Some introduction to giant resonances and related physics
Experiment and Theory

Muhsin N. Harakeh

KVI, Groningen & GANIL, Caen

Lectures at 4th international conference on "Collective Motion in Nuclei under Extreme Conditions" (COMEX4)

22-26 October 2012

Lecture 2: Spin-Isospin Modes

1. Importance of studying GT$^+$ in *fp*-shell nuclei
2. Experimental method
3. Case Study: ^{58}Ni
4. Measurements on several *fp*-shell nuclei
5. Measurements on 2β-decaying nuclei
6. Conclusions and outlook

Spin-isospin excitations

Neutral (ν,ν') and charged (ν_e,e^-), (ν_e,e^+) currents

NC ⇒ Inelastic electron and proton scattering

⇒ M0, M1, M2

CC ⇒ Charge-exchange reactions

Isovector charge-exchange modes

⇒ GTR, IVSGMR, IVSGDR, etc.

Importance for nuclear astrophysics,

ν-physics, 2β-decay, n-skin thickness, etc.

(p,n), (^{3}He,t) {GT$^-$}; (n,p), (d,^{2}He) & (t,^{3}He) {GT$^+$}

Why are Gamow-Teller transitions in *fp*-shell nuclei important ?

- **Role of *fp*-shell nuclei in supernova explosions: Core of supernova star is composed of *fp*-shell nuclei.**

  ⇒ electron capture

- **Neutrino absorption cross sections by *fp*-shell nuclei are essential in understanding of nuclear synthesis in Supernova explosions in cosmos.**

➔ **Difficulties in shell-model calculations for *fp*-shell nuclei.**

➔ **Importance to measure spin-isospin responses of *fp*-shell nuclei to gauge theoretical calculations.**

Charge-exchange probes

(*p*,*n*)-type ($\Delta T_z = -1$)

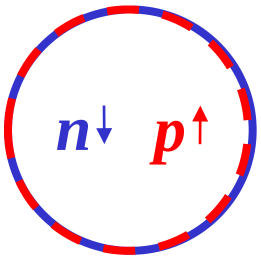
- β^--decay
- (*p*,*n*)
- (^{3}He,*t*)
- heavy ion

(*n*,*p*)-type ($\Delta T_z = +1$)

- β^+-decay
- (*n*,*p*)
- (*d*,^{2}He)
- (*t*,^{3}He)
- heavy ion; (^{7}Li,^{7}Be)

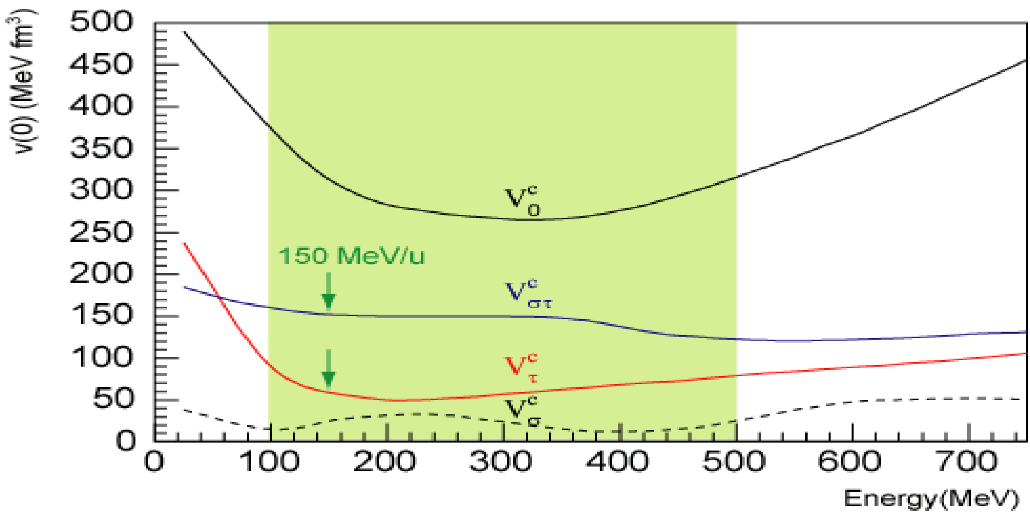
- Energy per nucleon (>100 MeV/u)
- Spin-flip versus non-spin-flip
- Complexity of reaction mechanism
- Experimental considerations

Spin-isospin excitations



ΔL=0 ΔS=1 ΔT=1

GTR



- **Gamow-Teller transitions;**

  Isospin (ΔT=1)

  Spin (ΔS=1)

Advantages

- **Cross section peaks at θ° (ΔL=0)**
- **Strong excitation of GT states at E/A=100-500 MeV/u**

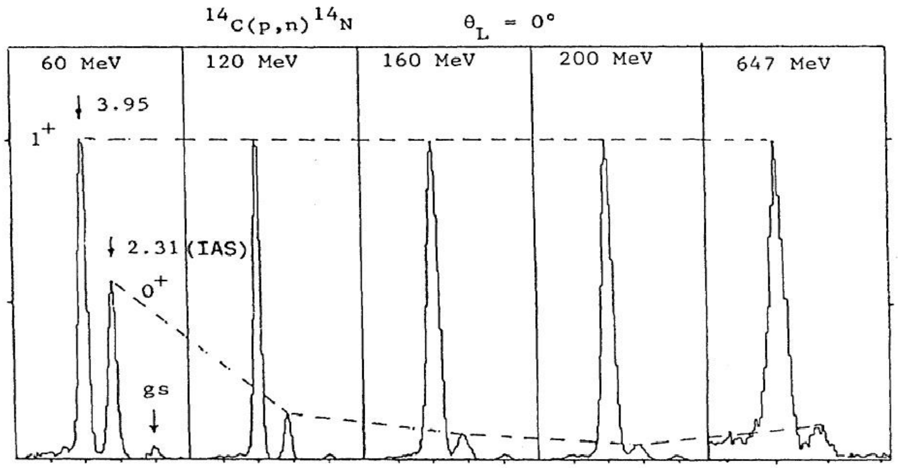


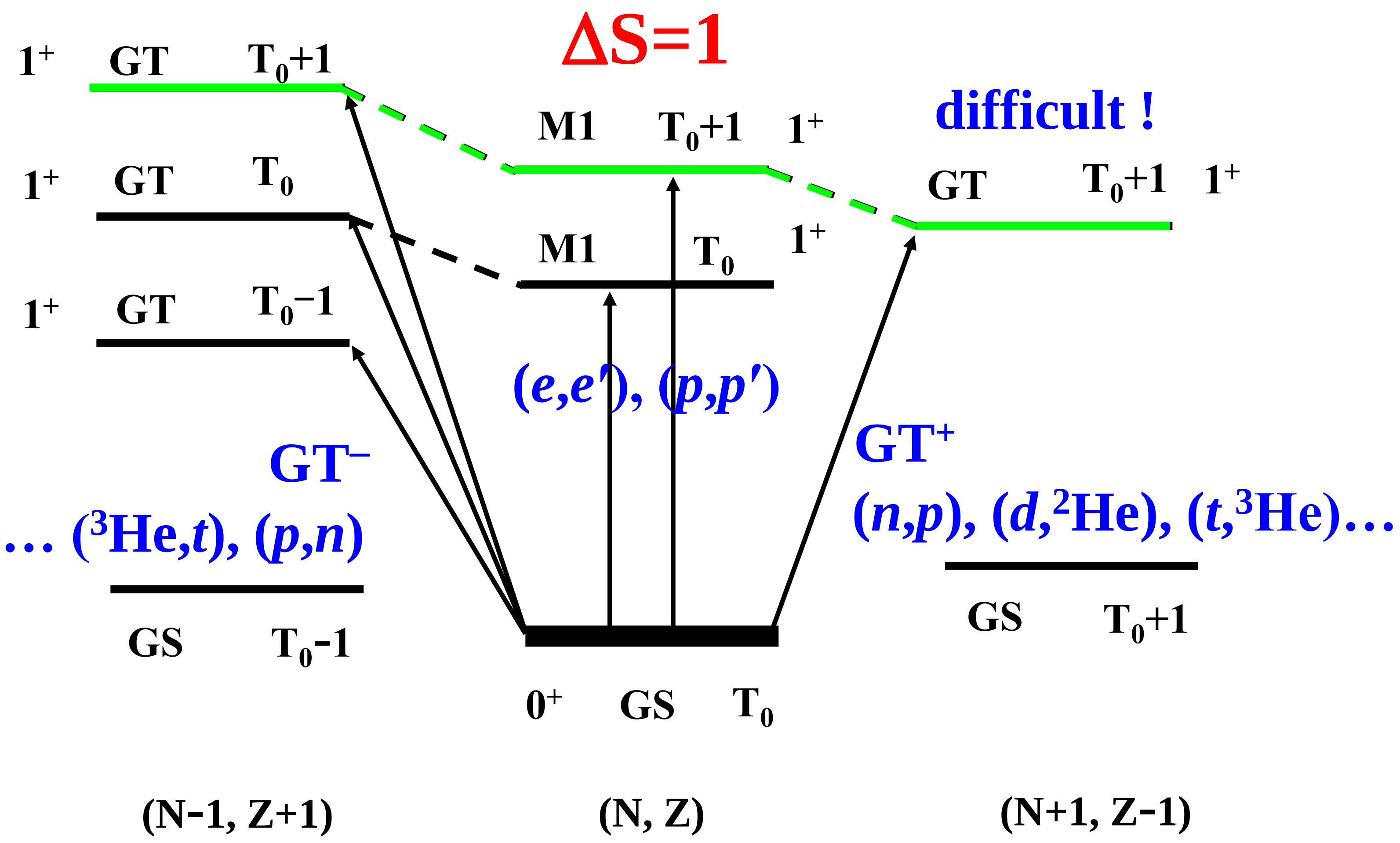
FIG. 4. Zero-degree cross-section spectra for the $^{14}C(p,n)^{14}N$ reactions at the indicated bombarding energies. The spectra have been arbitrarily normalized. From Gaarde (1985) and Rapaport (1989).

Nucleus → **Many-body system with a finite size**

Vibrations → **Multipole expansion with r, Y_{lm}, τ, σ**

	$\Delta S=0, \Delta T=0$	$\Delta S=0, \Delta T=1$	$\Delta S=0, \Delta T=1$	$\Delta S=1, \Delta T=1$	$\Delta S=1, \Delta T=1$
L=0: Monopole	**ISGMR** r^2Y_0	**IAS** τY_0	**IVGMR** τr^2Y_0	**GTR** $\tau \sigma Y_0$	**IVSGMR** $\tau \sigma r^2Y_0$
L=1: Dipole	**ISGDR** r^3Y_1		**IVGDR** $\tau r Y_1$		**IVSGDR** $\tau\sigma r Y_1$
L=2: Quadrupole	**ISGQR** r^2Y_2		**IVGQR** τr^2Y_2		**IVSGQR** $\tau\sigma r^2Y_2$
L=3: Octupole	**LEOR, HEOR** r^3Y_3				

Spin-flip & GT transitions

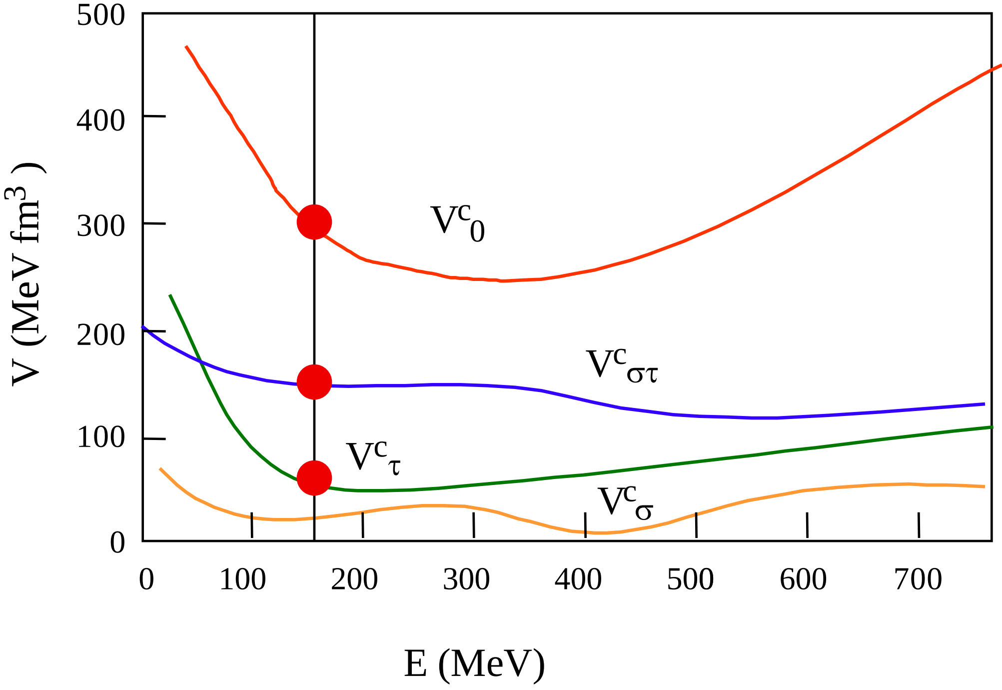


(^{3}He,*t*) Reaction ≥ 100 MeV/u

- **Energy dependence of effective interactions.**

- **At RCNP, Osaka**

  E(^{3}He) ≈ 150 MeV/u
  - **V_0 part: Minimum.**
  - **$V_{\sigma t}$ part: Relatively large.**
  - **V_t part: Minimum.**



The (^{3}He,*t*) reaction at 0 degree

- **Cross sections at E(^{3}He)=450 MeV, q=0 for (^{3}He,*t*) reactions**

$$\frac{d\sigma}{d\Omega} = \frac{\mu_i \mu_f}{(\pi\hbar^2)^2}\left(\frac{k_f}{k_i}\right)(N_\tau^D \,|\, J_\tau \,|^2\, B(F) + N_{\sigma\tau}^D \,|\, J_{\sigma\tau}\,|^2\, B(GT))$$

T. N. Taddeucci *et al*., Nucl. Phys. A469, 125 (1987)
I. Bergqvist *et al*., Nucl. Phys. A469, 648 (1987)

- **Neutrino absorption cross sections**

$$\sigma = \frac{1}{\pi\hbar^4 c^3}\left[G_V^2 B(F) \;\; + G_A^2 B(GT)\right] \times F(Z, E_e)\, p_e E_e$$

$F(Z, E_e)$ is the relativistic Coulomb barrier factor

Importance of charge-exchange reactions at intermediate energies

Measuring GT strengths

$$\frac{d\sigma}{d\Omega}(q=0) = KN_D\left|J_{\sigma\tau}\right|^2 B(GT)$$

kinematic factor

distortion factor

nucleon-nucleus interaction

Gamow-Teller strength

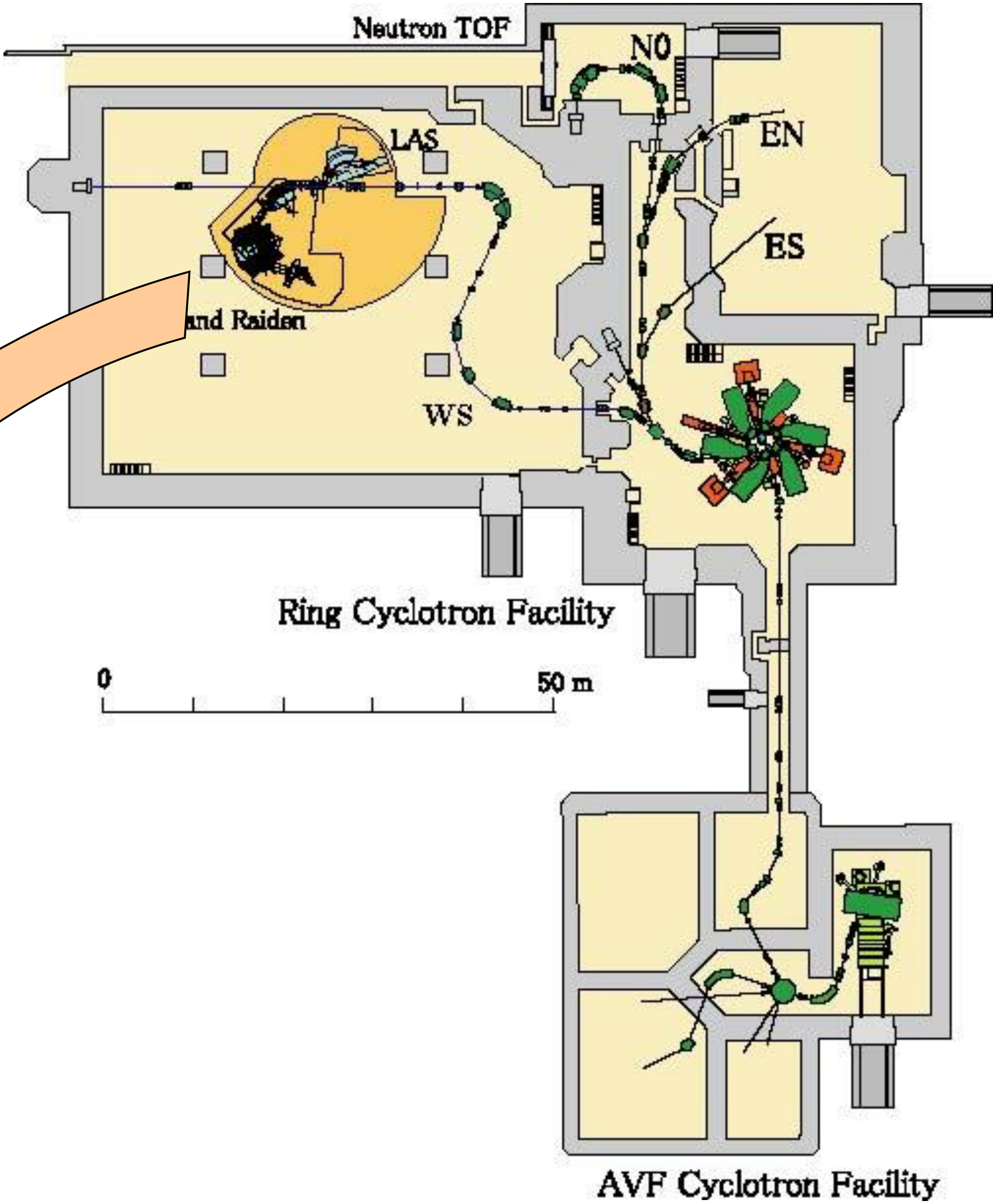
Calibration of B(GT) to cross section for known transitions (e.g. from β-decay)

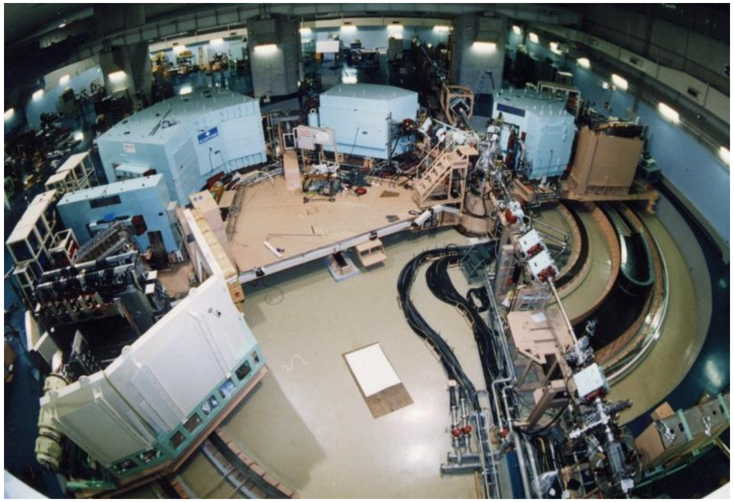
Experiments

- **RCNP facility**

  K=400 MeV ring cyclotron

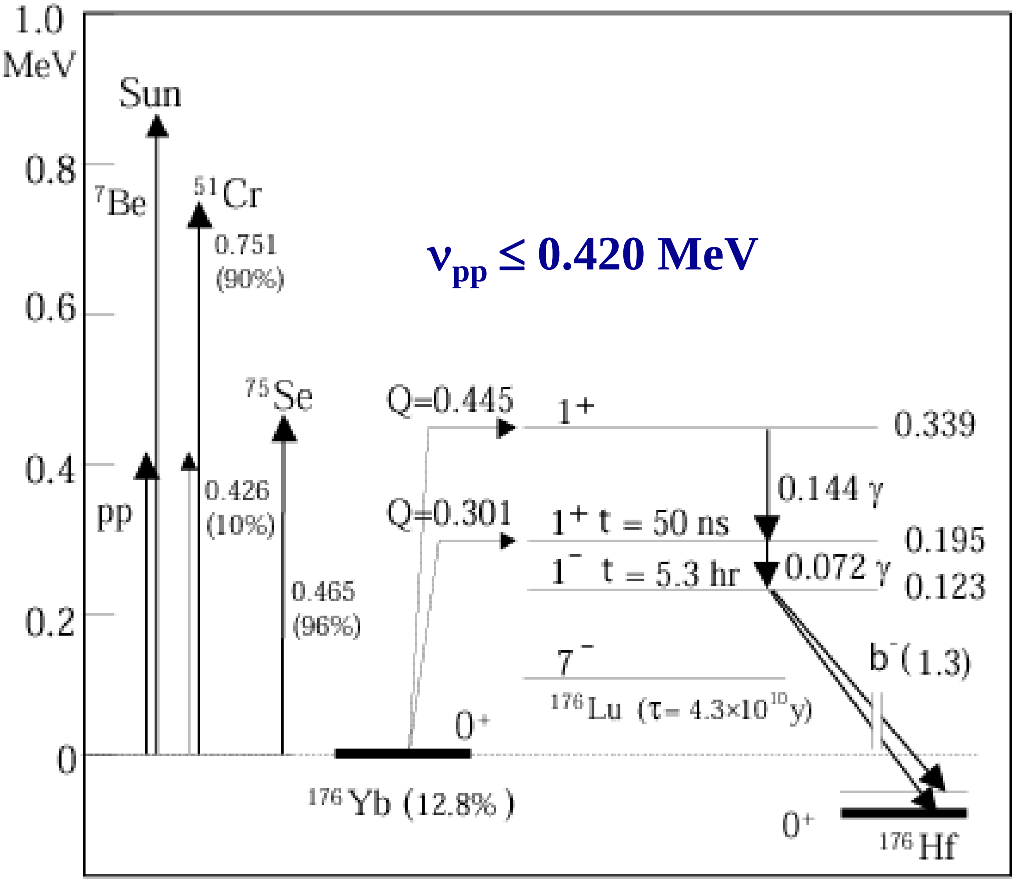
  Grand Raiden spectrometer
- **Beam: ^{3}He^{++}, 450 MeV**





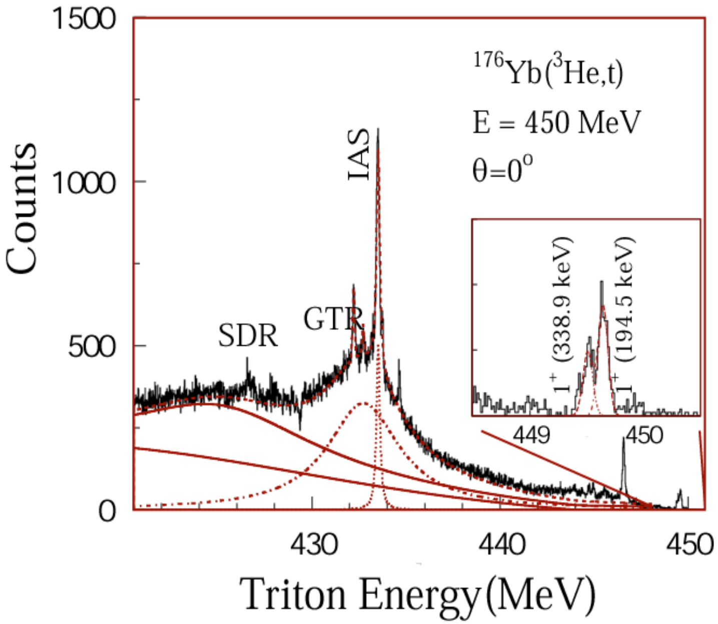
M. Fujiwara *et al.*, NIM A422 (1999) 484

Used ^{164}Dy(^{3}He, t)^{164}Ho (g.s., 1+) reaction for calibration: logft 4.6 → B(GT) = 0.293±0.006



$\nu_{pp} \leq$ **0.420 MeV**

M. Fujiwara *et al.*, PRL 85 (2000) 4442



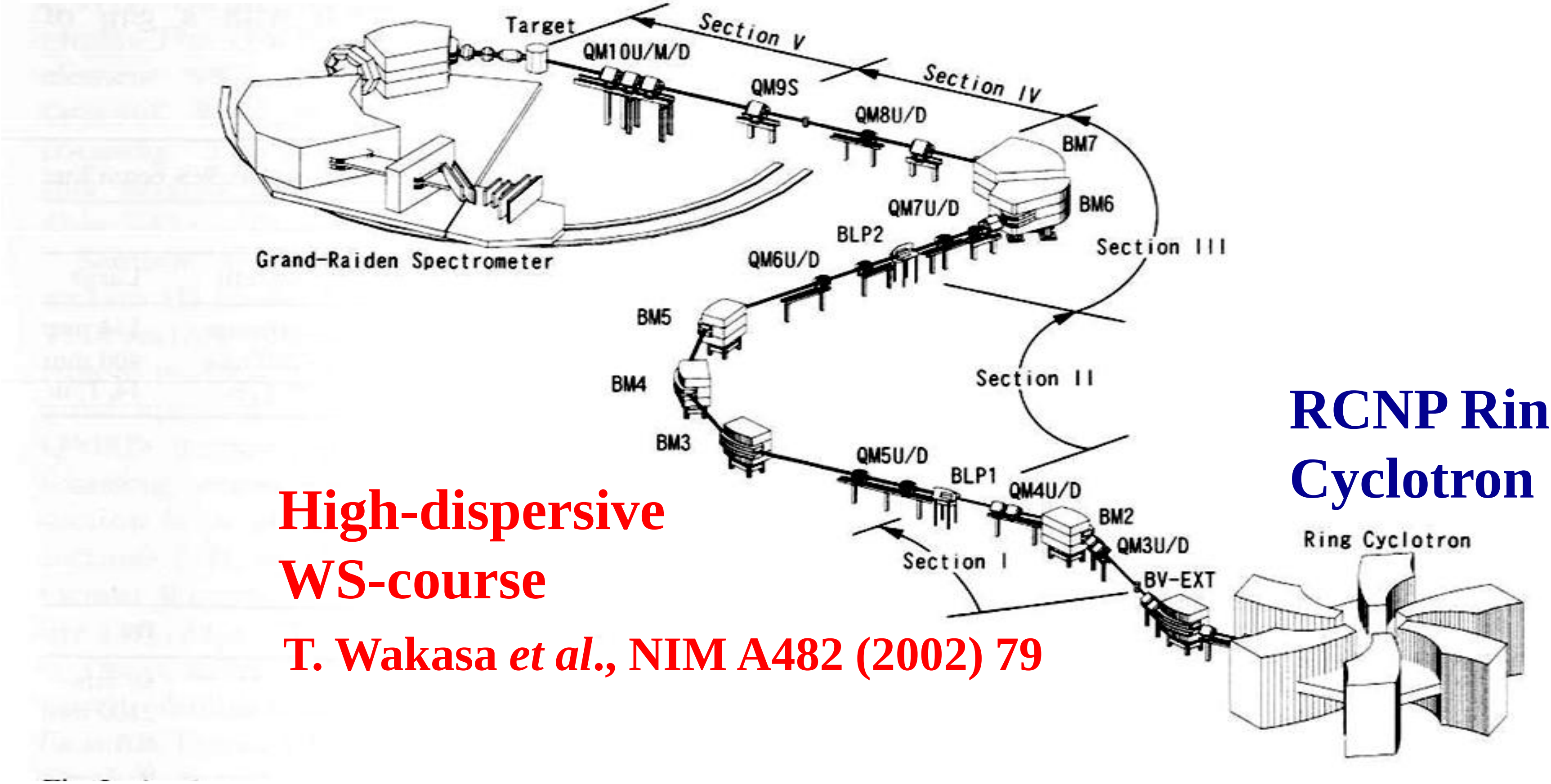
Resolution ≈ 100 to 130 keV

E_x (MeV)	0.195+0.339 (p,n)	0.195 (^{3}He,t)	0.339 (^{3}He,t)
B(GT)	0.32±0.04	0.20±0.04	0.11±0.02

Beam line WS-course

Grand-Raiden Spectrometer

M. Fujiwara *et al.*, NIM A422 (1999) 484

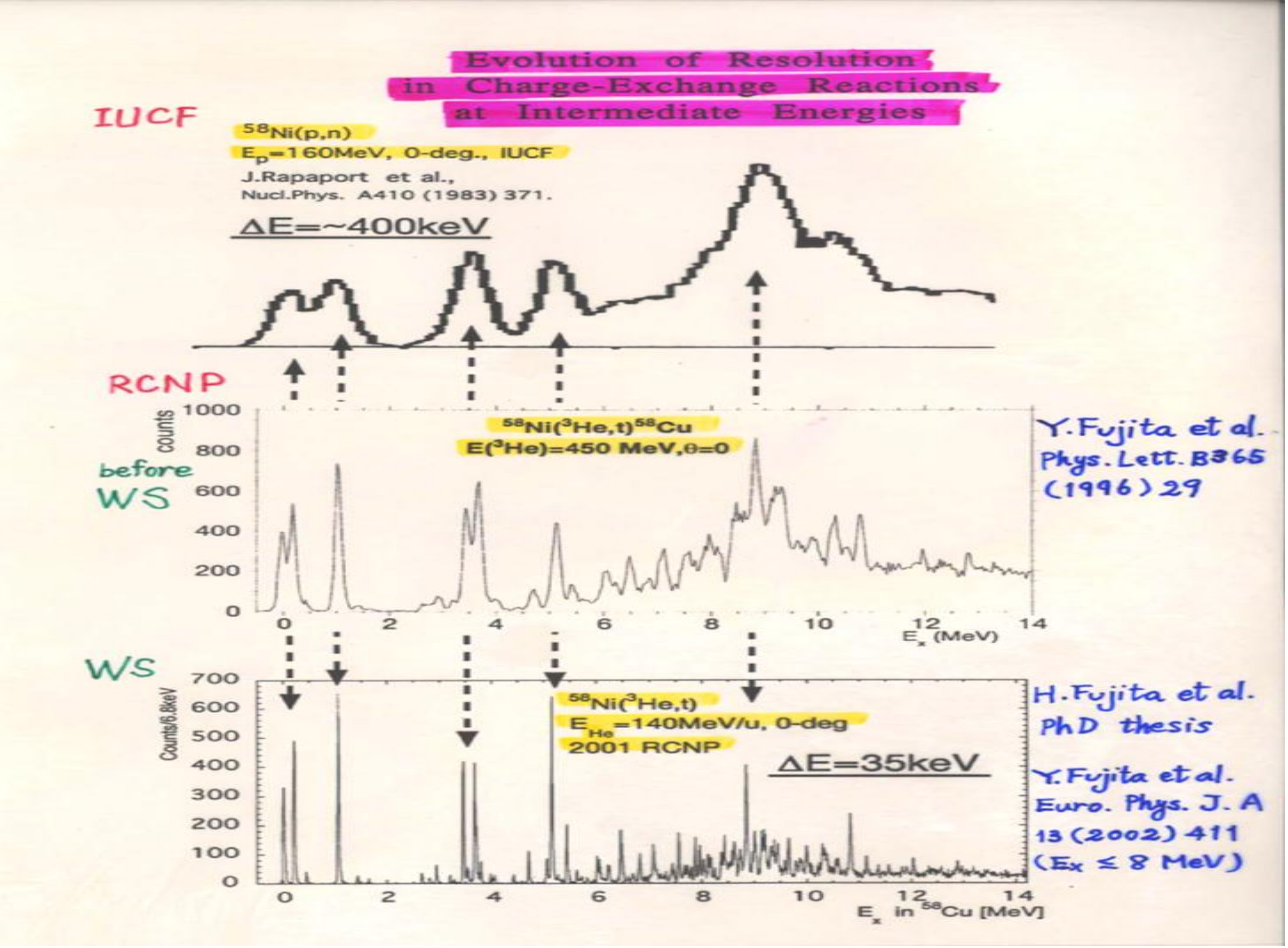


RCNP Ring Cyclotron

High-dispersive WS-course

T. Wakasa *et al.*, NIM A482 (2002) 79

Evolution of Resolution in Charge-Exchange Reactions at Intermediate Energies



IUCF

^{58}Ni(p,n)

E_p=160MeV, 0-deg., IUCF

J.Rapaport et al.,
Nucl.Phys. A410 (1983) 371.

ΔE=~400keV

RCNP

before WS

^{58}Ni(^{3}He,t)^{58}Cu

E(^{3}He)=450 MeV,θ=0

Y.Fujita et al.
Phys. Lett. B365
(1996) 29

WS

^{58}Ni(^{3}He,t)

E_{He}=140MeV/u, 0-deg

2001 RCNP

ΔE=35keV

H.Fujita et al.
PhD thesis

Y.Fujita et al.
Euro. Phys. J. A
13 (2002) 411
($E_x \leq 8$ MeV)

Decomposition of the isospin component of the excited state in ^{58}Cu

- **Isospin of ^{58}Ni g.s. : T_0=1**

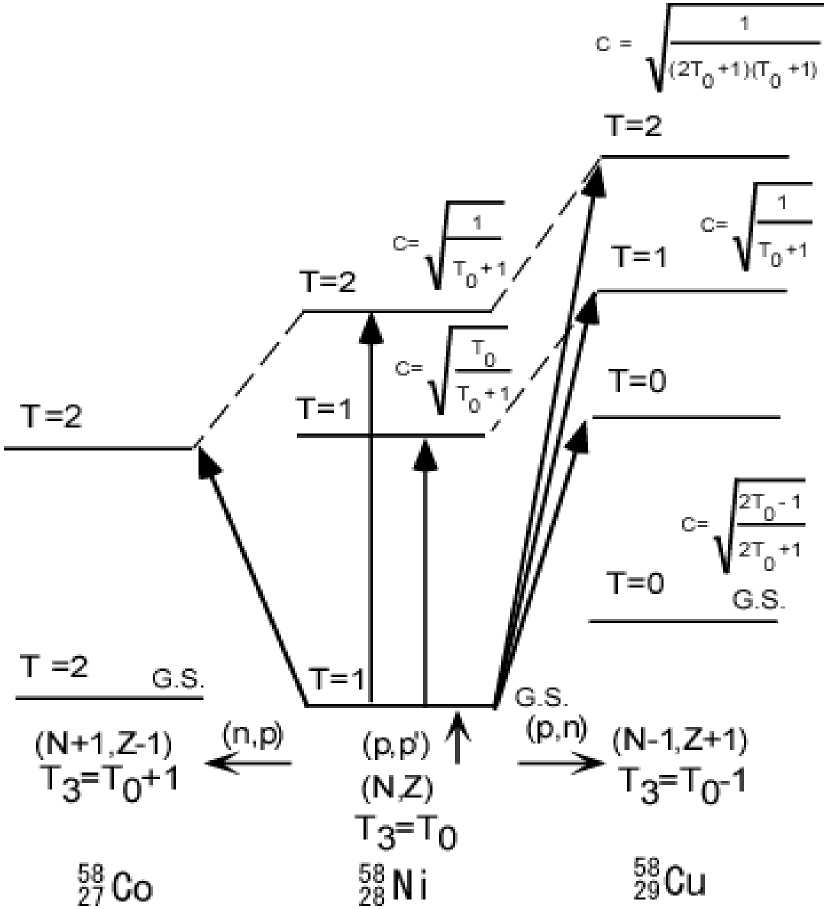
- **In principle, comparison among (*n*,*p*), (*p*,*p*), (*p*,*n*) spectra**

  → Separates isospin components

  But, very difficult in practice because of high level density for T=1 and T=2 states.

- **CG**

  $\sigma_{T=0}:\sigma_{T=1}:\sigma_{T=2}$ **= 2:3:1 (T_0=1)**

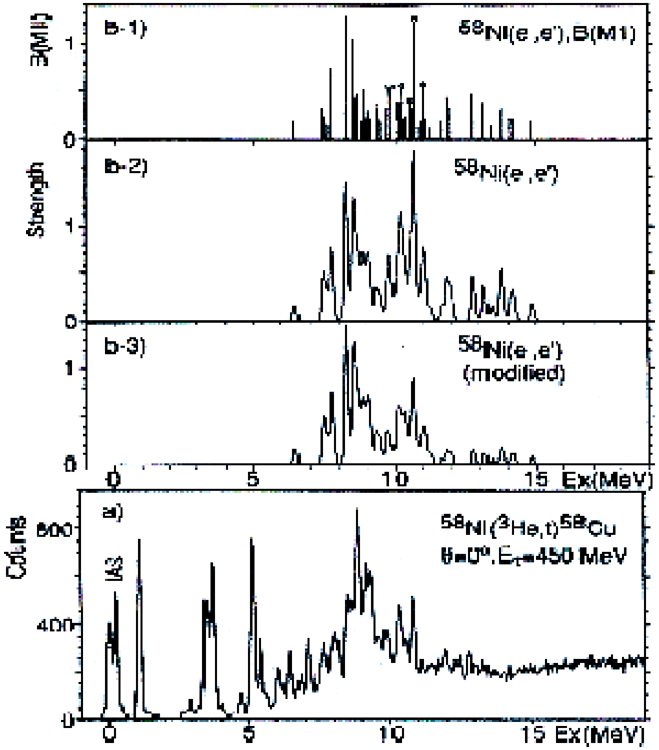


Comparison of (^{3}He,*t*) and (*e*,*e*′) spectra

- Comparison of (^{3}He,*t*) with (*e*,*e*′) spectra ➔ Try to separate isospin components
- At E_x= 6-10 MeV (T=1 region)
  - Rather good correspondence
- At E_x=10-15 MeV (T=2 region)
  - No good correspondence

Fujita *et al.*, Phys. Lett. B 365, 29 (1996).

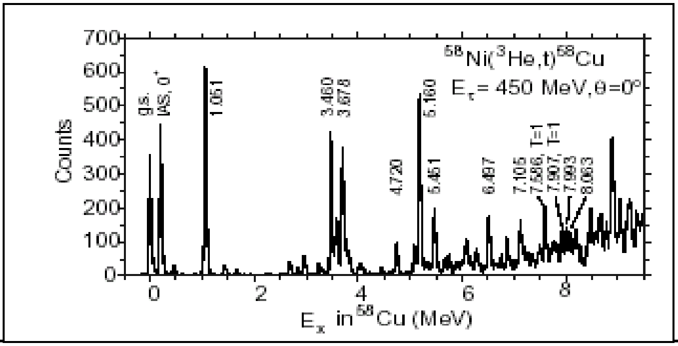
Fujita *et al.*, Eur. Phys. J A13, 411 (2002).



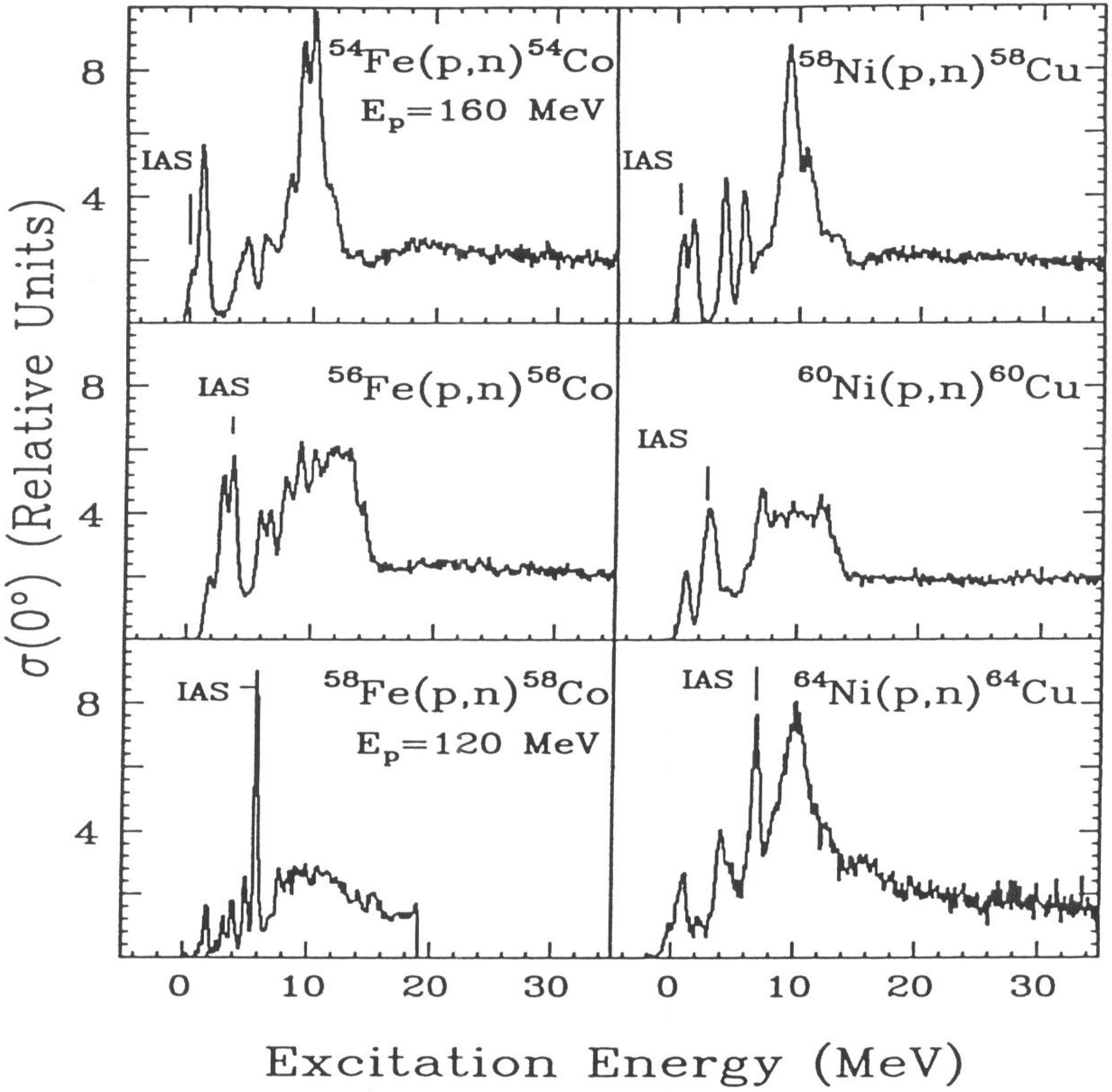
σ(T=1):σ(T=2)

= 1 : 1

σ(T=1):σ(T=2)
= 3 : 1

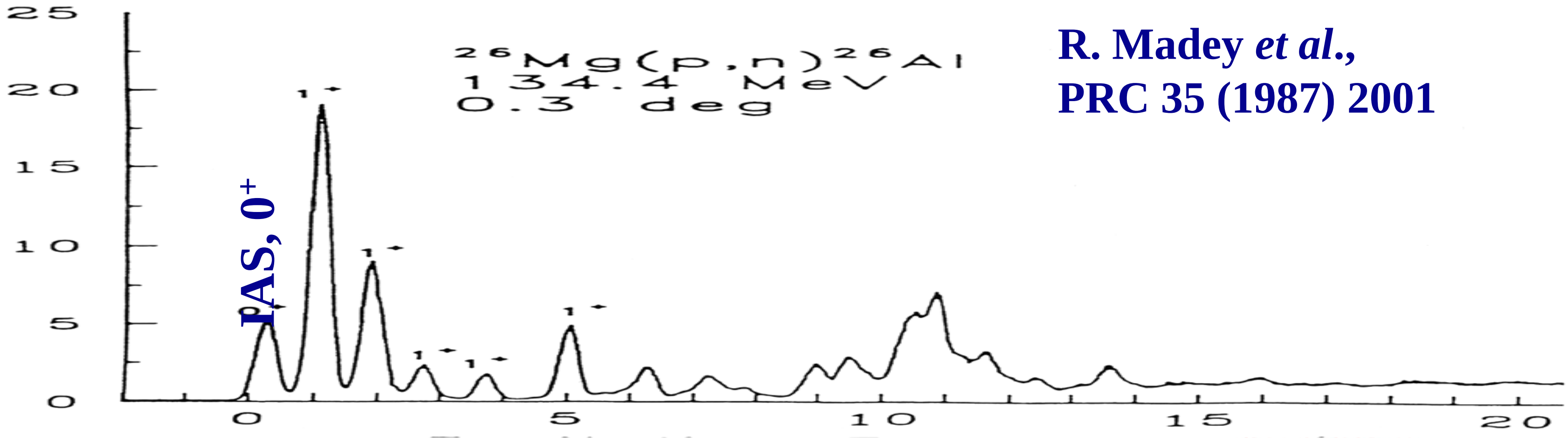


(*p*, *n*) spectra for Fe and Ni Isotopes

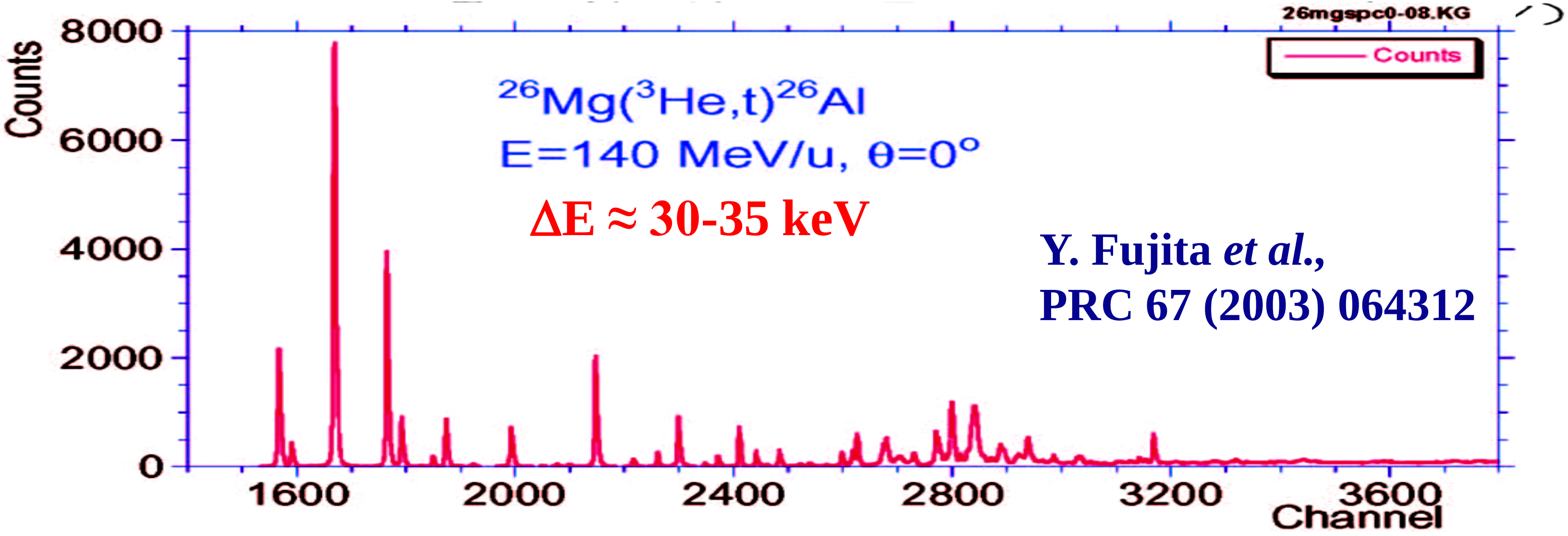


Rapaport
&
Sugarbaker
Rev. Mod. Phys.
('94)

^{26}Mg(*p*,*n*)^{26}Al & ^{26}Mg(^{3}He,*t*)^{26}Al spectra



R. Madey *et al.*,
PRC 35 (1987) 2001

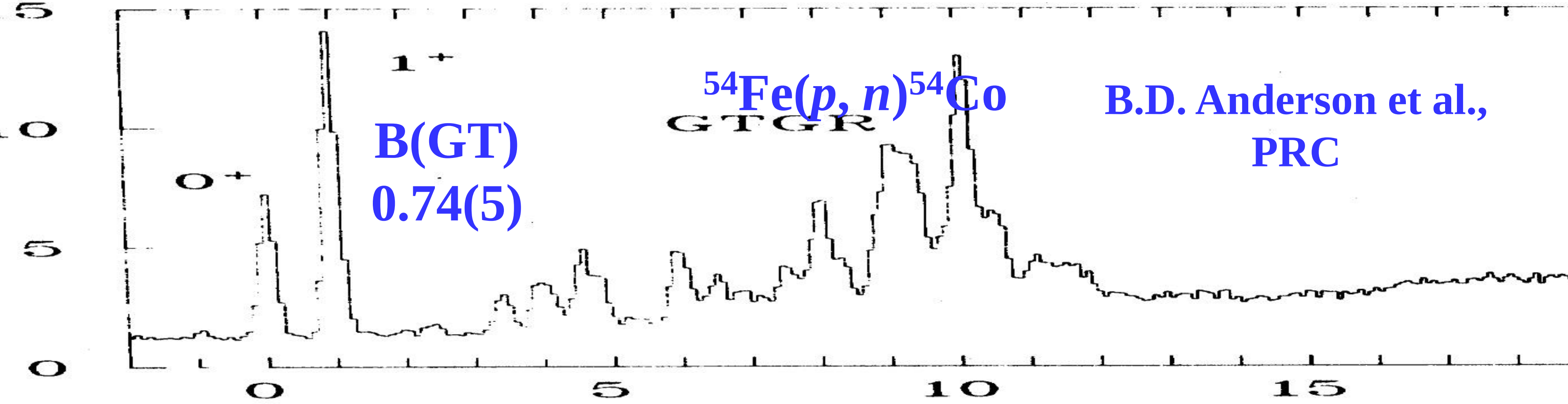


ΔE ≈ 30-35 keV

Y. Fujita *et al.*,
PRC 67 (2003) 064312

Prominent states are GT states and the IAS !

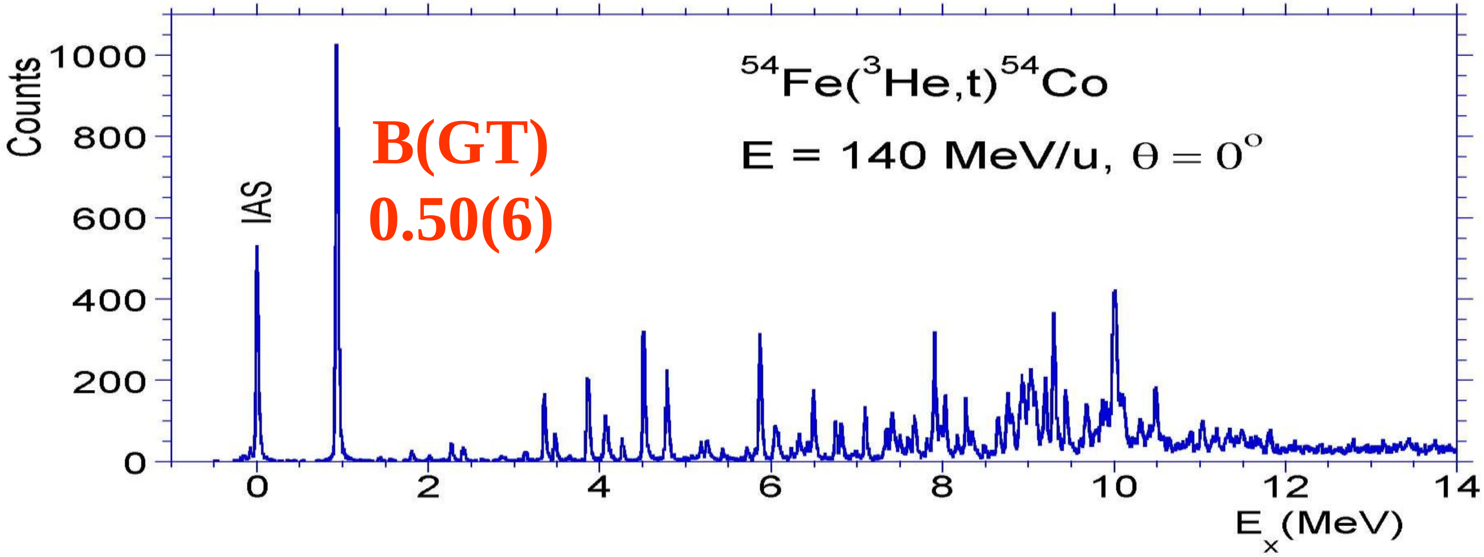
^{54}Fe(*p*,*n*) & ^{54}Fe(^{3}He,*t*)



^{54}Fe(*p*, *n*)^{54}Co

B(GT) 0.74(5)

B.D. Anderson et al., PRC



B(GT) 0.50(6)

^{136}Xe(^{3}He,*t*)^{136}Cs

E(^{3}He) = 420 MeV

ΔE = 42 keV

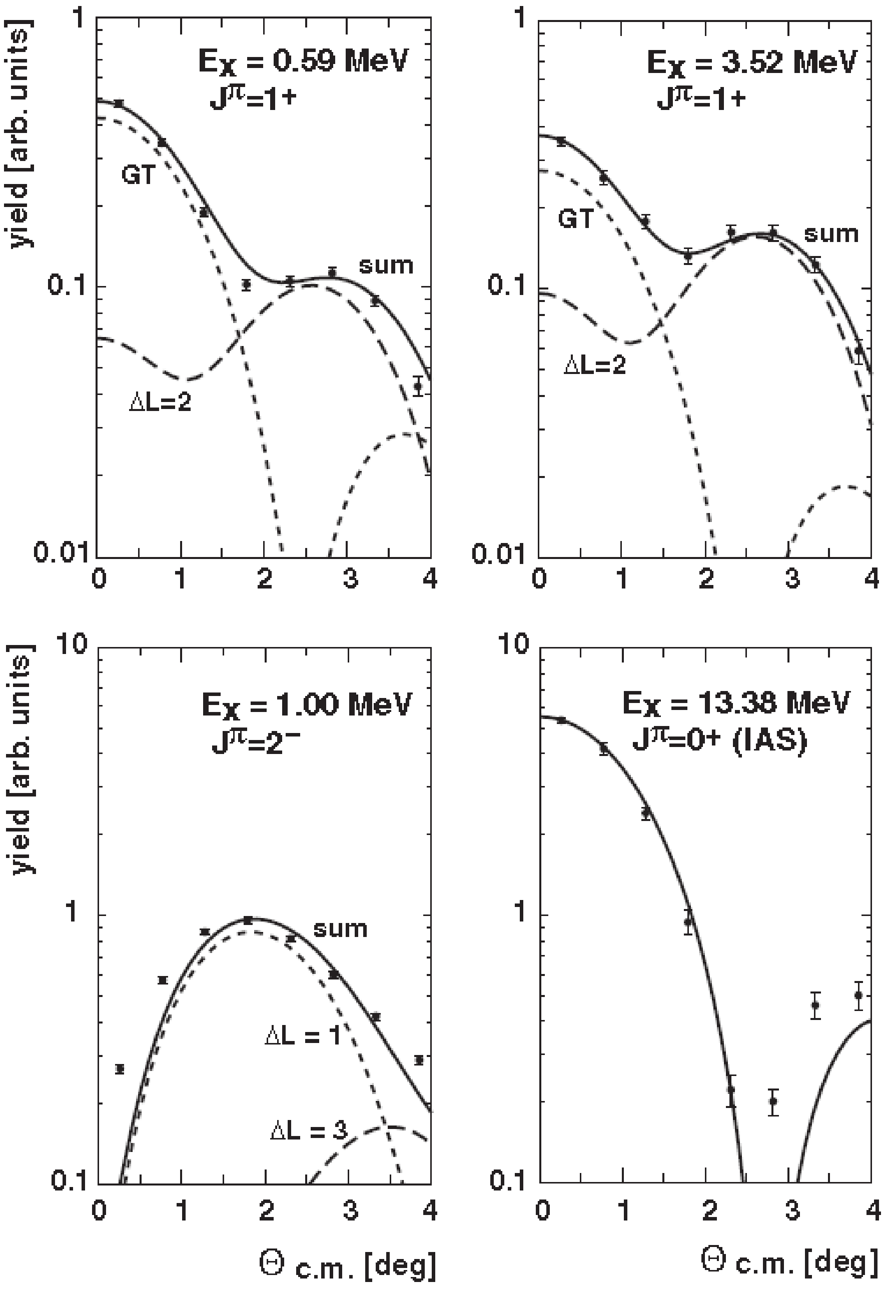
$$B_{\mathrm{exp}}(\mathrm{GT+}) = \frac{d\sigma(q=0)}{d\Omega}\cdot\left[\frac{d\hat{\sigma}(GT)}{d\Omega}\right]^{-1}$$

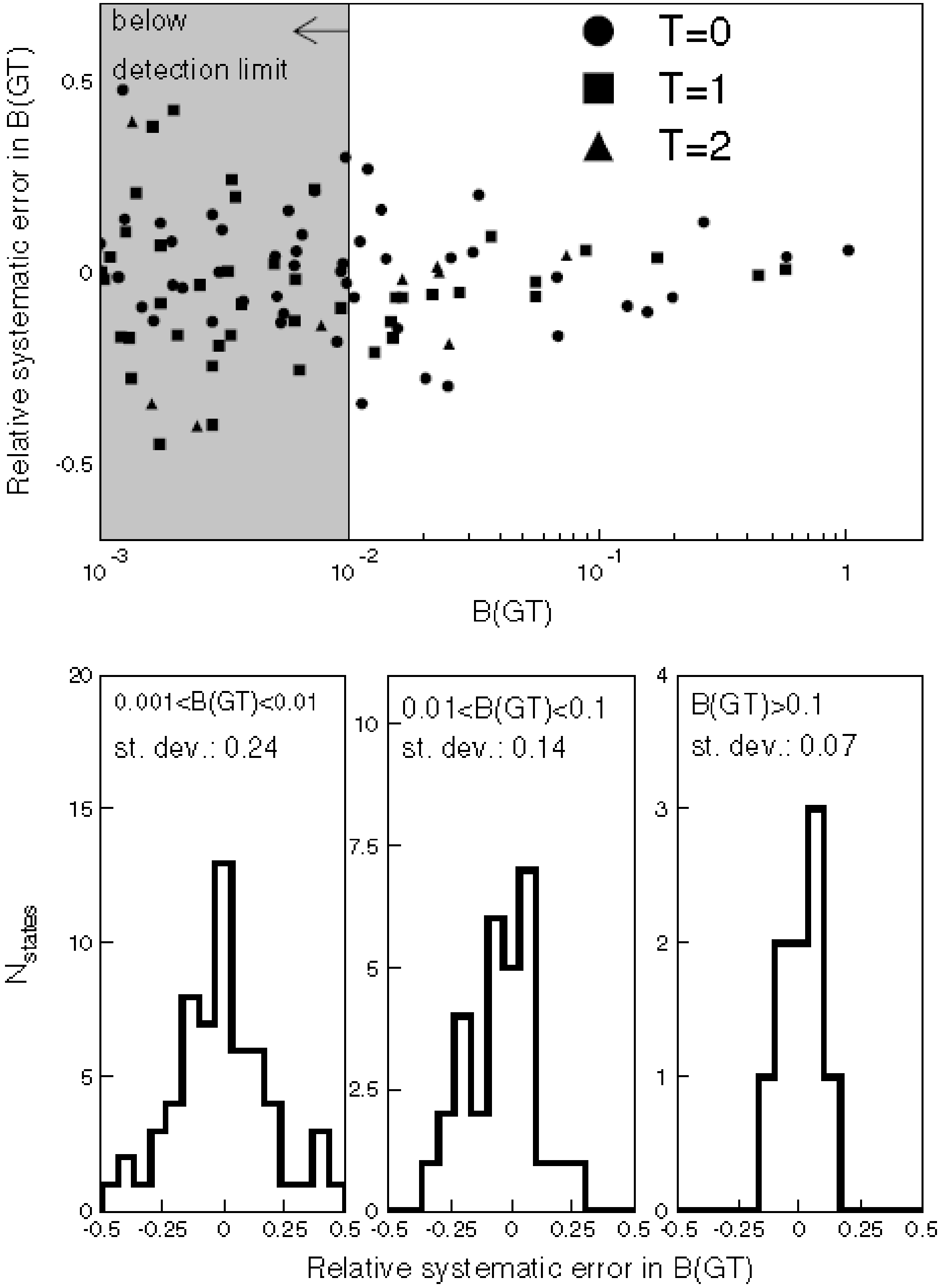
extrapolated (DWBA)

unit cross section

ΔL = 2 & ΔL = 0 incoherent

P. Puppe *et al.*, PRC 84 (2011) 051305(R)





Theoretical Study
^{26}Mg(^{3}He,t)^{26}Al

Effects of $\Delta L = 2$, $\Delta S = 1$ contributions mediated via the T_τ interaction that interfere with $\Delta L = 0$, $\Delta S = 1$ contributions to Gamow-Teller transitions.

$$\text{Rel. syst. error} = \frac{B(GT)_{DWBA} - B(GT)_{SM}}{B(GT)_{SM}}$$

R.G.T. Zegers *et al.*, PRC74 (2006) 024309

Determination of GT^+ Strength and its Astrophysical Implications

In supernova explosions, electron capture (EC) on *fp*-shell nuclei plays a dominant role during the last few days of a heavy star with $M > 10\ M_{\odot}$

Presupernova stage; deleptonization ⇒ core collapse ⇒ subsequent type IIa Supernova (SN) explosion

H.A. Bethe *et al.*, Nucl. Phys. A324 (1979) 487

Electron capture in *fp*-shell

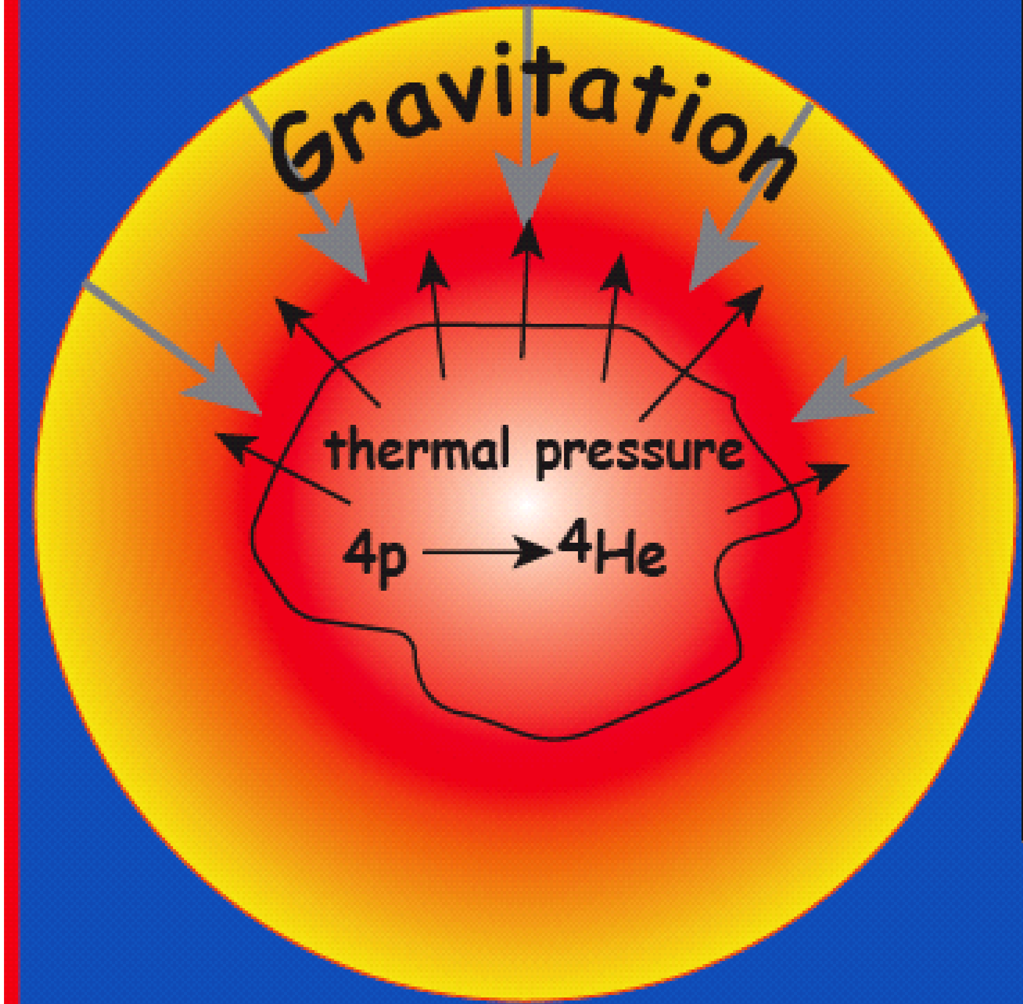
- **The rate for EC is governed by the GT$^+$ strength distribution at low excitation energy; not accessible to β-decay.**

- **Fuller, Fowler and Newman (FFN) (1982-1985); estimates of stellar rates in stellar environments using s.p. model.**

- **Caurier *et al*., Martínez-Pinedo & Langanke (1999), Otsuka *et al*. ⇒ Large shell-model calculations ⇒ marked deviations from FFN EC rate; generally smaller EC rates.**

- **Experiments and theory relied on (*n*,*p*) data (TRIUMF) which have a rather poor energy resolution.**

Nuclear processes and energy household of supernovae



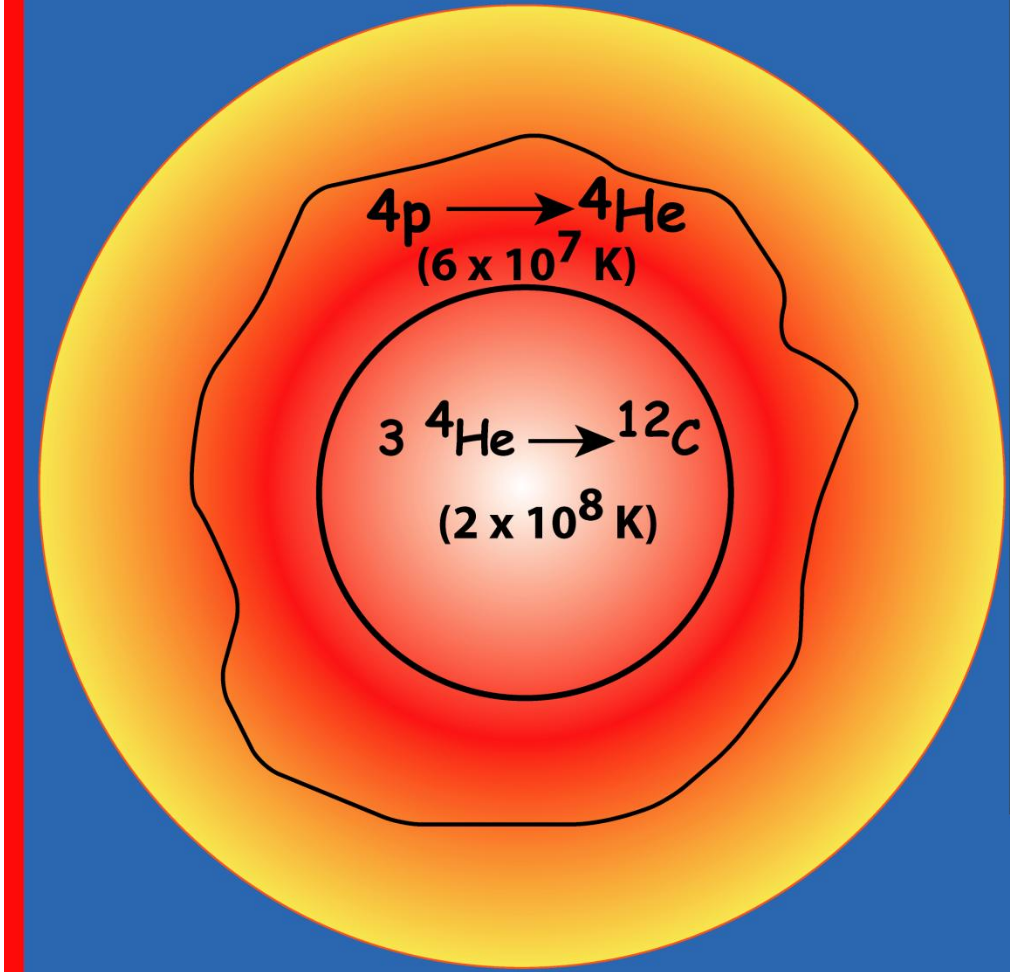
initial condition:
$M > 10\ M_\odot$

energy:
fusion $4p \rightarrow {}^4He$

at: $T \sim 10^7 - 10^8$ K

lifetime: $10^6 - 10^7$ y

after 10^6 - 10^7 y



end of H-burning

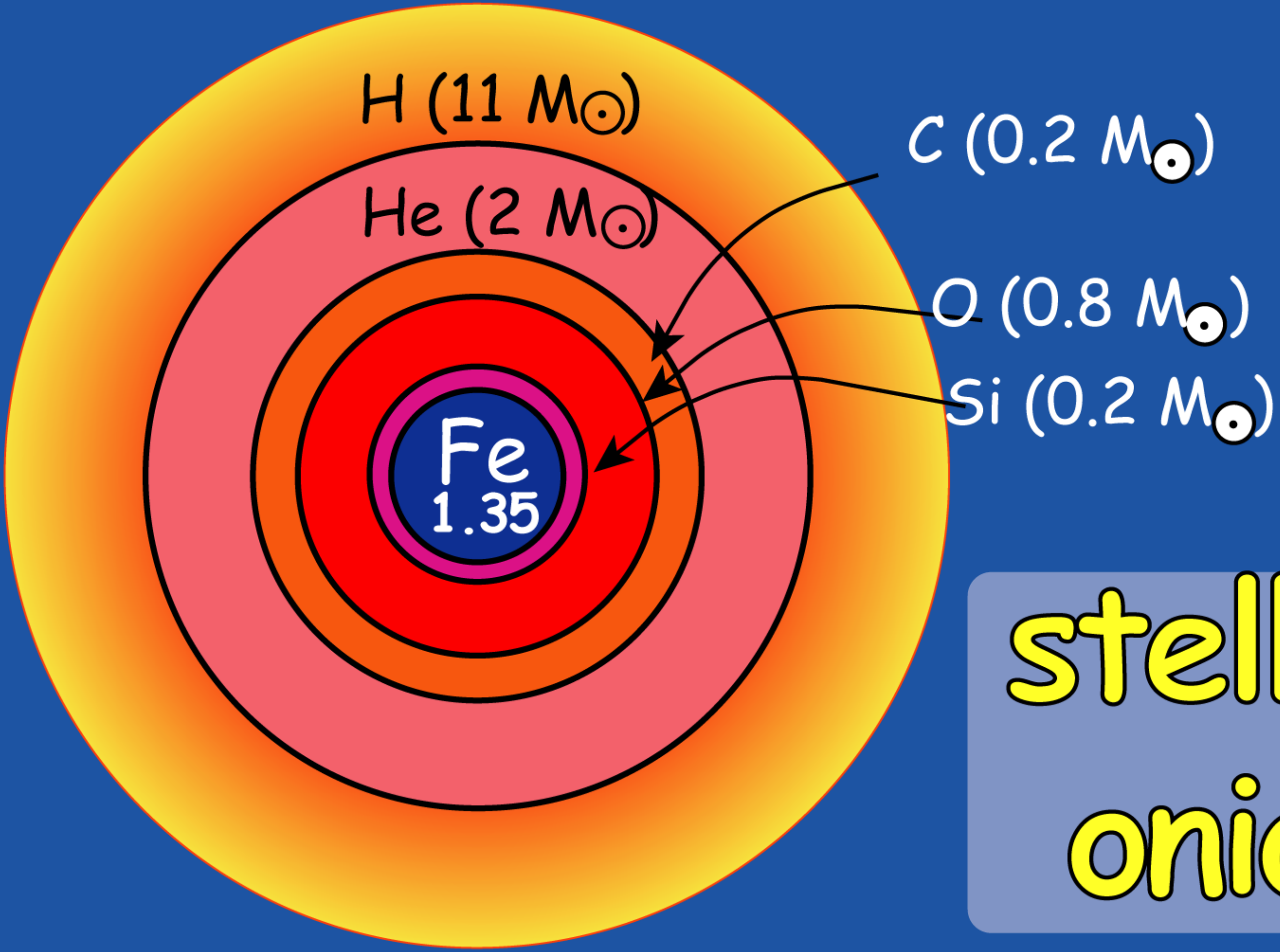
contraction of star

temperature increase

Red Giant (Super-Giant)

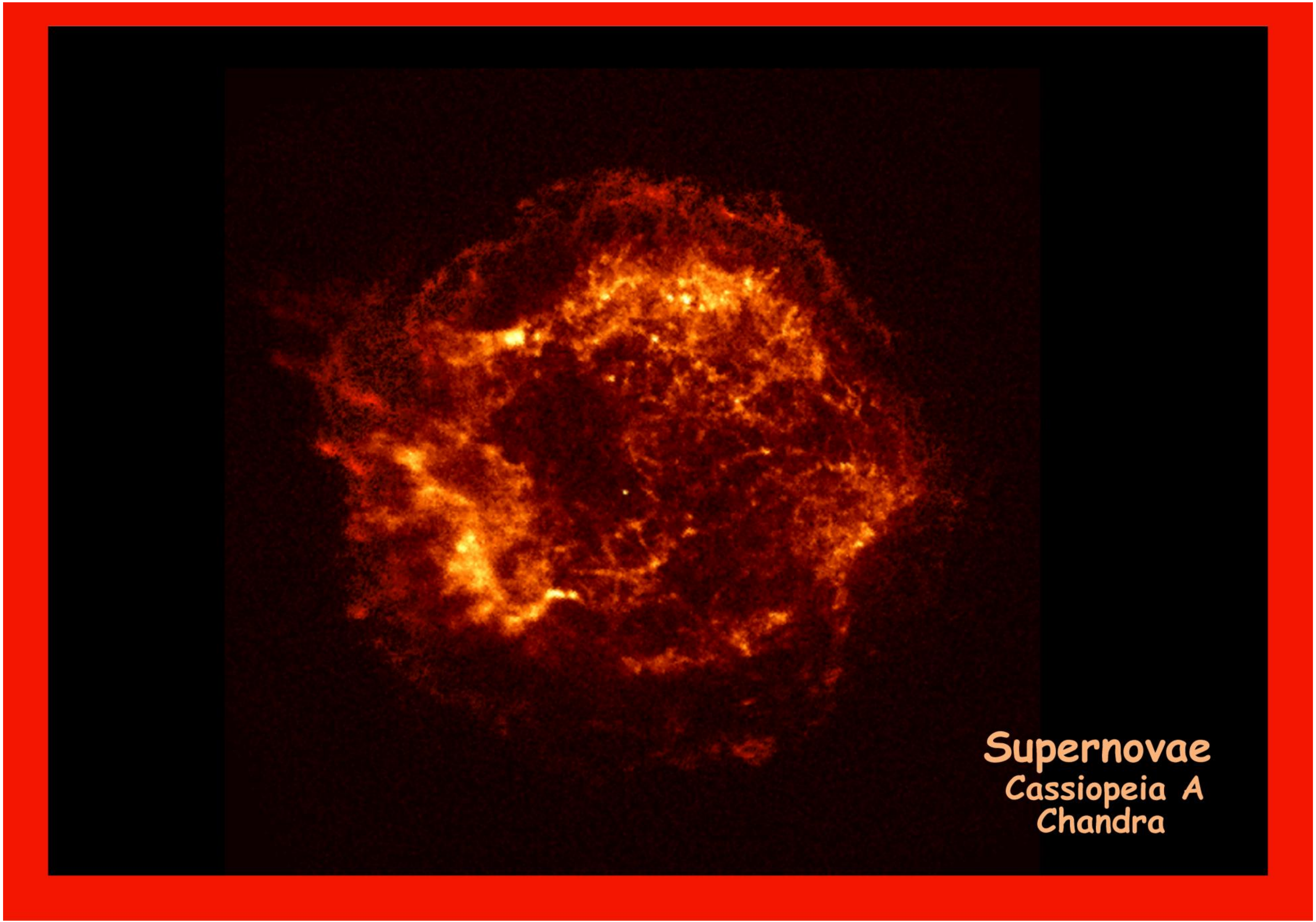
lifetime: 5×10^5 y

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



stellar onion

Determination of GT Strength is imperative



Courtesy of D. Frekers

Supernova Simulatie

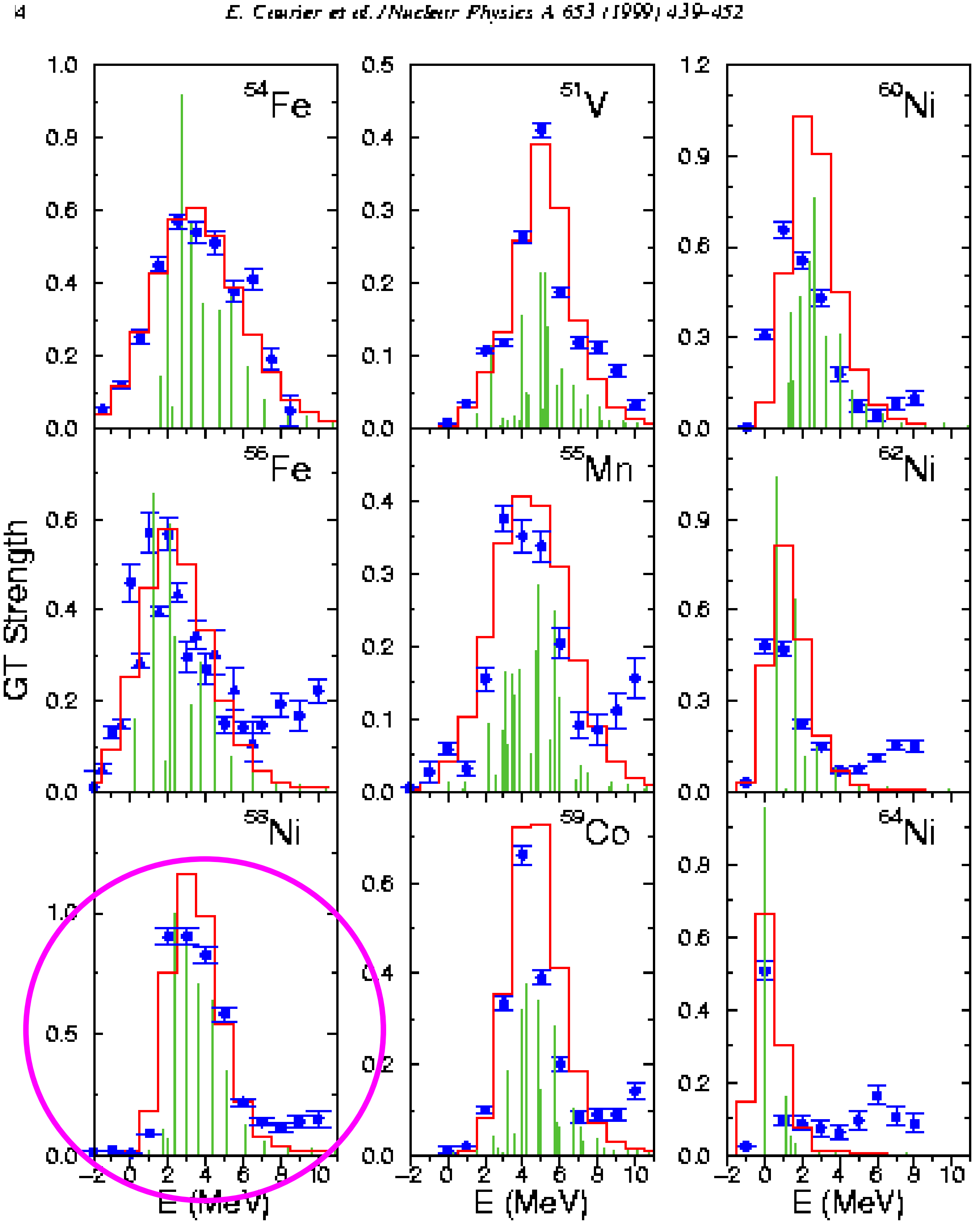
fp-shell nuclei: large scale shell model calculations

E. Caurier *et al.*
NPA 653 (1999) 439

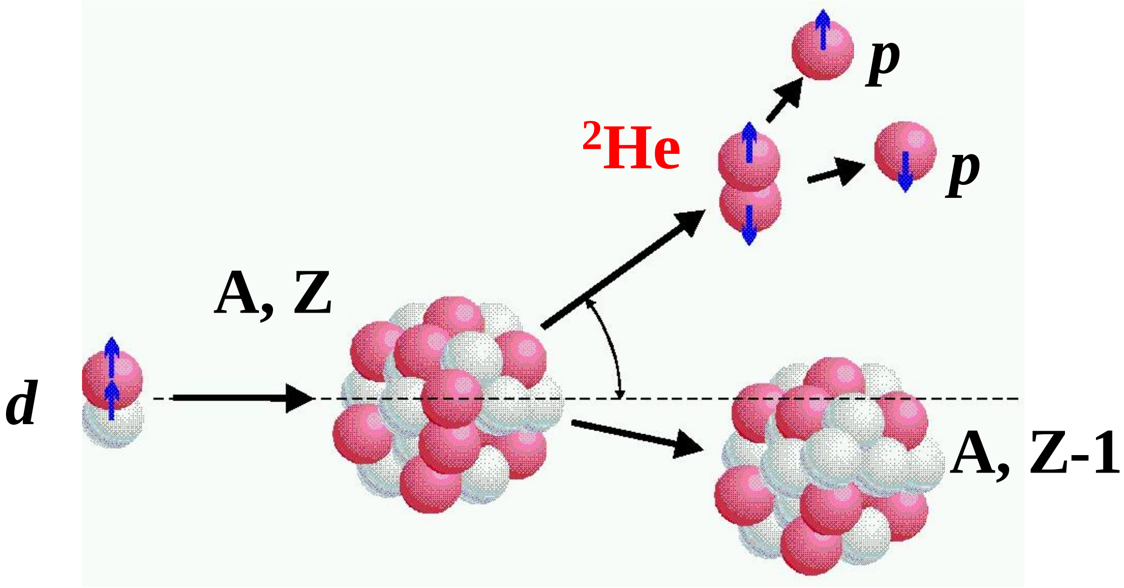
- Stellar weak reaction rates with improved reliability
- Large scale shell model (SM) calculations
- Tuned to reproduce GT$^+$ strength measured in (*n,p*)

- (*n,p*) data from TRIUMF
- GT$^+$ strength from SM
- Folded with 1 MeV energy resolution

Case study: ^{58}Ni



Exclusive excitations ΔS=ΔT=1: (*d*,^{2}He)

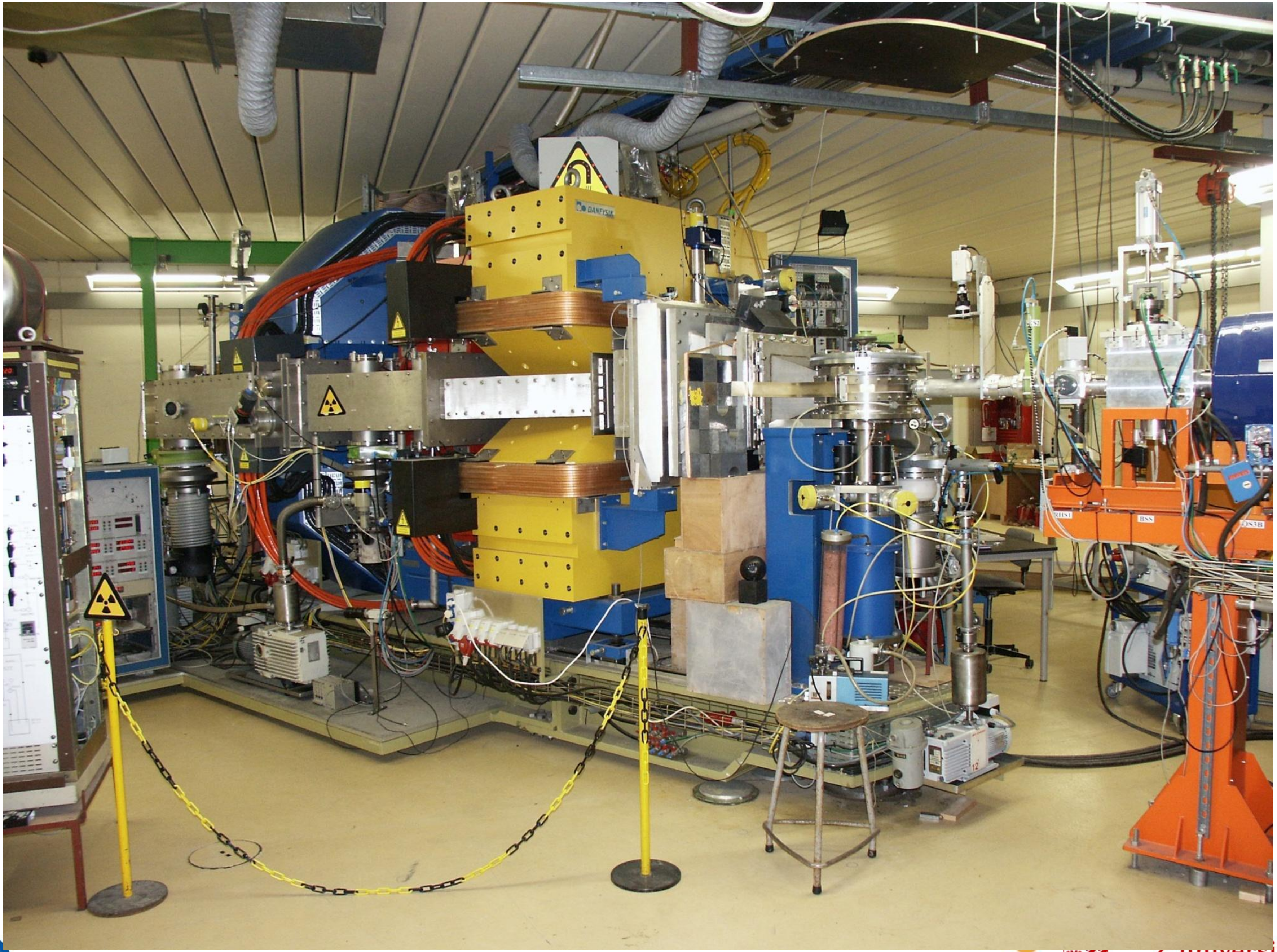


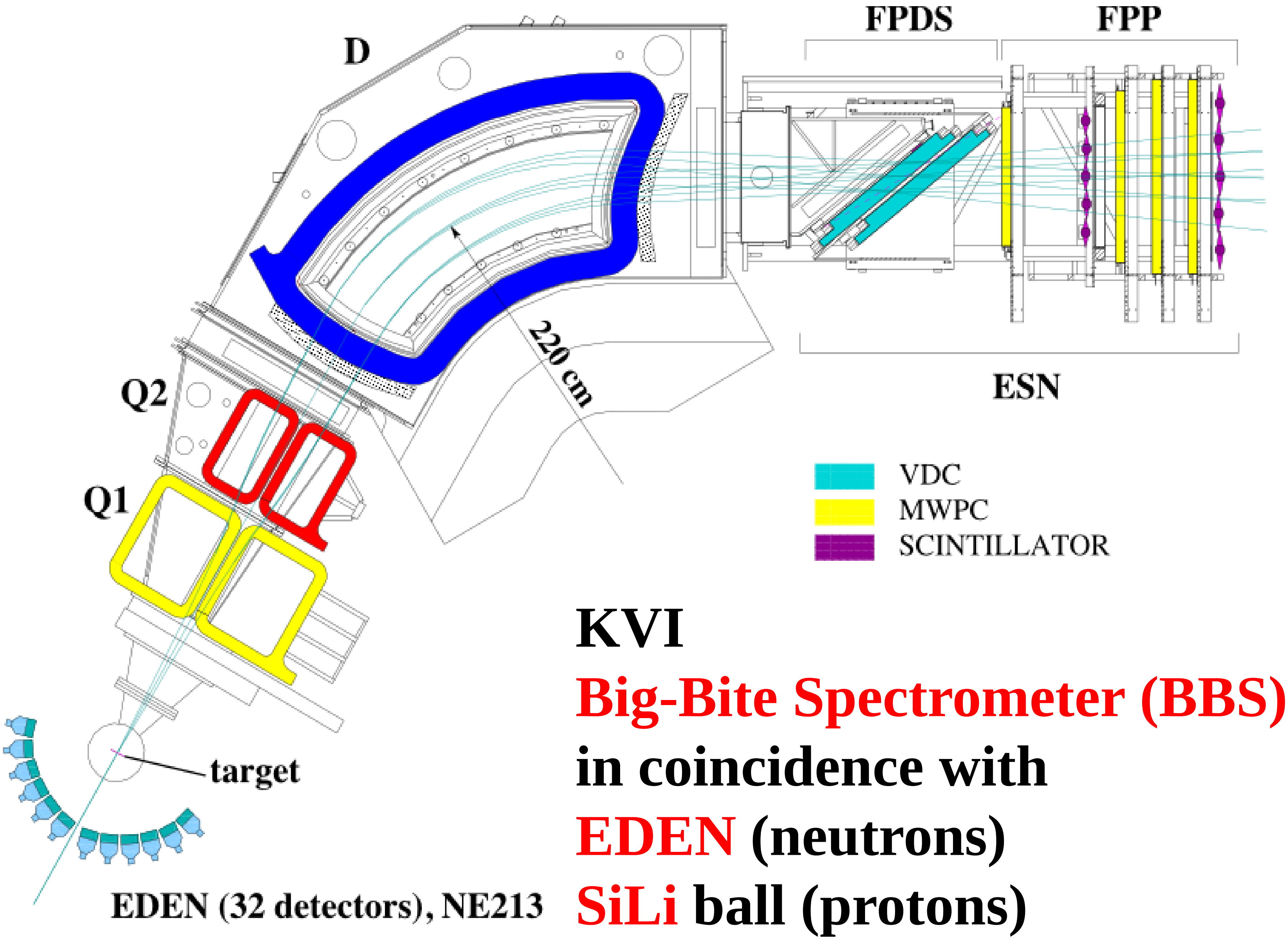
$^3S_1$ deuteron ⇒ $^1S_0$ di-proton (^{2}He)

$^1S_0$ dominates if (relative) 2-proton kinetic energy ε < 1 MeV

(*n*,*p*)-type probe with exclusive ΔS=1 character (GT$^+$ transitions)

But near 0°: tremendous background from *d*-breakup





KVI

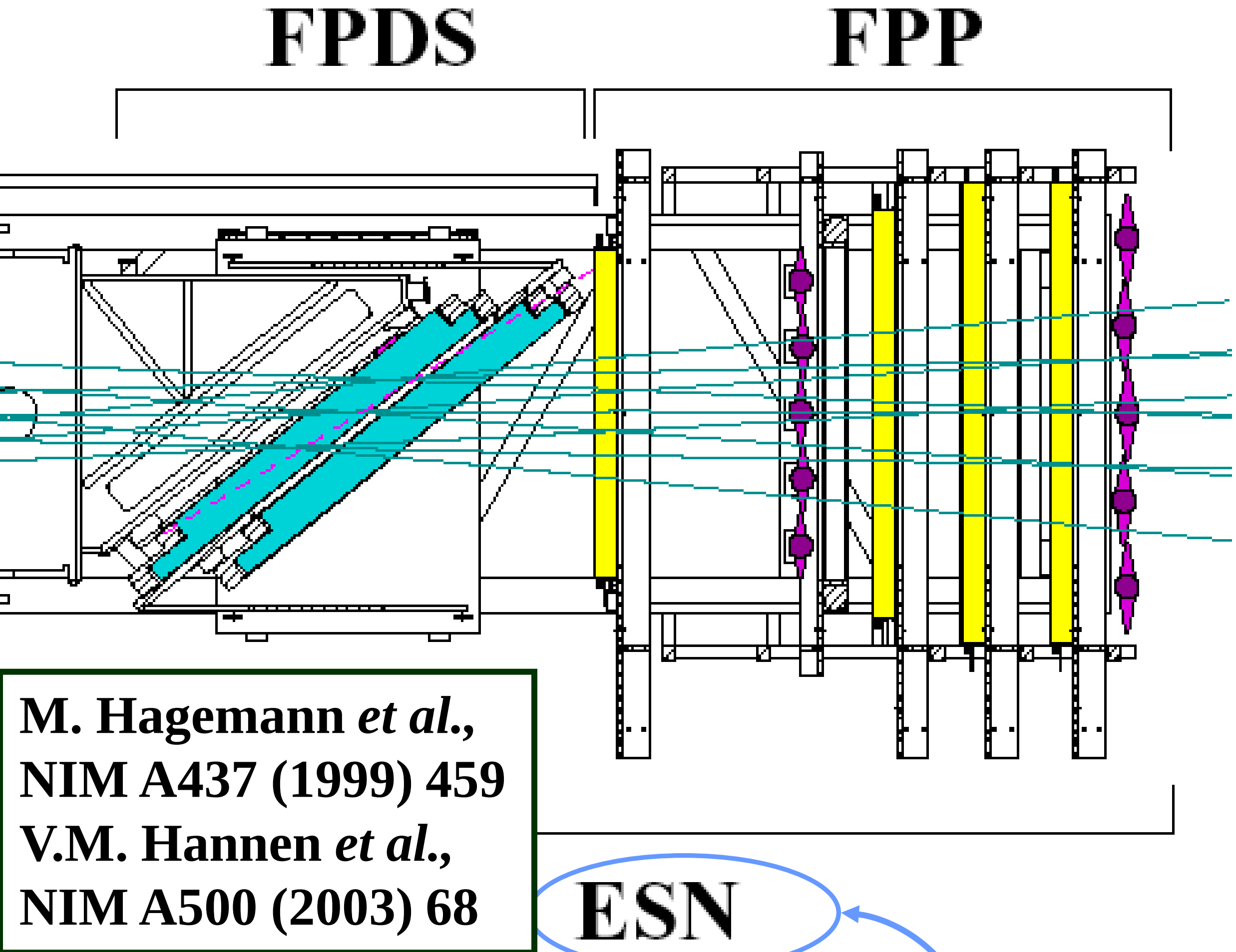
Big-Bite Spectrometer (BBS)

in coincidence with

EDEN (neutrons)

SiLi ball (protons)

Setup: ESN detector



M. Hagemann *et al.*,
NIM A437 (1999) 459
V.M. Hannen *et al.*,
NIM A500 (2003) 68

Focal-Plane Detector:
(FPDS): 2 VDCs

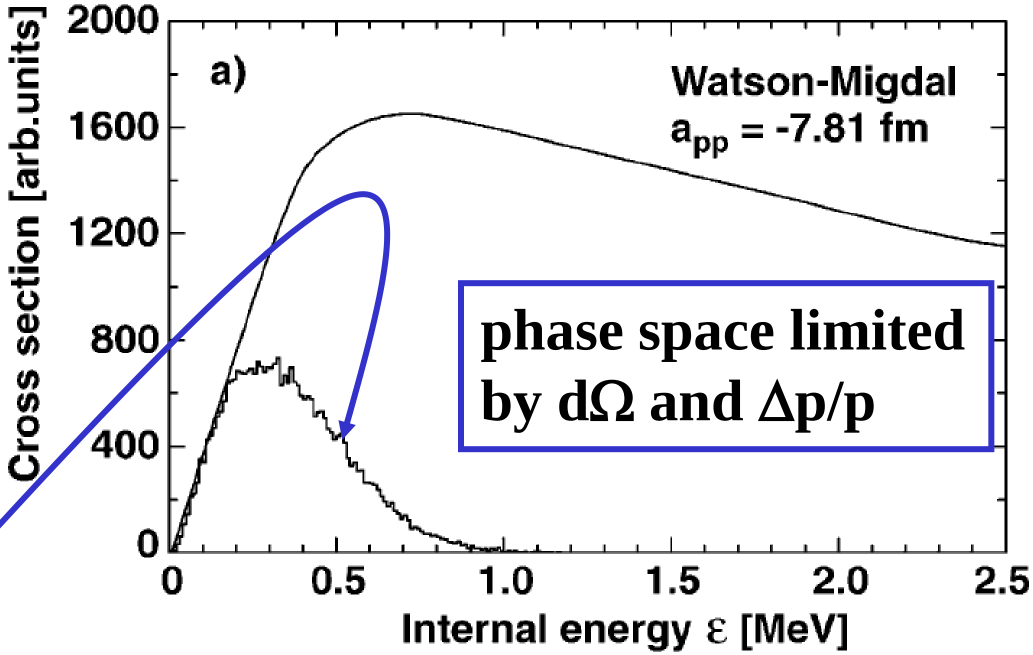
Focal-Plane Polarimeter:
(FPP): 4 MWPCs &
graphite analyzer

features a.o.:
fast readout
VDC readout pipeline
TDC's
VDC decoding using
imaging techniques
DSP based online analysis

Bari, Darmstadt, Gent, Iserlohn, KVI, Milano, Münster, TRIUMF

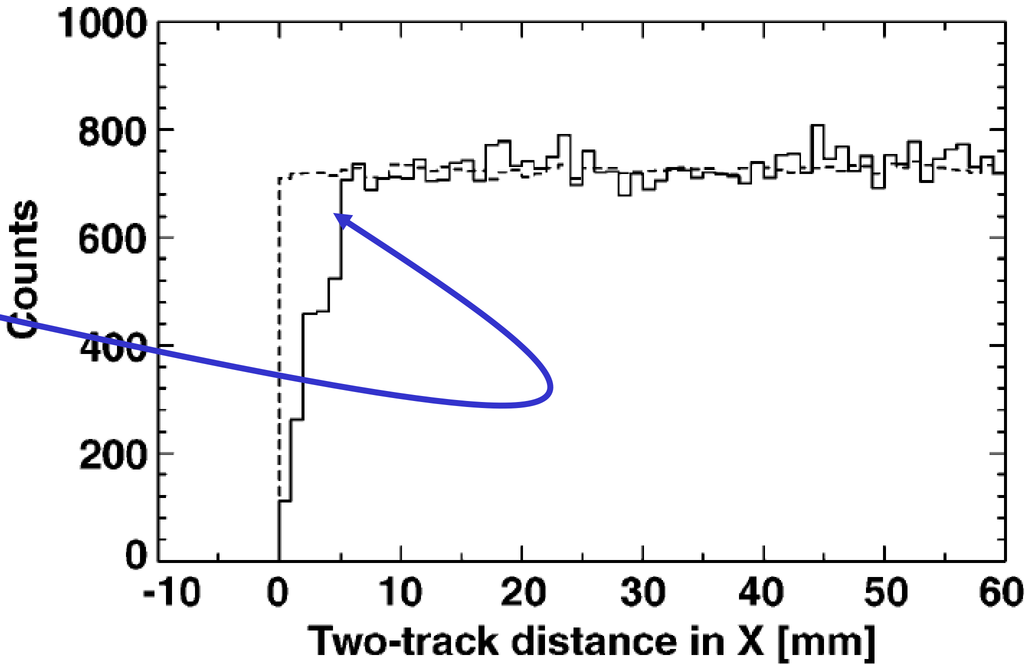
- **Good double tracking**
- **Use VDC information**
- **Good phase-space coverage for small relative proton energies**

S. Rakers *et al.*,
NIM A481 (2002) 253



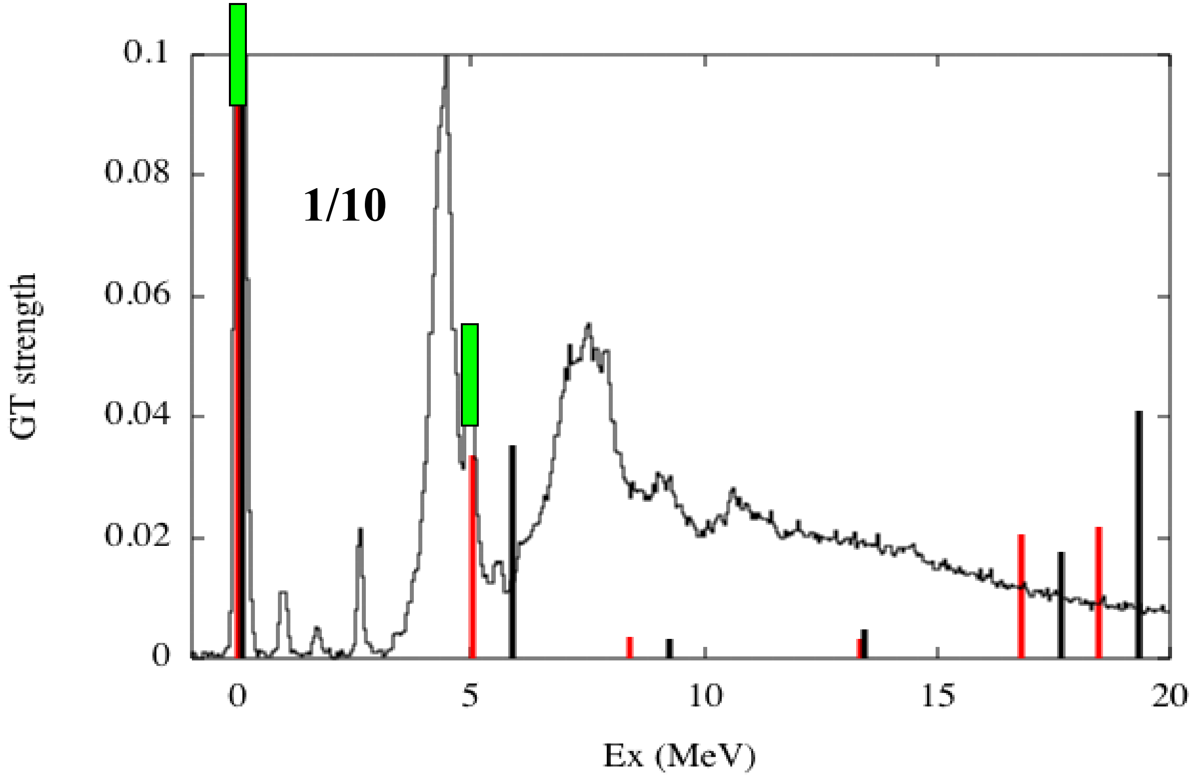
phase space limited by dΩ and Δp/p

measured



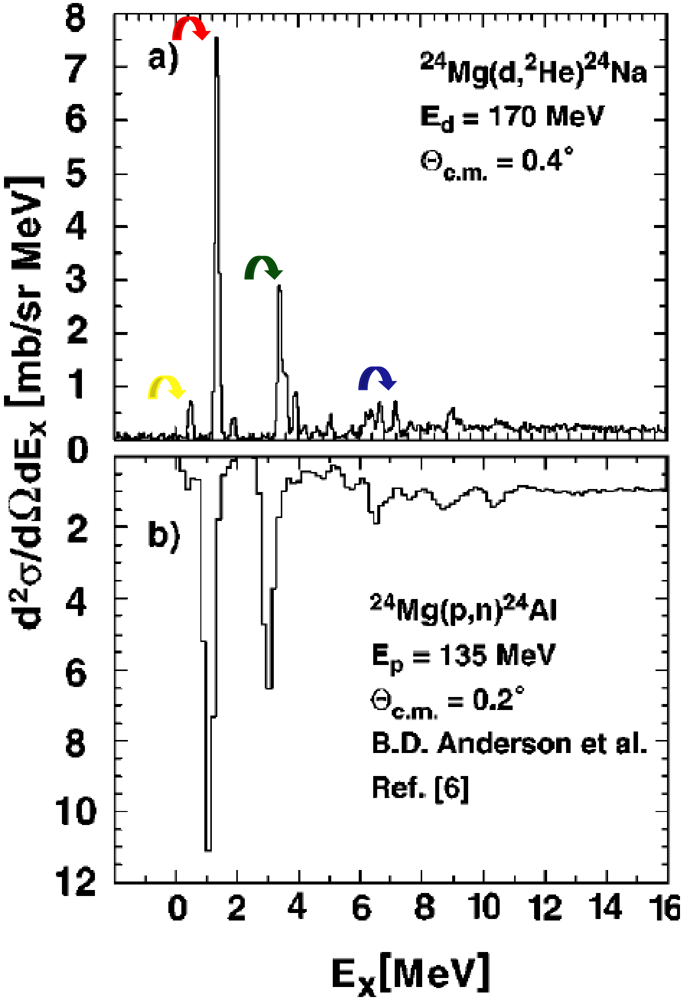
Exclusive measurement of ΔS= ΔT =1 strength: $^{12}\mathrm{C}(d,{}^{2}\mathrm{He})^{12}\mathrm{B}$

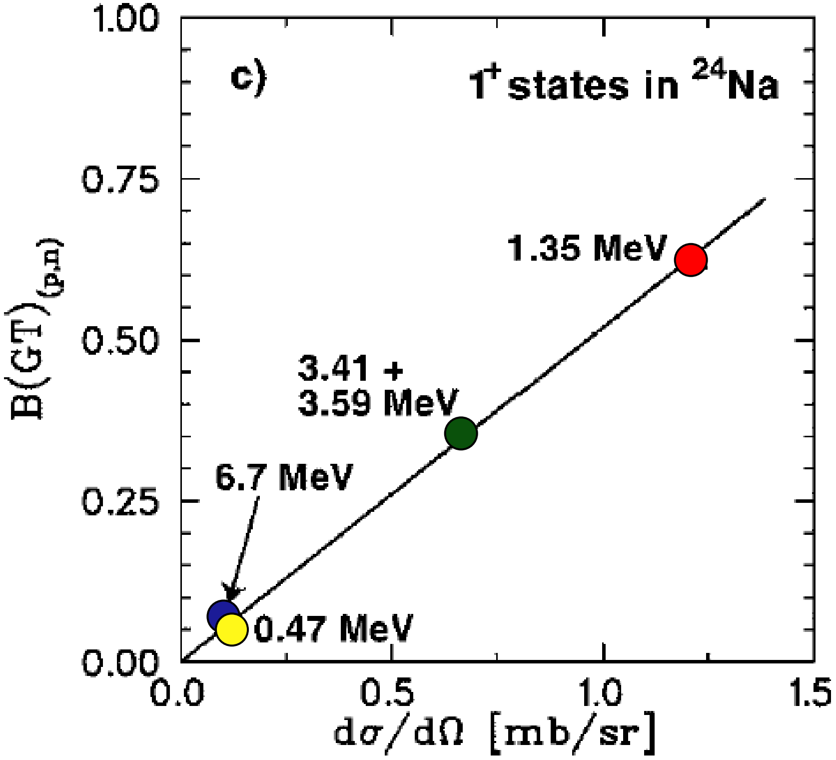
E_d = 171 MeV, θ = 0°



- **Shell-model calculations $4\,\hbar\omega$ & $6\,\hbar\omega$ (G. Martínez-Pinedo)**
- **B (GT$^+$) (S. Rakers)** 🟩

(*p*,*n*) vs. (*d*,^{2}He): Calibration

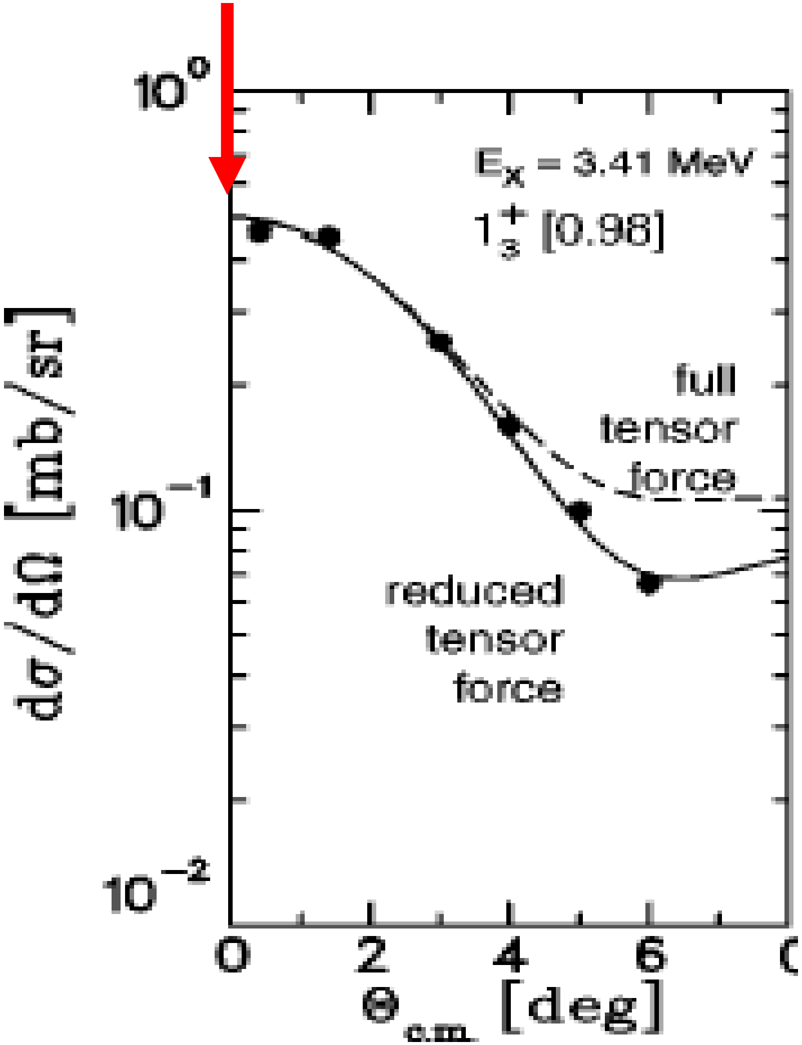




Self-conjugate ^{24}Mg

S. Rakers *et al.*
PRC 65 (2002) 044323

Experimental cross section and GT strength



$$B_{exp}(GT+) = \frac{d\sigma(q=0)}{d\Omega} \cdot \left[\frac{d\sigma(GT)}{d\Omega}\right]^{-1}$$

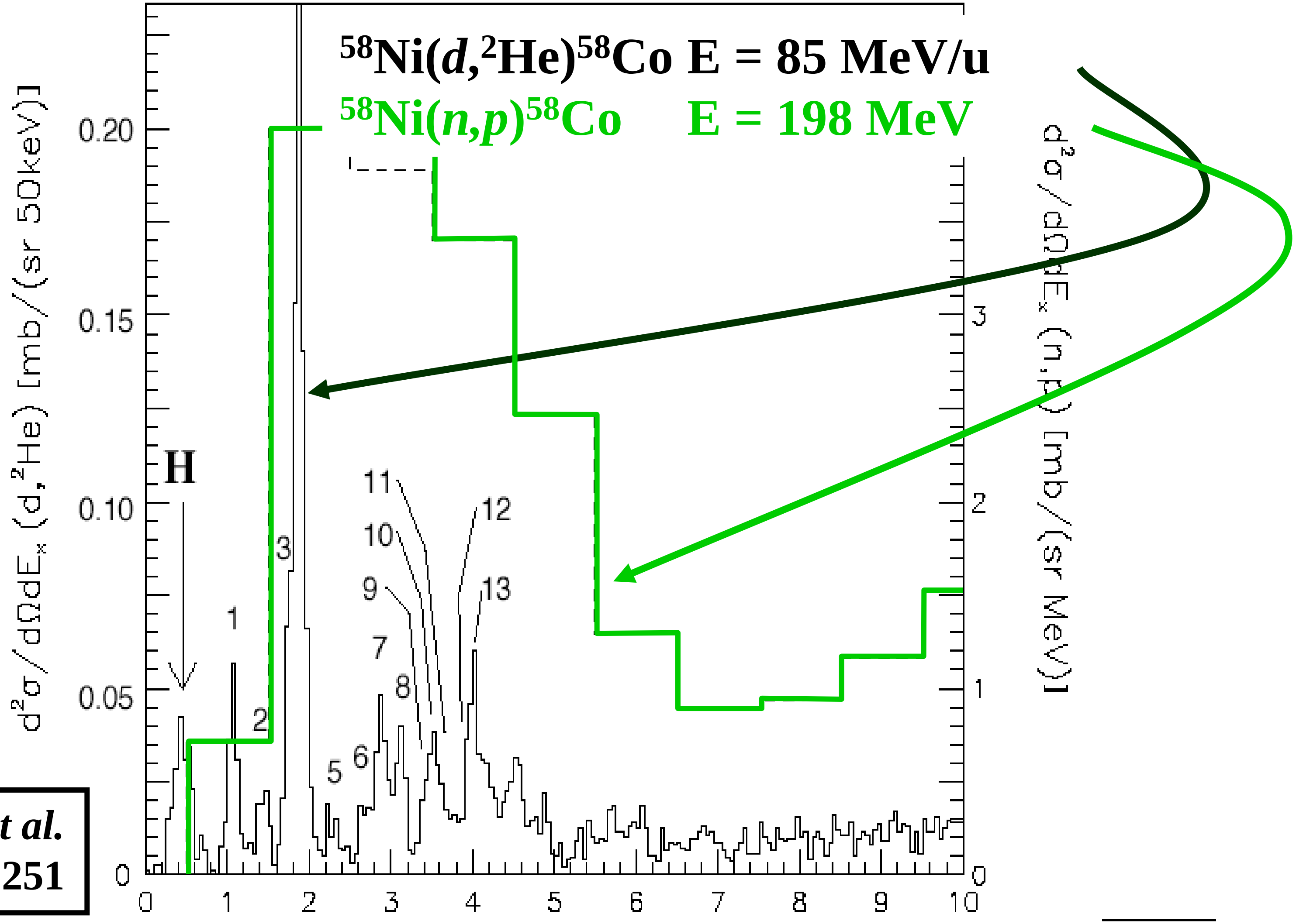
extrapolated (DWBA)

unit cross section

GT Strength in ^{12}B and ^{24}Na from (d,^{2}He) reaction

Target	Reference data		Present data			
	E_x	$B(GT_-)$	E_x	$d\sigma/d\Omega(q=0)$	$\sigma(L=0)/\sigma(\tau o\tau)$	$B(GT_+)$
	[MeV]		[MeV]	[mb/sr]	(q=0)	(C=0.267)
^{12}B	0.00	0.998	0.00	2.580±0.138	0.988	0.930±0.050
			5.00	0.138±0.010	0.976	0.050±0.004
^{24}Na	0.44	0.050	0.47	0.138±0.012	0.821	0.049±0.004
	1.07	0.613	1.35	1.563±0.085	0.948	0.654±0.035
	1.58	0.020	1.89	0.087±0.026	0.649	0.025±0.008
	2.98	0.362	3.41	0.667±0.039	0.980	0.290±0.016
			3.59	0.266±0.018	0.806	0.095±0.006
	3.33	0.059	3.92	0.193±0.058	0.809	0.070±0.022
	4.69	0.015	5.06	0.093±0.027	0.561	0.024±0.007
			6.24	0.086±0.026	0.818	0.031±0.010
	6.46	0.068	6.70	0.161±0.012	0.972	0.071±0.005
	6.87	0.029	7.20	0.173±0.013	0.642	0.050±0.004

(d,^{2}He) as GT$^+$ probe in *fp*-shell nuclei

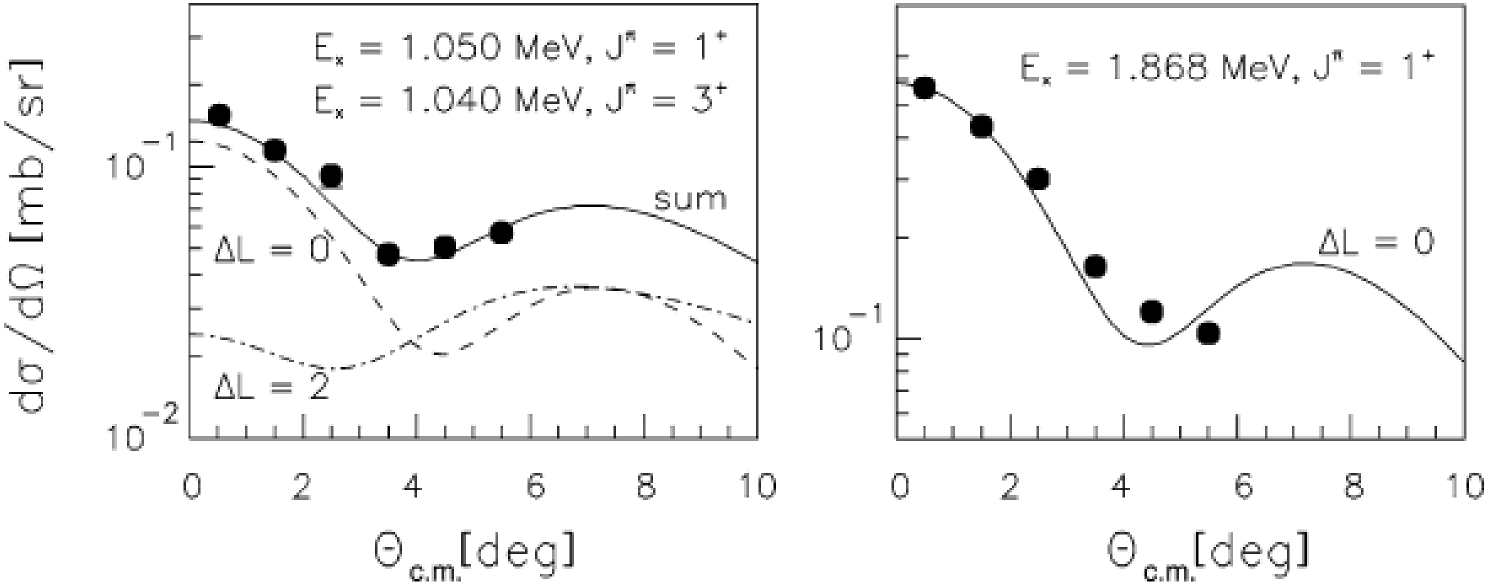


^{58}Ni(d,^{2}He)^{58}Co E = 85 MeV/u

^{58}Ni(n,p)^{58}Co E = 198 MeV

M. Hagemann *et al.*
PLB 579 (2004) 251

^{58}Ni(d,^{2}He)^{58}Co E=85 MeV/u

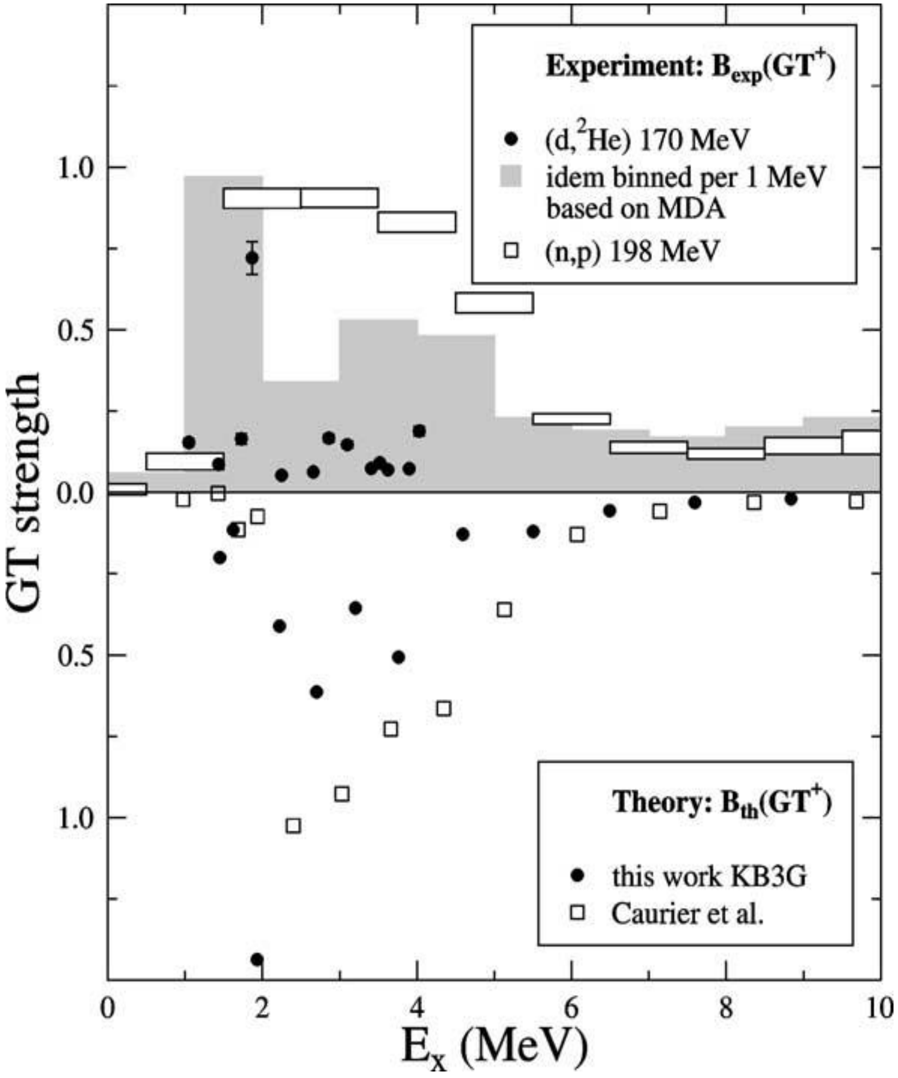


$$\mathbf{B}_{\mathrm{exp}}(\mathrm{GT+}) = \frac{\mathrm{d}\sigma(q=0)}{d\Omega}\cdot\left[\frac{d\hat{\sigma}(GT)}{d\Omega}\right]^{-1}$$

GT Strength in ^{58}Co from (d,^{2}He) reaction

E_x	dσ/dσ(0.5°)	σ(L=0)/σ(τοτ)	B(GT+)
[MeV]	[mb/sr]		
1.050	0.159±0.009	0.88	0.15±0.01
1.435	0.078±0.006	1.00	0.09±0.01
1.729	0.148±0.014	1.00	0.16±0.02
1.868	0.648±0.020	1.00	0.72±0.05
2.249	0.047±0.004	1.00	0.05±0.01
2.660	0.057±0.005	0.96	0.06±0.01
2.860	0.145±0.009	0.99	0.17±0.01
3.100	0.126±0.008	0.99	0.15±0.01
3.410	0.065±0.007	0.96	0.07±0.01
3.520	0.080±0.009	0.95	0.09±0.01
3.625	0.067±0.007	0.87	0.07±0.01
3.900	0.062±0.006	0.97	0.07±0.01
4.030	0.155±0.010	1.00	0.19±0.01
4.05-5.00	0.381±0.061		0.49±0.09

GT$^+$ strength: comparison (*n*,*p*), (*d*,^{2}He) & theory



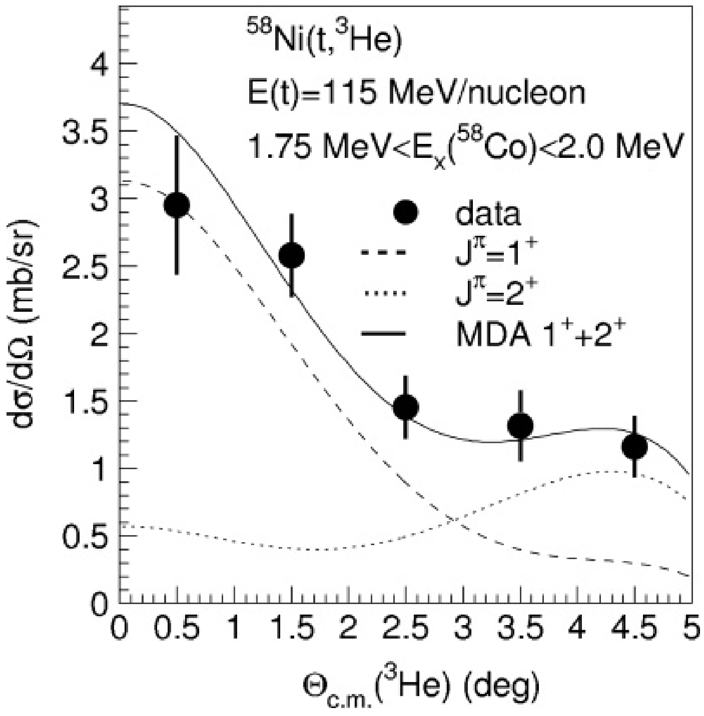
Up to 4 MeV excitation:

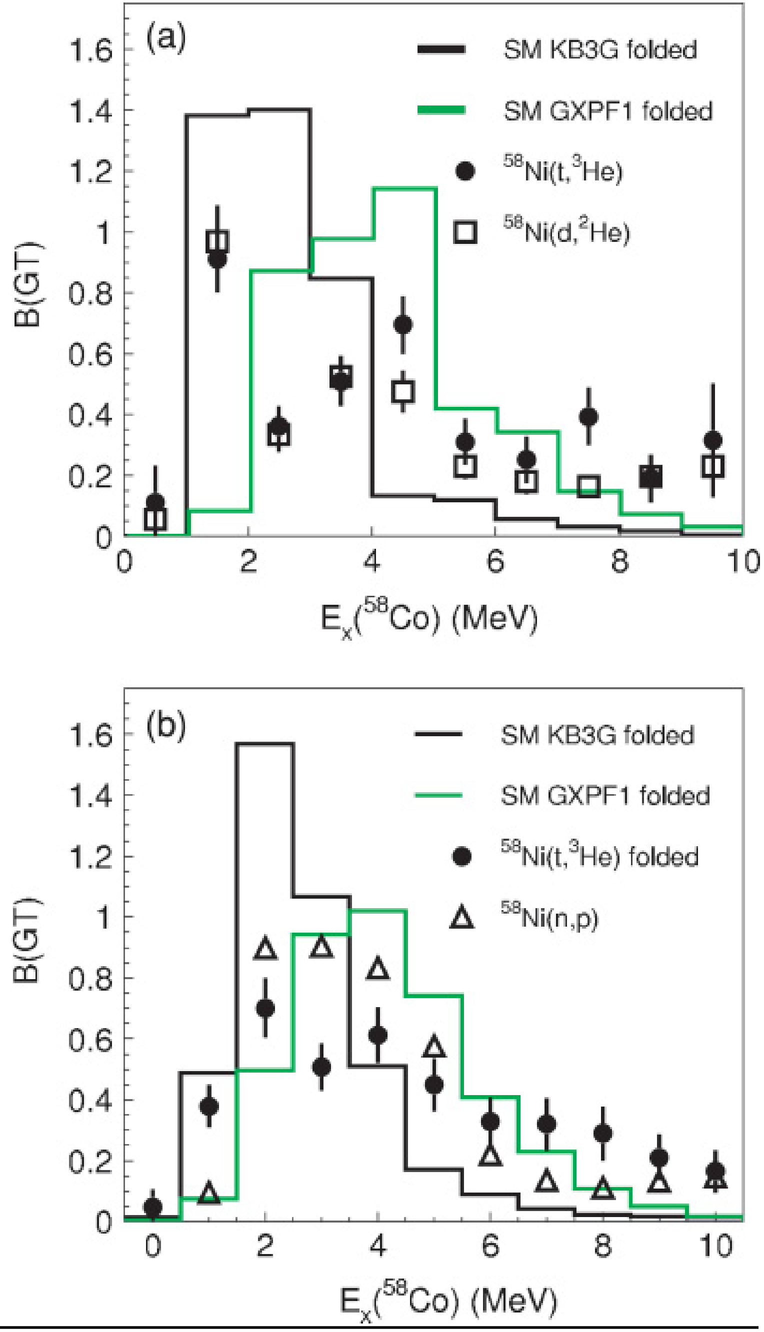
13 GT transitions measured (*d*,^{2}He)

Strength re-binned in 1 MeV bins

Significant differences

Updated shell model calculations by Martínez-Pinedo/Langanke using KB3G interaction





^{58}Ni(t,^{3}He)^{56}Co

Et = 115 MeV/u

Resolution = 250 keV

A.L. Cole *et al.*, PRC74 (2006) 034333

Electron capture rate

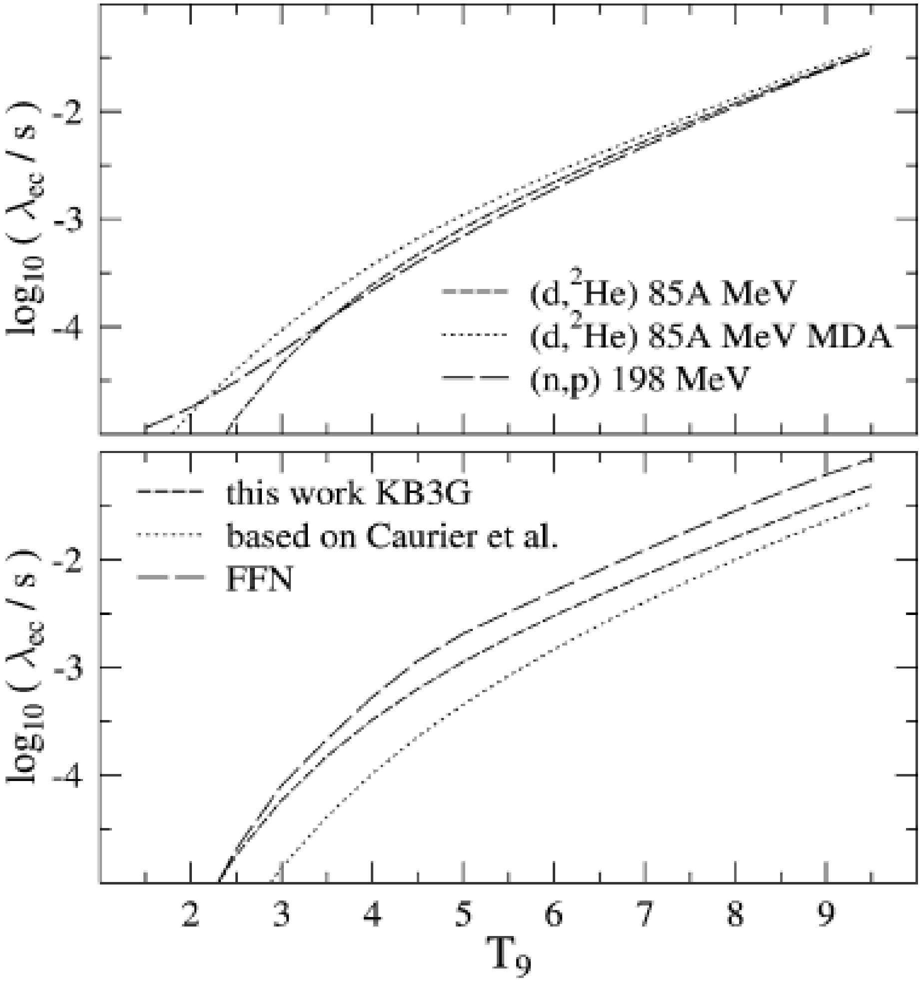
$$\lambda_{ec} \approx \sum_i B_i(GT) \int_{\omega_l}^{\infty} \omega p \left(Q_i + \omega\right)^2 F(Z,\omega) S_e(\omega,T) d\omega$$

With

- ***$B_i(GT)$*** **Gamow-Teller strength distribution**
- ***ω*** **and** ***p*** **energy and momentum of electrons**
- ***$F(Z,\omega)$*** **is the relativistic Coulomb barrier factor**
- ***$S_e(\omega,T)$*** **Fermi-Dirac distribution electron gas at temperature** ***T***

e^--capture rates using experimental strengths

(Martínez-Pinedo, Langanke)



Evolution of core of 25 $M_\odot$ star. Conditions following silicon depletion.

$T_9 = 4.05$

$\rho = 3.18\times10^7$ g/cm^3

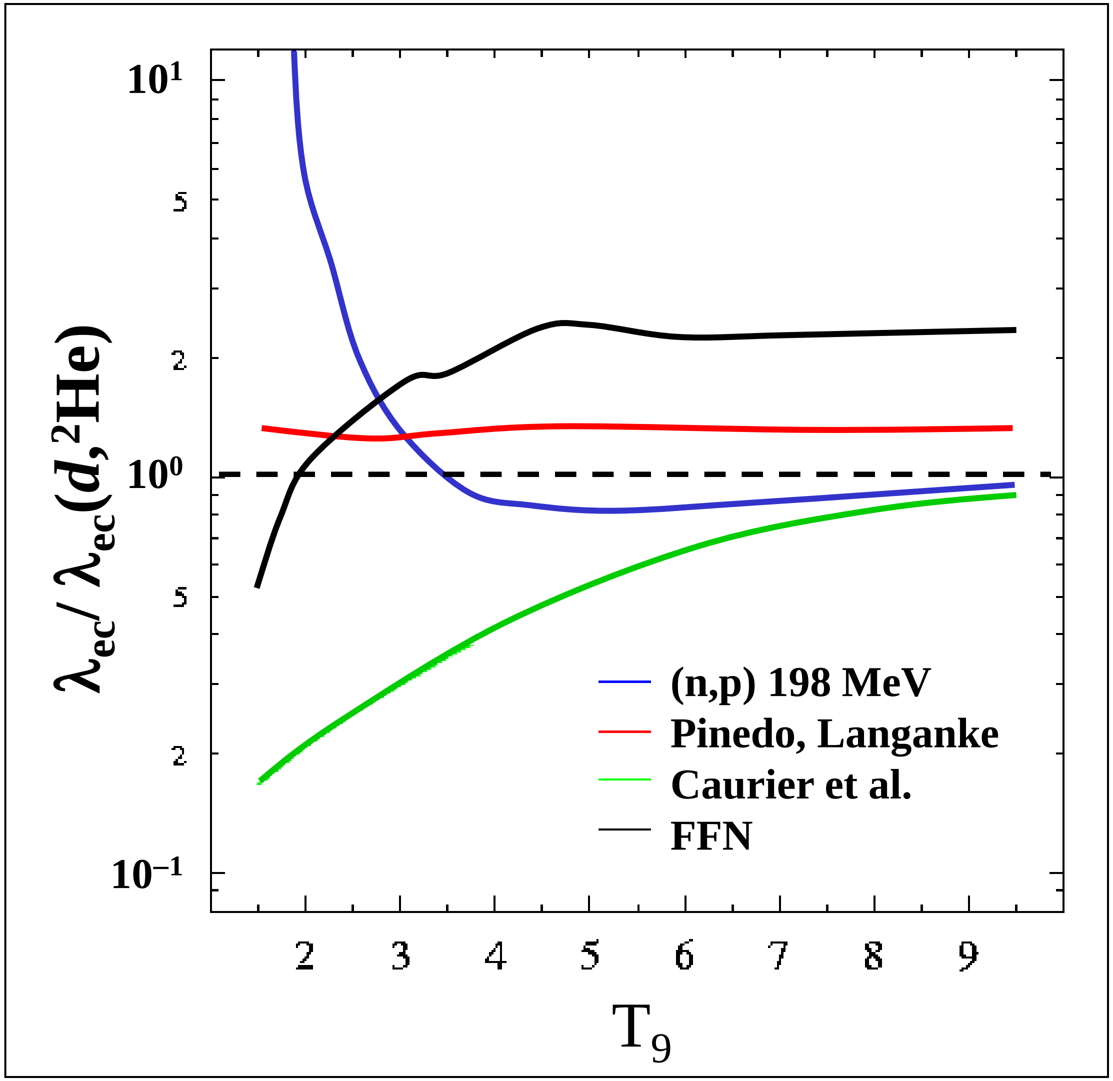
$Y_e = 0.48$

[Heger *et al*., Astrophys. J. 560 (2001) 307]

Calculate EC rates as function of T_9 for GT transitions from $^{58}Ni_{g.s.}$

Strength deviations at low excitation ⇒ rates deviation at low T

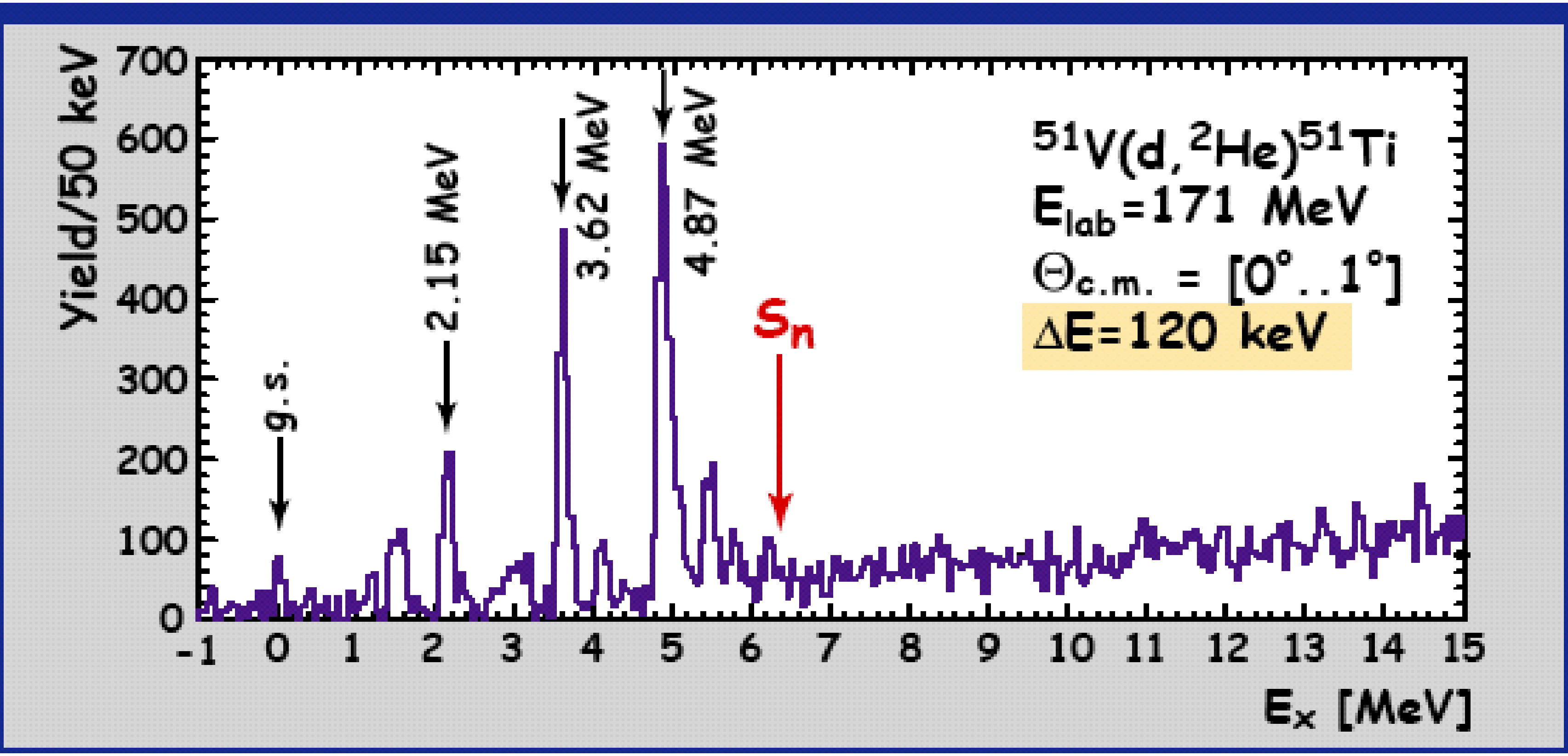
^{58}Ni: comparison of *e*-capture rates theory/experiment



- **Influence of GT strength distribution on calculated capture rate is dramatic, especially at low temperatures**
- **rates vary up to a factor 5-6**
- **FFN not too far off**
- **large scale shell-model calculations fail at low T**
- **calculations with improved residual interaction (KB3G) in reasonable agreement**

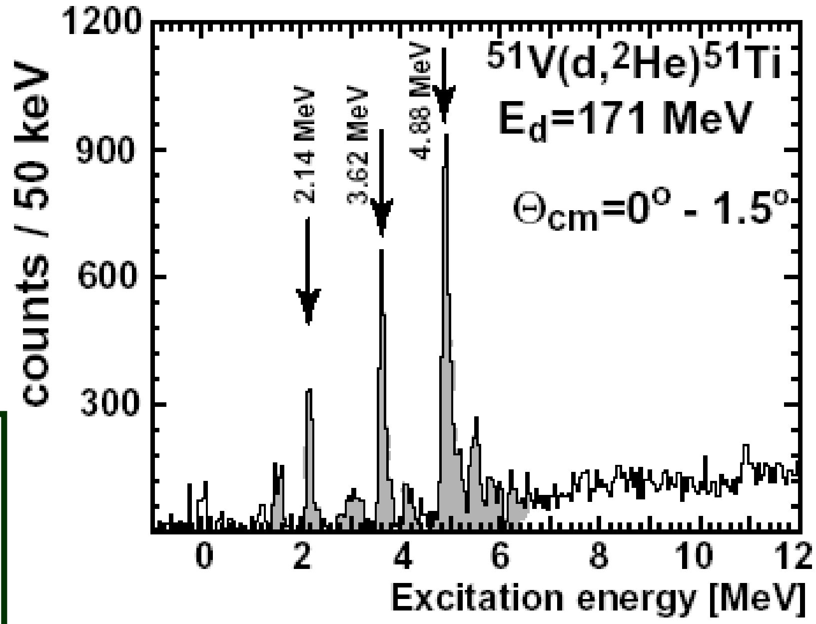
^{51}V(d,^{2}He)^{51}Ti: B(GT^{+}) for proton-odd *fp*-shell nucleus

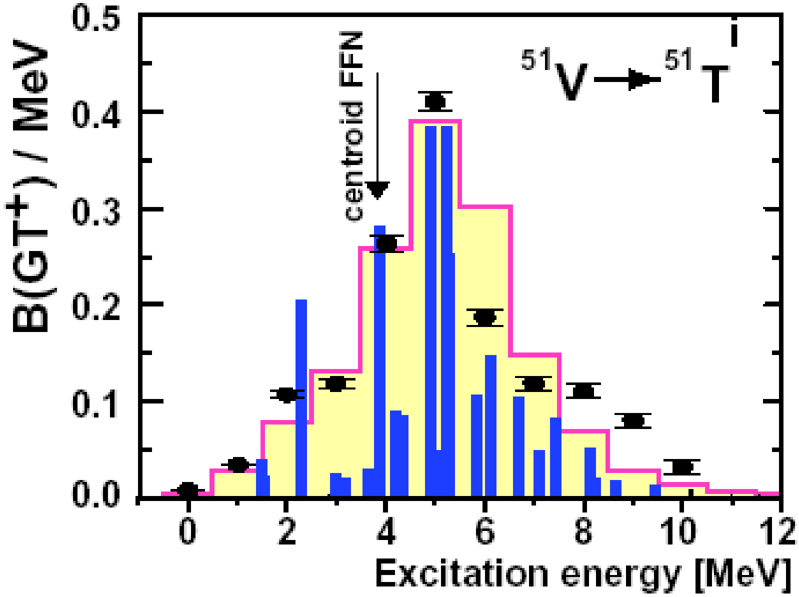
^{51}V g.s. ($J^{\pi}=7/2^{-}$, T=5/2) $\Rightarrow$ ^{51}Ti ($J^{\pi}=5/2^{-}, 7/2^{-}, 9/2^{-}$, T=7/2)
Independent single-particle model (FFN): E_x(GTR)=3.83 MeV



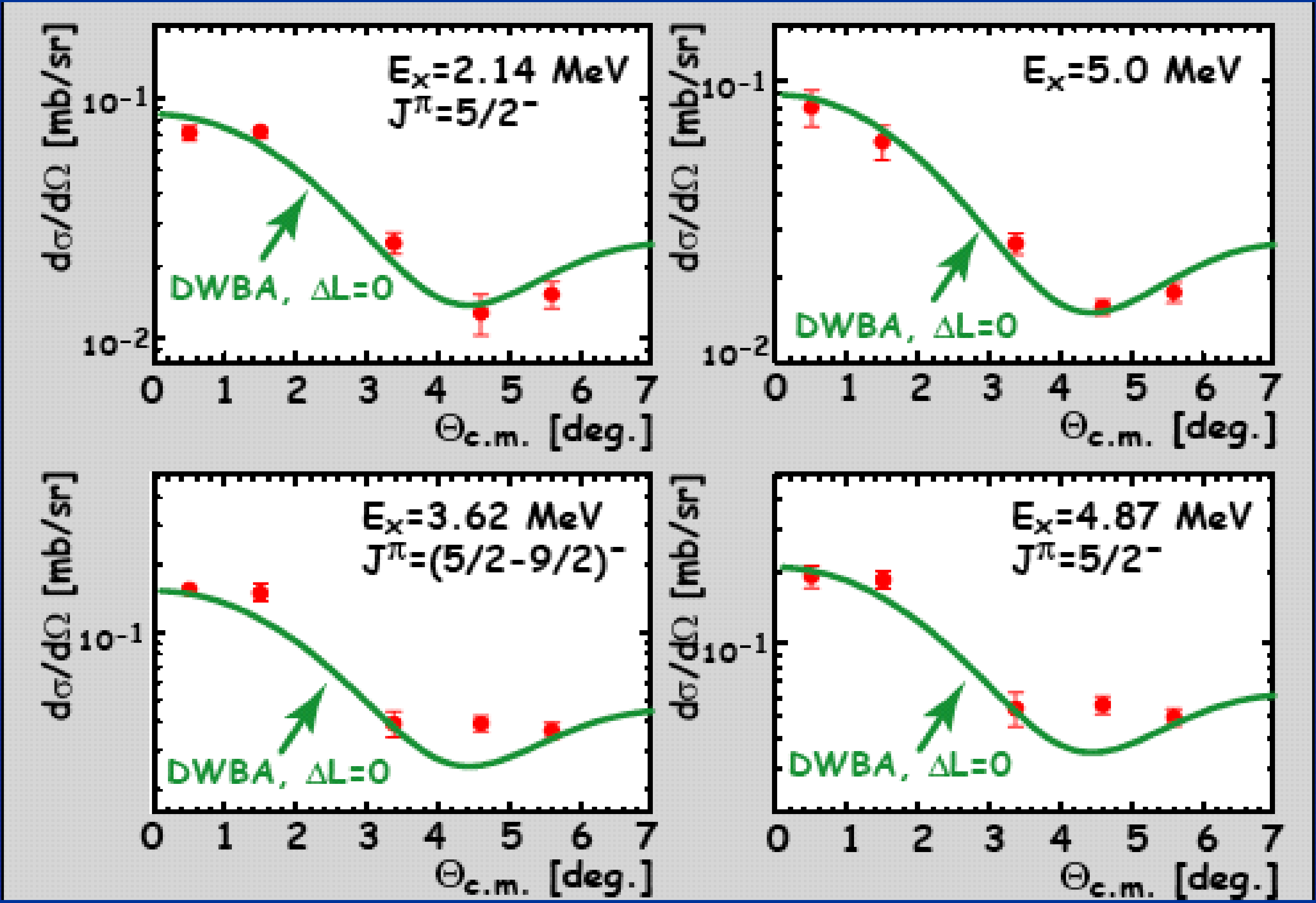
C. Bäumer *et al.*, PRC **68**, 031303(R) (2003)

C. Bäumer *et al.*, PRC **68**, 031303(R) (2003)

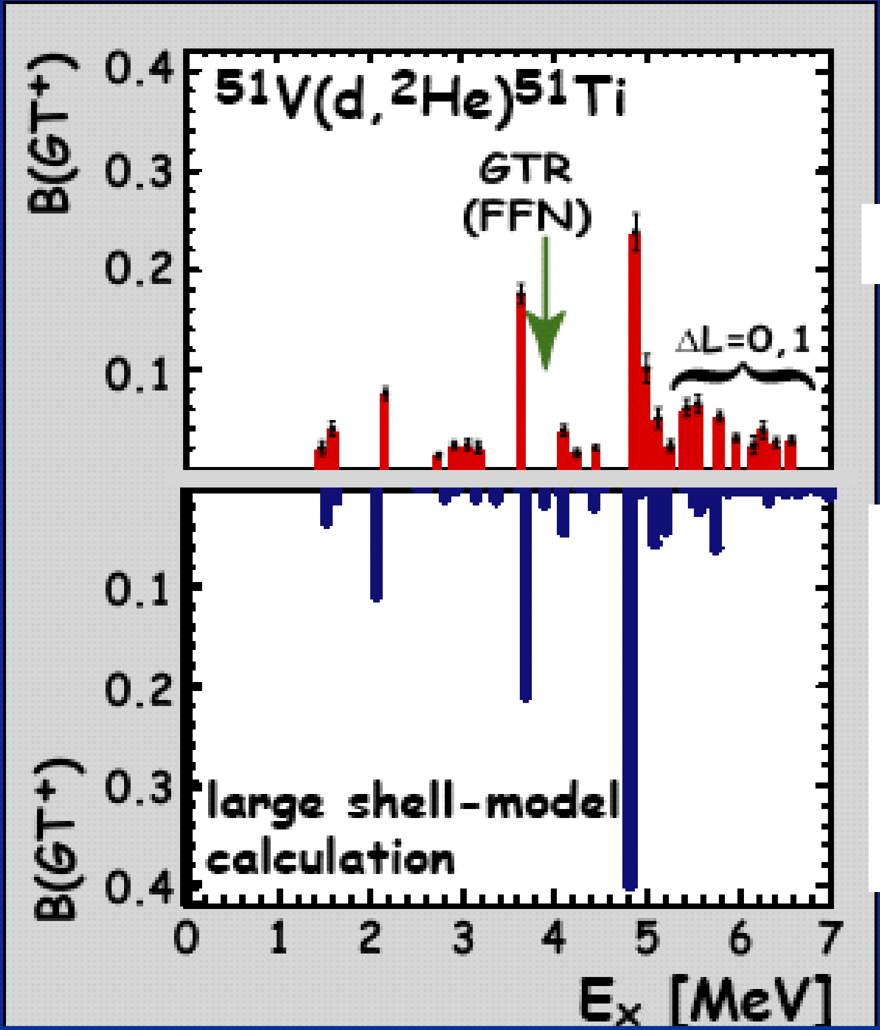




^{51}V(d,^{2}He): Angular distributions of dσ/dΩ



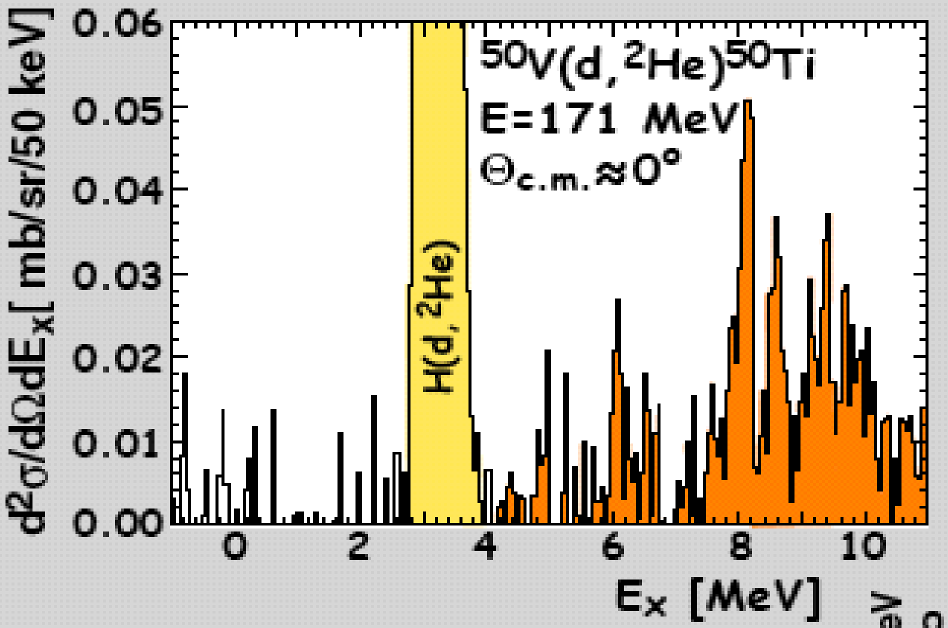
^{51}V(*d*,^{2}He): Comparison with shell-model calculations



← **Experimental result**

← **Full *fp*-shell model calculations**
quenching factor $(0.74)^2$
G. Martínez-Pinedo,
K. Langanke

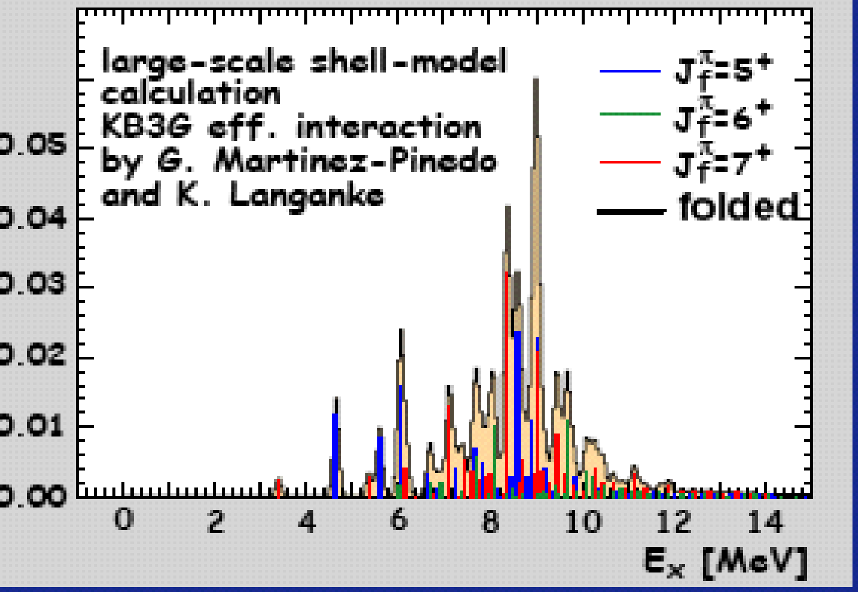
^{50}V(*d*,^{2}He): GT$^+$ transitions from odd-odd nucleus



^{50}V GT$^+$ ^{50}Ti

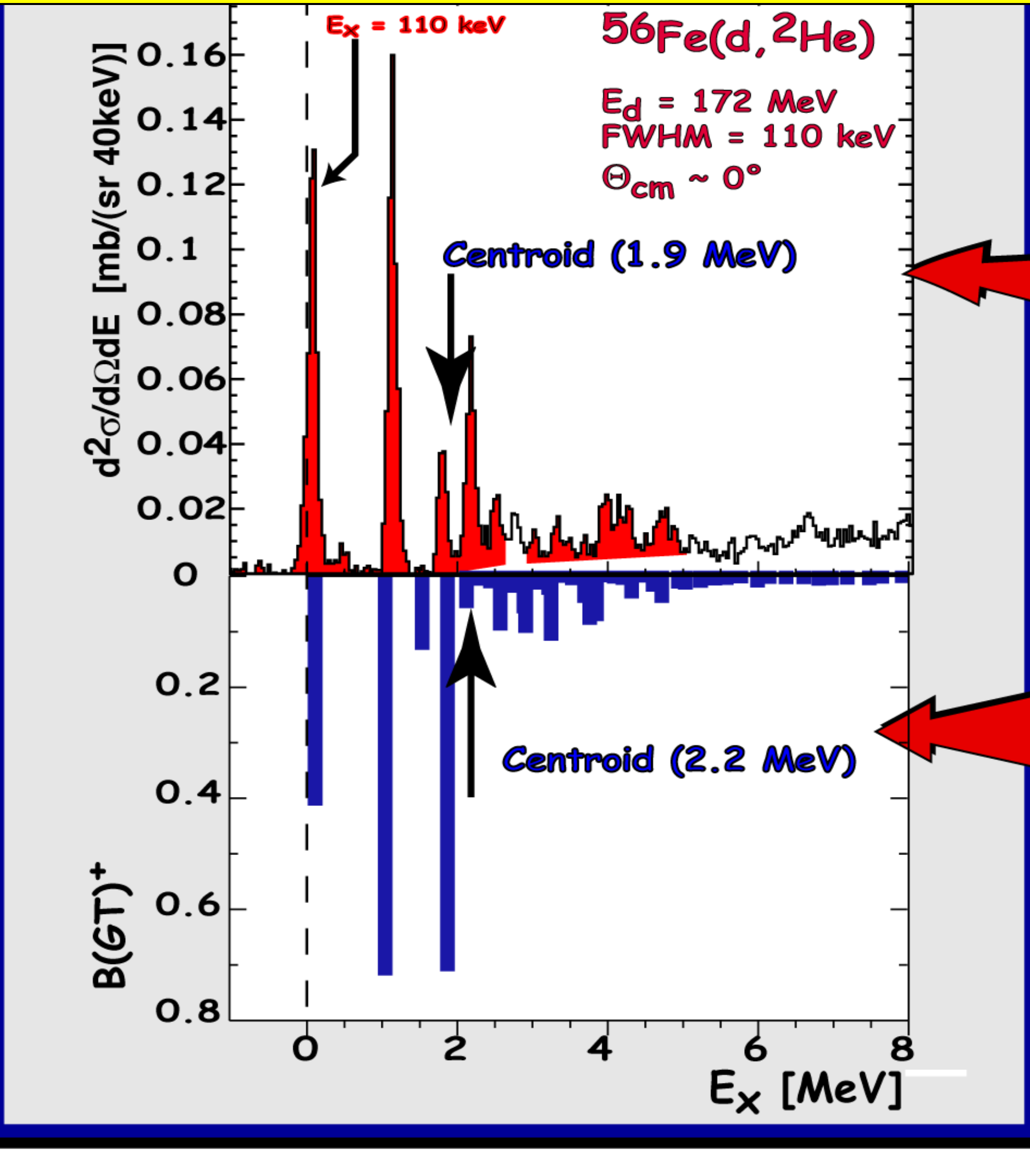
J$^\pi$=6$^+$ → J$^\pi$=5$^+$, 6$^+$, 7$^+$

T=2 T=3



GT-centroid located at ~ 9 MeV

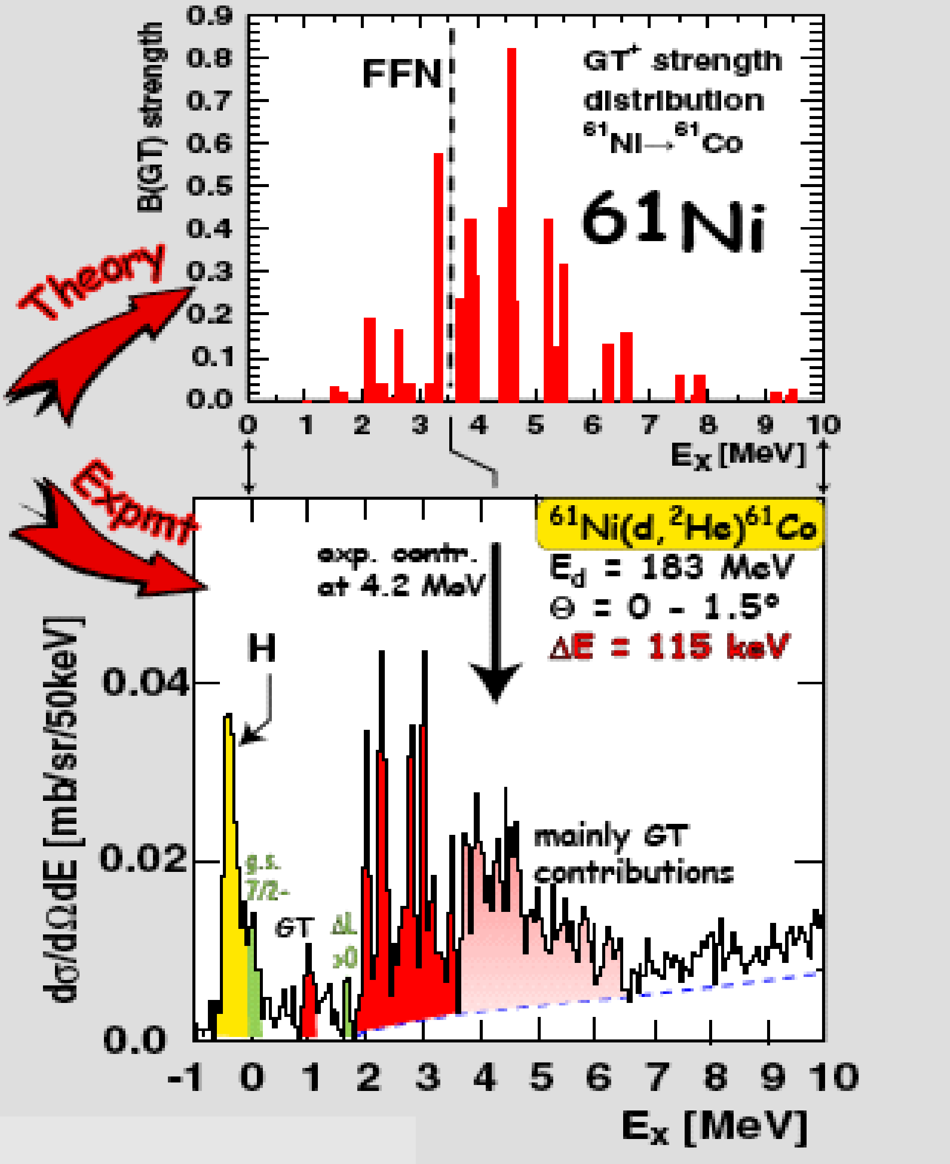
^{56}Fe(d,^{2}He): Comparison with shell-model calculations



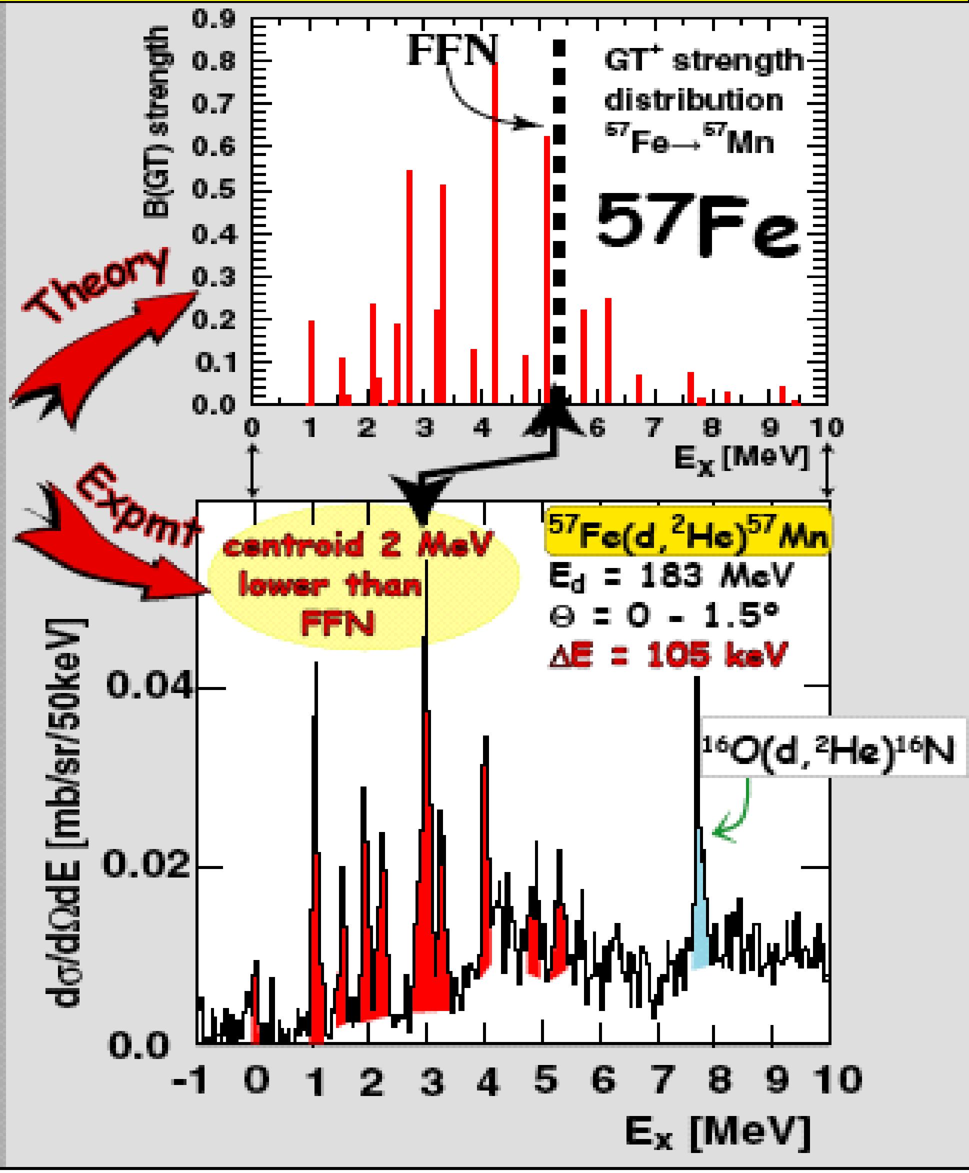
Experiment

Full *fp*-shell model calculations (KB3G) (G. Martínez-Pinedo)

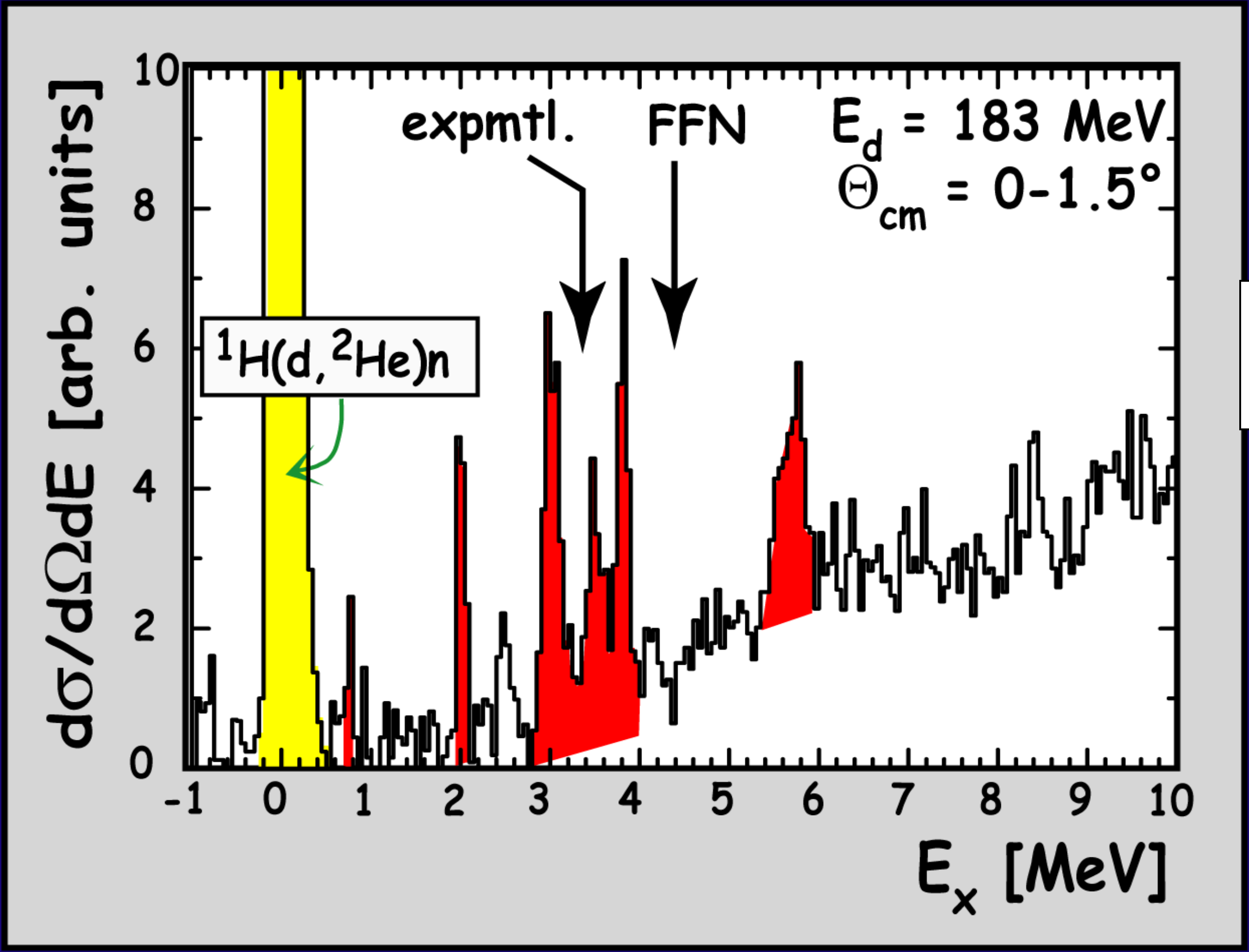
^{61}Ni(d,^{2}He)^{61}Co: GT^{+} distribution



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



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



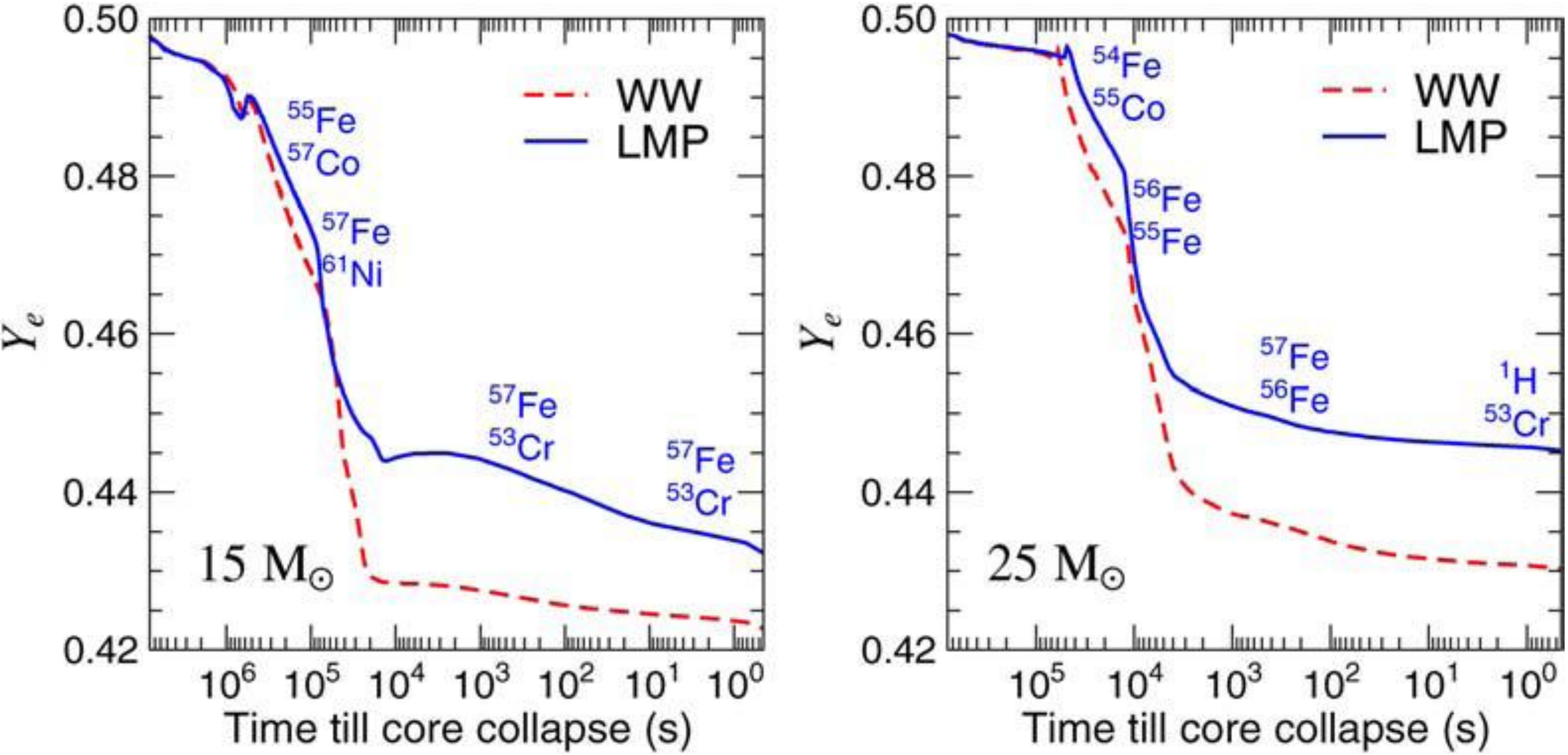
No shell-model calculations yet

Comparison of centroids (MeV) of GT$^+$ Strength distribution

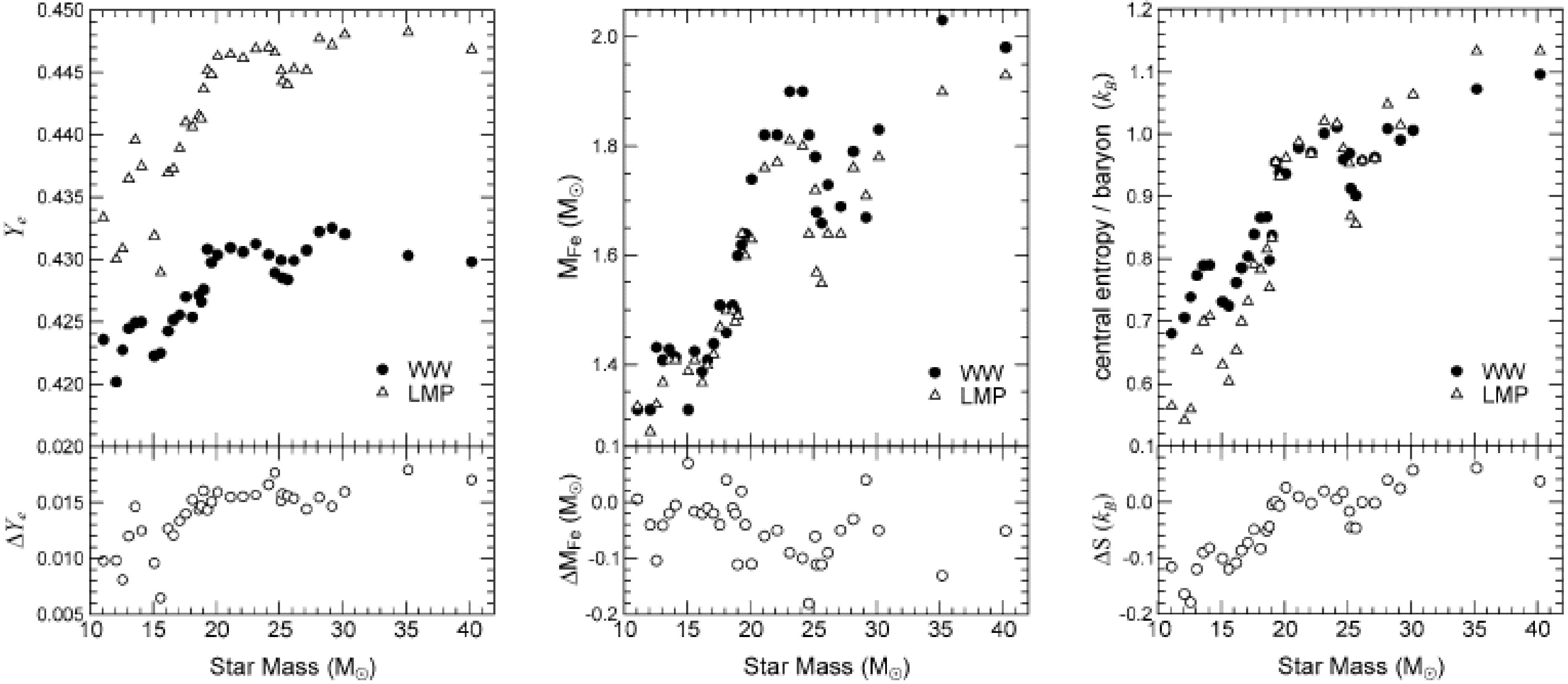
	Nucleus	FFN	SM	Exp.
Even-Even	^{56}Fe	3.8	2.2	1.9
	^{58}Ni	3.8	3.6	3.4
Odd *A*-Odd *p*	^{51}V	3.8	4.7	4.1
Odd *A*-Odd *n*	^{57}Fe	5.3	4.1	2.9
	^{61}Ni	3.5	4.6	4.2
	^{67}Zn	4.4	--	3.4
Odd-Odd	^{50}V	9.7	8.5	8.8

WW = Woosley-Weaver Model calculations (FFN rates)

LMP = Langanke-Martínez-Pinedo Large shell-model calculations {G. Martínez-Pinedo *et al*., NPA 777 (2006) 395}



Y_e = Central electron-to-baryon ratio



Conclusions

- **Presupernova models depend sensitively on EC rates.**
- **GT^+ transitions in *fp*-shell nuclei play a decisive role in determining EC rates and thus provide input into modeling of explosion dynamics of massive stars.**
- **Large shell-model calculations are needed especially as function of T. (Caurier *et al*.; Martínez-Pinedo & Langanke [KB3G]; Otsuka *et al*. [GXPF]) ⇒ smaller EC rates for A=45-60 than FFN ⇒ Larger Y_e (electron to baryon ratio) and smaller iron core mass (Heger *et al*.)**
- **New high resolution (*d*,^{2}He) experiments provide essential tests for shell model calculations at 0 T.**

Microscopic Structure of GTR and IVSGDR in ^{208}Bi

- Proton decay of ^{208}Bi:
  - Direct decay dominant
    - $E_x > E_{th}(n) > E_{th}(p)$
    - High Coulomb Barrier (Z=83)
  - Statistical proton decay negligible.
- Angular correlations
  - For IAS and GTR decay isotropic $\Delta L=0$
  - For IVSGDR anisotropic but not strongly
- Direct decay is influenced by:
  - Low n-decay threshold
  - High Coulomb barrier.

- $\Gamma_{GTR}^{\uparrow}/\Gamma \ll \Gamma_{IAS}^{\uparrow}/\Gamma \approx 0.5$
  - **IAS n-decay: isospin forbidden.**
  - **Centroid energy shift: cut off by Coulomb barrier**
- $\Gamma_{IVSGDR}^{\uparrow}/\Gamma > \Gamma_{GTR}^{\uparrow}/\Gamma$
  - **Higher proton energy**
- **Width Γ:**

$$\Gamma = \Gamma^{\uparrow} + \Gamma^{\downarrow}$$

Escape: Direct decay
Spreading: Statistical Decay

$$\Gamma^{\uparrow} = \Gamma_{p}^{\uparrow} = \sum_{i} \Gamma^{\uparrow}_{pi}$$

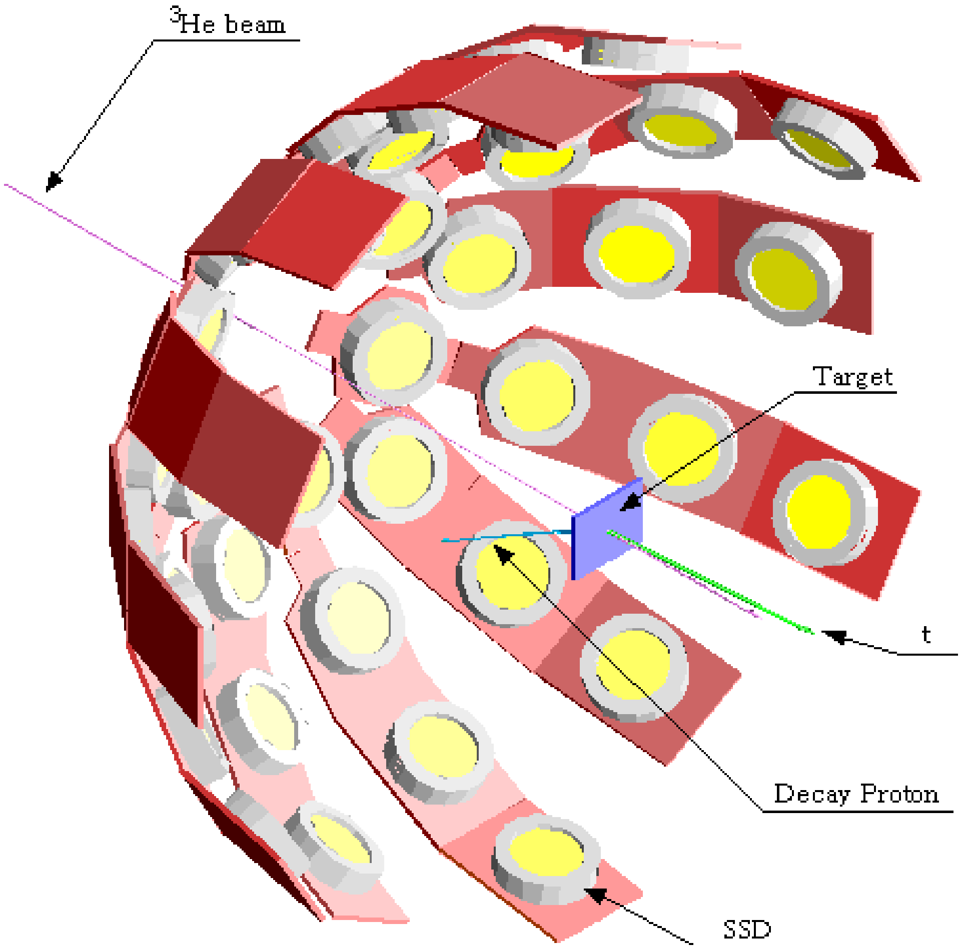
Partial Escape Width

$$\frac{\Gamma^{\uparrow}_{pi}}{\Gamma} = \frac{\int d^2\sigma_{pi}/(d\Omega_t d\Omega_p) d\Omega_p}{d\sigma/d\Omega_t}$$

Branching ratio

Set-up of the Proton Counter

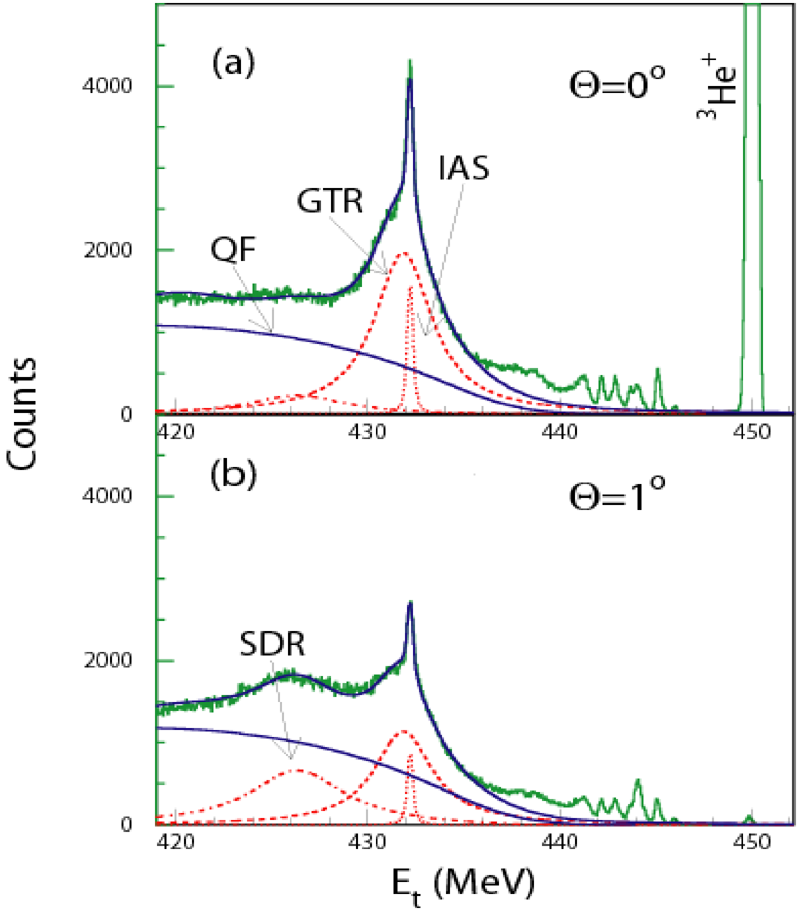
- Si(Li) detectors with a thickness of 5 mm, covering a solid angle of 5.7% in total.
- 35 keV (^{241}Am test)



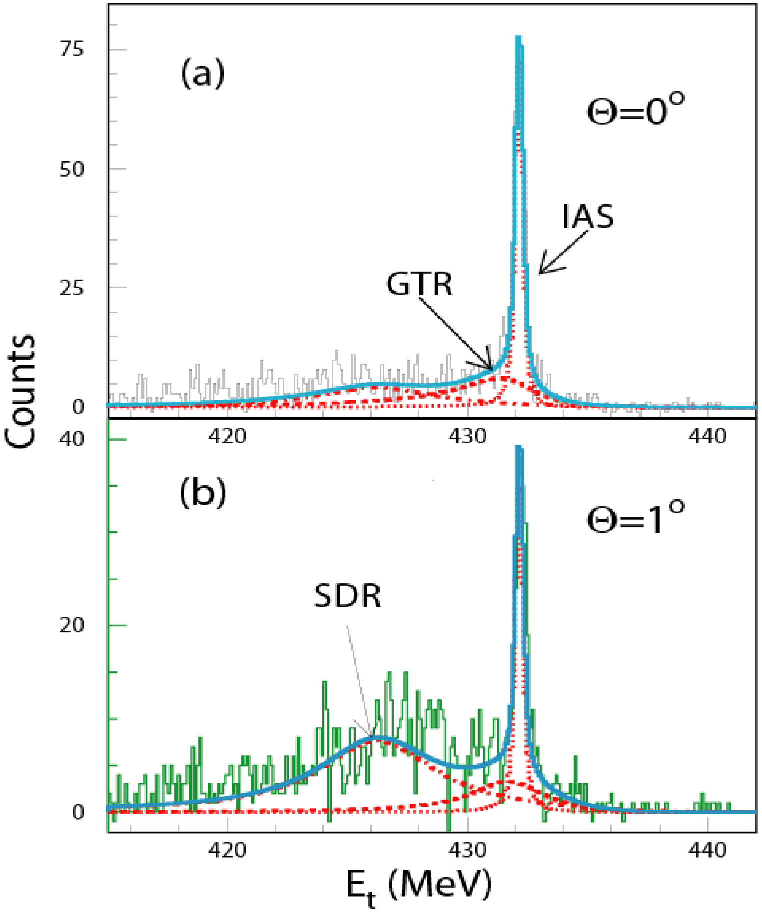
Spin-isospin-flip transitions in charge-exchange reactions and proton decay

A. Krasznahorkay et al., PRC 64 (2001) 067302.
A. Krasznahorkay et al., PRL 82 (1999) 3216.
H. Akimune et al., PRC 52 (1995) 604.
H. Akimune et al., Phys. Lett. B 233 (1994) 107

(^{3}He,t) reactions E(^{3}He)=450 MeV



(^{3}He,tp) Coincidence data



Experimental Results and Theoretical Calculations

Partial escape width for GTR

		Theory		This work	
channel	E_x(keV)	$\Gamma_i^{\uparrow}$(keV)	branch (%)	$\Gamma_i^{\uparrow}$(keV)	branch (%)
$3p_{1/2}$	0	48.7	1.23	58.4 ± 19.8	1.8 ± 0.5
$2f_{5/2}$	570	46.2	2.12	inc. in $p_{3/2}$	
$3p_{3/2}$	898	44.7	2.5	101.5 ± 31.3	2.7 ± 0.6
$1i_{13/2}$	1633	0.87	3.57	8.3 ± 9.4	0.2 ± 0.2
$2f_{7/2}$	2340	5.89	2.97	15.6 ± 7.6	0.4 ± 0.2
$1h_{9/2}$	3413	0.24	0.63	–	–
Total		146.6	13.02	184 ± 49	4.9 ± 1.3

Theory:
E. Moukhai,
V.A. Rodin,
M.H. Urin
Continuum RPA

Partial escape width for IVSGDR

		Theory		This work	
channel	E_x(keV)	$\Gamma_i^{\uparrow}$(keV)	branch (%)	$\Gamma_i^{\uparrow}$(keV)	branch (%)
$3p_{1/2}$	0	103.4	1.23	83.4 ± 24.3	0.99 ± 0.29
$2f_{5/2}$	570	178.1	2.12	170.8 ± 49.3	2.12 ± 0.61
$3p_{3/2}$	898	210.1	2.5	240 ± 69.6	2.86 ± 0.83
$1i_{13/2}$	1633	299.8	3.57	330.4 ± 95.7	3.74 ± 1.08
$2f7_{/2}$	2340	249.3	2.97	282.2 ± 86.8	3.36 ± 0.97
$1h_{9/2}$	3413	52.6	0.63	86.7 ± 25.1	1.03 ± 0.29
Total		1209.6	14.4	1180 ± 340	14.1 ± 4.2

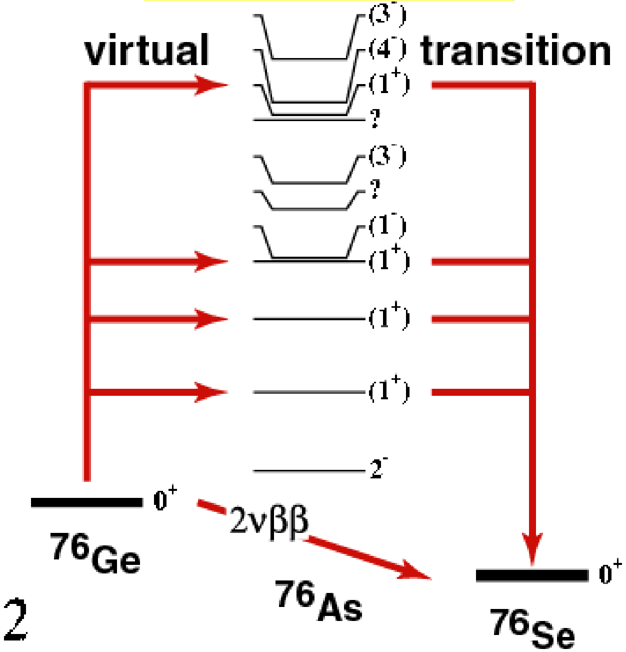
Summary: ^{208}Pb(^{3}He,tp)

- GTR: $\Gamma^{\uparrow}/\Gamma$~4.9% , $\Gamma^{\uparrow}$=184±49 keV
  - Small branching ratio:
    - Spreading effect is very important.
    - Coupling to underlying 2p-2h states.
    - Centroid energy shift caused by
      High Coulomb barrier.
- IVSGDR: $\Gamma^{\uparrow}/\Gamma$~14.1% , $\Gamma^{\uparrow}$= 1180±340 keV
  - Larger p-decay $\Gamma^{\uparrow}/\Gamma$ compared to GTR.
    - E_p: enough higher than
      Coulomb barrier, centrifugal barrier.
  - Enhancement of decay to high-spin 1n-hole states

ββ decay

2νββ decay

Allowed in SM and observed in many cases



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

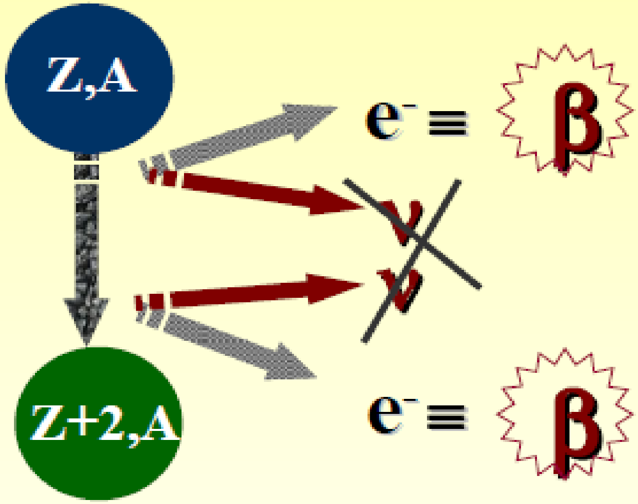
$$M_{\rm DGT}^{(2\nu)} = \sum_m \frac{(0_{\rm g.s.}^{(f)}\|\sum_i\sigma(i)\tau^{\pm}(i)\|1_m^+)(1_m^+\|\sum_i\sigma(i)\tau^{\pm}(i)\|0_{\rm g.s.}^{(i)})}{[\frac{1}{2}Q_{\beta\beta}(0_{\rm g.s.}^{(f)})+E(1_m^+)-M_i]/m_e+1}$$

Accessible through charge-exchange reactions in (*n*,*p*) and (*p*,*n*) direction [e.g. (*d*,^{2}He) or (^{3}He,*t*)]

Forbidden in MSM
Lepton number violated
Neutrino enters as virtual particle, → **q~0.5fm^{-1}**

nuclear neutrino-less double-beta decay

0ν2β



Majorana ν

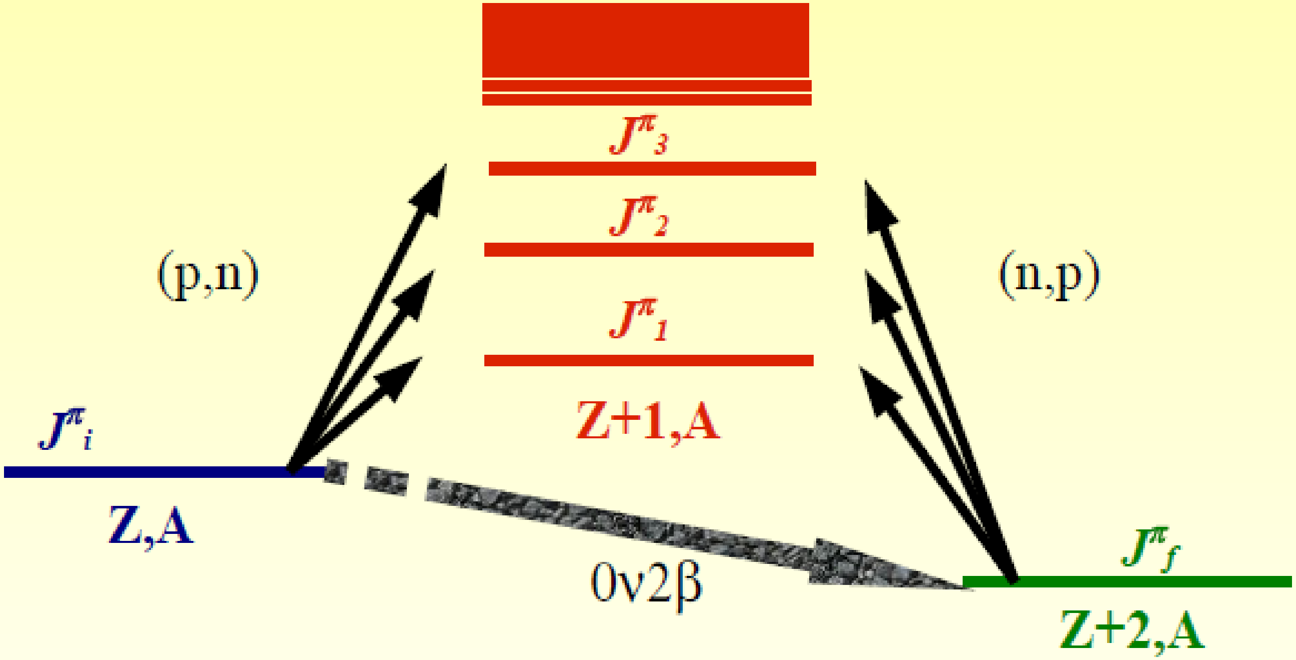
$$decay\ rate \sim \left|NME^{0\nu 2\beta}\right|^2 \langle m_\nu \rangle^2$$

nuclear matrix element

Mass of Majorana neutrino!!

Approach

Study the spectroscopy of virtual states in the *2*-quantum process

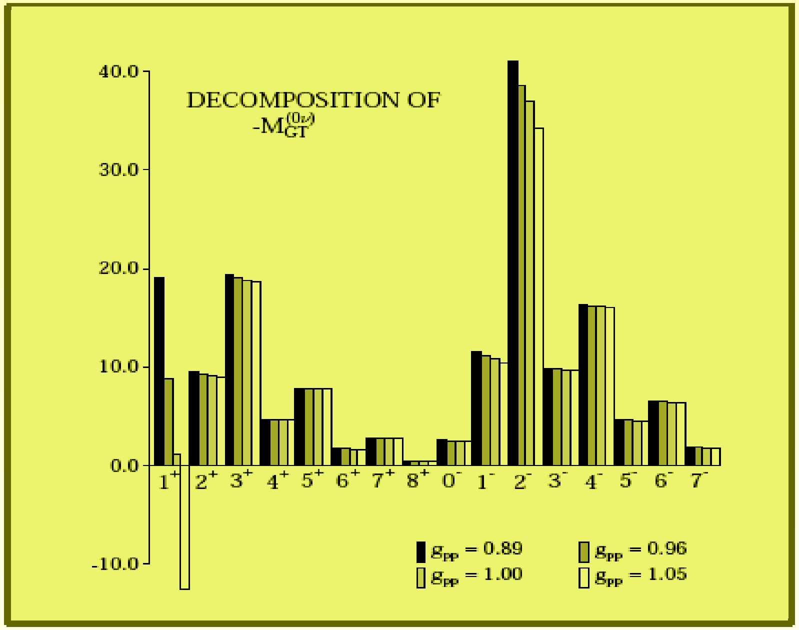


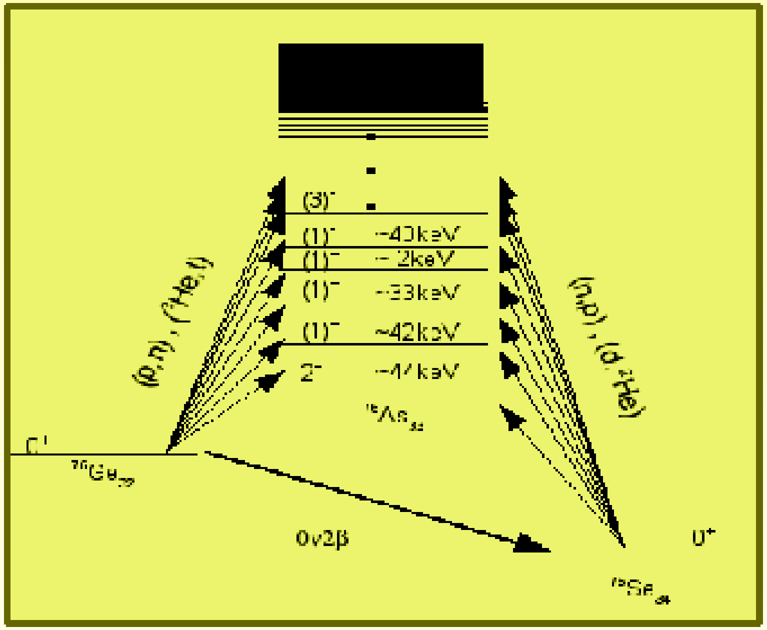
theory:

$$NME^{0\nu 2\beta} = \sum_m \frac{\langle J^\pi_i \| Operator \| J^\pi_m \rangle \langle J^\pi_m \| Operator \| J^\pi_f \rangle}{f(E_m)}$$

Physics case for 0ν2β study: ^{76}Ge

- recent claim of the observation of 0ν2β-decay in ^{76}Ge





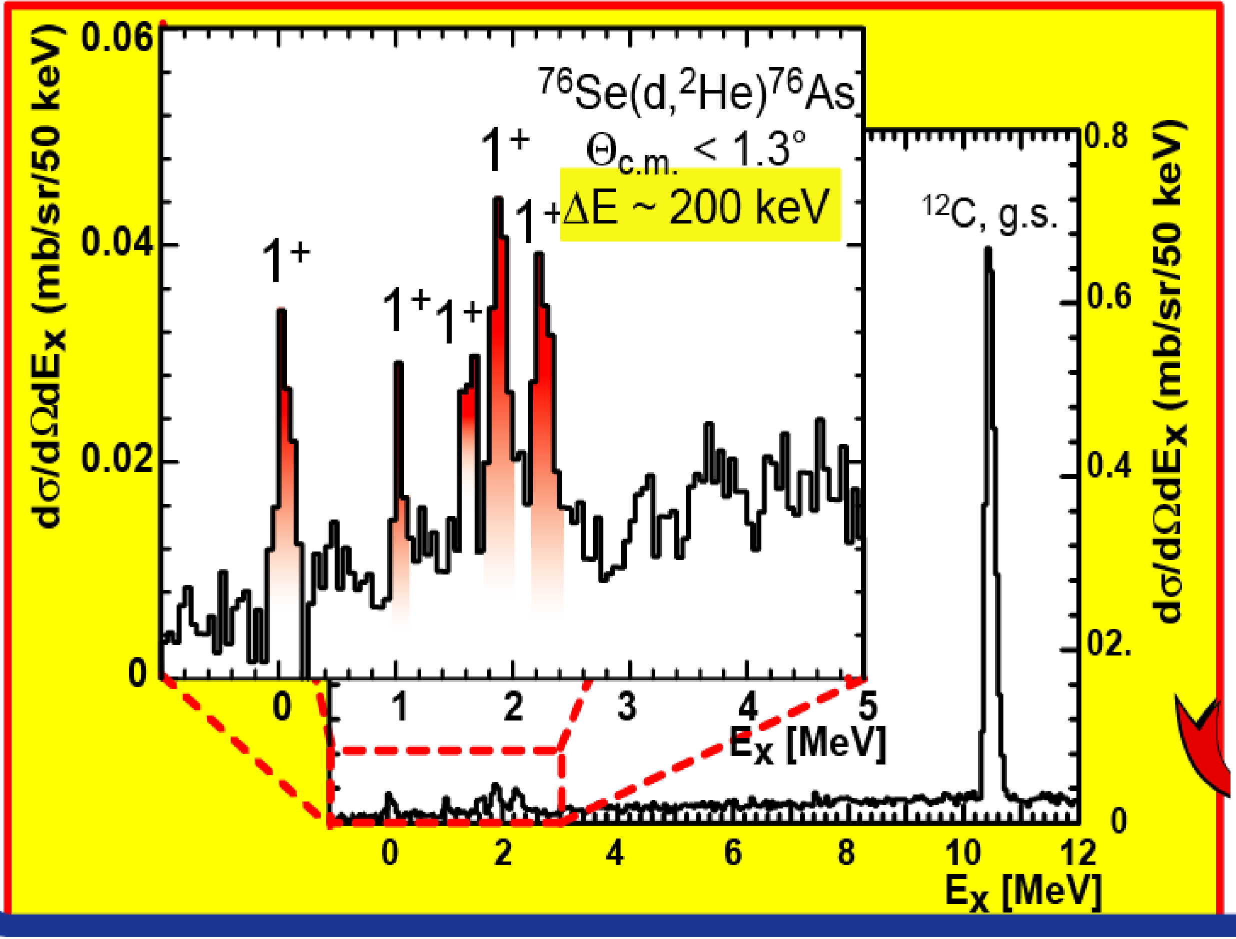
- ☞ contribution of many multi-poles
- ☞ dominance of dipole components
- ☞ the g_{pp} parameter affects mainly the $J^{\pi} = 1^+$ component
- ☞ it becomes imperative to study experimentally higher multi-pole components

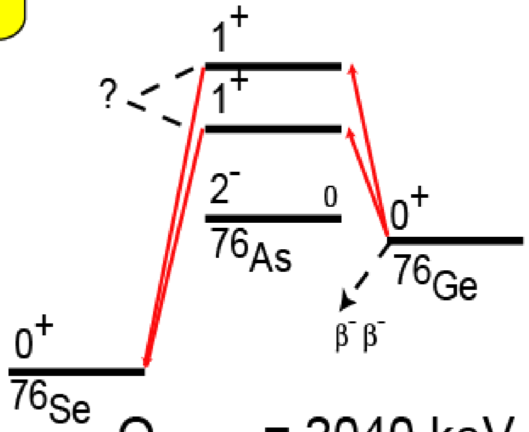
^{76}Ge - ^{76}As - ^{76}Se

- Intensively studied ββ-emitter
- $T_{1/2}$ determined by the Heidelberg-Moscow group: 1.55×10^{21}y
- $T_{1/2}$ deduced from (n,p) and (p,n) data with poor energy resolution

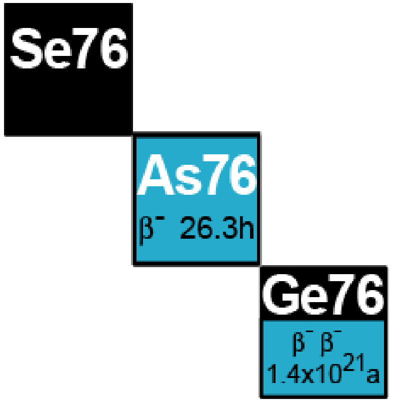
multipole decomposition: 7.4×10^{20}y

0°-6° subtraction method: 8.7×10^{21}y

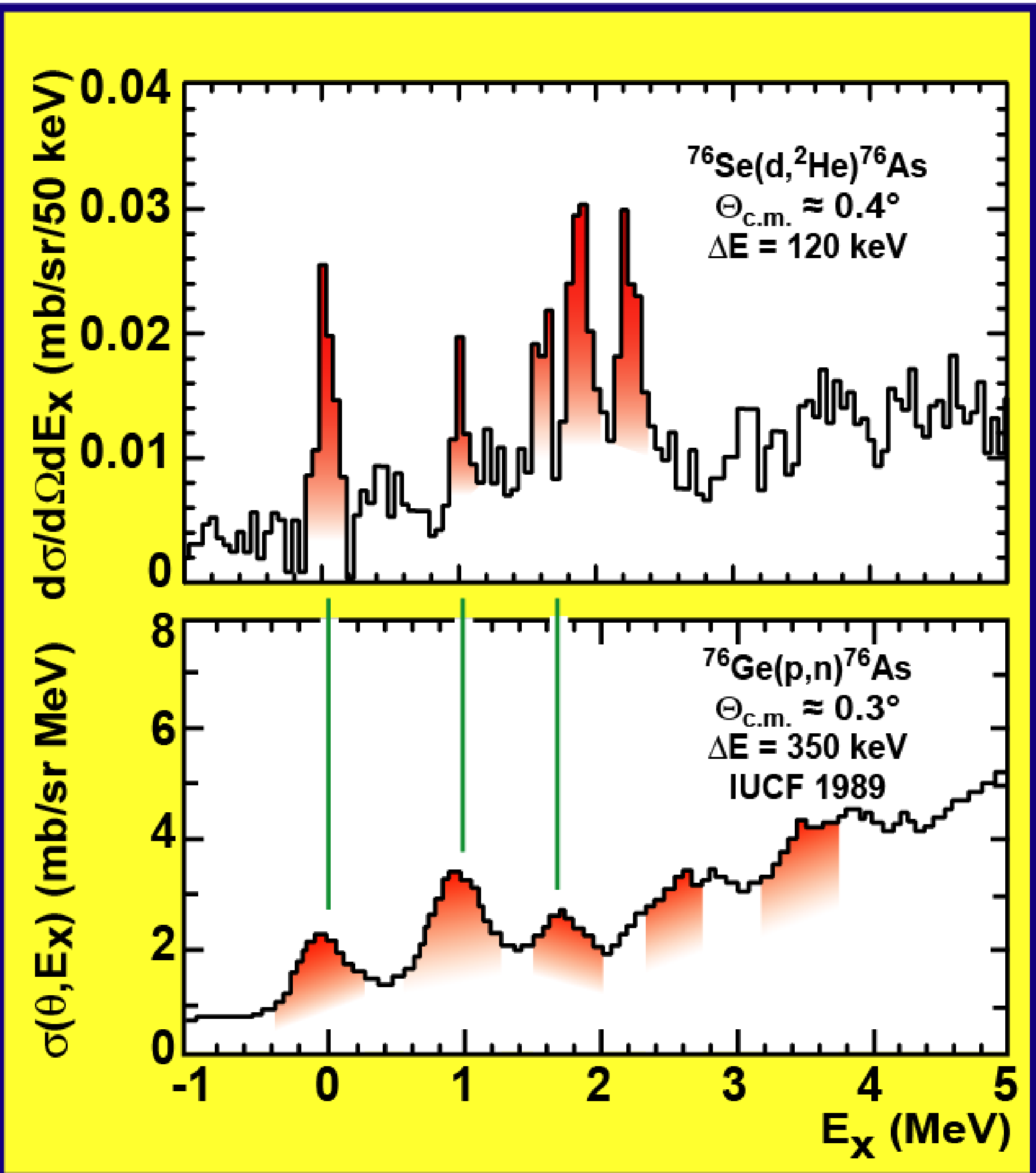




$Q_{\beta^-\beta^-} = 2040$ keV



$\Sigma B(GT^+) \sim 0.56$



$2\nu\beta\beta$-matrix element

0.16 ± 0.04 MeV^{-1}

with

$G^{(2\nu)} = 3.4 \times 10^{-20}\ MeV^2\ a^{-1}$

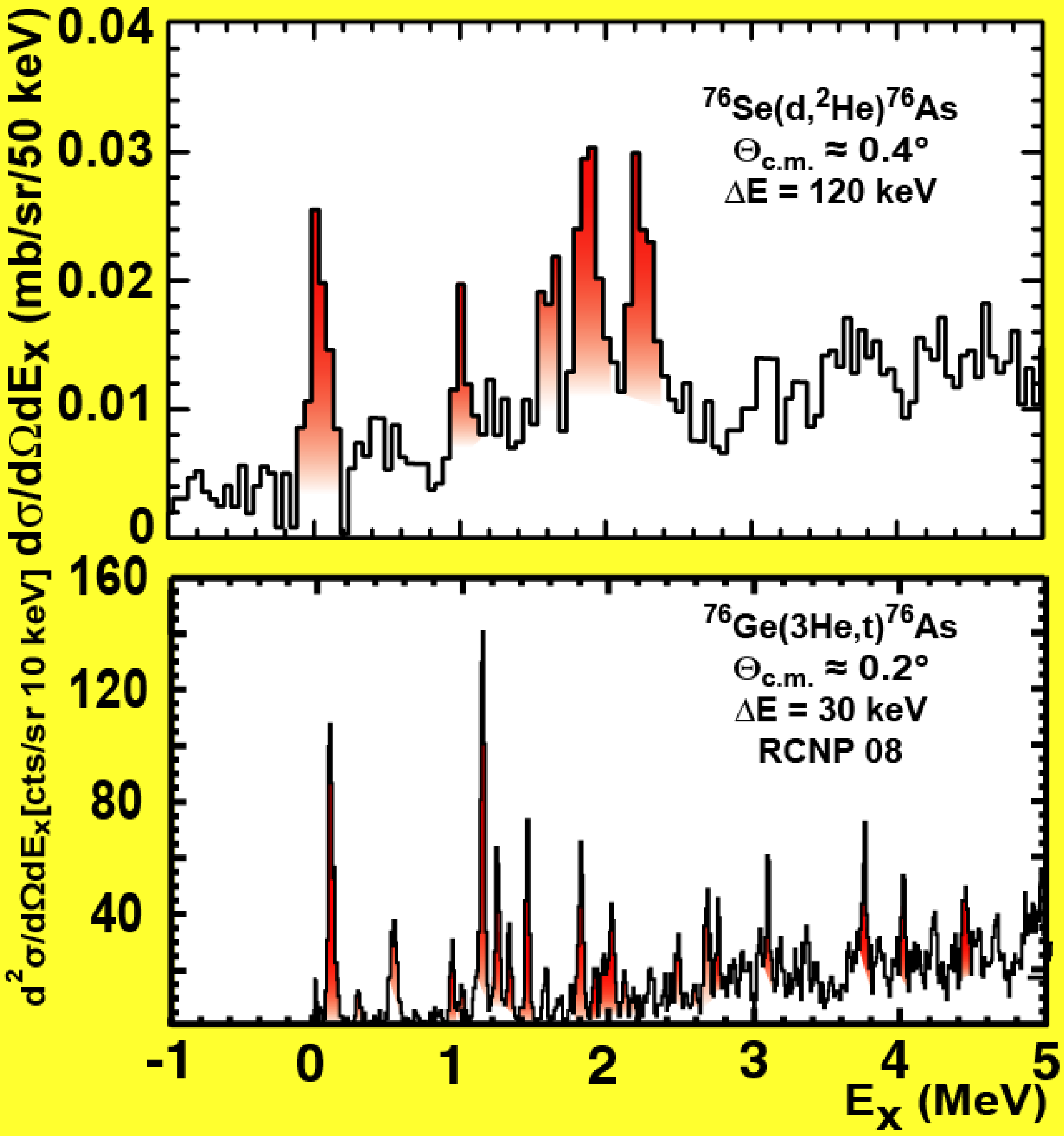
$2\nu\beta\beta$ - half-life

$(1.1 \pm 0.2) \times 10^{21}$ a

recommended. exp. value:

$(1.5 \pm 0.1) \times 10^{21}$ a

$G^{(2\nu)}$ taken from: J. Suhonen and O. Civitarese, Phys. Rep. 300, 123 (1998)



2νββ-matrix element

0.16 ± 0.04 MeV^{-1}

with

$G^{(2\nu)} = 3.4 \times 10^{-20}$ MeV^2 a^{-1}

2νββ - half-life

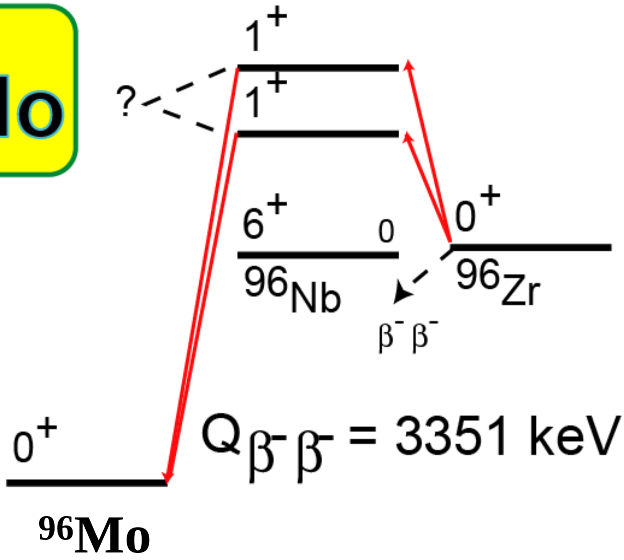
$(1.1 \pm 0.2) \times 10^{21}$ a

recommended. exp. value:

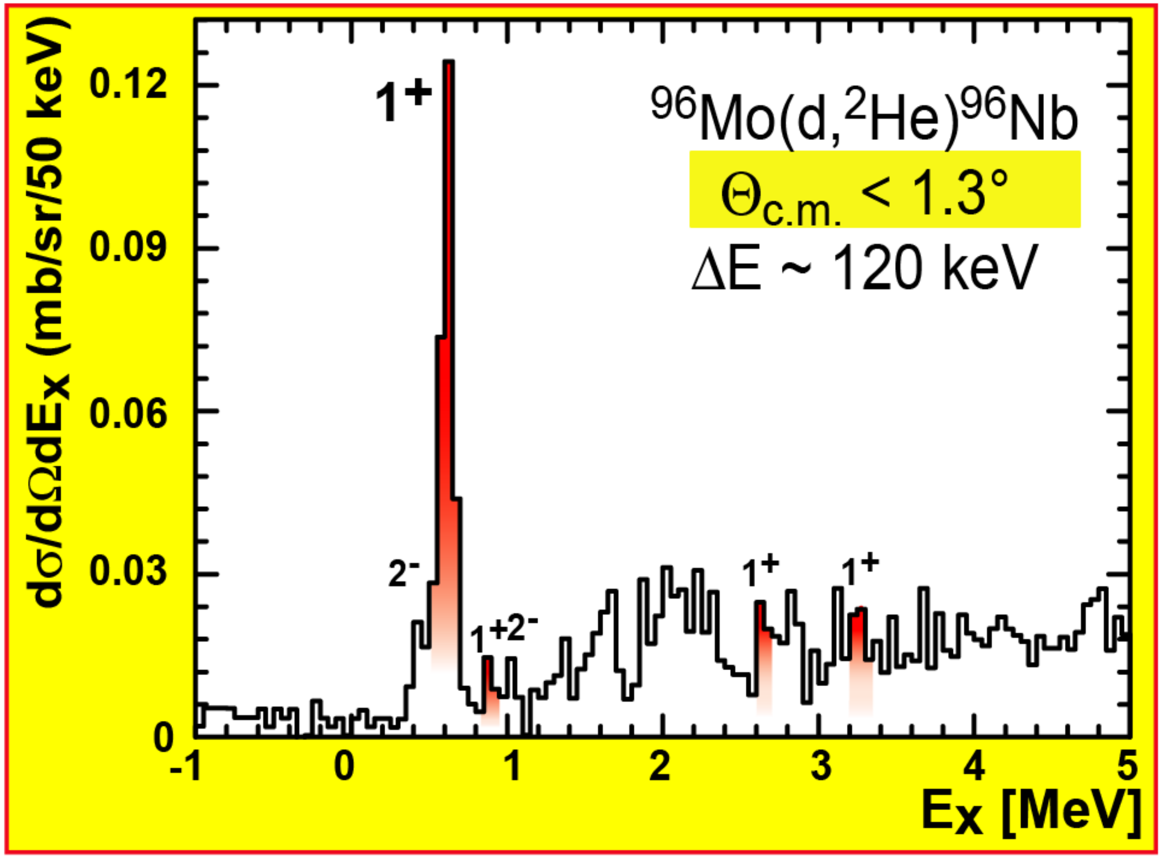
$(1.5 \pm 0.1) \times 10^{21}$ a

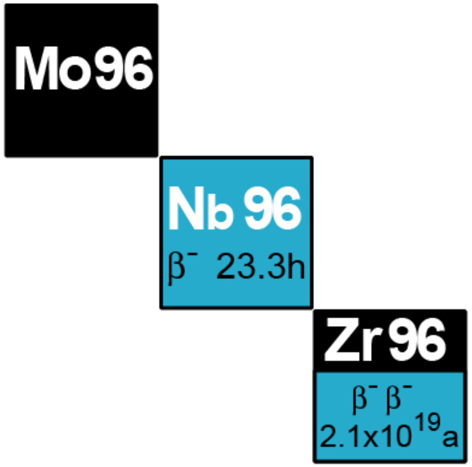
$G^{(2\nu)}$ taken from: J. Suhonen and O. Civitarese, Phys. Rep. 300, 123 (1998)

^{96}Zr - ^{96}Nb - ^{96}Mo

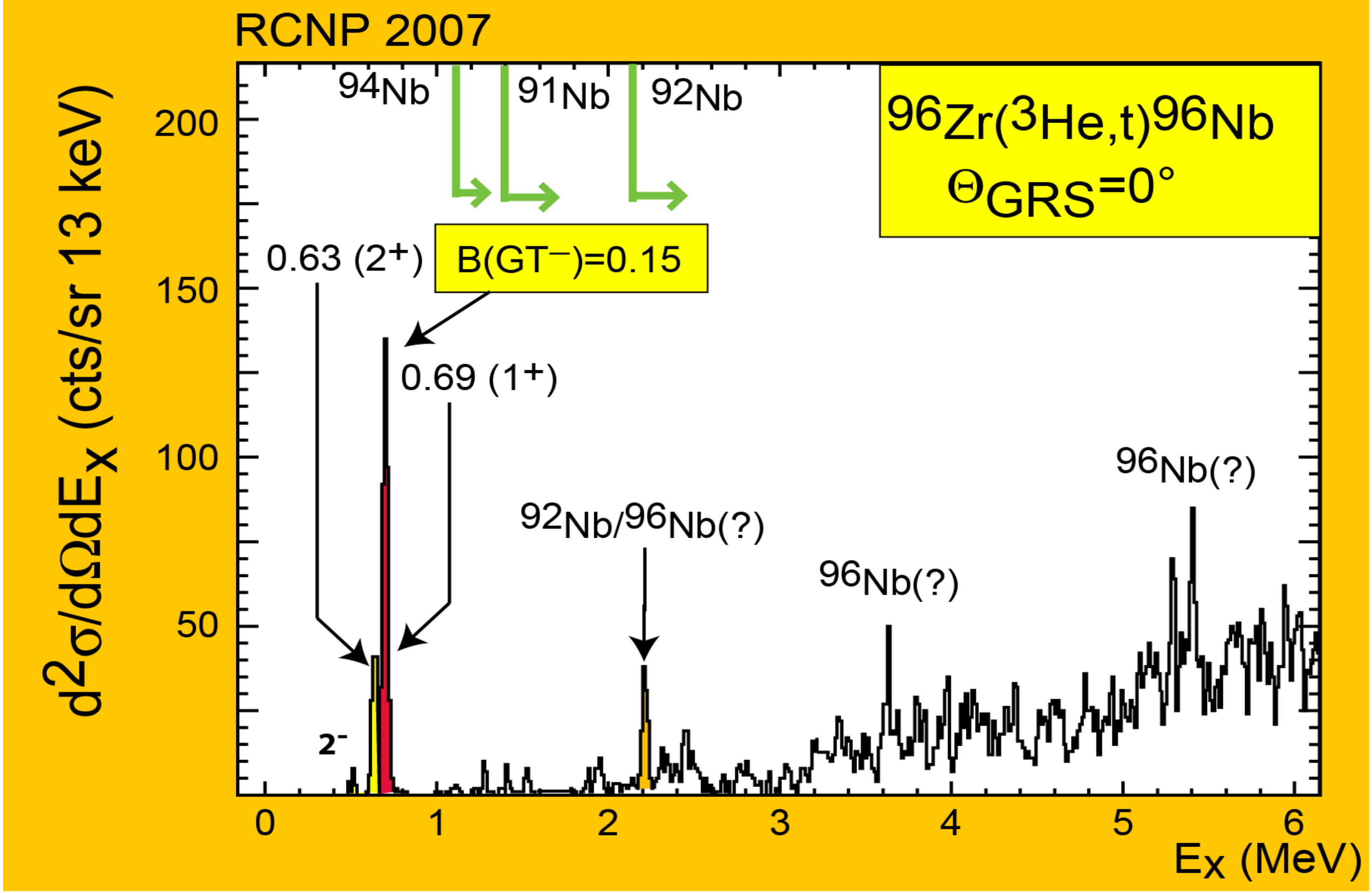


- $T_{1/2}$ available:
  - counting experiments: 2.1 x 10^{19}y
  - geochemical methods: 9.4 x 10^{18}y
- g.s. transition forbidden
- strength concentrated in one transition





B(GT⁺) ~ 0.3



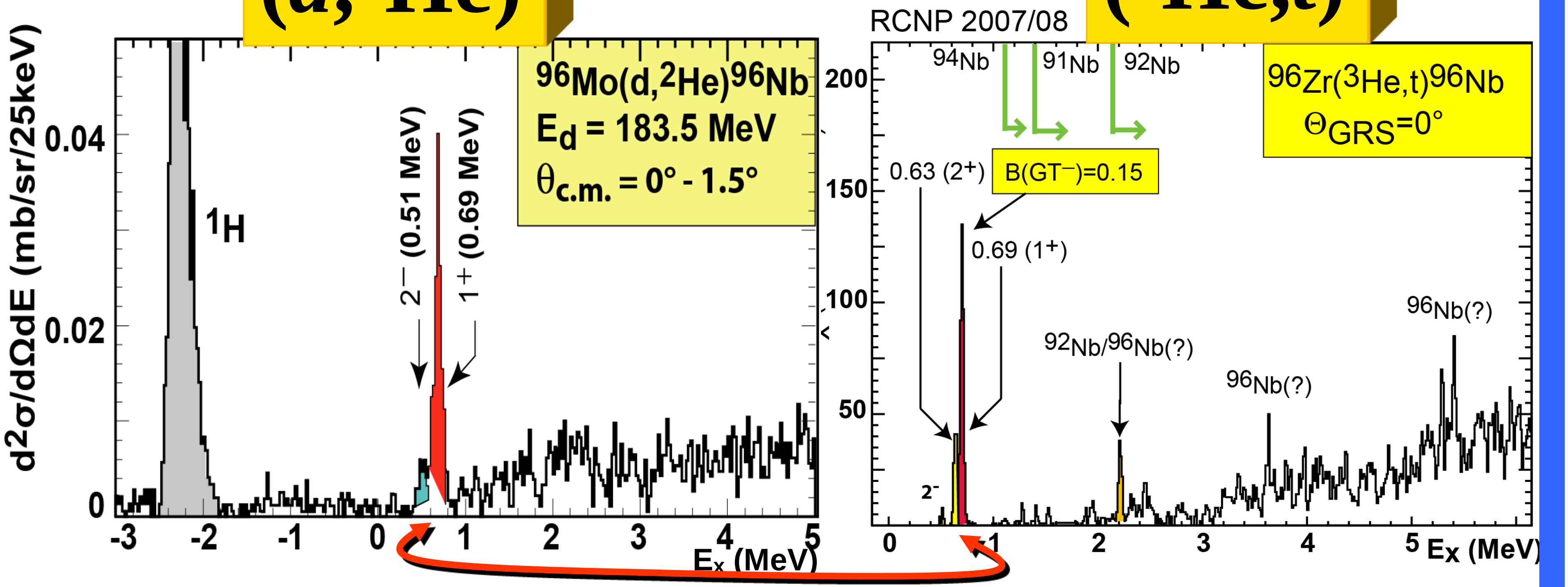
In (*p*,*n*) direction:

1 - exceptionally small B(GT⁻) below 6 MeV

2 - concentrated in one low-lying level only

$(d,{}^2He)$

$({}^3He,t)$



$B(GT^+) = 0.3$

$B(GT^-) = 0.15$

With this 1 level only

$$T_{1/2}^{calc.}(2\nu\beta\beta) = (2.4 \pm 0.3) \cdot 10^{19}\ \text{years}$$

$$T_{1/2}^{exp.}(2\nu\beta\beta = (2.2 \pm 0.4) \cdot 10^{19}\ \text{years} \quad \text{(NEMO3-result)}$$

Conclusions

- Charge-exchange reactions provide important input for $2\nu\beta\beta$ decay ME; *i.e.* (d,^{2}He) (t,^{3}He) for GT^+ leg and (^{3}He,t) for the GT^- leg

- ^{96}Zr and ^{100}Mo exhibit Single-State-Dominance (at 0.69 MeV (^{96}Zr) and g.s. (^{100}Mo))

Outlook

Radioactive ion beams will be available at energies where it will be possible to study GT transitions (RIKEN, NSCL, FAIR, EURISOL)

- **Determine $GT^{\pm}$ strength in unstable *sd* & *fp* shell nuclei**

  Electron capture rates (presupernova) and neutrino capture rates and inelastic scattering cross sections

- **Use IV(S)GDR as tool to determine n-skin**

  Charge-exchange cross section proportional to n-skin

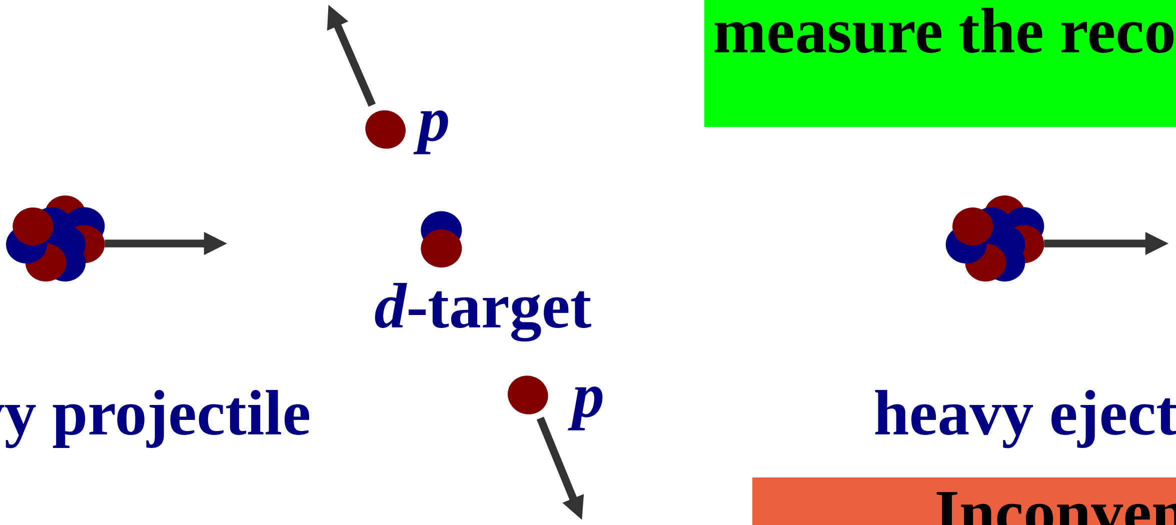
- **Exotic excitations such as Double GT**

Nuclear structure studies with CE reactions in inverse kinematics

- Possible at FAIR and RIKEN

(intermediate beam energies are needed!)

Approach (at FAIR):
measure the recoiling protons



(d,^{2}He)

heavy projectile

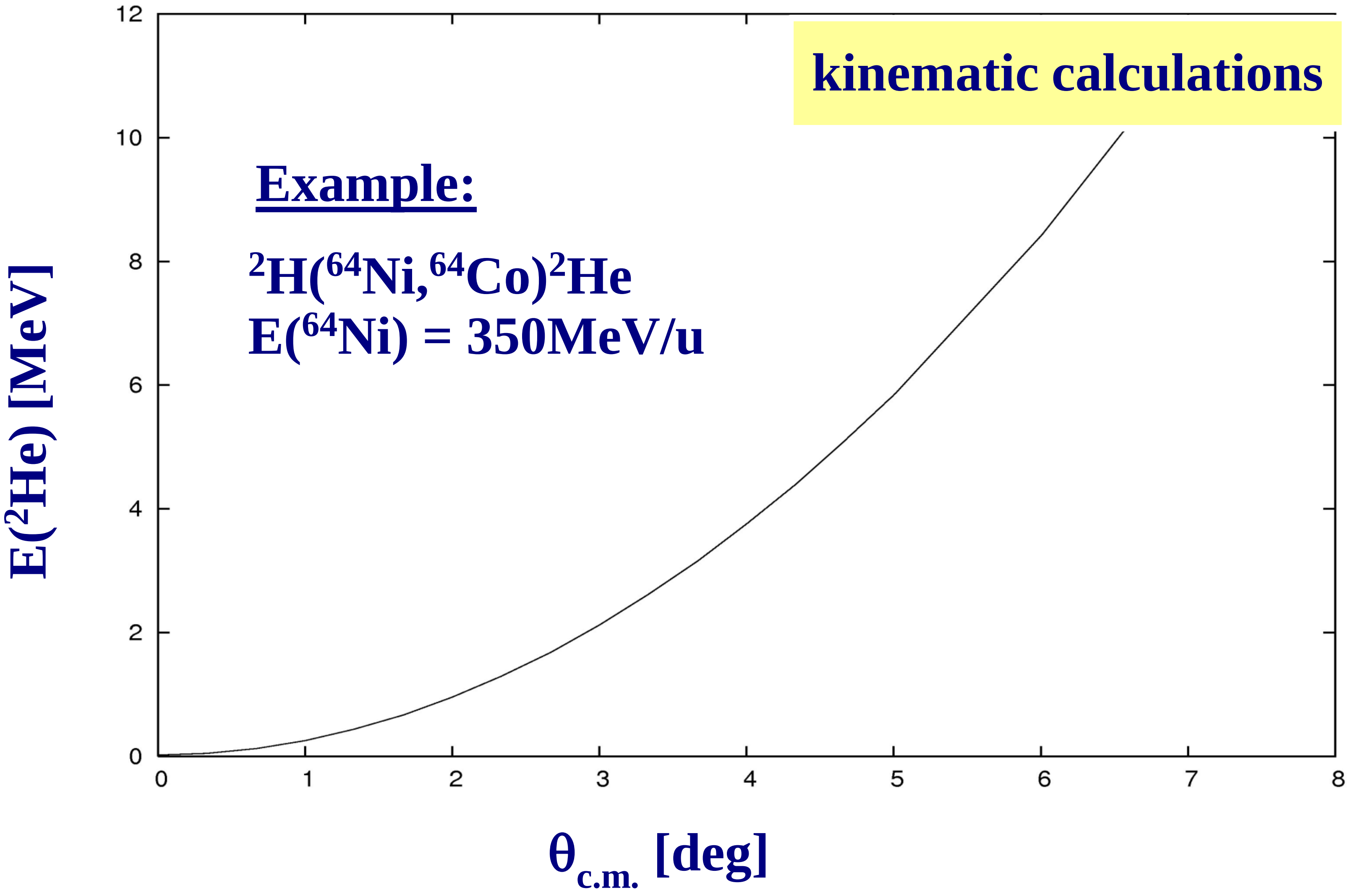
heavy ejectile

recoiling protons

Inconvenience:
difficulty to detect the low-energy protons

Courtesy
Lucia-Ana Popescu

How low?

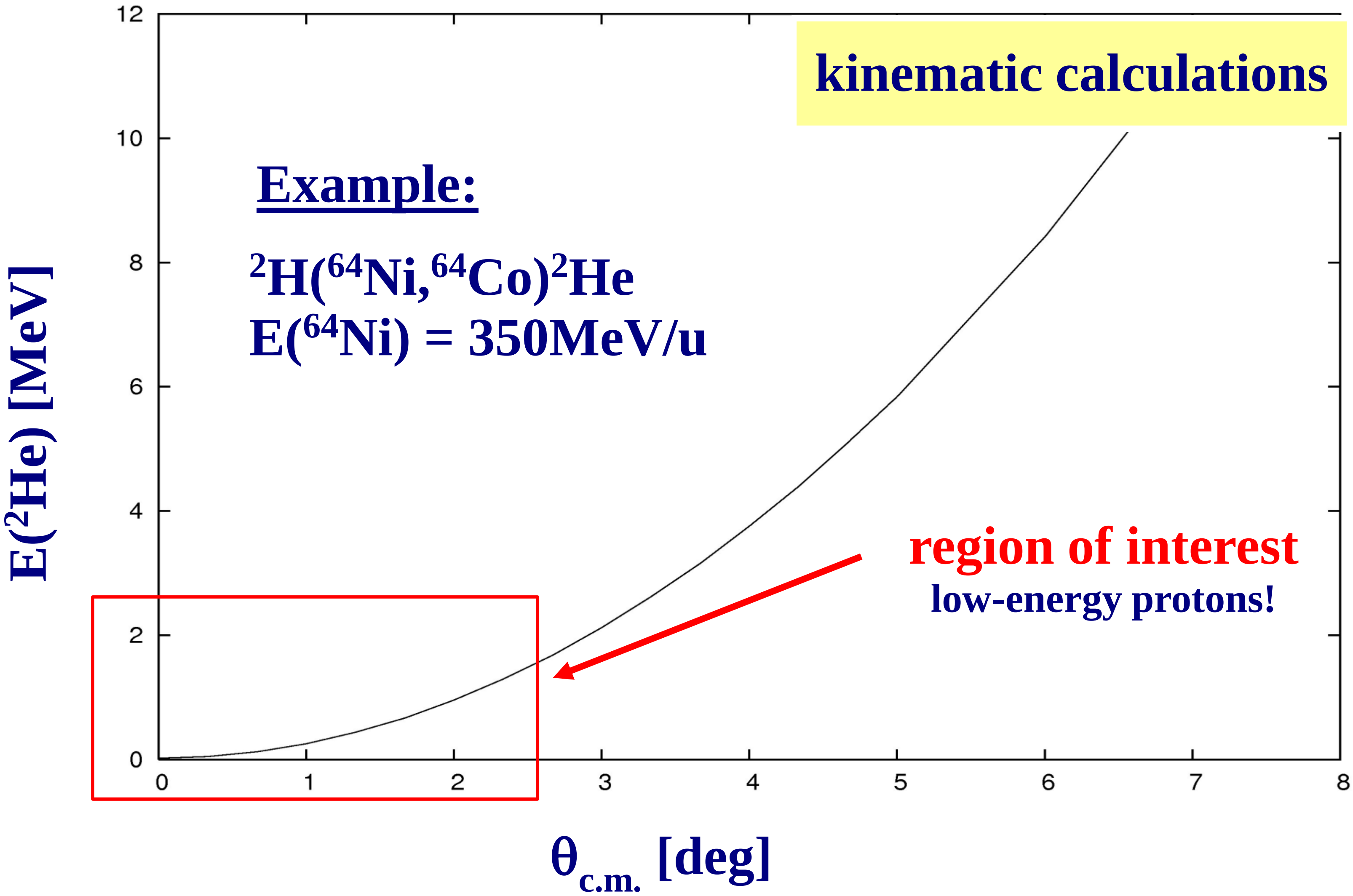


kinematic calculations

Example:

$^{2}H(^{64}Ni,^{64}Co)^{2}He$
$E(^{64}Ni) = 350 MeV/u$

How low?



kinematic calculations

Example:

$^2H(^{64}Ni,^{64}Co)^2He$

$E(^{64}Ni) = 350MeV/u$

region of interest

low-energy protons!

Detection system @ FAIR

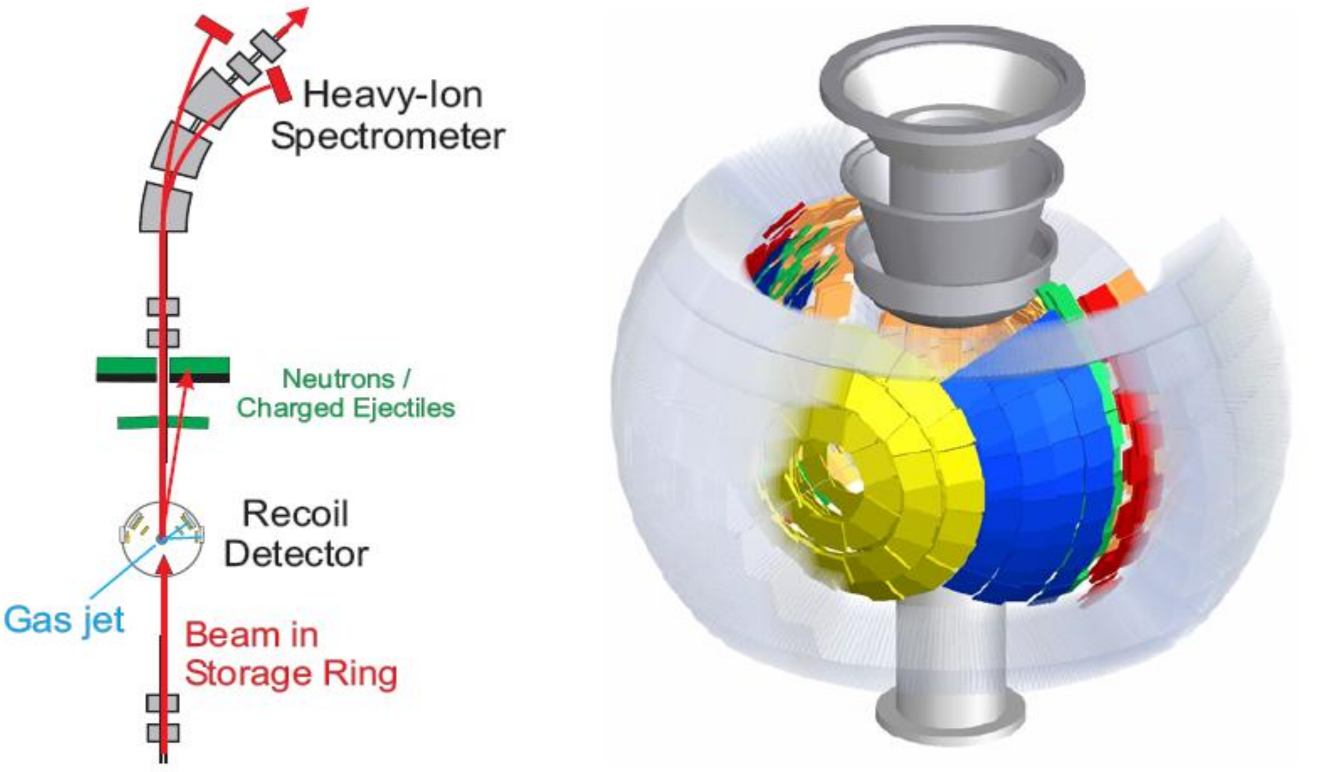


Figure 1: *Schematic view of the EXL detection systems. Left: Set-up built into the NESR storage ring. Right: Target-recoil detector surrounding the gas-jet target.*

- **Use of EXL recoil detector is under evaluation**
- **Design & implementation of a dipole magnet for the momentum analysis of the protons**

SN-explosion scenario

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

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

$$\frac{\#\text{ electrons}}{\#\text{ nucleons}}$$

- start of collapse at $T = 10^9$ K and $\rho = 3 \times 10^7$ g/cm^3

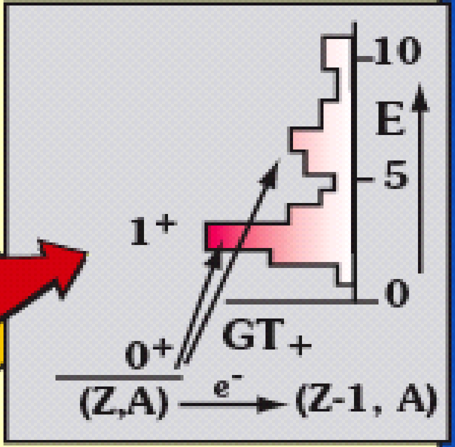
  accelerated by neutronization (de-leptonization)

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

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

escaping

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

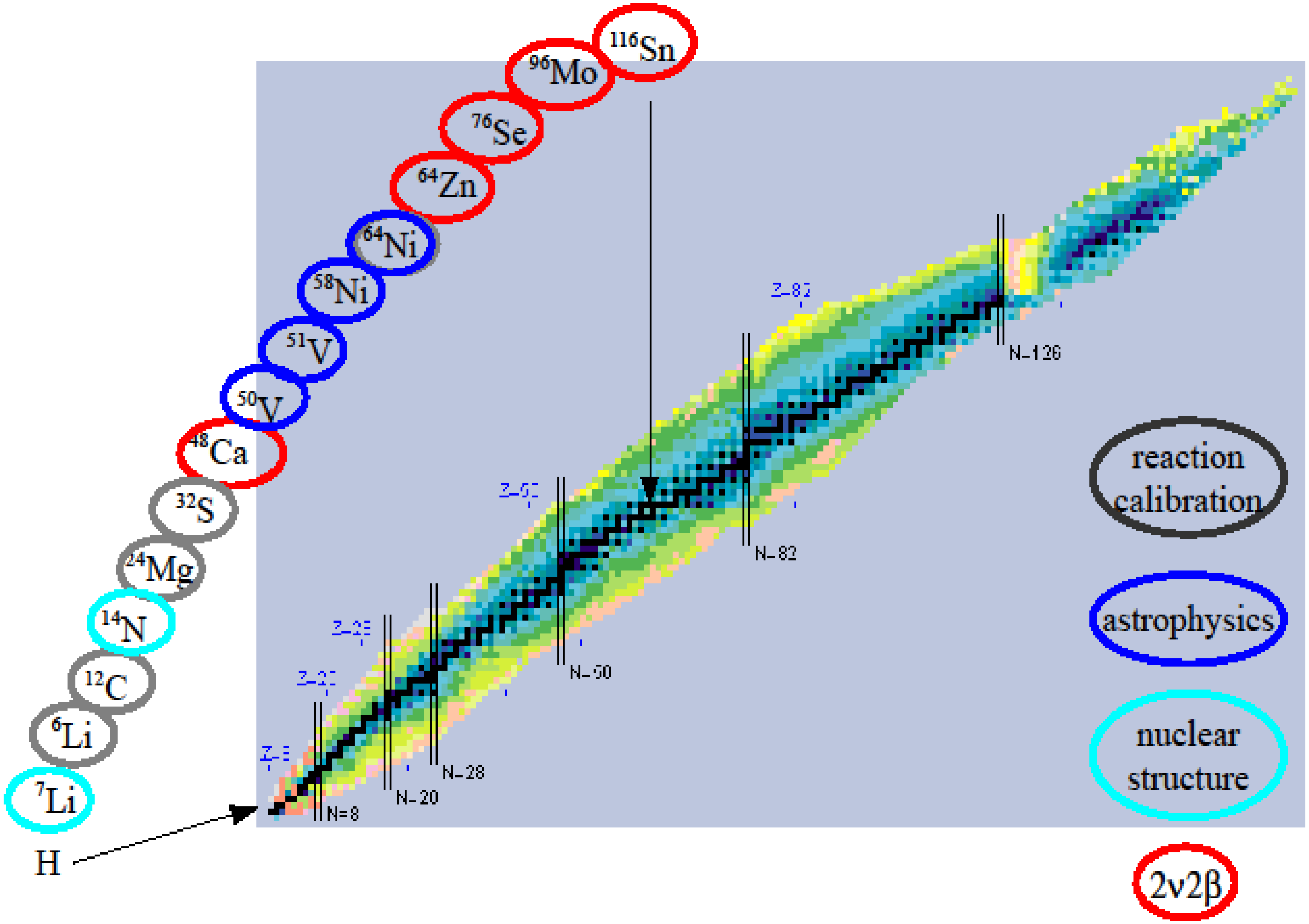


- loss of pressure
- accelerated collapse
- reduction of Y_e

  and loss of energy!!

Y_e at freeze-out determines the explosive energy!!

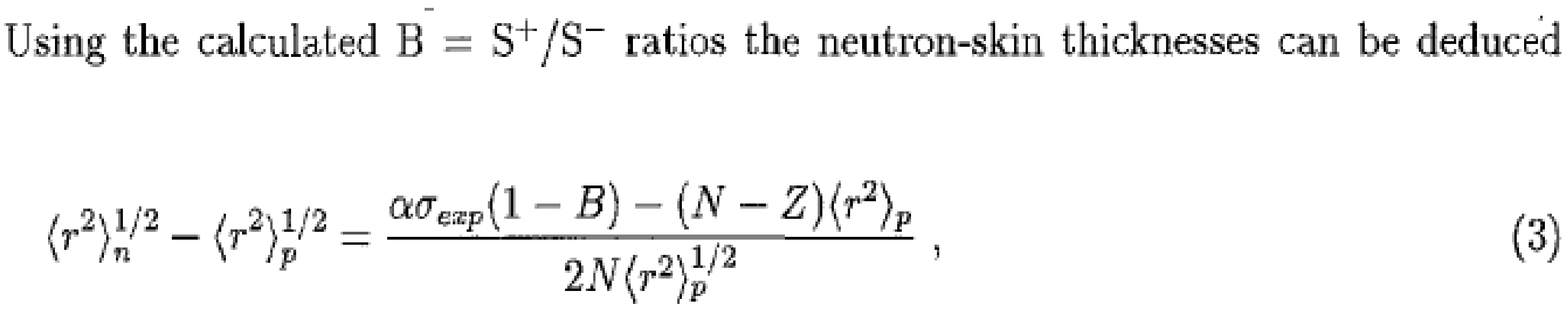
Performed (d,^{2}He) reactions @ KVI



Summed ΔL=1 strength depends on the neutron-skin thickness as follows:

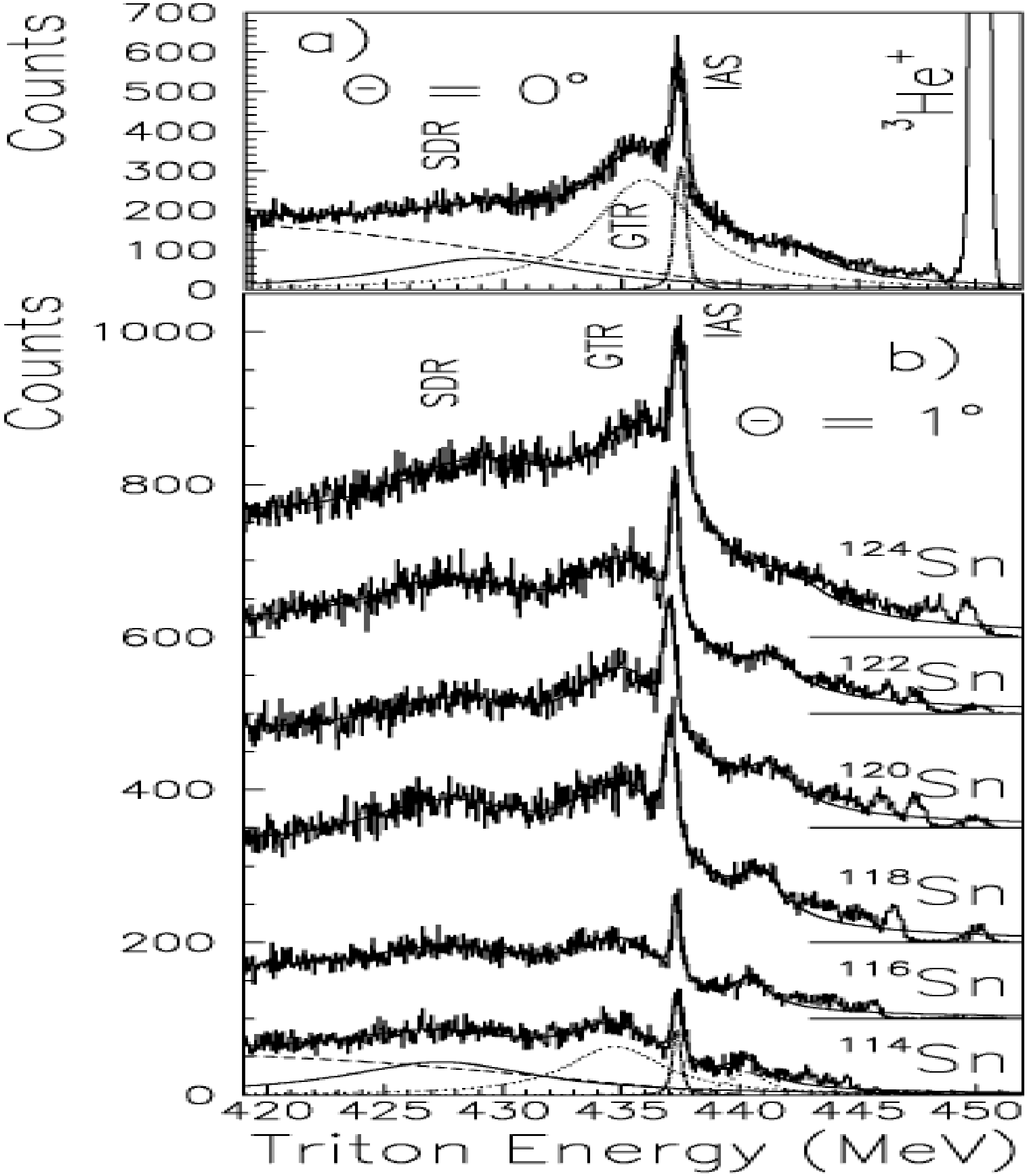
$$S^{-}_{IVSGDR} - S^{+}_{IVSGDR} = \frac{9}{2\pi}\left(N\langle r^2\rangle_n - Z\langle r^2\rangle_p\right)$$

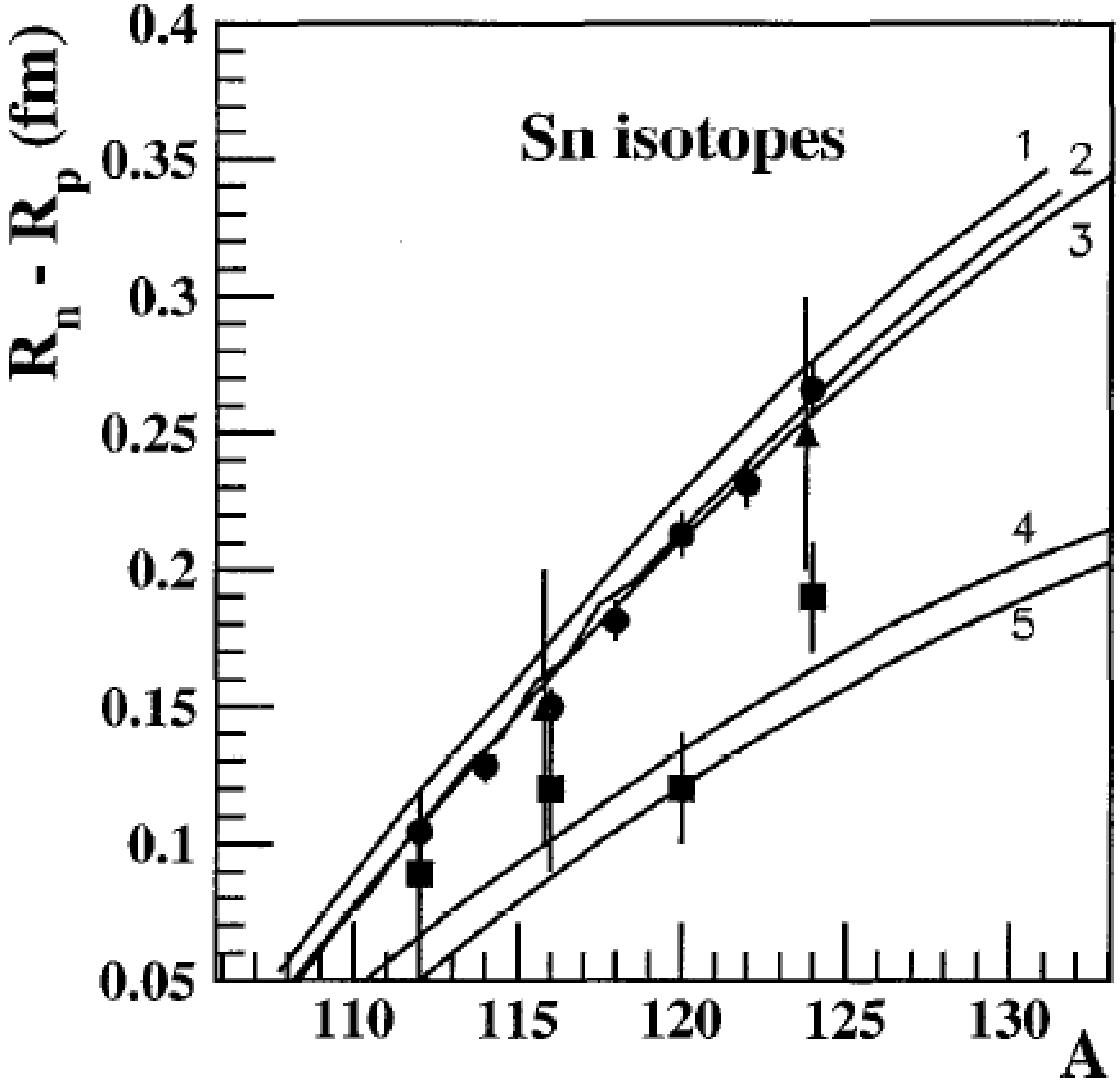
Here, S^{-} and S^{+} are the spin-dipole total strengths in β^{-} and β^{+} channels



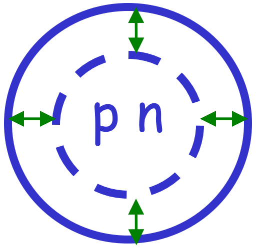
Using the calculated B = S^{+}/S^{-} ratios the neutron-skin thicknesses can be deduced

$$\langle r^2\rangle_n^{1/2} - \langle r^2\rangle_p^{1/2} = \frac{\alpha\sigma_{exp}(1-B) - (N-Z)\langle r^2\rangle_p}{2N\langle r^2\rangle_p^{1/2}}\ , \qquad (3)$$

a)
Θ = 0°
Counts
700
600
500
400
300
200
100
0
SDR
GTR
IAS
$^3He^+$
b)
Θ = 1°
Counts
1000
800
600
400
200
0
SDR
GTR
IAS
^{124}Sn
^{122}Sn
^{120}Sn
^{118}Sn
^{116}Sn
^{114}Sn
420
425
430
435
440
445
450
Triton Energy (MeV)

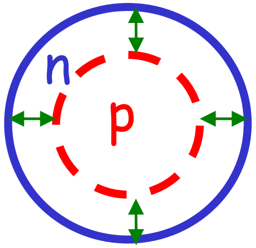

Sn isotopes
$R_n - R_p$ (fm)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
110
115
120
125
130
A
1
2
3
4
5

Isovector giant monopole resonances



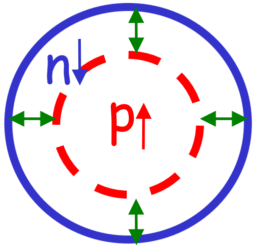
$\Delta L=0$ $\Delta S=0$ $\Delta T=0$

ISGMR



$\Delta L=0$ $\Delta S=0$ $\Delta T=1$

IVGMR



$\Delta L=0$ $\Delta S=1$ $\Delta T=1$

IVSGMR

$O=r^{\lambda}[\sigma\otimes Y_L]_J\tau_-$

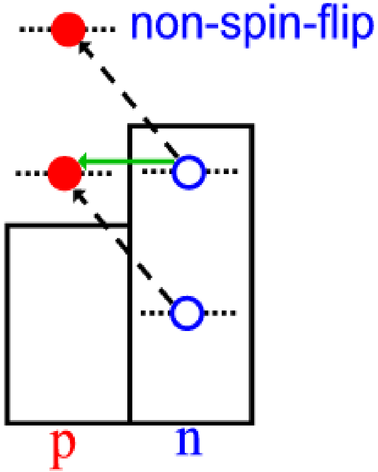
IAS: $\lambda=0$ S=0 L=0 J=0

GTR: $\lambda=0$ S=1 L=0 J=1

IVGMR: $\lambda=2$ S=0 L=0 J=0

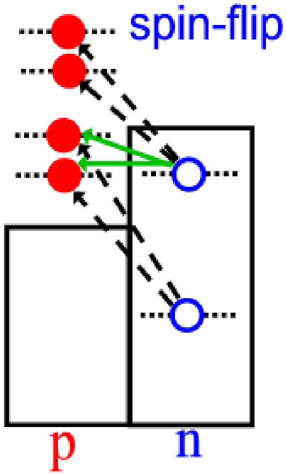
IVSGMR: $\lambda=2$ S=1 L=0 J=1

IVSGDR: $\lambda=1$ S=1 L=1 J=0,1,2



—IAS - - -IVGMR

$\Phi_{njl}\rightarrow\Phi_{njl}$ $\Phi_{njl}\rightarrow\Phi_{n+1jl}$

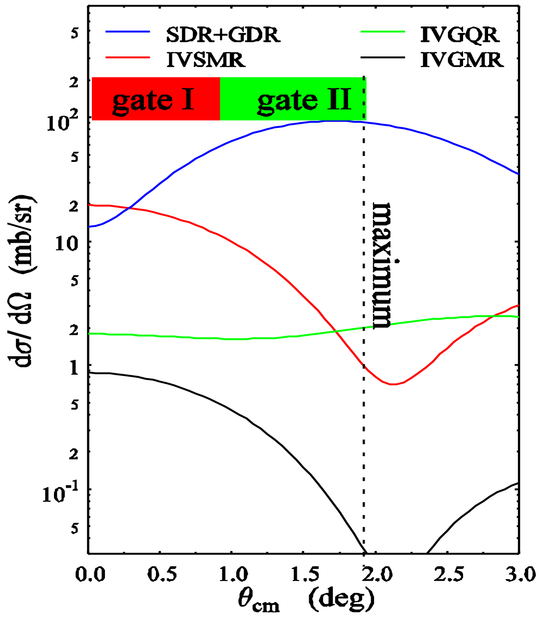


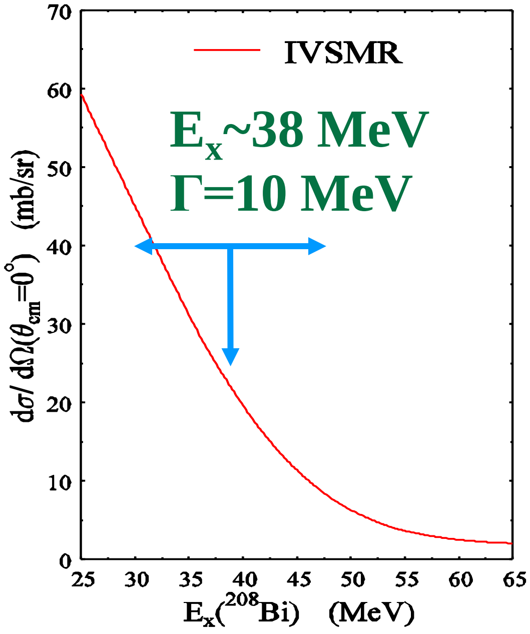
—GTR - - -IVSGMR

$\Phi_{njl}\rightarrow\Phi_{njl}$ $\Phi_{njl}\rightarrow\Phi_{n+1jl}$

$\Phi_{njl}\rightarrow\Phi_{nj+1l}$ $\Phi_{njl}\rightarrow\Phi_{n+1j+1l}$

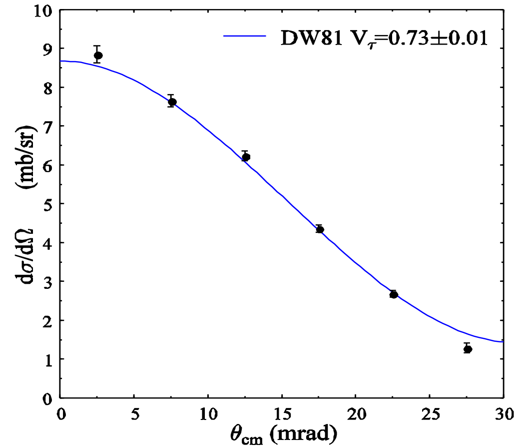
Measurement of IVSGMR via ^{208}Pb(^{3}He,t+p)





- **DW81 (Raynal)**
- **Effective ^{3}He-N potential**
  - **V_τ=0.73±0.01 MeV (IAS)**
  - **$V_{\sigma\tau}$=-2.1 ±0.2 MeV (known ratio to V_τ)**
  - **$V_{T\tau}$=-2.0 MeV/fm^2**
- **most coherent 1p-1h wave-function (normal modes).**

^{208}Pb(^{3}He,t)^{208}Bi(IAS)



Use *difference-of-angle* to identify the monopole excitations

Continuum suppression

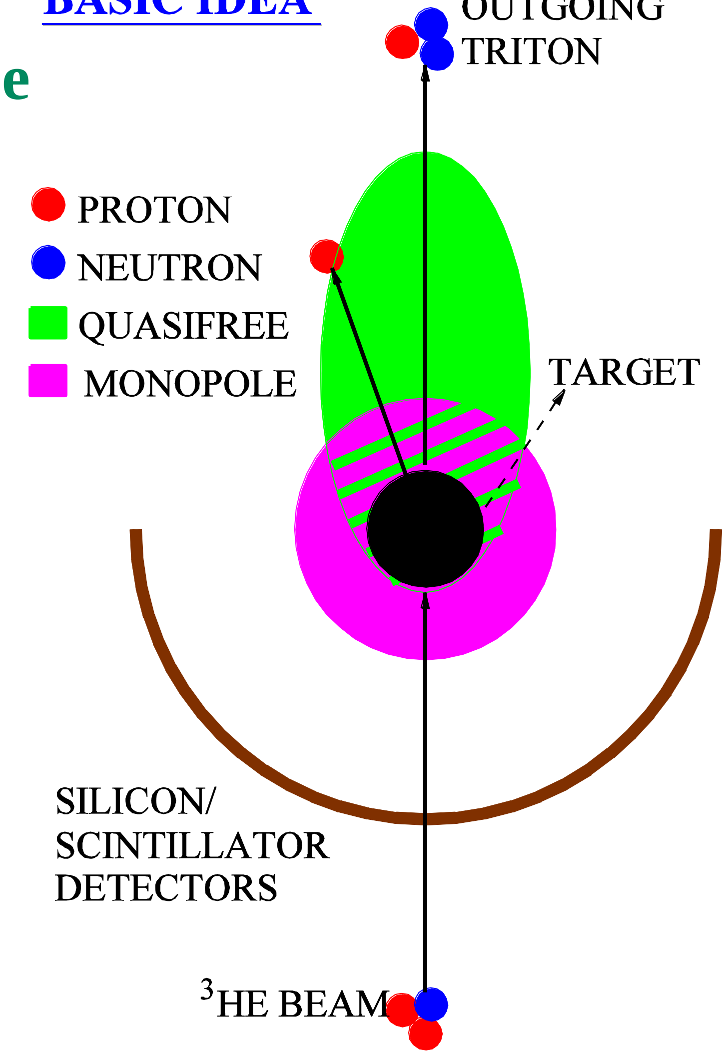
Physical background (continuum) due to:

- breakup-pickup reactions
- quasifree knock-on reactions

IVSGMR is wide (~10 MeV) and lying on top of the continuum.

Continuum has a very flat angular distribution at forward angles

BASIC IDEA



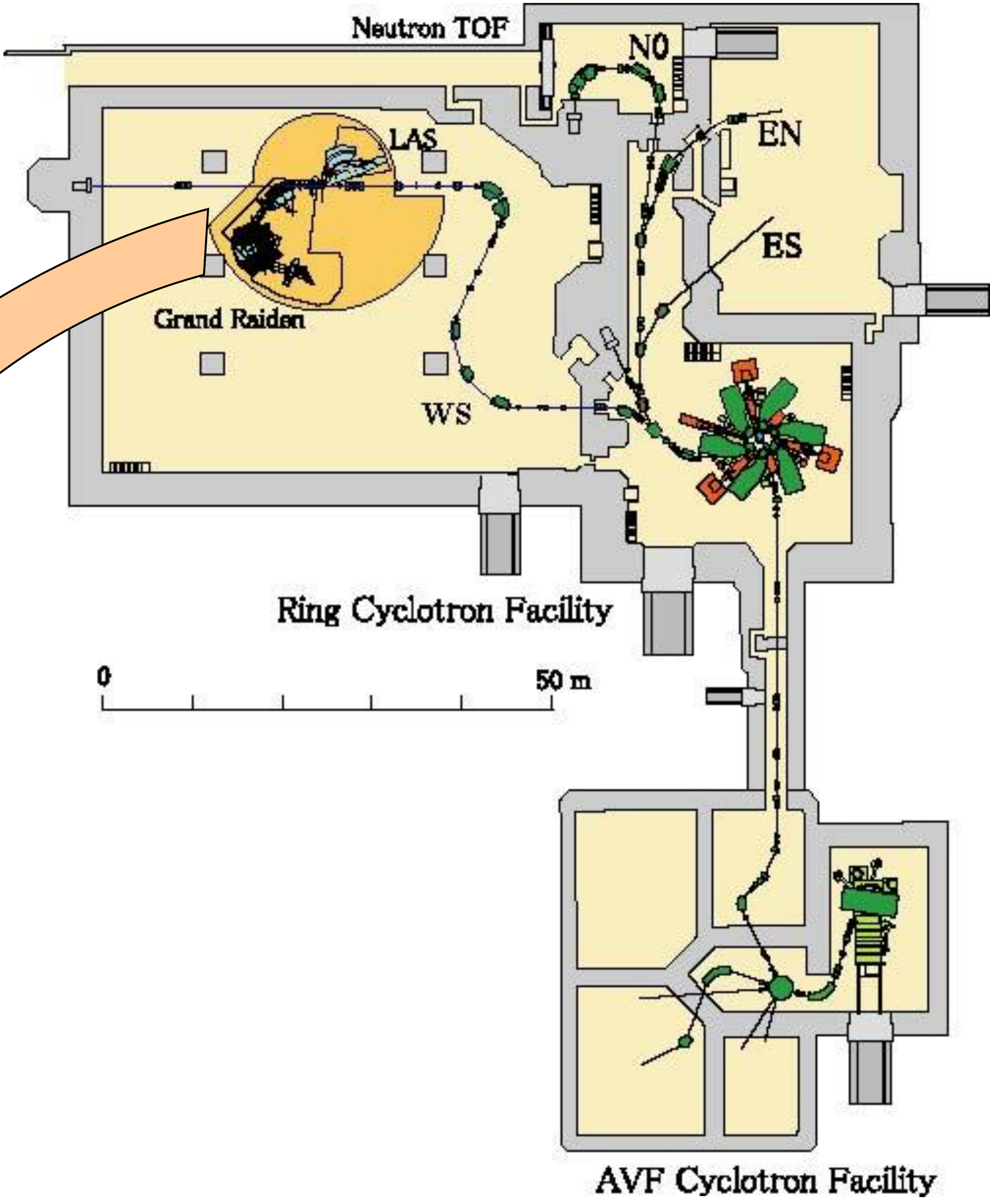
Experiment

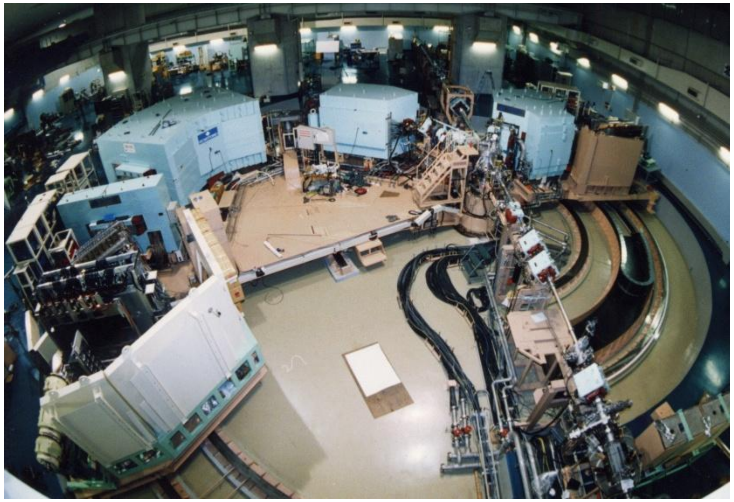
- **RCNP facility**

K=400 MeV ring cyclotron

Grand Raiden spectrometer

- **Beam: ^{3}He^{++}, 450 MeV**
- **Target: ^{208}Pb foil**

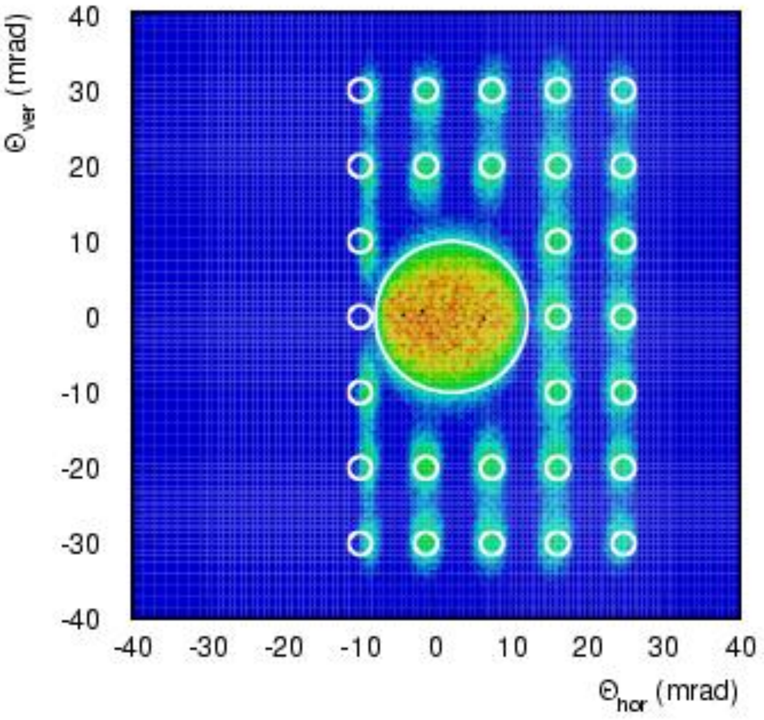




M. Fujiwara et al., NIM A 422 (1999) 484

Experimental Considerations

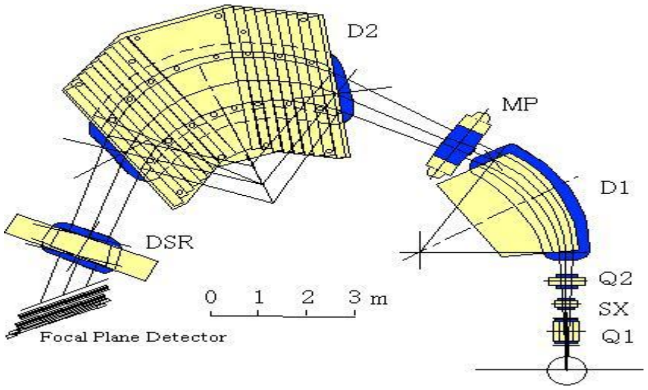
- **Over-focus mode for Grand-Raiden (H. Fujita *et al*. NIM A469, 55) refined to get:**



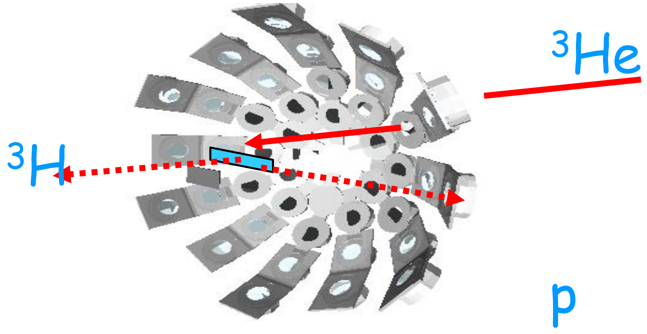
- **Vertical angle resolution: 0.4° FWHM**
- **Horizontal angle resolution: 0.2° FWHM**
- **Negligible systematic errors**
- **Sieve-slit is used for calibrations**

Experiment: 410 MeV ^{3}He-beam @ RCNP

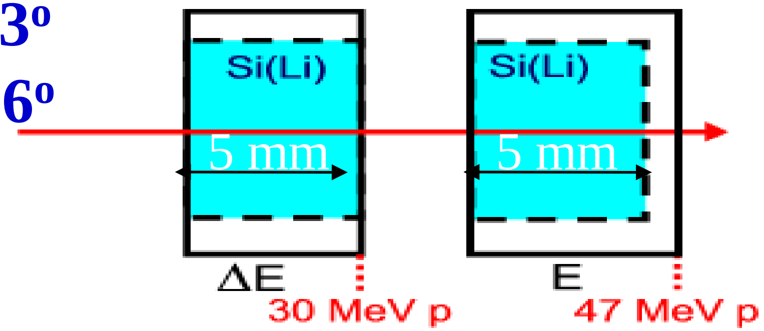
Grand Raiden @ RCNP



- Measure both t-singles and t-p coincidences



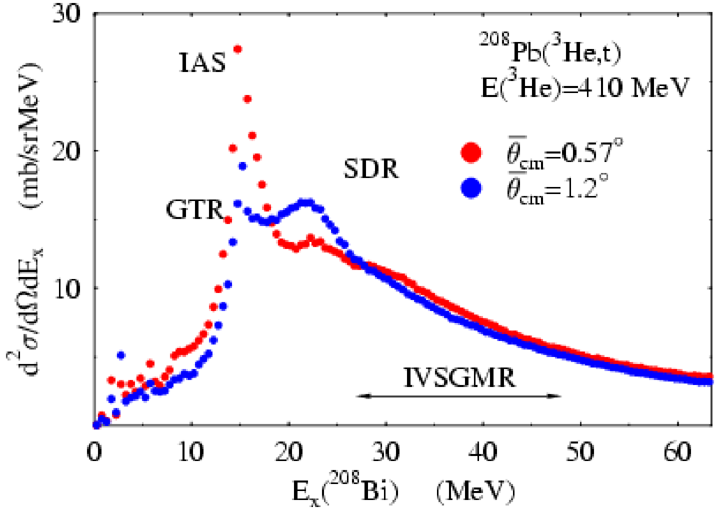
- **8 ΔE-E telescopes**
  - **4@113^o**
  - **4@136^o**



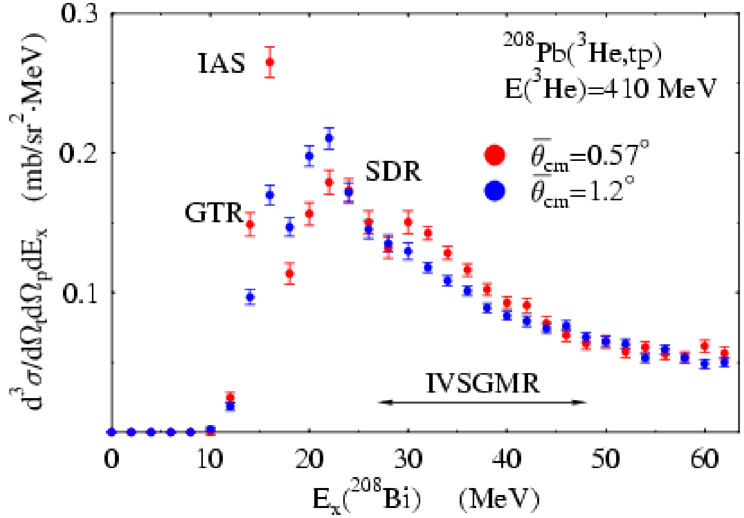
Results

R.G.T. Zegers et al., PRL 90 (2003) 202501

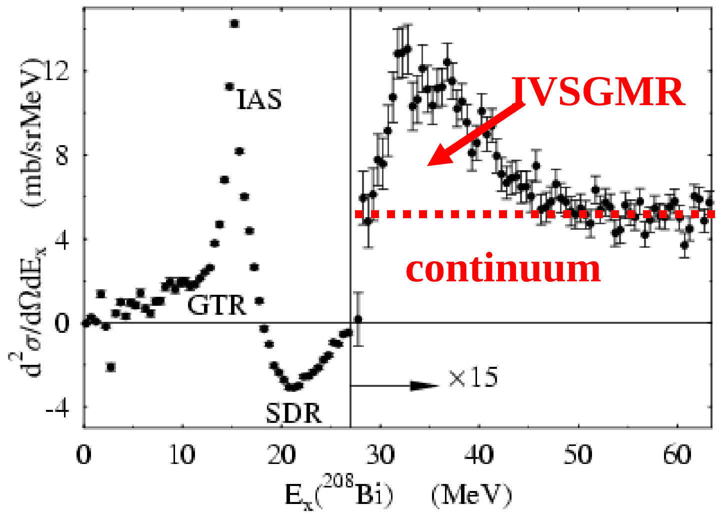
t singles

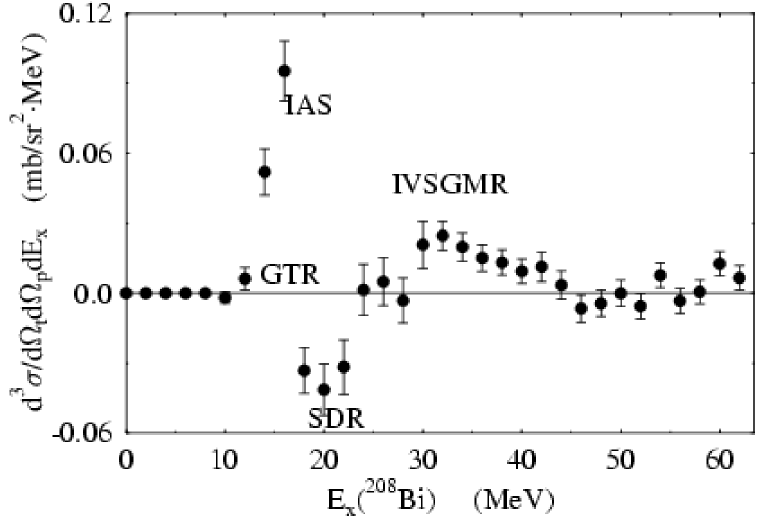


t-p coincidences



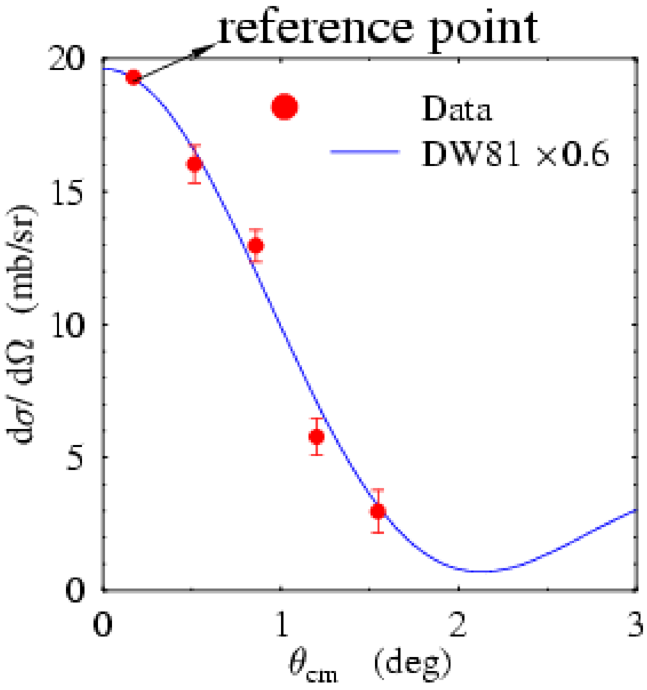
Difference of angles





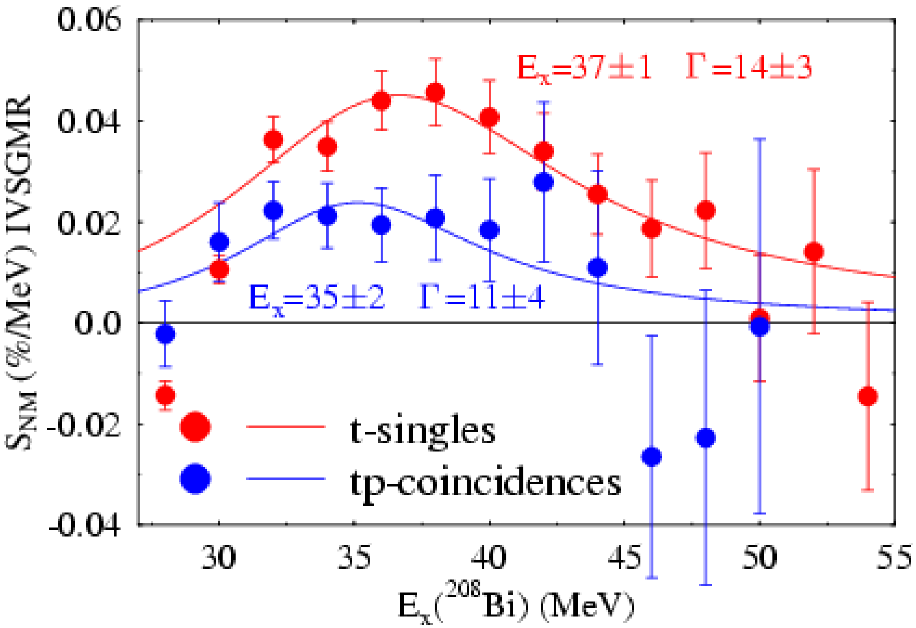
Angular distribution

Use difference-of-angle method between narrow angular bins to extract angular distribution of the resonance



IVSGMR angular distribution confirmed

Strength exhaustion



Summed strength: (46±4±10)•10^3 fm^4
(contribution from IVGMR subtracted)

method	Exhaustion(%) ($\pm\sigma_{stat}$ $\pm\sigma_{sys}$)
Normal modes	**60±5±14**
Tamm-Dancoff **Hamamoto & Sagawa** **PRC 62, 024319**	**68±6±17**
Continuum RPA **Rodin & Urin** **NPA 687, 276c**	**103±9±25**
HF-RPA* **Auerbach & Klein** **PRC 30, 1032**	**210±16±45**

Systematic errors:

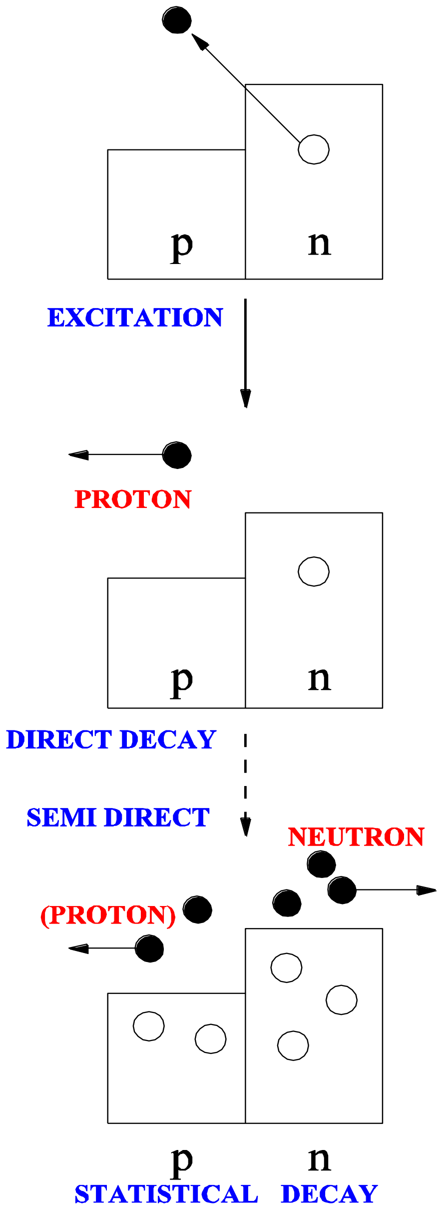
- **extrapolation of continuum: 5%**
- **high-lying GT strength: small**
- **tail of the IVSGDR: 10%**
- **DWBA: 10% of measured value**

*** Different operator, includes GT**

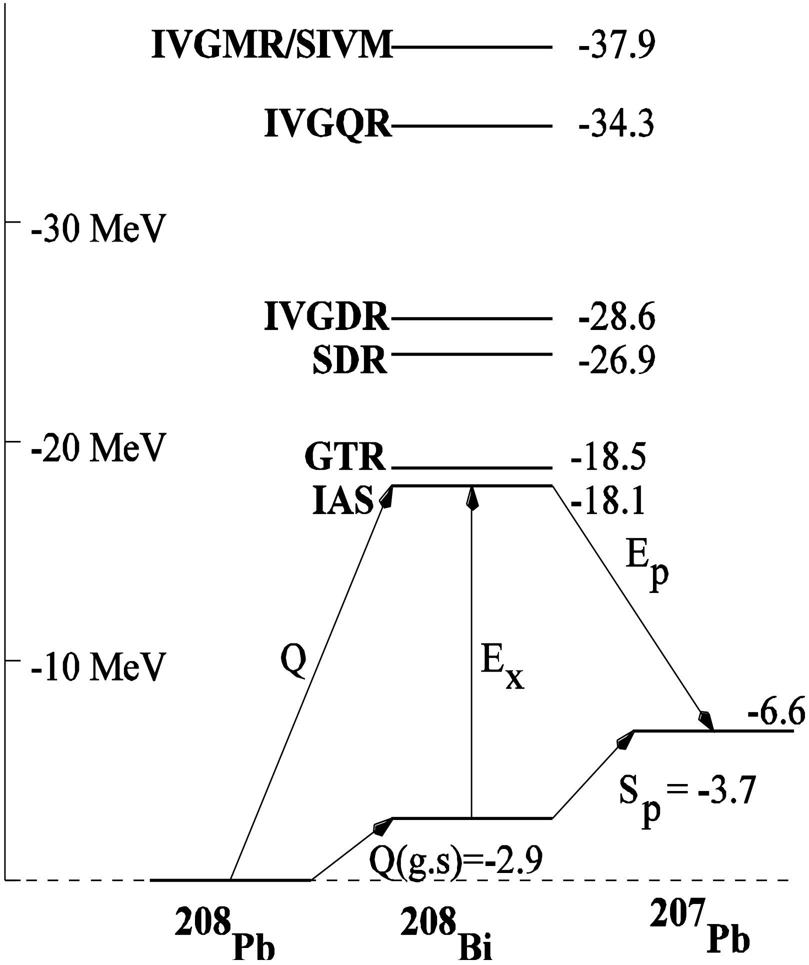
Decay studies

- **Successful:**
  - **GTR, IVSGDR in ^{208}Pb(^{3}He,t+p) at 450 MeV (Akimune et al.)**
  - **IVGMR/IVSGMR in Pb(^{3}He,t+p) at 177 MeV at KVI**

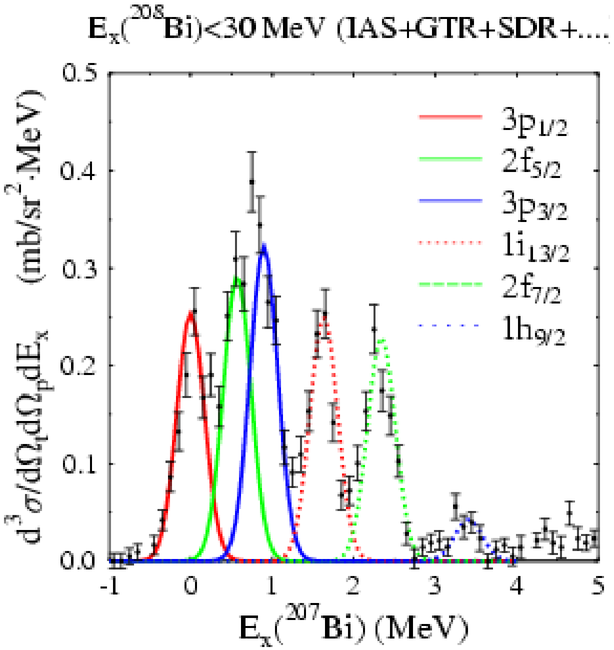
    & 410 MeV at RCNP (Zegers et al.)
- **Unsuccessful:**
  - **IVGMR/IVSGMR ^{124}Sn(^{3}He,t+n) at 200 MeV at IUCF**

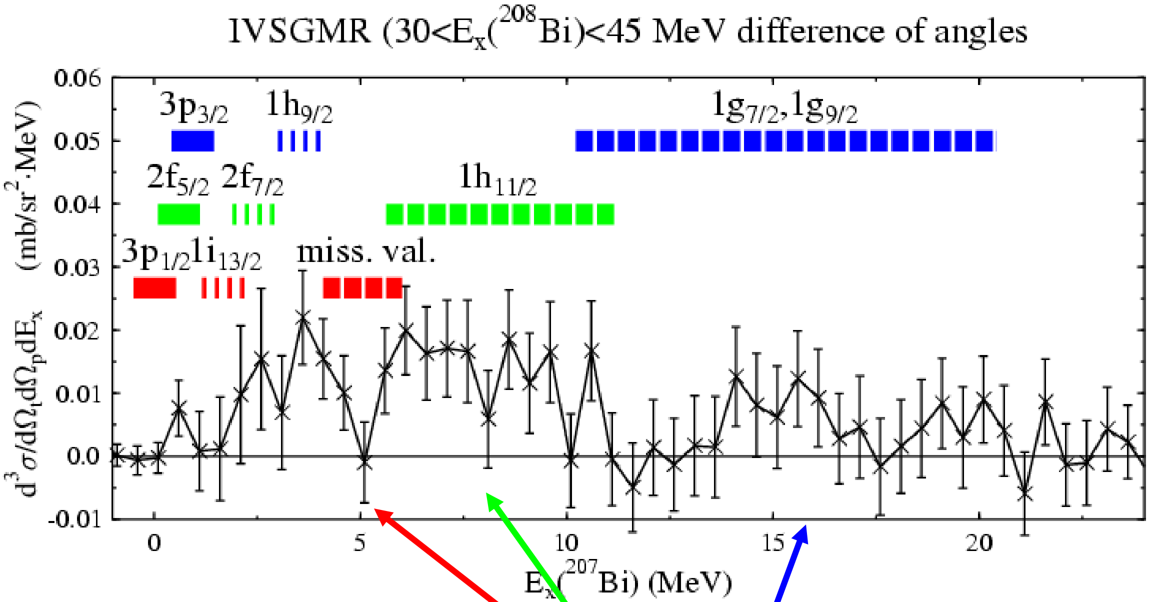


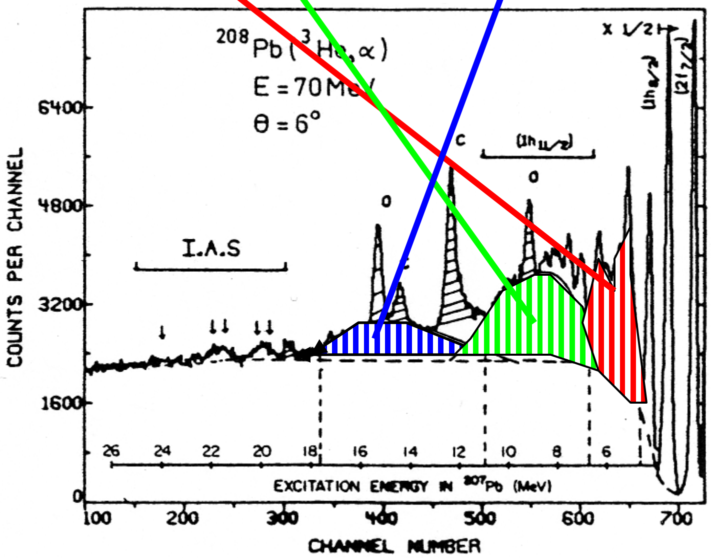
Proton decay from the IVSGMR



Final state spectra







Comparison with
$^{208}Pb(^3He,\alpha)$
Galès *et al.*
Phys. Rep. 166,255

Final state population in ^{207}Pb

Final state	Data(%)	Theory(%)*
$3p_{1/2}$ $2f_{5/2}$ $3p_{3/2}$	< 3	11.3
$1i_{13/2}$		21.4
$2f_{7/2}$ $1h_{9/2}$	13±5	9.5
$1h_{11/2}$	22±8	22.8
$1g_{7/2}$ $1g_{9/2}$	17±8	
All	52±12	66

*Rodin & Urin NPA 687, 276c (continuum RPA)

Large discrepancies for partial **branchings**!!

Outlook

Radioactive ion beams will be available at energies where it will be possible to study GT transitions (RIKEN, NSCL, FAIR, EURISOL)

- **Determine GT strength in unstable *sd* & *fp* shell nuclei**
- **Measure ISGMR and ISGDR in extended isotope chain**
- **Unravel the nature of the pygmy dipole resonance**
- **Use IV(S)GDR as tool to determine n-skin [IV(S)GDR]**
- **Exotic excitations such as double GT (SHARAQ)**