DF

European Supernova Collaboration

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FACETS OF (d,^{2}He) CHARGE-EXCHANGE REACTIONS:
From nucleon-nucleon physics to the mysteries of supernova explosions and the double-beta decay

astrophysics !

double-beta decay

NN-studies

halo nuclei

stretched states

Albert Singlestone & John Doe ----Questions and Answers

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Nucleosynthesis

Question:

- When did it start ??
- what elements were produced and can we understand the isotopic composition ??
- do parameters of the Early Universe have an influence ??

1945: G. Gamow's hypothesis

"all of todays elements were made during the early BIG BANG phase of the Universe"

wrong!

Nucleosynthesis

wrong *for 3 simple reasons!!!*

- Binding energy of deuteron (2.22 MeV) is too small !!
- Binding energy of ^{4}He is too large (28.3MeV) !!
- There are no stable isotopes with A=5 and A=8 !!

deuterons are being dissociated until the Universe has cooled down to ***80 keV*** *!!!*

$N_\gamma \sim 10^{10} N_N$

for further fusion the train has long left the station!!

Universe composition:
~76% H and ~23% ^{4}He

Elements are made in stars

but

stars have to be big

and

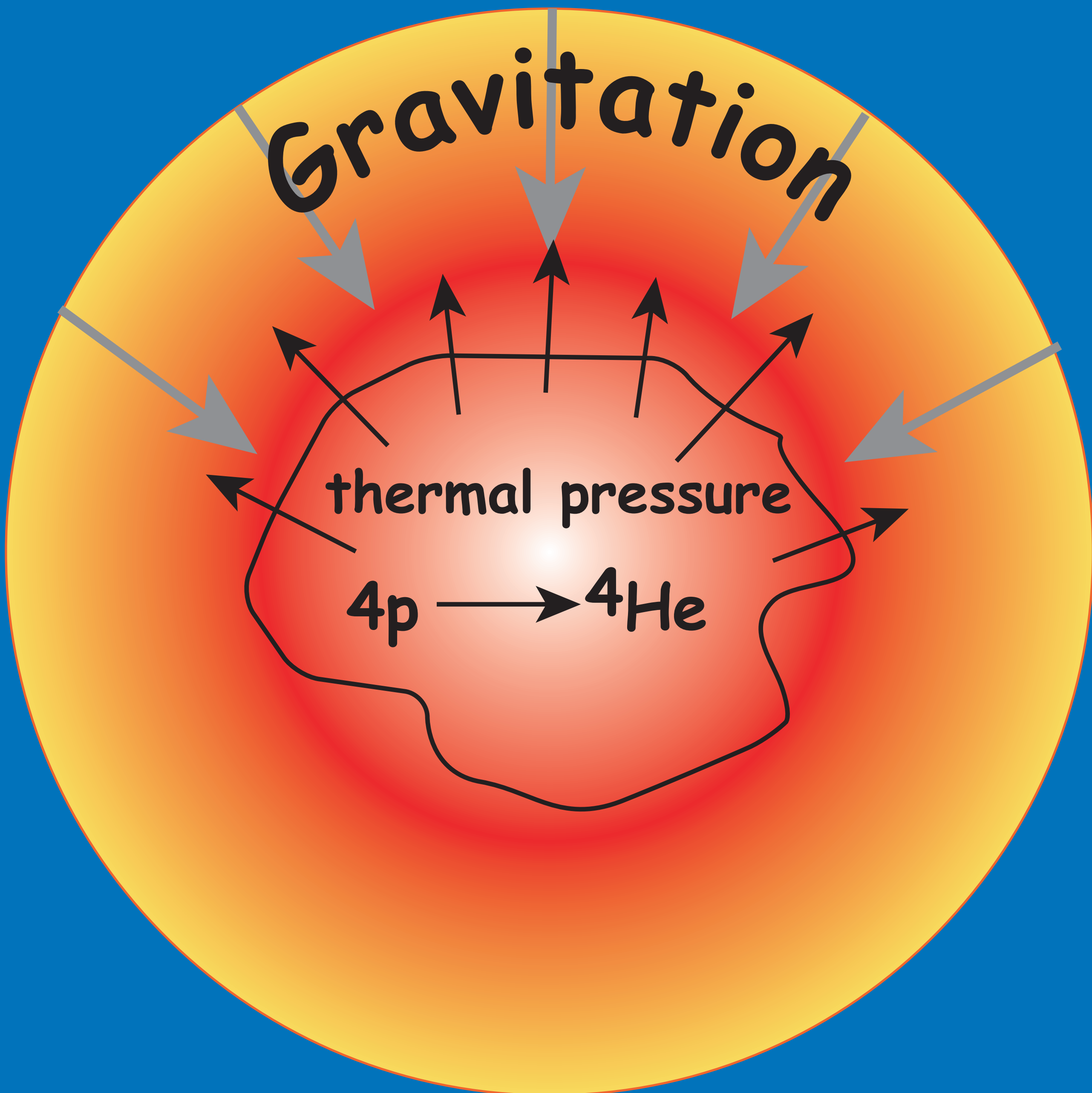
they have to explode

Supernovae

Cassiopeia A

Chandra

Nuclear processes and energy houshold of supernovae



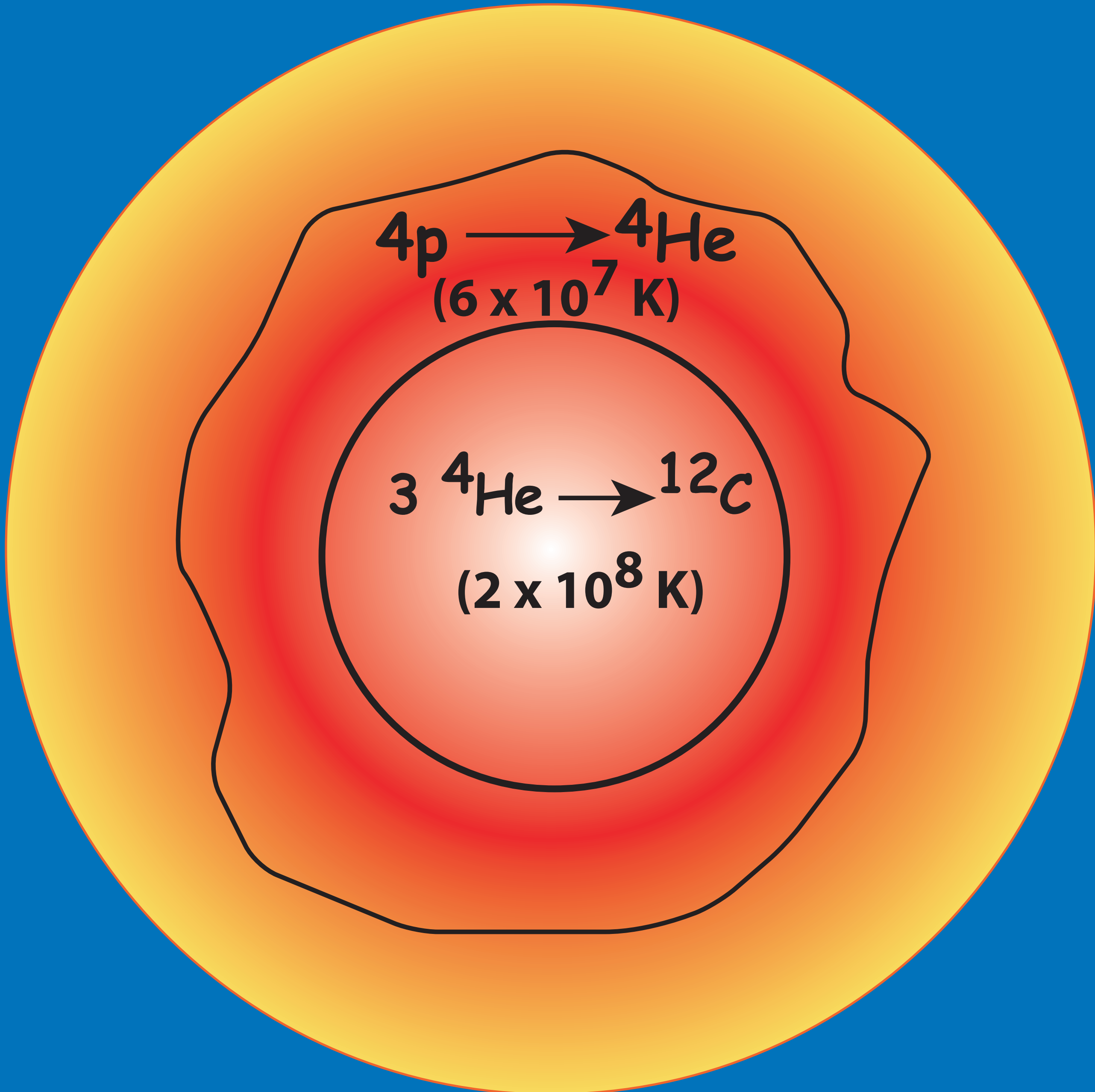
initial condition:
$M > 10\ M_\odot$

energy:
fusion 4p -> ^4He +7MeV

at: T ~ 10^7 - 10^8 K

lifetime: 10^6 - 10^7 y

after 10^6 - 10^7 y



end of H-burning

↓

contraction of star

↓

temperature increase

↓

Red Giant (Super-Giant)

↓

lifetime: 5×10^5 y

THEN

600y ^{12}C burning ($^{12}C + {}^{12}C \longrightarrow {}^{20}Ne + \alpha$ +4 MeV)
$T = 10^9$ K

1y ^{20}Ne burning (many paths) $T = 2 \times 10^9$ K
(ashes mainly ^{16}O)

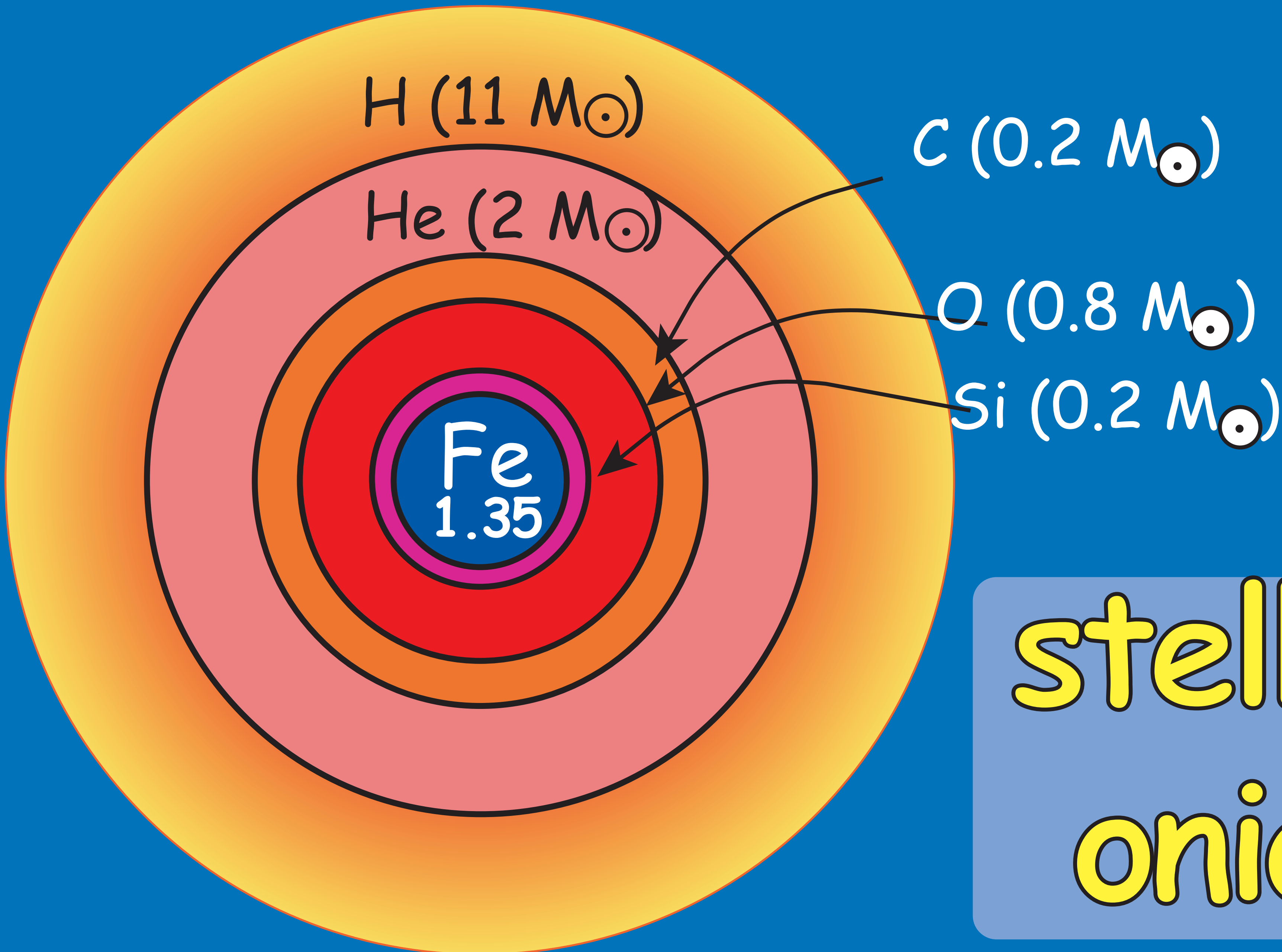
0.5 y ^{16}O burning $T = 2\text{-}3 \times 10^9$ K
(ashes mainly ^{28}Si (Fe))

~1 day ^{28}Si burning $T = 4 \times 10^9$ K
(ashes mainly Fe) $\rho = 2 \times 10^7$ g/cm^3

then core collapse (~ sec) $T = 10^{11}$ K
core bounce & explosion (~msec) $\rho = 10^{14}$ g/cm^3
nucleosynthesis (0.1 - 10 sec)

entering physics at

end of stellar evolution $M_{star} \sim 15\, M_\odot$



stellar onion

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SN-explosion scenario

- interior of star gets enriched with Fe
- gravitational pressure increases
  balanced by degenerate electron gas up to
  Chandrasekhar limit: $M_{ch} = 1.44\,(2Y_e)^2\,M_\odot$

$Y_e = \frac{\#\ \text{electrons}}{\#\ \text{nucleons}}$!

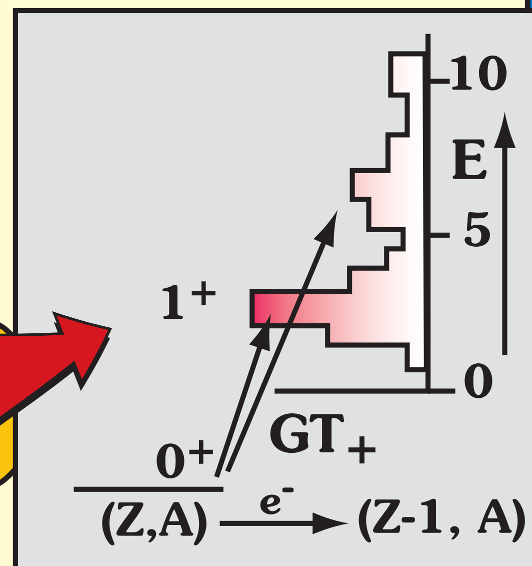
- start of collapse at
  $T = 10^9$ K and $\rho = 3 \times 10^9$ g/cm^3
  accelerated by neutronization (de-leptonization)

$e^- + p \longrightarrow n + \nu_e$

$e^- + (Z,A) \longrightarrow (Z-1,A) + \nu_e$

escaping

rate determined by GT-strength ($\Delta S = 1, \Delta T = 1, \Delta L = 0$)



- loss of pressure
- accelerated collapse
- reduction of Y_e
  and loss of energy!!

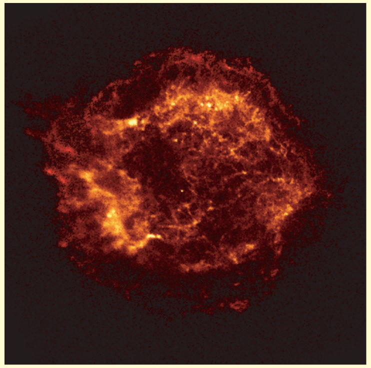
Y_e at freeze-out determines the explosive energy!!

SN-explosion scenario (cont.)

- neutrino trapping and Y_e freeze-out
  R_{core} ~ 30km
  $\lambda_{mfp}(\nu)$ ~ 0.4km
  core decouples (Y_e freezes out --- but what is its value?)
  $e^- + e^+ \longrightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$ (all 3 types)
  conversion of gravitational energy into neutrinos

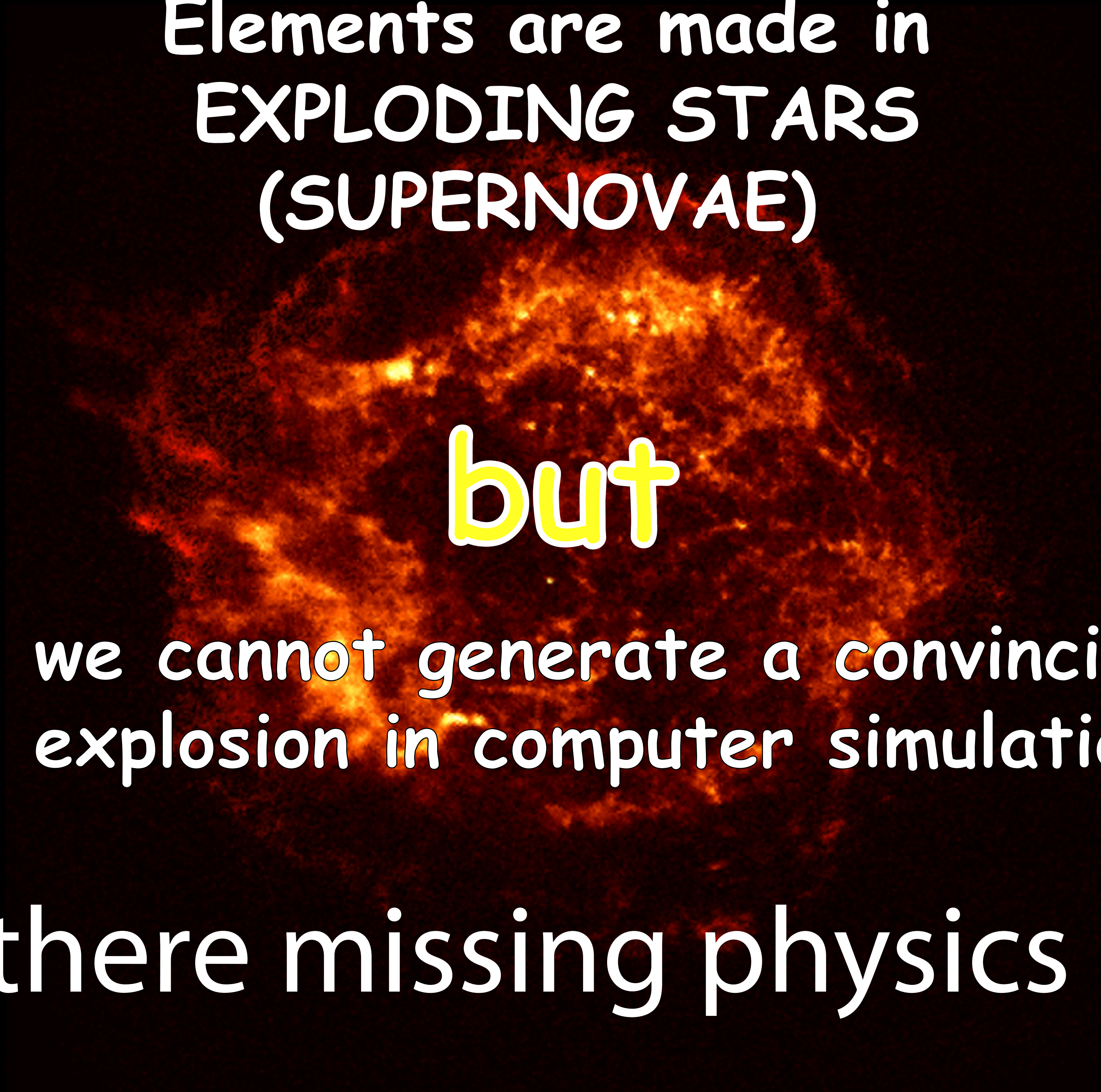
- imploding core reaches nuclear matter density
  (ρ ~ 10^{15}g/cm^3) and rebounds

- rebounding shock wave meets infalling material
  - rapid nucleosynthesis
  - explosion into interstellar space



- optical/kinetic eneregy 10^{51} erg
  neutrino energy 10^{53} erg (10^{57} - 10^{58} neutrinos!!)

Elements are made in
EXPLODING STARS
(SUPERNOVAE)



but

we cannot generate a convincing
explosion in computer simulations

are there missing physics pieces ?

SN-explosion scenario

- interior of star gets enriched with Fe
- gravitational pressure increases

balanced by degenerate electron gas up to Chandrasekhar limit: $M_{ch} = 1.44\,(2Y_e)^2\,M_\odot$

$Y_e = \frac{\#\,\text{electrons}}{\#\,\text{nucleons}}$!

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$T = 10^9$ K and $\rho = 3 \times 10^9$ g/cm^3

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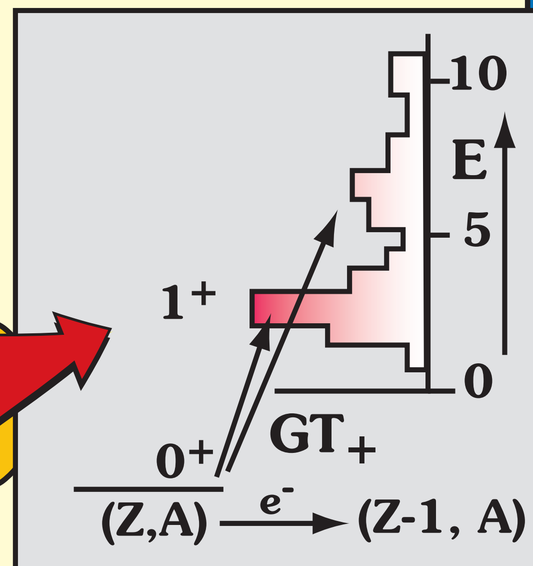
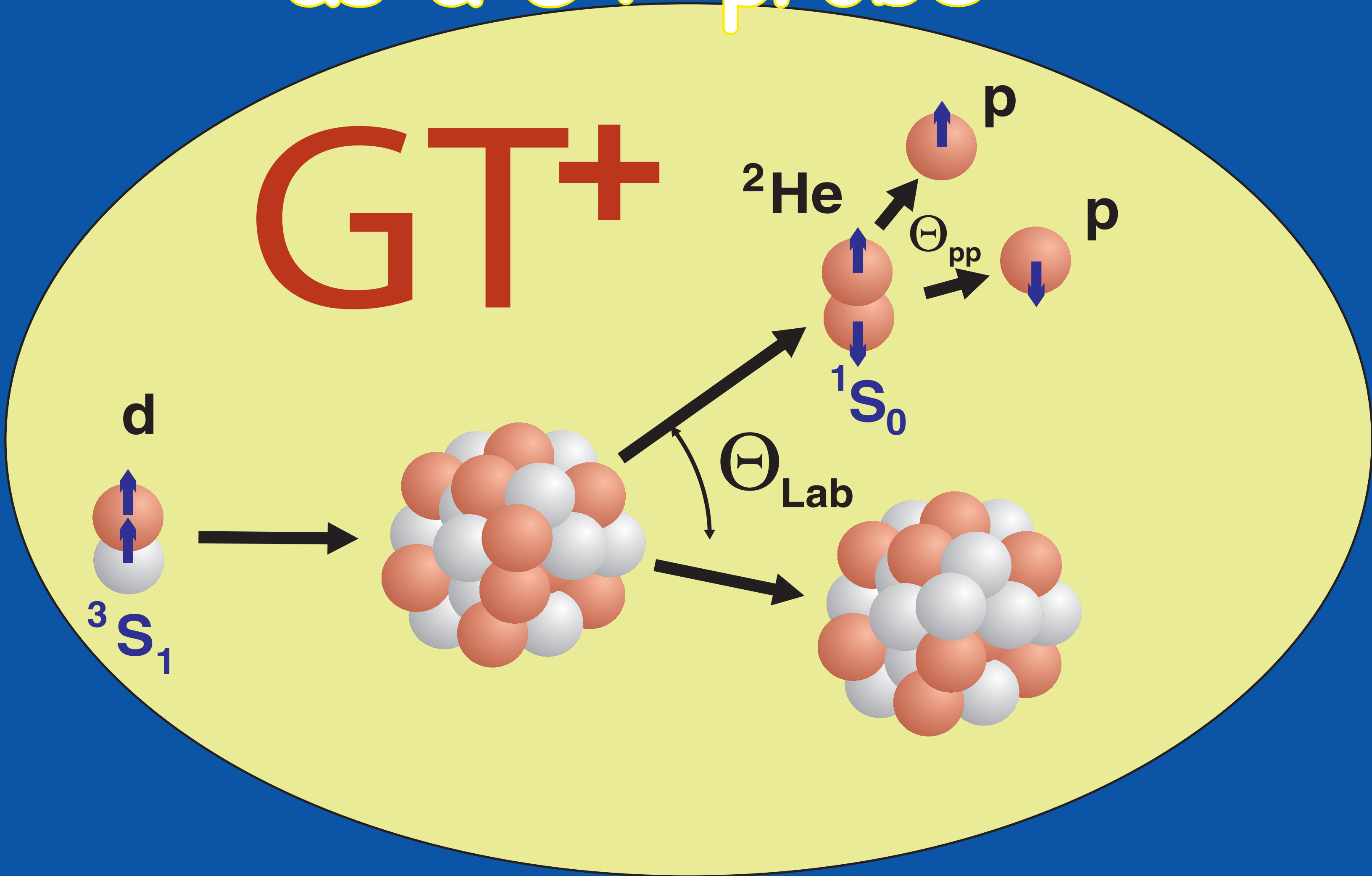


- loss of pressure
- accelerated collapse
- reduction of Y_e and loss of energy!!

Y_e at freeze-out determines the explosive energy!!

The (d,^{2}He) charge exchange reaction as a GT-probe



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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

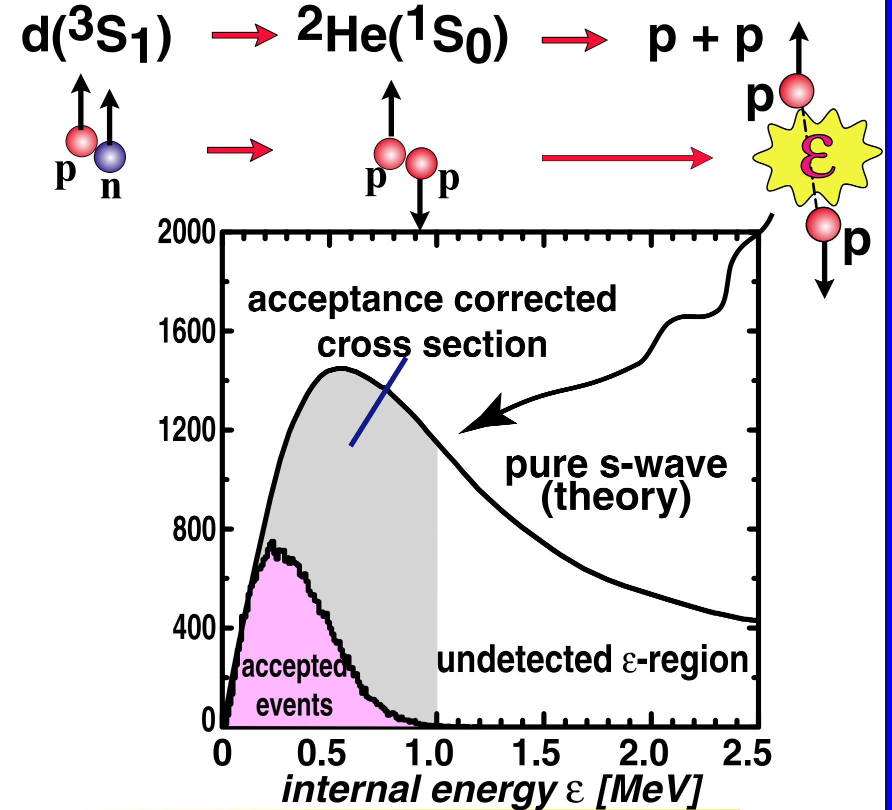
2)- coincident detection of two protons from ^{2}He decay
➡ background-free spectra
but need large accptnc spectrometer

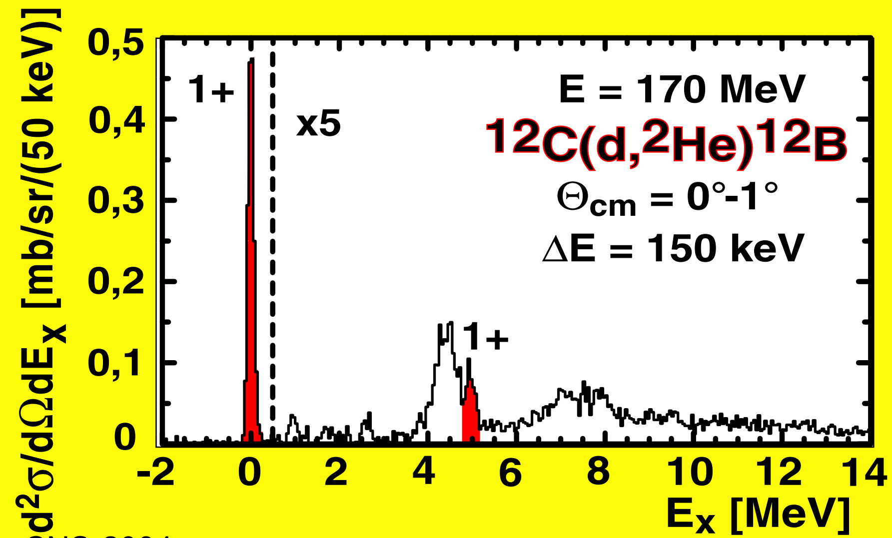
3)- contributions from higher p-p partial waves? Dont'worry!!

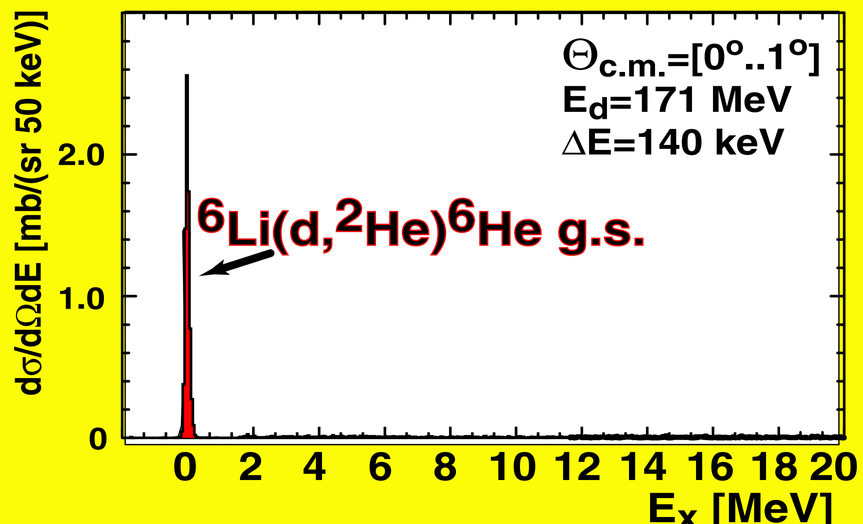
Alternatives:

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

$S=1, T=0 \rightarrow S=0, T=1$

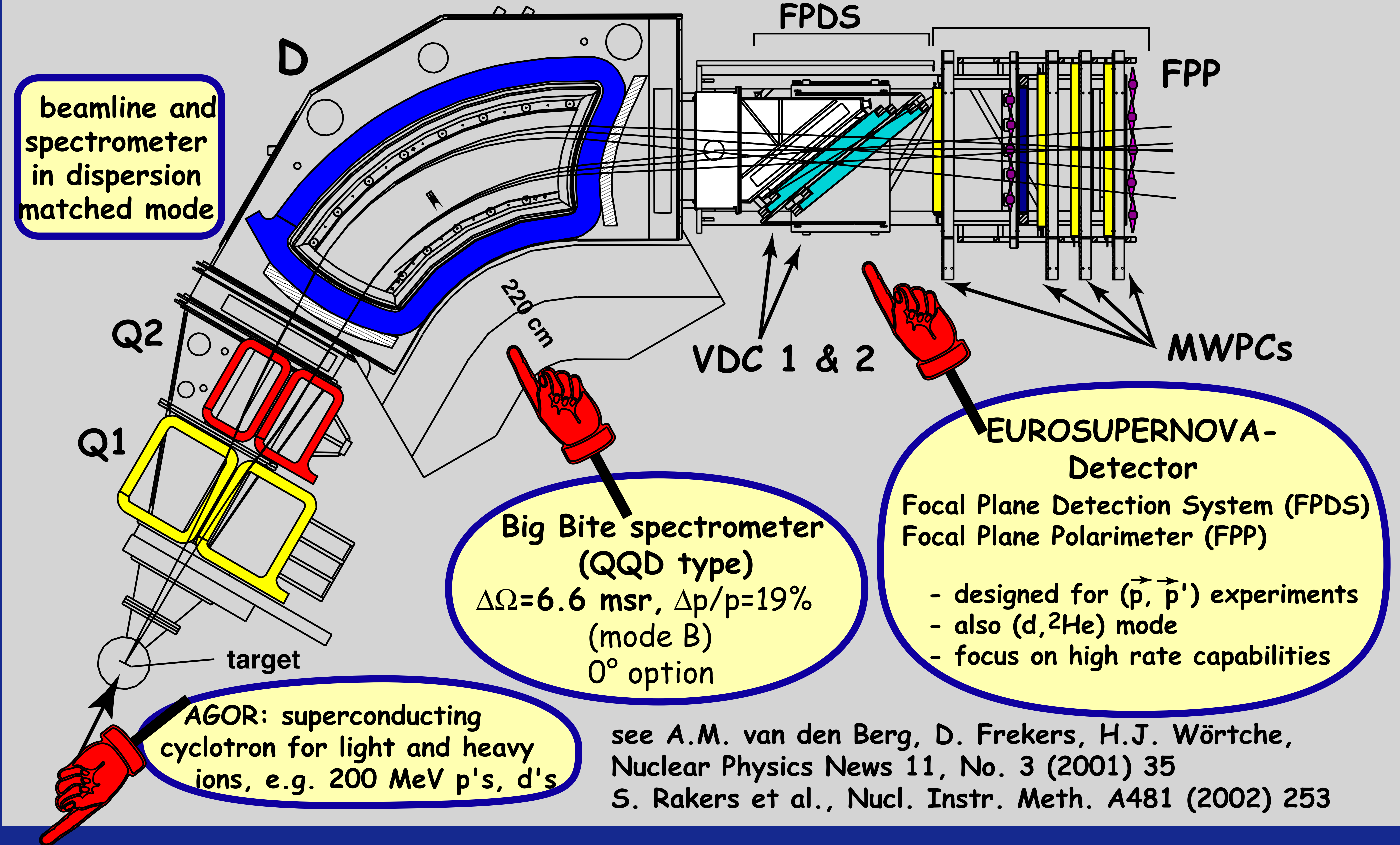






The experimental setup

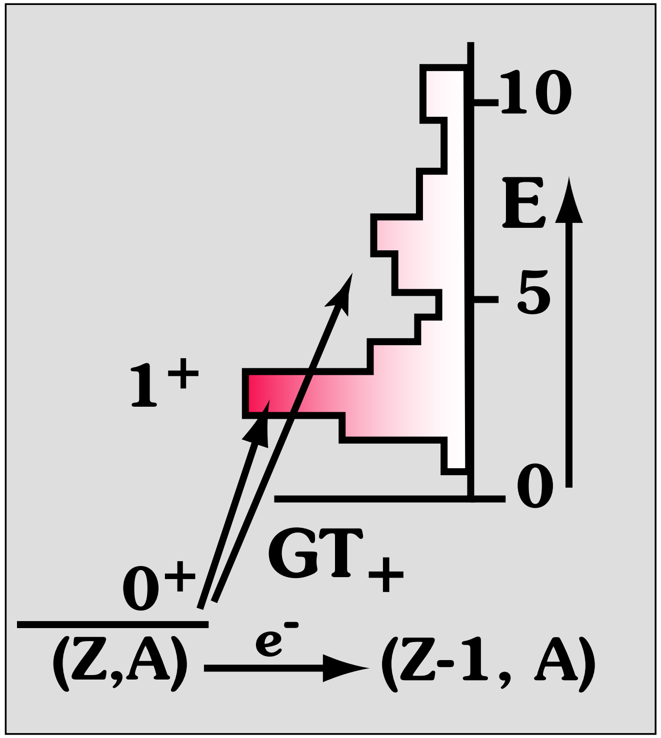
at AGOR facility, KVI Groningen



see A.M. van den Berg, D. Frekers, H.J. Wörtche, Nuclear Physics News 11, No. 3 (2001) 35
S. Rakers et al., Nucl. Instr. Meth. A481 (2002) 253

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
-> calculations of GT-centroids only

FFN

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

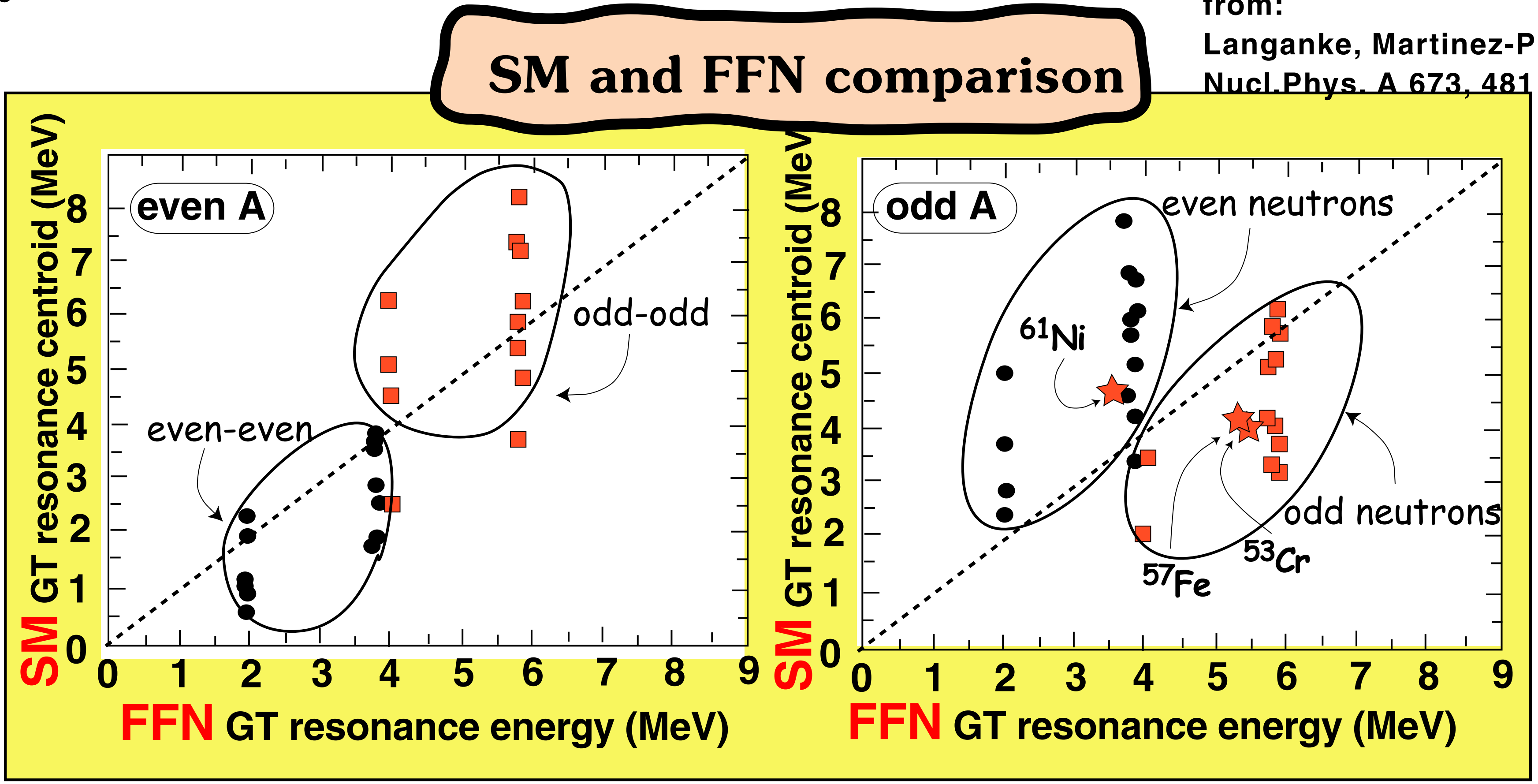
Stellar EC rates

at a given temperature

important parameters

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

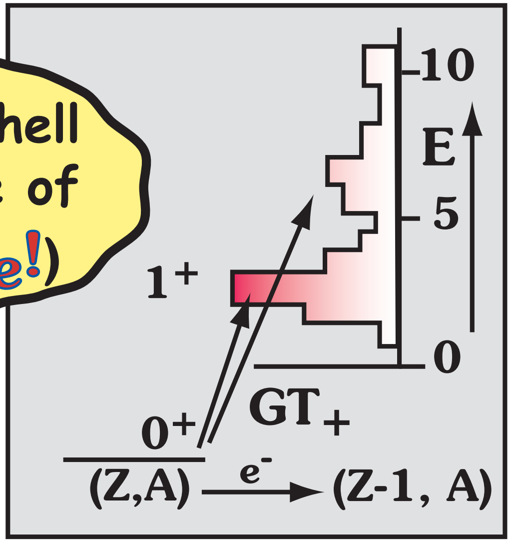
from:
Langanke, Martinez-Pinedo
Nucl.Phys. A 673, 481 (2000)



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

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
ν-cooling before collaps up
Ye 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 protons 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)

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

largest at 100 - 200 MeV/A

Q: How to connect the weak $\vec{\sigma}\tau_+$ GT operator with hadronic reactions?

A: at intermediate energies exploit the dominance of $V_{\sigma\tau}$ interaction.

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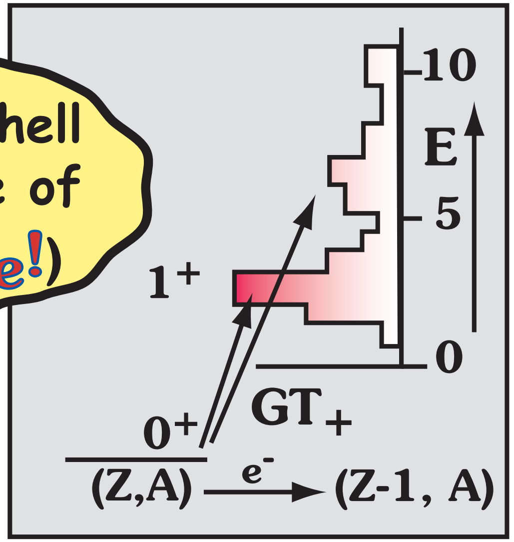

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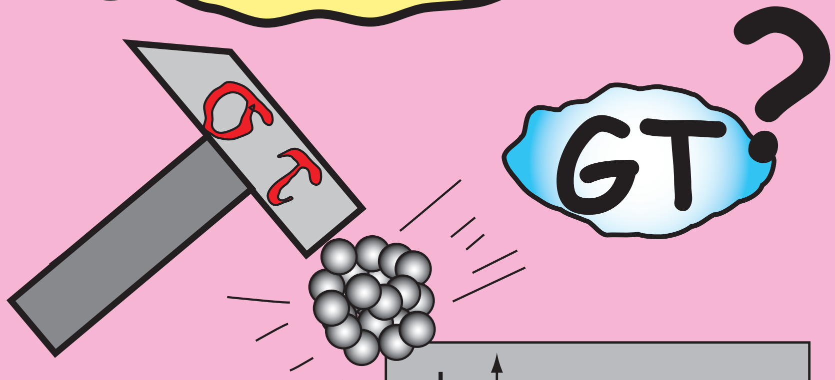
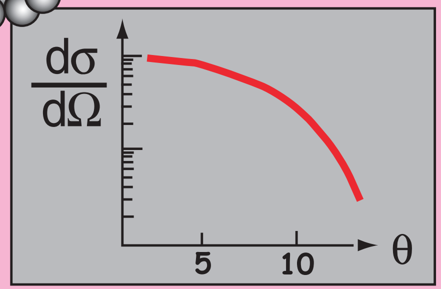


Gentle Touch:

→ $q_{tr} = 0$

→ $\Delta l = 0$

→ $0\,\hbar\omega$ excitation



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SM and FFN comparison

from:
Langanke, Martinez-Pinedo
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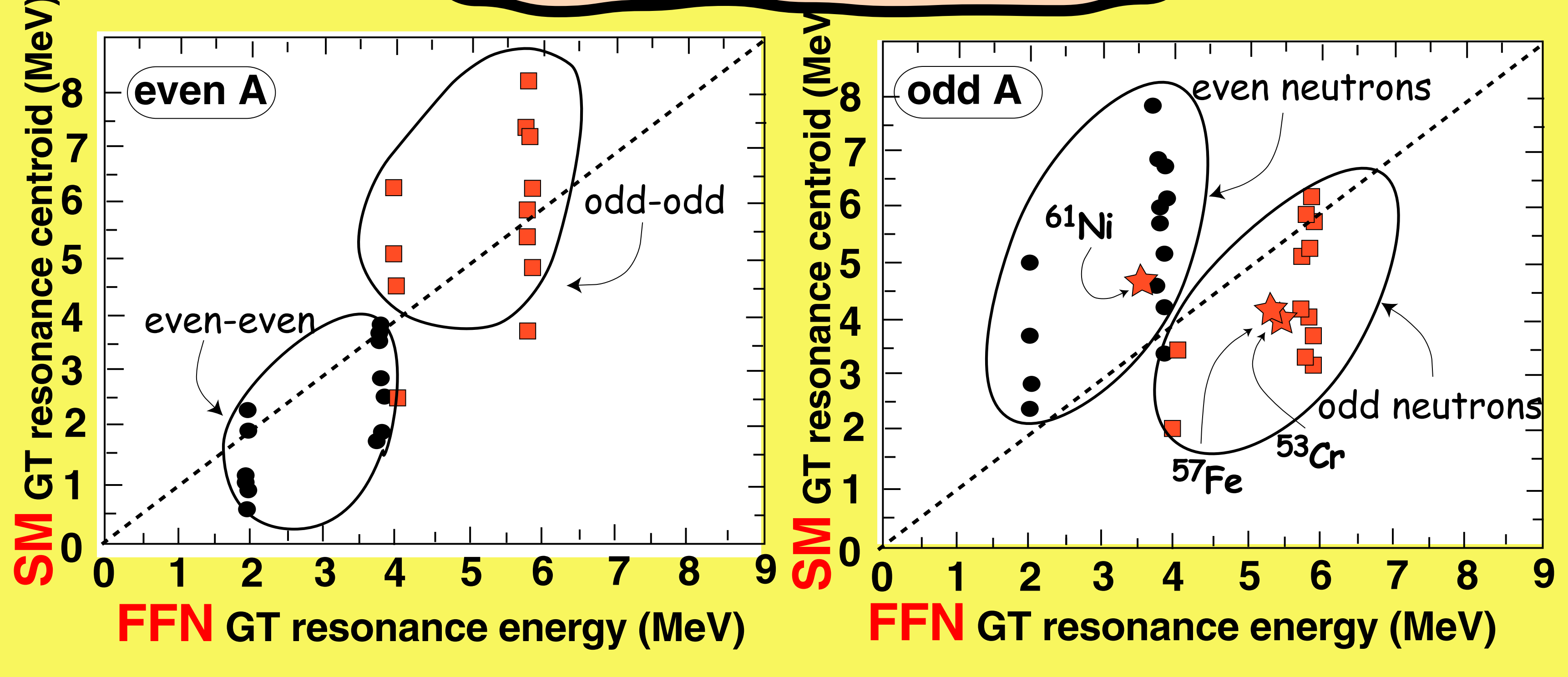

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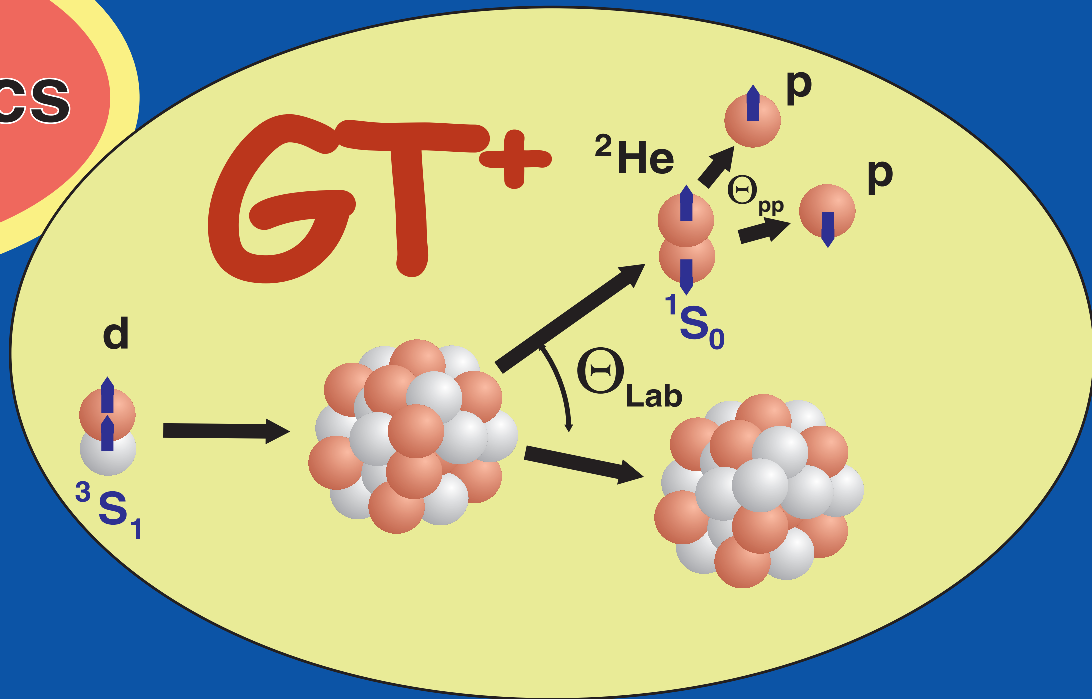
- no exp. data on odd-odd nuclei (^{50}V is the only stable one)

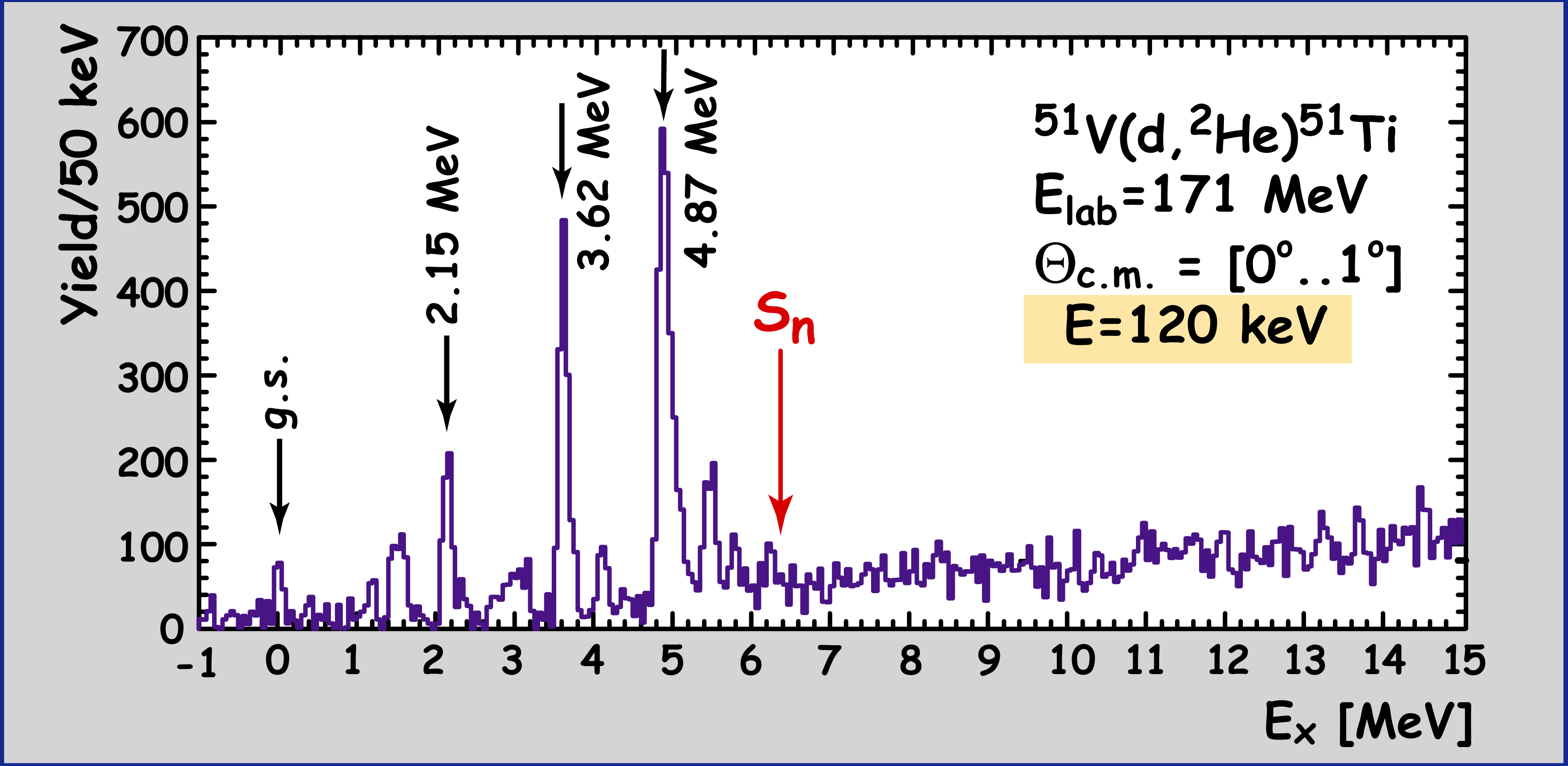
odd-A odd-p nuclei

Astrophysics



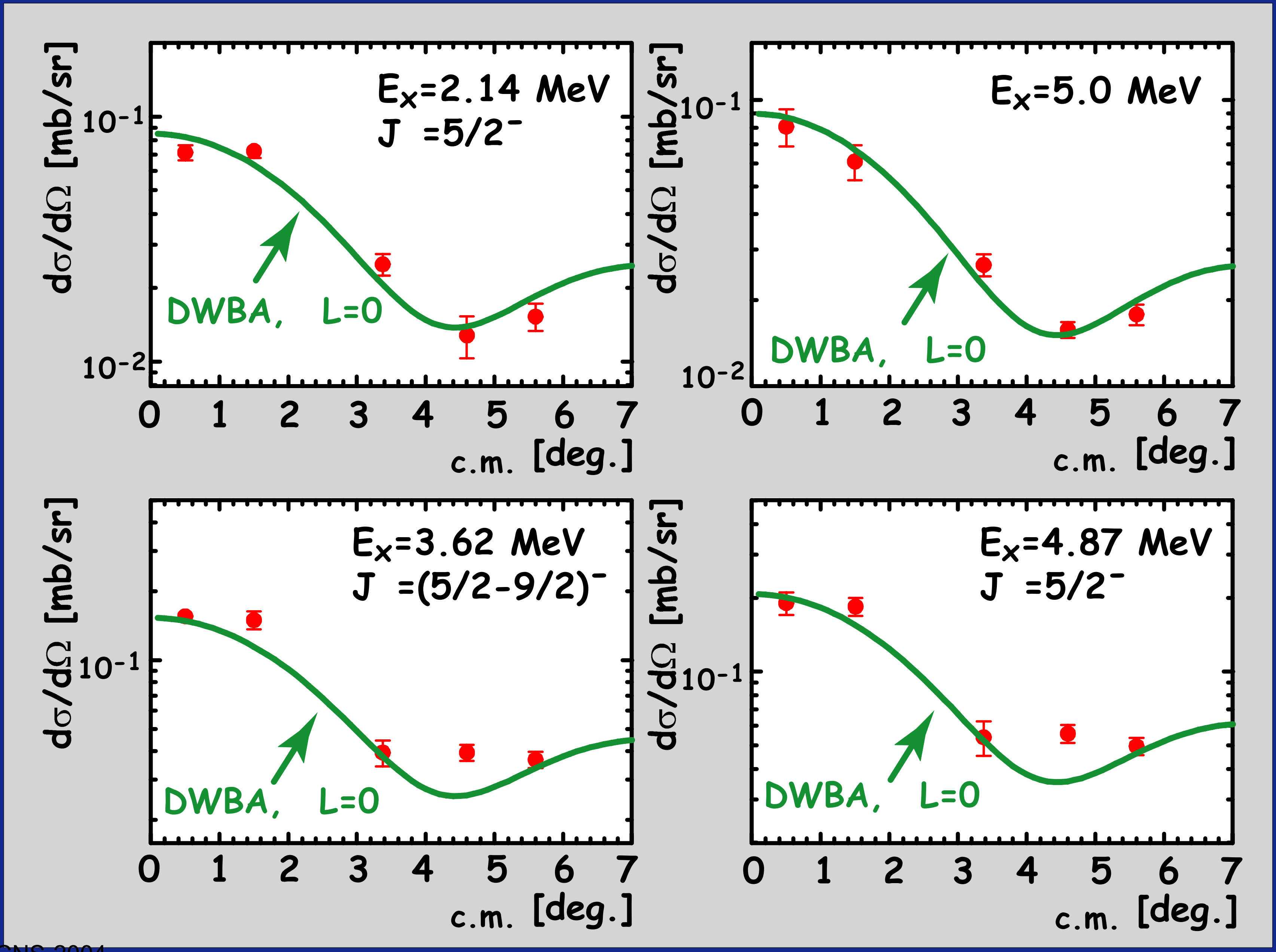
B(GT⁺) from a proton-odd pf-shell nucleus: $^{51}V(d,^{2}He)^{51}Ti$

- ^{51}V g.s. ($J = 7/2^-$, $T=5/2$) ⟶ ^{51}Ti ($J = 5/2^-, 7/2^-, 9/2^-$, $T=7/2$)
- independent single particle model: $E_x(GTR)=3.83$ MeV (FFN)

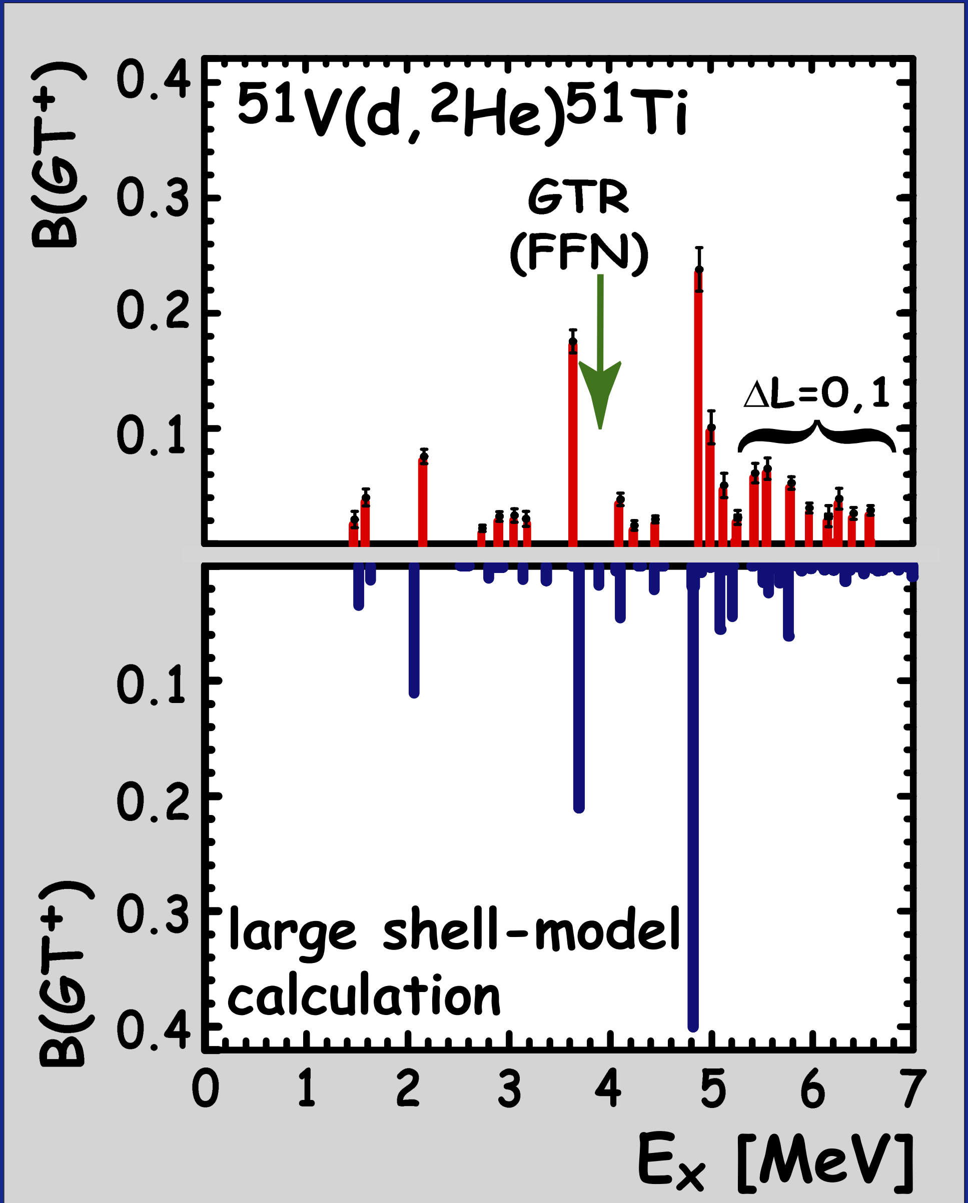


C. Bäumer et al., Phys. Rev. C 68 (2003) 031303(R)

$^{51}V(d,^2He)$: Angular distributions of $d\sigma/d\Omega$



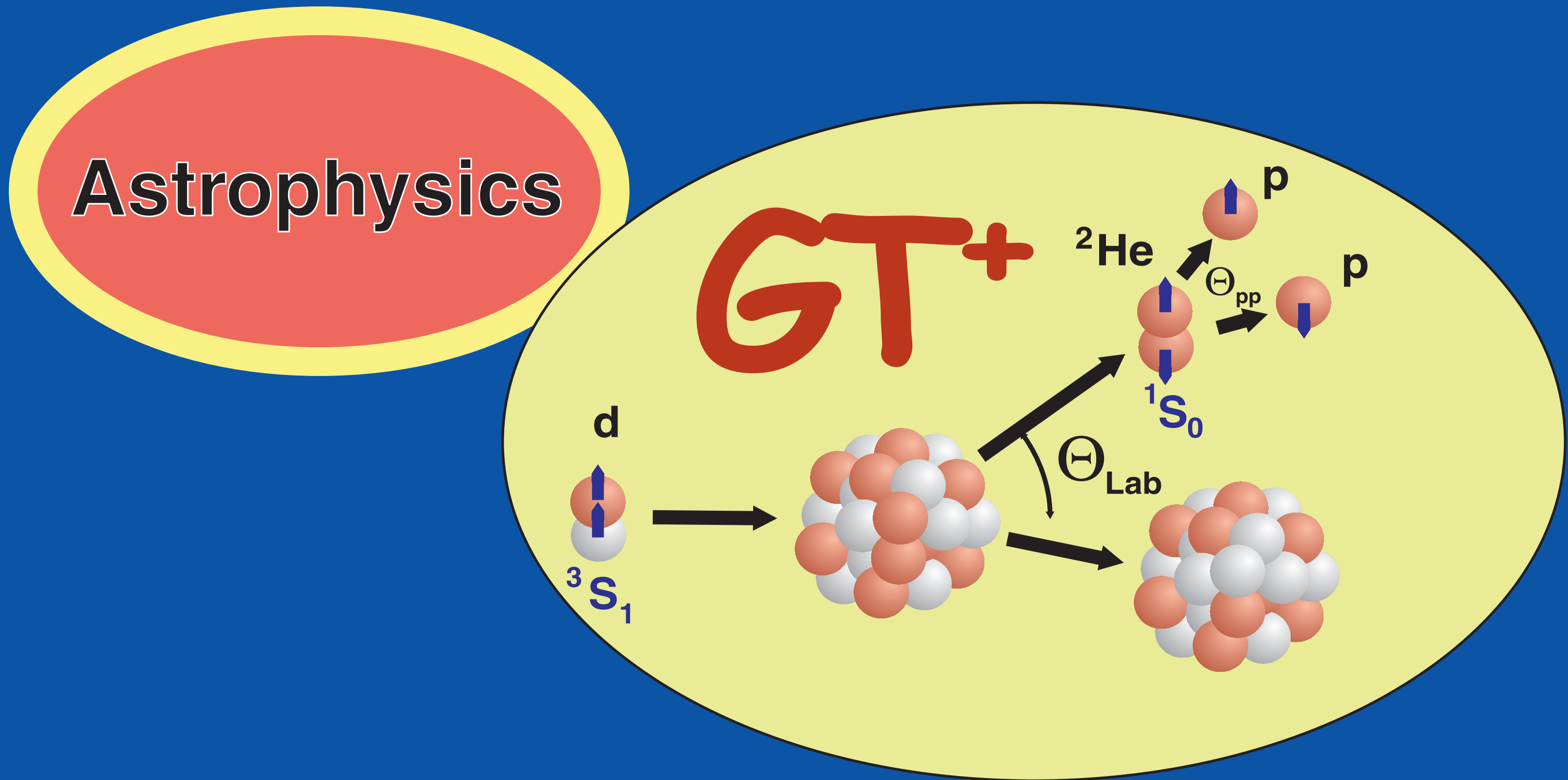
$^{51}V(d,^2He)$: Comparison with shell-model calculation



← experimental result

← full pf-shell model calculation (G. Martinez-Pinedo, K. Langanke)

odd-A odd-n nuclei



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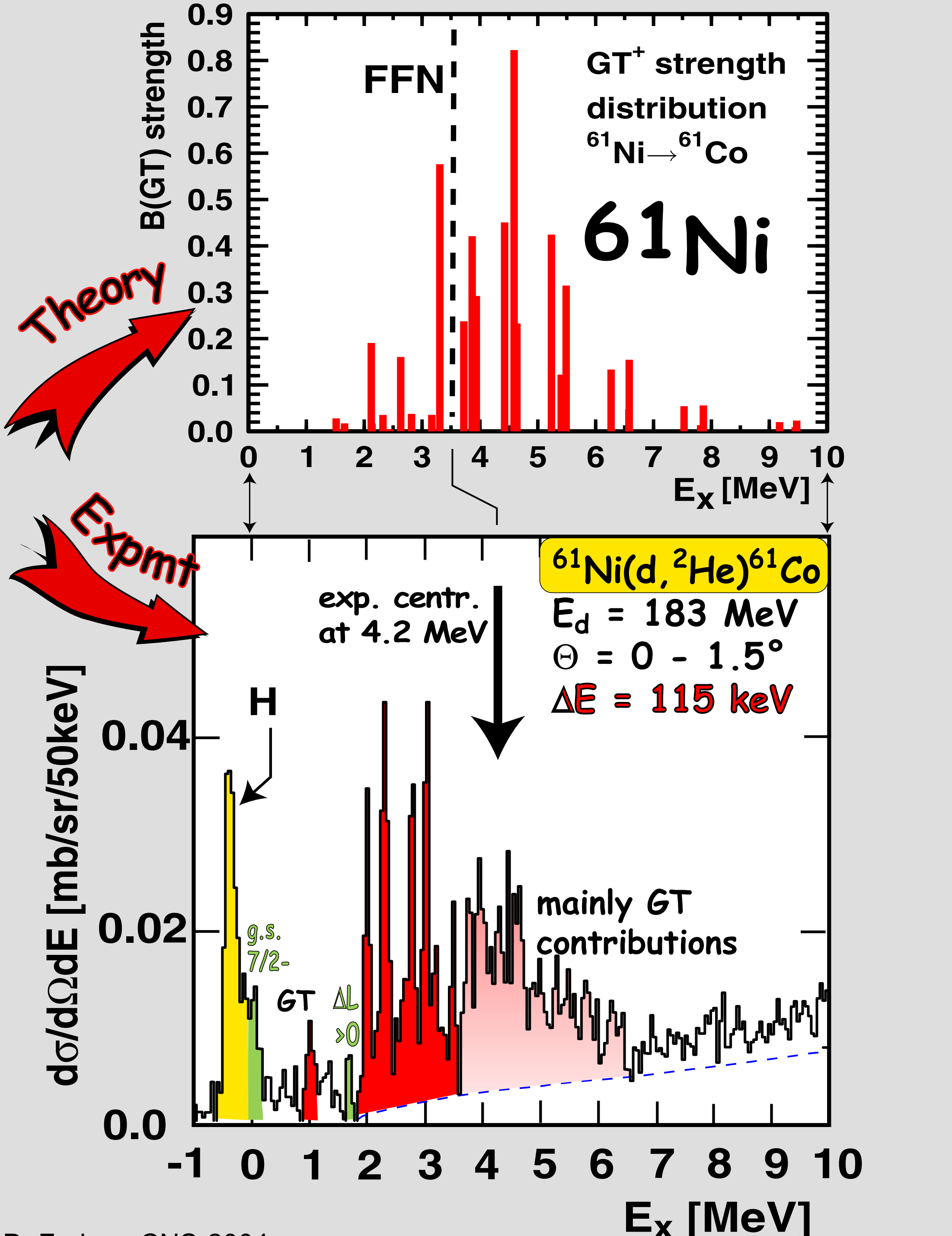
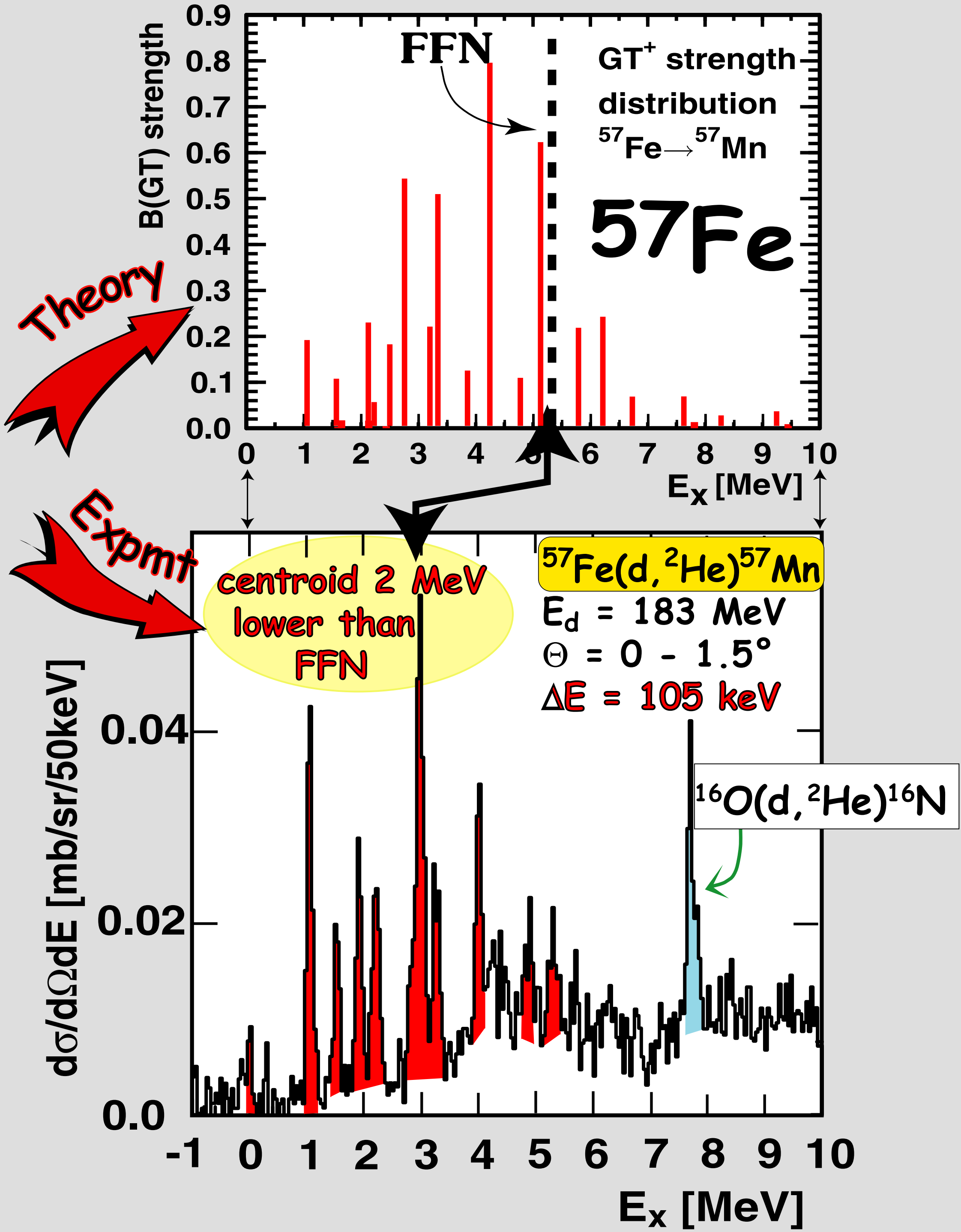
$^{61}Ni(d,^{2}He)^{61}Co$: GT distribution



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



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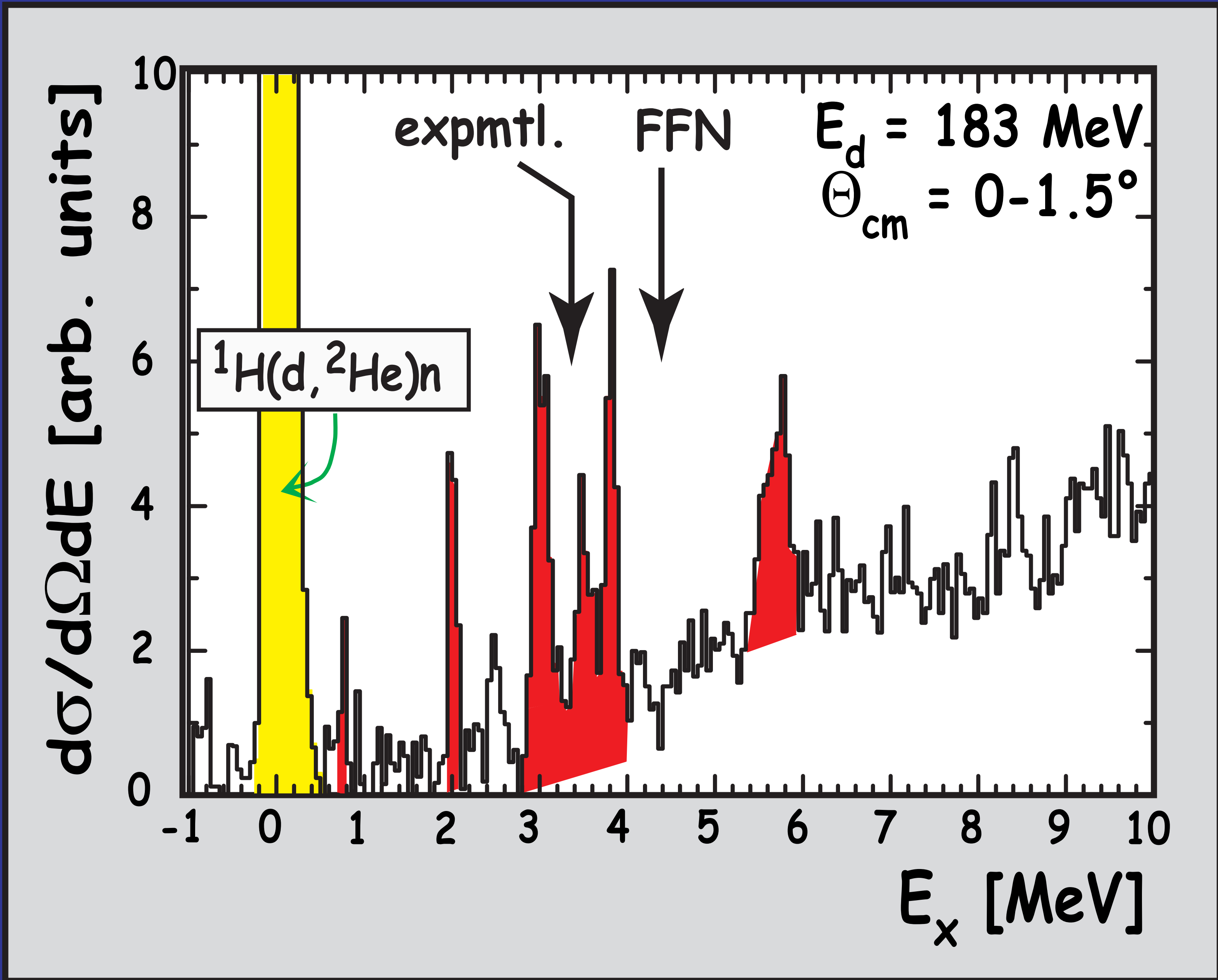
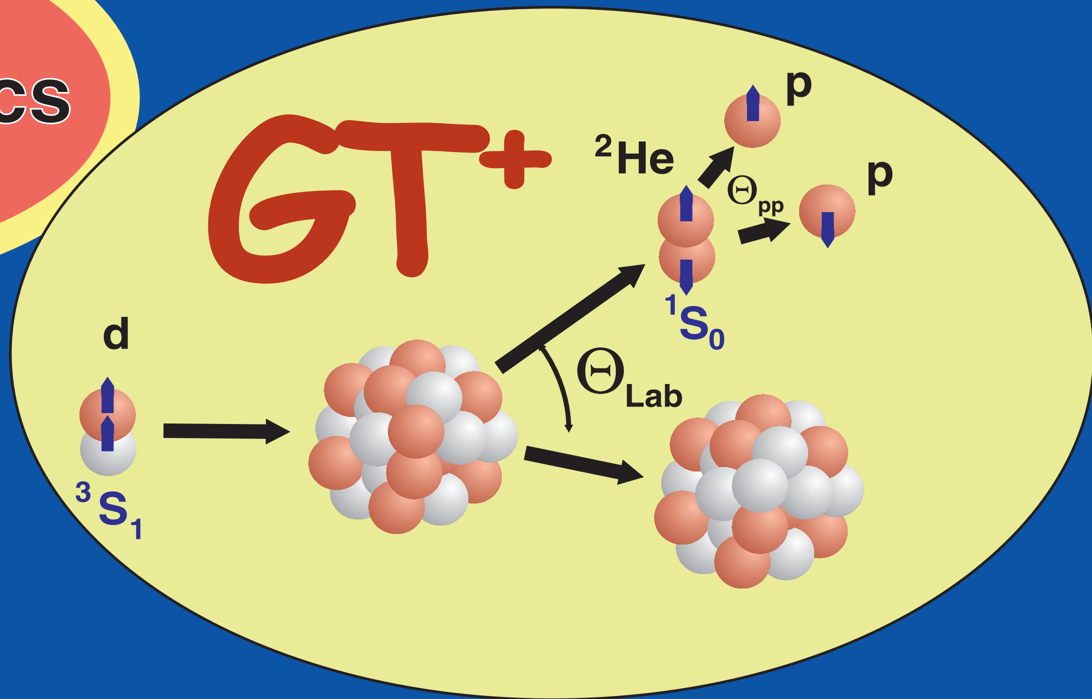
$^{67}Zn(d,^{2}He)^{67}Cu$: GT^{+} distribution



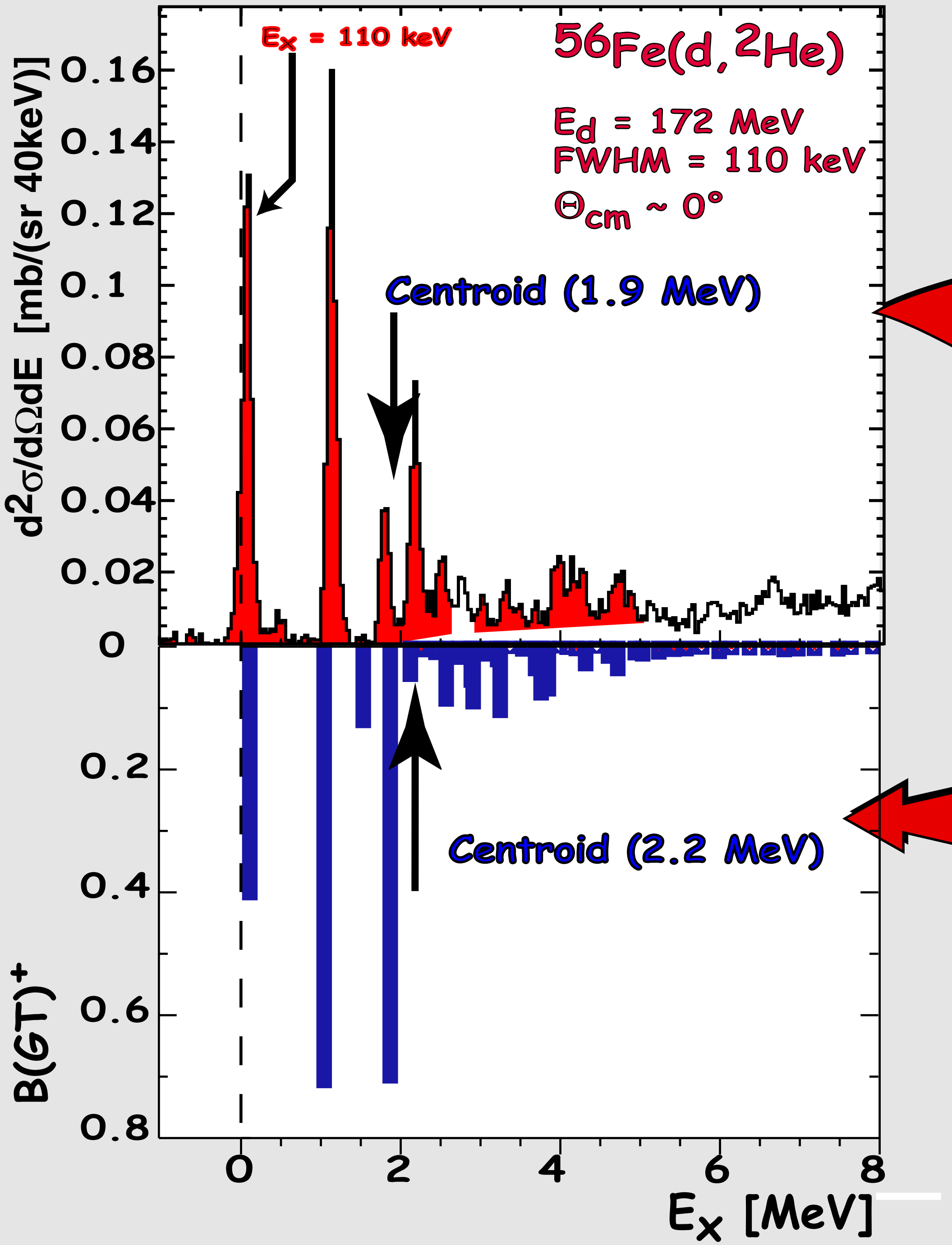
no shell-model calculations yet

even-even nuclei

Astrophysics



$^{56}Fe(d,^{2}He)$: Comparison with shell-model calculations

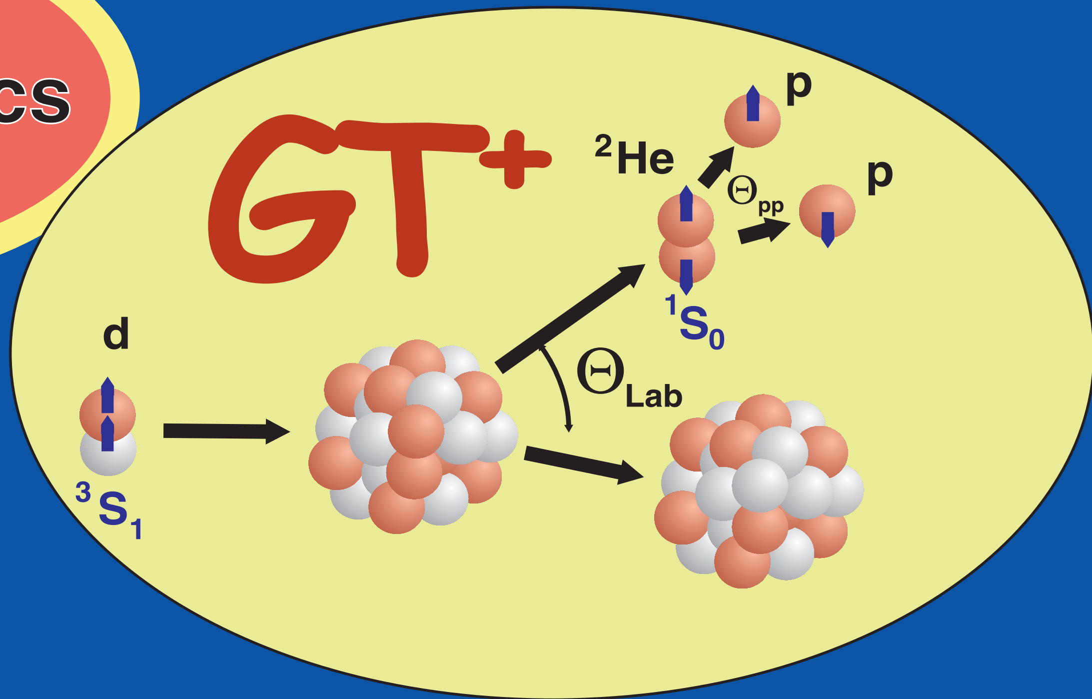


experiment

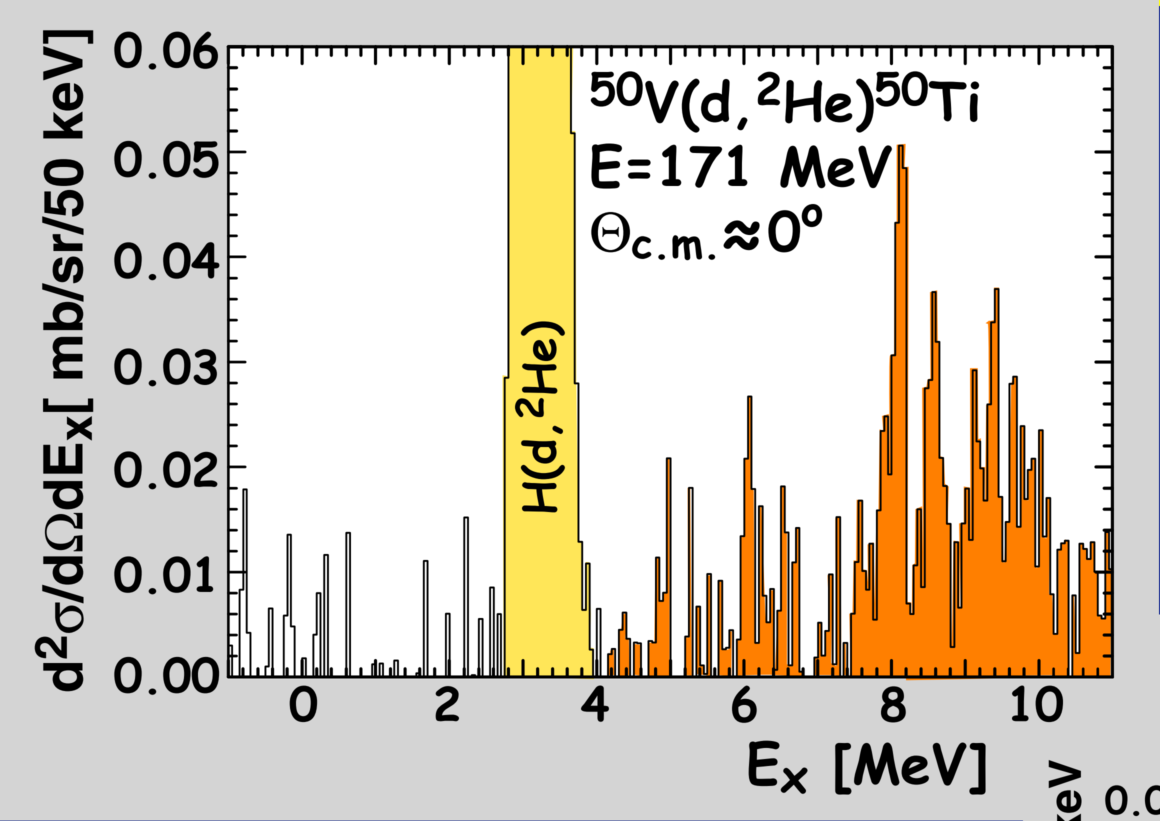
full fp-shell model calculations (KG3G) (G. Martinez-Pinedo)

odd-odd nuclei

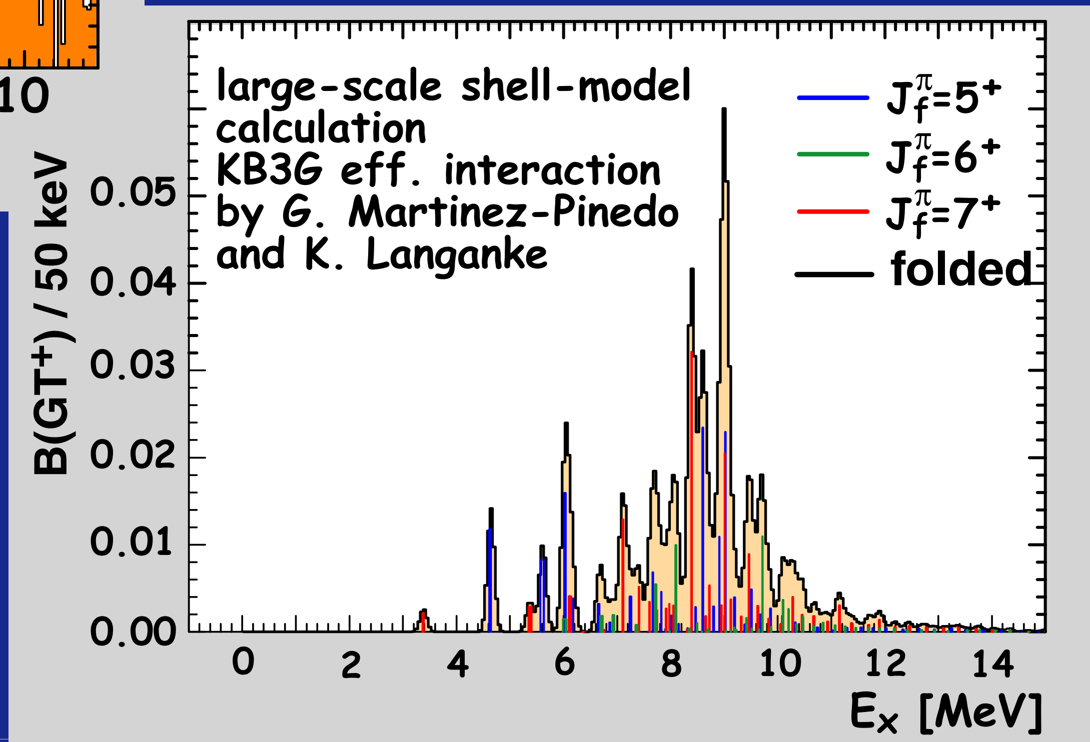
Astrophysics



GT+ transitions from odd-odd nucleus $^{50}V(d,^{2}He)$



^{50}V $J^{\pi}=6^{+}$ T=2 —GT+→ ^{50}Ti $J^{\pi}=5^{+},6^{+},7^{+}$ T=3



GT- centroid located at ~ 9 MeV !!

GT+ centroid comparison

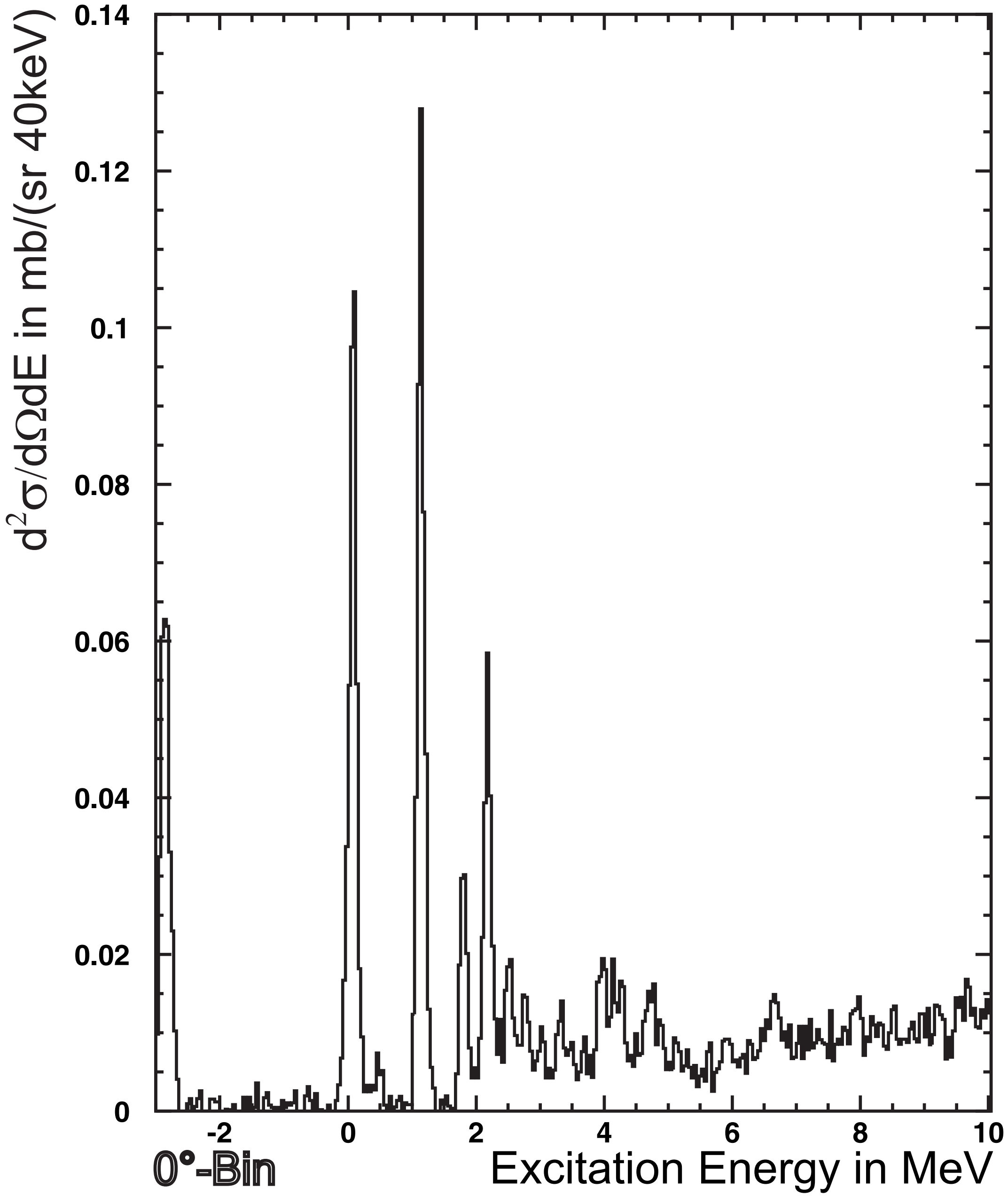
		FFN	SM	Exp.
even-even	Fe-56	3.8	2.2	1.9
	Ni-58	3.8	3.6	3.4
odd-A odd-p	V-51	3.8	4.7	4.6
odd-A odd-n	Fe-57	5.3	4.1	2.9
	Ni-61	3.5	4.6	4.2
	Zn-67	4.4	--	3.4
odd-odd	V-50	9.7	8.5	8.8

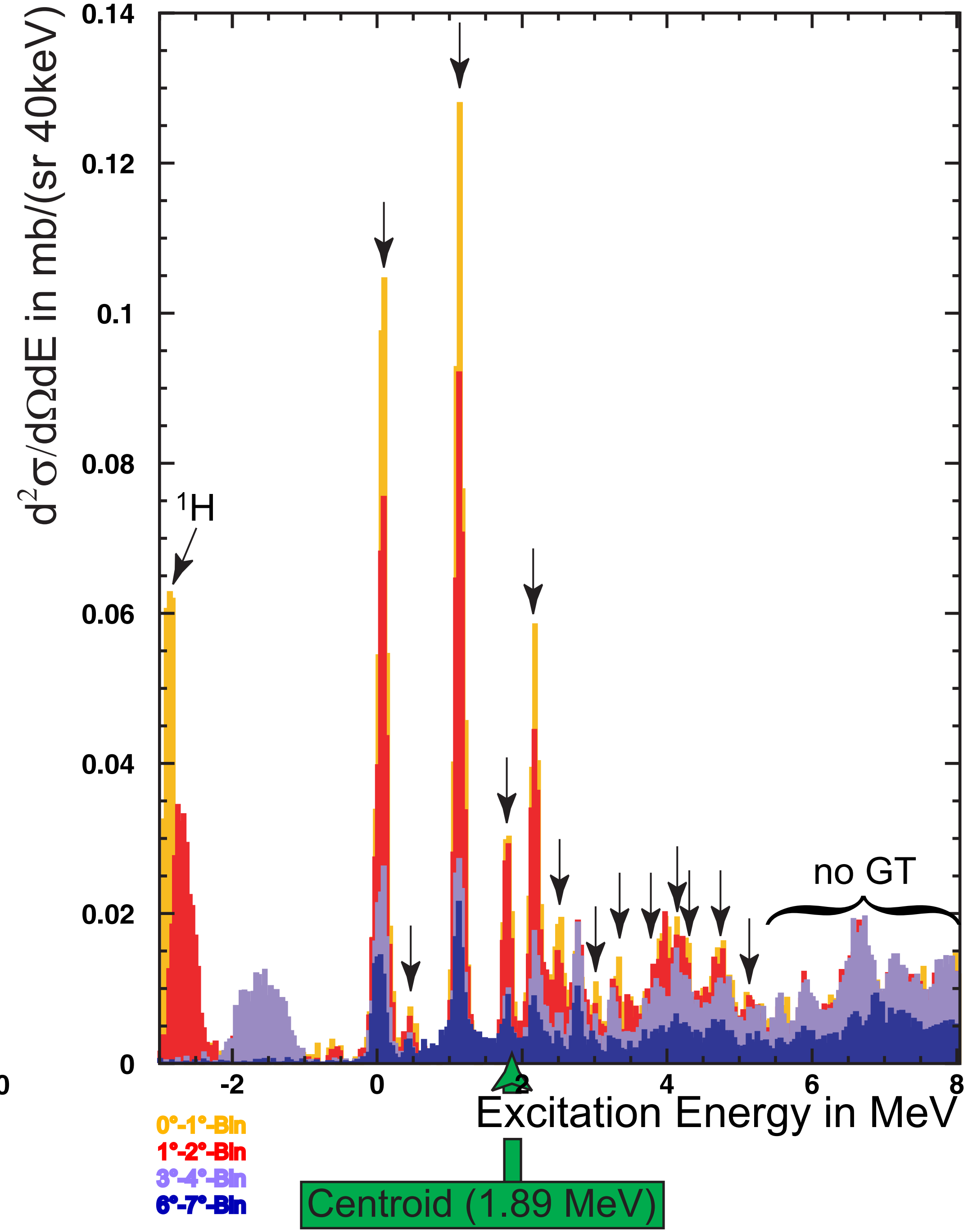
CONCLUSIONS:

There are
good news and bad news
for a
"SUPERNOVA in a computer"

we keep on the struggle

Spectrum of the $^{56}Fe(d,^{2}He)^{56}Mn$-Reaction





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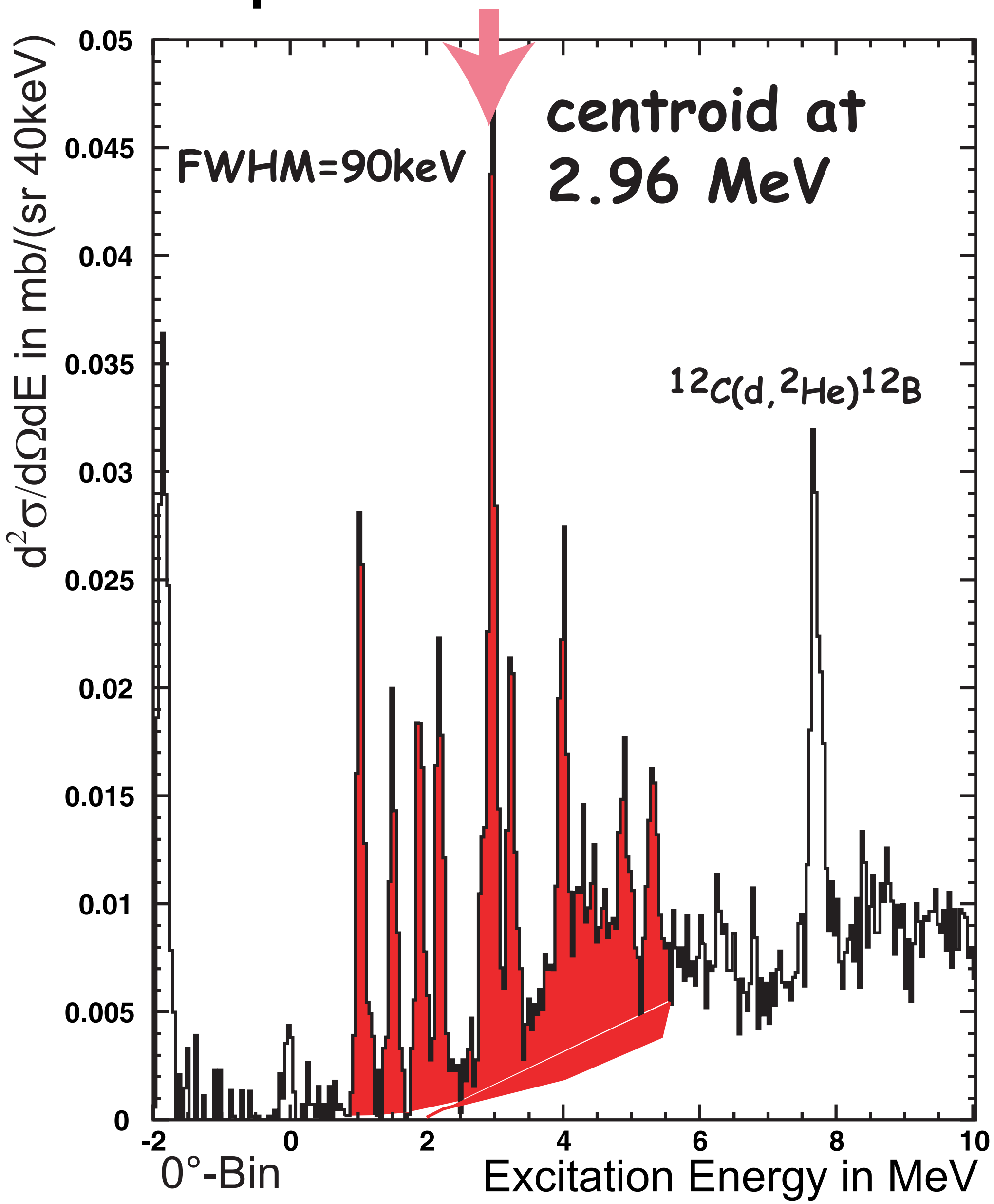
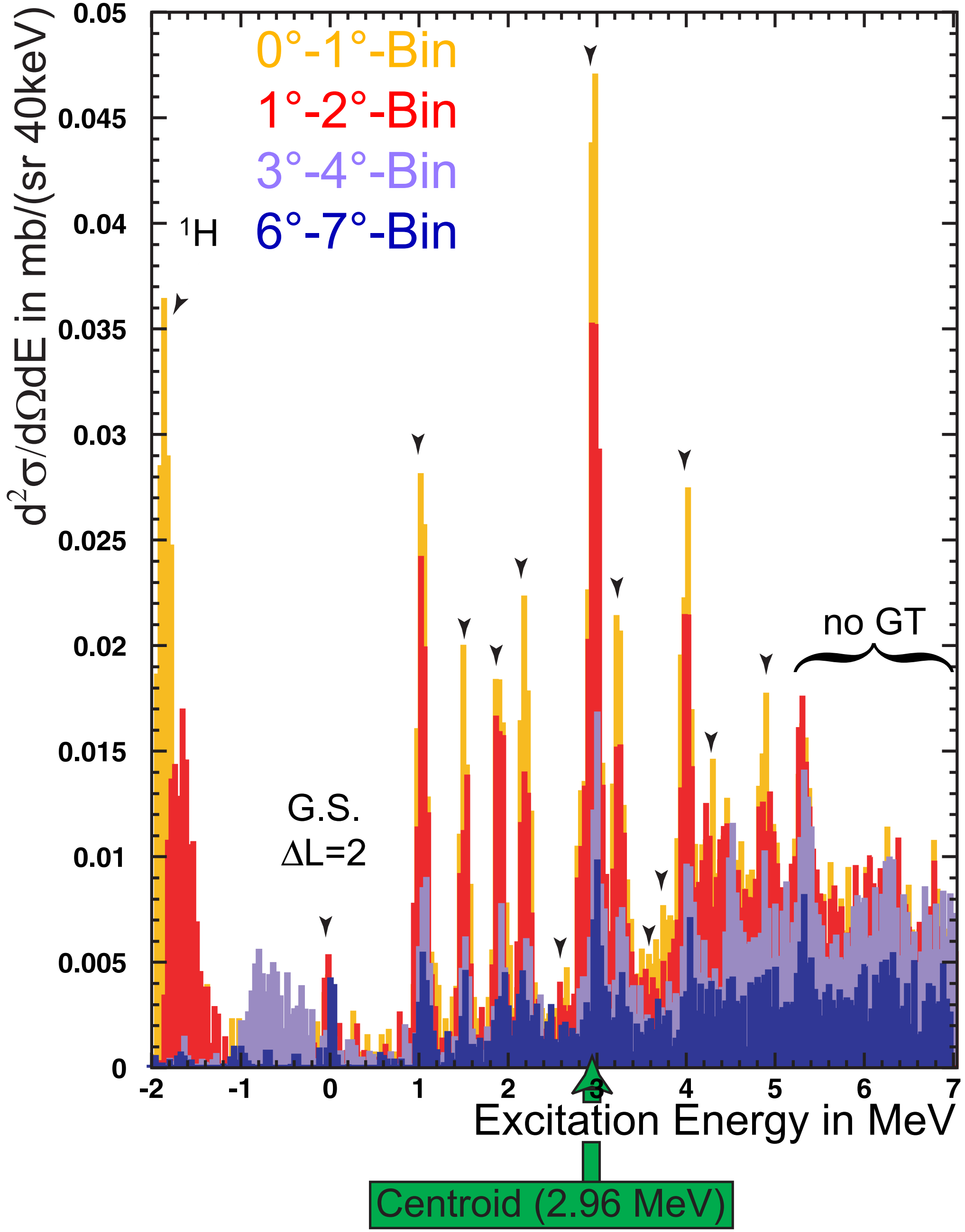
Spectrum of the $^{57}Fe(d,^{2}He)^{57}Mn$-Reaction





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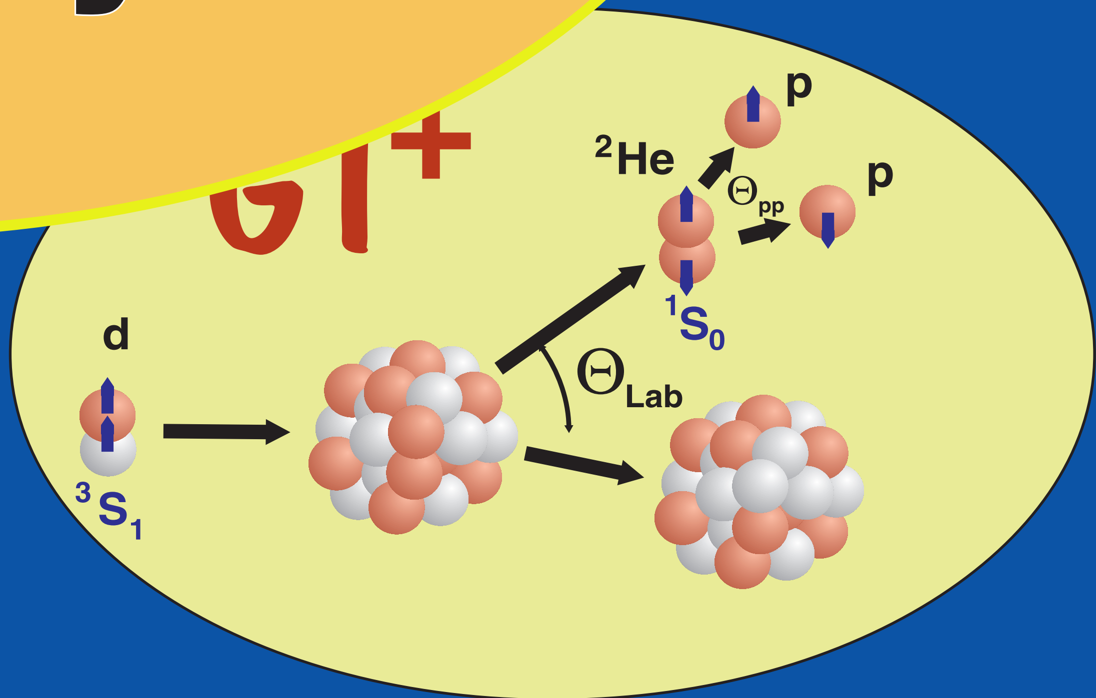
Double beta decay



Neutrino questions

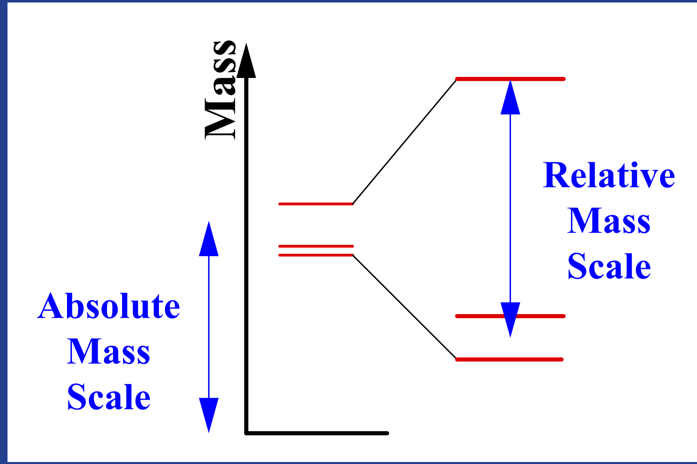
Main results from ν-oscillation experiments:

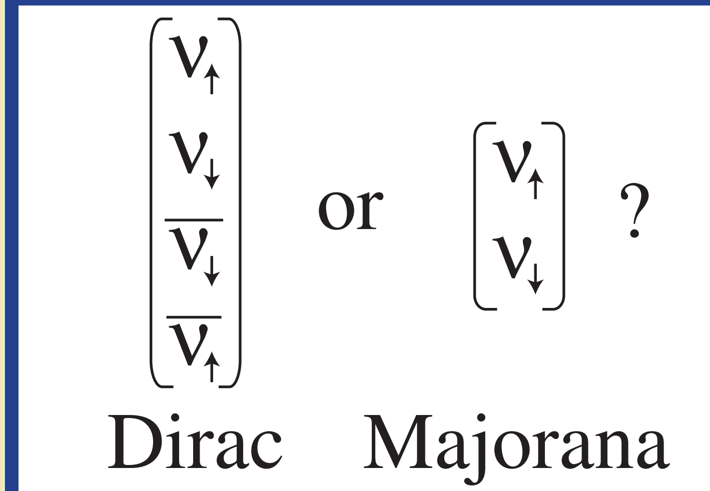
- neutrinos have mass
- mass scale is ~50 meV (but no absolute m_ν!)
- flavour lepton number not conserved

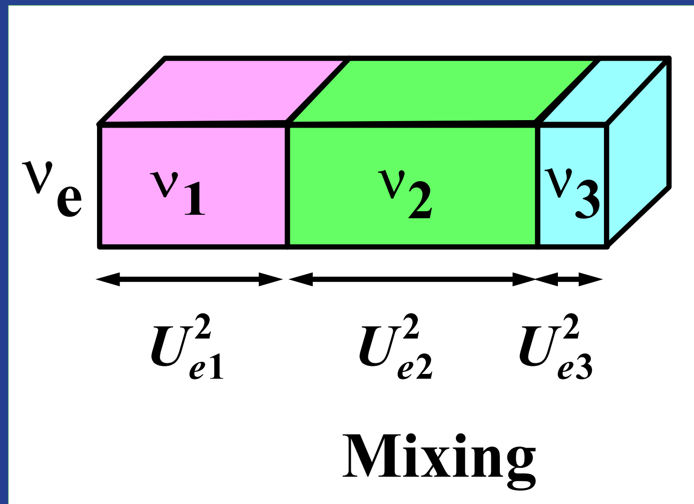
Total L-conservation?
Hierarchical / degenerate mass pattern?

New information from 0νββ-decay:

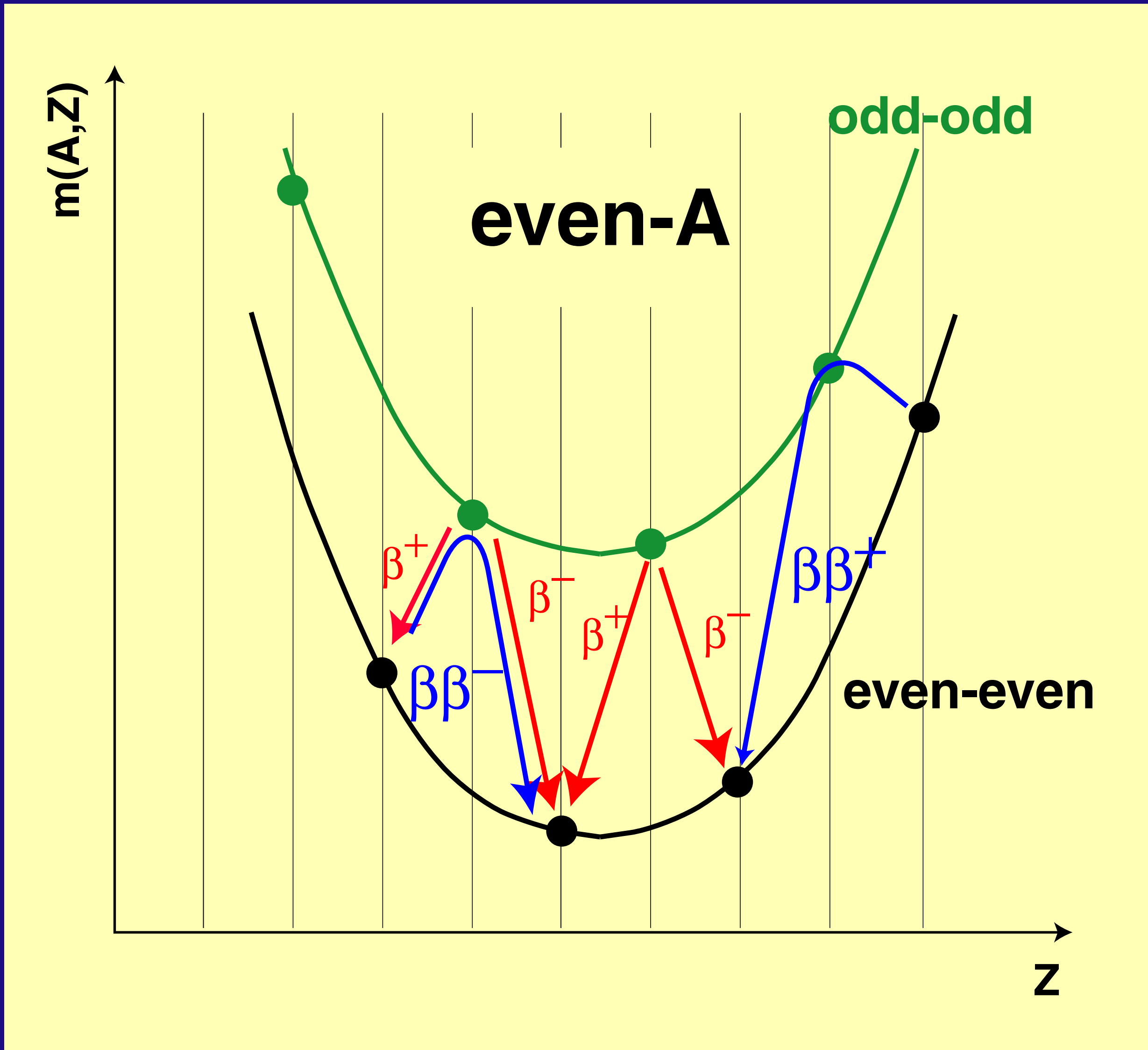
- Dirac or Majorana particle?
- Majorana neutrino violates L-conservation!
- Value for effective Majorana mass!

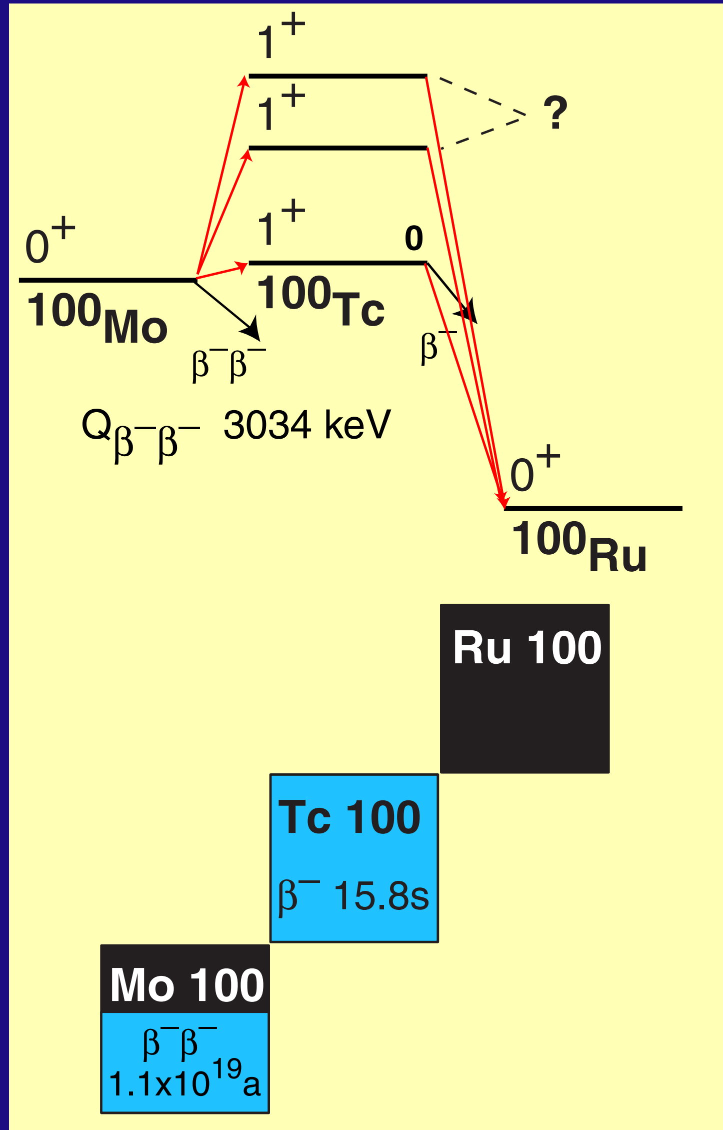






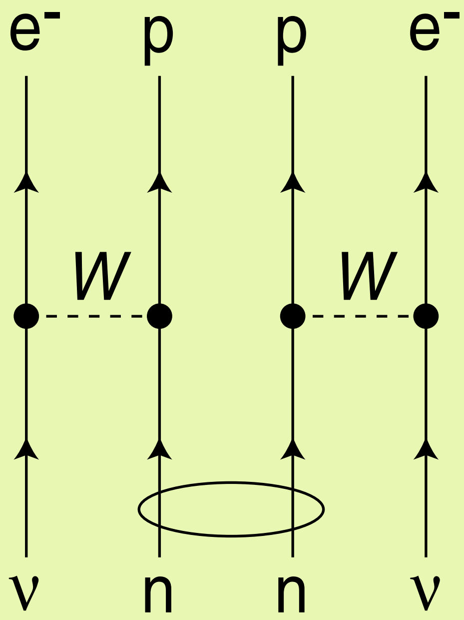
Nuclear double beta decay





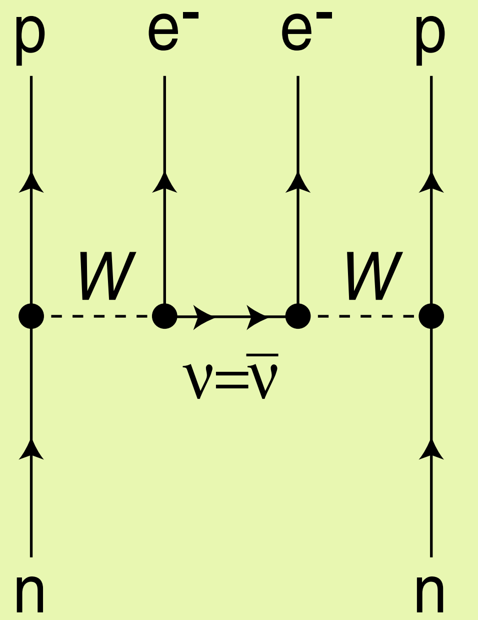
Important ββ decay modes

(2νββ)



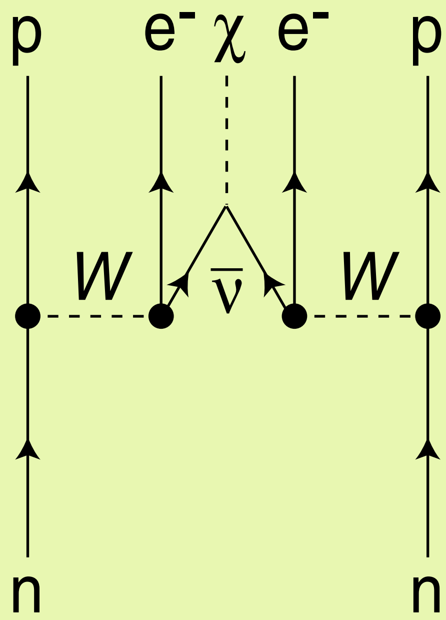
Dirac-Decay

(0νββ)



Majorana-Decay

(0νχββ)



Majoron-Decay

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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

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

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

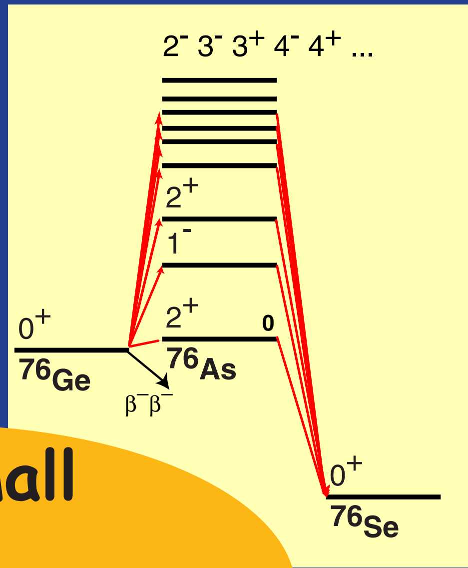
Neutrino potential
(ν's don't escape
from nucleus)

0νββ-decay: half-life & neutrino mass

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

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

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:

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

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

$\beta\beta$ matrix element:

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

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

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2ν DBD Experimental / theoretical results

Isotope	experimental $T_{1/2}$ [yr]	calculated $T_{1/2}$ [yr]
^{48}Ca	$(4.2\pm1.2) \times 10^{19}$	6×10^{18} ... 5×10^{20}
^{76}Ge	$(1.3\pm0.1) \times 10^{21}$	7×10^{19} ... 6×10^{22}
^{82}Se	$(9.2\pm1.0) \times 10^{19}$	3×10^{18} ... 6×10^{21}
^{96}Zr	$(1.4\pm0.8) \times 10^{19}$	3×10^{17} ... 6×10^{20}
^{100}Mo	$(8.0\pm0.6) \times 10^{18}$	1×10^{17} ... 2×10^{22}
^{116}Cd	$(3.2\pm0.3) \times 10^{19}$	3×10^{18} ... 2×10^{21}
^{128}Te	$(7.2\pm0.3) \times 10^{24}$	9×10^{22} ... 3×10^{25}
^{130}Te	$(2.7\pm0.1) \times 10^{21}$	2×10^{19} ... 7×10^{20}
^{150}Nd	$(7.0\pm1.7) \times 10^{18}$	2×10^{16} ... 4×10^{20}

Matrix elements from different nuclear structure models vary by factor 10

Factor 100 on half-life

Similar situation for 0ν ββ-decay

Need calibration points for ββ-decay calculations!

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

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

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

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

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

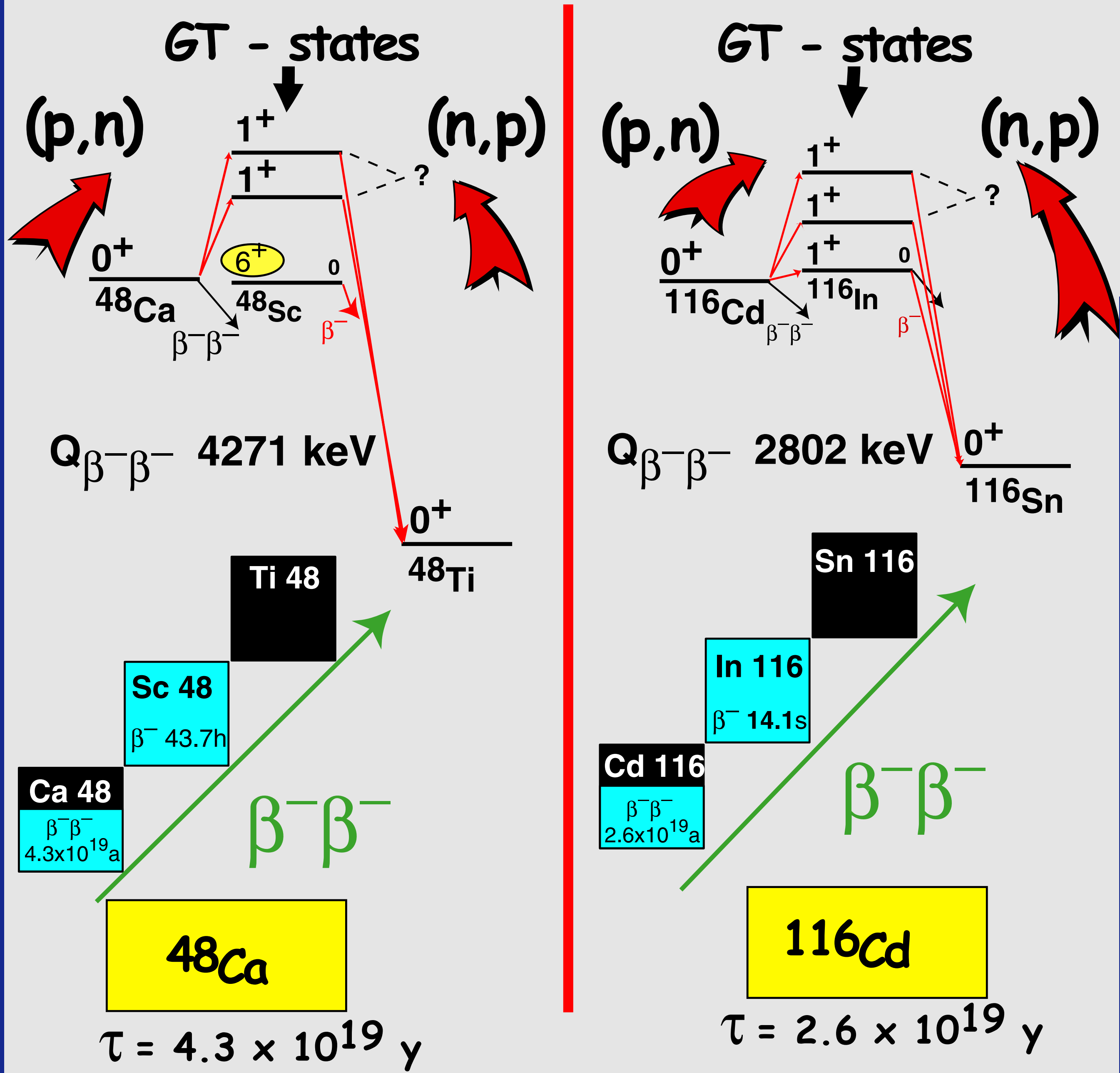
$$B(GT) = \frac{1}{2J_i + 1} \, | M(GT) |^2$$

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

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 ($\beta^- \to \beta^-$) !!!

Half life:

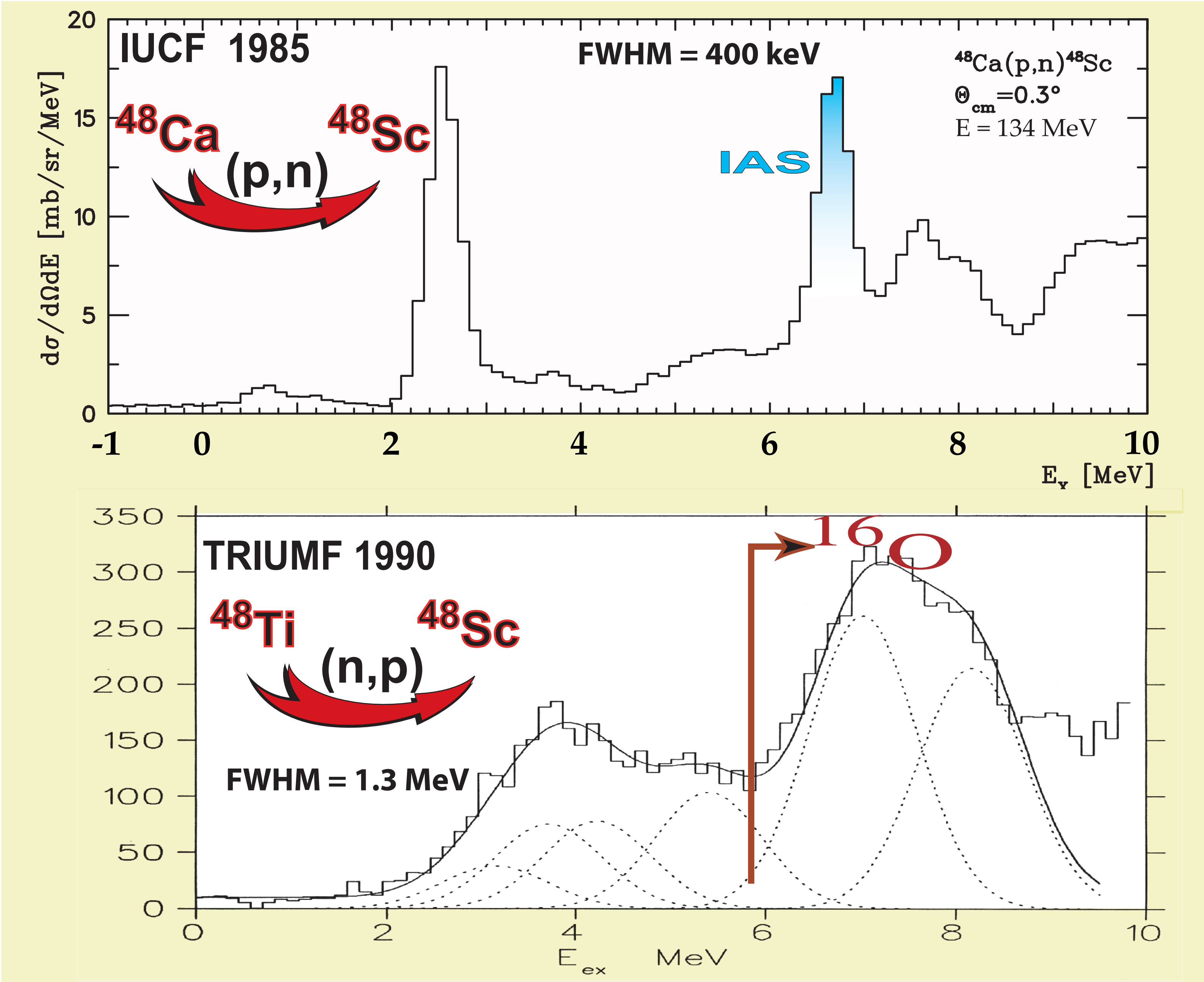
$$[t_{1/2}]^{-1} = G^{(2\nu)} \,|\, M_{DGT} \,|^2$$

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

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

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

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

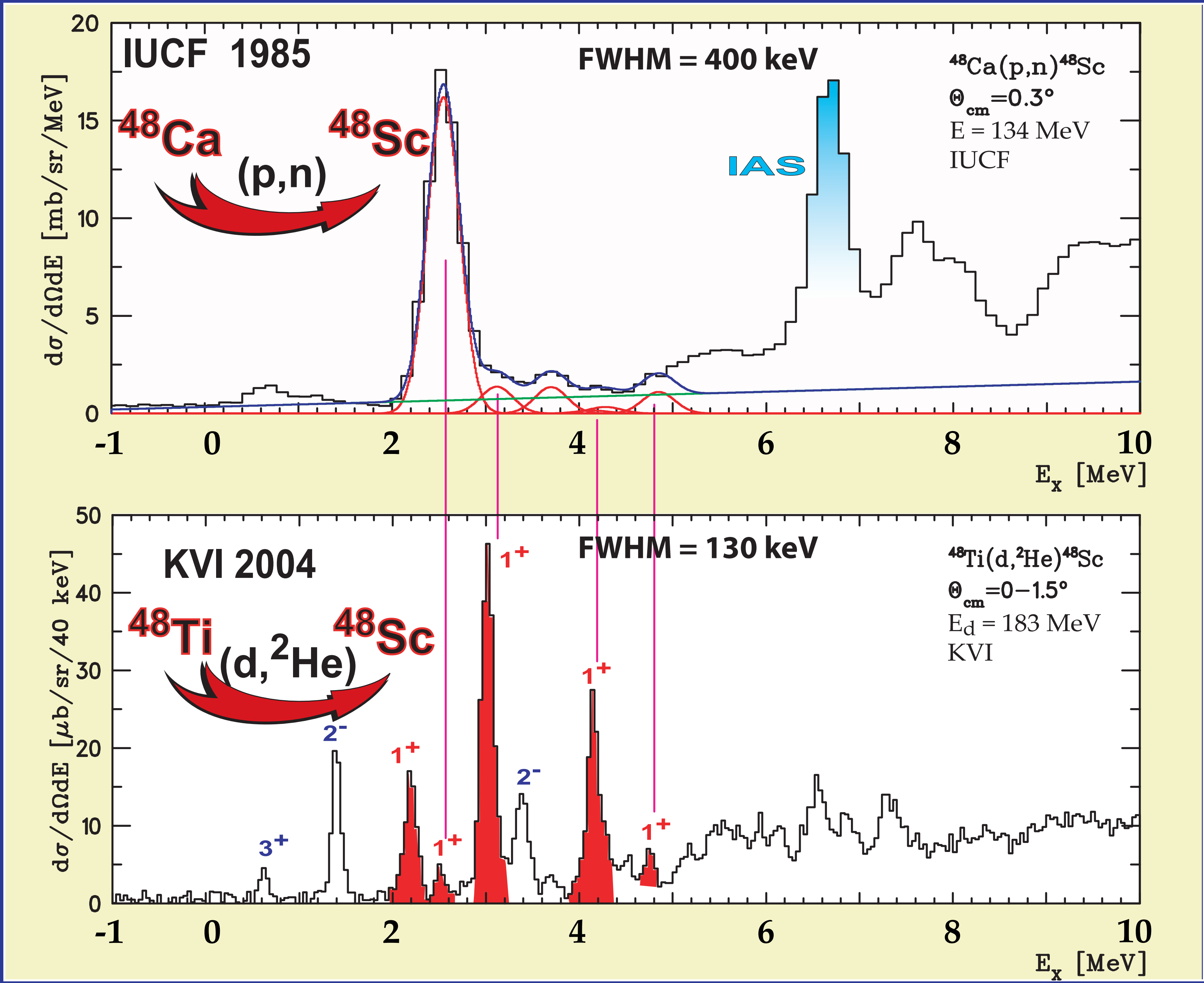


(p,n)

(n,p)

How to connect these states ??

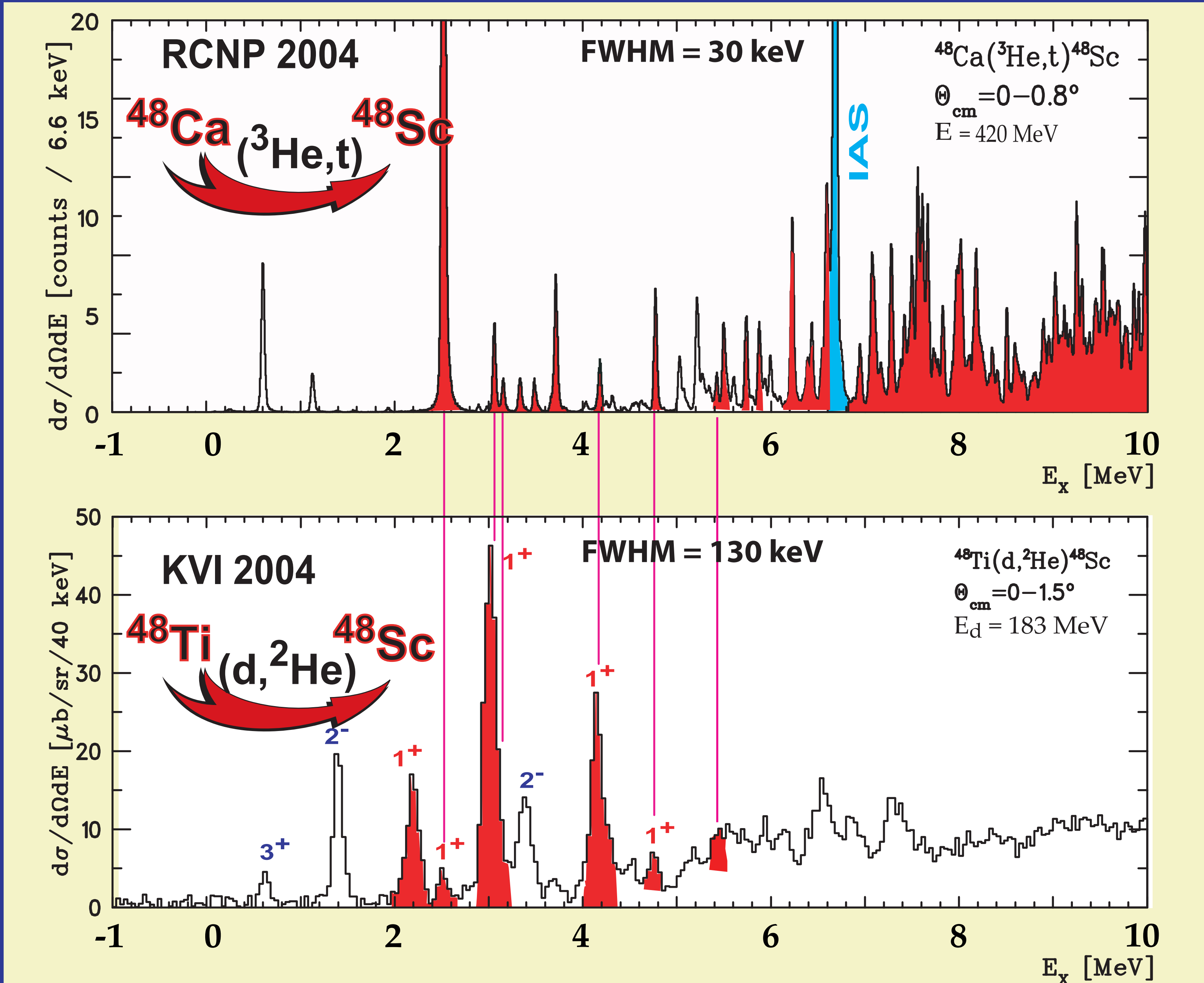
^{48}Ca - ^{48}Sc - ^{48}Ti



(p,n)

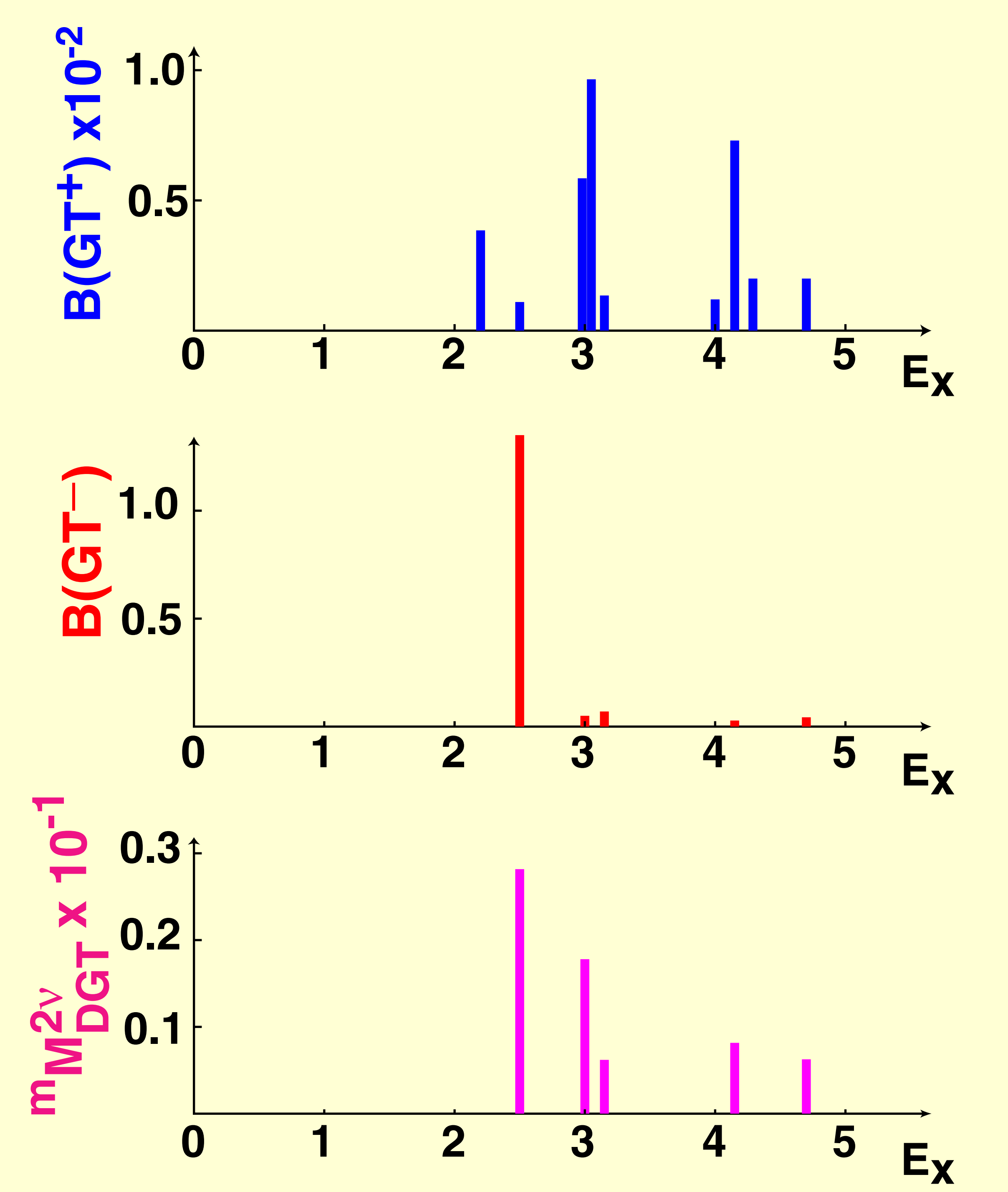
(d,^{2}He)

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



(^{3}He,t)

(d,^{2}He)



Experimental matrix elements

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

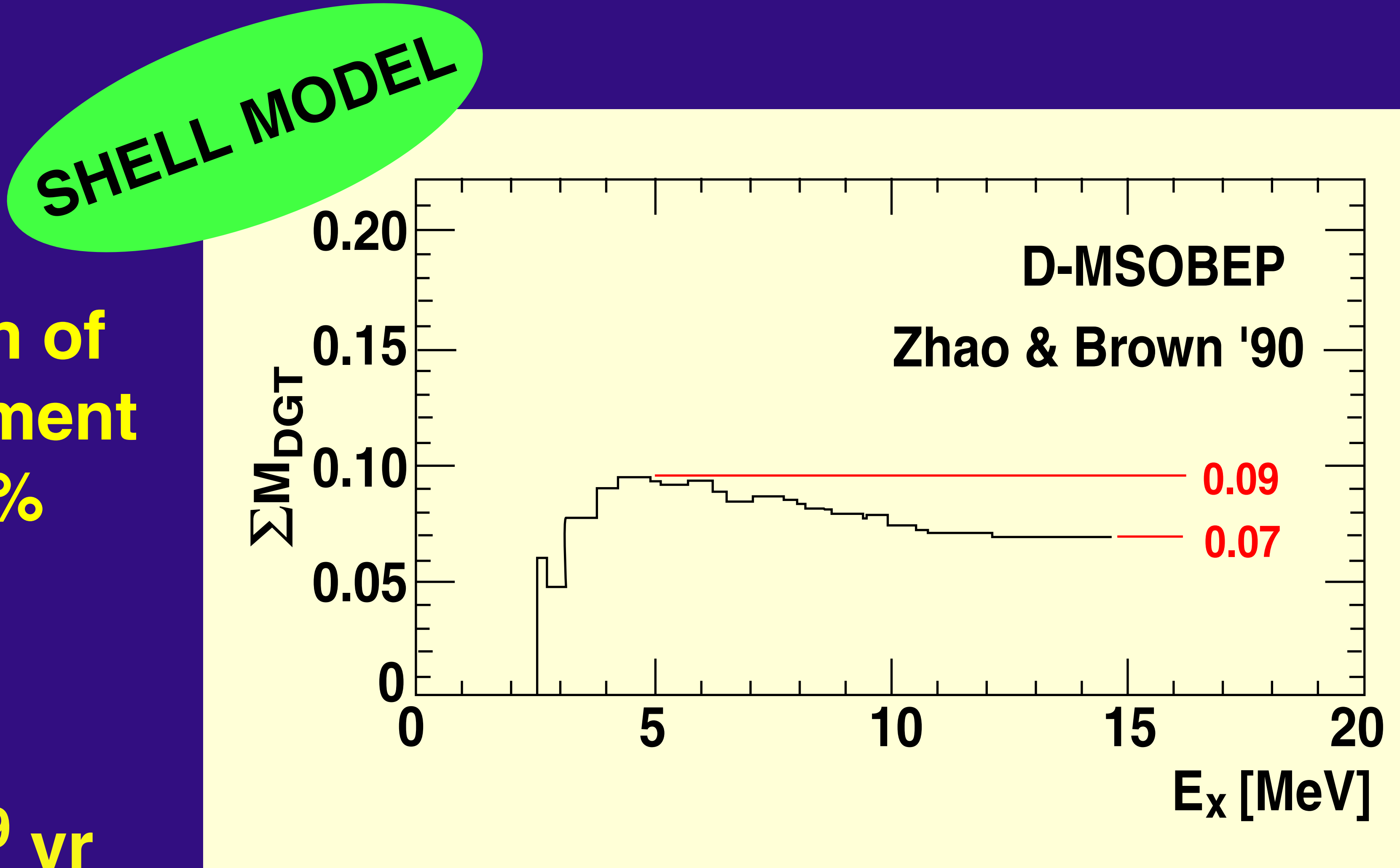
$$= 0.0668 \pm 0.0097$$

$T_{1/2} =$
$(2.04 \pm 0.60) \times 10^{19}$ 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)



Reduction of matrix element by ~ 25%

$T_{1/2}$ = 3.5×10^{19} yr

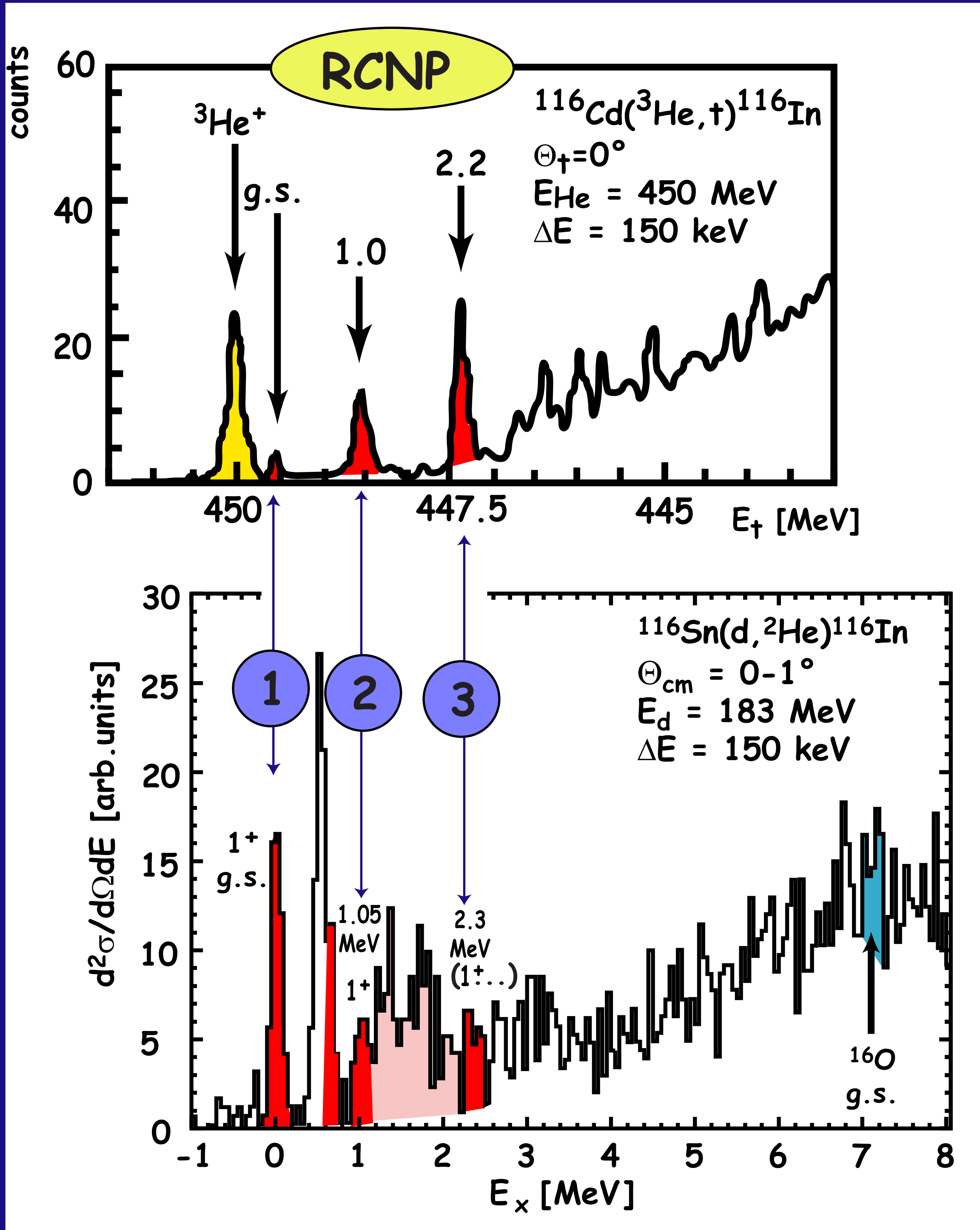
^{116}Cd 2νββ decay

	B(GT⁻)	B(GT⁺)	M^m_{DGT}	running sum ΣM_{DGT}
1	0.032	0.235	0.028	0.028
2	0.12	0.12	0.029	0.057
3	0.17	0.05	0.017	0.074

ft-value (arrow to 0.235)

Matrix element from counting experiment:

$\Sigma M_{DGT} = 0.069 \pm 0.009$



preliminary

European Supernova Collaboration

Study of Gamow-Teller transitions to intermediate states in $\beta\beta$-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

The case of ^{48}Ca

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

48Ca

$Q = 4.27$ MeV

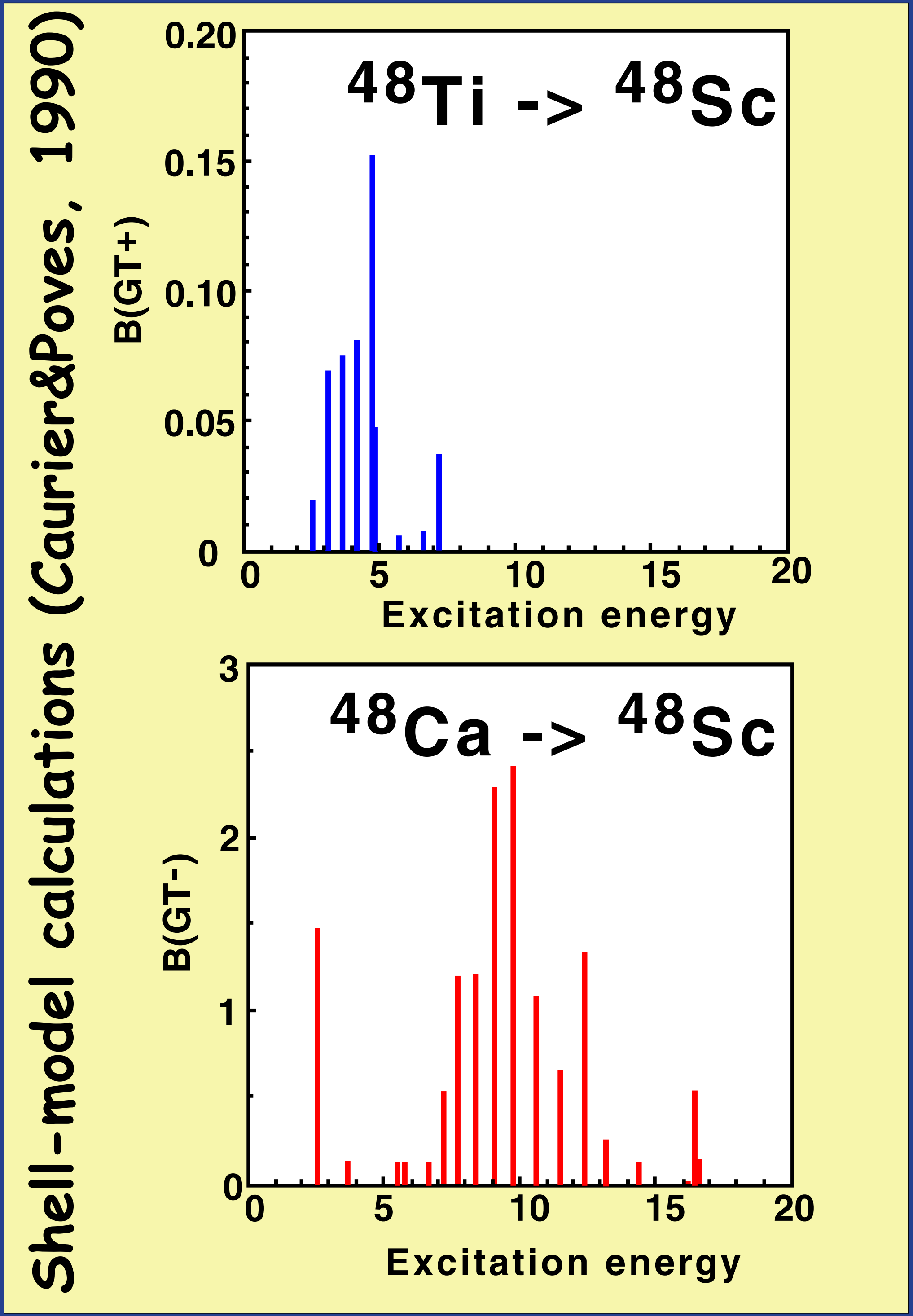
$T_{1/2} = 4.3 \times 10^{19}$ yr

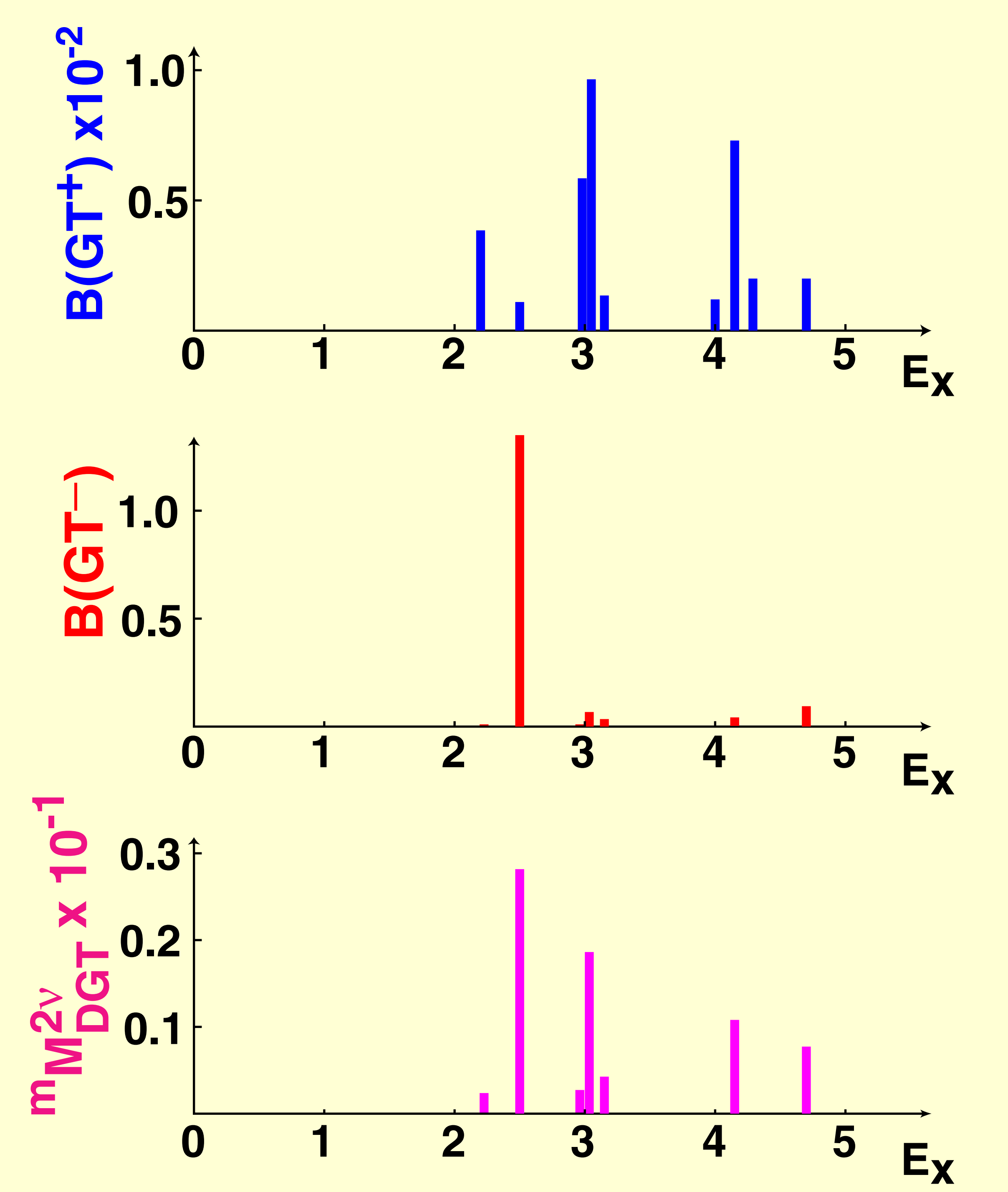
116Cd

$Q = 2.80$ MeV

$T_{1/2} = 3.8 \times 10^{19}$ yr

NUCLEAR STRUCTURE





Experimental matrix elements

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

$= 0.0726 \pm 0.0155$ (all positive)

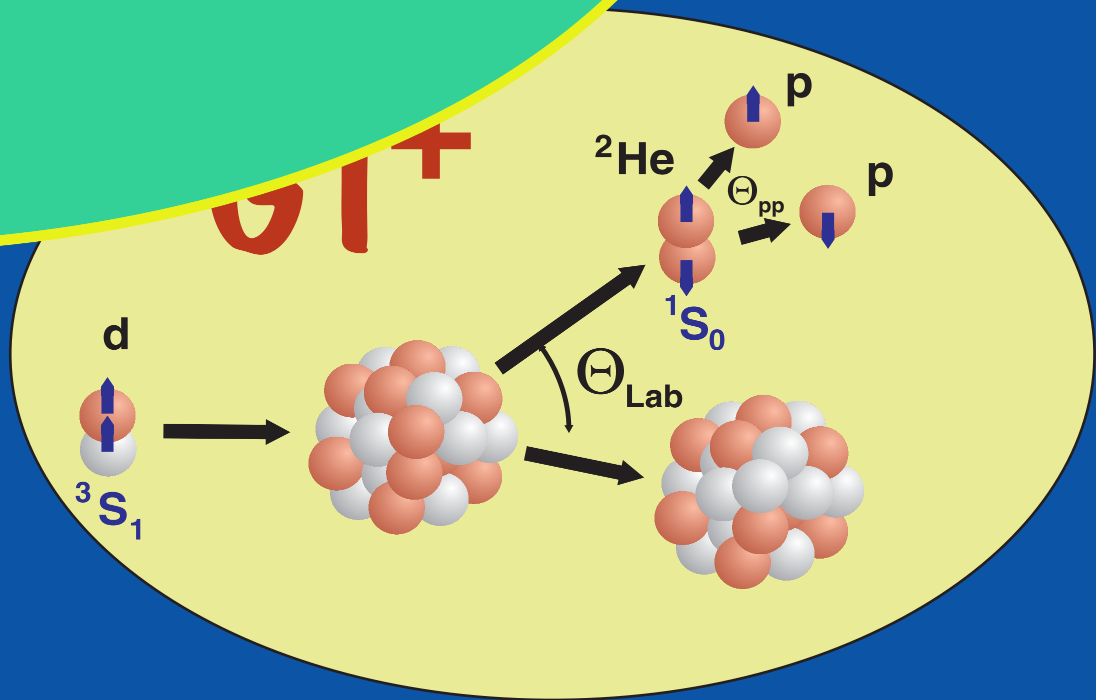
$T_{1/2} =$
$(1.72 \pm 0.73) \times 10^{19}$ yr

Compare to counting exp't:

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

DF

Halo nuclei



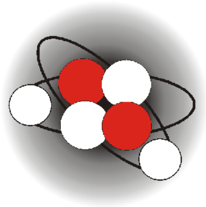
Halo nuclei

^{7}He

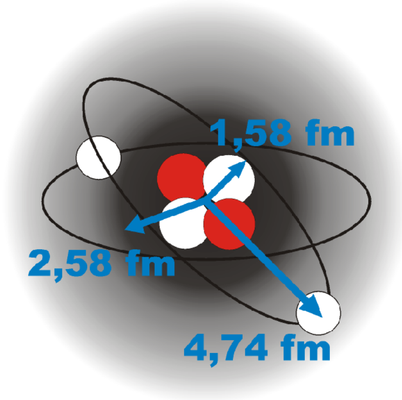
reduced
spin-orbit force?

low-lying
p1/2
spin-orbit partner
at ~ 600 keV?

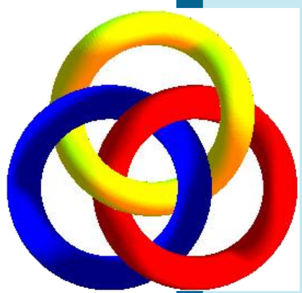
continuum structure



skin
or
halo?



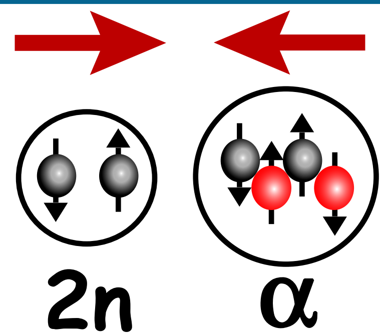
^{6}He



Borromean
structure

↓

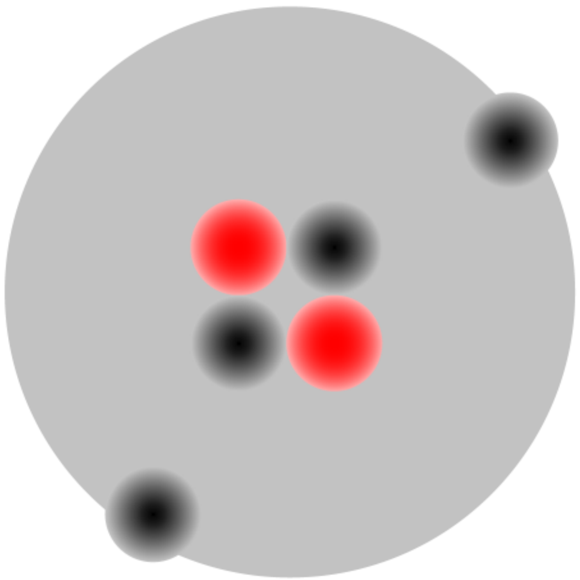
reduced
spin-orbit force ?



Soft dipole resonance ?

$^{6}Li(d,^{2}He)^{6}He$
$^{7}Li(d,^{2}He)^{7}He$

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



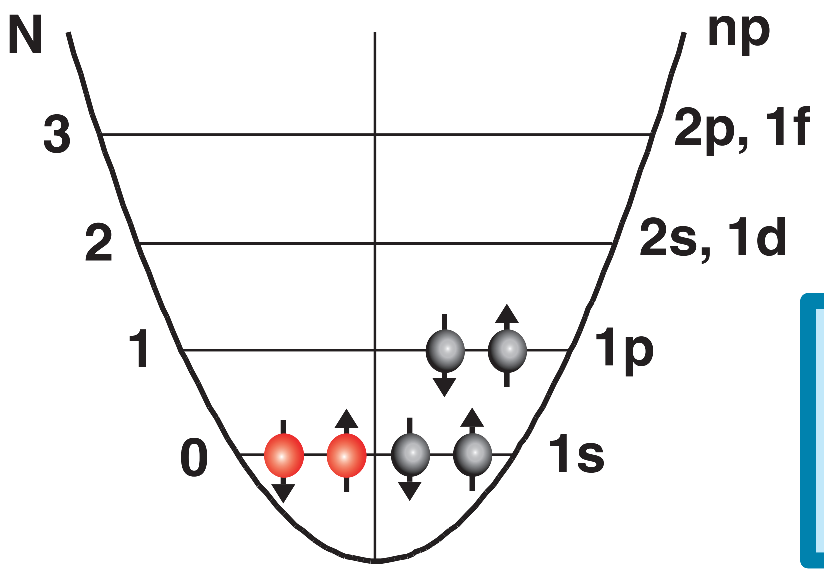
3-body α+n+n structure
("Borromean system")

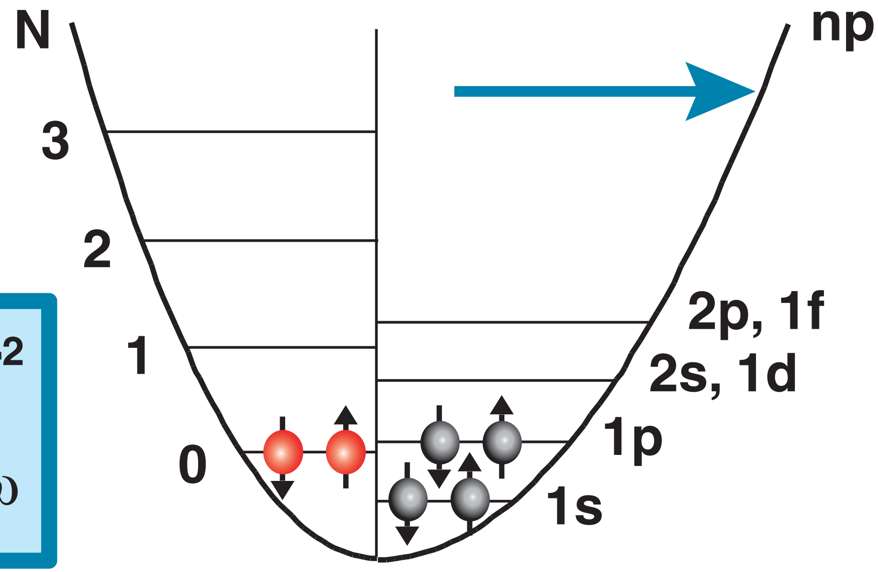
3-body calculations*:

- 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

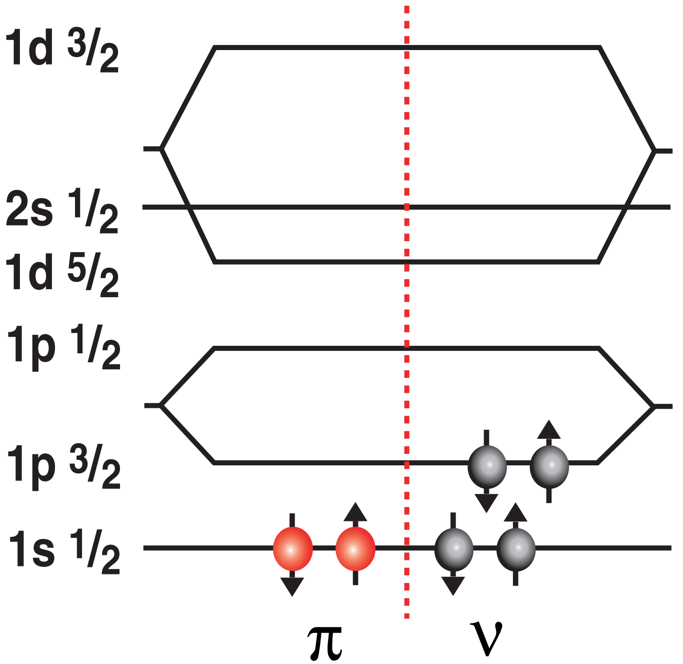




harmonic oscillator

$$V(r) = \frac{1}{2} m\, \omega^2 r^2$$

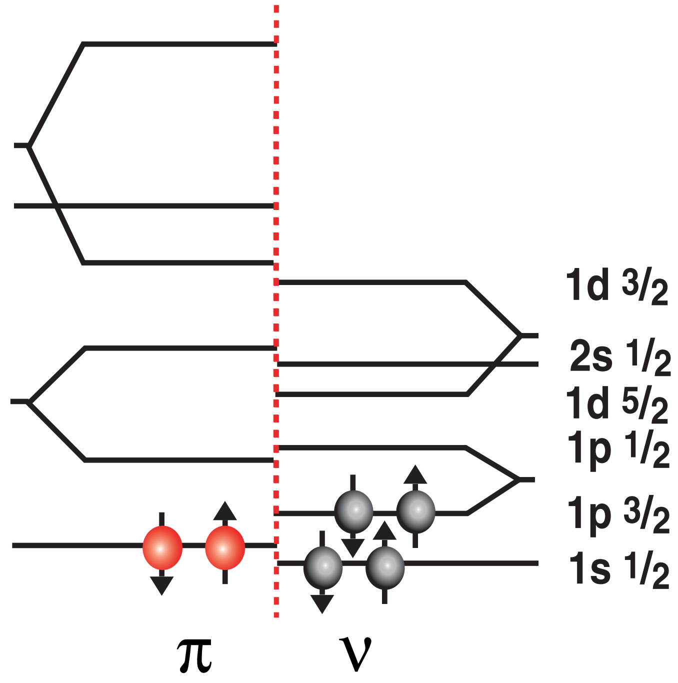
$$E = (N + \frac{3}{2})\, \hbar\, \omega$$



spin-orbit potential

$$V_s(r) = V_{0s} \frac{1}{r} \frac{d}{dr} f(r)$$

$$f(r) = \frac{1}{1 + \exp[(r-R)/a]}$$



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

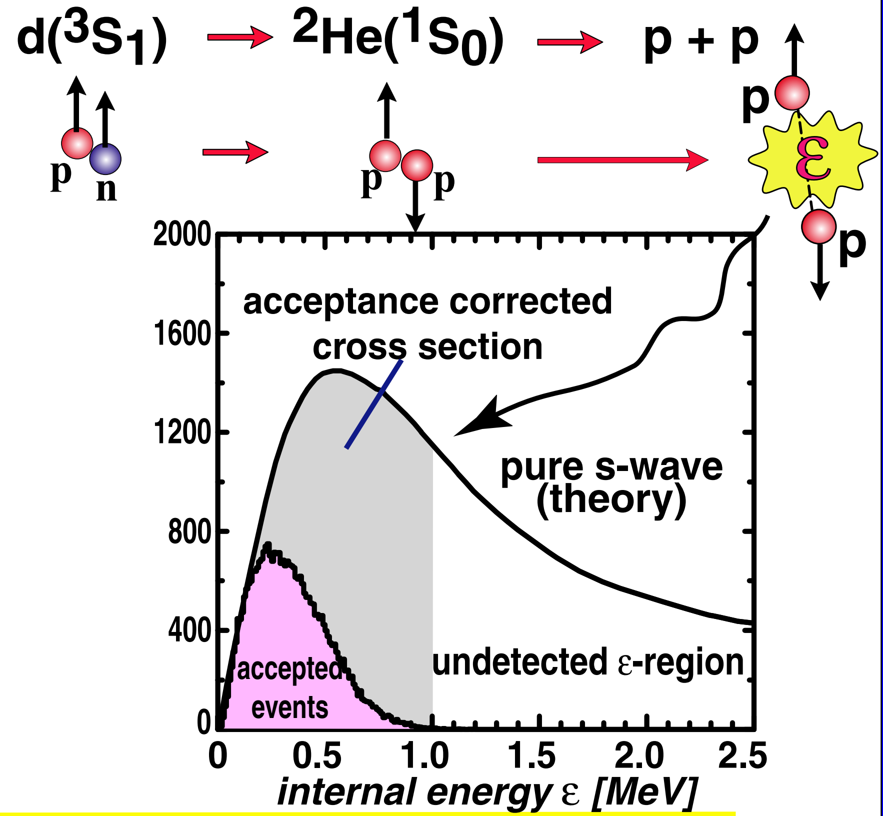
2)- coincident detection of two protons from ^{2}He decay
→ background-free spectra
but need large accptnc spectrometer

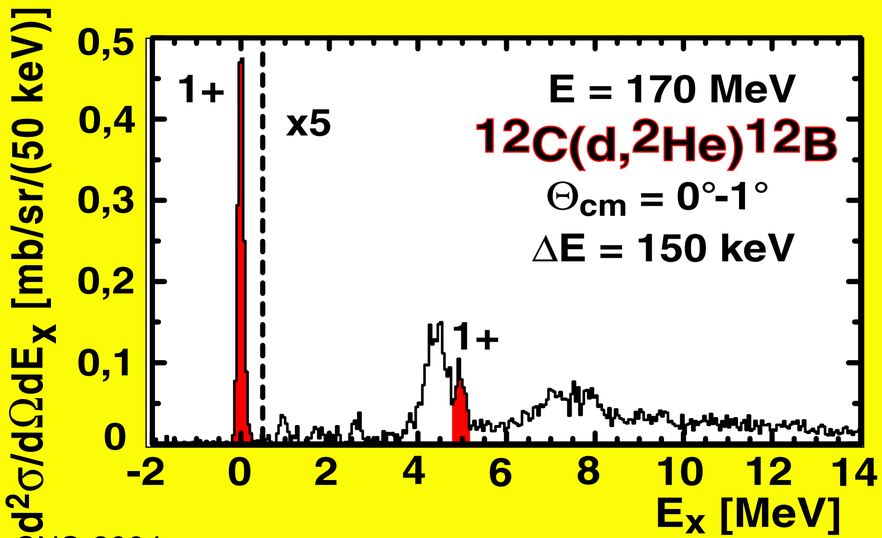
3)- contributions from higher p-p partial waves? Dont'worry!!

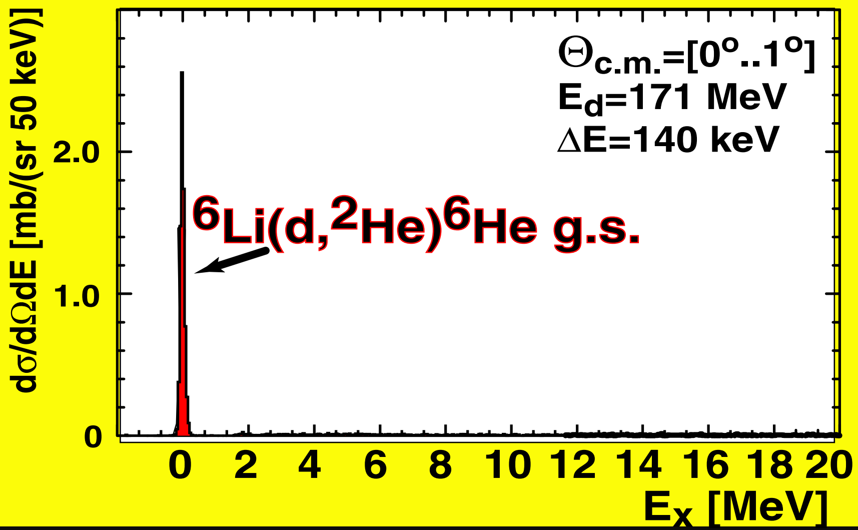
Alternatives:

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

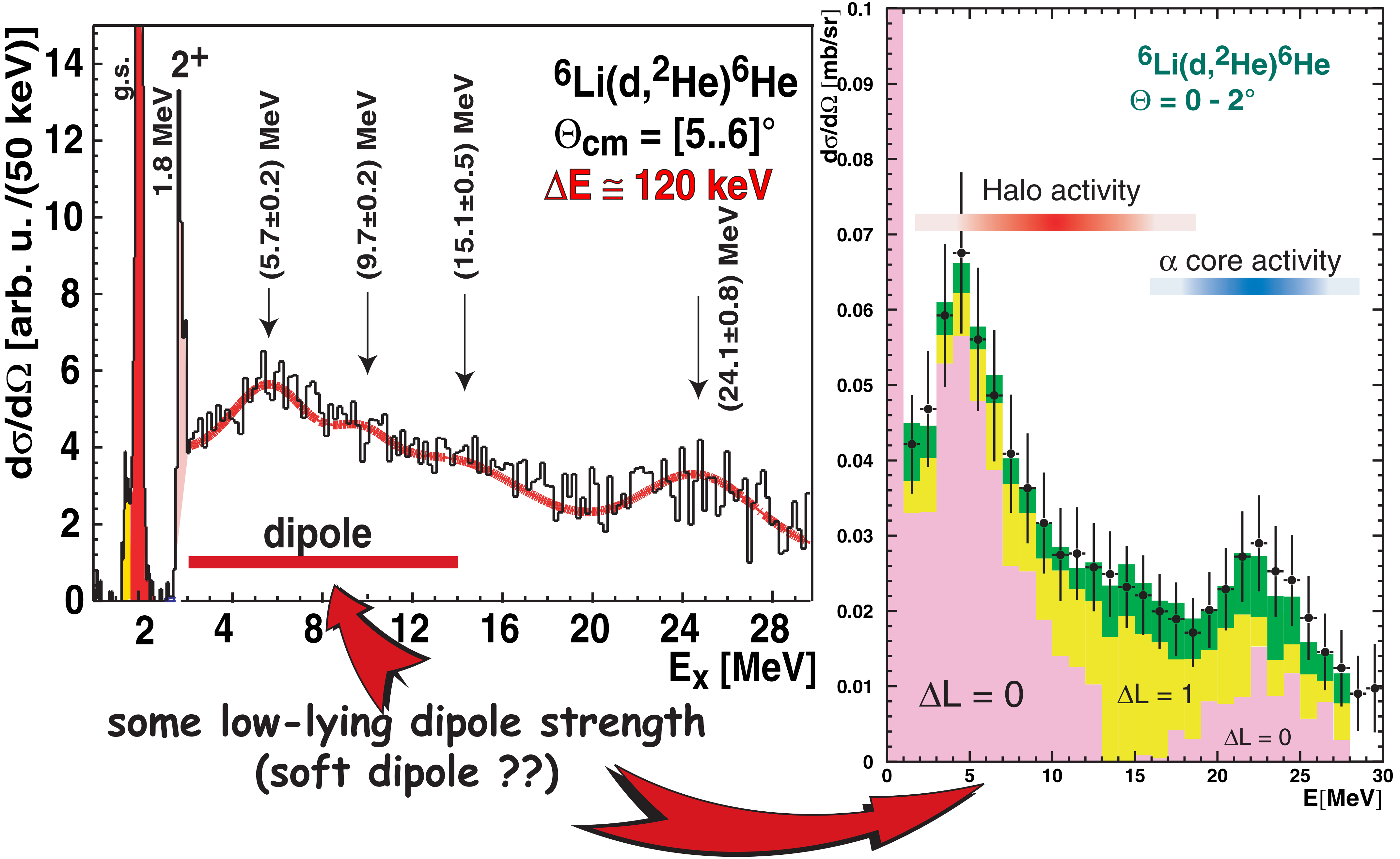
S=1, T=0 → S=0, T=1







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



some low-lying dipole strength
(soft dipole ??)

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Spin-orbit splitting halo nucleus ^7He

Origin and strength of spin-orbit force?

- p- and sd-shell nuclei: $V_{s.o.}$ ~ 5-6 MeV
- halo nuclei: reduction of s.o. interaction because of large radial extent?

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

large scale shell models Resonating Group Methods	2 - 3 MeV
Quantum Monte Carlo	~ 1 MeV

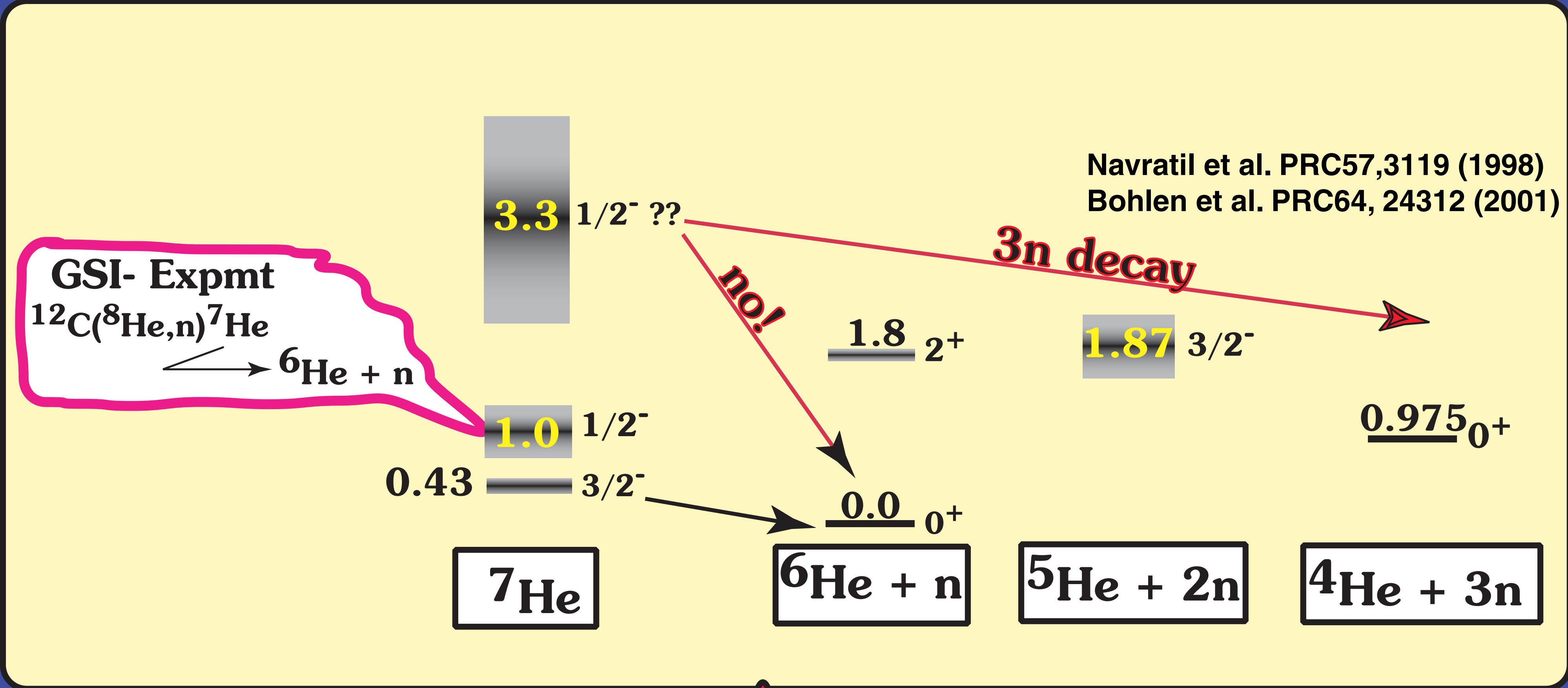
^7He g.s. : $J^\pi=3/2^-$
^7He s.o. : $J^\pi=1/2^-$
partner

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

Reaction	E_x [MeV]	Γ [MeV]	method
$^{12}C(^8He,n)^7He$	0.6	0.75	inv. mass
$^1H(^8He,d)^7He$	2.9	2.2	miss. mass
$^9Be(^{15}N,^{17}F)^7He$	2.95	1.9	miss. mass
$^{10}B(\pi^-,pd)^7He$	2.8	2.0	miss. mass
$^7Li(n,p)$	~6, 20.0	?,9.0	charge-ex.

claimed by recent GSI expmt !

The A = 7 system



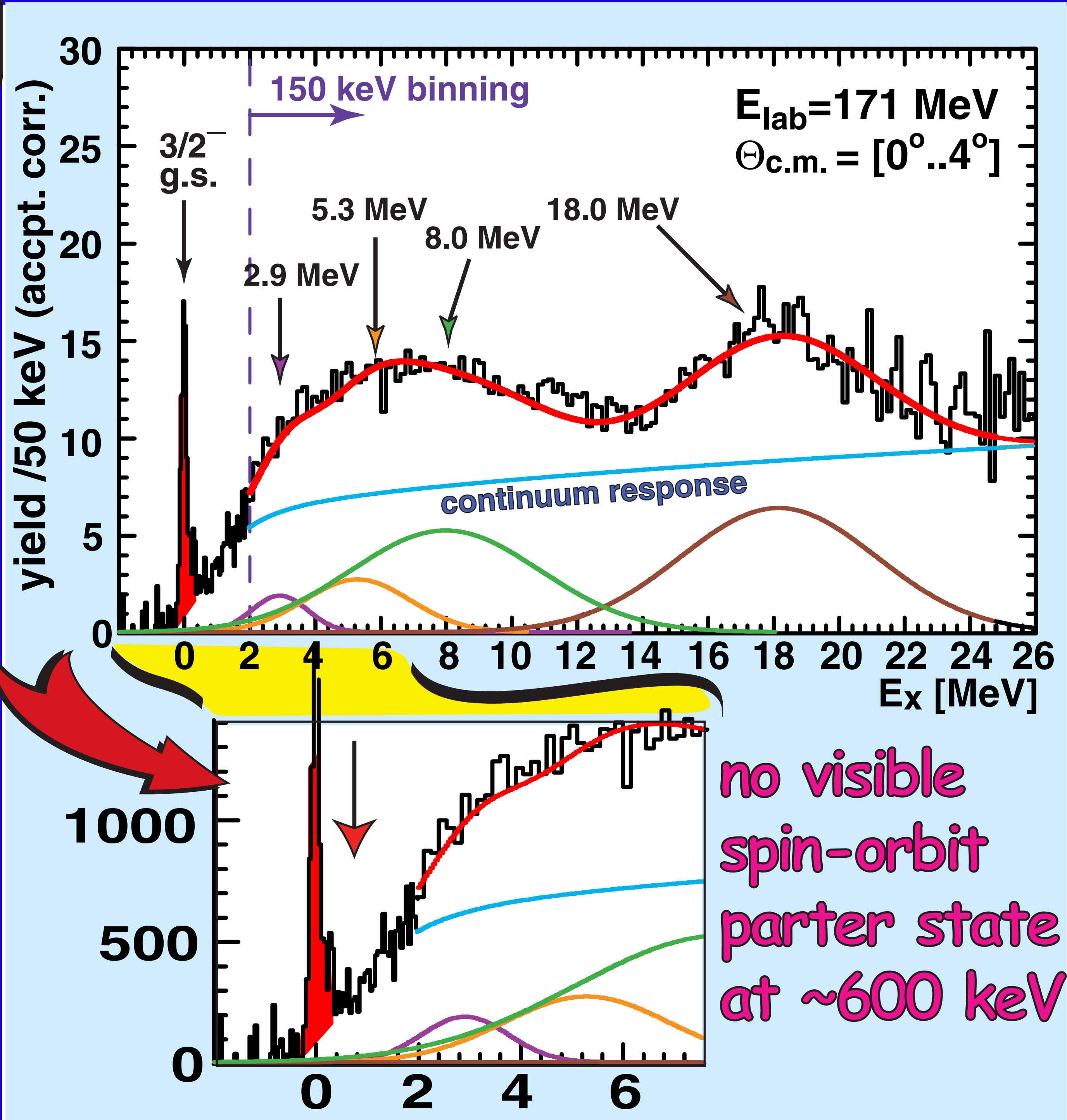
^7He (0.43, g.s.): Γ = 160 keV
^7He (1.0): Γ = 750 keV
^7He (3.3): broad

!

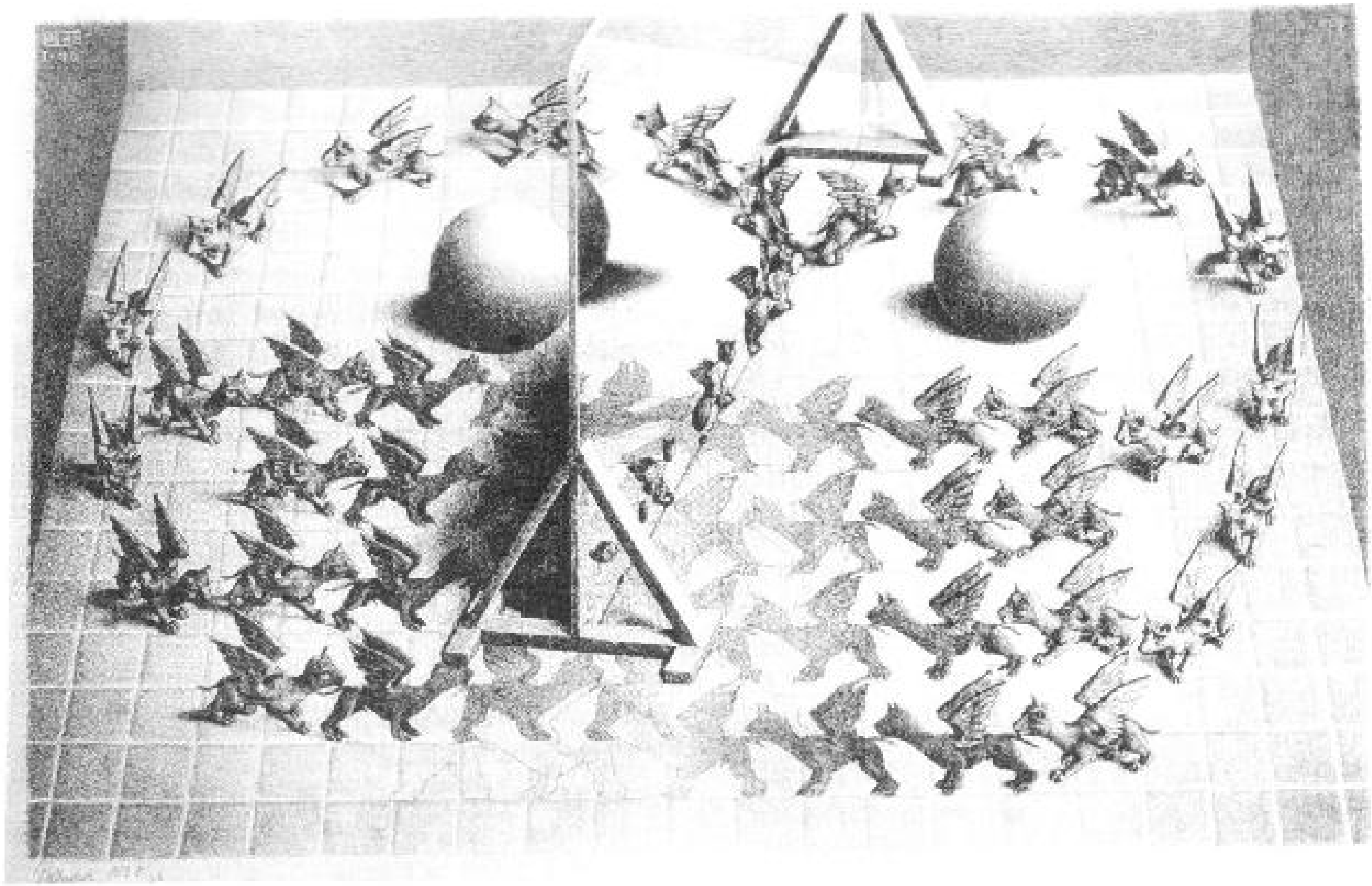
$^7Li\ (d,{}^2He)\ {}^7He$
exploit GT-tool !!!

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

- unexpectedly weak GT-transition strength ($^{7}Li = \alpha + t$)
- 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!!)



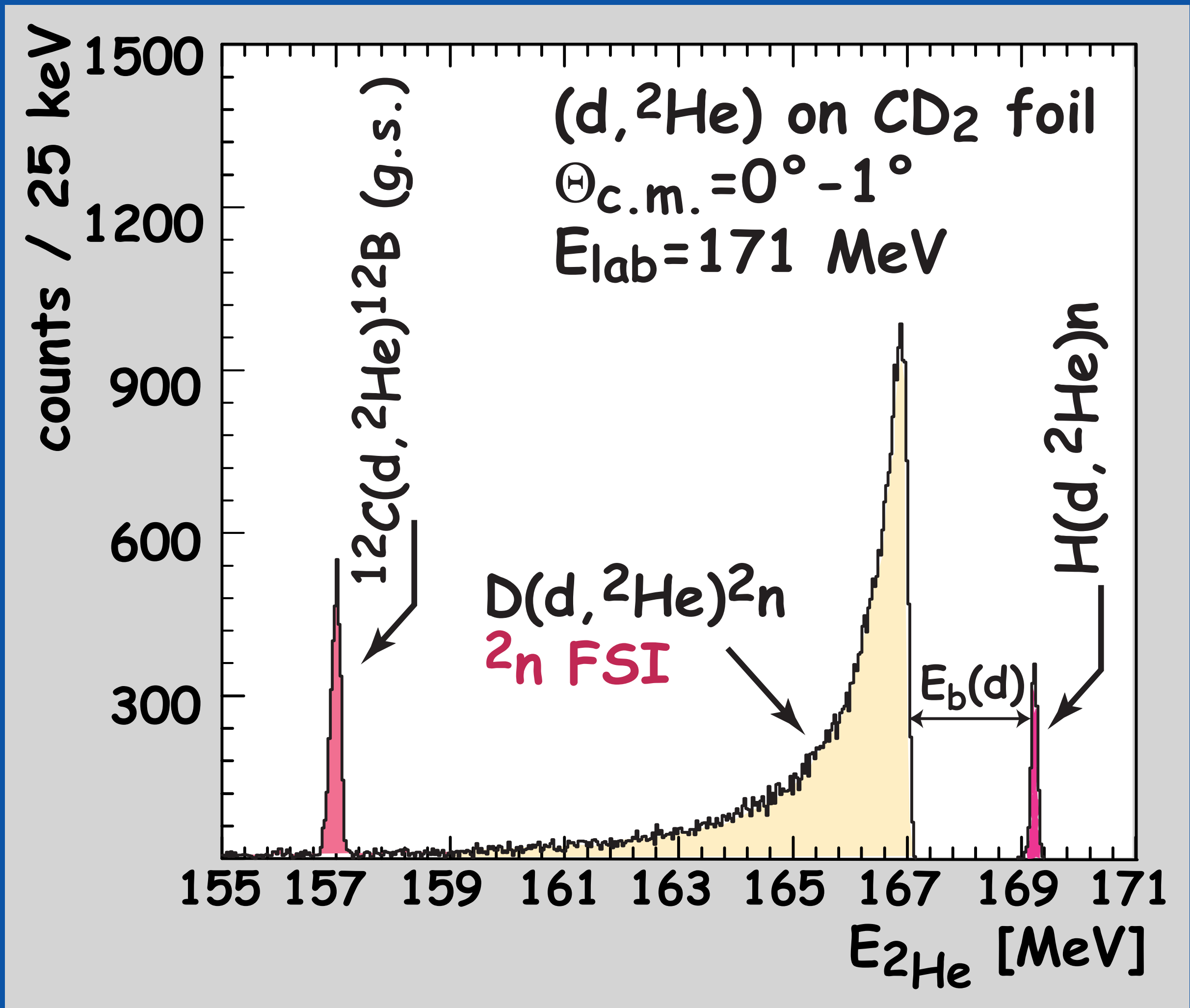
Charge Symmetry Breaking



M.C. Escher

Measurement of nn-scattering length a_{nn} thru $D(d,{}^2He)^2n$

Spectroscopy of n-n FSI thru $(d,{}^2He)$ on CD_2 foil at $\Theta_{BBS}=0°$



idea:

- GT operator populates ^2n in $^1S_0$ state
- a_{nn} determined by shape of GT strength function

data:

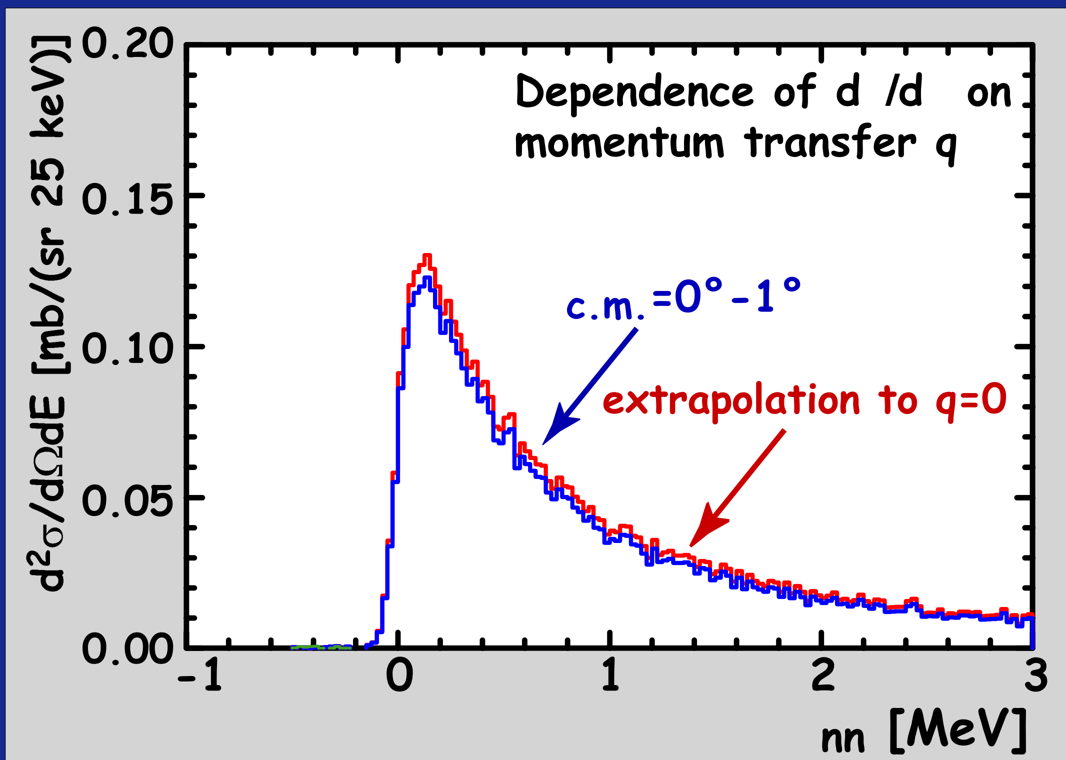
- $\Delta E = 115$ keV [FWHM]
- check energy calibration with ^1H and ^{12}C target components

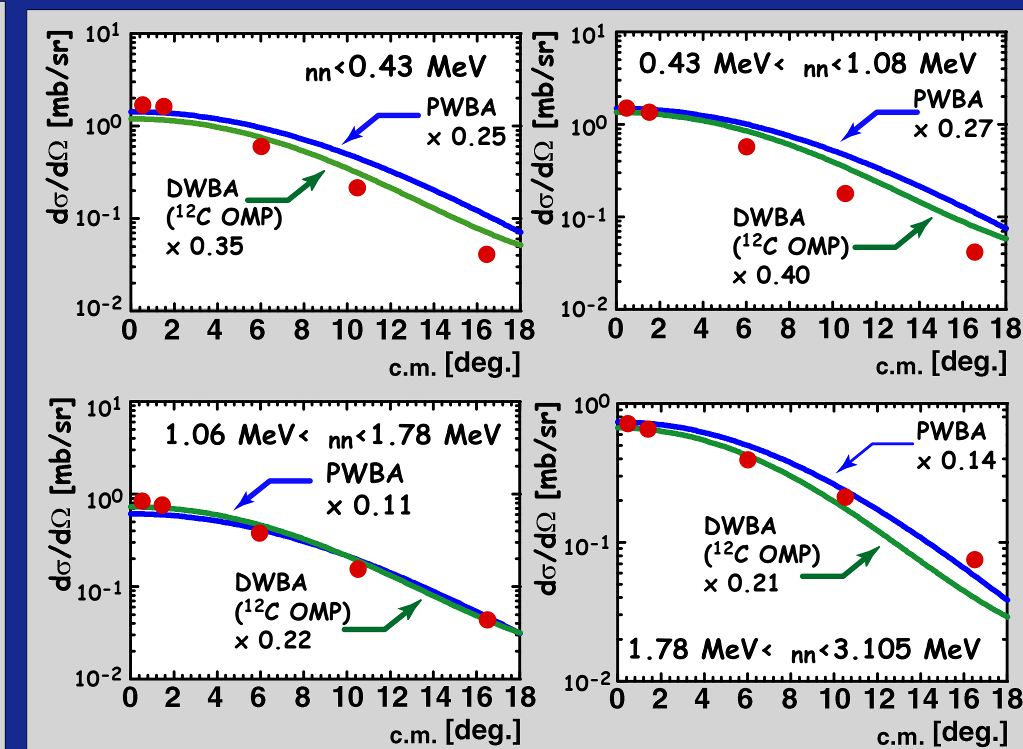
Momentum dependence of $D(d,{}^2He){}^2n$: extrapolation to momentum transfer q=0

Experimental data at $_{c.m.}$=[0°-1°] and $_{nn}$<9 MeV correspond to momentum transfers q: 0.05 fm^{-1} < q < 0.18 fm^{-1}

Apply transformation to q=0: $\frac{d\ \ (q=0)}{d} = \frac{_{DWBA}(q=0)}{_{DWBA}(q)} \frac{d\ \ _{exp}(q)}{d}$

Check q-dependence of d /d with angular distributions: data and DWBA-calculation



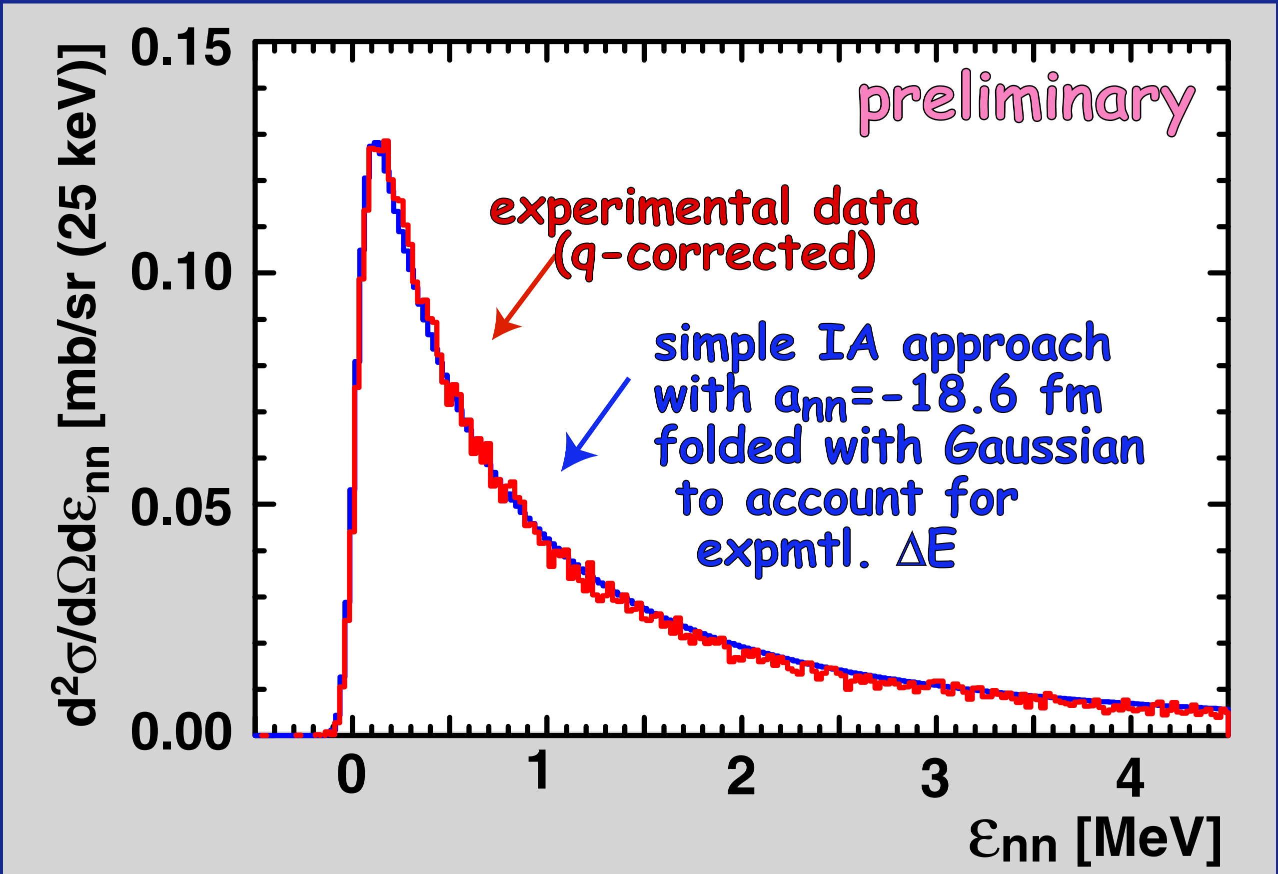


ann

Impulse Approximation, leading order:

$$\frac{d\sigma}{d\Omega}(\epsilon_{pp},\epsilon_{nn}) \sim \frac{k_f}{k_i}\sqrt{\epsilon_{pp}\,\epsilon_{nn}}\,|t_{\sigma\tau}|^2\; B_{GT^-}(\epsilon_{pp}, d\rightarrow\,^2He)\, B_{GT^+}(\epsilon_{nn}, d\rightarrow\,^2n)$$

$$B_{GT}(\epsilon_{NN}) = \frac{1}{3}\,|\langle\, NN(\epsilon_{NN}, a_{NN})\,||\sum_k \vec{\sigma}_k\tau_k||\, d\,\rangle|^2\;, N = n,p$$



Integrate over ε_{pp}:

$$\frac{d\sigma}{d\Omega}[(\mathrm{d},^2\mathrm{He})] = \int_{0\ MeV}^{1\ MeV} d\epsilon_{pp}\;\frac{d^2\sigma}{d\Omega\, d\epsilon_{pp}}$$

Fitting procedure: fit only shape of spectrum

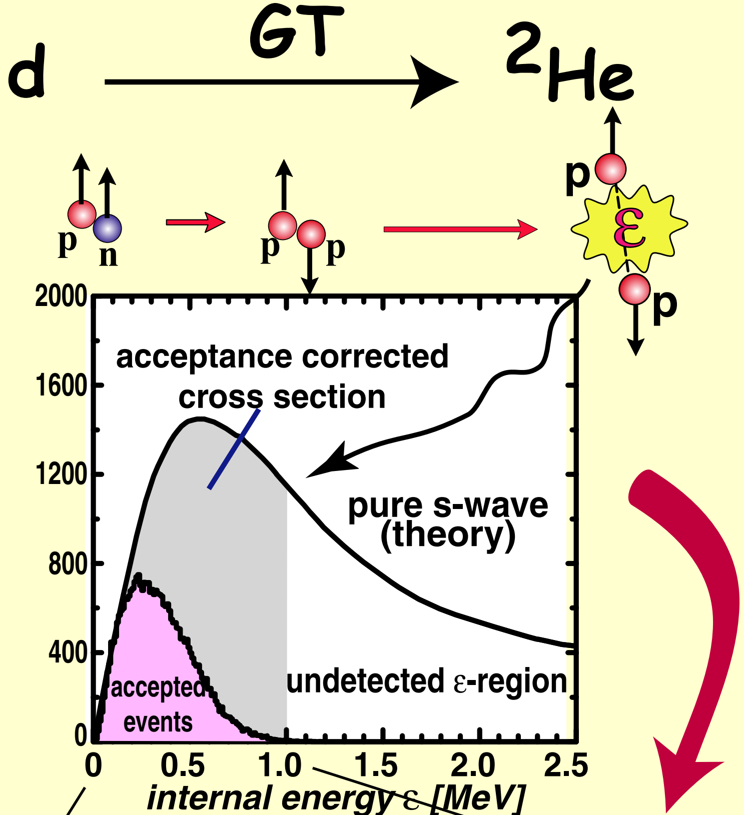
Result in agreement with recommended value

a_{nn}=-18.6 fm

how to calibrate (d,^{2}He)

- detector and acceptance calibration
- cross section calibration
- does the cross section scale with B(GT)

$$\frac{d\sigma}{d\Omega}(q=0) = C\left[\frac{\mu}{\pi\hbar}\right]^2 \frac{k_f}{k_i} N_D \left|V_{\sigma\tau}\right|^2 B(GT+)$$

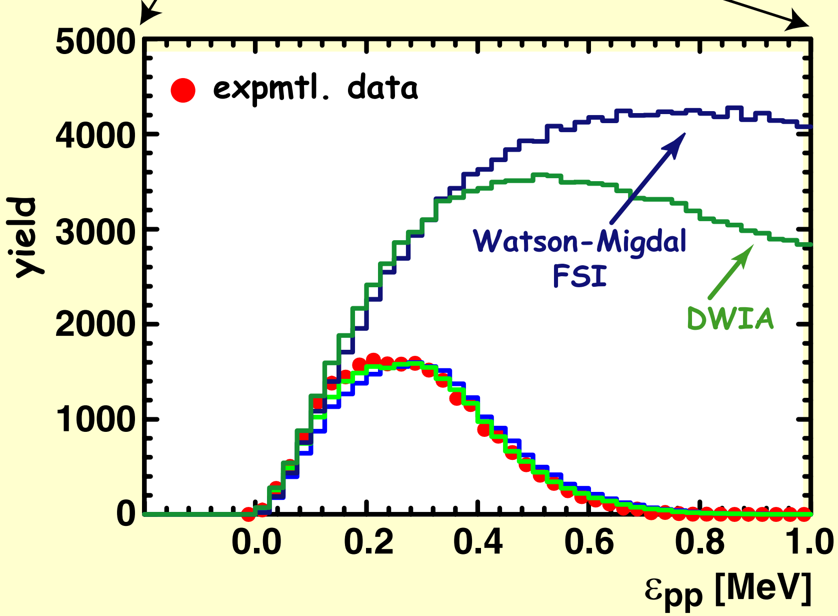


1) get a model for $^1S_0$ of 2p-system

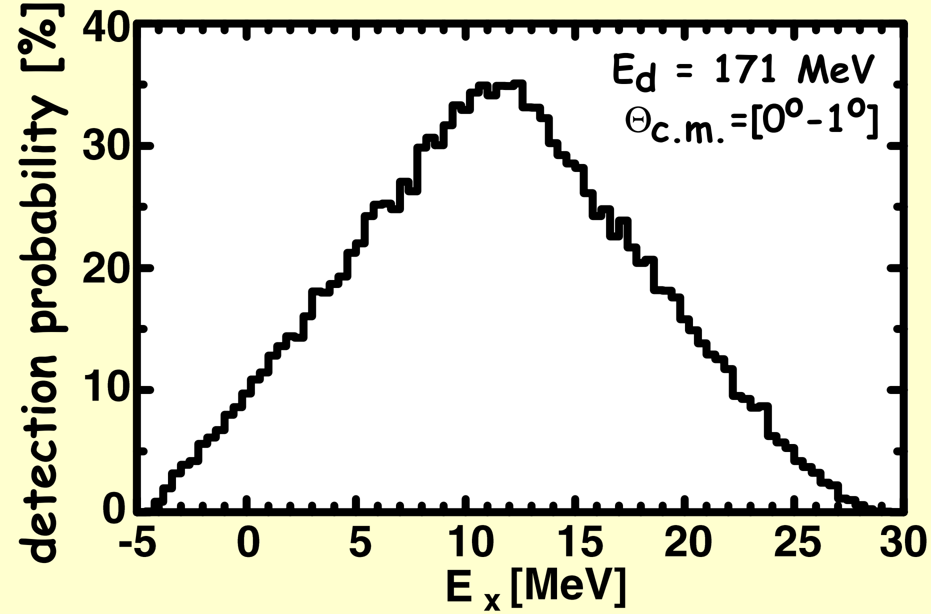
2) Monte-Carlo ε-acceptance for the ε-bin [0-1MeV]

3) evaluate acceptance correction function for each excitation energy bin

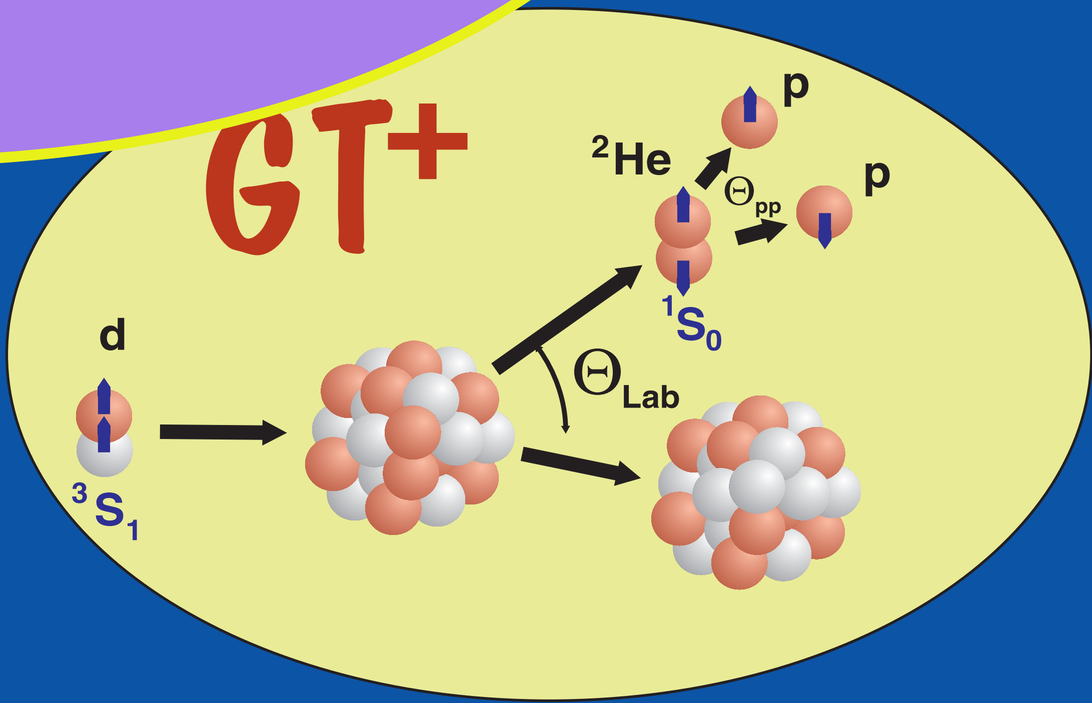
4) calculate $d\sigma/d\Omega = \int_{\varepsilon=0\,\mathrm{MeV}}^{\varepsilon=1\,\mathrm{MeV}} d\sigma/d\Omega(\varepsilon)\, d\varepsilon$



Calculated 2-proton acceptance as a function of **excitation energy**



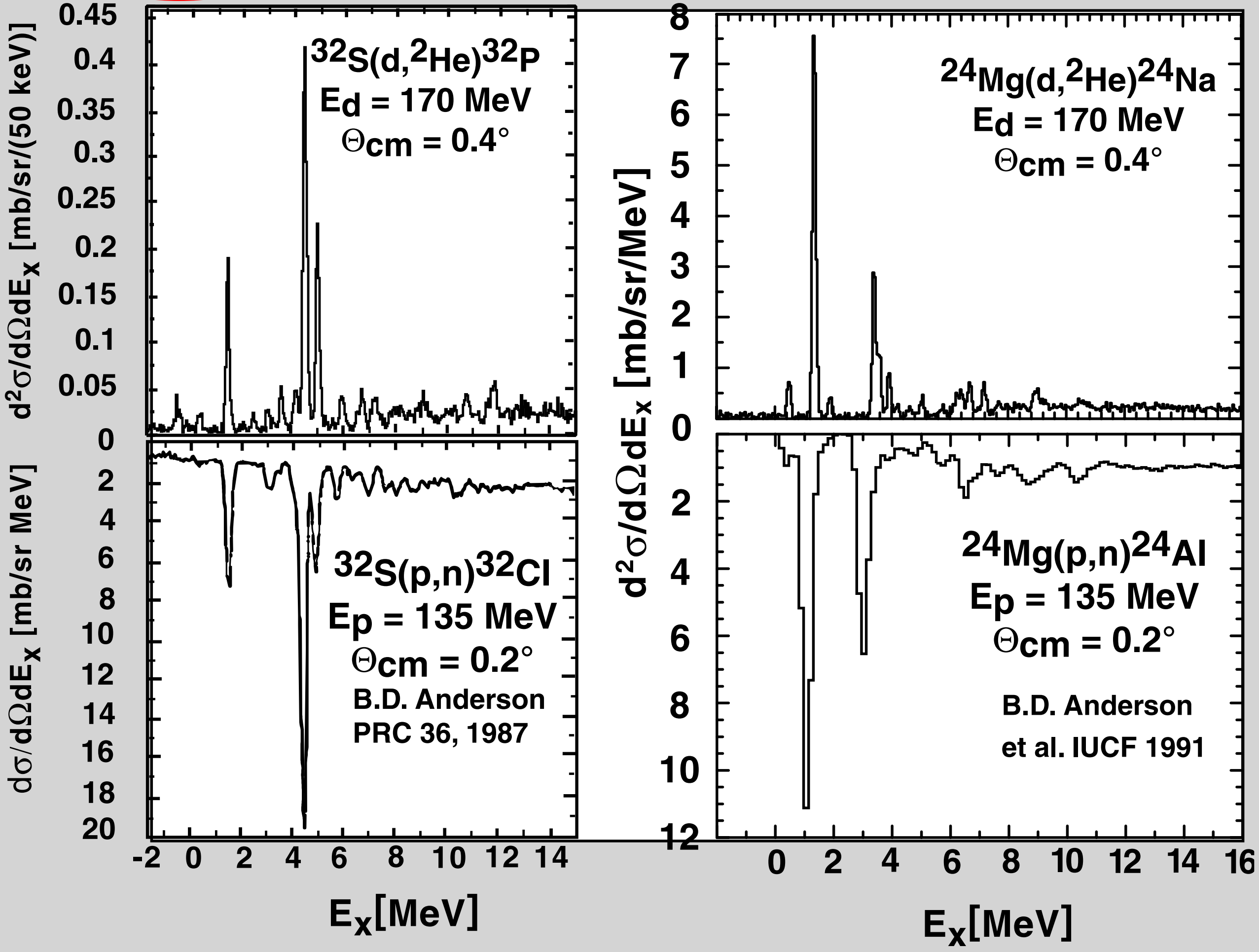
Isospin symmetry

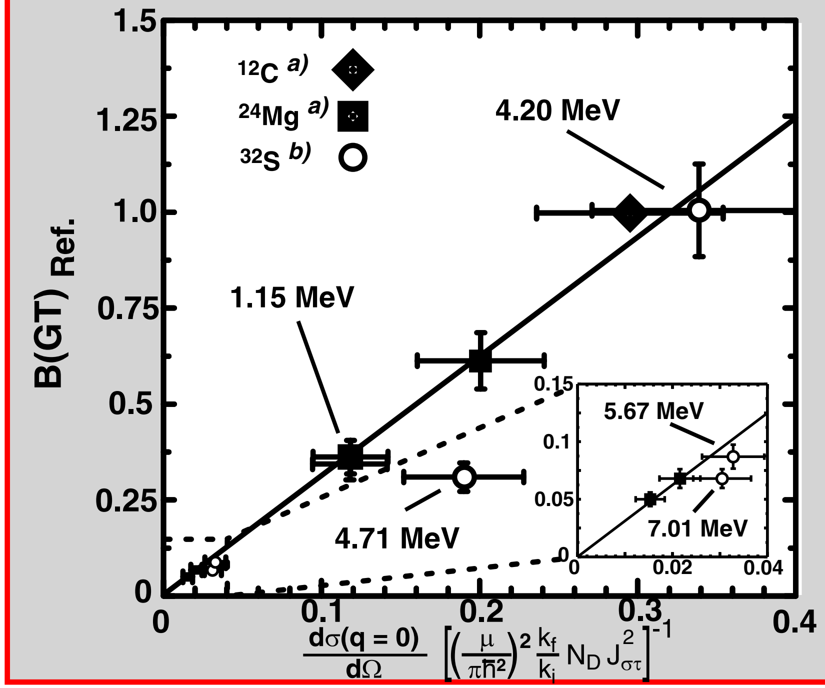


(d,^{2}He) reaction & B(GT) extraction

(comparison with (p,n), (p,p'), (e,e') in N=Z nuclei)

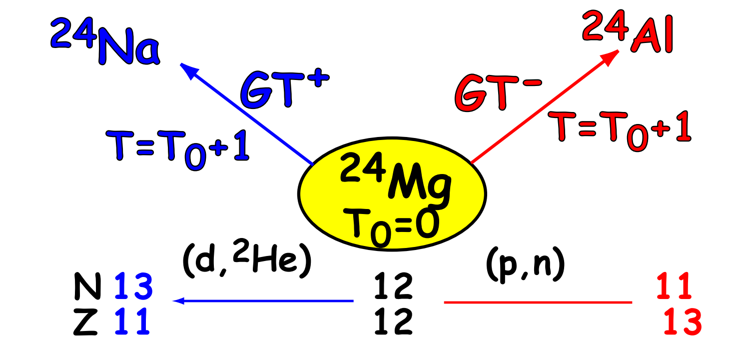
Isospin symmetry



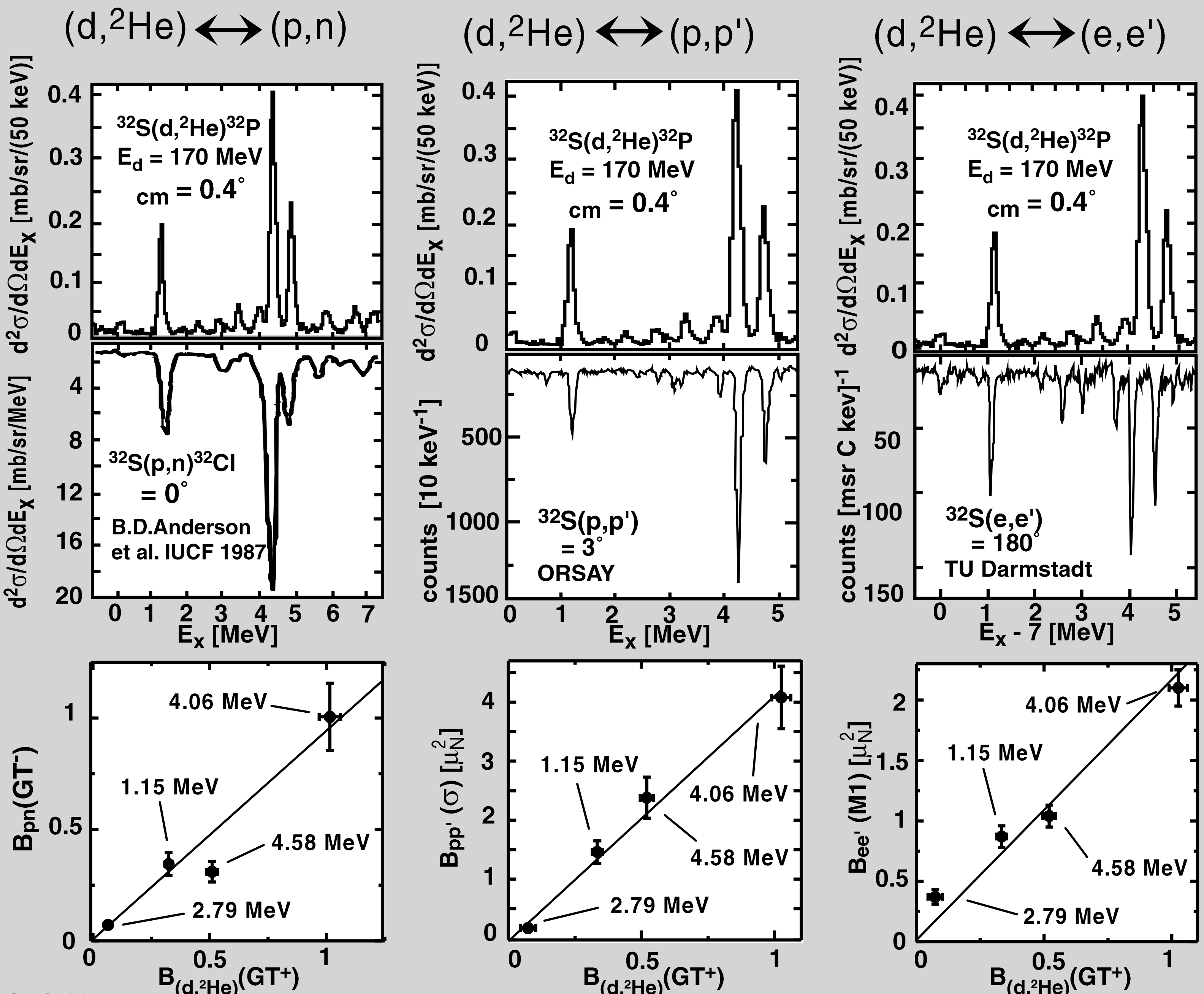


Isospin-symmetrie:

B(GT$^+$) = B(GT$^-$) for N=Z nuclei



B(GT$^+$) from ^{32}S and analog transitions



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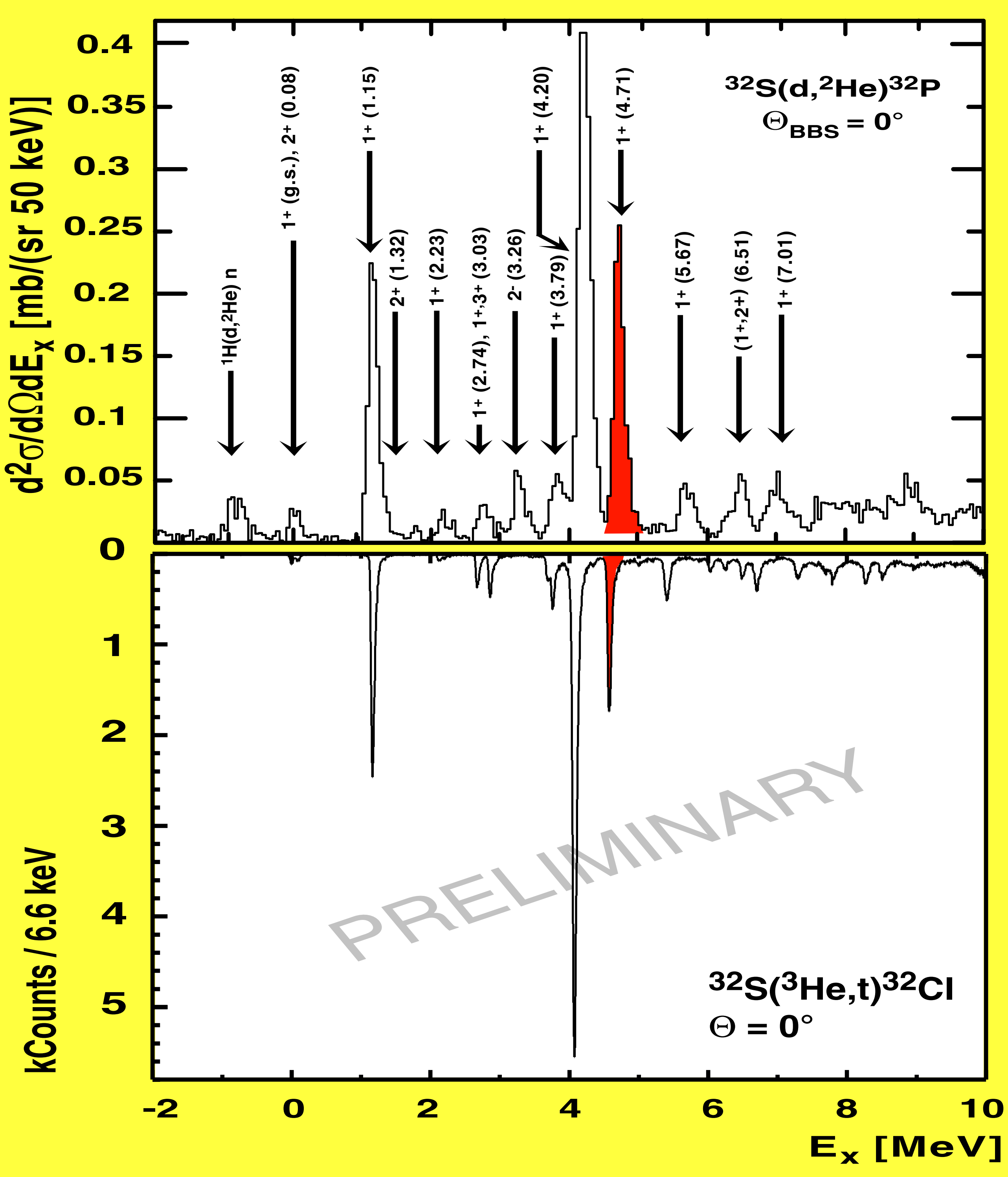
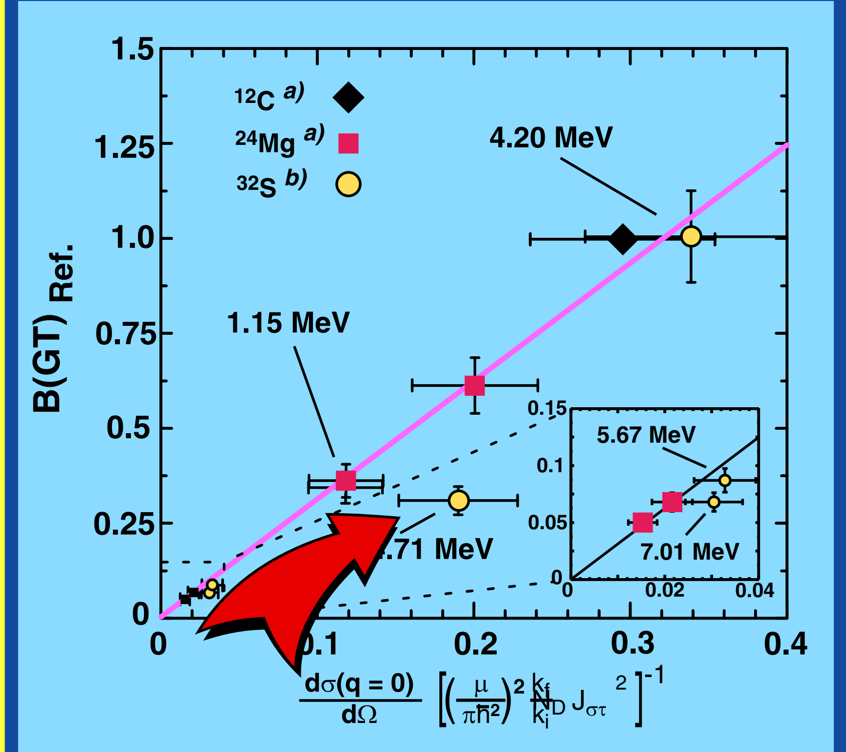


Isospin breaking in A=32 isobars



Reason:
low proton threshold in 32Cl ?

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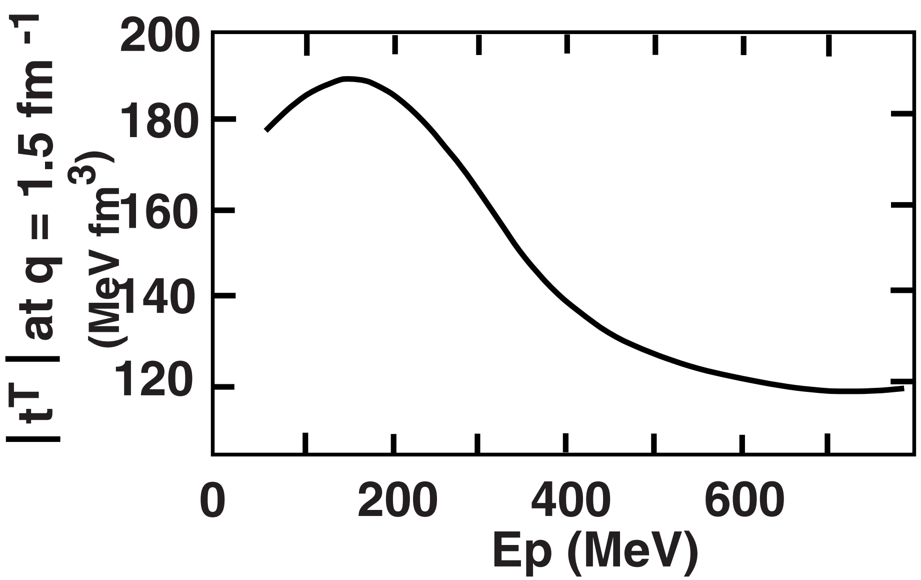
Stretched states -- another case for (d,^{2}He) ??

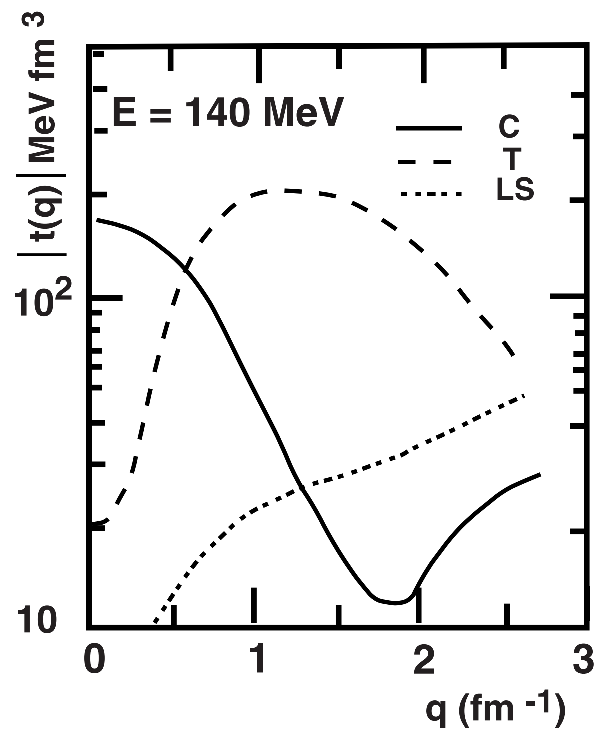
The reaction would have to be mediated by the tensor force (analogue to (n,p))

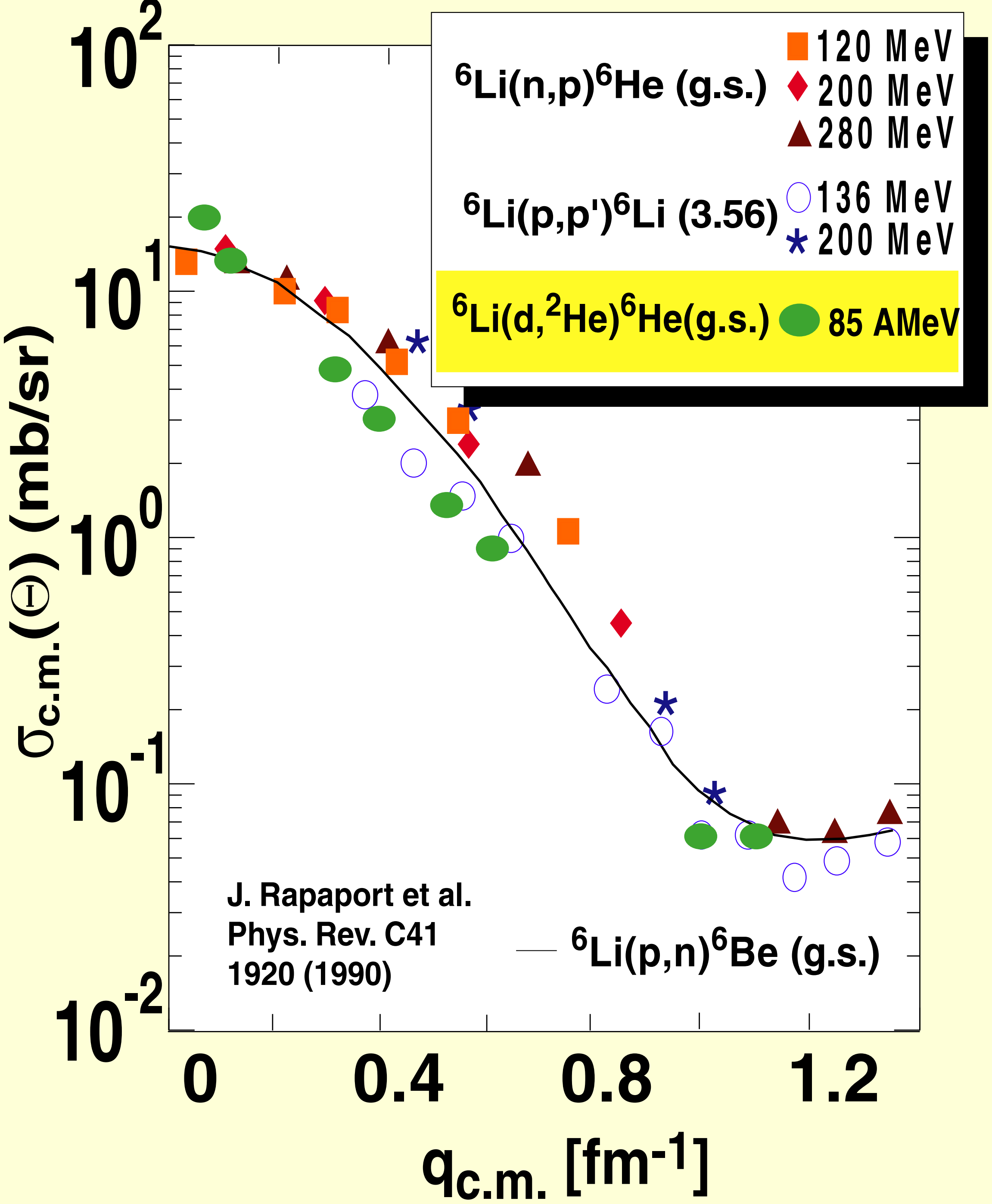
Stretched states form factors peak at q_{tr} = L/R (> 1 fm^{-1})

BUT

can ^{2}He survive??



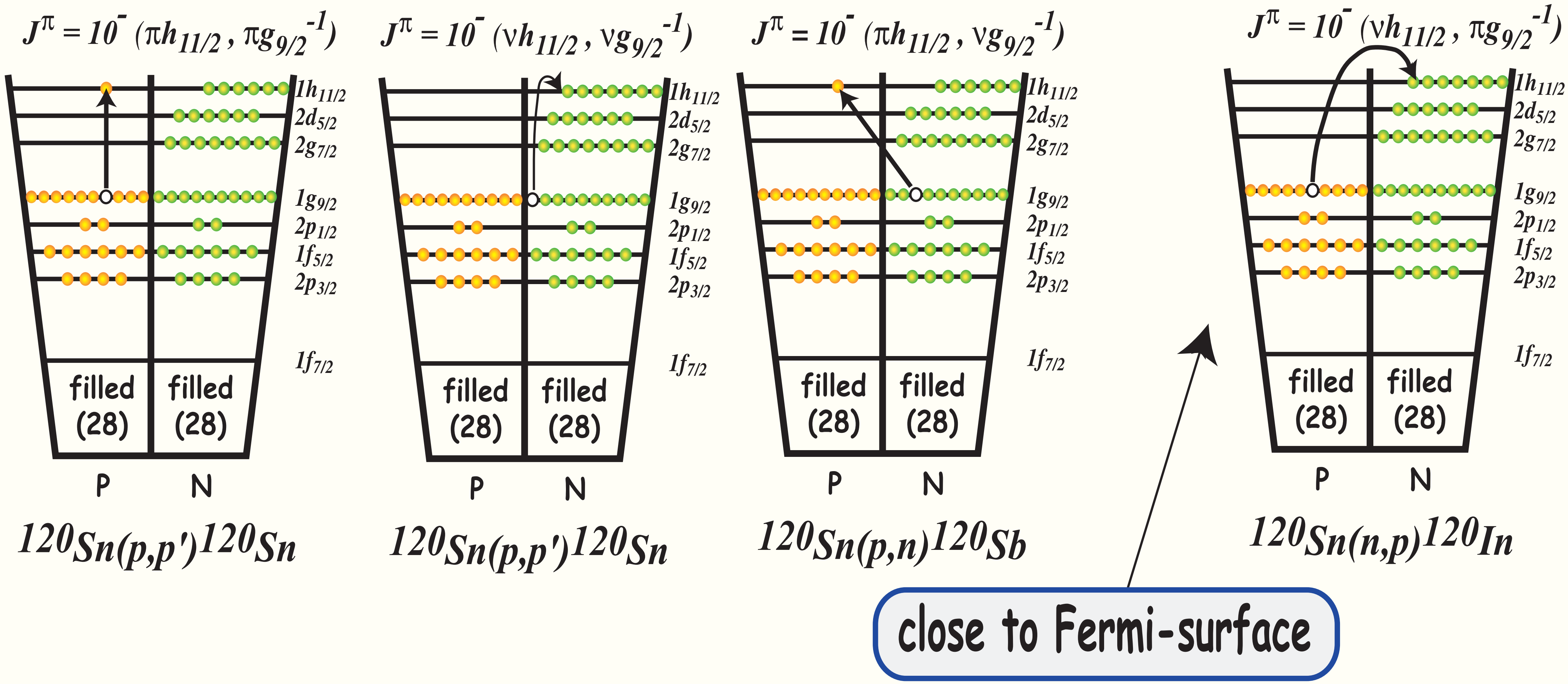




q-dependence of (d,^{2}He) reaction

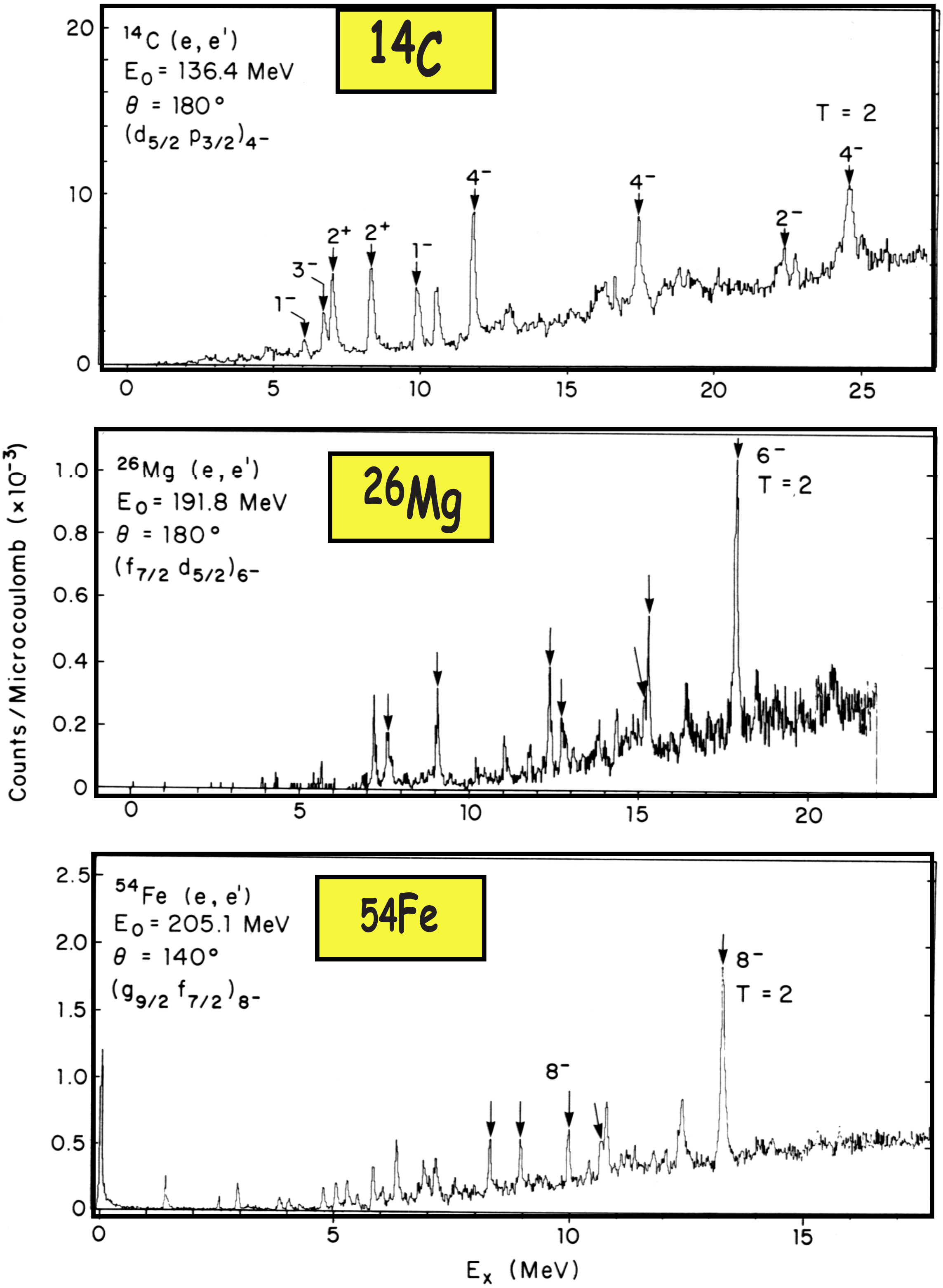
or

when does the ^{2}He fall apart?

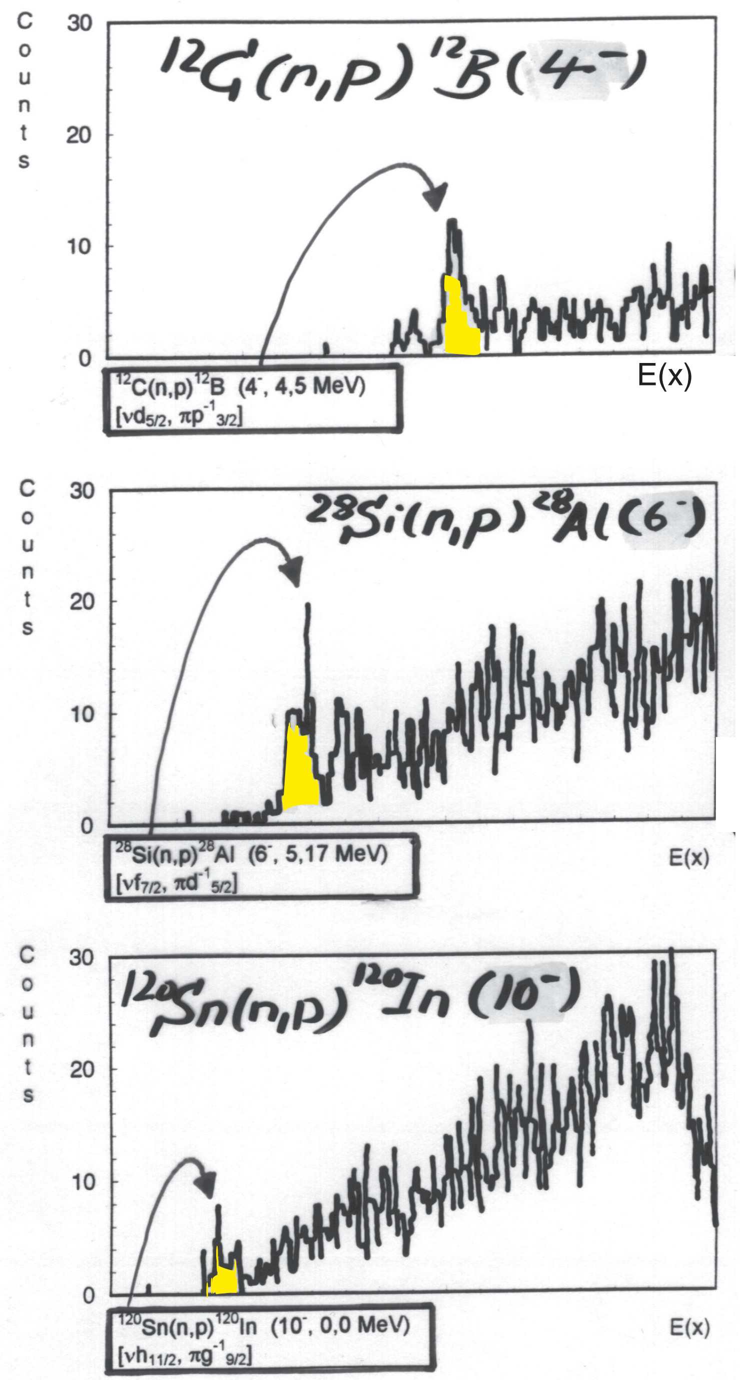


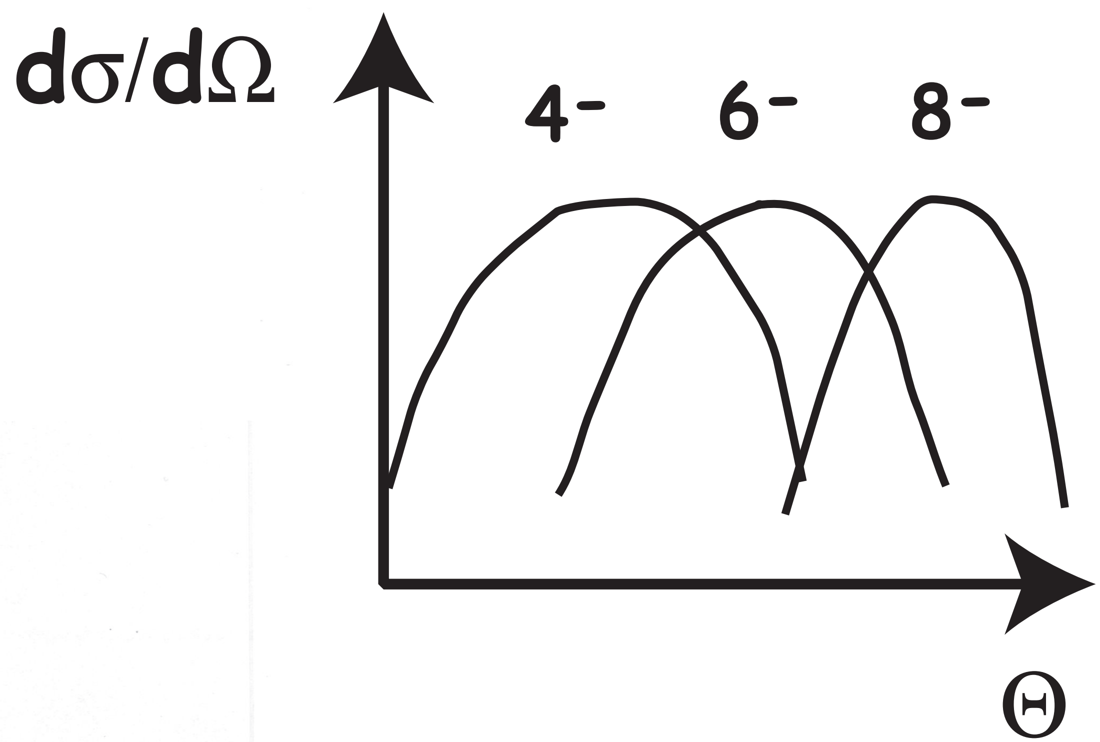
Fragmentation of stretched particle-hole states

stretched states excitation through (e,e')



stretched states spectroscopy using (n,p) at large q

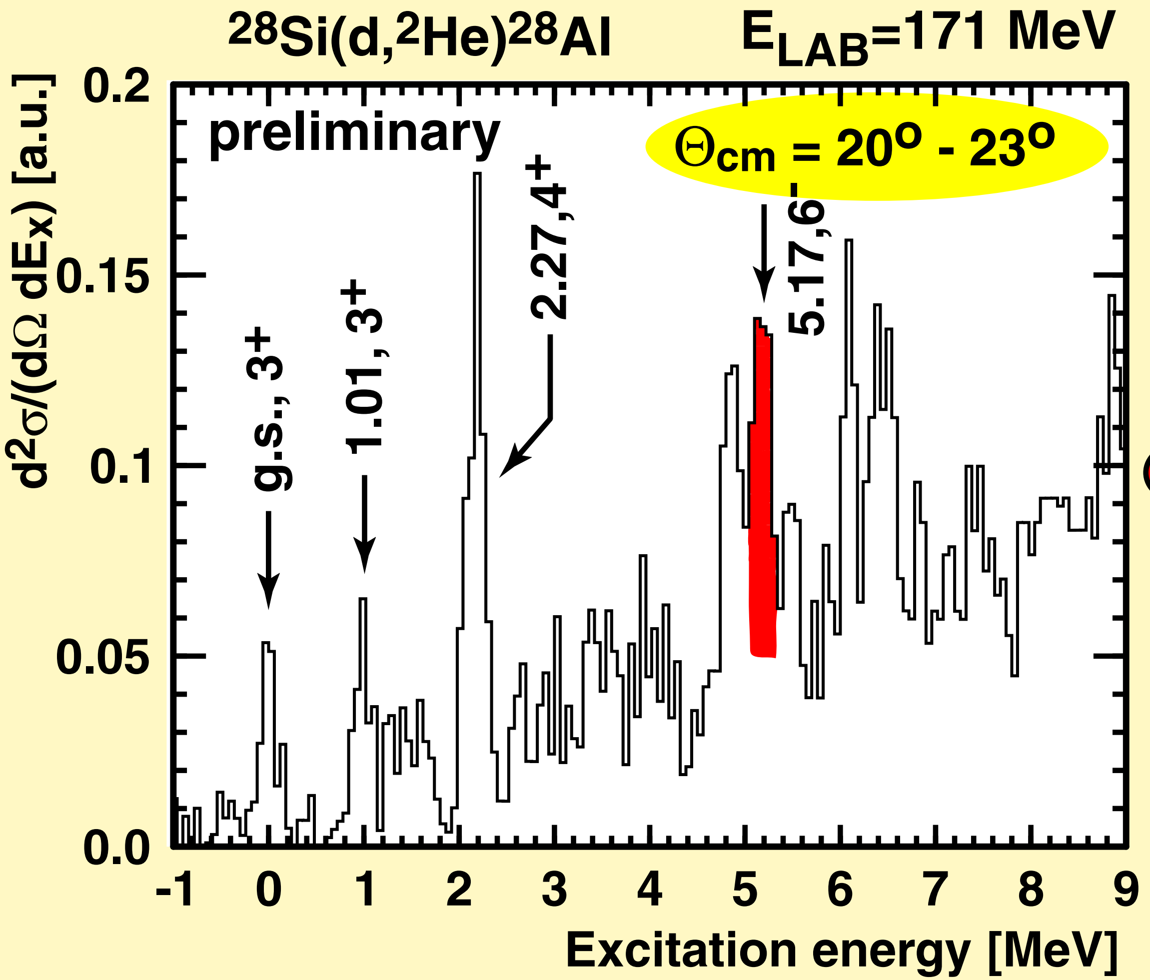




TRIUMF-data

Study of the tensor force
thru excitation of "Stretched States"

(d, ^{2}He)



6^- state is not as strong as expected

- q-dependence of tensor force for (d,^{2}He)?
- momentum transfer only through one single nucleon?

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:

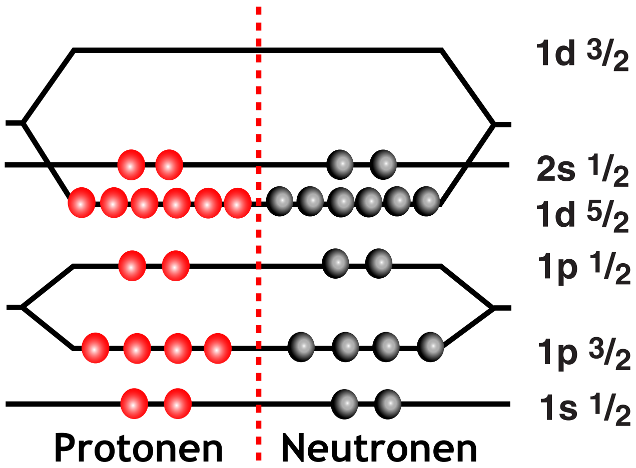
the potential still not fully exploited
need more test cases
need information of phase cancellation of GT states
$2\nu-\beta^+\beta^+$ (EC-EC) could be a further potential

further applications:

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

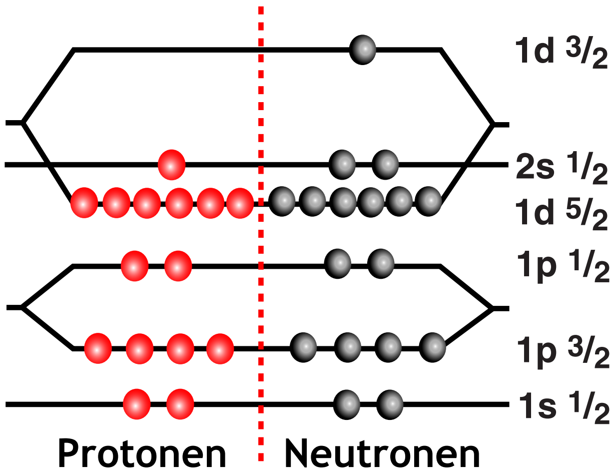
The l-forbidden transition

Ground state in ^{32}S 0^+

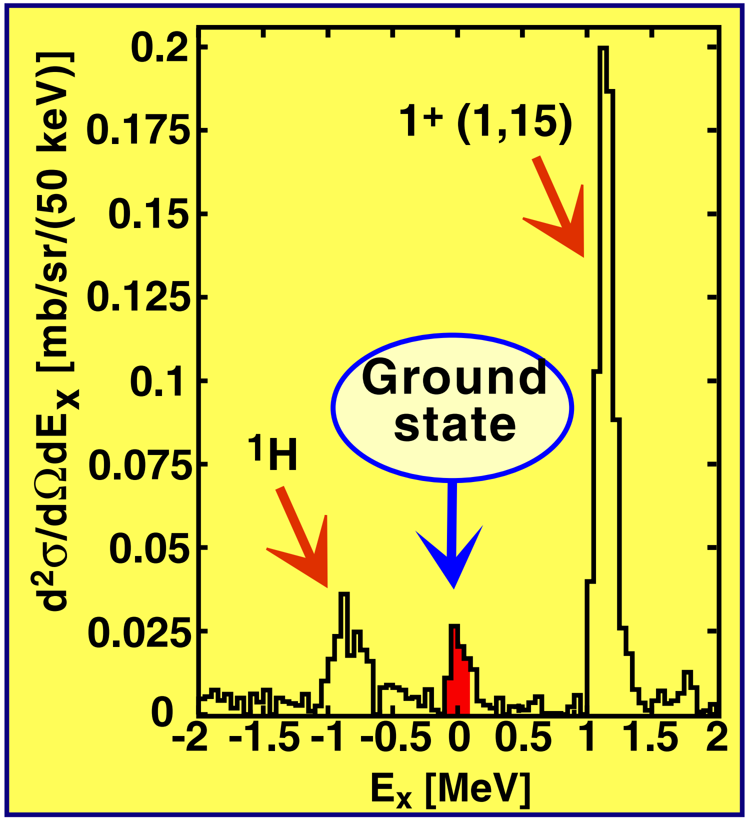


log ft = 7.9 ?

Ground state in ^{32}P 1^+



$(d,^2He) \rightarrow \Delta l=0$!



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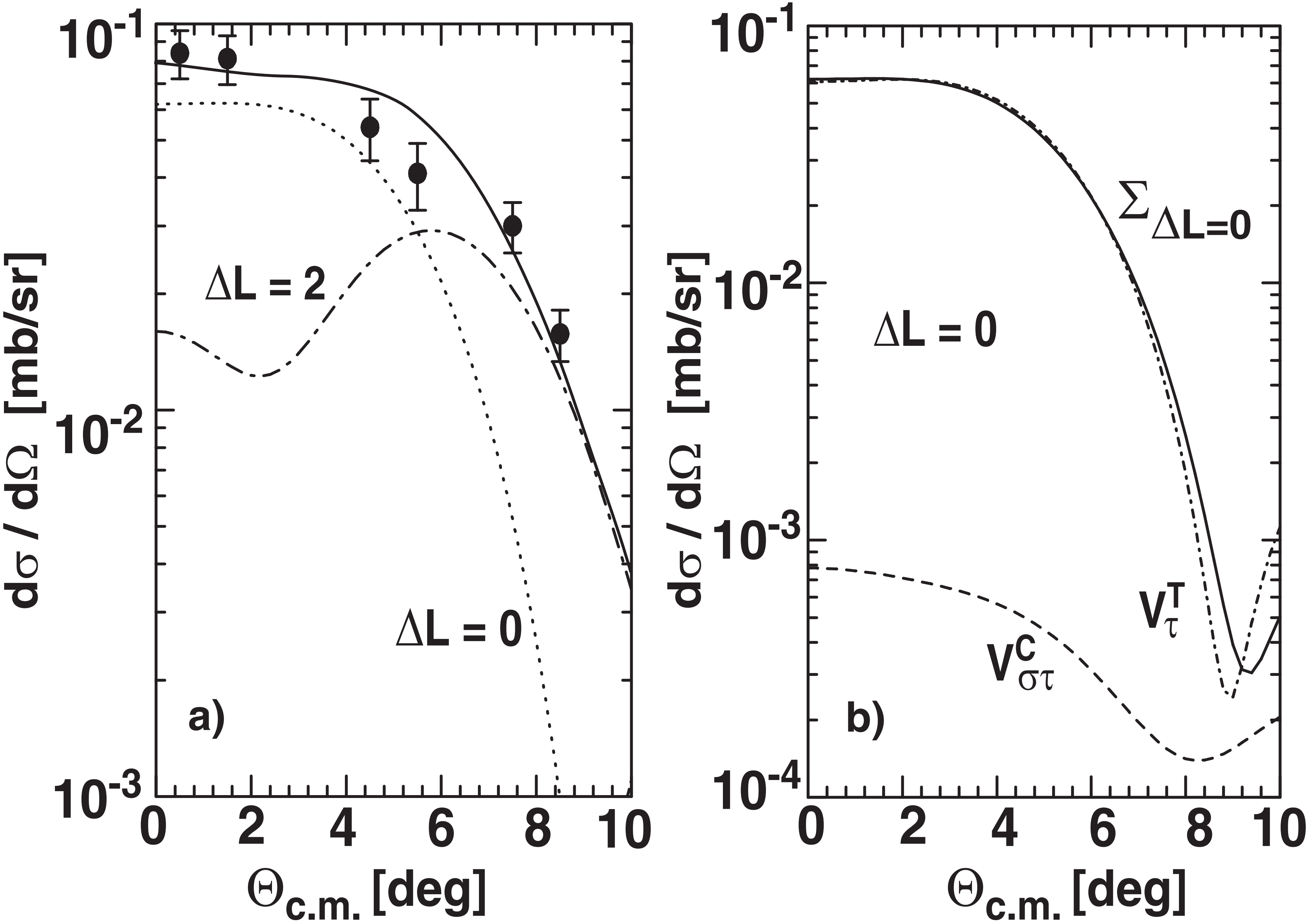

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Experimental Background Reduction