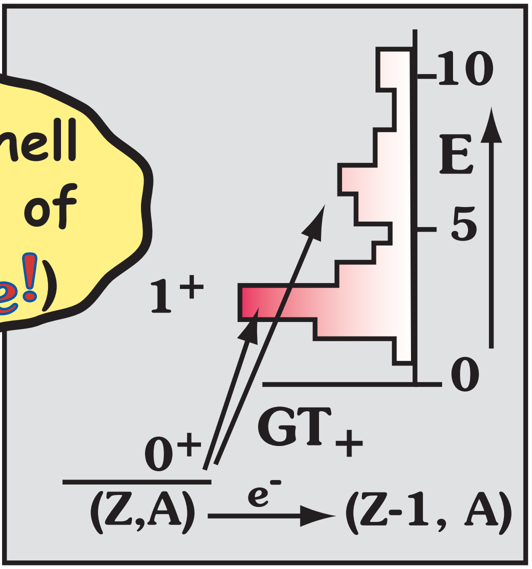
-> Y_e increases to about 0,445
(FFN: ~ 0,430)

!

most dramatic cases are odd-odd nuclei ^{60}Co, ^{58}Mn

Astrophysics applications, SN explosions, EC-rates and Y_e

GT-strength in (pf)-shell nuclei determines fate of SN-explosion (Y_e!)



EC-rates up
deleptonization up
n-cooling before collaps up
Y_e down
total energy down

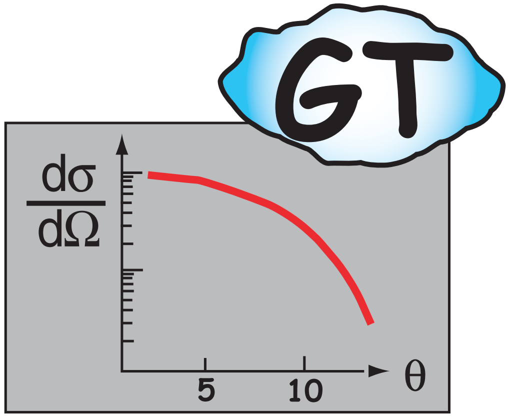
$Y_e > 0.45$ explosion
$Y_e < 0.43$ no explosion

$$B(GT^+) = \sum_{i,f} \frac{n_i^p \, n_f^h}{(2j_i+1)\,(2j_f+1)} \left| \langle f | \vec{\sigma}\,\tau_+ | i \rangle \right|^2$$

n_i^p → # of proton in orbital i of g.s. (j_i)
n_f^h → # of neutron holes in orbital (j_f)

hadronic probes: (p,p'), (n,p), (p,n), (d,^{2}He)

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



Stellar EC rates

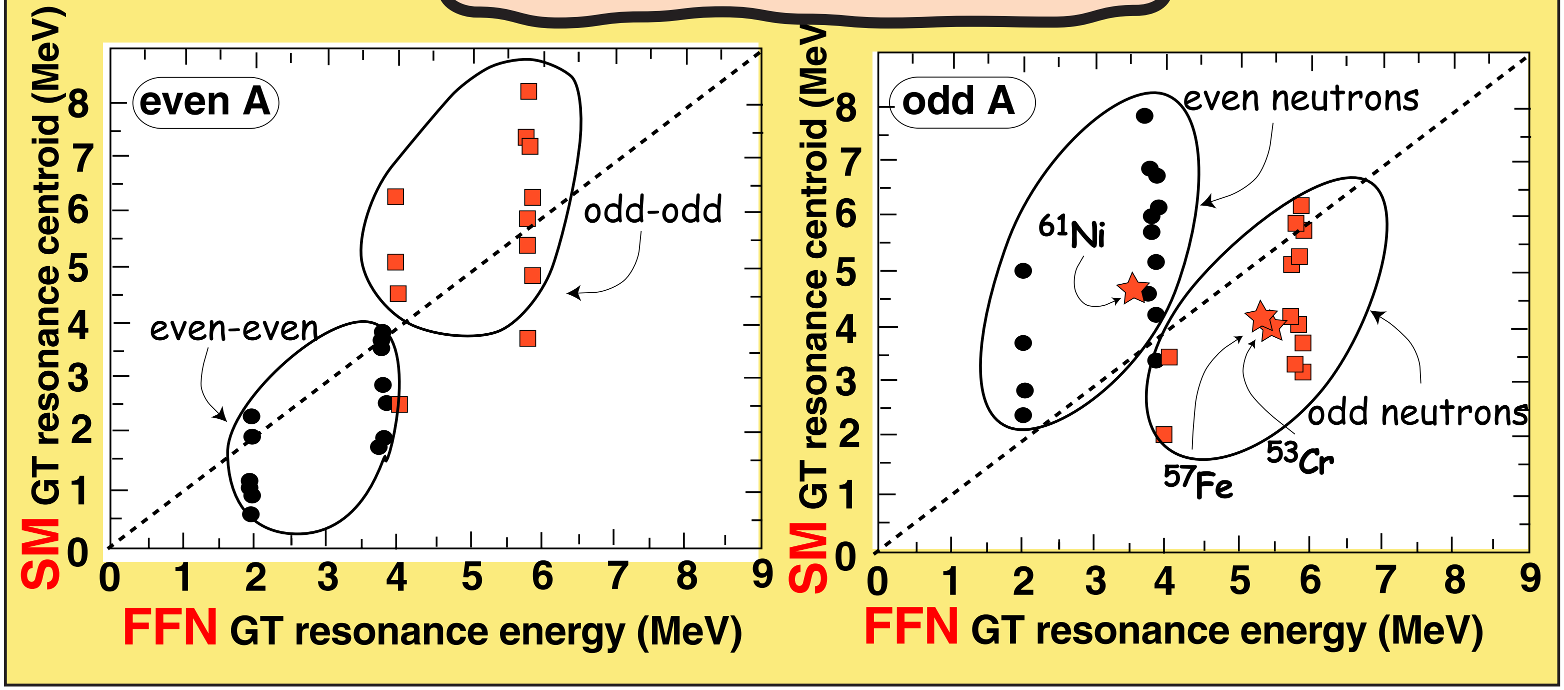
at a given temperature

important parameters

- location of GT resonance (most important)
- level of quenching
- fragmentation over excitation energy

from:
Langanke, Martinez-Pinedo
Nucl.Phys. A 673, 481 (2000)

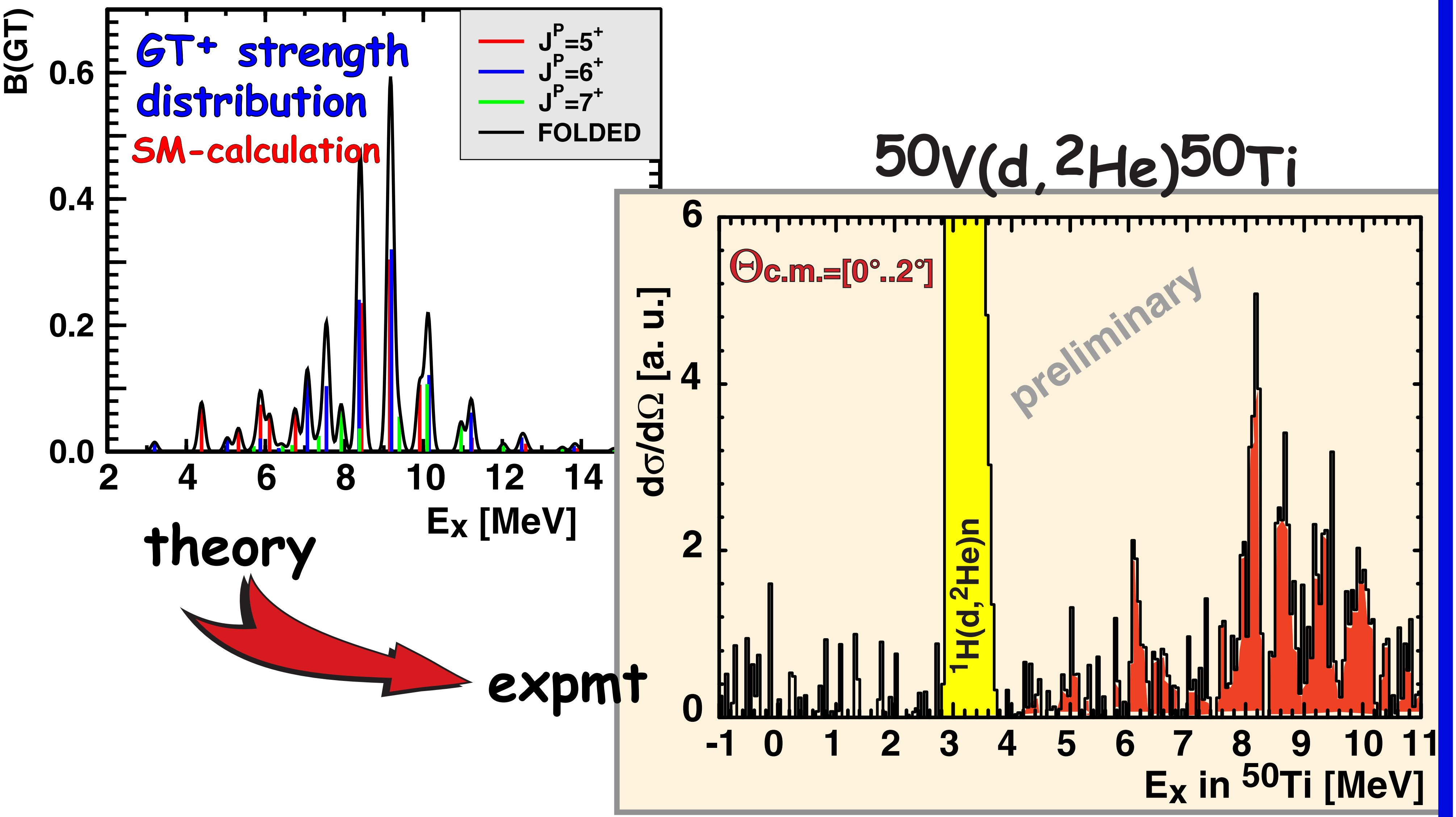
SM and FFN comparison



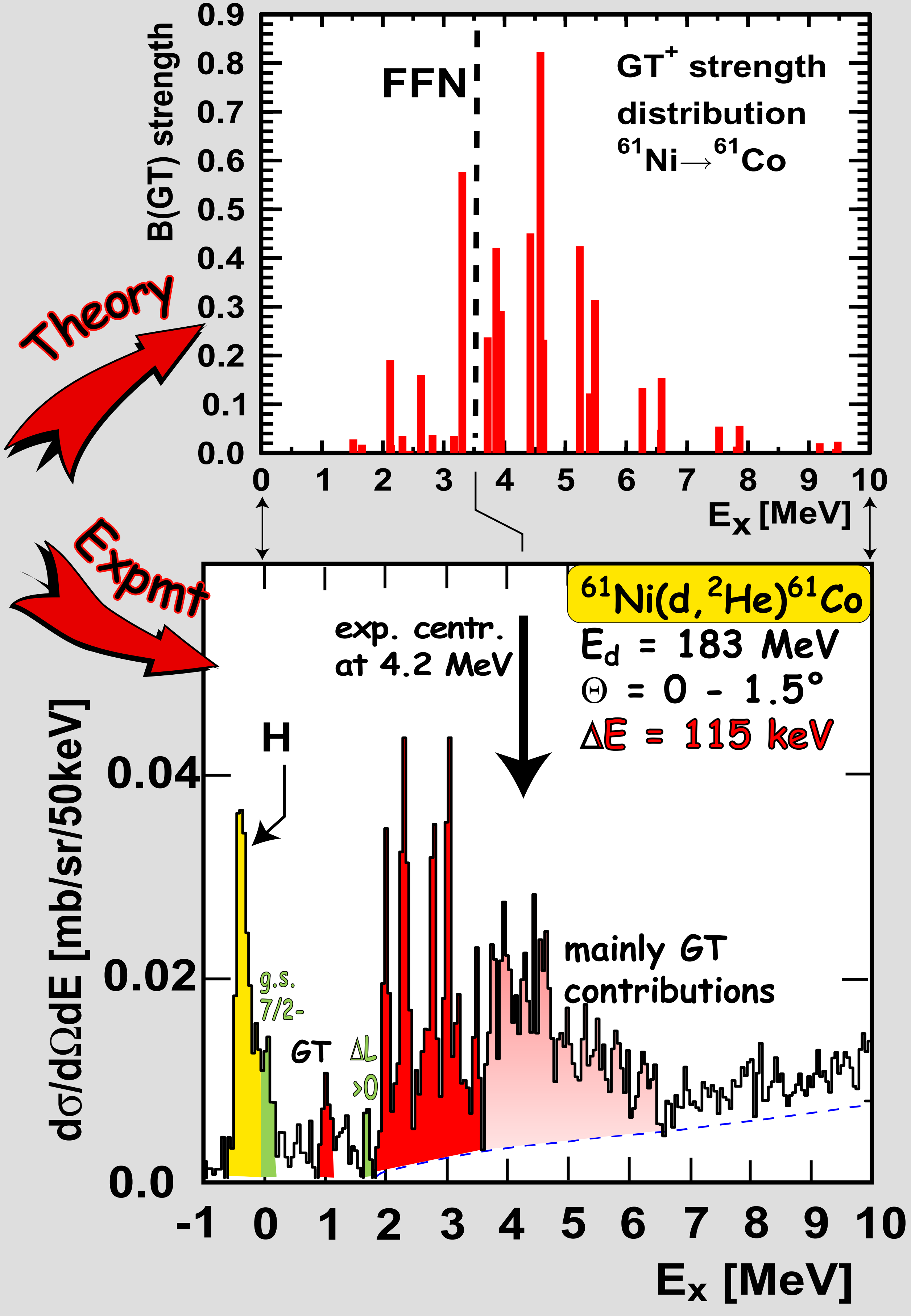
- no exp. data on odd-N nuclei (ususally rare!!)
- no exp. data on odd-odd nuclei (^{50}V is the only stable one)

GT$^+$- transitions from odd-odd nuclei

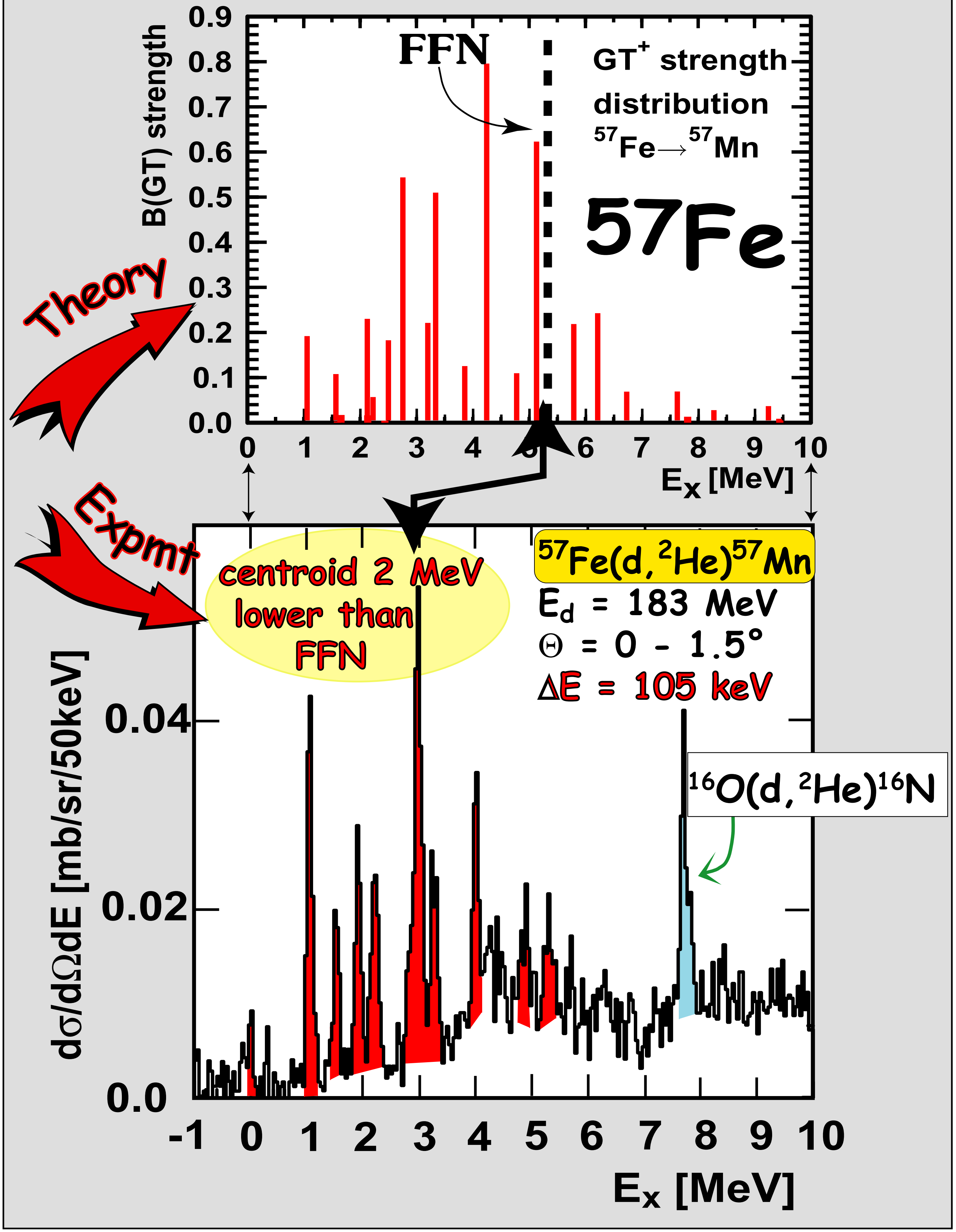
^{50}V (J^p=6$^+$, T=2) $\xrightarrow{GT^+}$ ^{50}Ti (J^p=5$^+$,6$^+$,7$^+$, T=3)



$^{61}Ni(d,^{2}He)^{61}Co$: GT distribution



^{57}Fe(d,^{2}He)^{57}Mn: GT distribution



Theory

FFN

GT$^+$ strength distribution ^{57}Fe→^{57}Mn

57Fe

Expmt

centroid 2 MeV lower than FFN

^{57}Fe(d,^{2}He)^{57}Mn

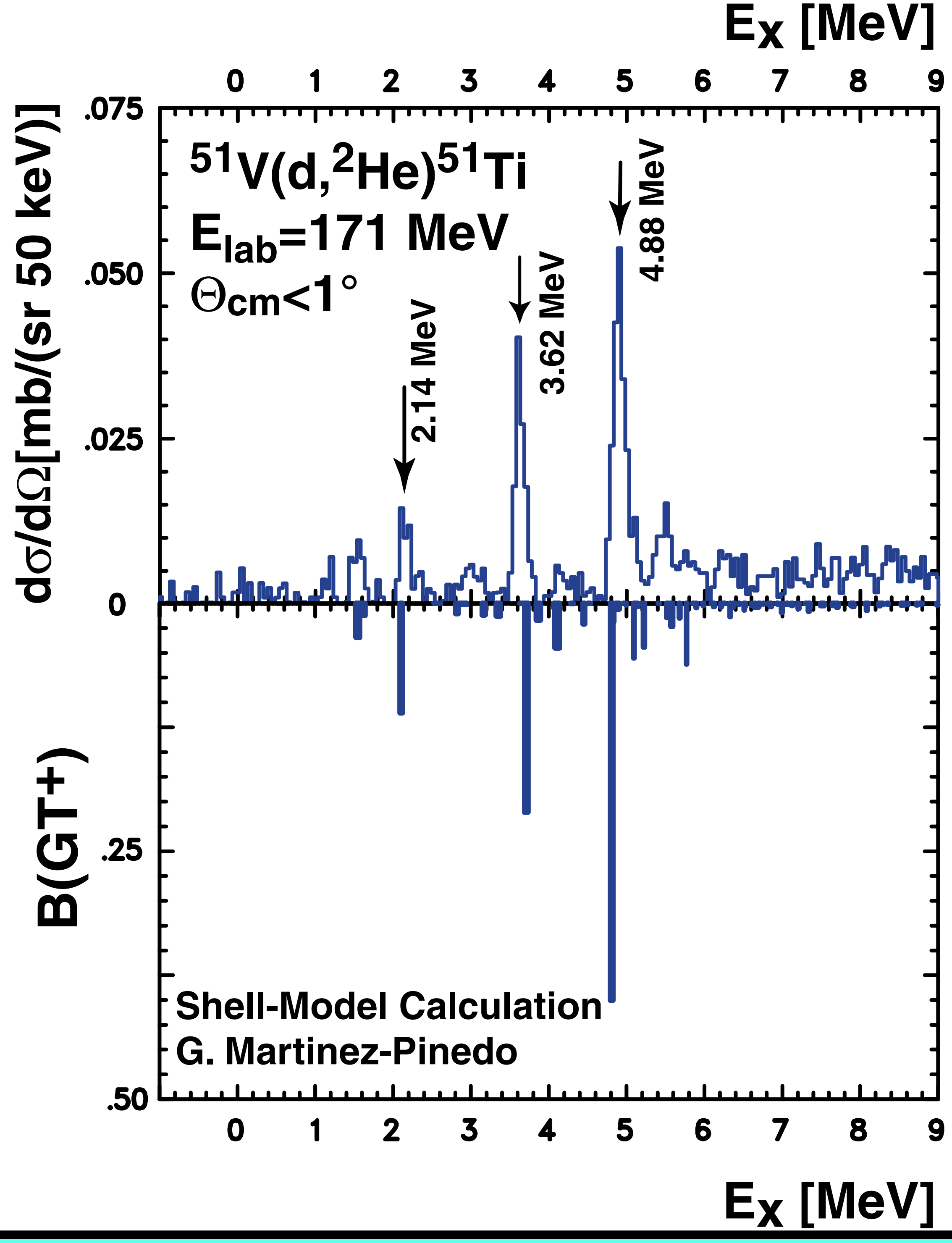
E_d = 183 MeV

Θ = 0 - 1.5°

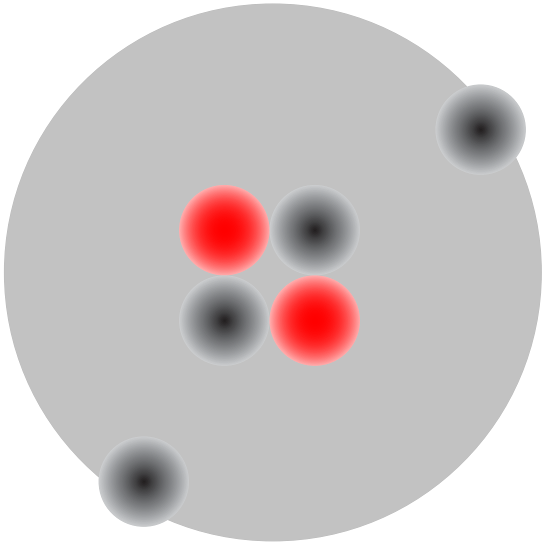
ΔE = 105 keV

^{16}O(d,^{2}He)^{16}N

Detailed comparison of GT transitions in ^{51}V



^{6}He - prototype of a halo-nucleus



3-body α+n+n structure
("Borromean system")

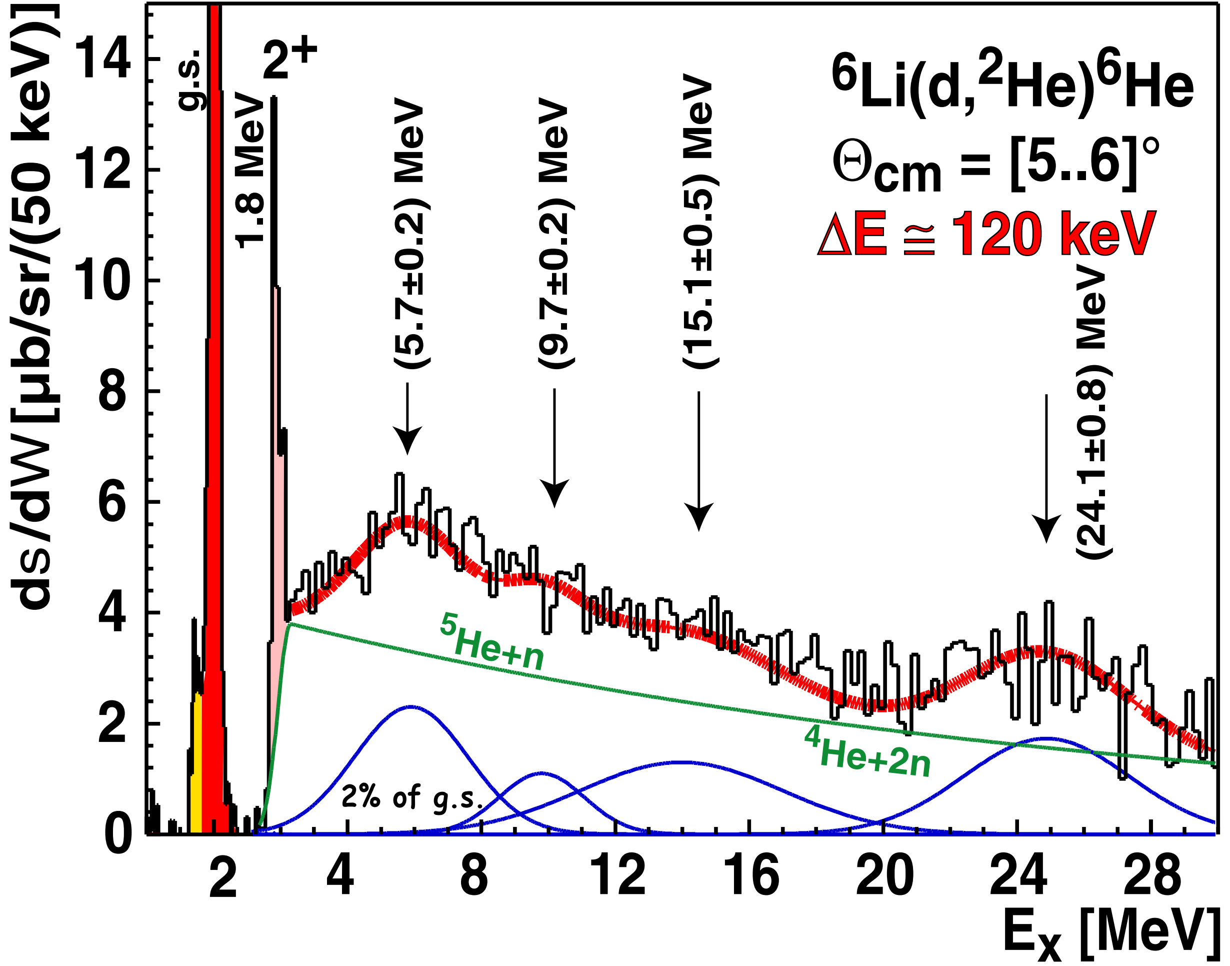
3-body calculations*:

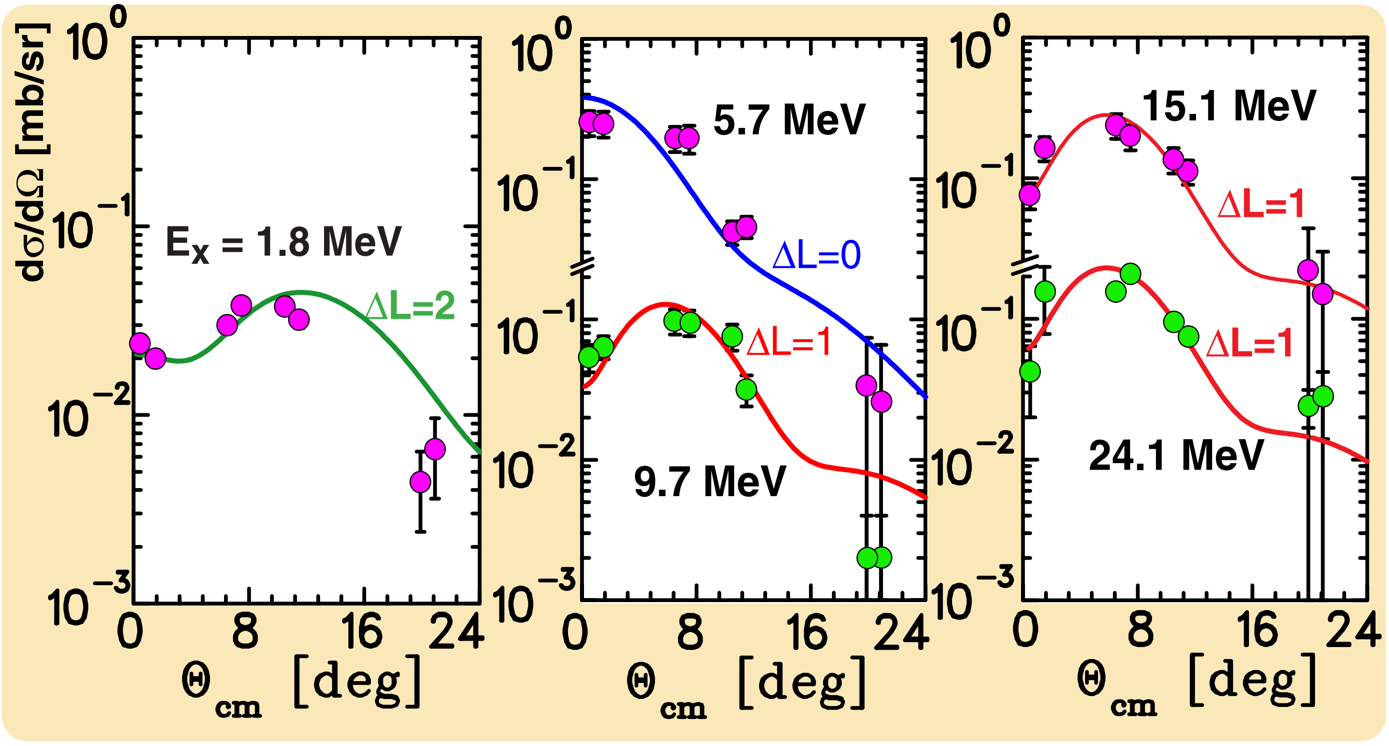
- narrow 0^+, 2^+ states (g.s., ~1.6 MeV)
- 2^+ "soft mode" state at
  4.3 MeV; Γ=1.2 MeV
- 1^+ resonance at 4.5 MeV
- 0^+ resonance at 5 MeV
- no conclusions about
  "soft dipole" modes (at low energies).

*B.V. Danilin et al., PRC 55, 577 (1997)

easily reachable thru ^{6}Li (d, ^{2}He) ^{6}He
resolution 120 keV
angular distributions

$^{6}Li(d,^{2}He)^{6}He$


dS/dW [µb/sr/(50 keV)]
0
2
4
6
8
10
12
14
g.s.
1.8 MeV
2+
(5.7±0.2) MeV
(9.7±0.2) MeV
(15.1±0.5) MeV
(24.1±0.8) MeV
$^{6}Li(d,^{2}He)^{6}He$
$\Theta_{cm} = [5..6]^{\circ}$
$\Delta E \cong 120$ keV
$^{5}He+n$
$^{4}He+2n$
2% of g.s.
2
4
8
12
16
20
24
28
E_x [MeV]


dσ/dΩ [mb/sr]
10^{0}
10^{-1}
10^{-2}
10^{-3}
E_x = 1.8 MeV
ΔL=2
5.7 MeV
ΔL=0
ΔL=1
9.7 MeV
15.1 MeV
ΔL=1
ΔL=1
24.1 MeV
0
8
16
24
Θ_{cm} [deg]

The structure of ^{7}He and the strength of the spin-orbit force through ^{7}Li(d,^{2}He)^{7}He

- identify the $p_{1/2}$ spin orbit partner of the ground state and clarify the claim of a low lying $1/2^{-}$ state (at ~ 650 keV)
- exploit ^{7}Li(d,^{2}He)^{7}He reaction and the properties of GT transition at 170 MeV
- get information about spin-orbit force in halo nucleus where nucleon is at far distance from the core
- angular distribution will give further information about level scheme

Spin- orbit splitting

nucleus	configuration	s.o. splitting
^{5}He	$3/2^{-} \longrightarrow 1/2^{-}$	~ 4.0 MeV ?
^{5}Li	$3/2^{-} \longrightarrow 1/2^{-}$	~ 7.5 MeV ?
^{9}Li	$3/2^{-} \longrightarrow 1/2^{-}$	2.69 MeV
^{15}O	$1/2^{-} \longrightarrow 3/2^{-}$	6.18 MeV
^{17}O	$5/2^{+} \longrightarrow 3/2^{+}$	5.09 MeV

Theoretical predictions for ^{7}He s.o. splitting:

$$\left.\begin{array}{l}\text{large scale shell models}\\ \text{Resonating Group Methods}\end{array}\right\} \quad 2 - 3\ \text{MeV}$$

Quantum Monte Carlo ~ 1MeV

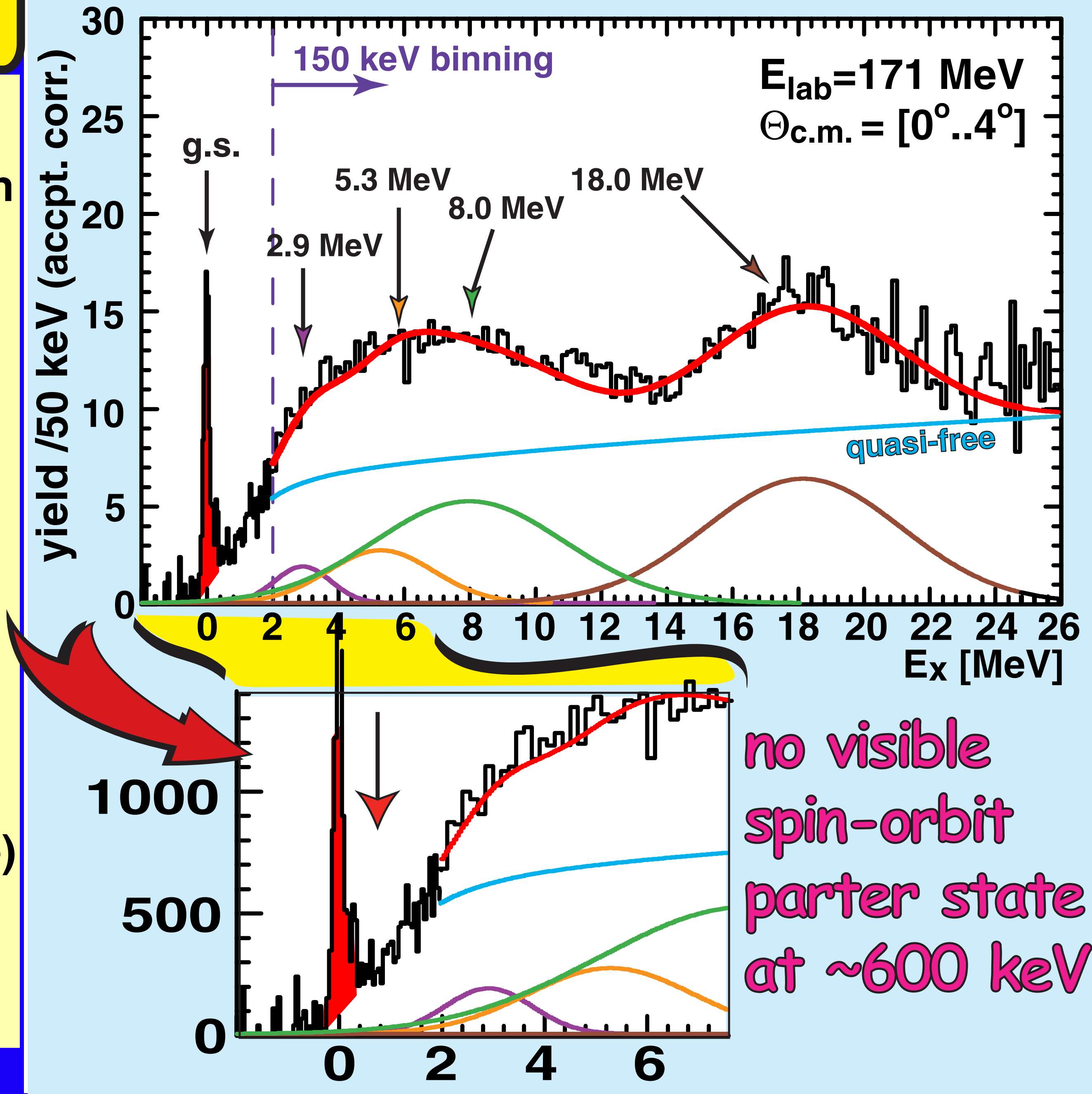
Experimental situation for ^{7}He states above g.s.

Reaction	E*	Γ	Method
$^{12}C(^{8}He,n)^{7}He$	0.6	0.75	inv. mass
$^{1}H(^{8}He,d)^{7}He$	2.9	2.2	miss. mass
$^{9}Be(^{15}N,^{17}F)^{7}He$	2.95	1.9	miss. mass
$^{10}B(\pi^{-},pd)^{7}He$	2.8	2.0	miss. mass

Meister et al., Korshennikov et al, Bohlen et al, Gornov et al

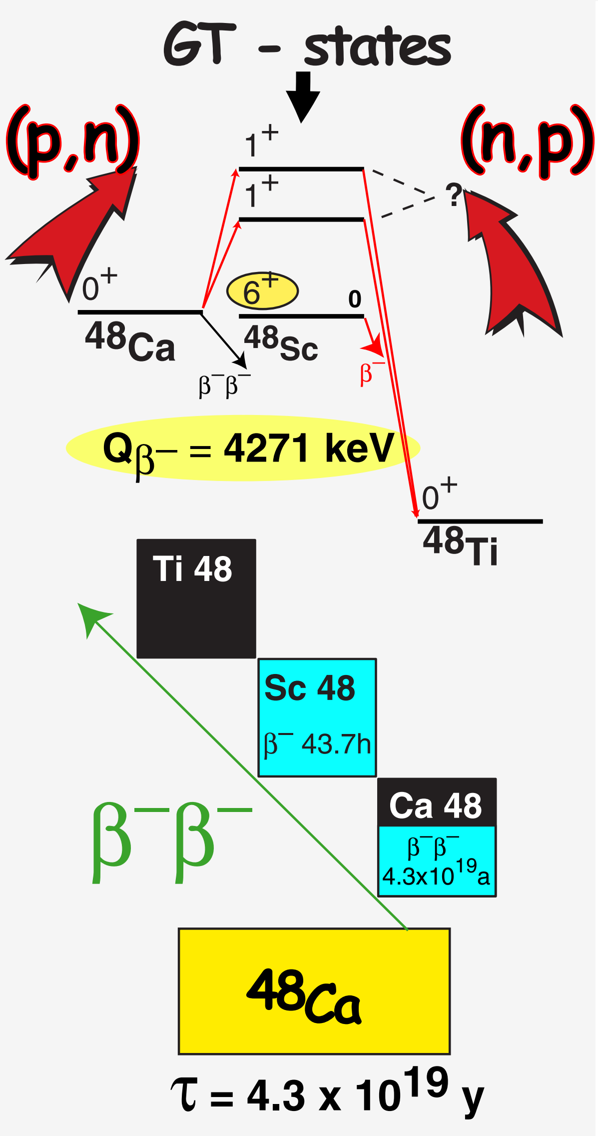
$^{7}Li(d,^{2}He)^{7}He$

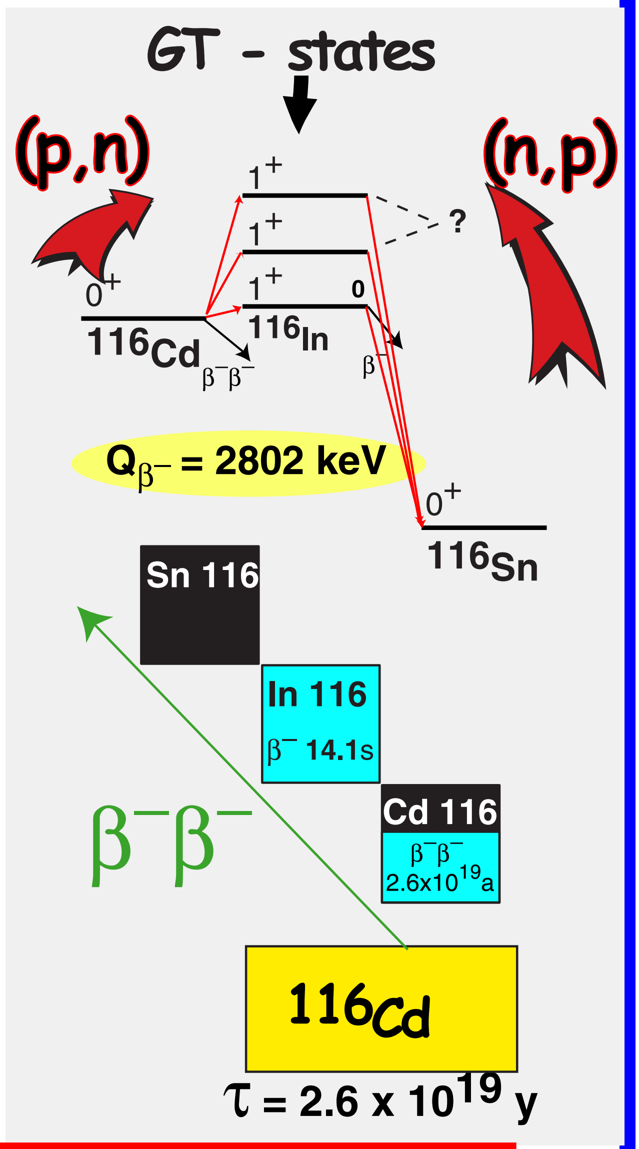
- unexpectedly weak GT-transition strength (^{7}Li = a +t)
- strong reduction of spin-orbit force not observed
- although favoured by GT-operator, no low-lying spin-orbit partner visible
- several braod states observed at:
  2.9 MeV (seen before)
  5.3 MeV
  8.0 MeV
  18.0 MeV (strong!!)



no visible spin-orbit parter state at ~600 keV

Nuclear double beta decay





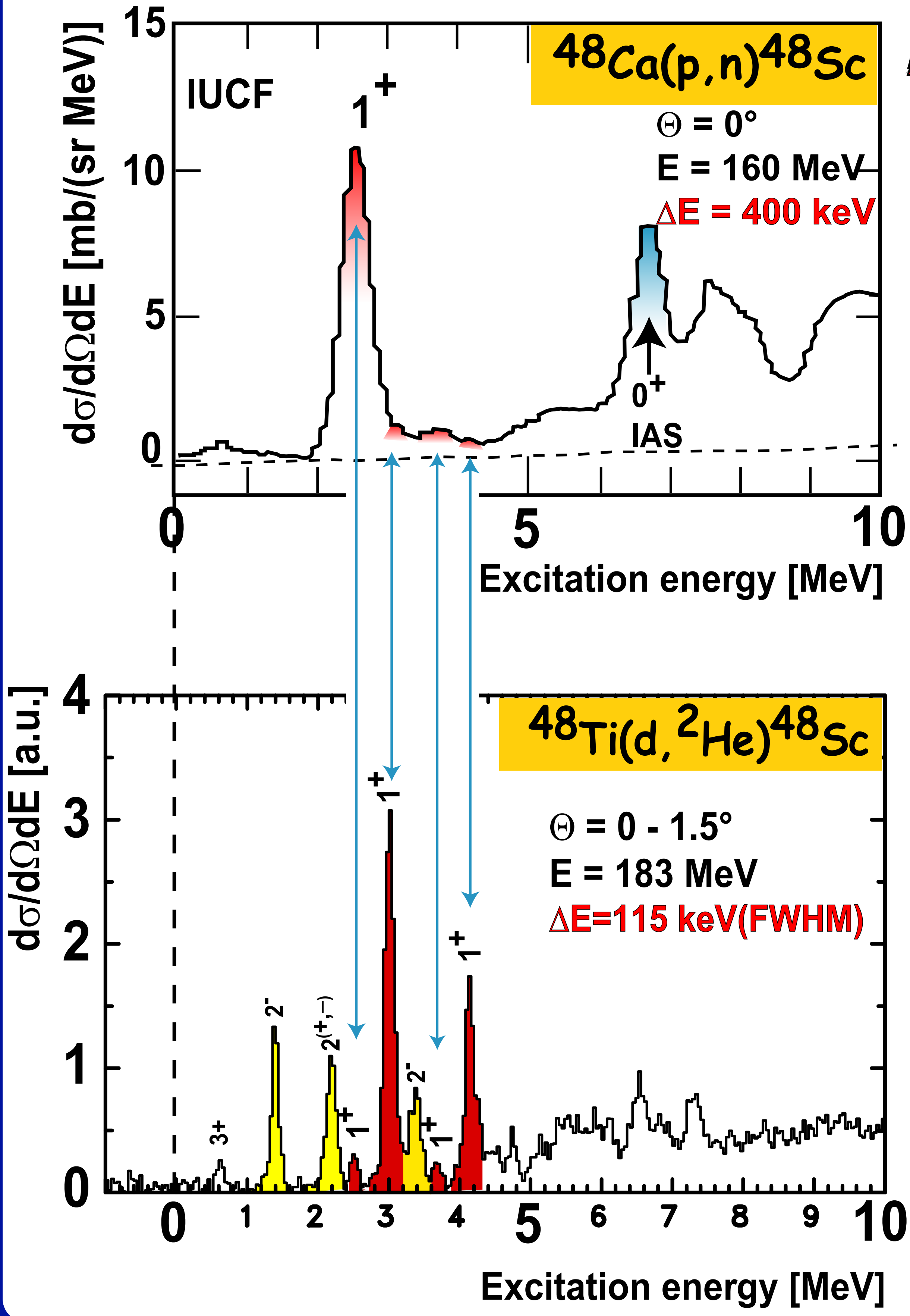
Half life:

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

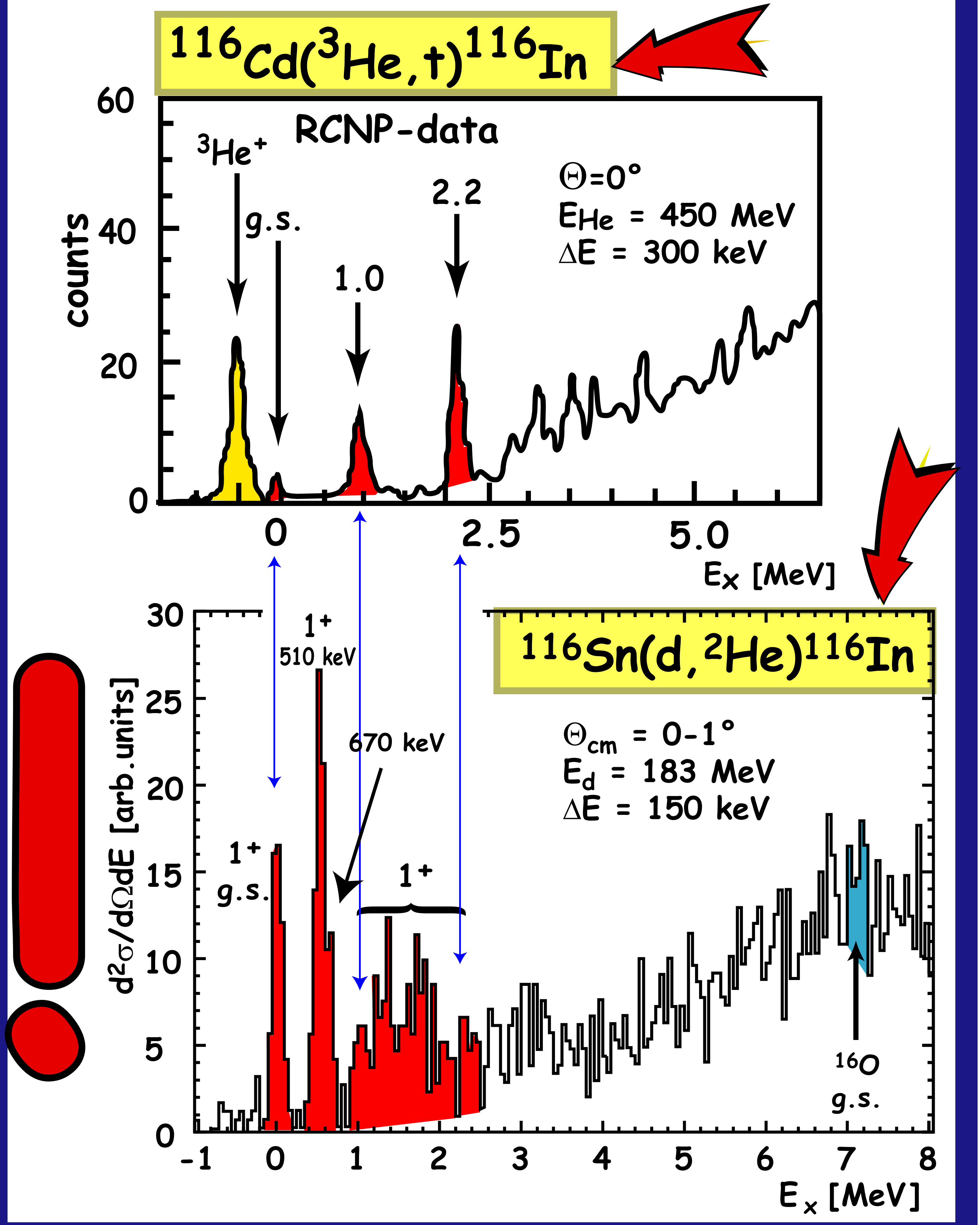
$$M_{DGT} = \sum_m \frac{<0^{(f)}_{g.s.}||\sigma\tau^-||1^+_m> <1^+_m||\sigma\tau^-||0^{(i)}_{g.s.}>}{[1/2\, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1^+_m) - M_i]/m_e + 1}$$

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

Why is ^{48}Ca so stable?



^{116}Cd double beta decay



^{116}Cd(^{3}He,t)^{116}In

^{116}Sn(d,^{2}He)^{116}In

Conclude:

astrophysics:

The (d,^{2}He) probably the best tool so far to locate GT transitions

GT transition strength need also be known for non-stable nuclei

experiment: radioactive beams, inverse kinematics
theory: needs to be credible, if to venture into the unstable region;
credibility will be gained by extended experiments

halo nuclei spectroscopy:

the (d,^{2}He) reaction was only a side-effect, the tool may be limited!

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

the potential still not fully exploited
need more test cases
need information of phase cancellation of GT states
$2\nu-\beta^{+}\beta^{+}$ (EC-EC) could be a further potential

further applications:

neutron-neutron scattering length
spin correlation of the 2p-system from ^{2}He decay (EPR)
stretched state spectroscopy

Special thanks to:

European
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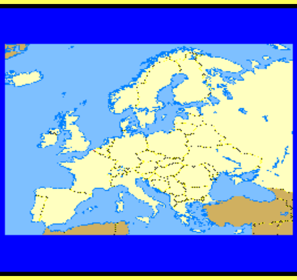

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