Spin-isospin responses by charge-exchange reactions and implications for astrophysics

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KVI, Groningen & GANIL, Caen

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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**
   (Dieter Frekers' Talk)
6. **Conclusions and outlook**

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.
  $\Rightarrow$ 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

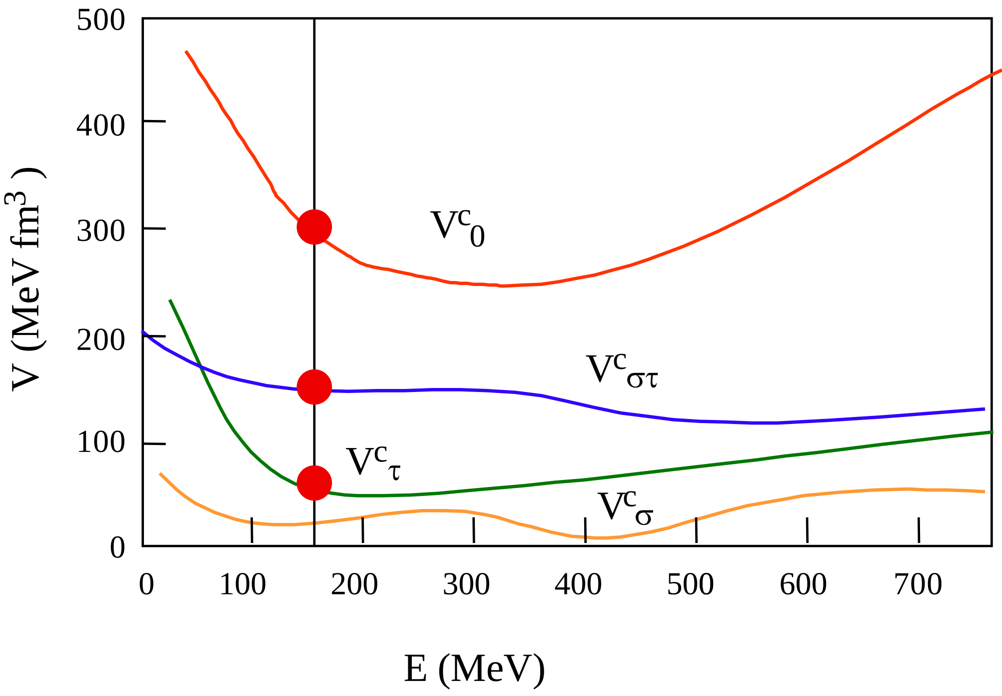
(n,p)-type ($\Delta T_z = +1$)

- 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

(^{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

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

kinematic factor

distortion factor

nucleon-nucleus interaction

Gamow-Teller strength

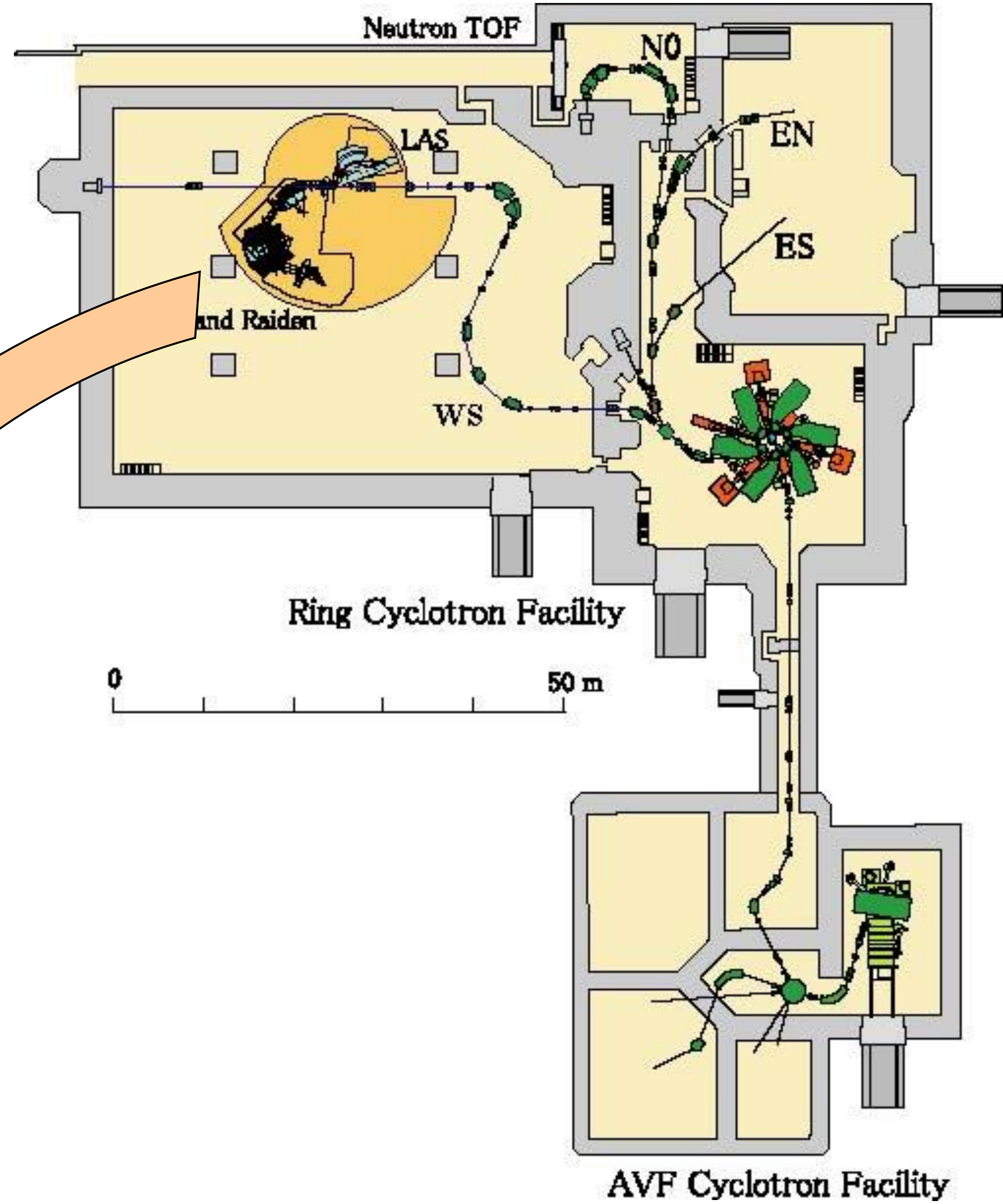
Calibration of B(GT) to cross section for known transitions (*e.g.* from β-decay)

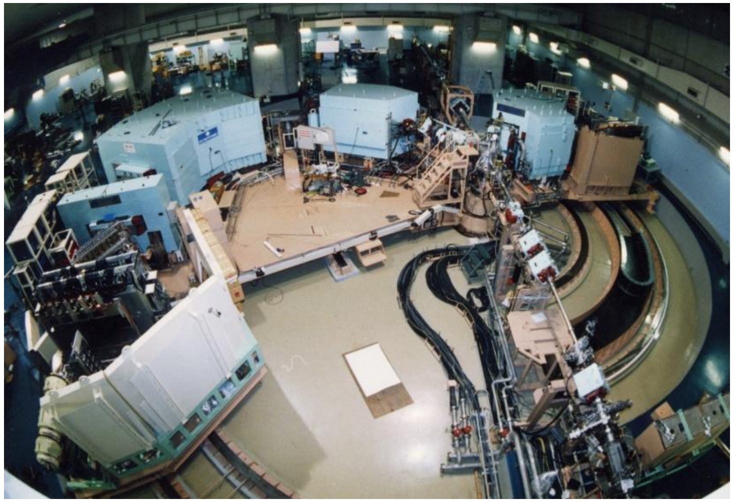
Experiments

- **RCNP facility**

  K=400 MeV ring cyclotron

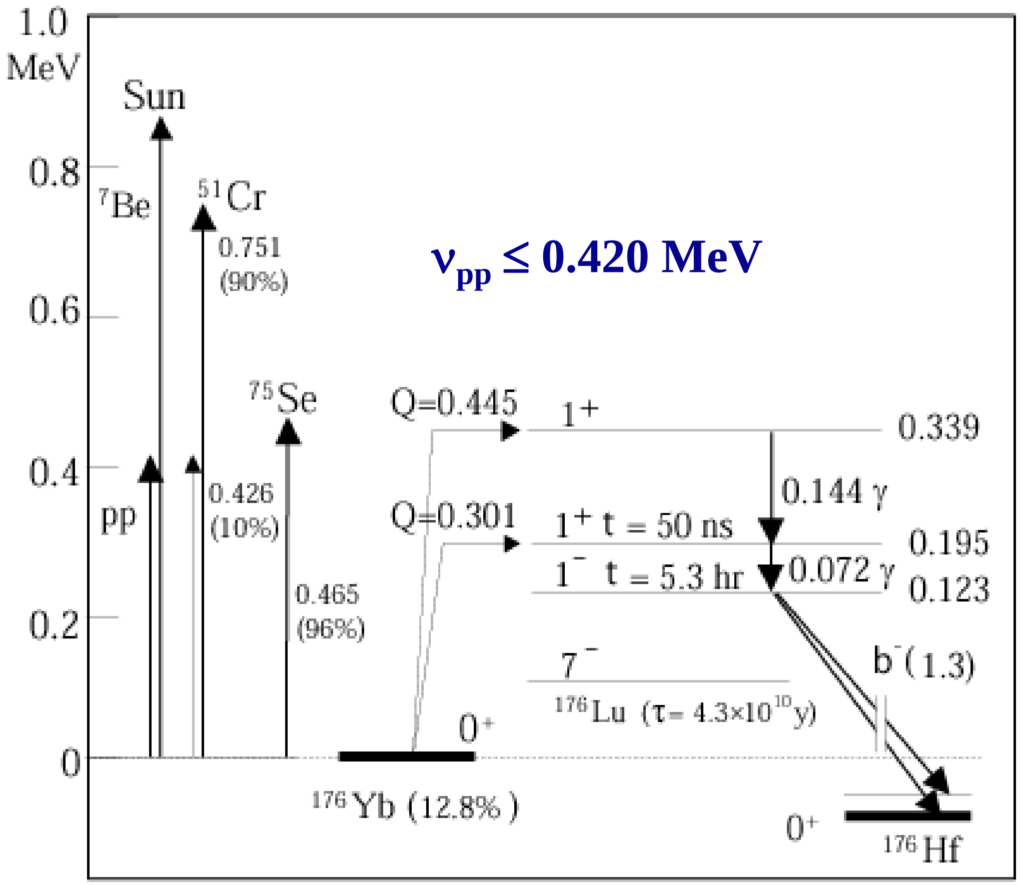
  Grand Raiden spectrometer
- **Beam: $^3He^{++}$, 450 MeV**



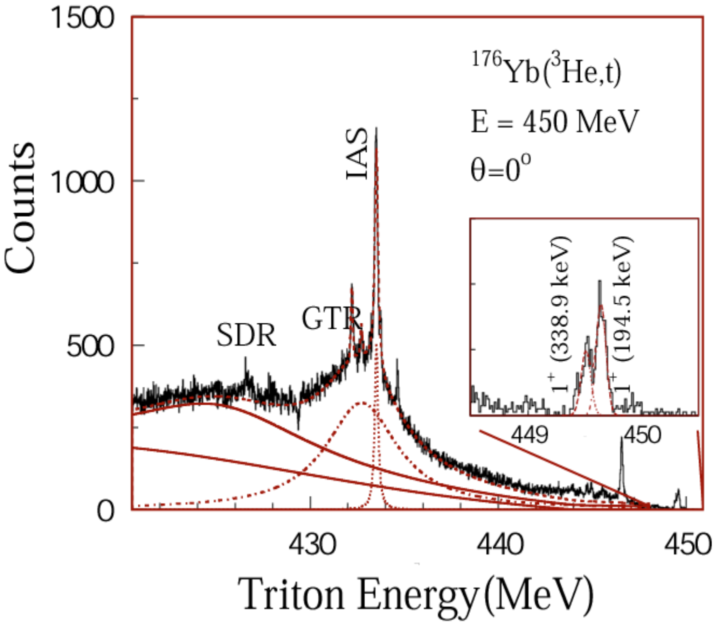


M. Fujiwara *et al.*, NIM A422 (1999) 484

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



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



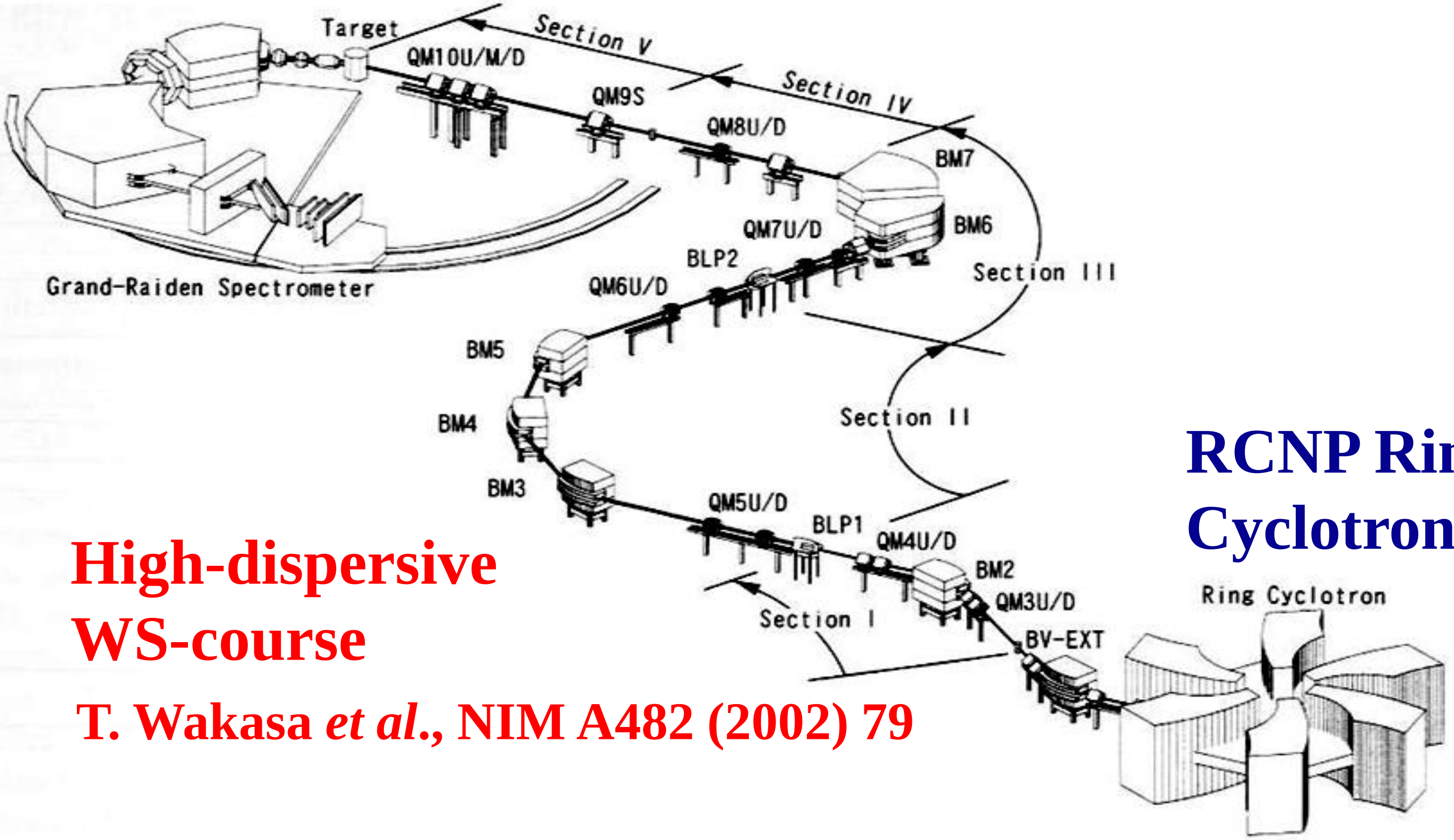
Resolution ≈ 100 to 130 keV

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

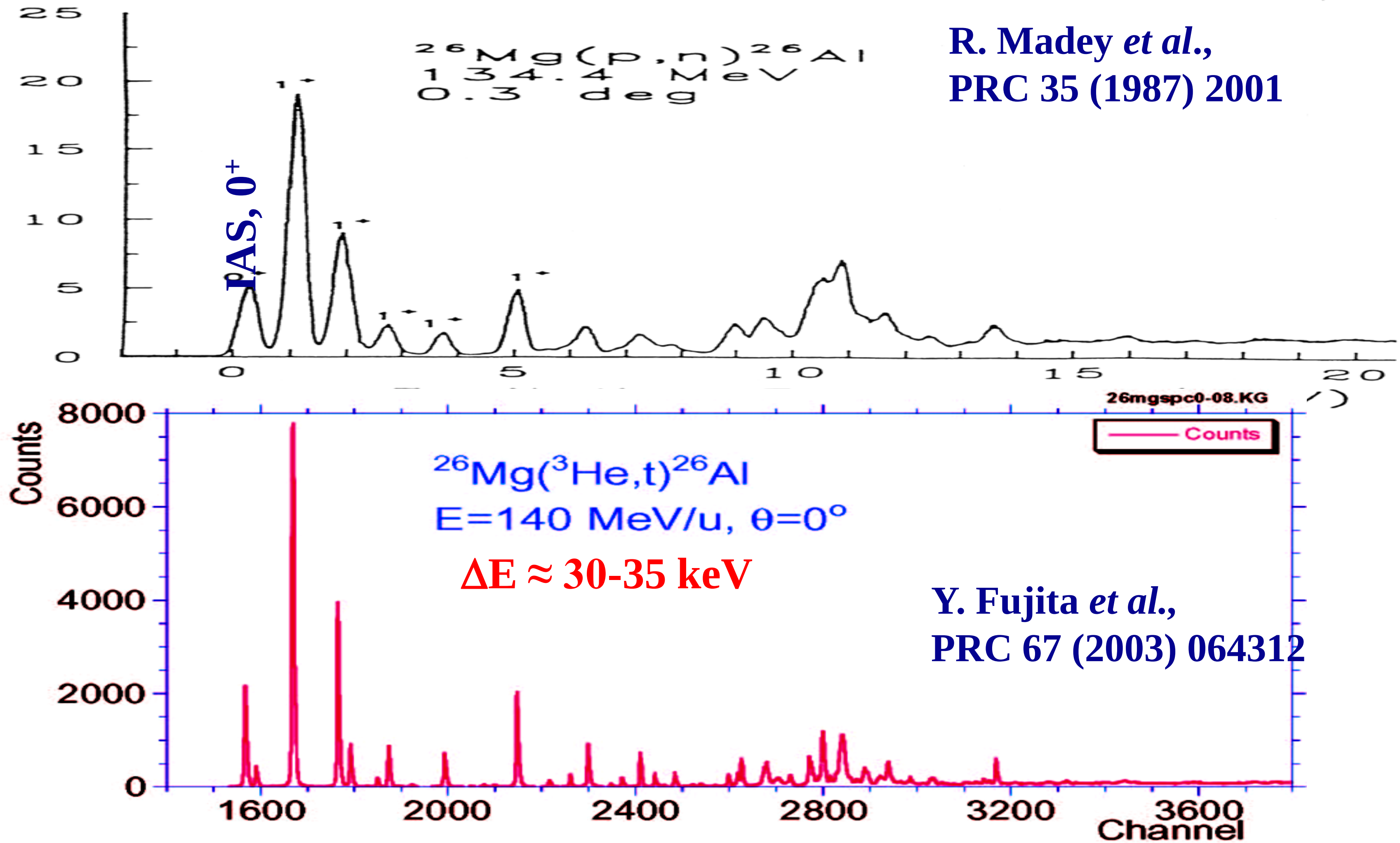


RCNP Ring Cyclotron

High-dispersive WS-course

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

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



Prominent states are GT states and the IAS !

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

E(^{3}He) = 420 MeV

ΔE = 42 keV

Bexp(GT+) =

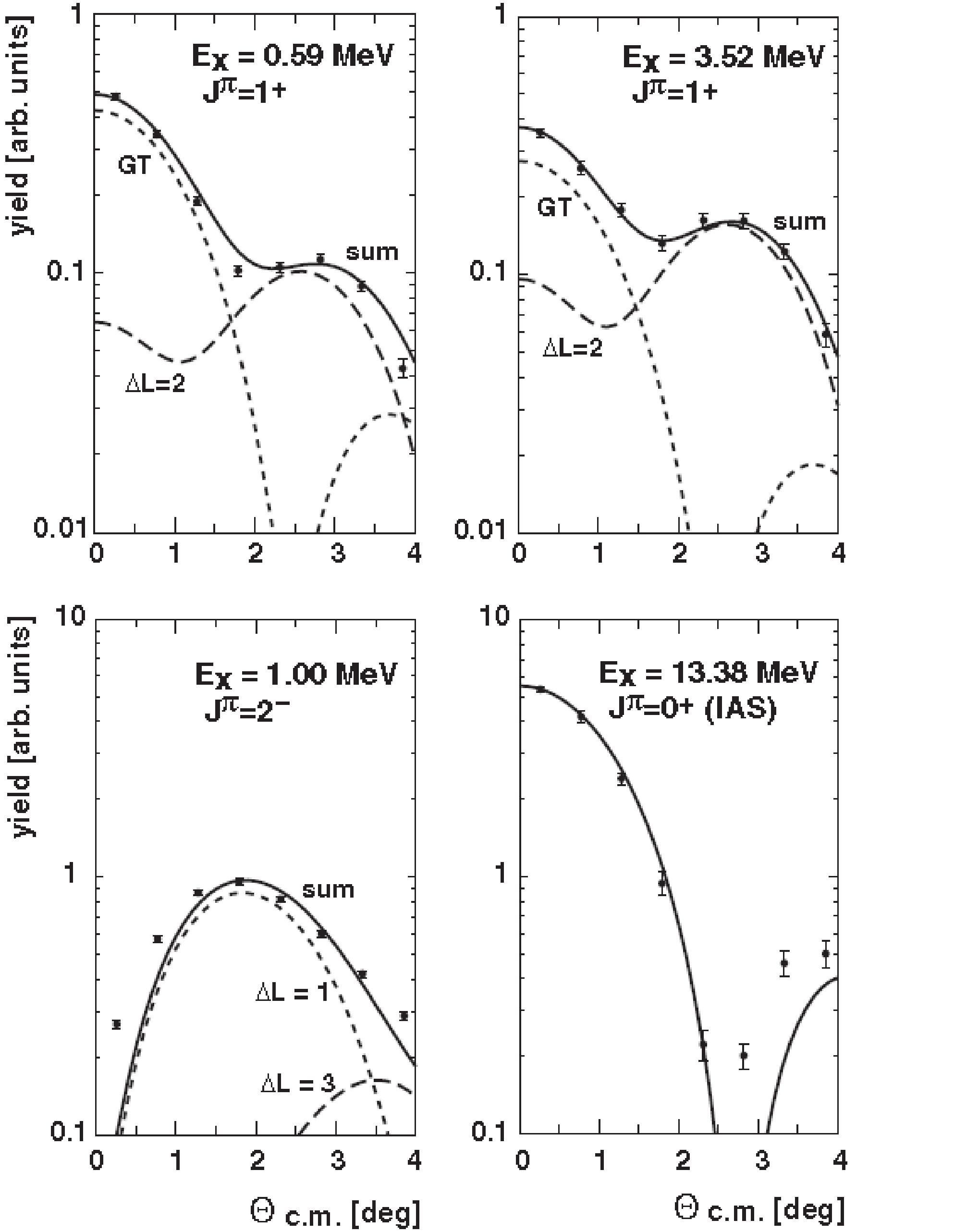
$$\frac{d\sigma(q=0)}{d\Omega}\cdot\left[\frac{d\hat{\sigma}(GT)}{d\Omega}\right]^{-1}$$

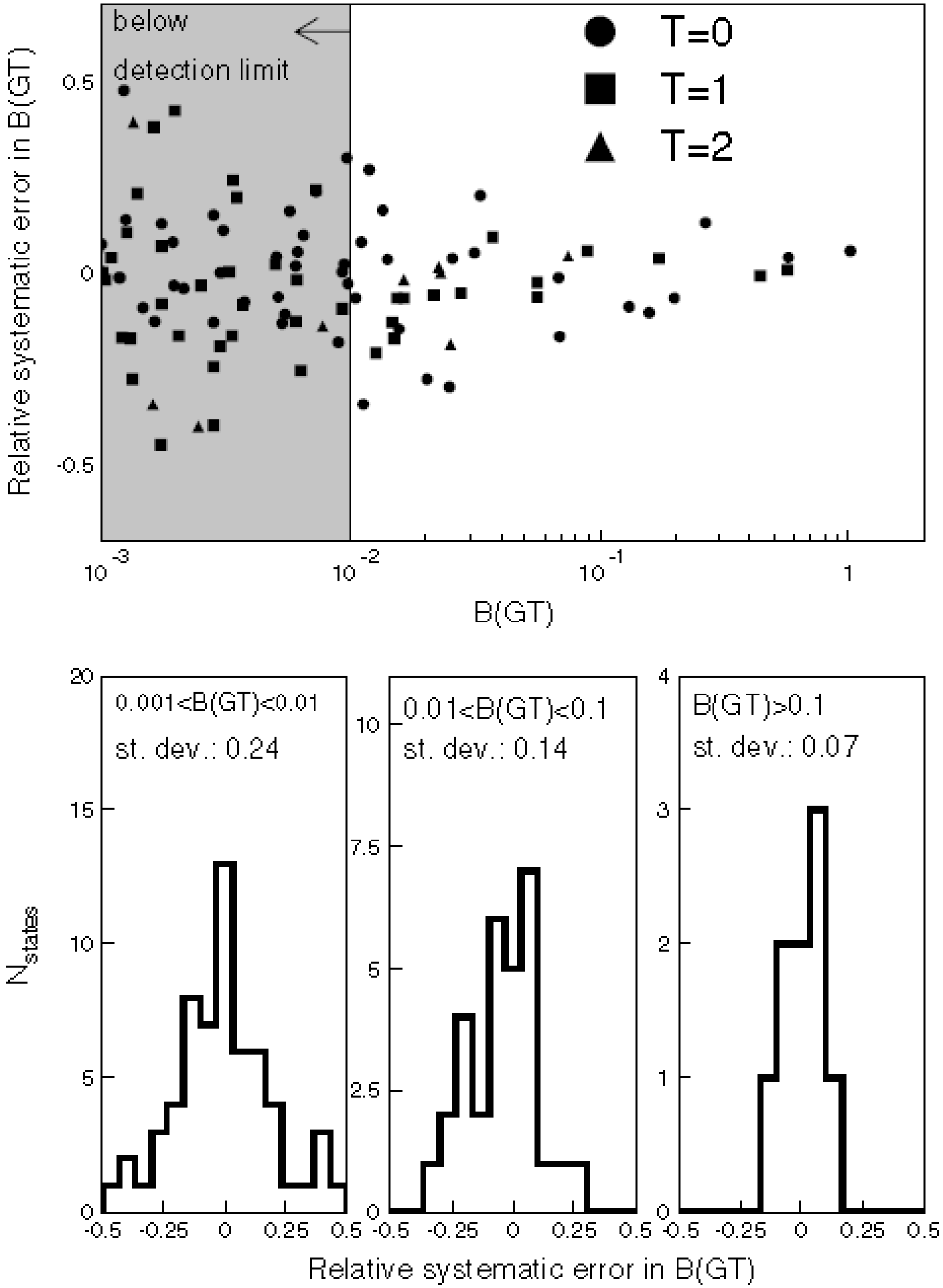
extrapolated (DWBA)

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.**

fp-shell nuclei: large scale shell model calculations

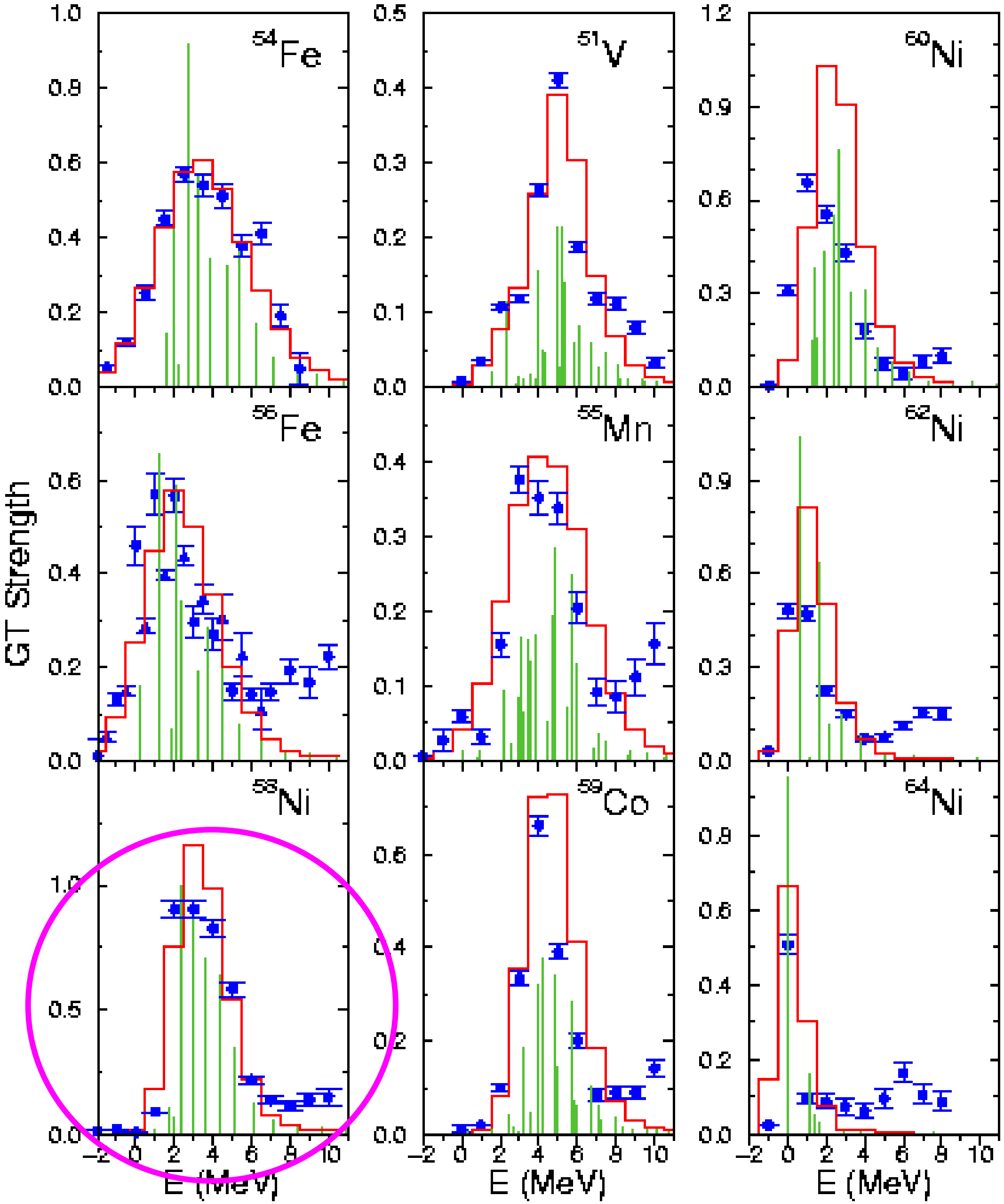
E. Caurier *et al.*
NPA 653 (1999) 439

- **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**

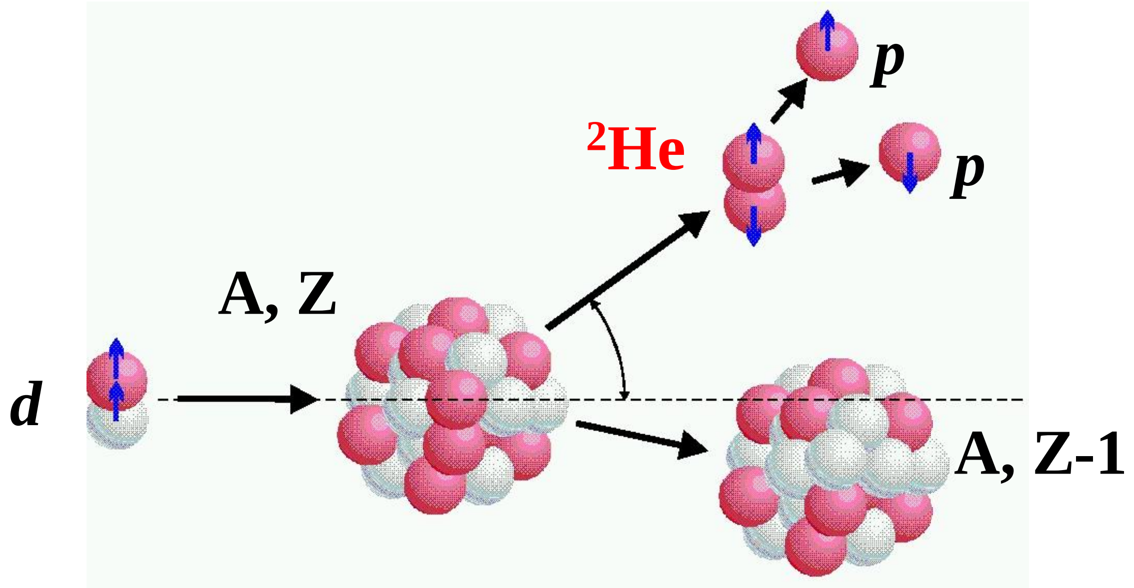
Case study: ^{58}Ni

E. Caurier et al. / Nuclear Physics A 653 (1999) 439-452



KVI GSI university of groningen

Exclusive excitations $\Delta S=\Delta T=1$: (d,^{2}He)

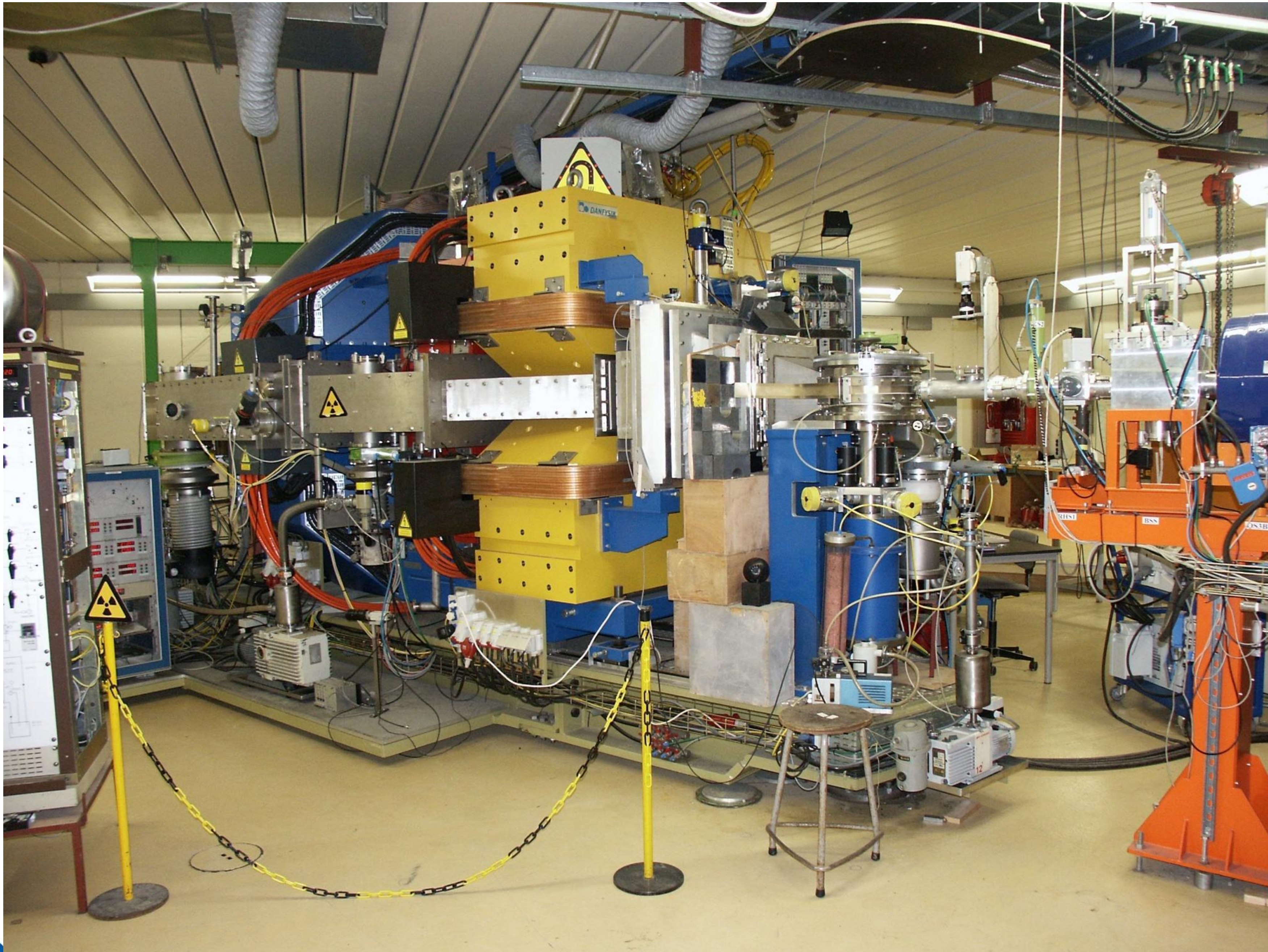


$^3S_1$ deuteron $\Rightarrow$ $^1S_0$ di-proton (^{2}He)

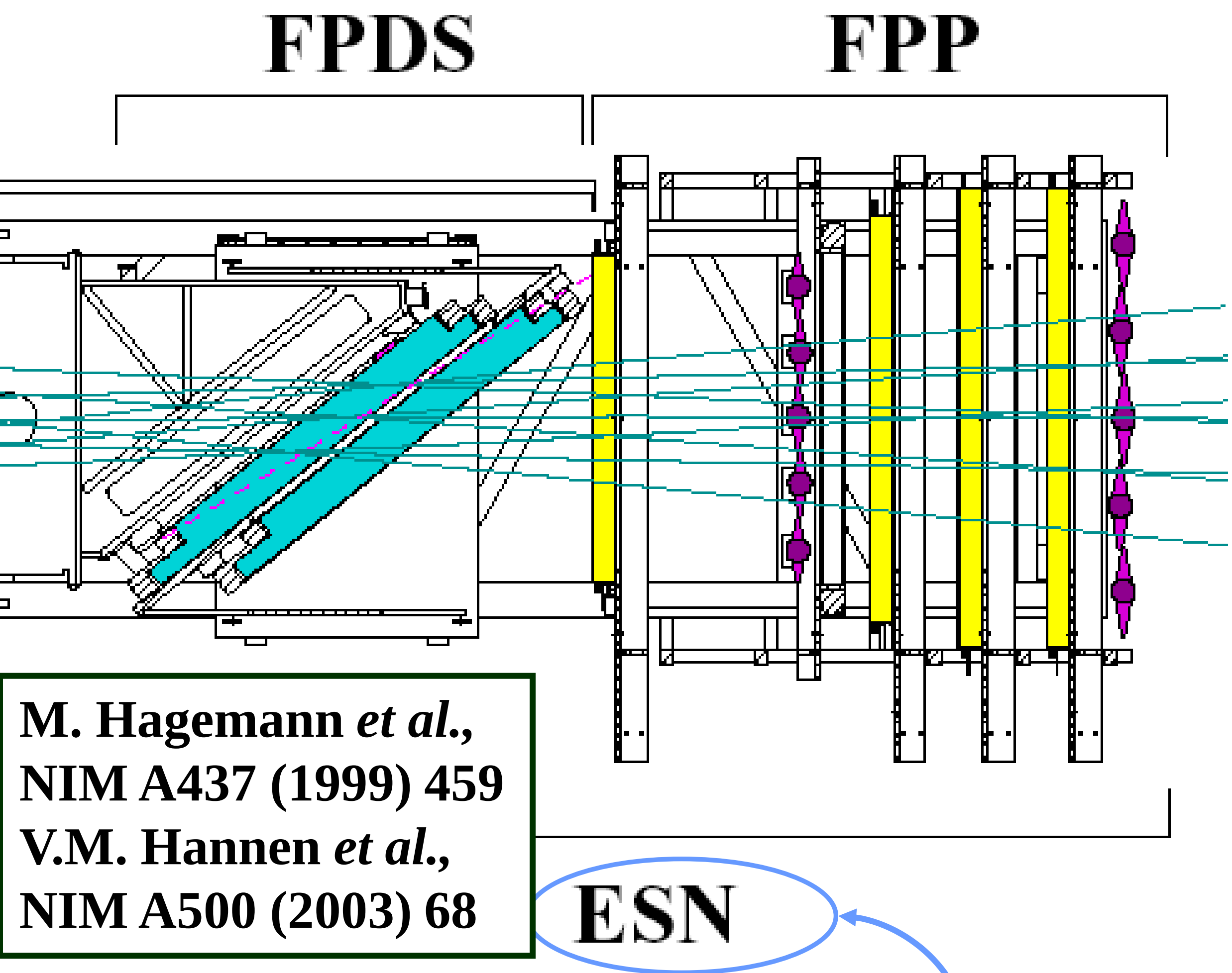
$^1S_0$ dominates if (relative) 2-proton kinetic energy $\varepsilon < 1$ MeV

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

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



Setup: ESN detector



Focal-Plane Detector:
(FPDS): 2 VDCs

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

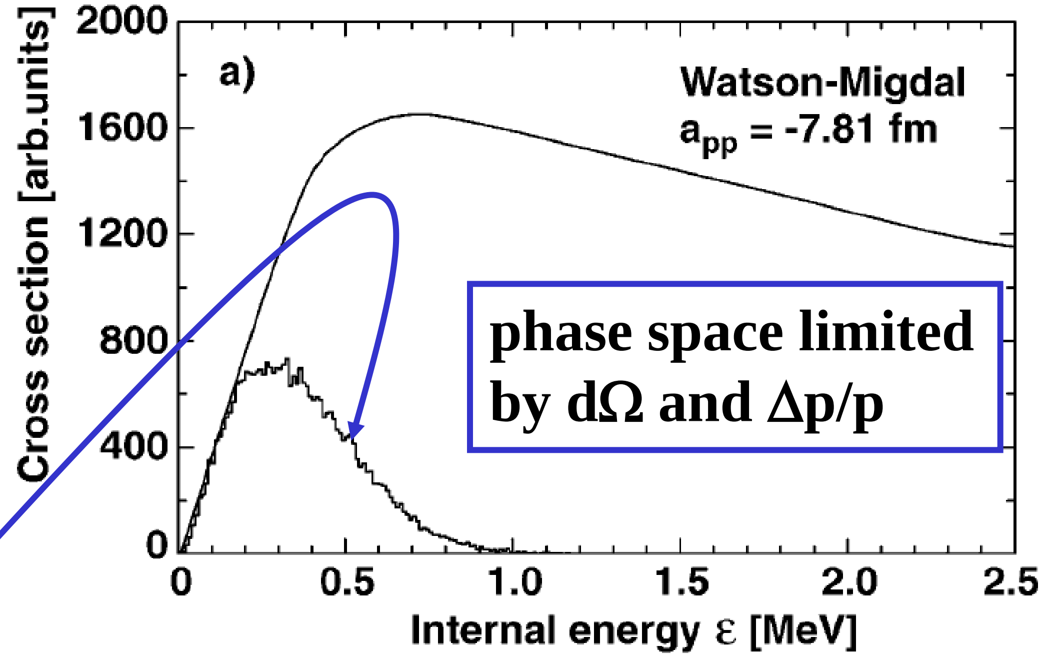
features a.o.:
fast readout
VDC readout pipeline
TDC's
VDC decoding using
imaging techniques
DSP based online analysis

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

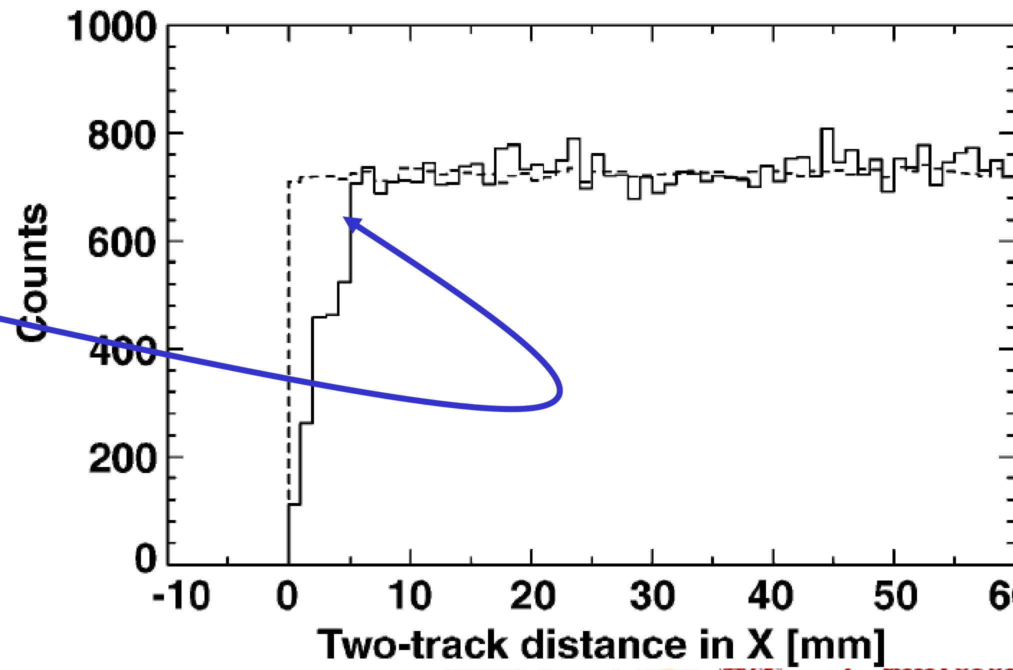
Bari, Darmstadt, Gent, Iserlohn, KVI, Milano, Münster, TRIUMF

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

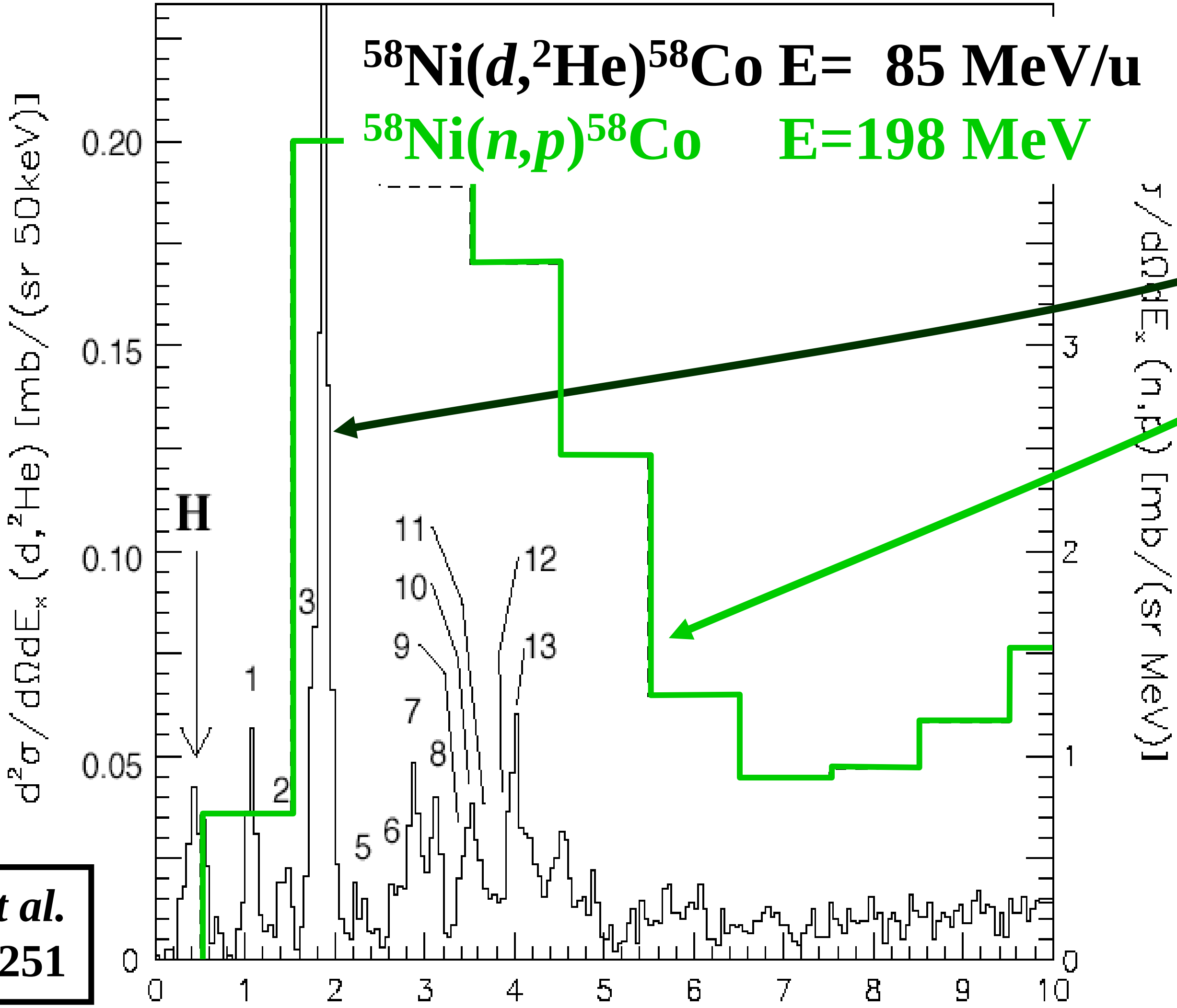
S. Rakers *et al.*, NIM A481 (2002) 253



measured

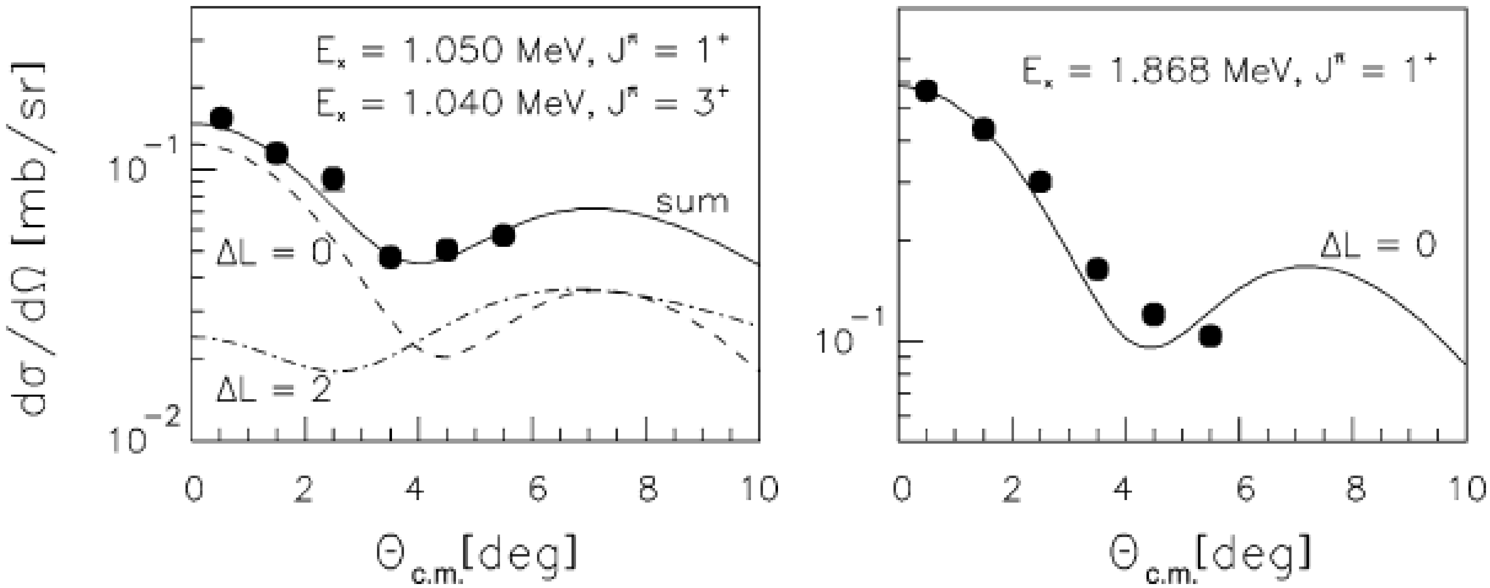


(d,^{2}He) as GT$^+$ probe in *fp*-shell nuclei



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

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



$$\mathbf{B}_{\exp}(\mathrm{GT}+) =$$

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

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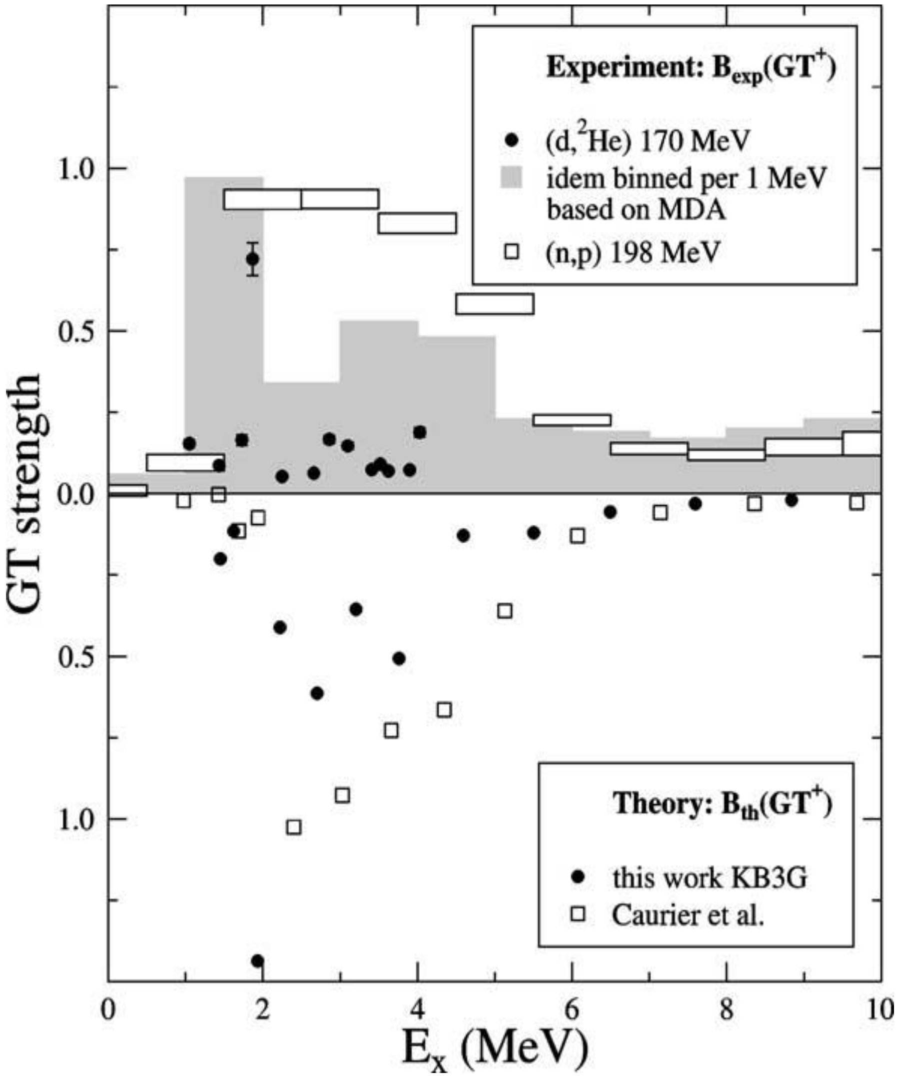
GT Strength in ^{58}Co from (d,^{2}He) reaction

E_x [MeV]	dσ/dσ(0.5°) [mb/sr]	σ(L=0)/σ(τoτ)	B(GT+)
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



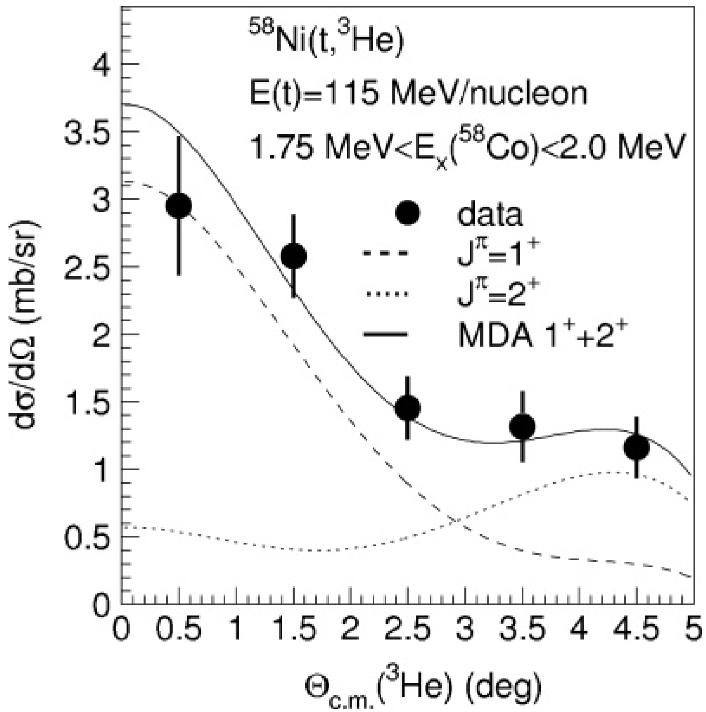
Up to 4 MeV excitation:

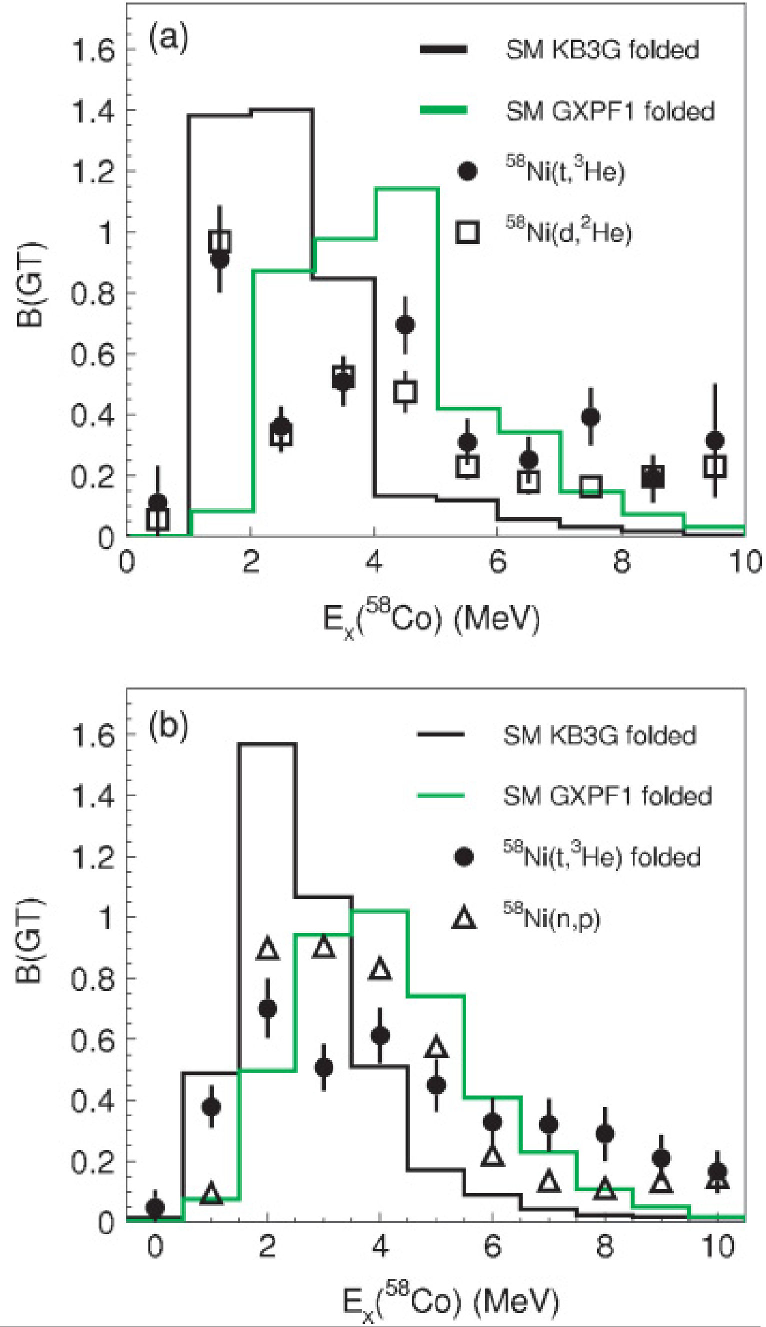
13 GT transitions measured (*d*,^{2}He)

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

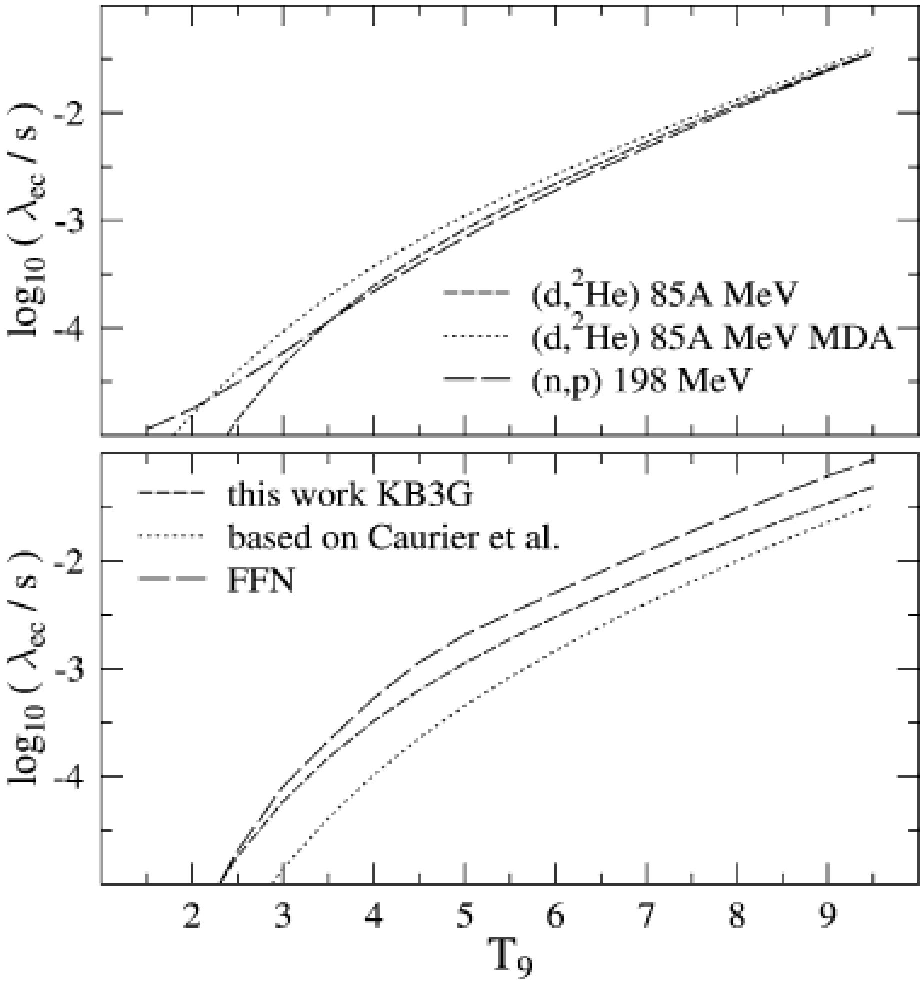
Electron capture rate

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

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

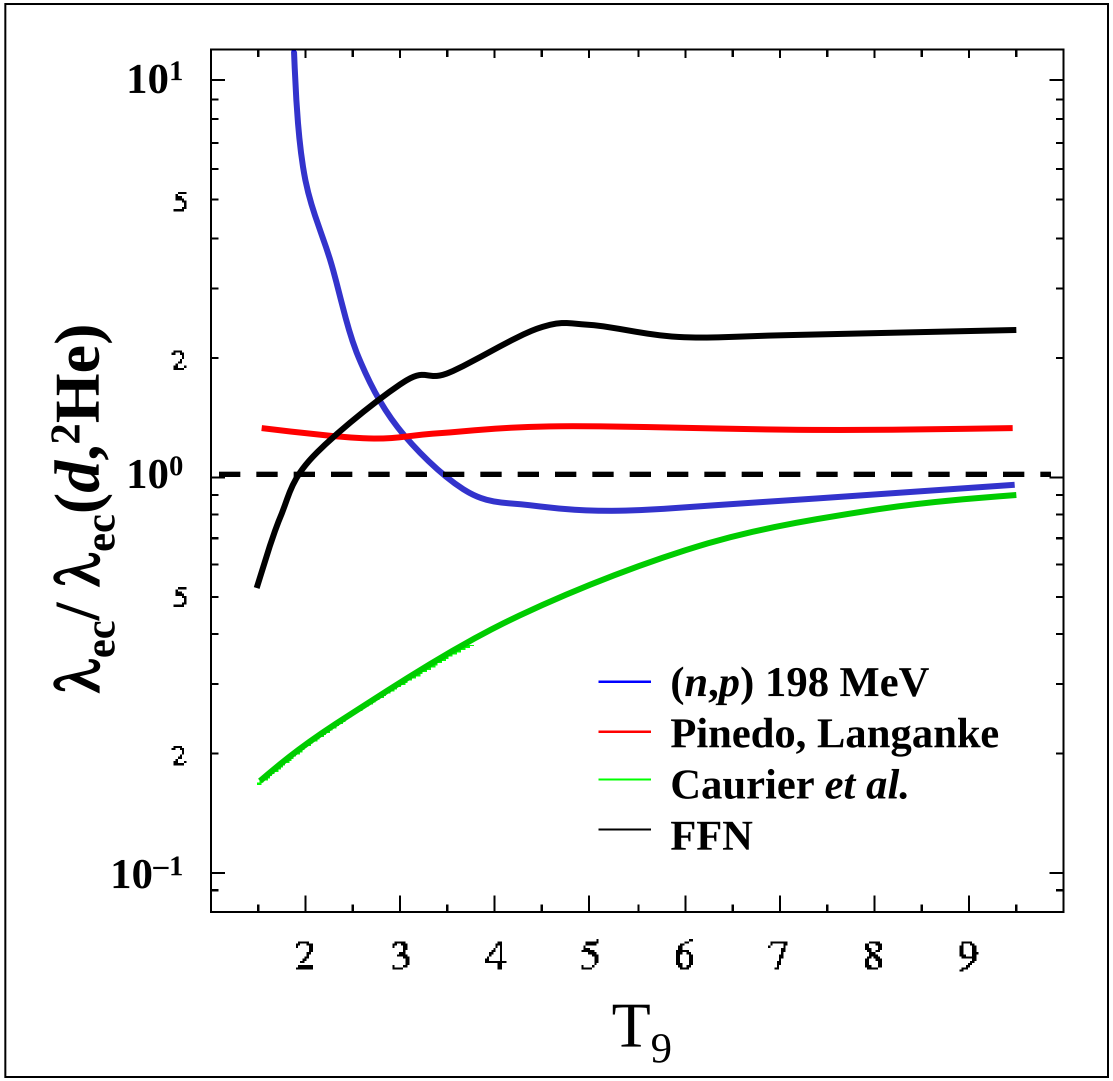
$Y_e = 0.48$

[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

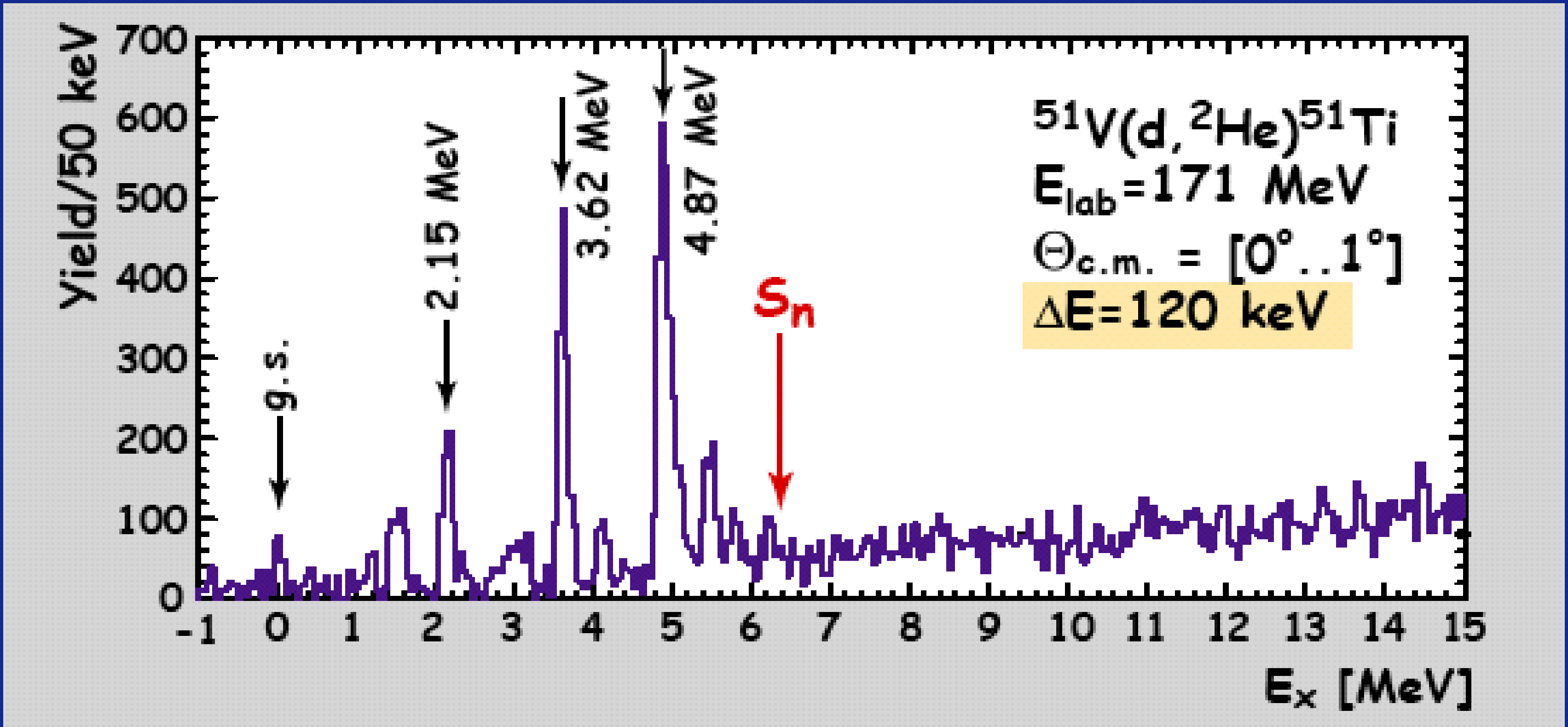
^{58}Ni: comparison of *e*-capture rates theory/experiment



- **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**

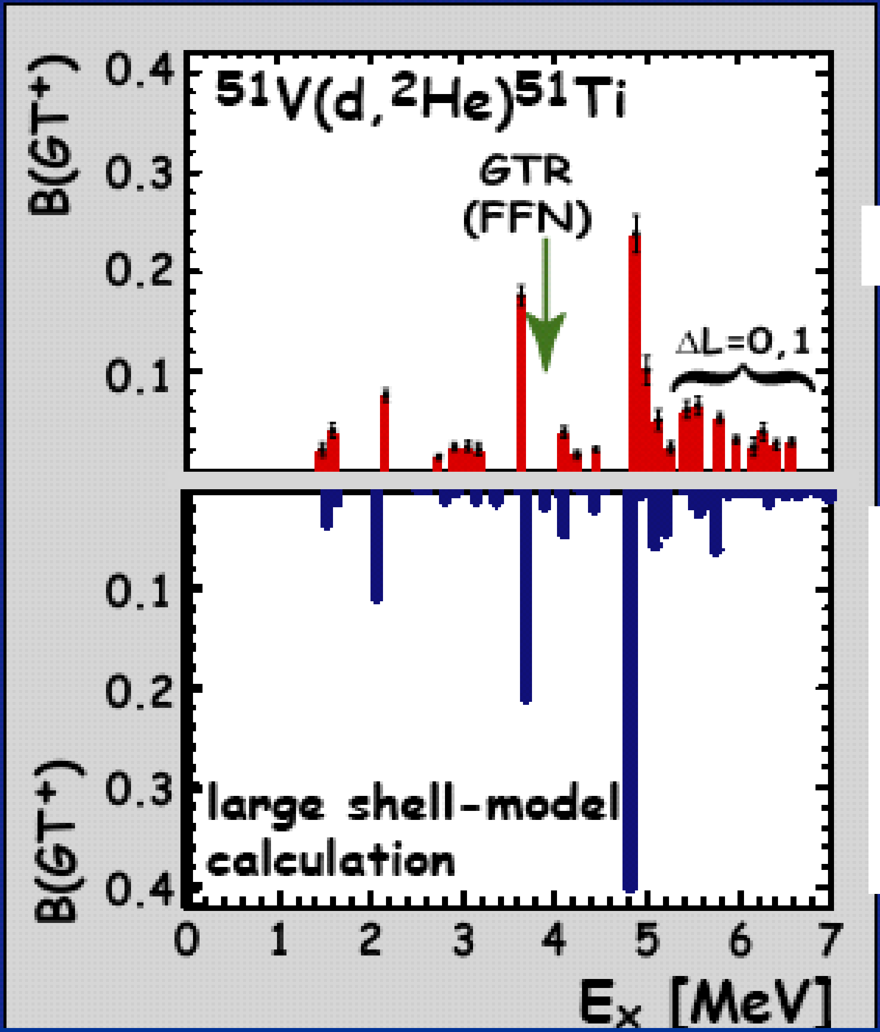
$^{51}V(d,^{2}He)^{51}Ti$: B(GT⁺) for proton-odd *fp*-shell nucleus

^{51}V g.s. ($J^{\pi}=7/2^{-}$, T=5/2) ⇒ ^{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)

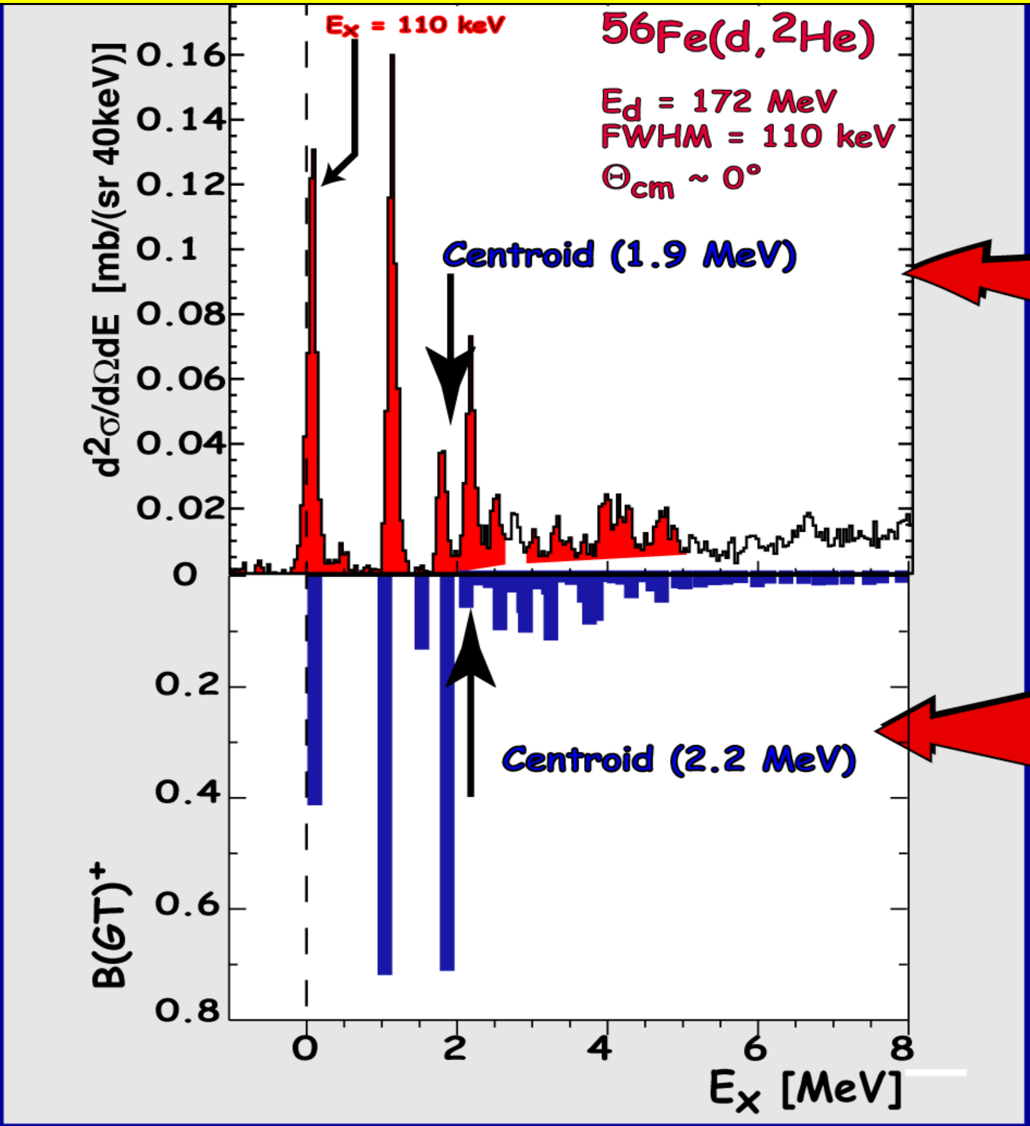
$^{51}V(d,^{2}He)$: Comparison with shell-model calculations



← Experimental result

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

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



Experiment

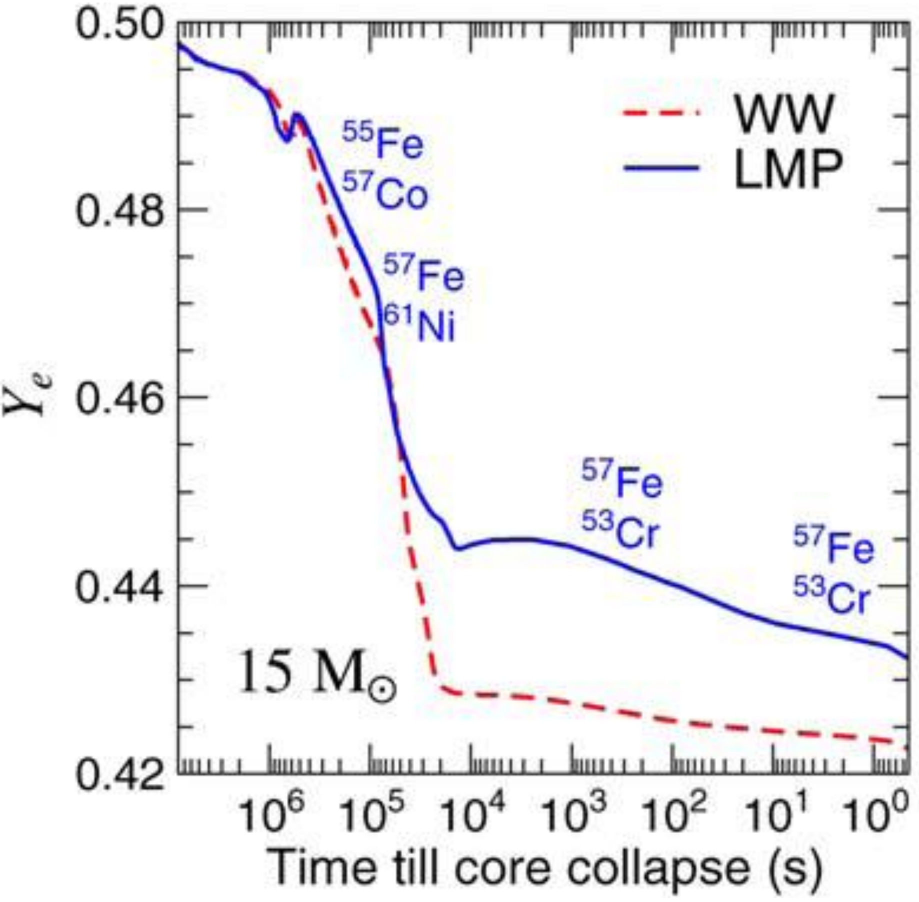
Full *fp*-shell model calculations (KB3G) (G. Martínez-Pinedo)

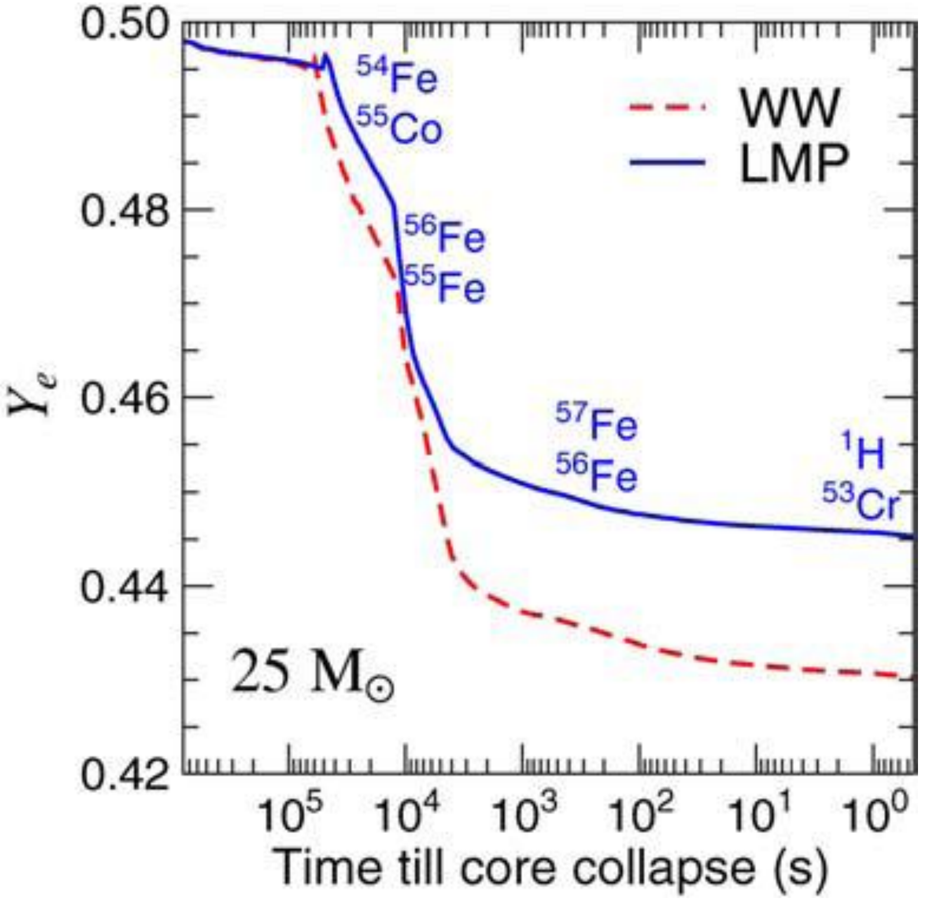
Comparison of centroids (MeV) of GT^+ Strength distribution

	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}





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]) $\Rightarrow$ smaller EC rates for A=45-60 than FFN $\Rightarrow$ 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.**

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

EuroSuperNova Collaboration

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Thank you for your attention

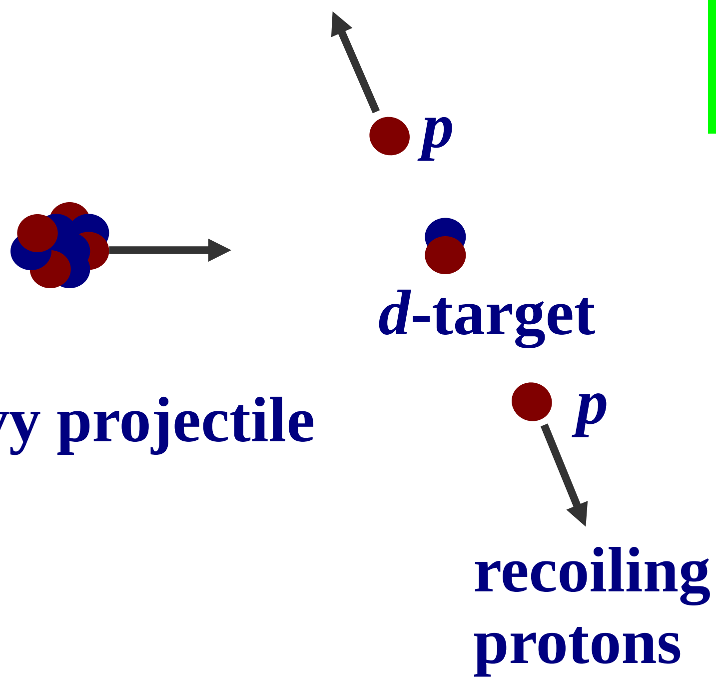
Nuclear structure studies with CE reactions in inverse kinematics

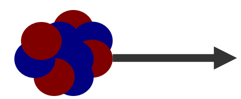
- Possible at FAIR and RIKEN

(intermediate beam energies are needed!)

Approach (at FAIR):
measure the recoiling protons

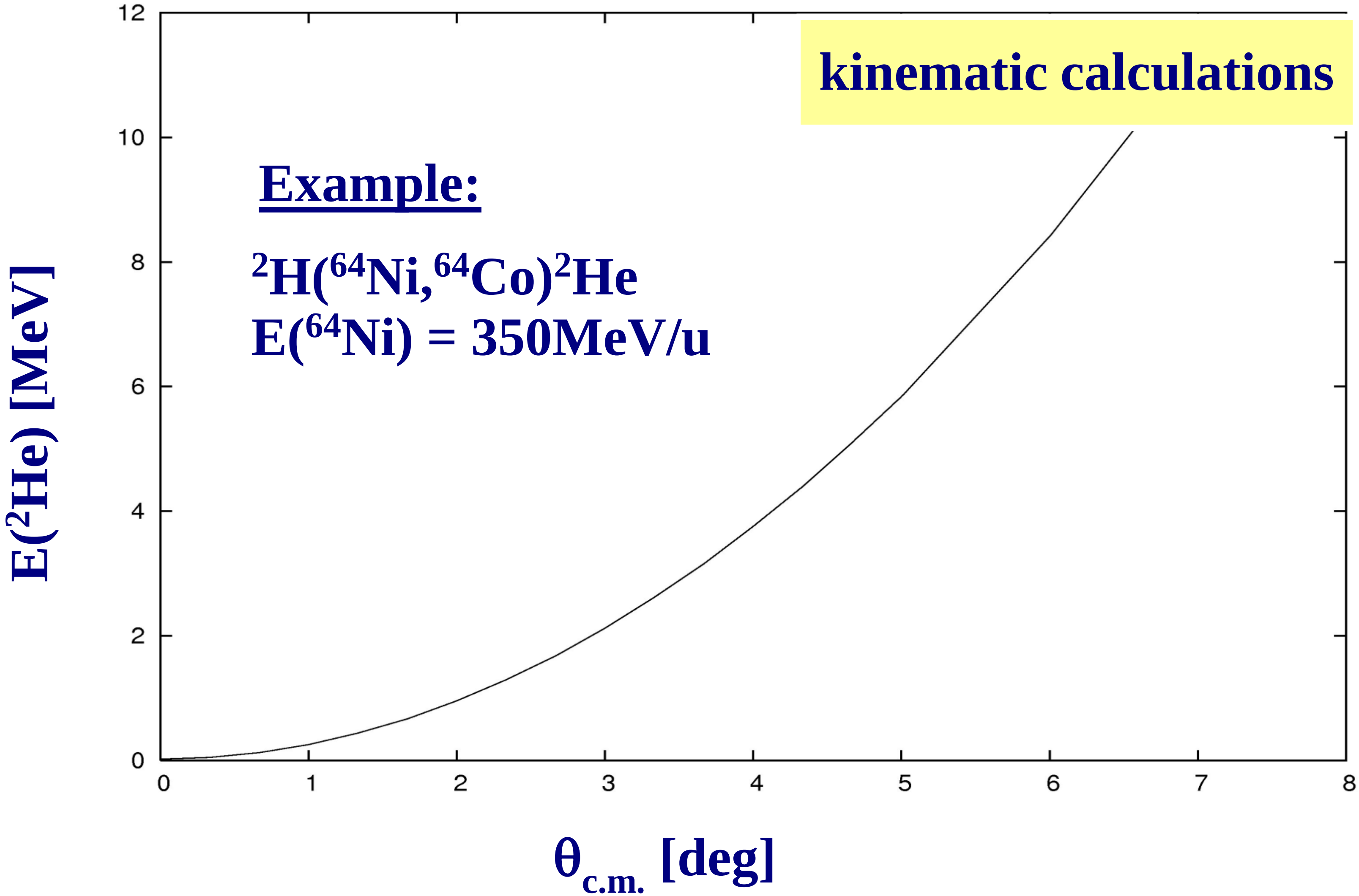
(*d*,^{2}He)





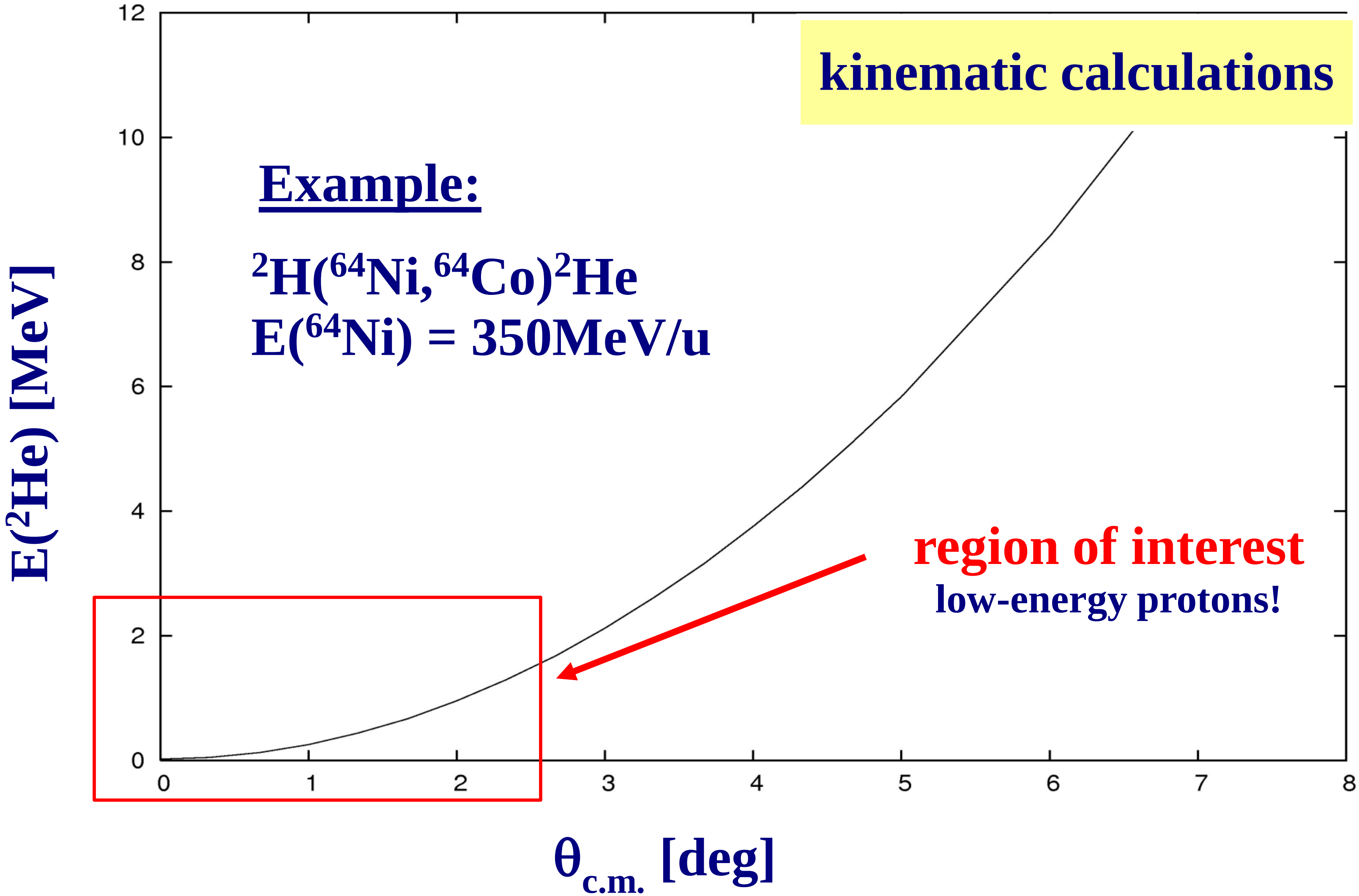
Inconvenience:
difficulty to detect the low-energy protons

How low?



kinematic calculations
Example:
$^{2}H(^{64}Ni,^{64}Co)^{2}He$
$E(^{64}Ni)$ = 350MeV/u
$E(^{2}He)$ [MeV]
$\theta_{c.m.}$ [deg]
0
2
4
6
8
10
12
0
1
2
3
4
5
6
7
8

How low?



kinematic calculations
Example:
$^{2}H(^{64}Ni,^{64}Co)^{2}He$
$E(^{64}Ni)$ = 350MeV/u
region of interest
low-energy protons!
E(^{2}He) [MeV]
$\theta_{c.m.}$ [deg]
0
2
4
6
8
10
12
0
1
2
3
4
5
6
7
8

Detection system @ FAIR

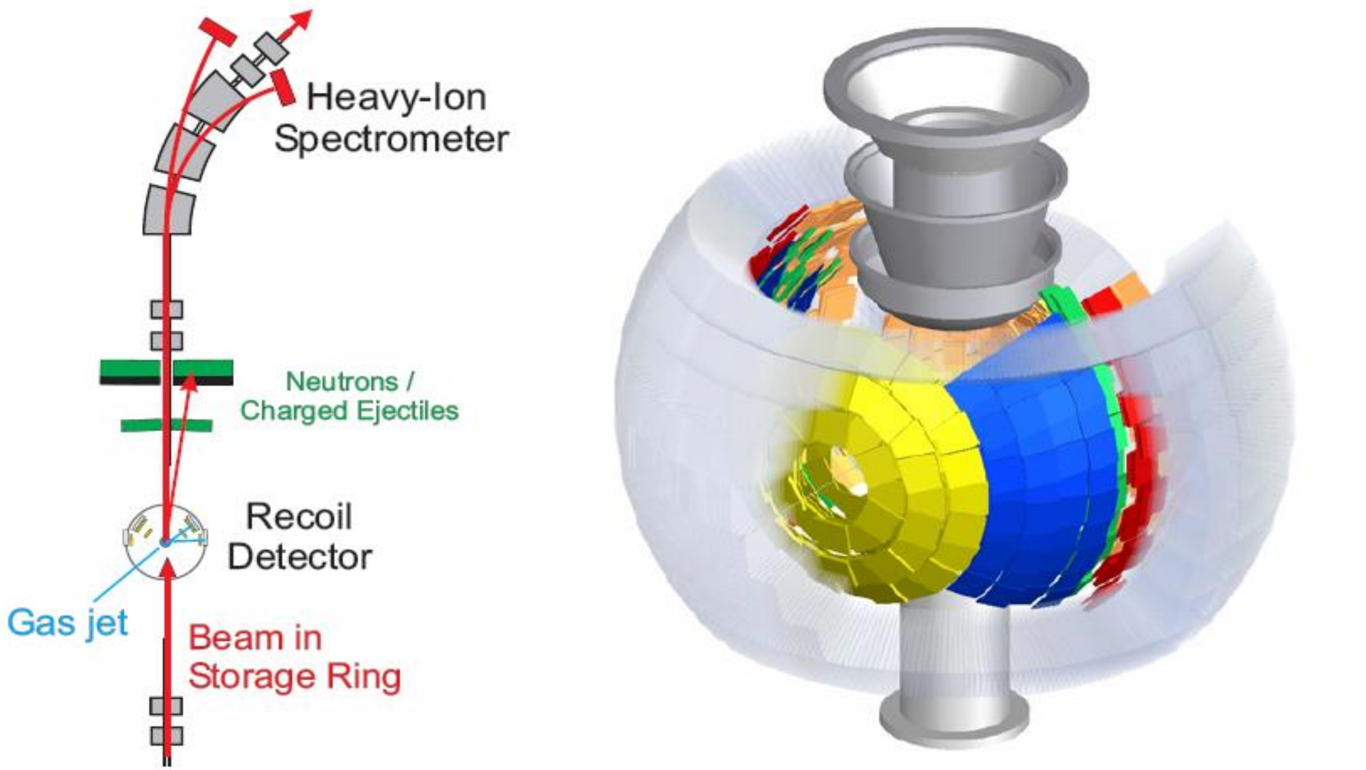


Figure 1: *Schematic view of the EXL detection systems. Left: Set-up built into the NESR storage ring. Right: Target-recoil detector surrounding the gas-jet target.*

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