Gamow-Teller Transitions
Implications for Supernova Scenarios
& Double-β Decay

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1. **Introduction**

2. **Importance of studying GT$^+$ in *fp*-shell nuclei**

3. **Experimental method**

4. **Case Study: ^{58}Ni**

5. **Measurements on several *fp*-shell nuclei**

6. **Measurements on 2β-decaying nuclei**

7. **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

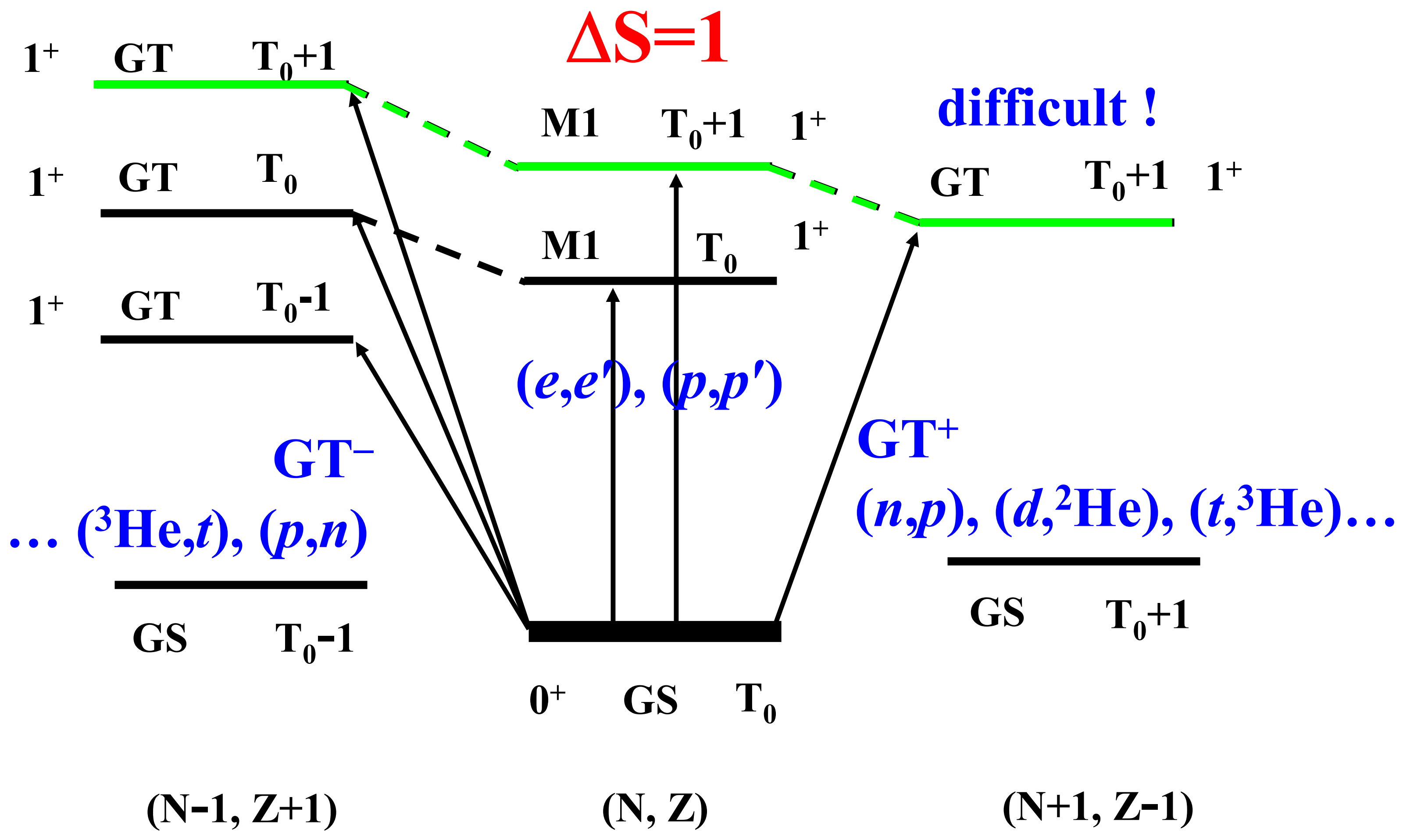
Isovector charge-exchange modes

⇒ 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$^+$}

Spin-flip & GT transitions



$\Delta S=1$

1^+ GT T_0+1

1^+ GT T_0

1^+ GT T_0-1

GT$^-$

… (^{3}He,*t*), (*p*,*n*)

GS T_0-1

M1 T_0+1 1^+

M1 T_0 1^+

(*e*,*e'*), (*p*,*p'*)

0^+ GS T_0

difficult !

GT T_0+1 1^+

GT$^+$

(*n*,*p*), (*d*,^{2}He), (*t*,^{3}He)…

GS T_0+1

(N-1, Z+1) (N, Z) (N+1, Z-1)

Charge-exchange probes

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

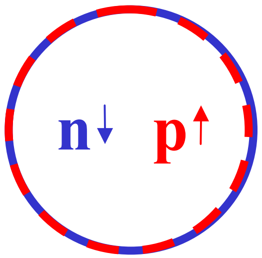
- β^--decay
- (p,n)
- (^{3}He,t)
- heavy ion

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

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

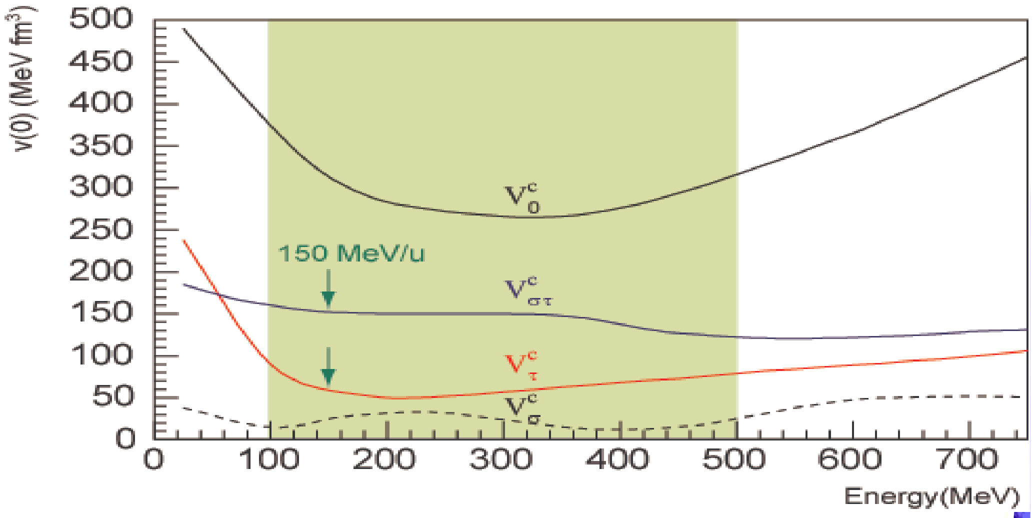
- Energy per nucleon (>100 MeV/u)
- Spin-flip versus non-spin-flip
- Complexity of reaction mechanism
- Experimental considerations

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**

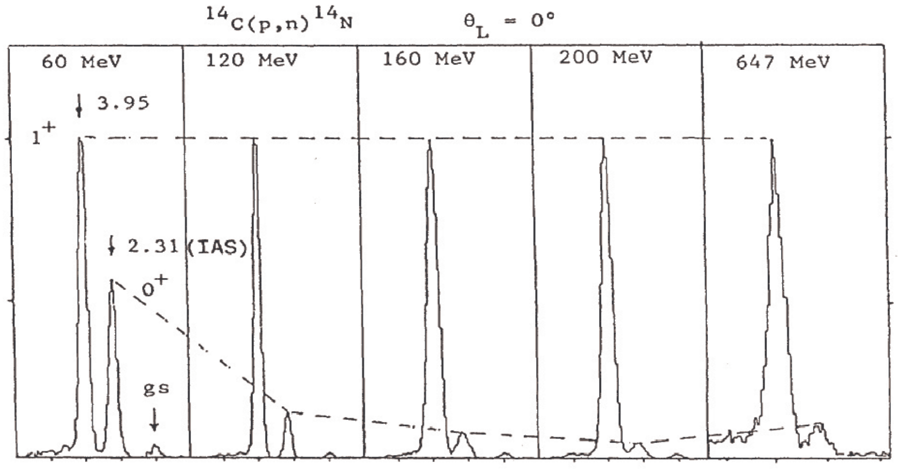


FIG. 4. Zero-degree cross-section spectra for the $^{14}C(p,n)^{14}N$ reactions at the indicated bombarding energies. The spectra have been arbitrarily normalized. From Gaarde (1985) and Rapaport (1989).

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.

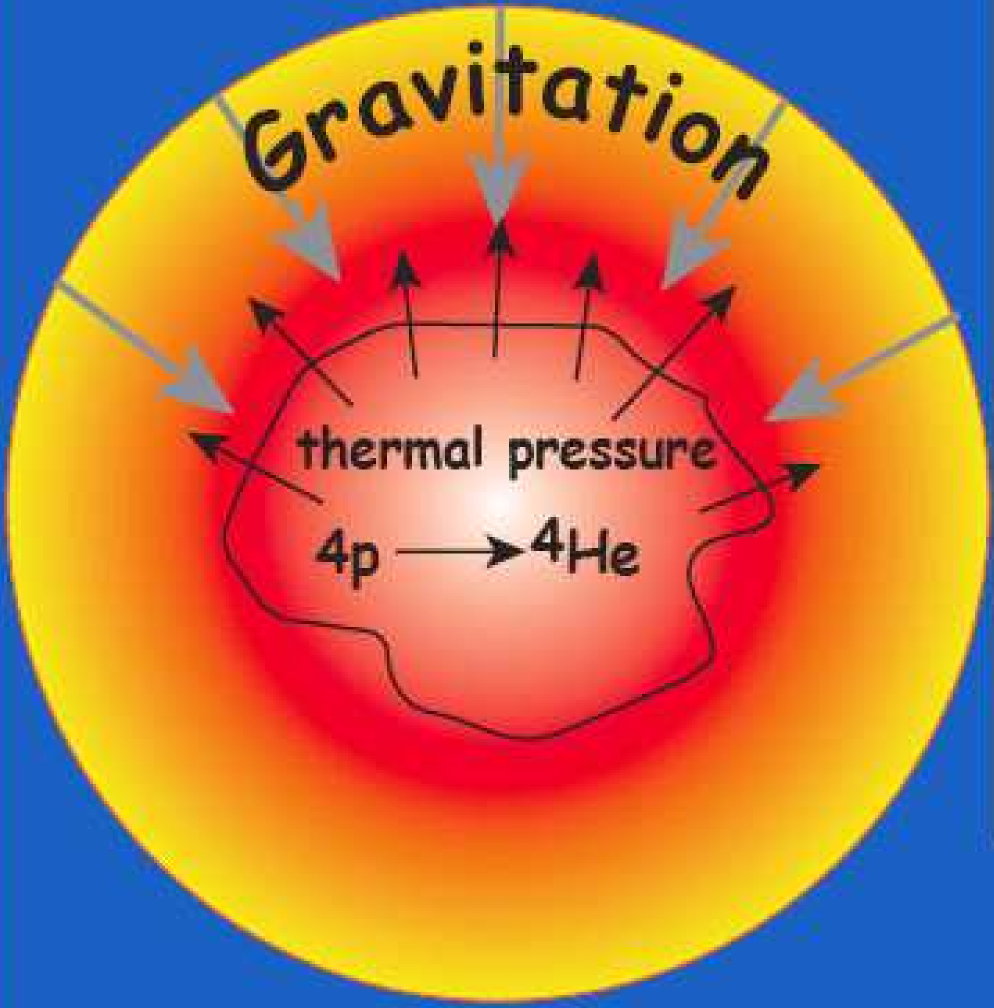
  ⇒ electron capture

- 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.

Nuclear processes and energy household of supernovae



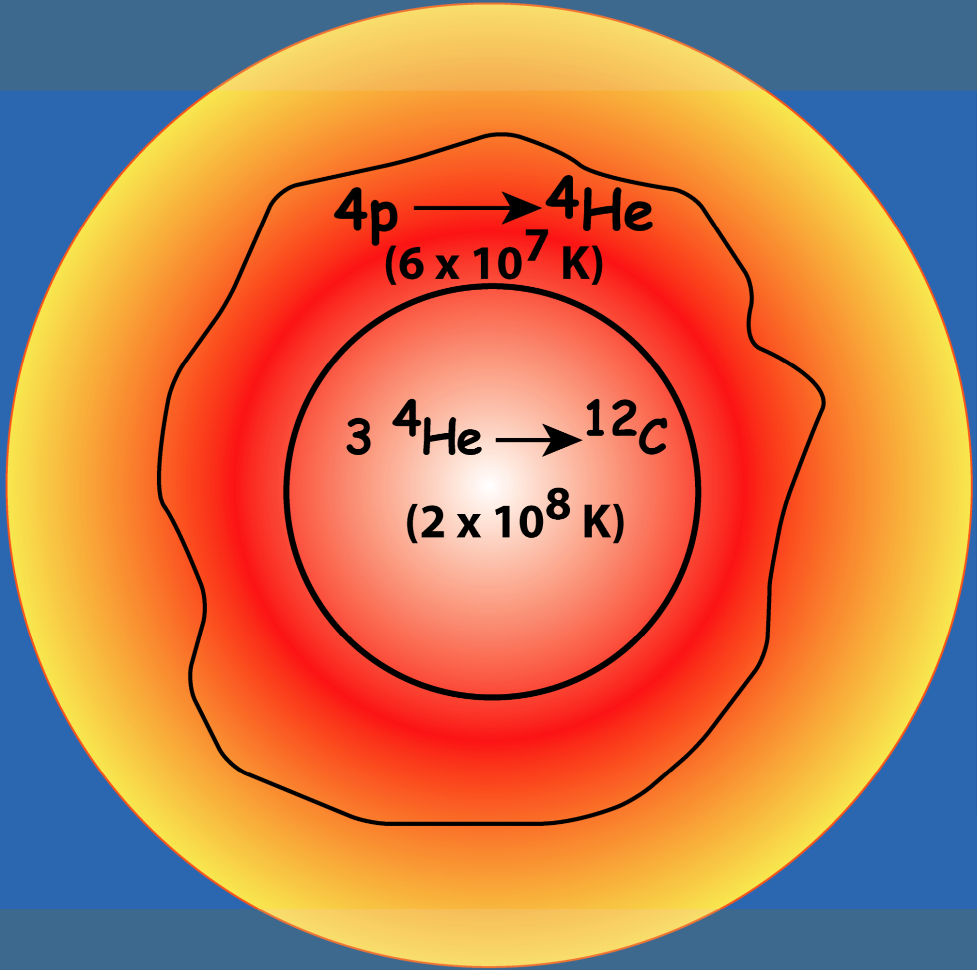
initial condition:
$M > 10\,M_{\odot}$

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

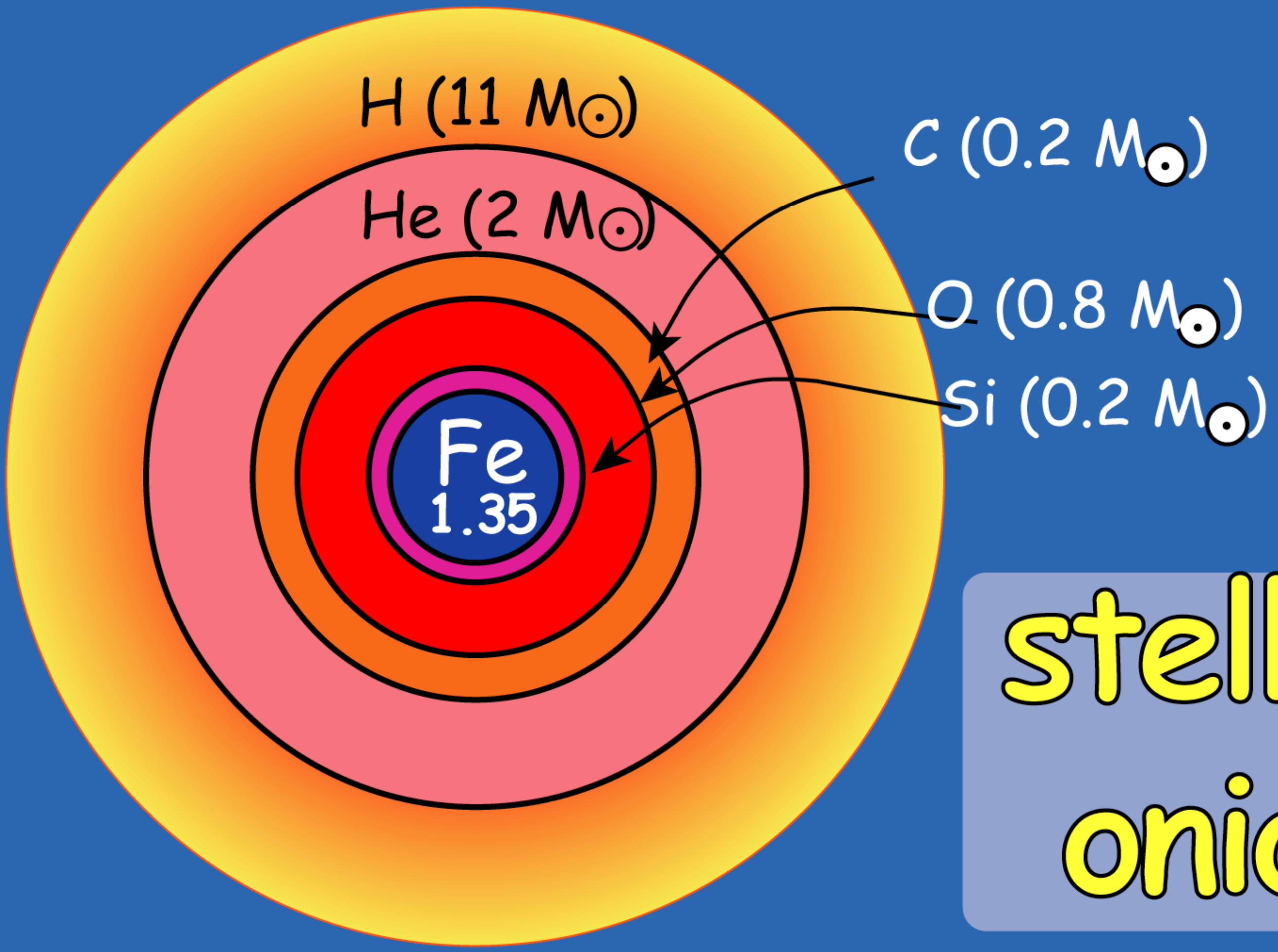
↓

Red Giant (Super-Giant)

↓

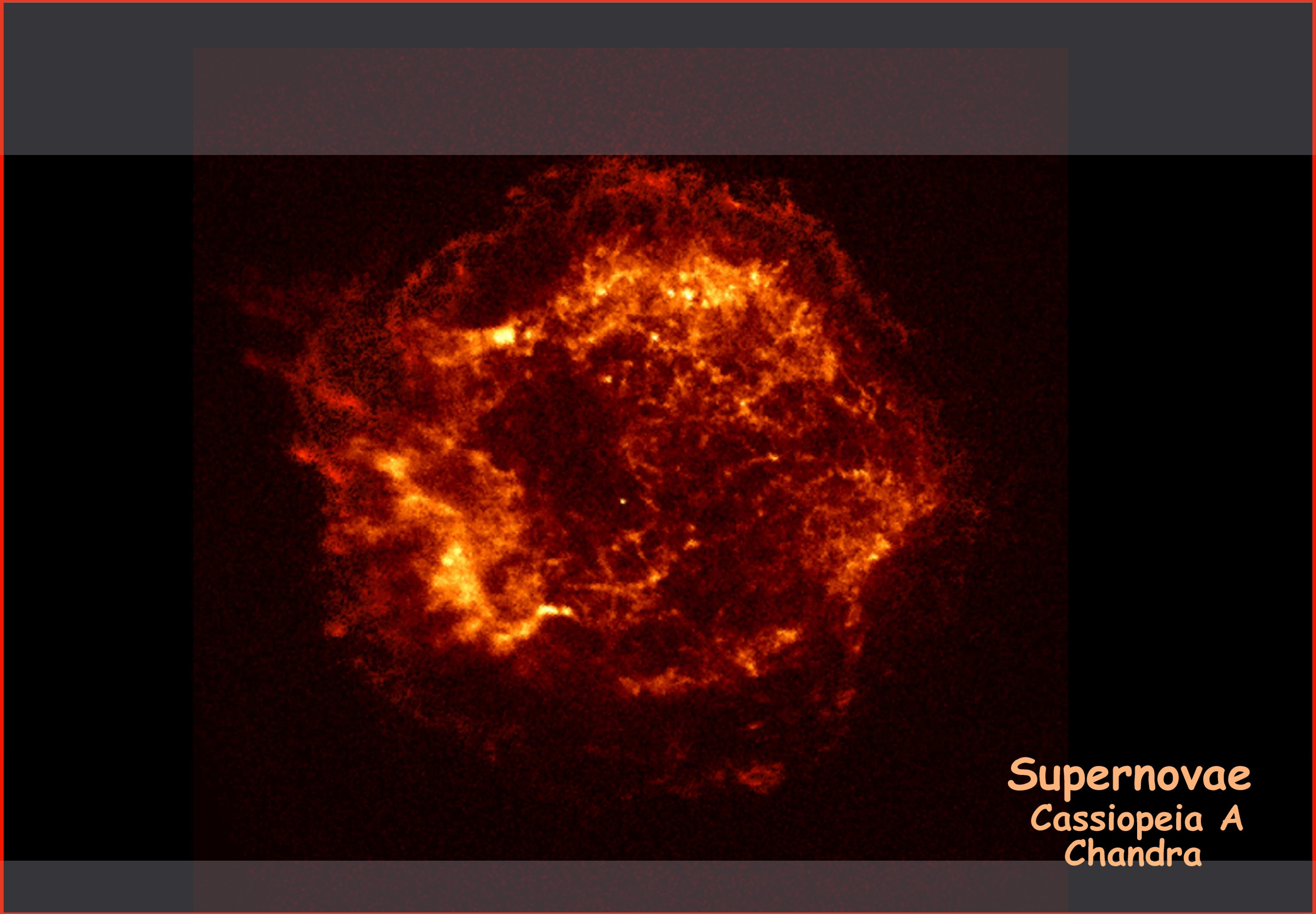
lifetime: 5×10^5 y

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



stellar onion

Determination of GT Strength is imperative



Supernovae
Cassiopeia A
Chandra

Courtesy of
D. Frekers

Electron capture in *fp*-shell

- **In supernova explosions, electron capture (EC) on *fp*-shell nuclei plays a dominant role during the last few days of a heavy star [presupernova stage; deleptonization ⇒ core collapse ⇒ subsequent type IIa Supernova (SN) explosion] Bethe *et al*. (1979)**
- **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.**

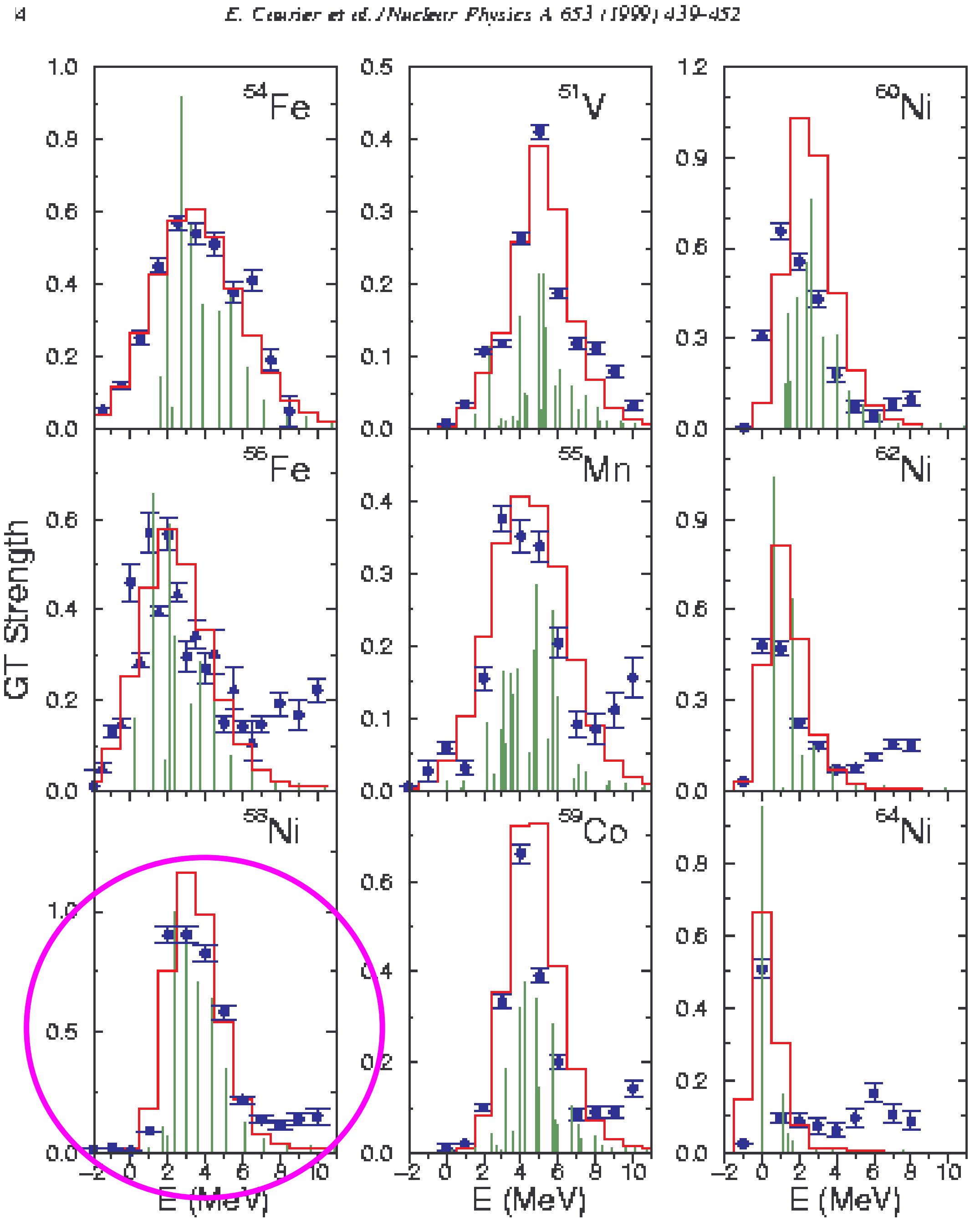
nuclei: large scale shell model calculations

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

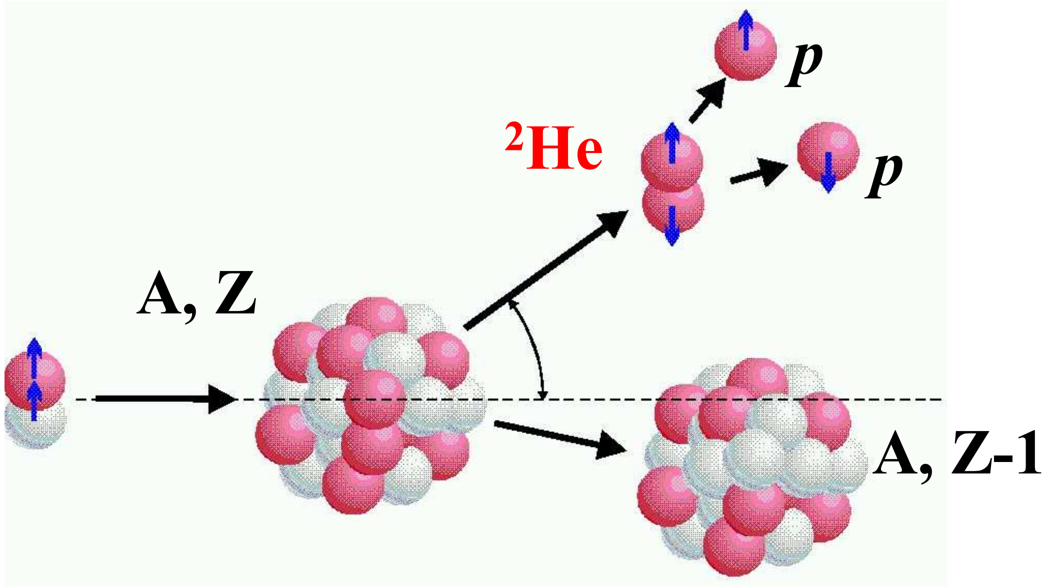
- Stellar weak reaction rates with improved reliability
- Large scale shell model (SM) calculations
- Tuned to reproduce GT$^+$ strength measured in (*n,p*)

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

Case study: ^{58}Ni



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

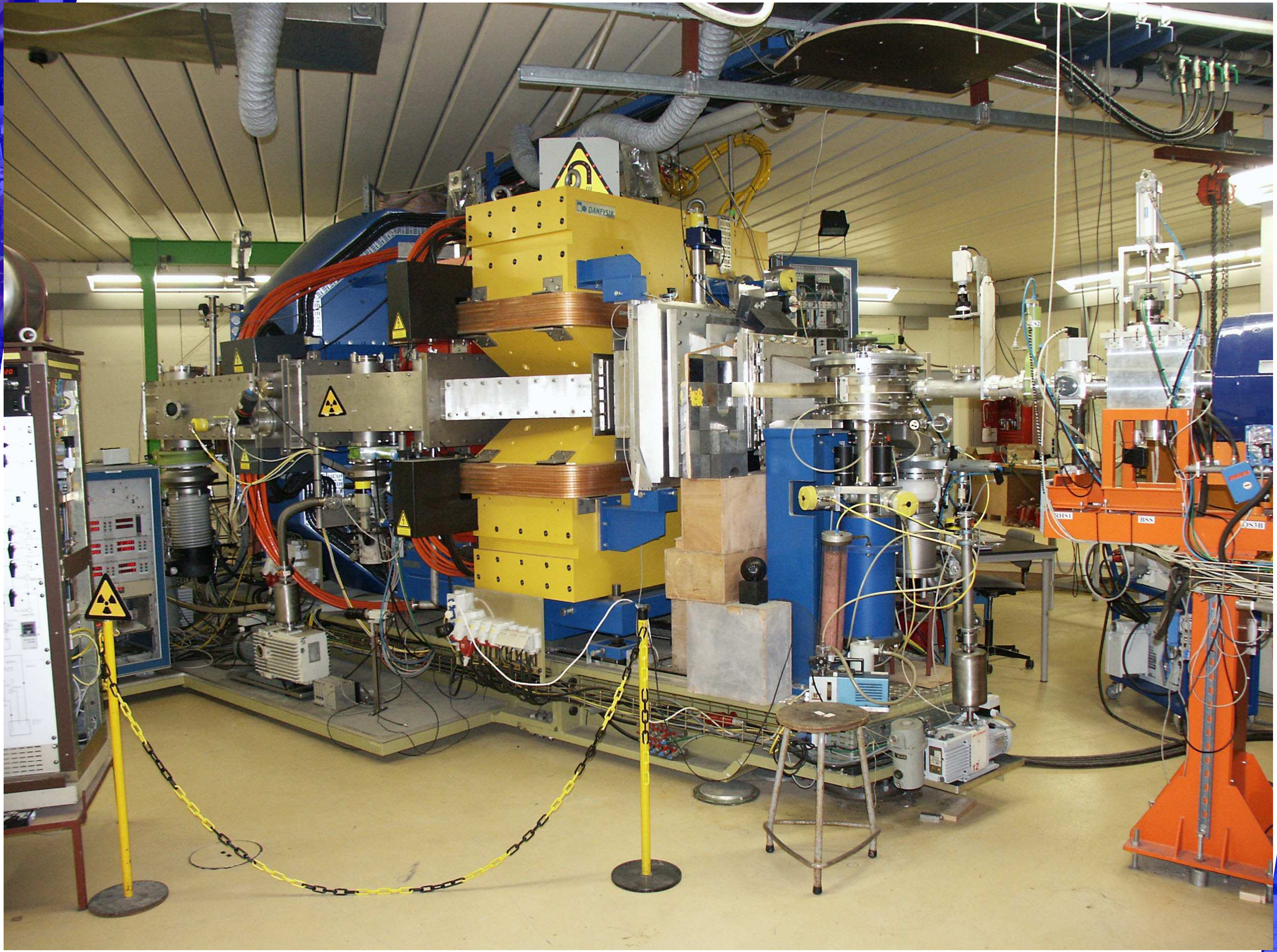


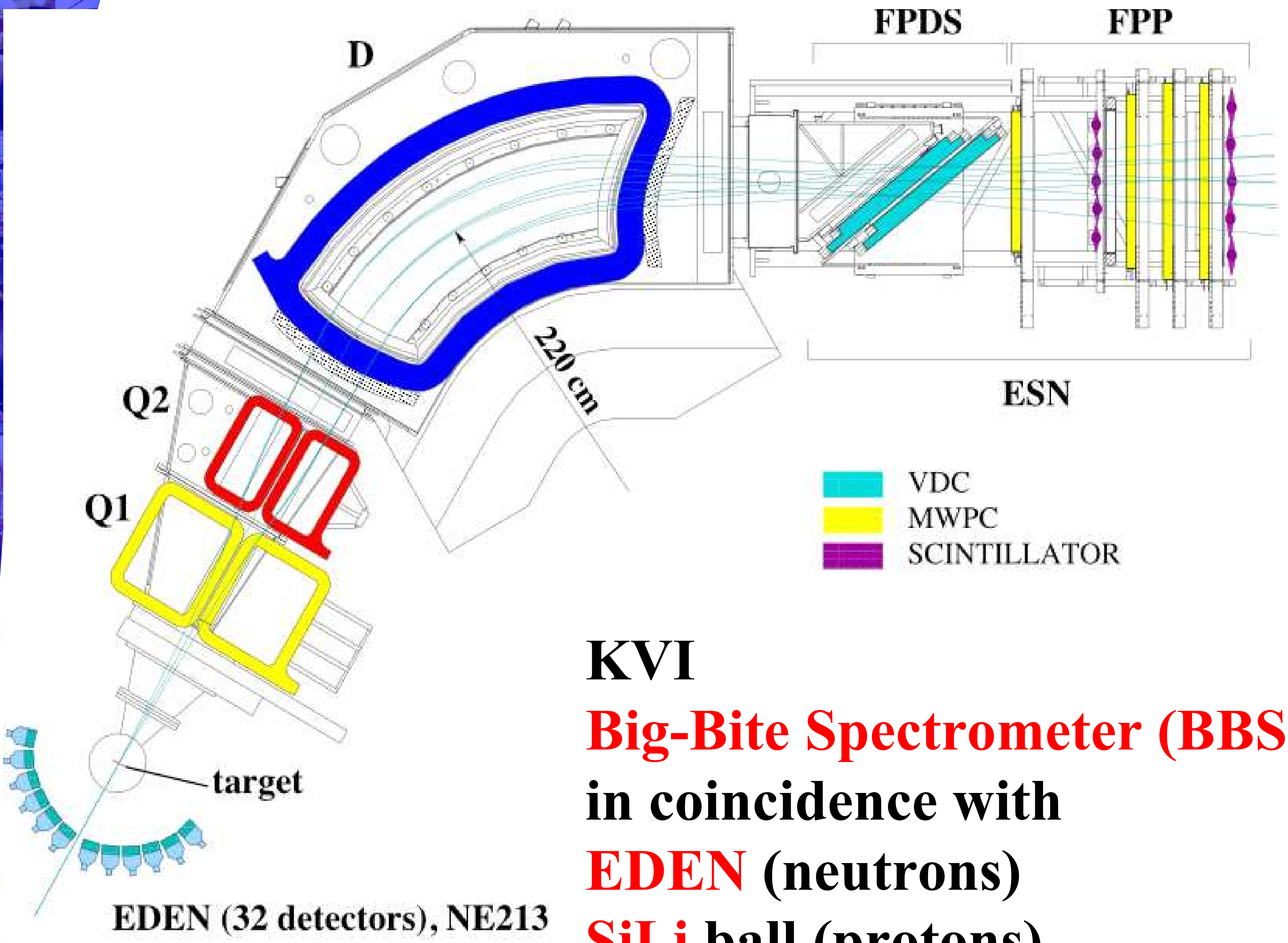
$^3S_1$ deuteron ⇒ $^1S_0$ di-proton (^{2}He)

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

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

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





KVI

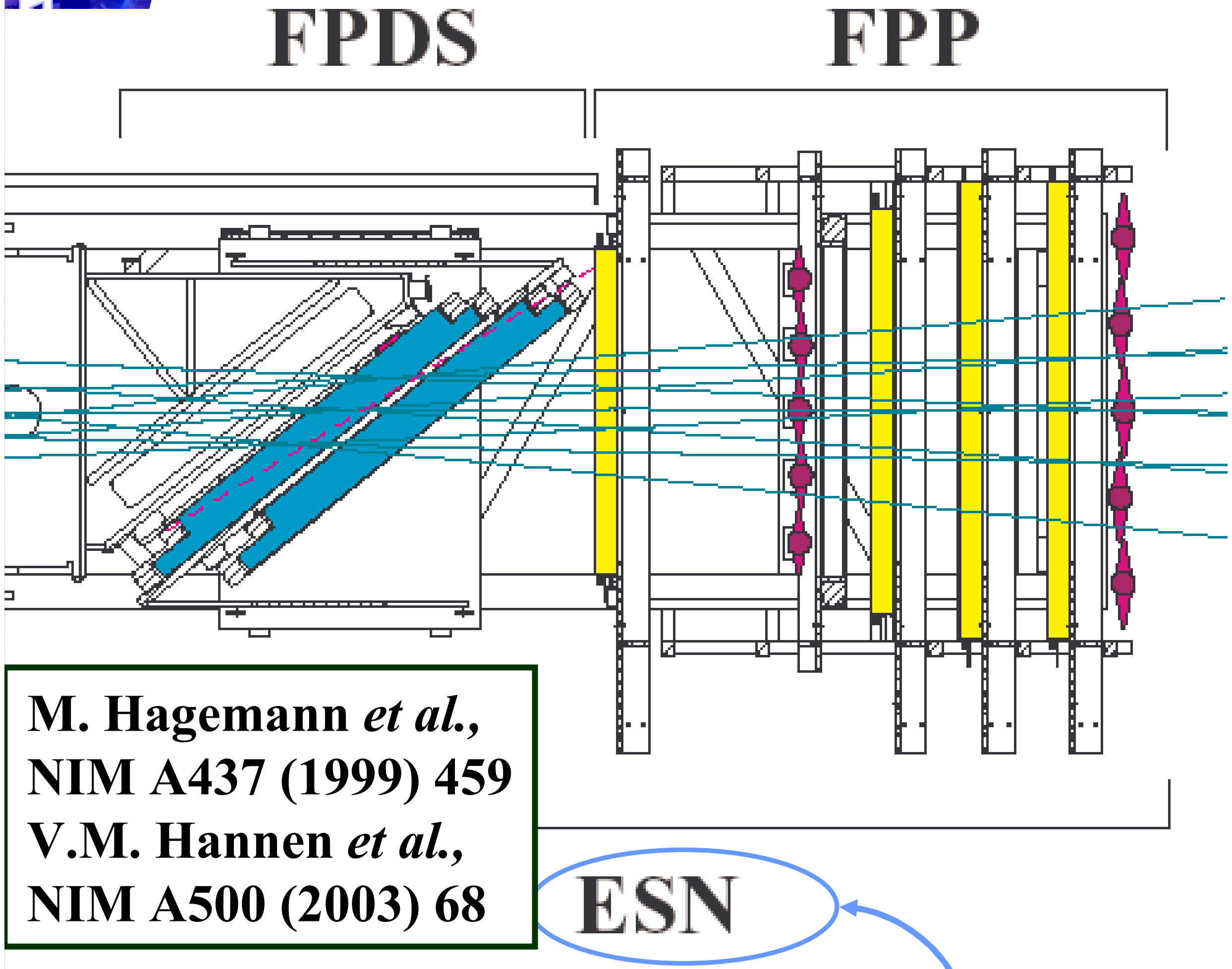
Big-Bite Spectrometer (BBS)

in coincidence with

EDEN (neutrons)

SiLi ball (protons)

Setup: ESN detector



Focal-Plane Detector:
(FPDS): 2 VDCs

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

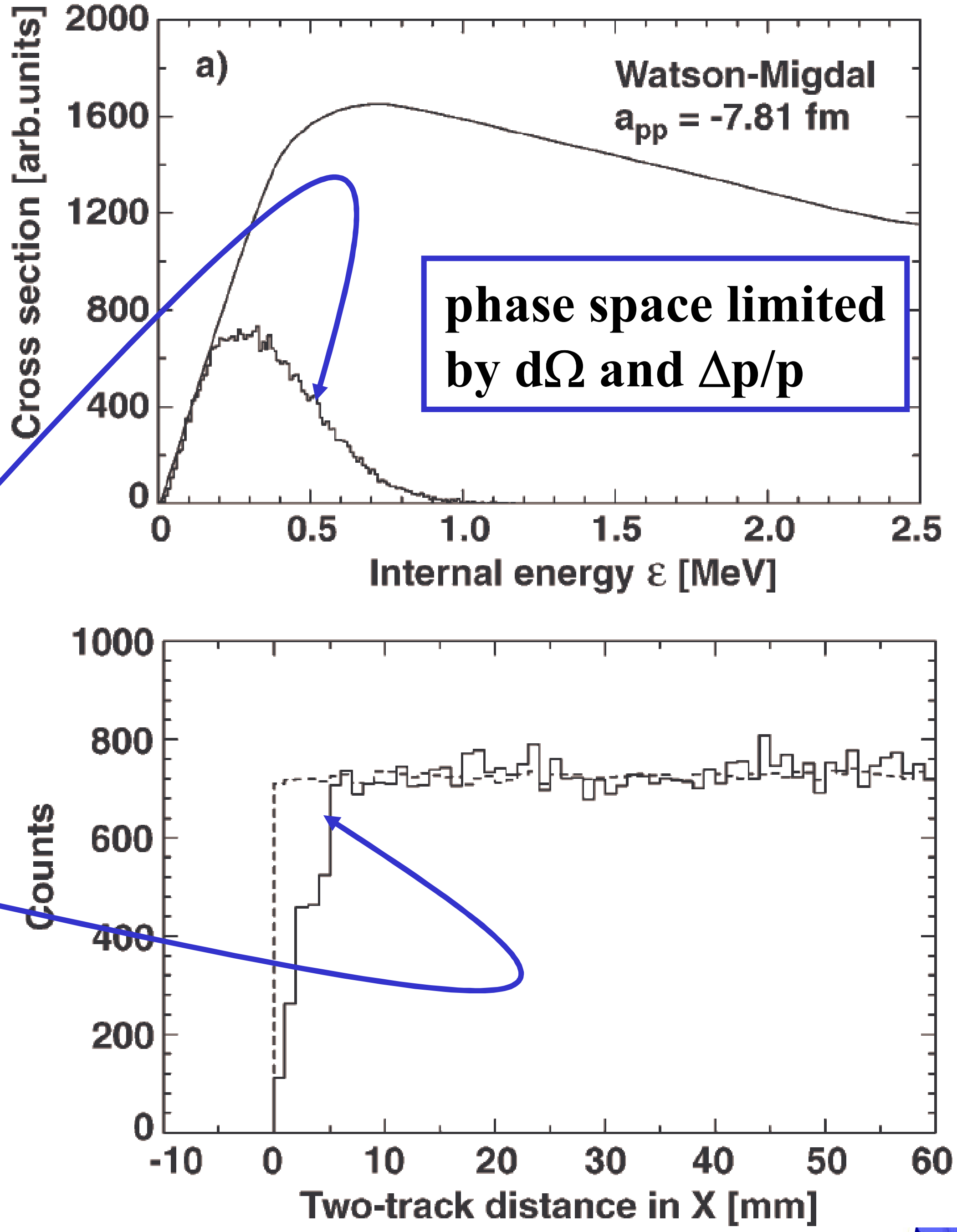
features a.o.:
fast readout
VDC readout pipeline
TDC's
VDC decoding using
imaging techniques
DSP based online analysis

**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**

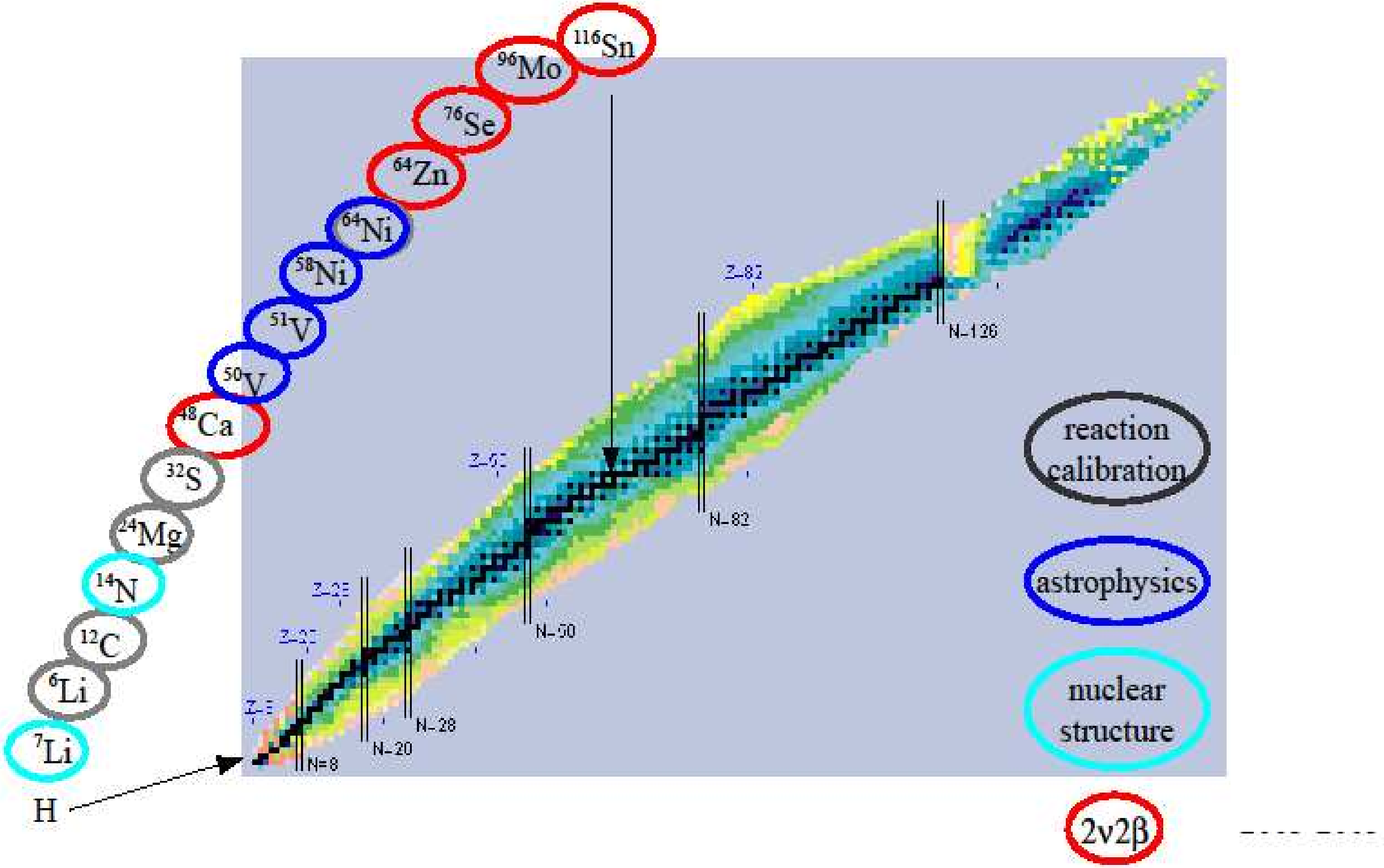
S. Rakers *et al.*,
NIM A481 (2002) 253



phase space limited by dΩ and Δp/p

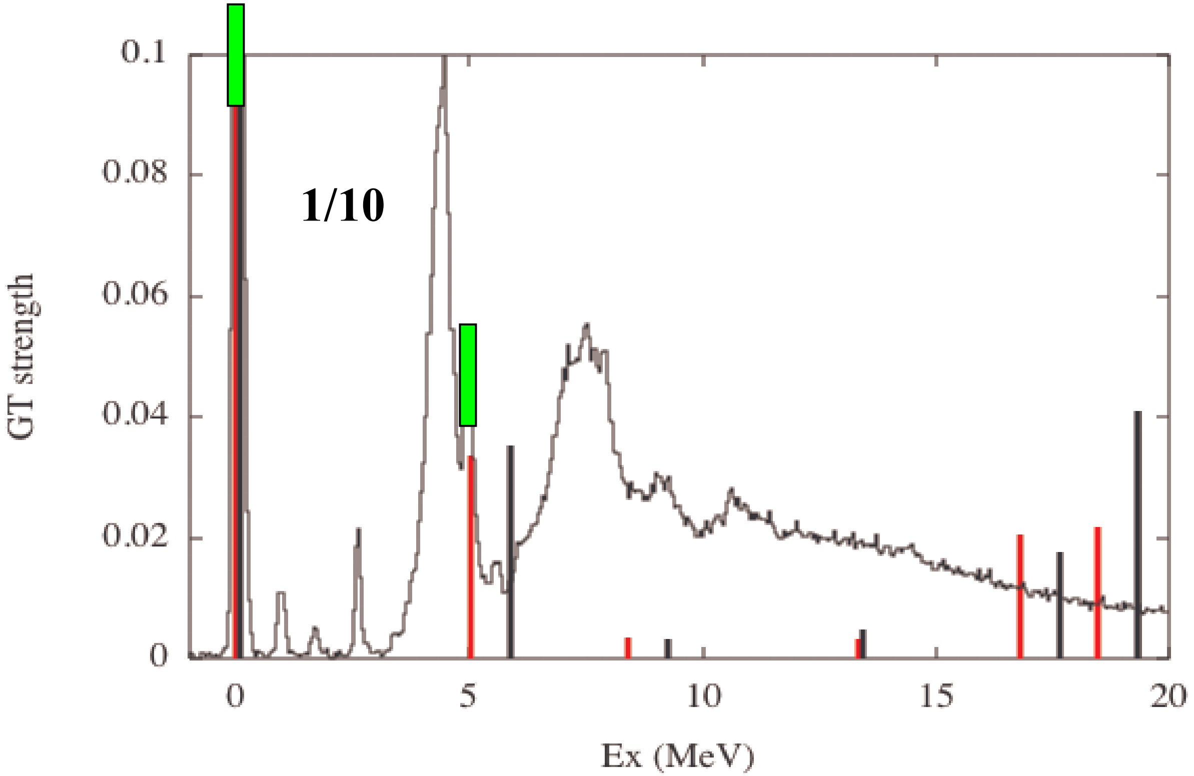
measured

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



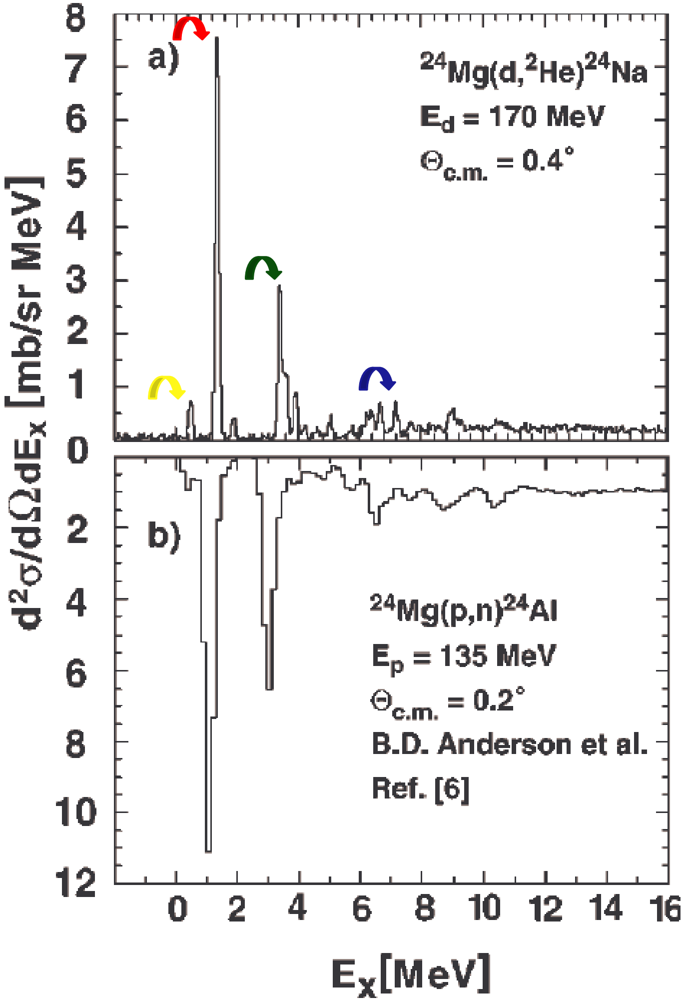
Exclusive measurement of $\Delta S = \Delta T = 1$ strength: $^{12}C(d,^{2}He)^{12}B$

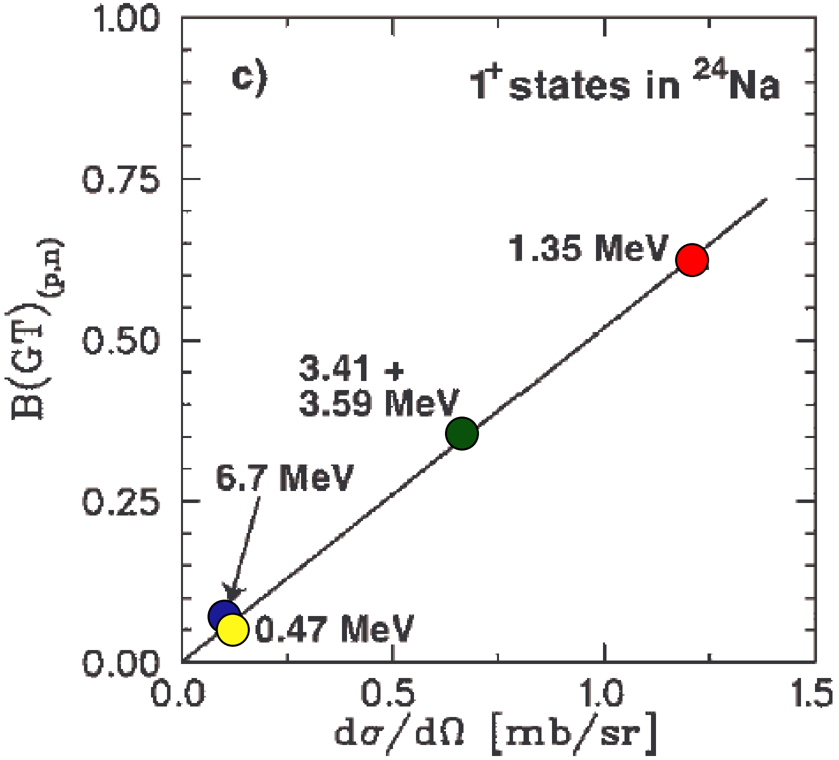
E_d = 171 MeV, θ = 0°



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

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

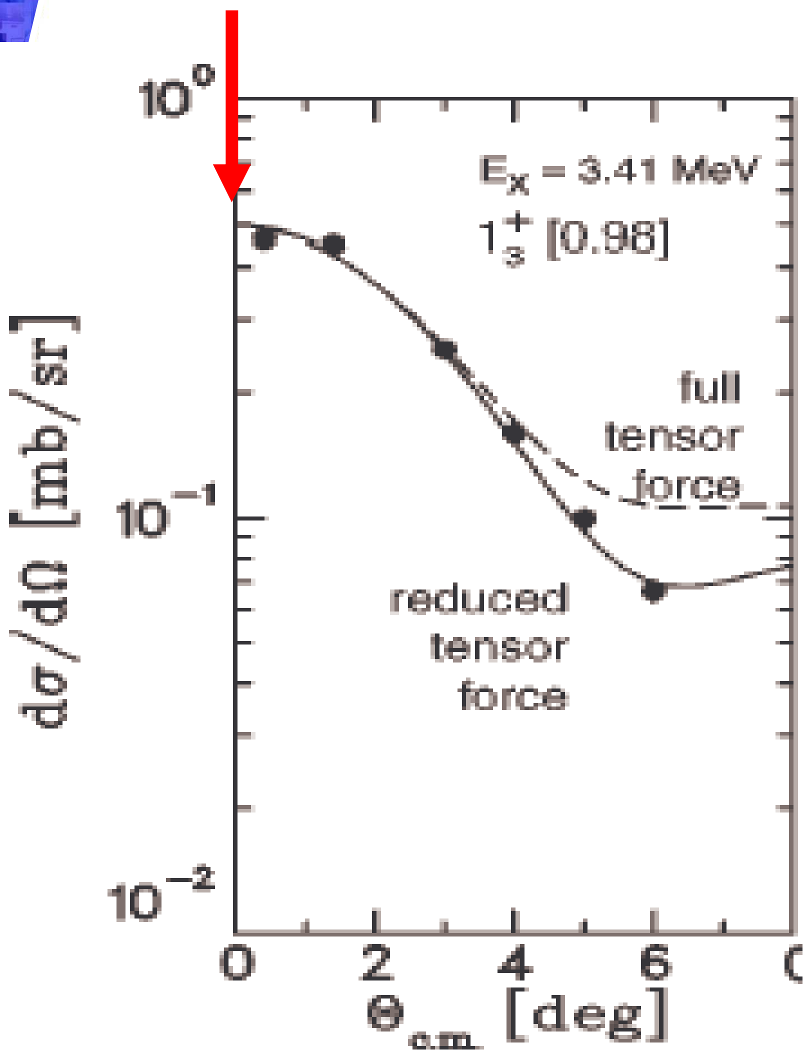




Self-conjugate ^{24}Mg

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

Experimental cross section and GT strength



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

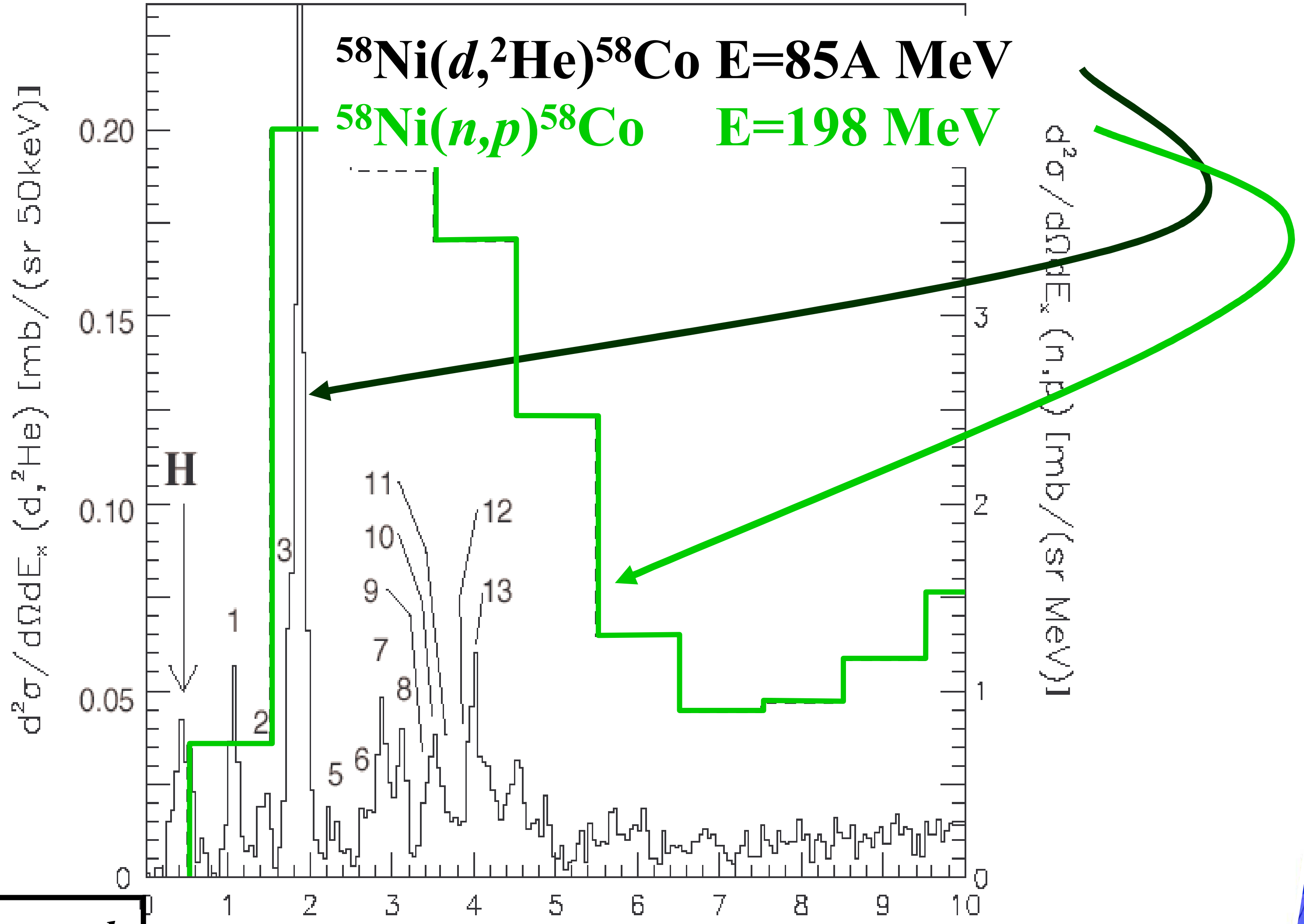
extrapolated (DWBA)

unit cross section

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

Target	Reference data					Present data	
	E_x [MeV]	$B(GT_-)$		E_x [MeV]	$d\sigma/d\Omega(q=0)$ [mb/sr]	$\sigma(L=0)/\sigma(\tau o \tau)$ $(q=0)$	$B(GT_+)$ $(C=0.267)$
^{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

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


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

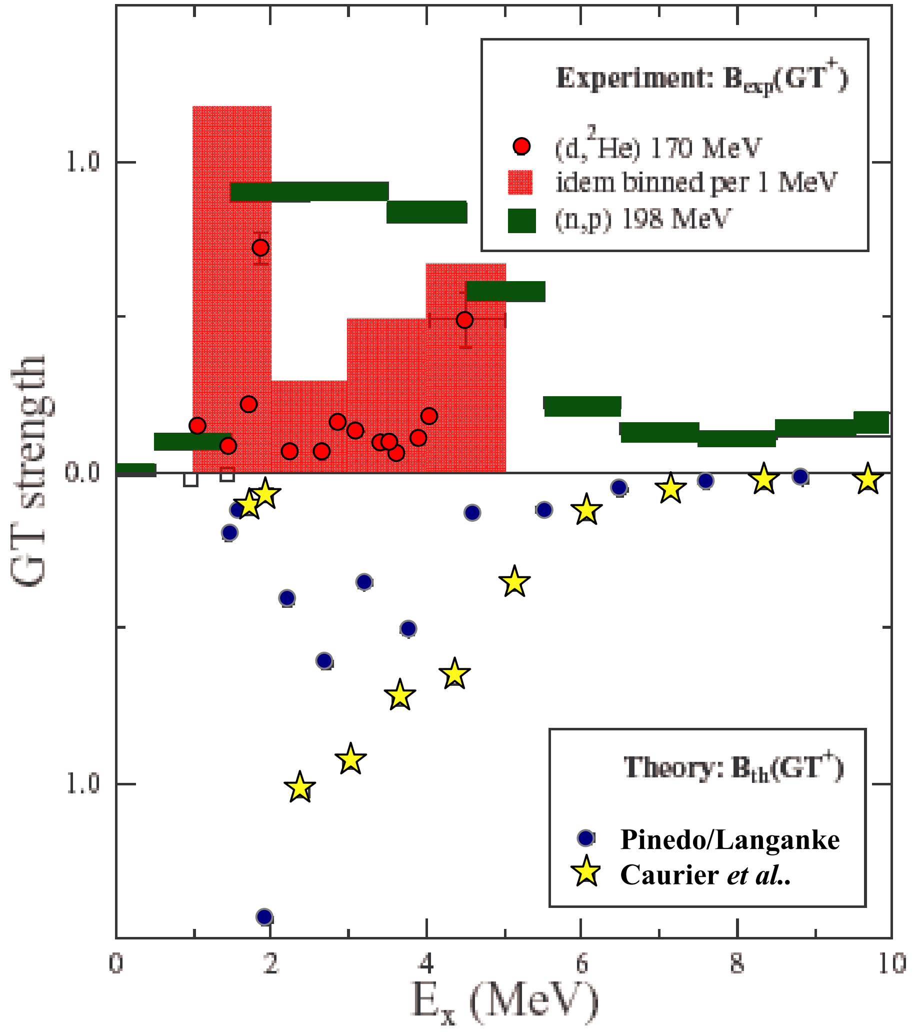
$^{58}Ni(n,p)^{58}Co$ E=198 MeV

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

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

E_x [MeV]	dσ/dσ(0.5°) [mb/sr]	σ(L=0)/σ(τοτ)	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 rebinned in 1 MeV bins

Significant differences

Updated shell model calculations by Martínez-Pinedo/Langanke

Electron capture rate

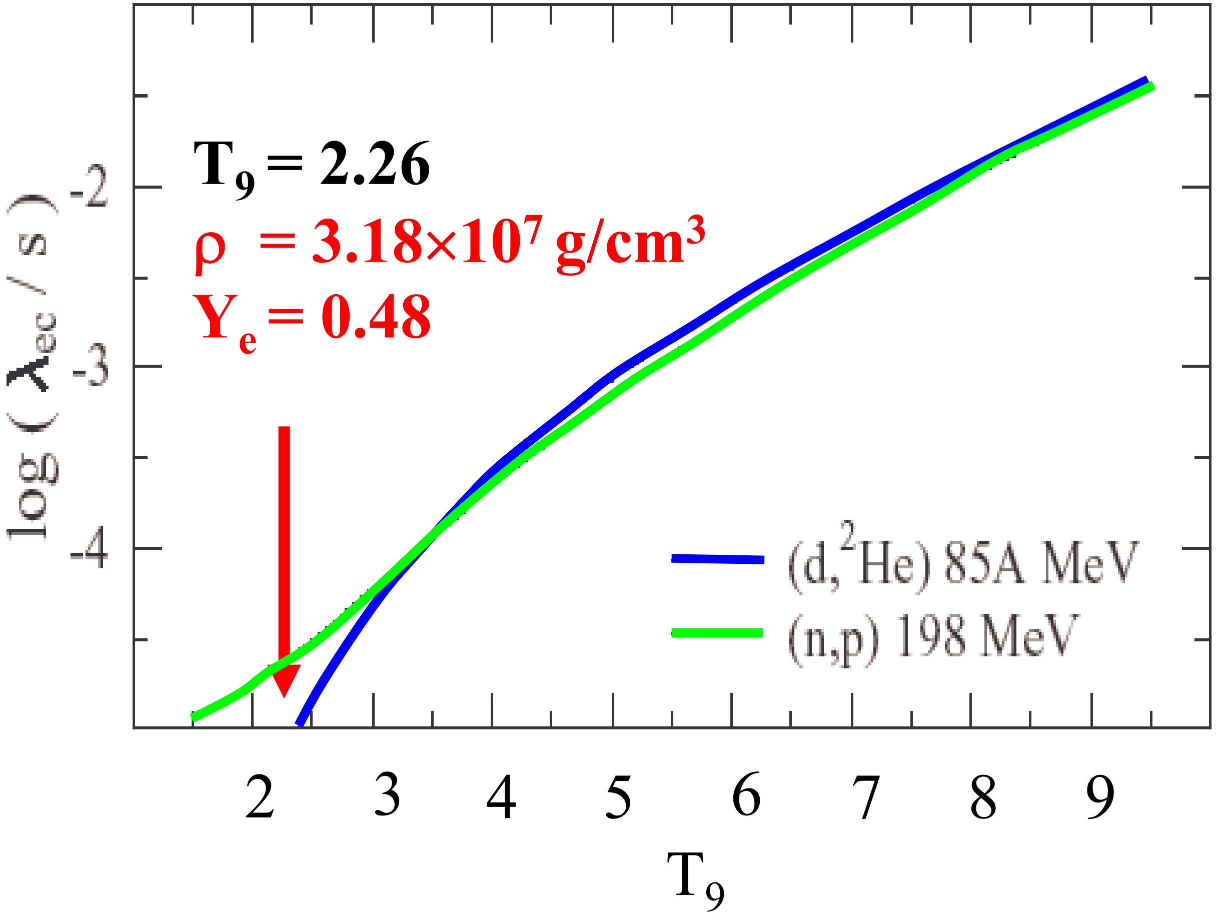
$$\lambda_{ec} \approx \sum_i B_i(GT) \int_{\omega_l}^{\infty} \omega p \left(Q_i + \omega\right)^2 F(Z,\omega) S_e(\omega,T)\, d\omega$$

With

- **$B_i(GT)$ Gamow-Teller strength distribution**
- **ω and p energy and momentum of electrons**
- **$S_e(\omega,T)$ Fermi-Dirac distribution electron gas at temperature T**

e^--capture rates using experimental strengths

(Martínez-Pinedo, Langanke)



T_9 = 2.26

ρ = 3.18×10^7 g/cm^3

Y_e = 0.48

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

T_9 = 4.05

ρ = 3.18×10^7 g/cm^3

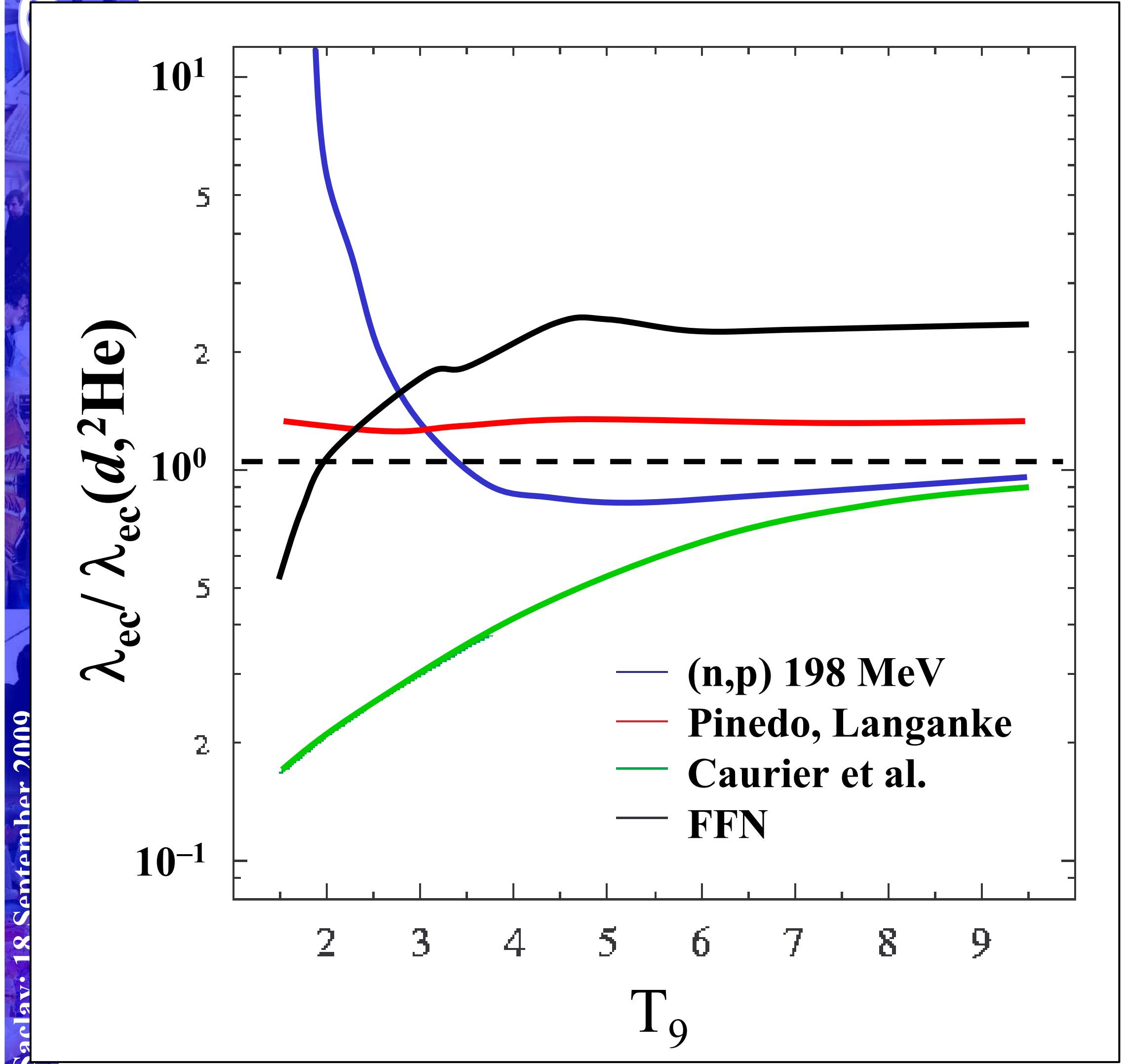
Y_e = 0.48

[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

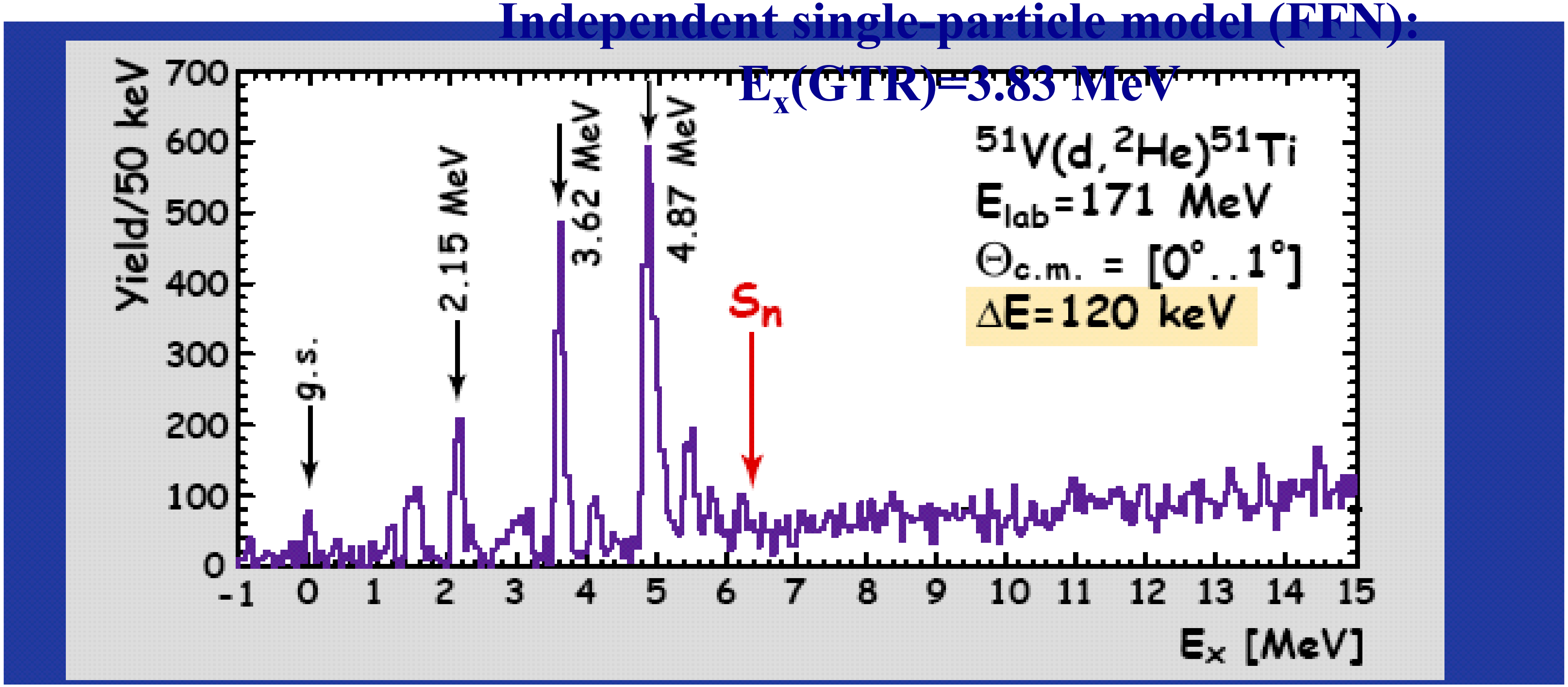


- Influence of GT strength distribution on calculated capture rate is dramatic, especially at low temperatures
- rates vary up to a factor 5-6
- FFN not too far off
- large scale shell-model calculations fail at low T
- calculations with improved residual interaction in reasonable agreement

nucleus

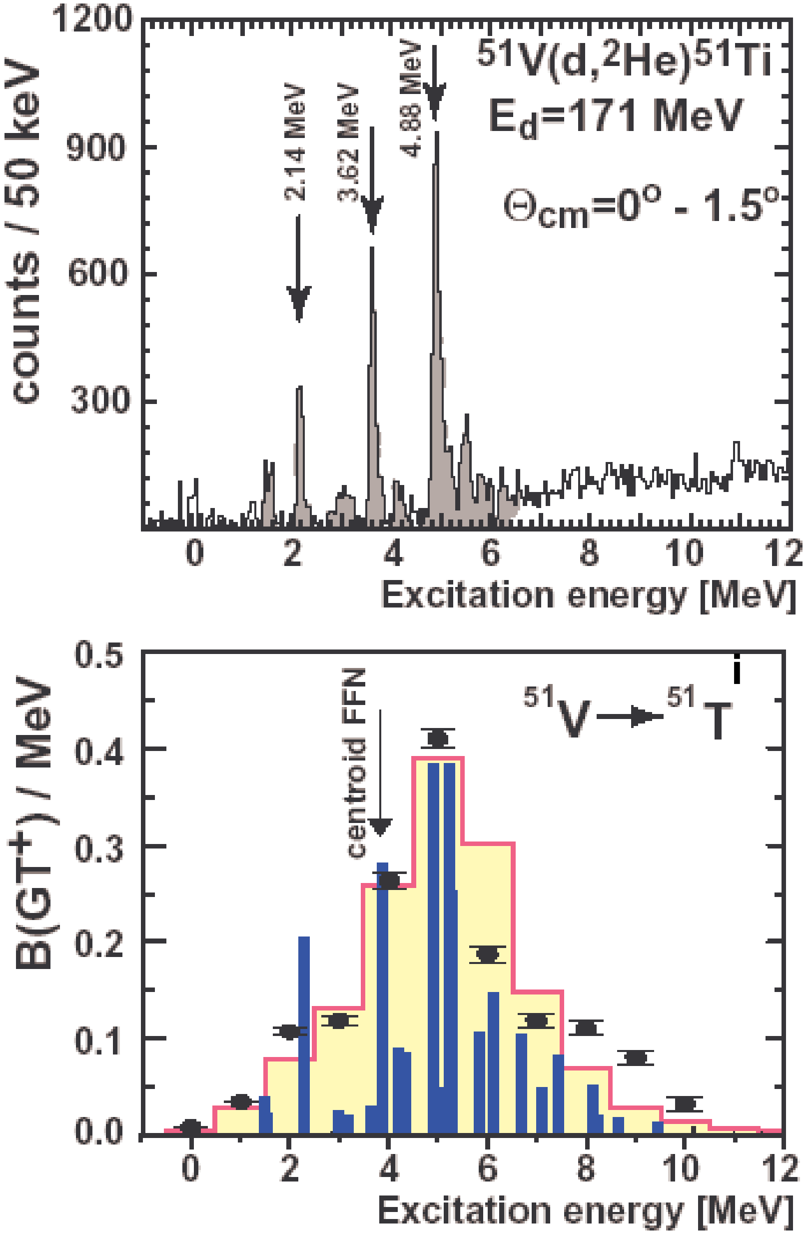
^{51}V g.s. ($J^\pi=7/2^-$, T=5/2) ⇒ ^{51}Ti ($J^\pi=5/2^-, 7/2^-, 9/2^-$, T=7/2)

Independent single-particle model (FFN): E_x(GTR)=3.83 MeV

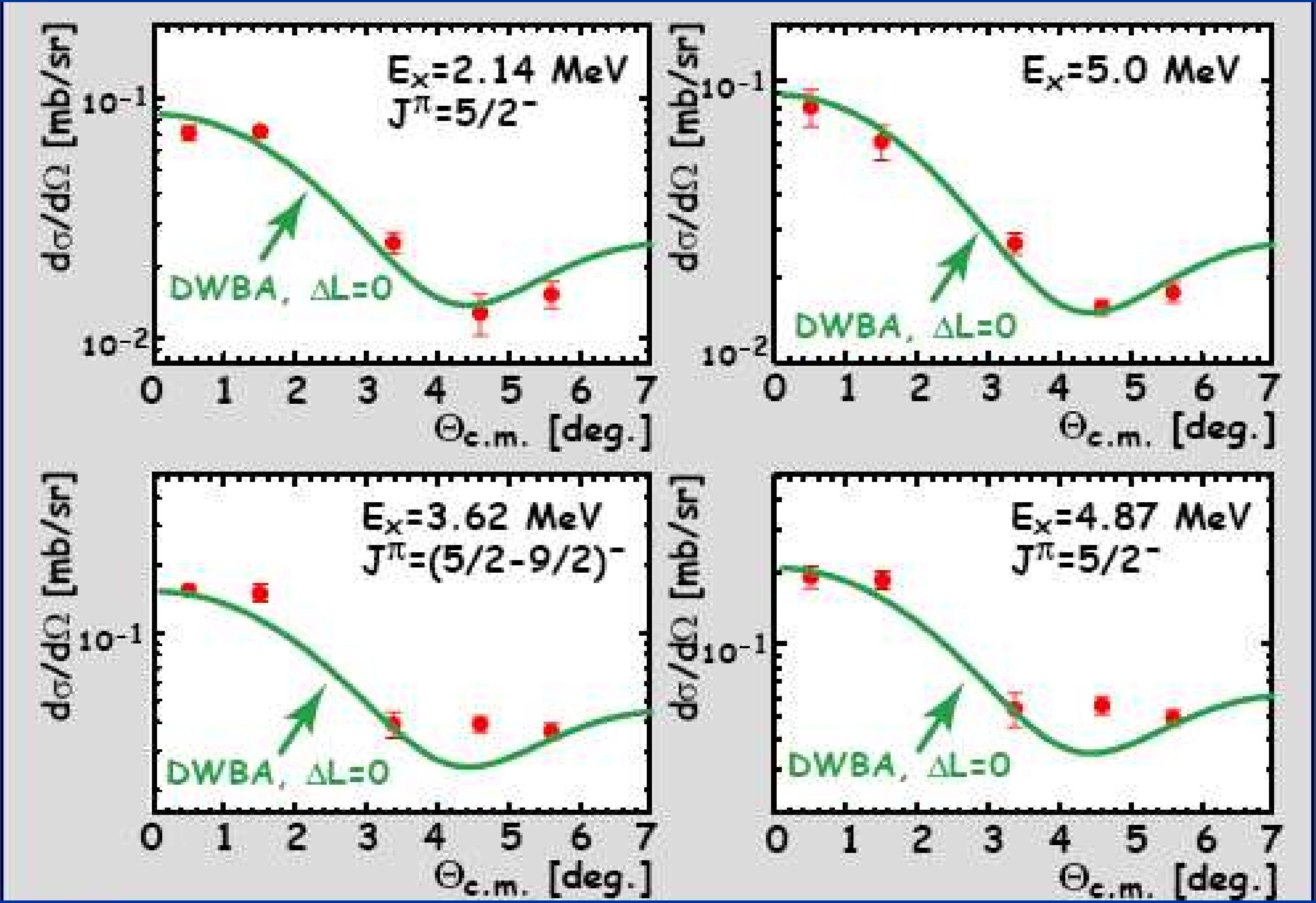


C. Bäumer *et al.,* PRC **68**, 031303(R) (2003)

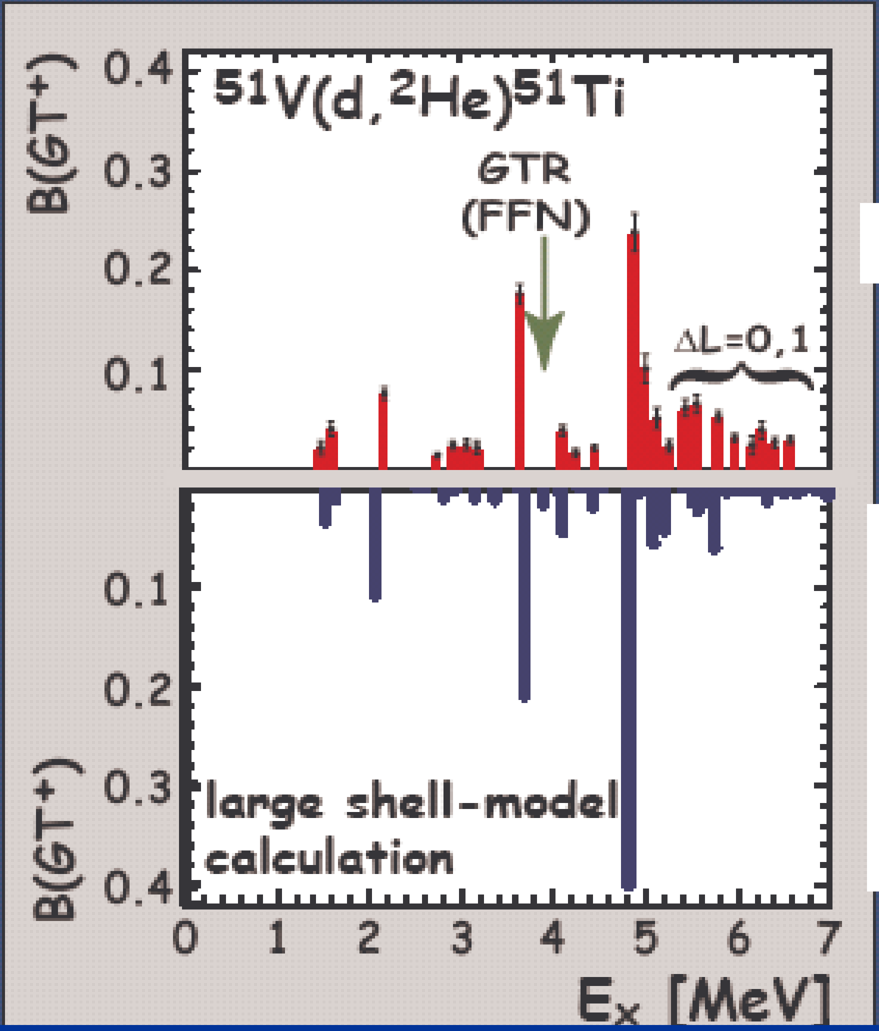
C. Bäumer *et al.*,
PRC **68**, 031303(R)
(2003)



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



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



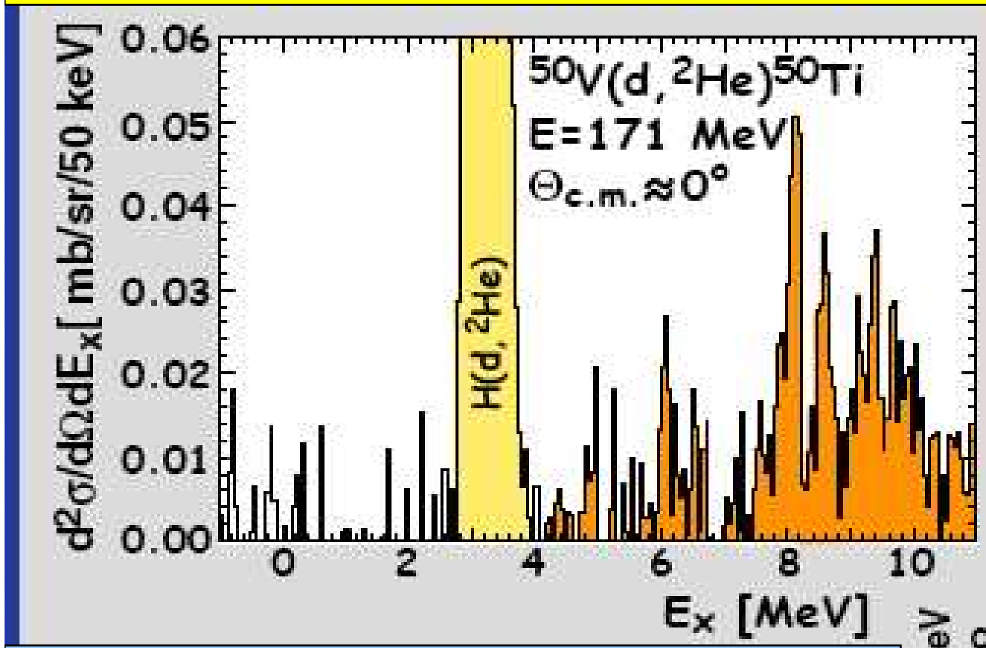
← Experimental result

← 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$^+$

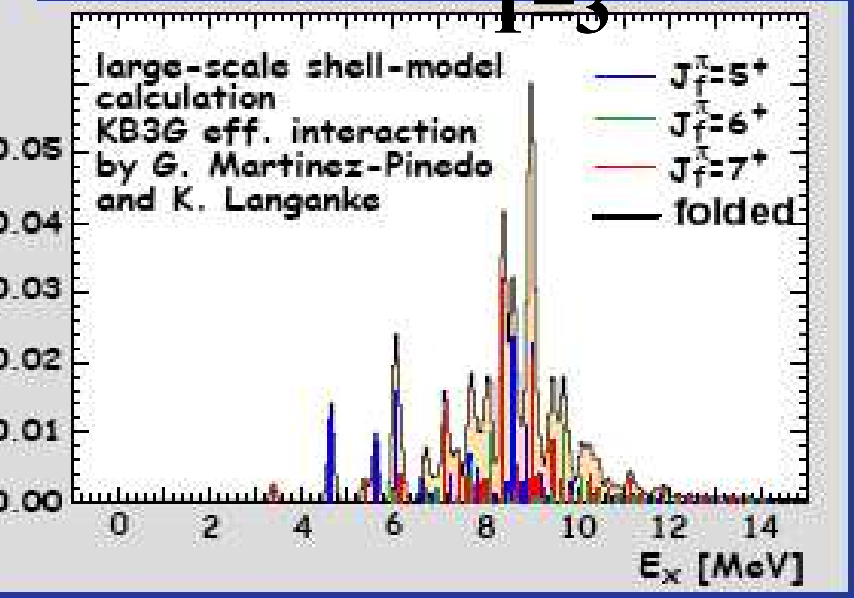
^{50}Ti

J$^\pi$=6$^+$ →

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

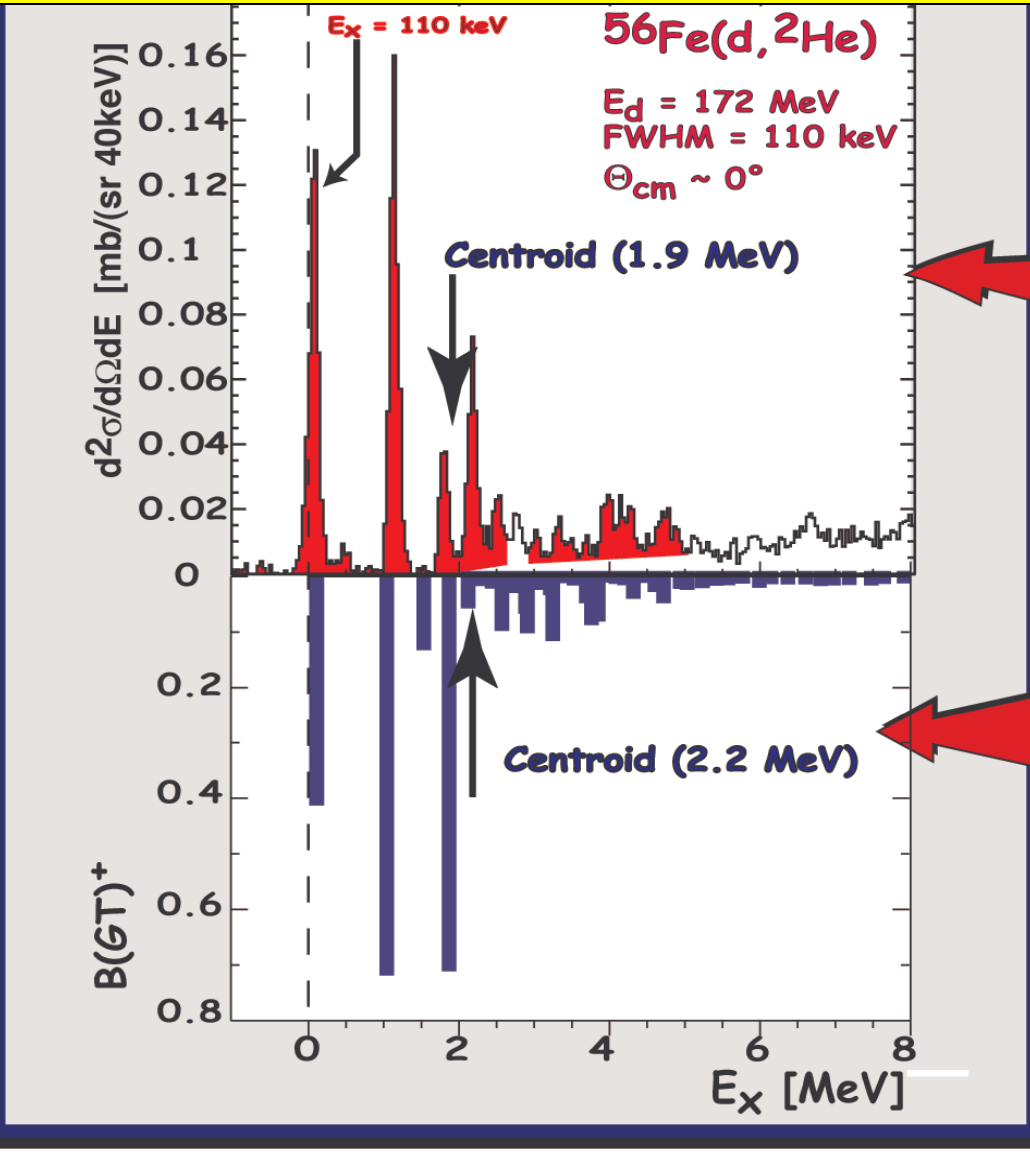
T=2

T=3



GT-centroid located at ~ 9 MeV

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



Experiment

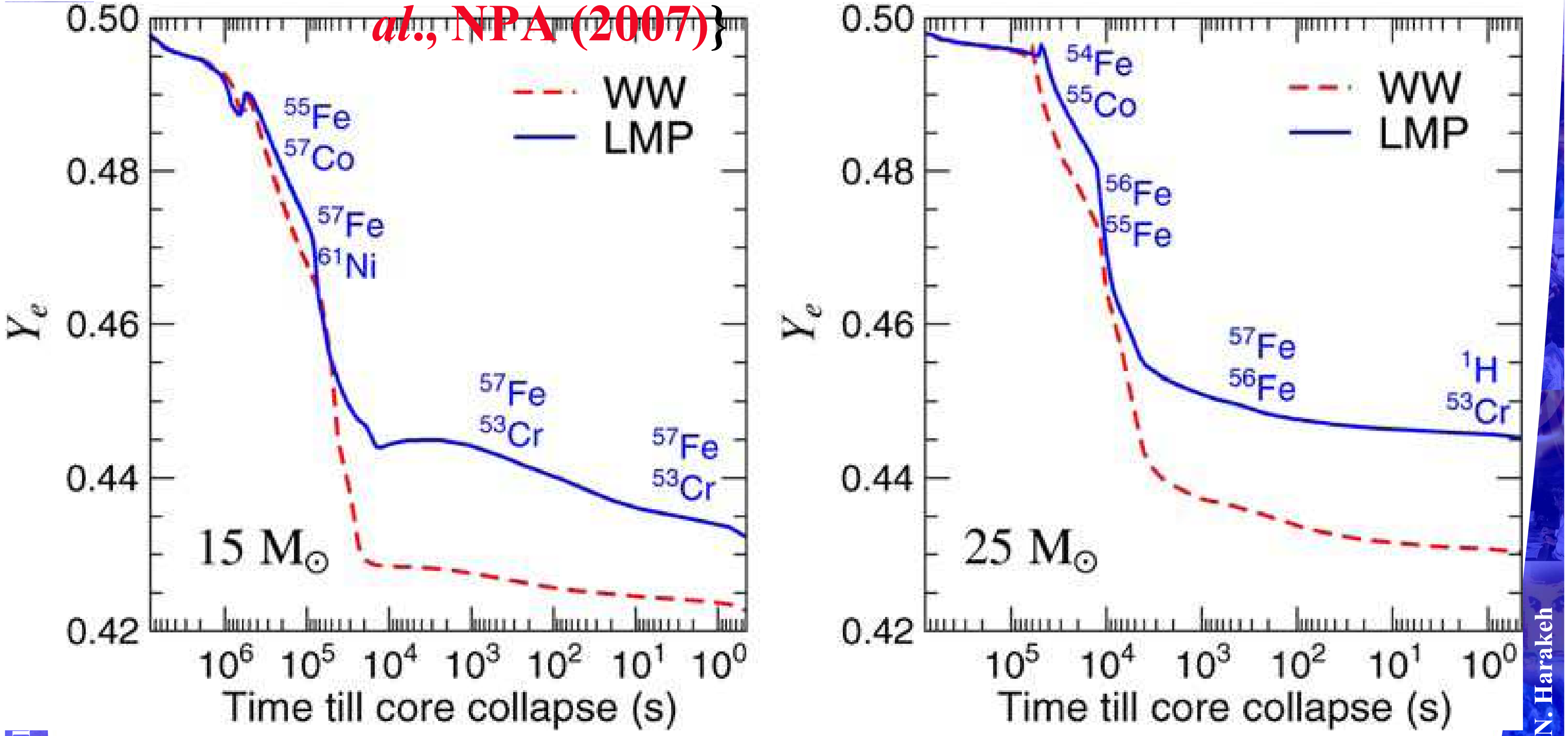
Full *fp*-shell model calculations (KB3G) (G. Martínez-Pinedo)

GT$^+$ centroid comparison

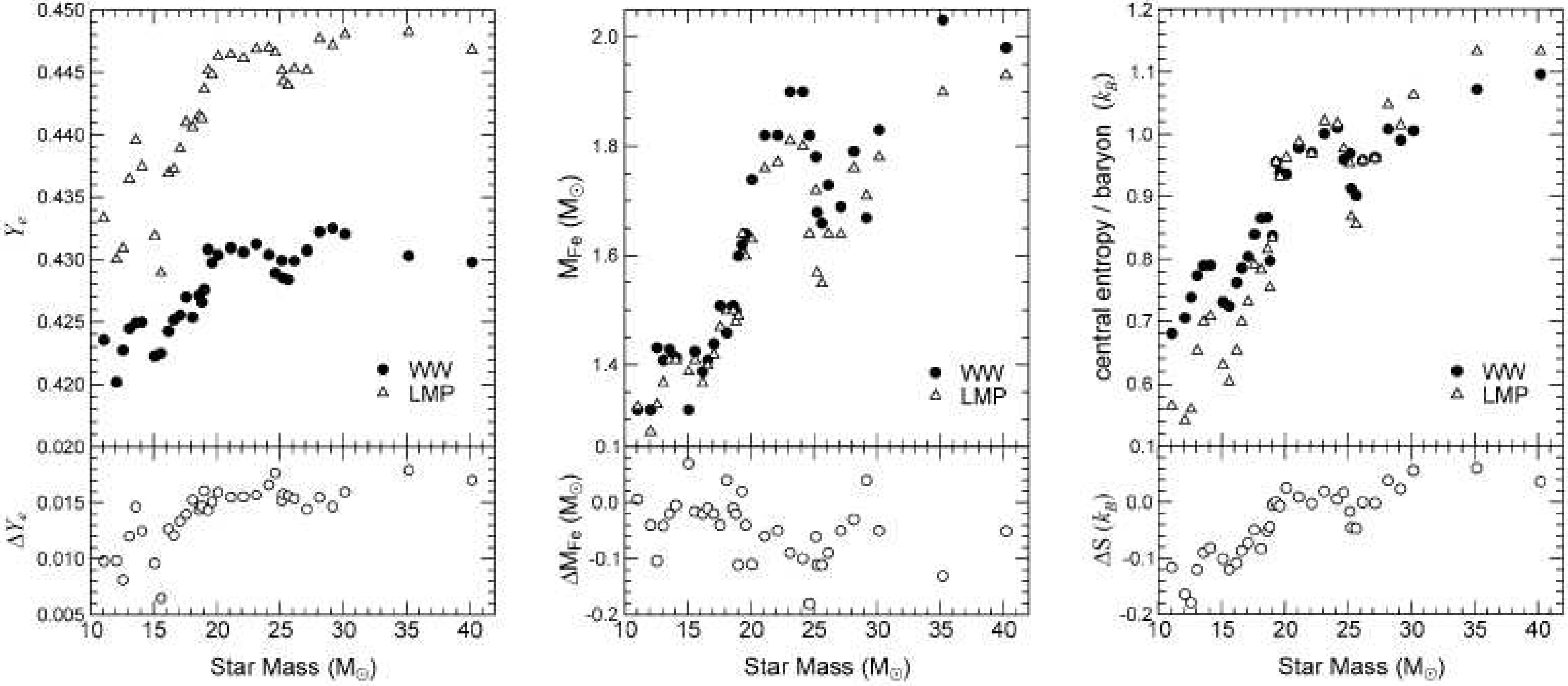
		FFN	SM	Exp.
even-even	Fe-56	3.8	2.2	1.9
	Ni-58	3.8	3.6	3.4
odd-A odd-p	V-51	3.8	4.7	
odd-A odd-n	Fe-57	5.3	4.1	2.9
	Ni-61	3.5	4.6	4.2
	Zn-67	4.4	--	3.4
odd-odd	V-50	9.7	8.5	8.8

(FFN rates)

LMP = Langanke-Martínez-Pinedo Large shell-model calculations {G. Martínez-Pinedo *et al.*, NPA (2007)}



Y_e = Central electron-to-baryon ratio



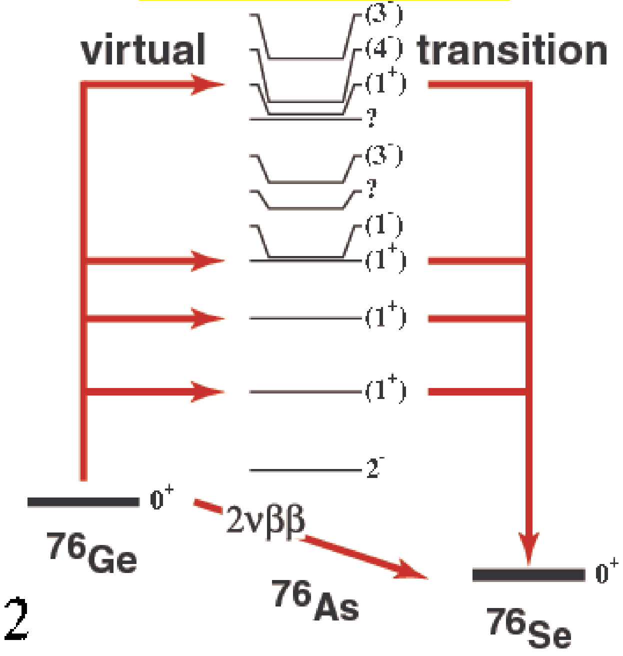
Conclusions

- 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.

2νββ decay

ββ decay

Allowed in SM and observed in many cases



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

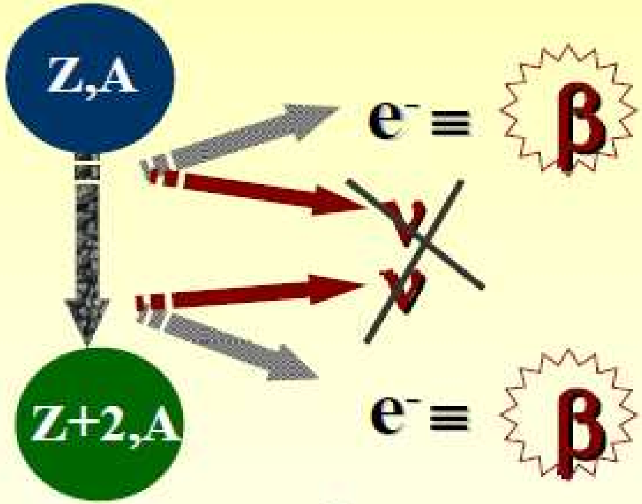
$$M_{\mathrm{DGT}}^{(2\nu)} = \sum_m \frac{(0^{(f)}_{\mathrm{g.s.}}\|\sum_i\sigma(i)\tau^{\pm}(i)\|1^+_m)(1^+_m\|\sum_i\sigma(i)\tau^{\pm}(i)\|0^{(i)}_{\mathrm{g.s.}})}{[\frac{1}{2}Q_{\beta\beta}(0^{(f)}_{\mathrm{g.s.}}) + E(1^+_m) - M_i]/m_e + 1}$$

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

$0\nu 2\beta$



Majorana ν

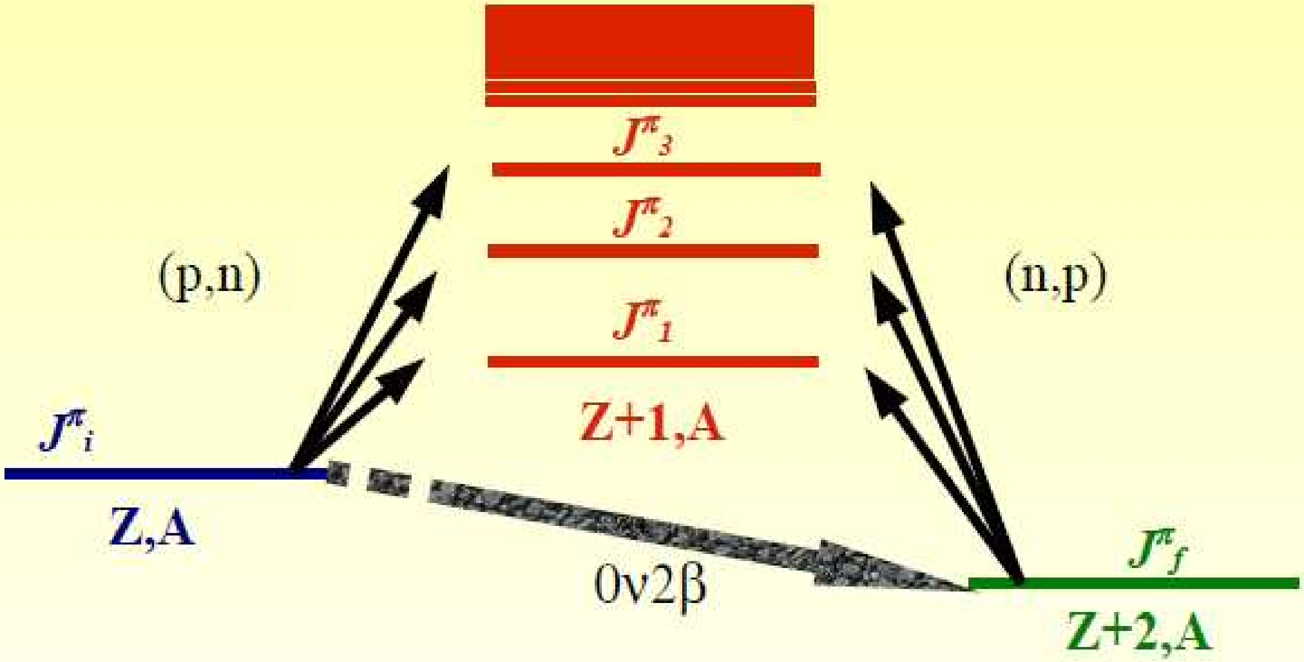
$$\text{decay rate} \sim \left|NME^{0\nu 2\beta}\right|^2 \langle m_\nu \rangle^2$$

nuclear matrix element

Mass of Majorana neutrino!!

Approach

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

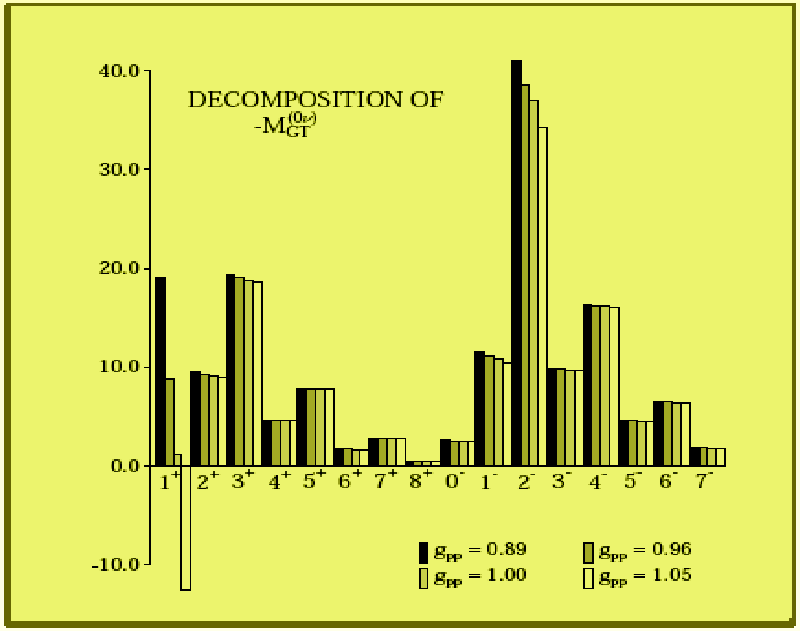


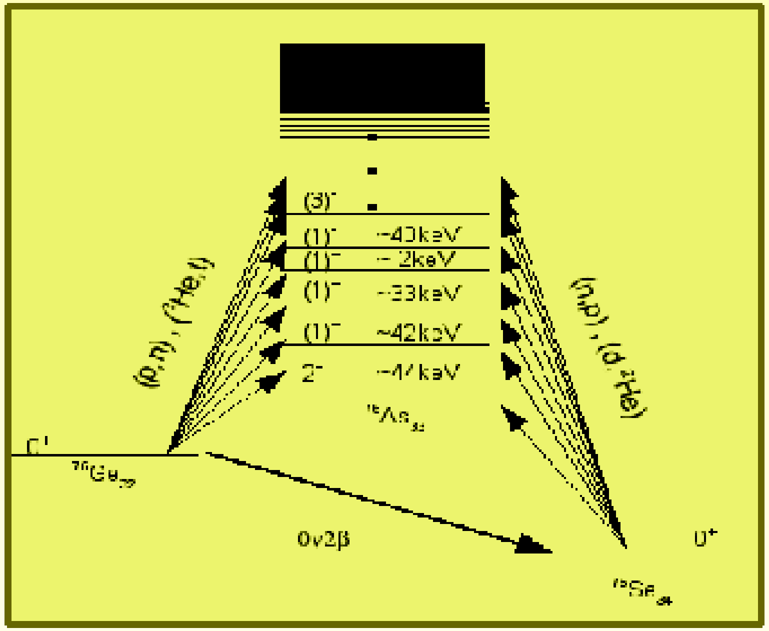
theory:

$$NME^{0\nu2\beta} = \sum_m \frac{\langle J^\pi_i \| Operator \| J^\pi_m \rangle \langle J^\pi_m \| Operator \| J^\pi_f \rangle}{f(E_m)}$$

Physics case for 0ν2β study: ^{76}Ge

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





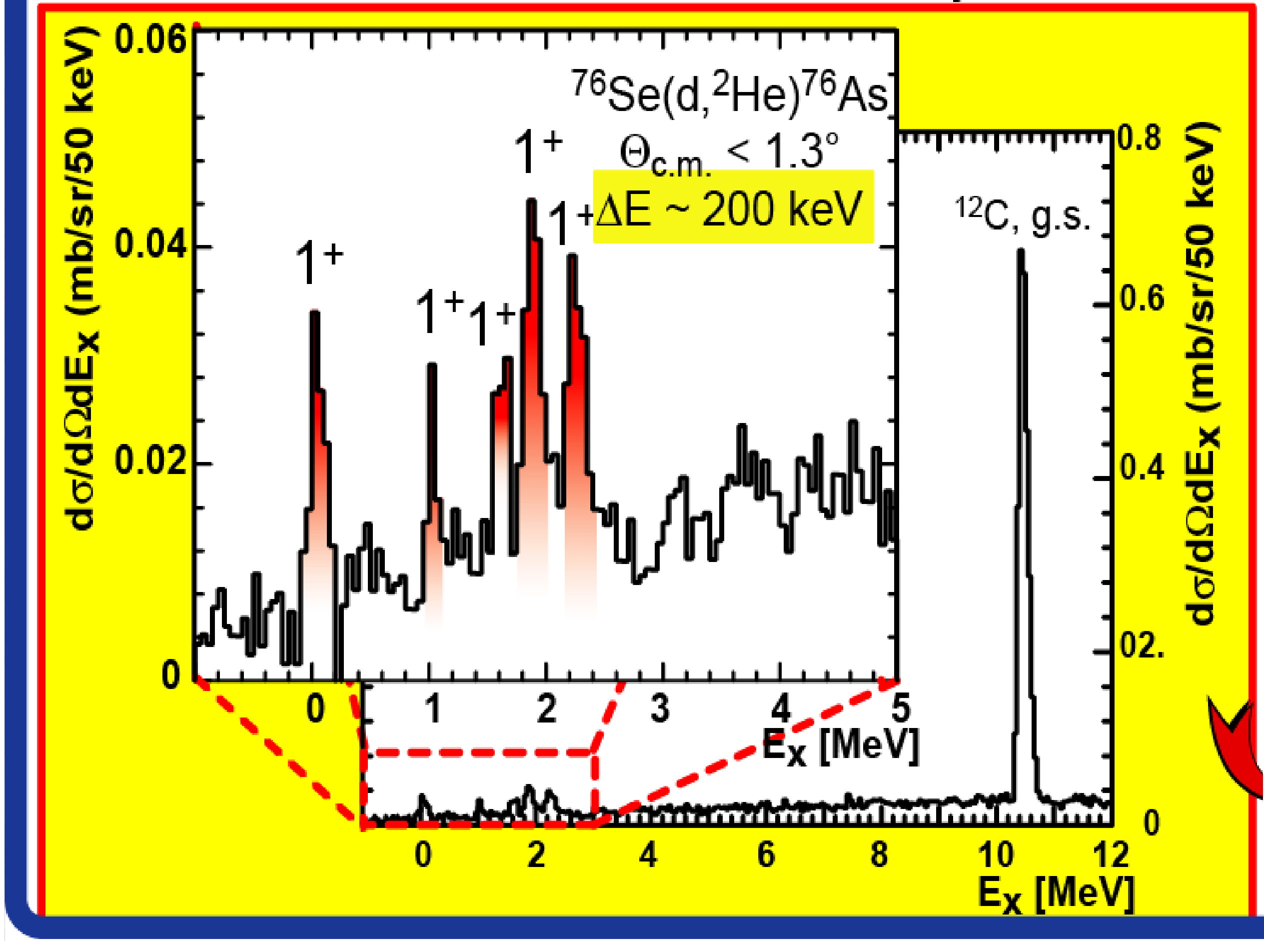
- ☞ contribution of many multi-poles
- ☞ dominance of dipole components
- ☞ the g_{pp} parameter affects mainly the $J^{\pi} = 1^+$ component
- ☞ it becomes imperative to study experimentally higher multi-pole components

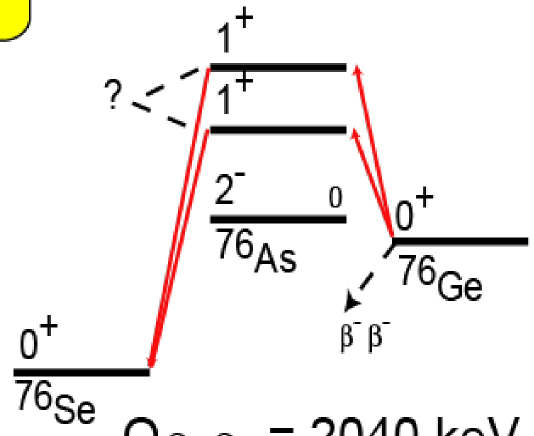
^{76}Ge - ^{76}As - ^{76}Se

- 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

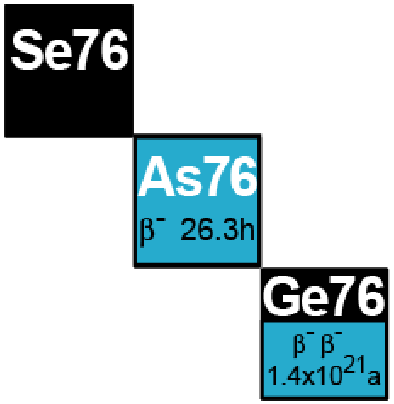
  multipole decomposition: 7.4×10^{20}y

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

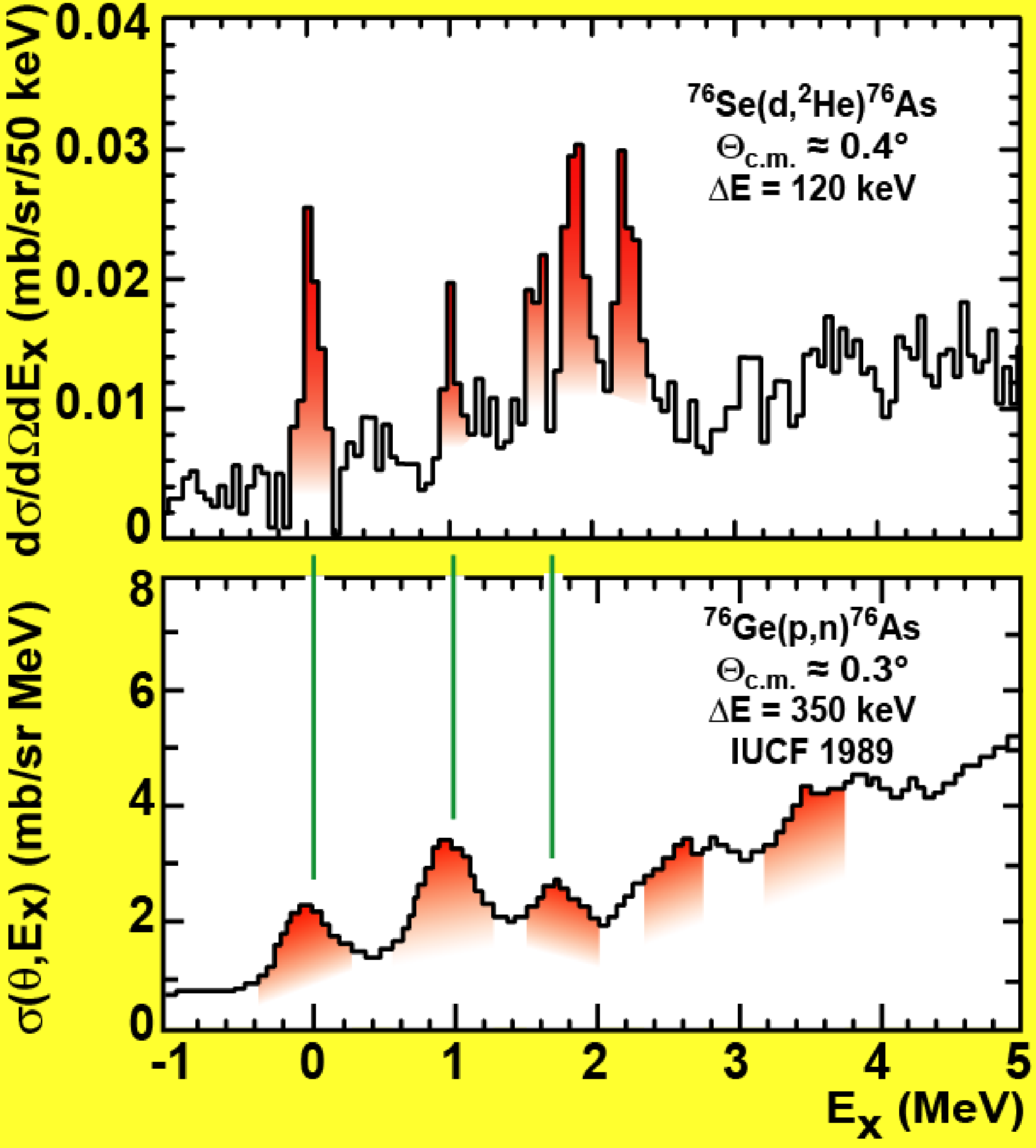




$Q_{\beta^- \beta^-}$ = 2040 keV



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



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

0.16 ± 0.04 MeV^{-1}

with

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

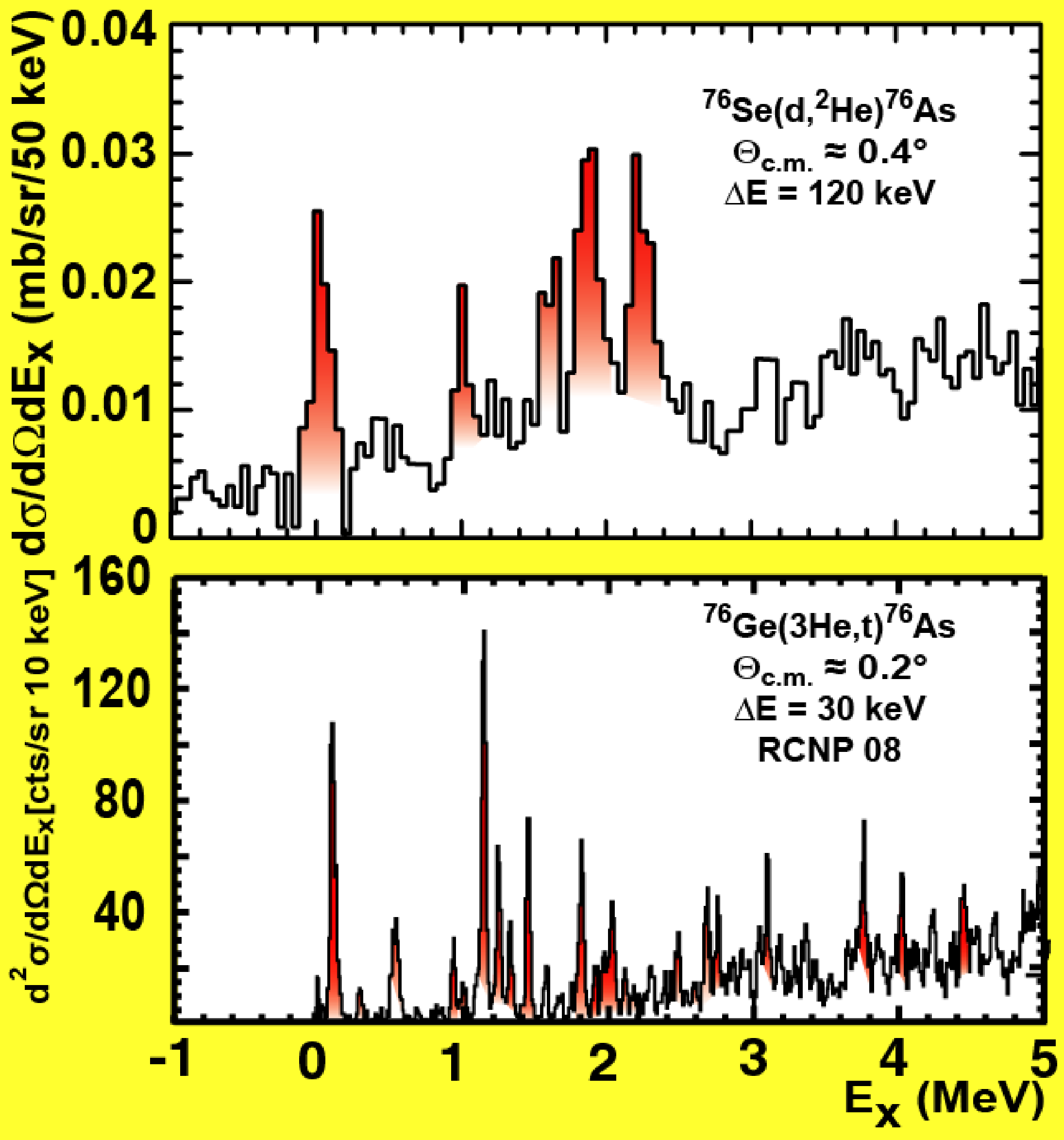
$2\nu\beta\beta$ - half-life

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



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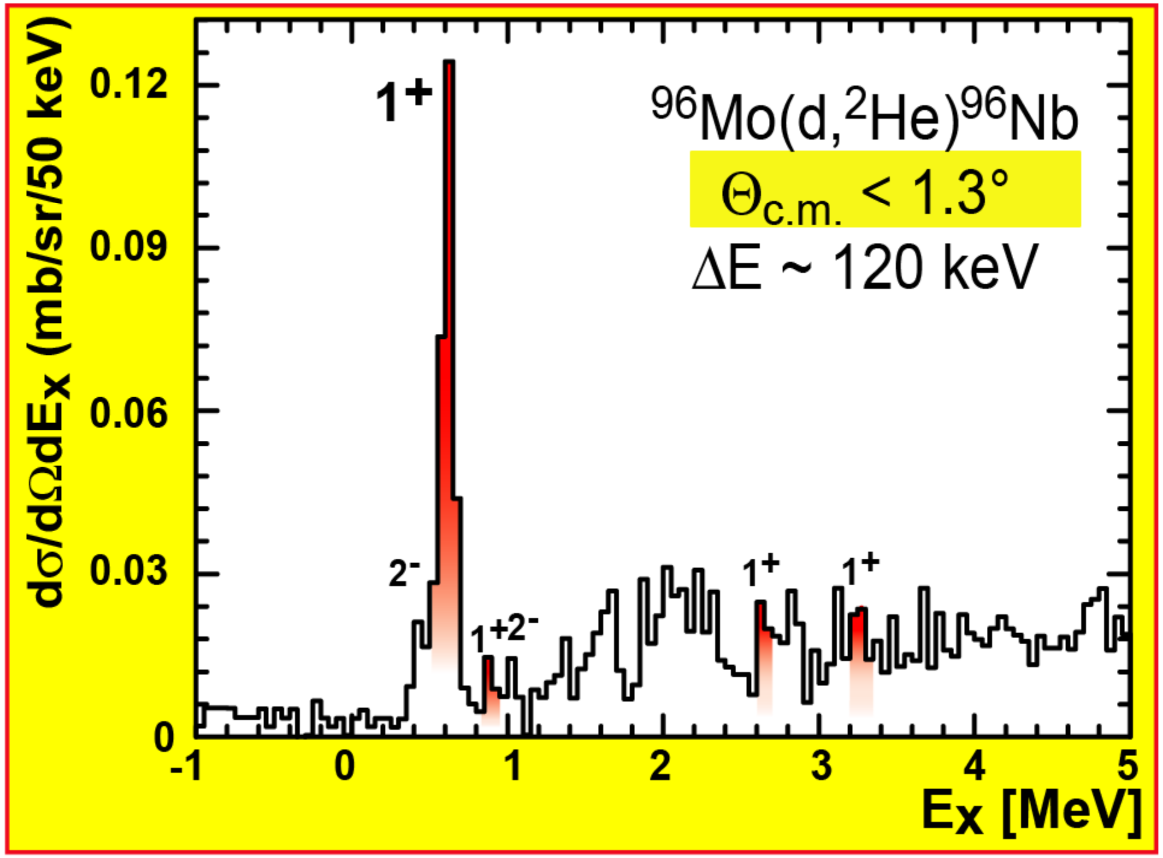
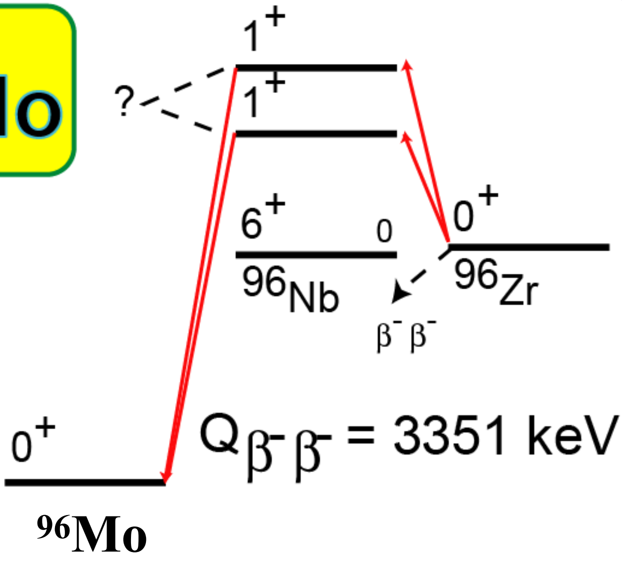
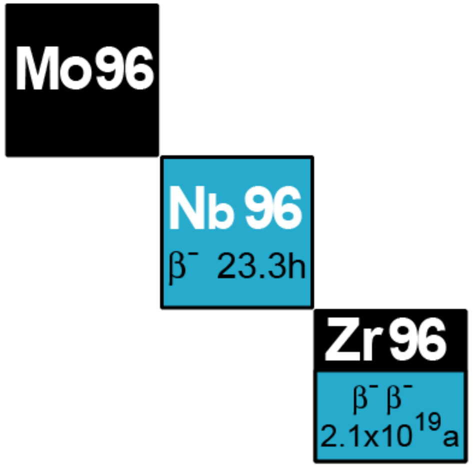
^{96}Zr - ^{96}Nb - ^{96}Mo

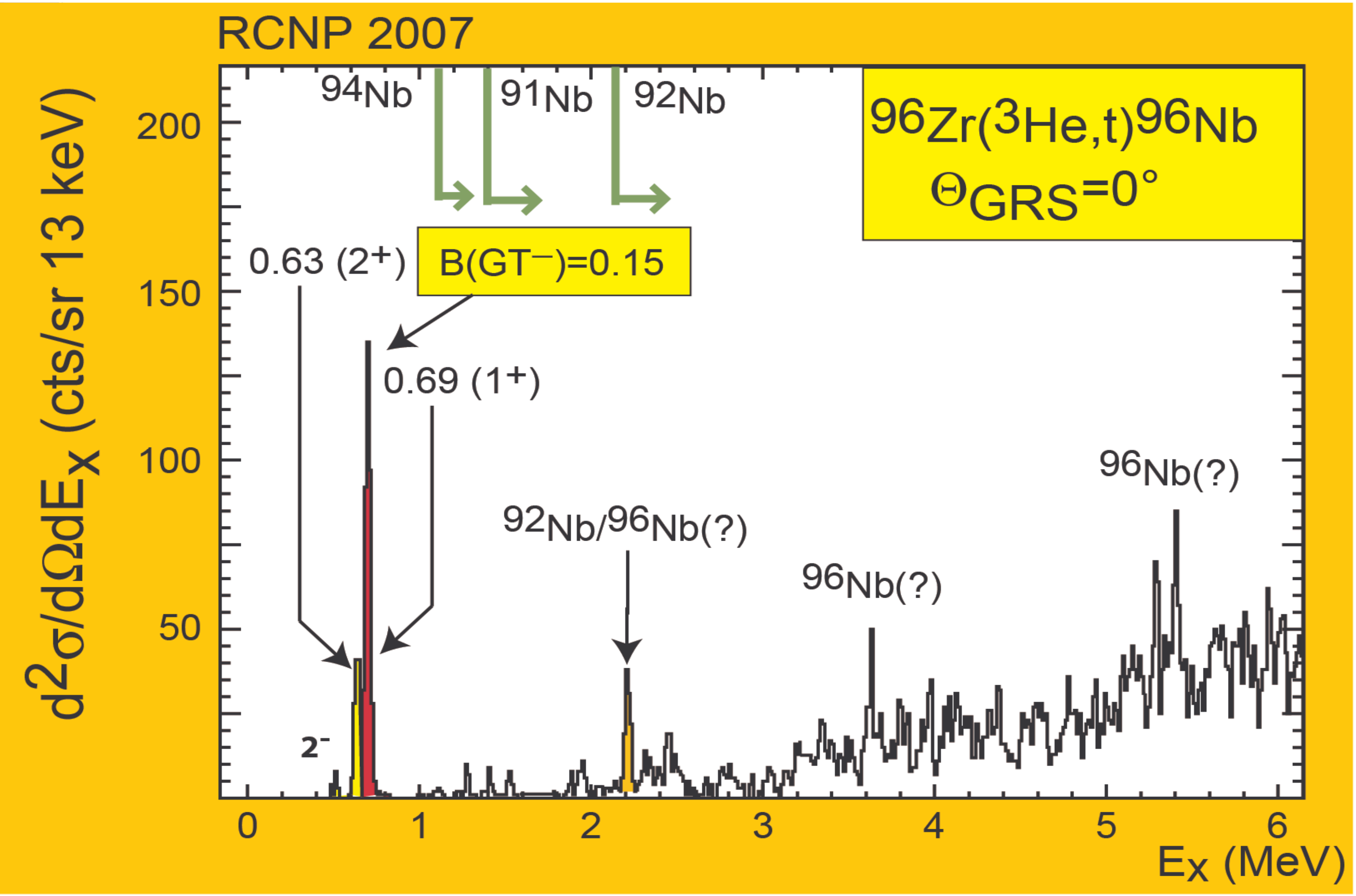
- $T_{1/2}$ available:
  - counting experiments: 2.1×10^{19}y
  - geochemical methods: 9.4×10^{18}y
- g.s. transition forbidden
- strength concentrated in one transition







B(GT+) ~ 0.3



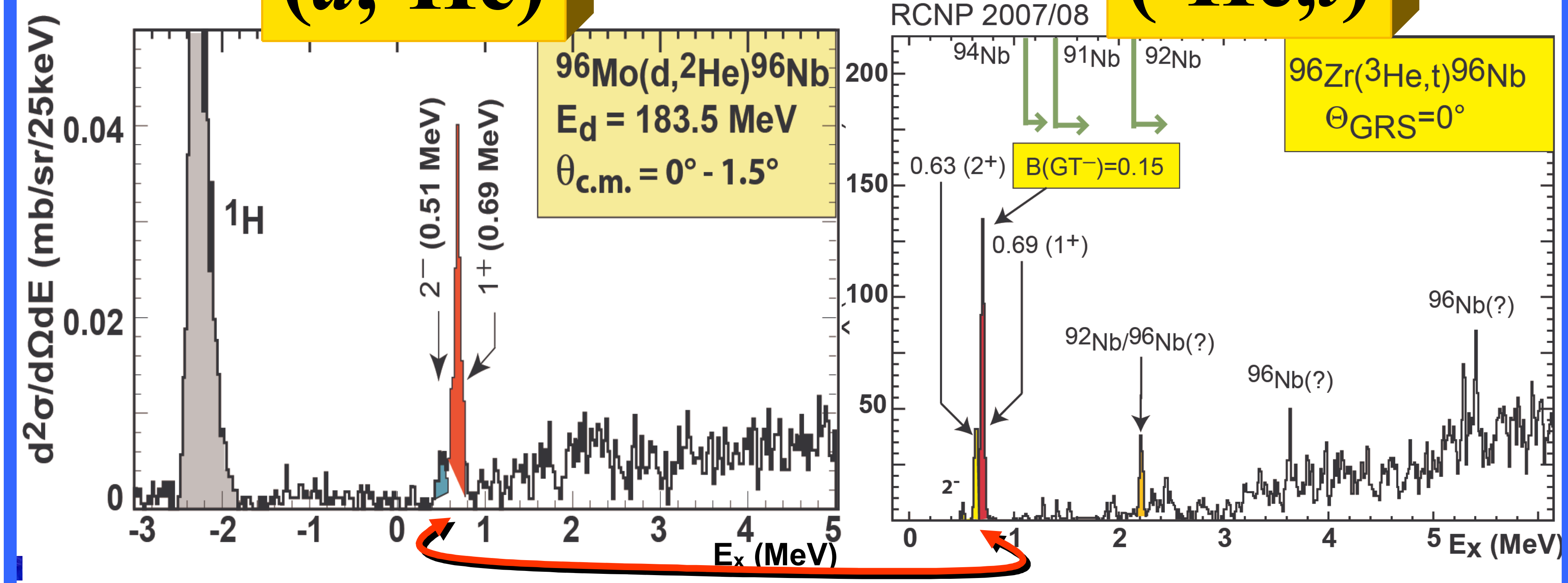
In (*p*,*n*) direction:

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 2νββ 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 strength in unstable *sd* & *fp* shell nuclei
- Use IVSGDR as tool to determine n-skin [IV(S)GDR]
- Exotic excitations such as Double GT

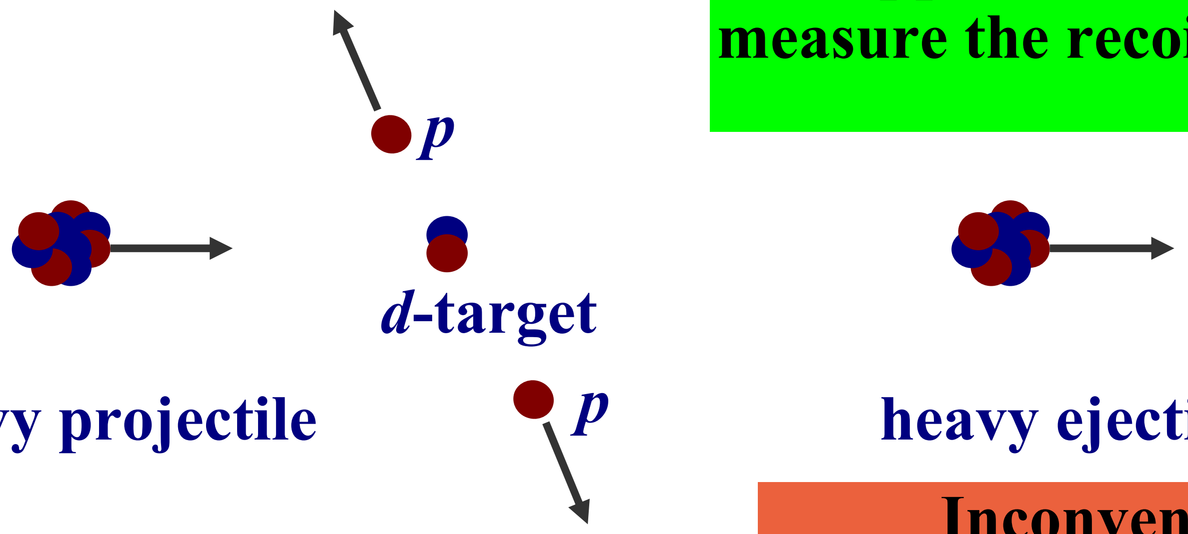
Nuclear structure studies with CE reactions in inverse kinematics

Possible at FAIR and RIKEN

(intermediate beam energies are needed!)

Approach (at FAIR):
measure the recoiling protons

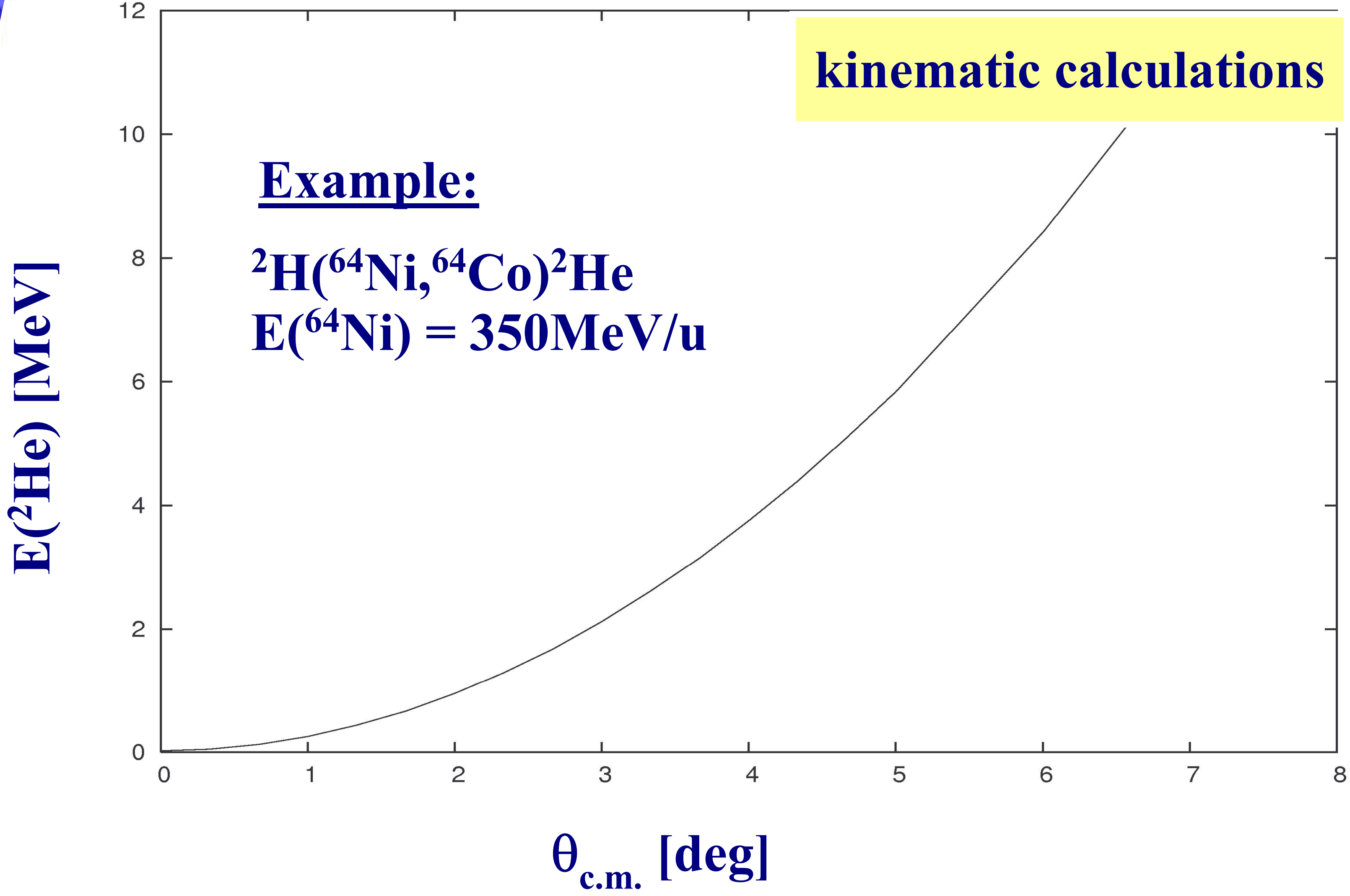
$(d,{}^2\text{He})$



Inconvenience:
difficulty to detect the low-energy protons

Courtesy
Lucia-Ana Popescu

How low?

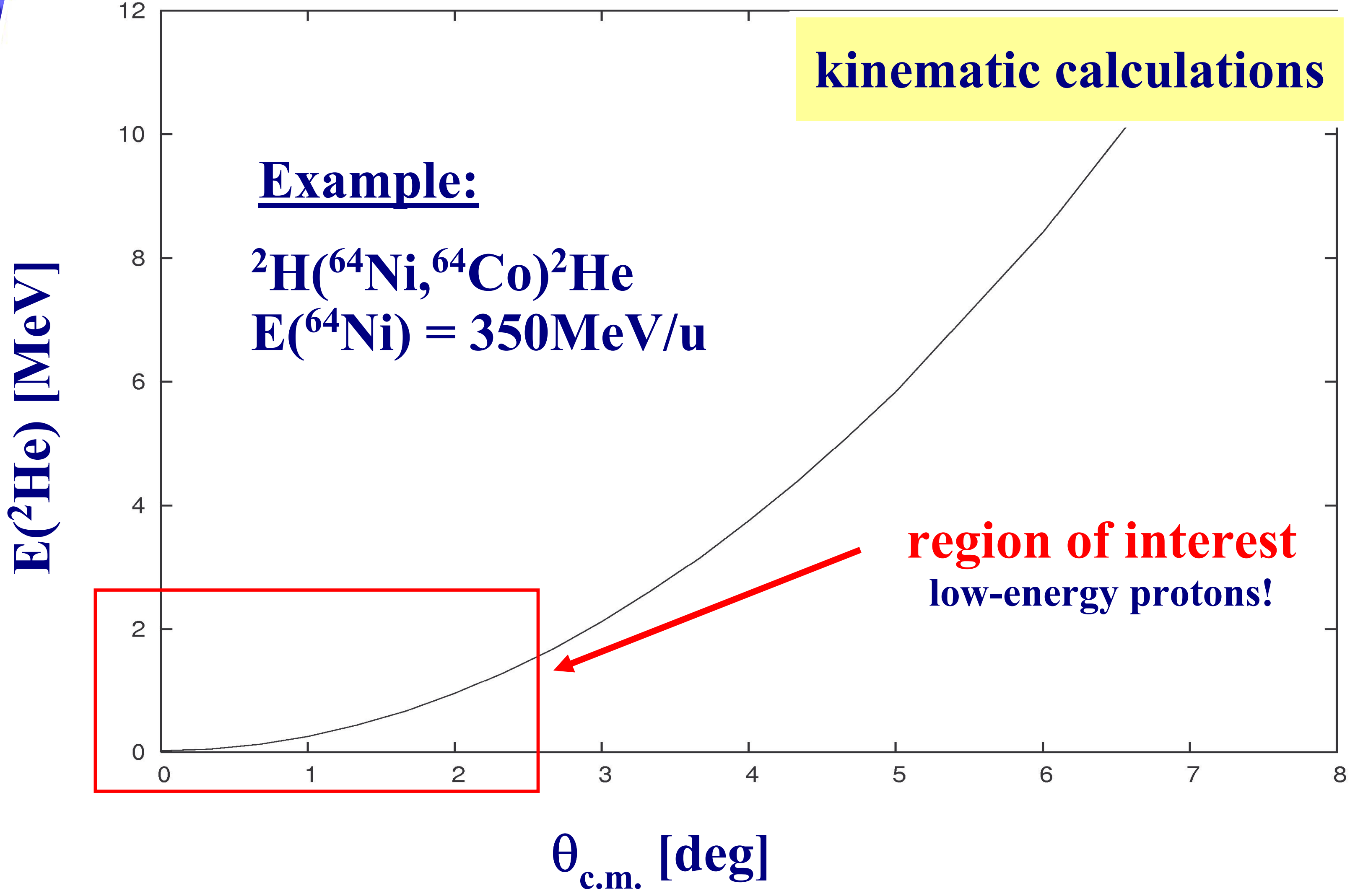


kinematic calculations

Example:

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

How low?



kinematic calculations

Example:

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

region of interest
low-energy protons!

Detection system @ FAIR

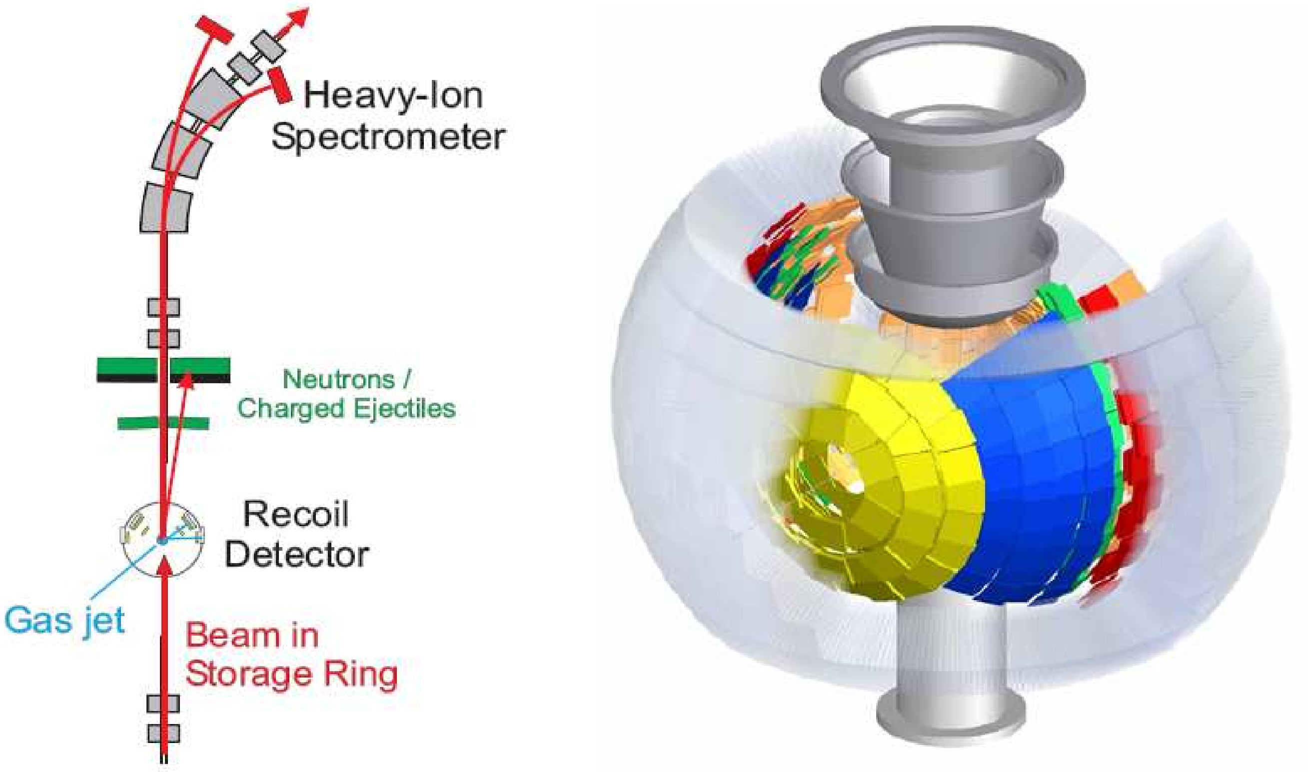


Figure 1: *Schematic view of the EXL detection systems. Left: Set-up built into the NESR storage ring. Right: Target-recoil detector surrounding the gas-jet target.*

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

EuroSuperNova Collaboration

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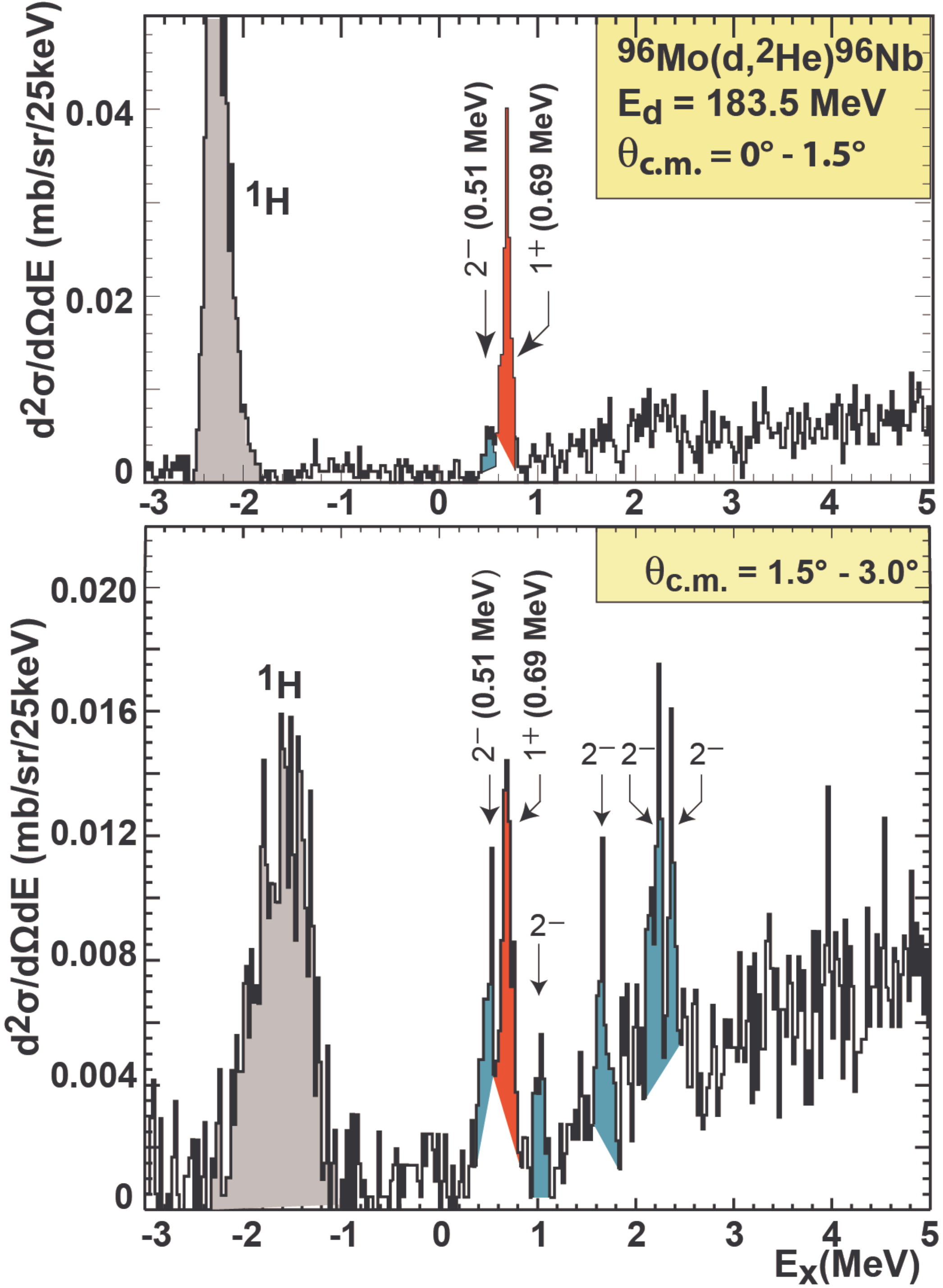


Zero-degree spectrum

only one 1^+ state visible

Finite-degree spectrum ($\langle \Theta_{cm} \rangle \sim 2^\circ$)

2^- states quickly become visible

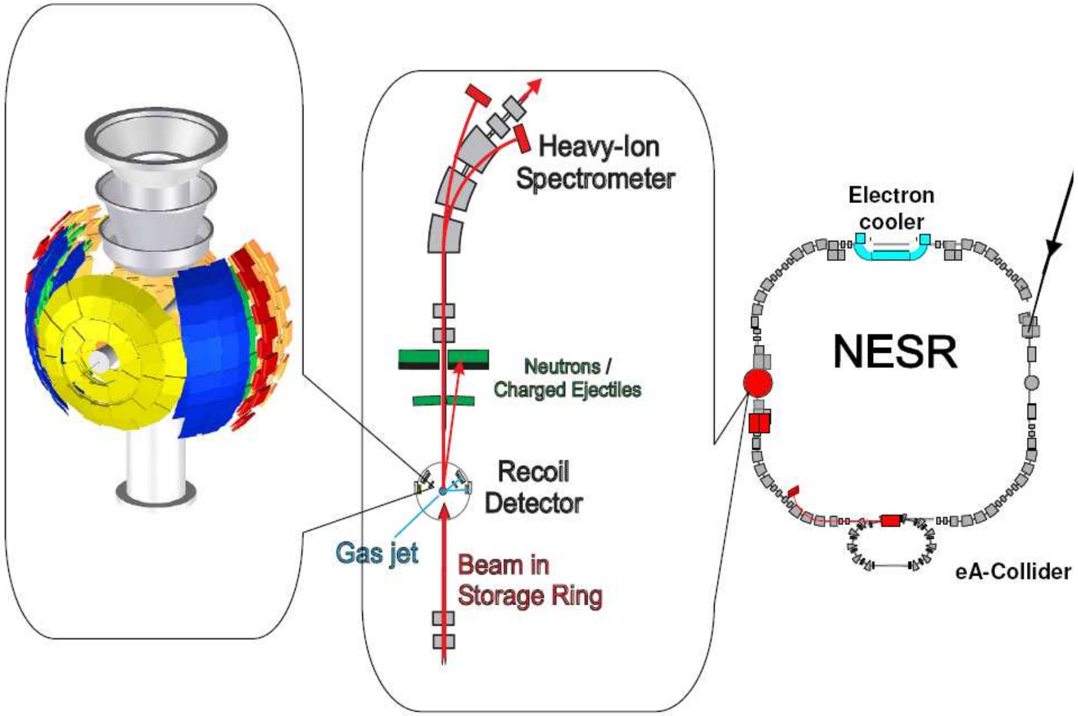
Scattering of stored exotic nuclei off light hadronic probes (EXL)

Inverse kinematics

thin gas target ($\sim10^{15}/\mathrm{cm}^2$)

kinematic complete measurements

- **elastic scattering (*p*,*p*) …**
- **inelastic scattering (*p*,*p′*), (α,α′) ...**
- **charge-exchange reactions (*p*,*n*), (^{3}He,*t*), (*d*,^{2}He) …**
- **quasi-free scattering (*p*,*pn*), (*p*,2*p*), (*p*,*p*α) …**



Studies with CE reactions on unstable nuclei

Studies with CE reactions in inverse kinematics

Applications:

- the study of spin-isospin excitations in unstable nuclei involved in nuclear processes that happen under extreme conditions, like in a supernova, is indispensable

- the study of the SDR, of which cross section is correlated to the neutron-skin thickness of nuclei (important for constraining the density dependence of the symmetry energy of nuclear matter) -systematic study is needed

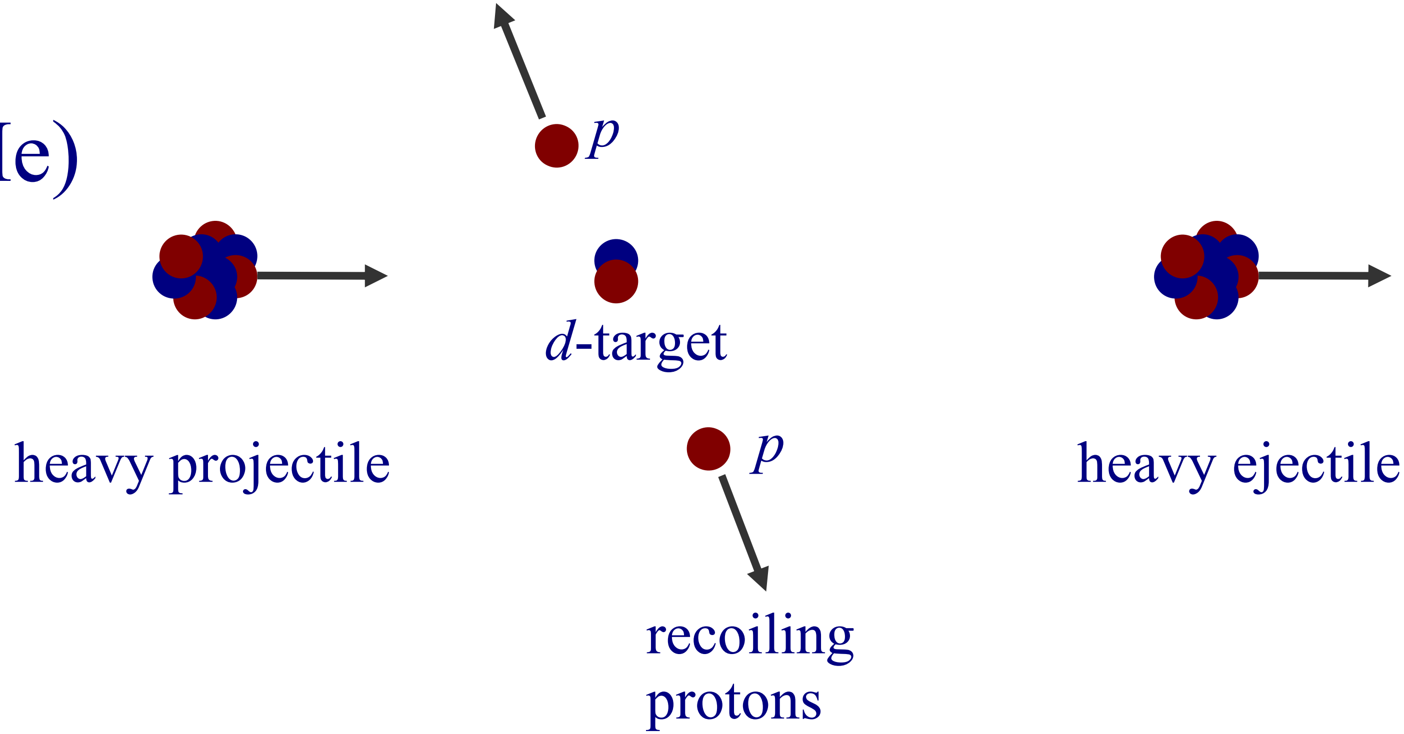
- GT strength distribution on N=Z unstable proton-rich nuclei (^{72}Kr, ^{76}Sr, ^{80}Zr, ^{84}Mo, ^{88}Ru, ^{92}Pd) – test for network calculations for rp-processes

- studies for calibrating presupernovae models: electron capture rates for all radioactive isotopes within $^{55-60}$Co, $^{56-61}$Ni, $^{54-58}$Mn and $^{54-59}$Fe are of interest for the first phase of the core collapse, whereas the neutron-rich Kr and Ge isotopes are relevant for the later phase

Nuclear structure studies with CE reactions in inverse kinematics

- possible at FAIR and RIKEN (intermediate beam energies are needed!)

$(d,{}^{2}\mathrm{He})$



p

d-target

heavy projectile

p

heavy ejectile

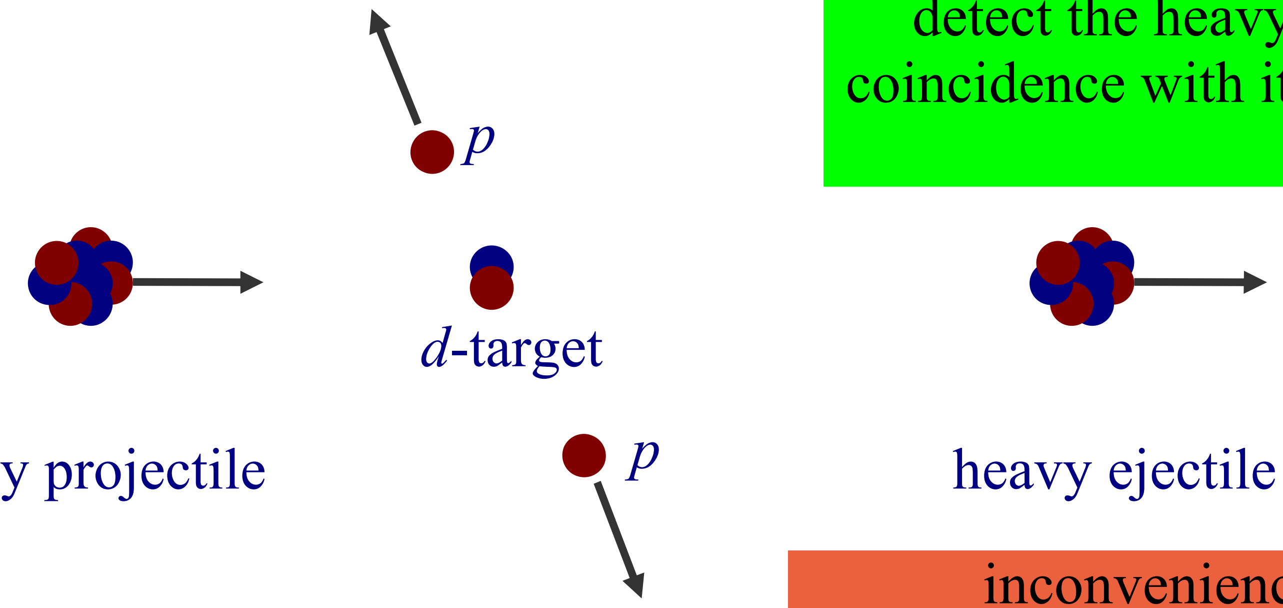
recoiling protons

Nuclear structure studies with CE reactions in inverse kinematics

- possible at FAIR and RIKEN (intermediate beam energies are needed!)

RIKEN approach:
detect the heavy ion in
coincidence with its γ-decay

(d,^{2}He)



heavy projectile

heavy ejectile

recoiling
protons

inconvenience:
limitation to the known states,
but good calibration for
determining the strengths

SN-explosion scenario

- interior of star gets enriched with Fe
- gravitational pressure increases
  balanced by degenerate electron gas up to
  Chandrasekhar limit: $M_{ch} = 1.44\,(2Y_e)^2\,M_\odot$
- start of collapse at
  $T = 10^9$ K and $\rho = 3 \times 10^9$ g/cm^3
  accelerated by neutronization (de-leptonization)

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

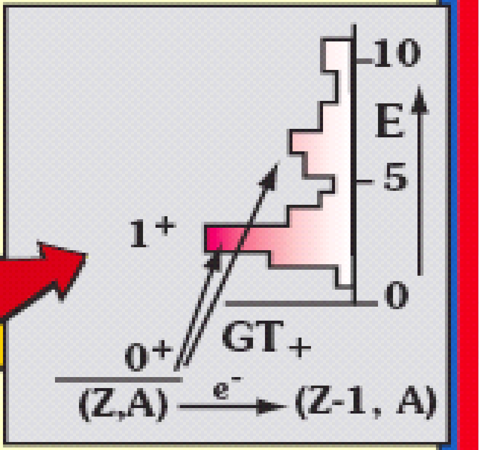
$$e^- + p \longrightarrow n + \nu_e$$

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

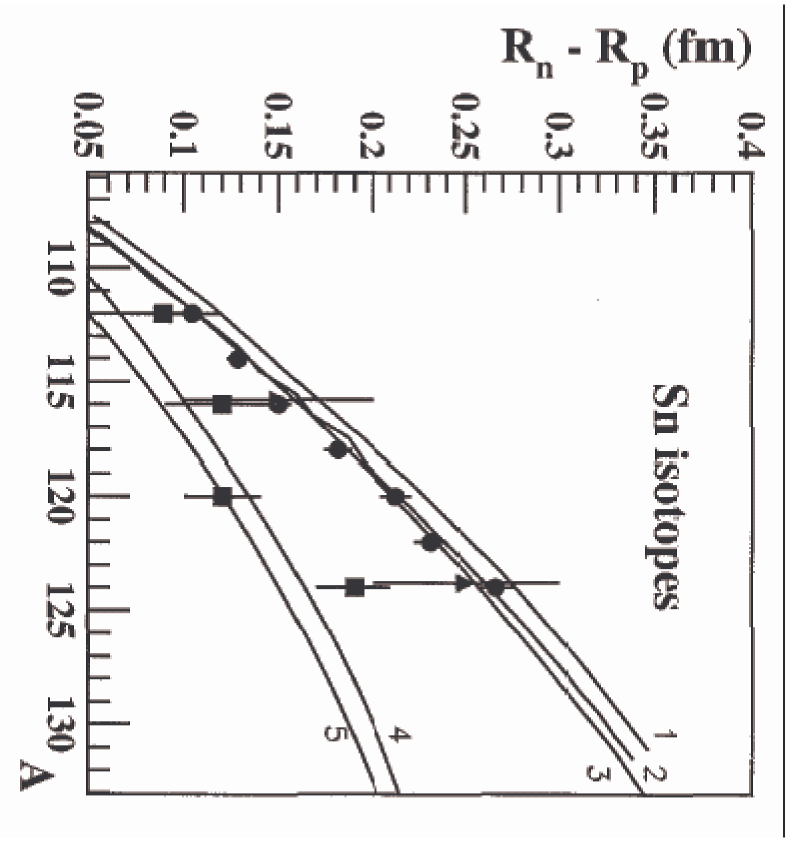
escaping

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

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



Y_e at freeze-out determines the explosive energy!!


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