Charge-exchange reactions & weak rates in stellar evolution.

Remco Zegers

Contents

- weak rates in late stellar evolution
- charge-exchange reactions & weak rates
- probes
- extracting strengths from the data
- an example: ^{58}Ni
- data needs?
- theory needs?

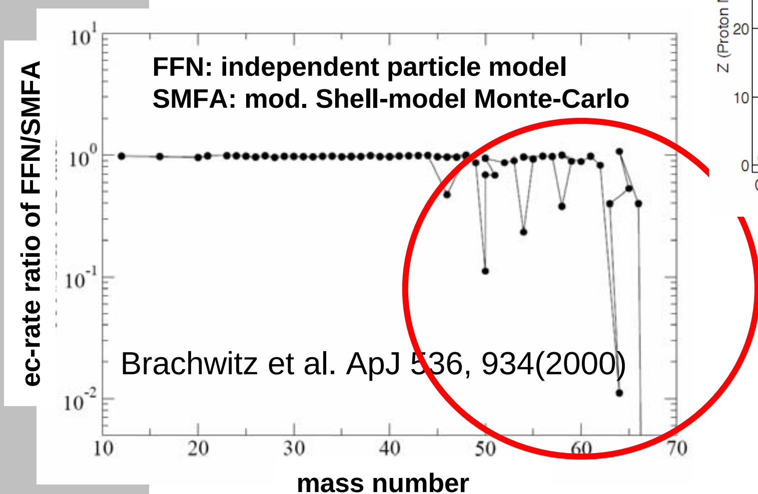
weak rates in stellar evolution

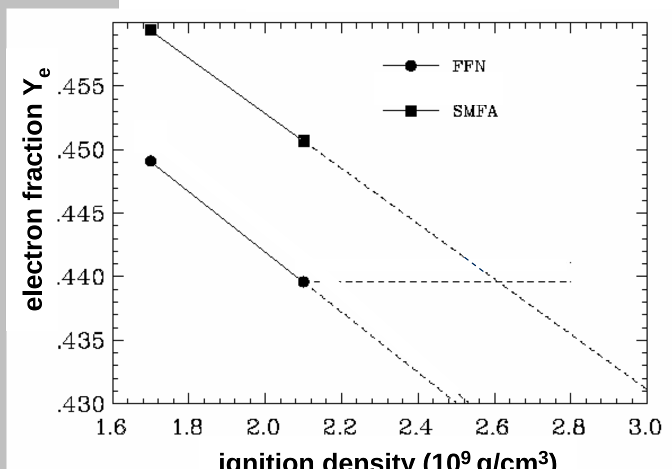
- **Type Ia Supernovae (accreting white dwarfs)**
  - e-capture controls isotopic composition
  - e-capture constrains ignition density & burning front speed
- **Type II Supernovae (core collapse)**
  - e-capture strongly affects pre-collapse trajectory
  - e-capture modifies properties of the core
- nuclei of importance: **pf and sdg shell (stable & unstable)**
- β-decay becomes important in later stages (neutron-rich nuclei)
- rates based on different models (independent-particle, large-scale shell-models, Monte-Carlo shell-model) lead to large differences in stellar evolutionary track:

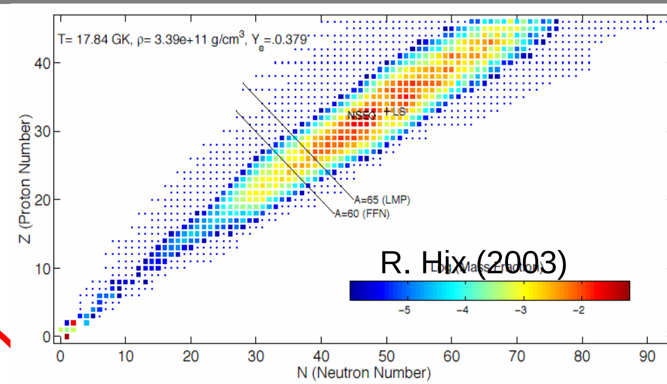
→experimental tests and validation of weak rates is crucial

Some examples

Type Ia



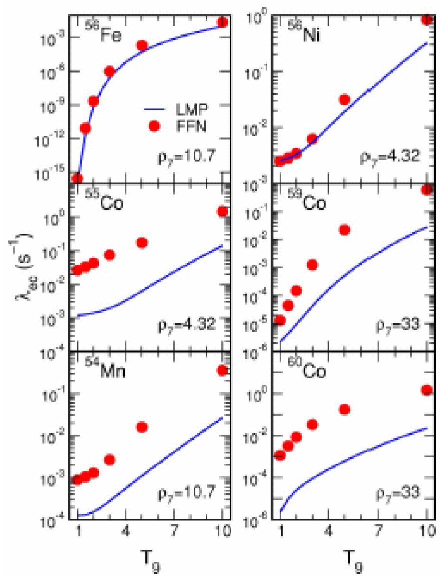


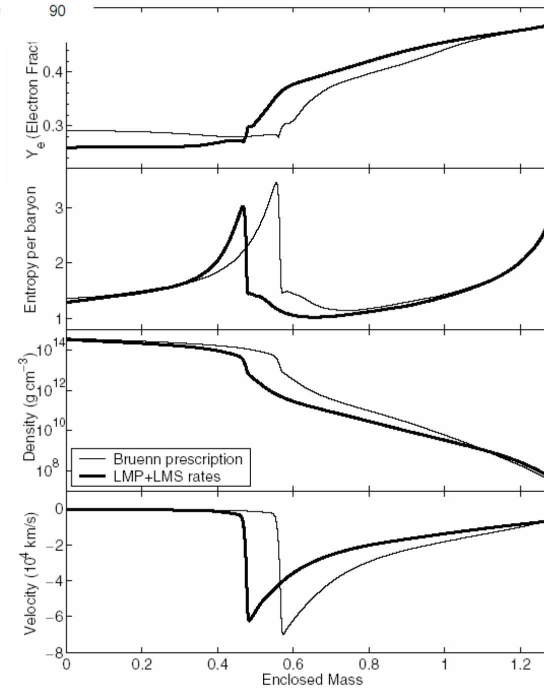


Type II

Large-scale shell model
independent particle model

Langanke, Martinez-Pinedo
Rev.Mod. Phys. 75, 819 (2003)

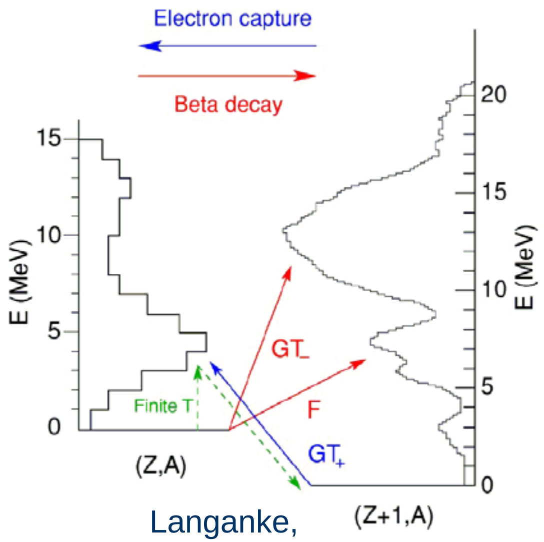




Hix et al. PRL 91, 201102 (2003)

weak rates and charge-exchange reactions

- electron-capture↔ΔT_z=+1 CE reactions
- β-decay↔ΔT_z=-1 CE reaction
- allowed transitions
  - Fermi
  - **Gamow-Teller**
- transitions from thermally populated states: not accessible in experiment



Langanke, Martinez-Pinedo Rev.Mod. Phys. 75, 819 (2003)

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

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

charge-exchange probes

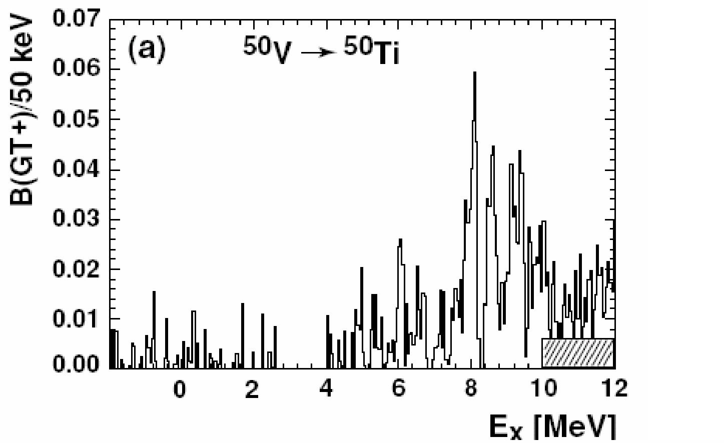
charge-exchange probes

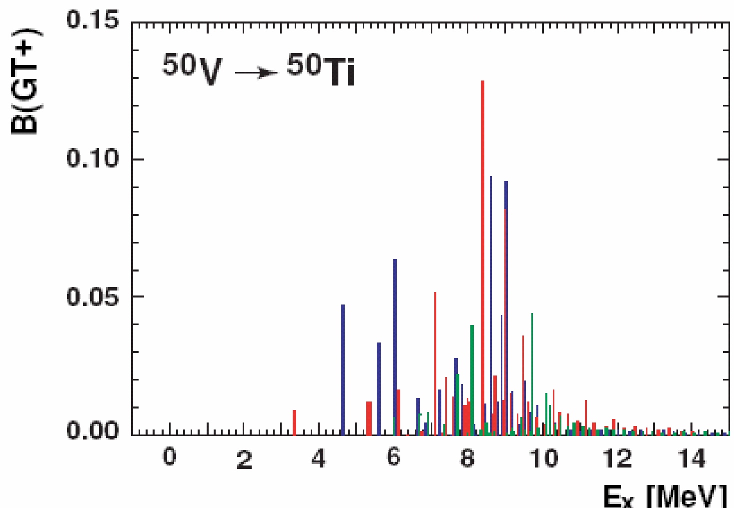
E/A>100 MeV/n

- $\Delta T_z = -1$
  - stable
    - (p,n)
    - (^{3}He,t)
    - heavy-ion
  - unstable
    - (p,n)
    - inverse kinematics: slow recoil must be measured! Difficult if charged.
- $\Delta T_z = +1$
  - stable
    - (n,p)
    - (d,^{2}He)
    - (t,^{3}He)
    - heavy-ion
  - unstable
    - (^{7}Li,^{7}Be+γ)
    - inverse kinematics: slow recoil must be measured! Use γ-decay from ^{7}Be
    - (d,^{2}He)???

IUCF, TRIUMF, KVI,RCNP,NSCL …

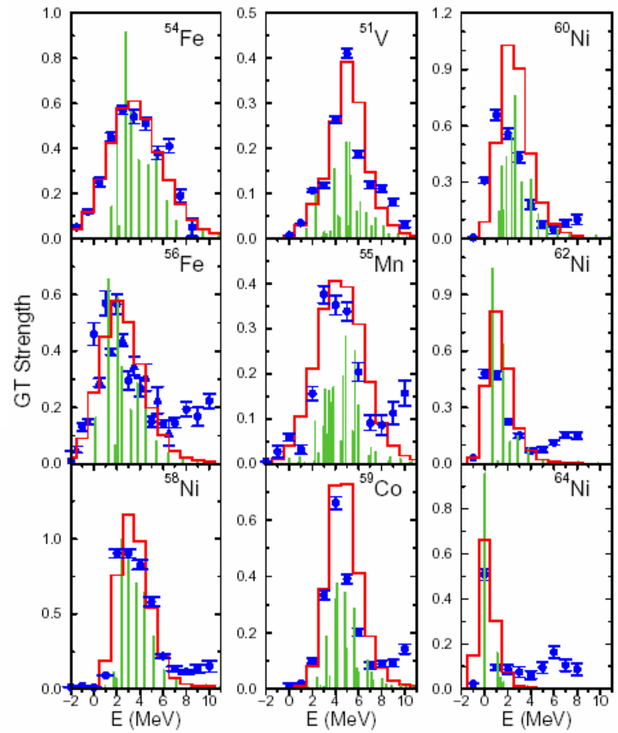
Some spectra





Bäumer et al. PRC 71,024603(2005)

(d,^{2}He)
Eurosupernova-KVI

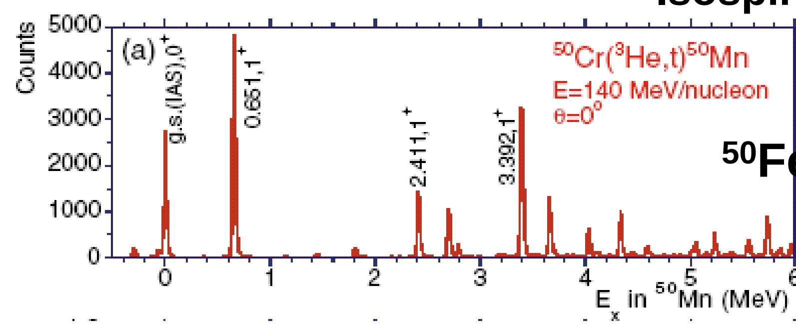


Caurier et al. Nucl. Phys. A653, 439 (1999)

(n,p) data TRIUMF

(t,^{3}He) – NSCL
A. Cole
M. Howard
W. Hitt

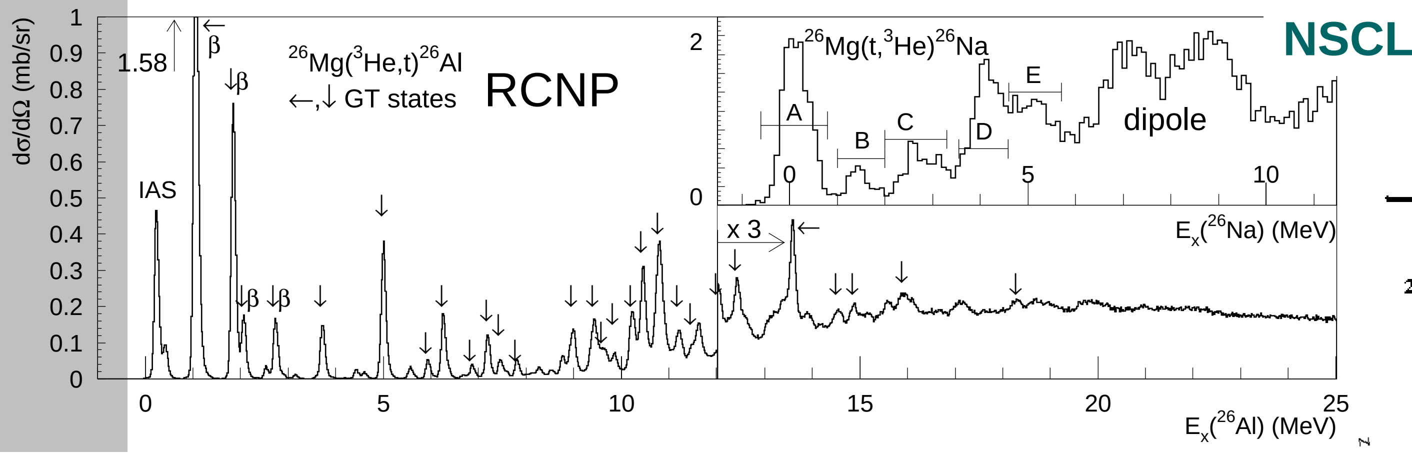
(^{3}He,t) RCNP
Isospin symmetry

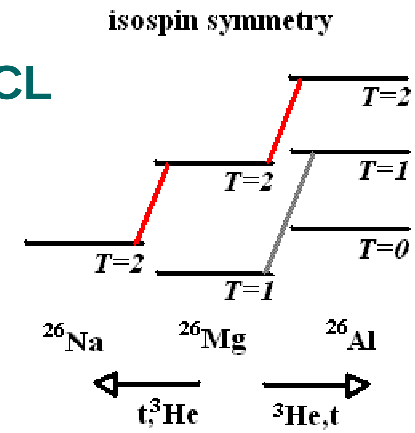


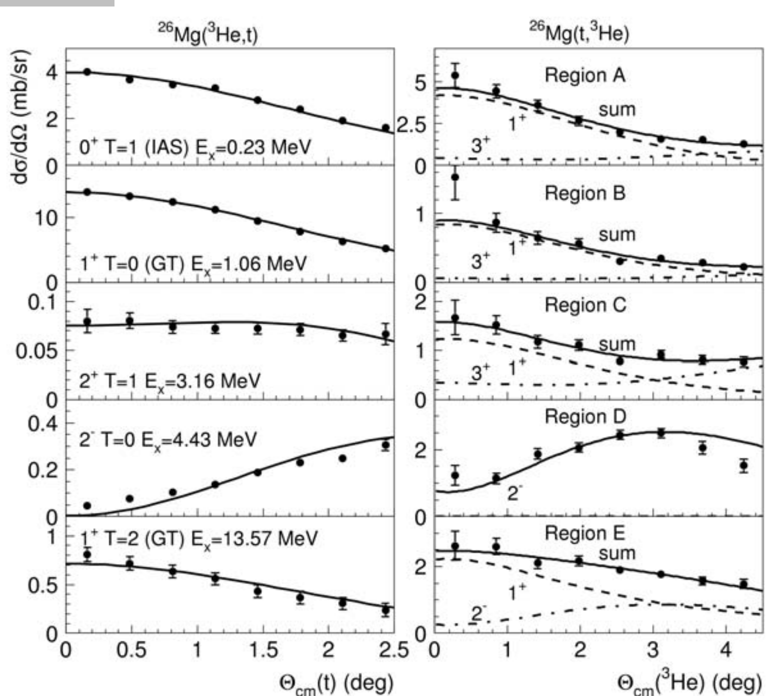
^{50}Fe β-decay

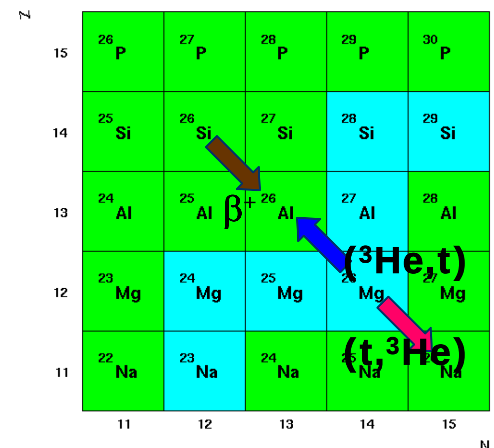
Y.Fujita PRL92, 212501, 2005

extracting Gamow-Teller strengths





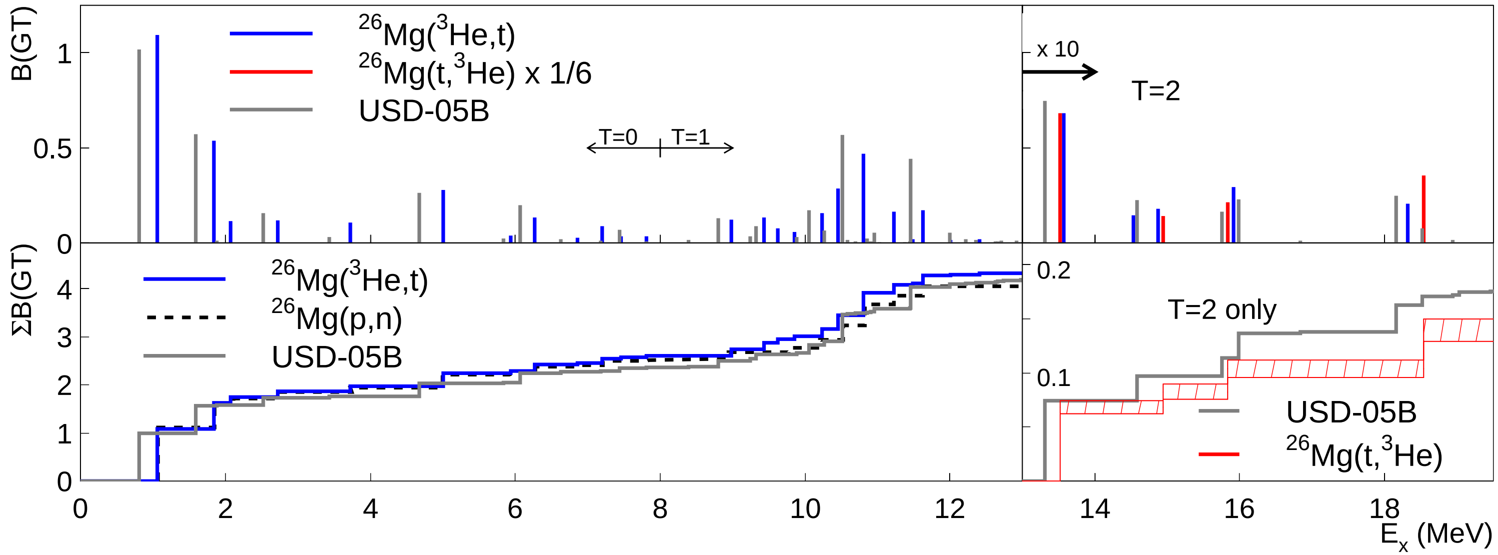


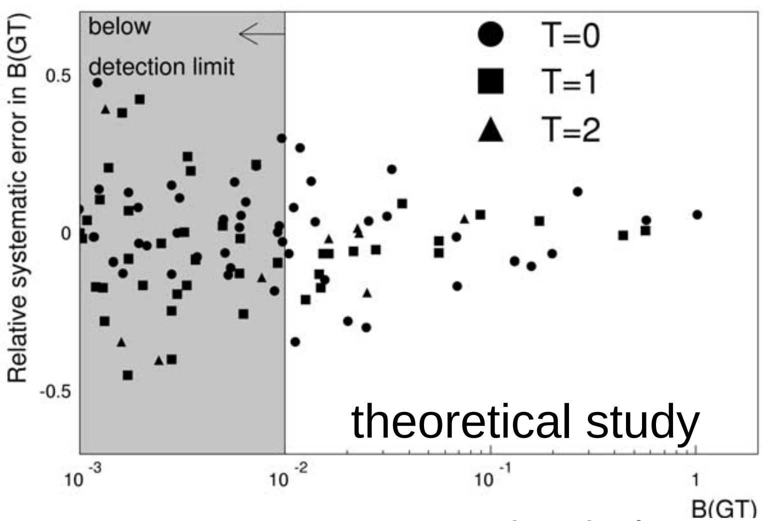


procedure

- identify GT states
- extract 0^o cross section (MDA)
- calibrate strength (β-decay)
- extract strength distribution

…and compare with theory





systematic error due to
- interference between ΔL=0,ΔS=1 & ΔL=2,ΔS=1 components (tensor-τ interaction)
- contribution from ΔL=2,ΔS=1 mediated via στ-interaction
- exchange terms in the interaction

analysis

charge-exchange data

$\Delta T_z = -1$
(p,n) (^{3}He,t) HIcex

$\Delta T_z = +1$
(n,p) (d,^{2}He) (t,^{3}He) HIcex

effective interaction

optical model

reaction (theory)

DWBA (DW81,FOLD)

structure (theory)

shell-model, large-scale SM
SM Monte Carlo, RPA's

weak interactions:
use proportionality

(IAS) Gamow-Teller

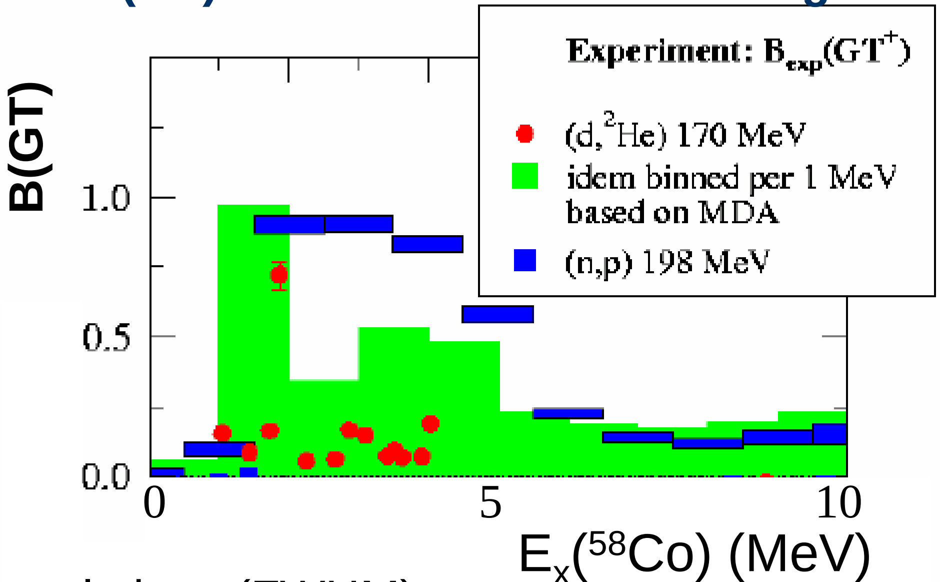
$$\left.\frac{d\sigma}{d\Omega}\right|_{q=0} = KN\left|J_x\right|^2 B(GT)$$

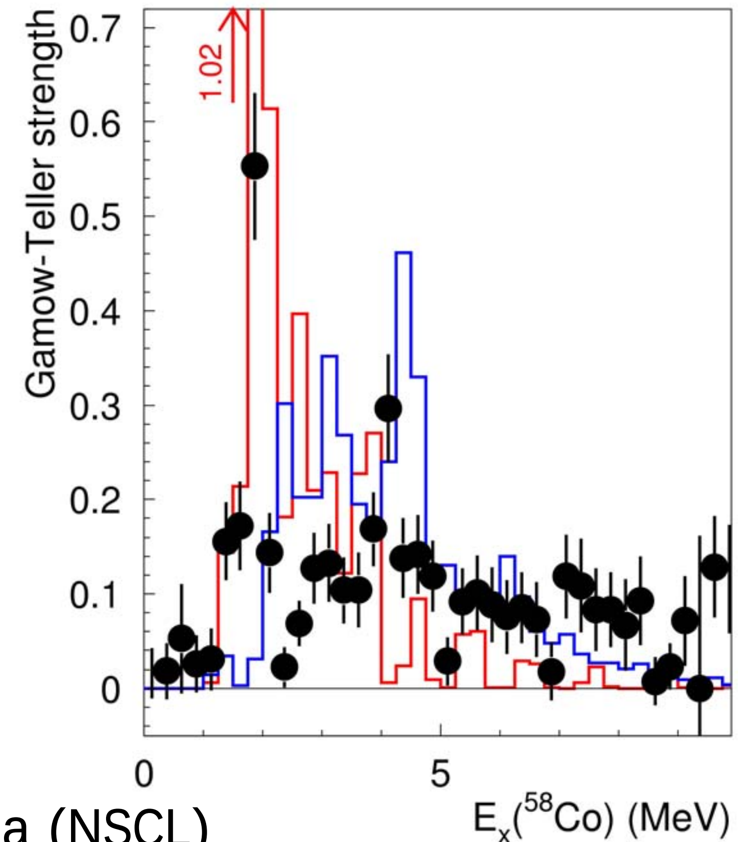
proportionality from
β-decay data

systematic errors?
Multipole decomposition

An example in the pf-shell: e-capture on ^{58}Ni

B(GT) normalized via T=2 analog excited via ^{58}Ni(^{3}He,t) – H. Fujita et al.





resolutions (FWHM):

^{58}Ni(n,p) 1.3 MeV (El-Kateb et al.)

^{58}Ni(d,^{2}He) 130 keV (Hagemann et al.)

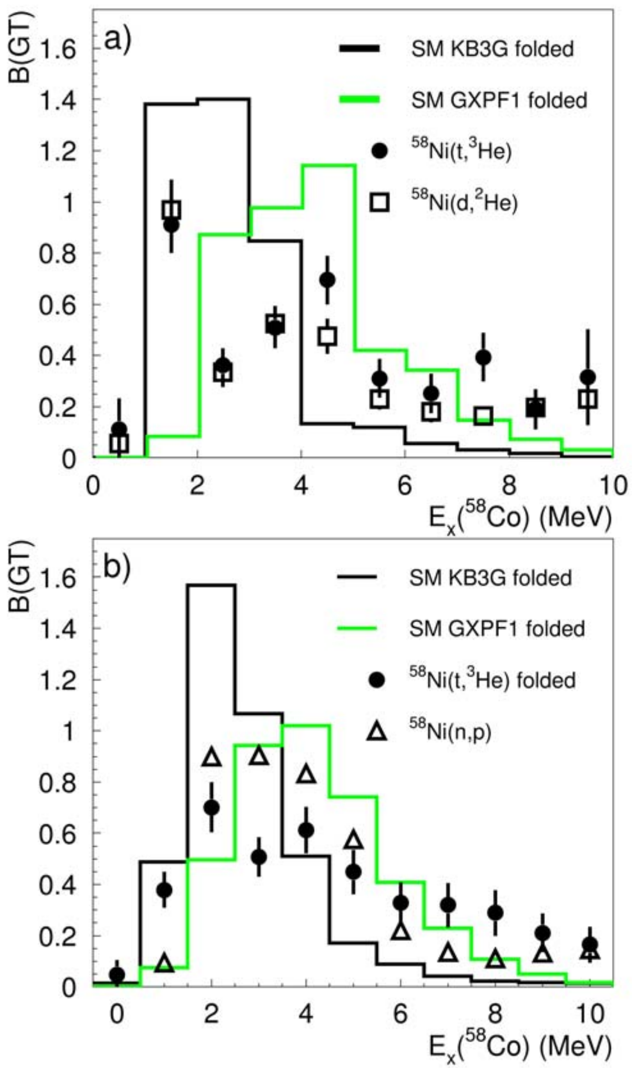
^{58}Ni(t,^{3}He) 250 keV (Cole et al.)

● ^{58}Ni(t,^{3}He) data (NSCL)

large-scale shell model KB3G interaction

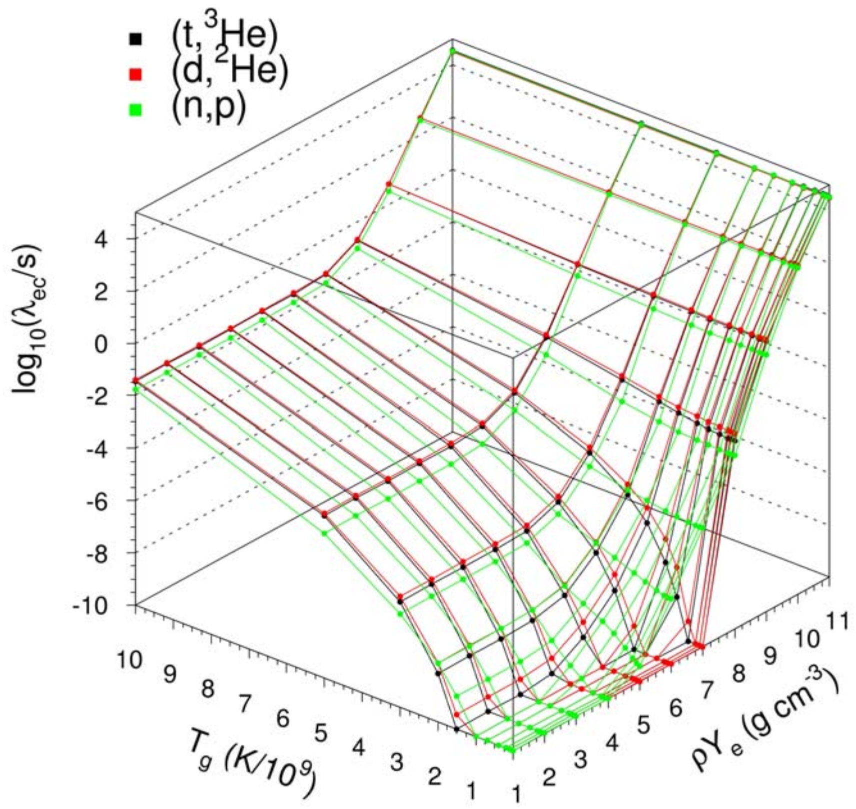
large-scale shell model GXPF1 interaction

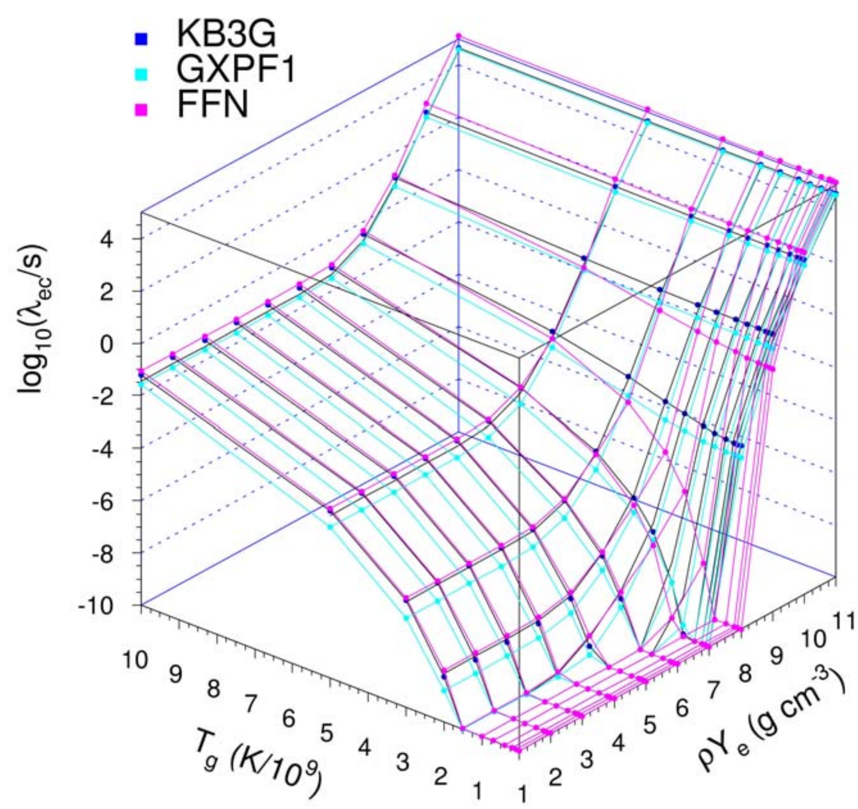
Strength and comparison with theory



- Experimental resolution is important
- Systematic error in experimental strength normalization ~25% (interference between ΔL=0 and ΔL=2 (both ΔS=1) amplitudes: one-body transition densities are important to estimate this (obtds by K. Honma, error does not depend strongly on interaction)
- Calculations with different interaction better reproduce different parts of the spectrum
- Summed strength ~4 for all experiments and theory

weak rates in the stellar environment



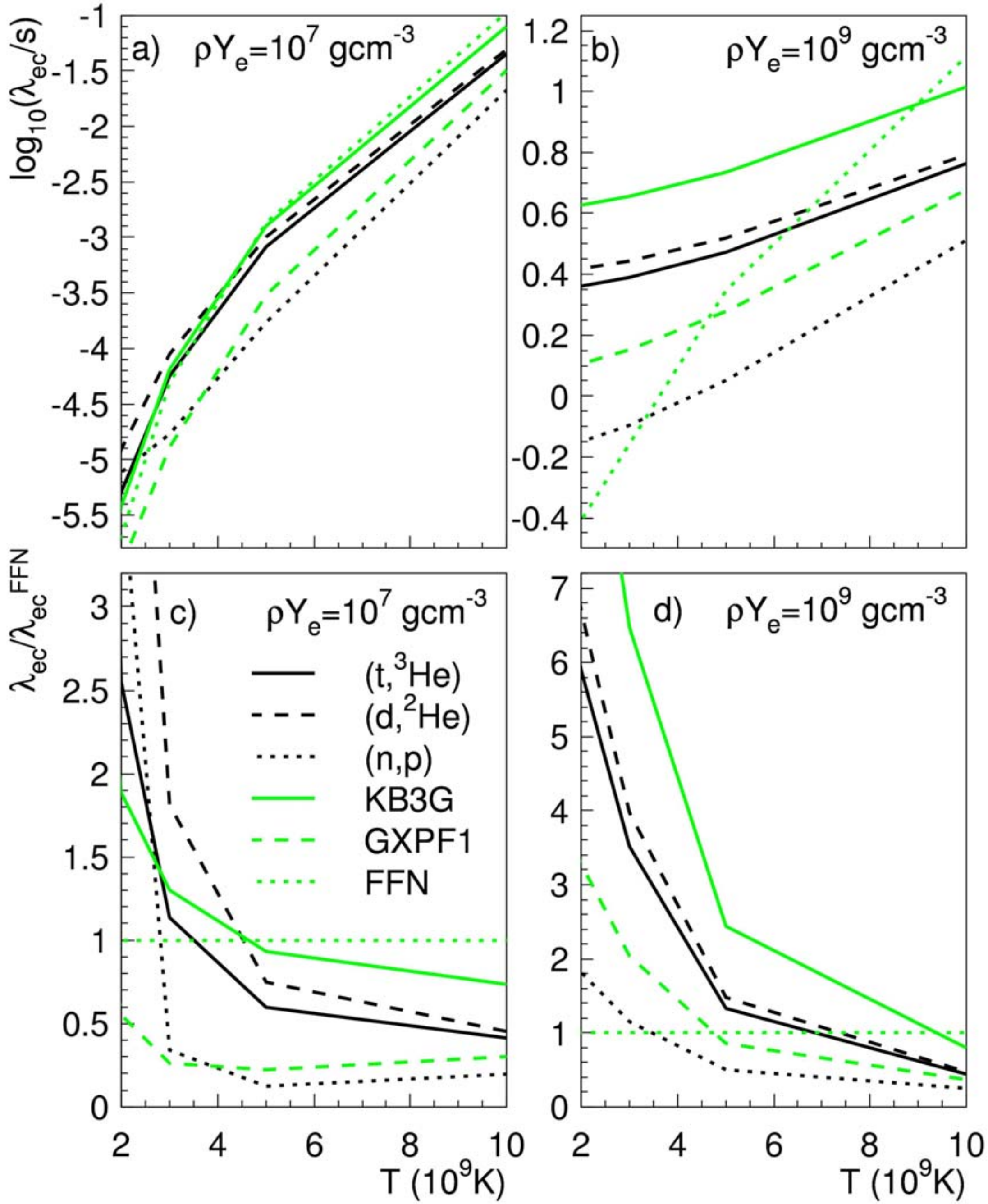


e-capture on ^{58}Ni (neglected contributions from transitions from excited states)

calculations by S. Gupta

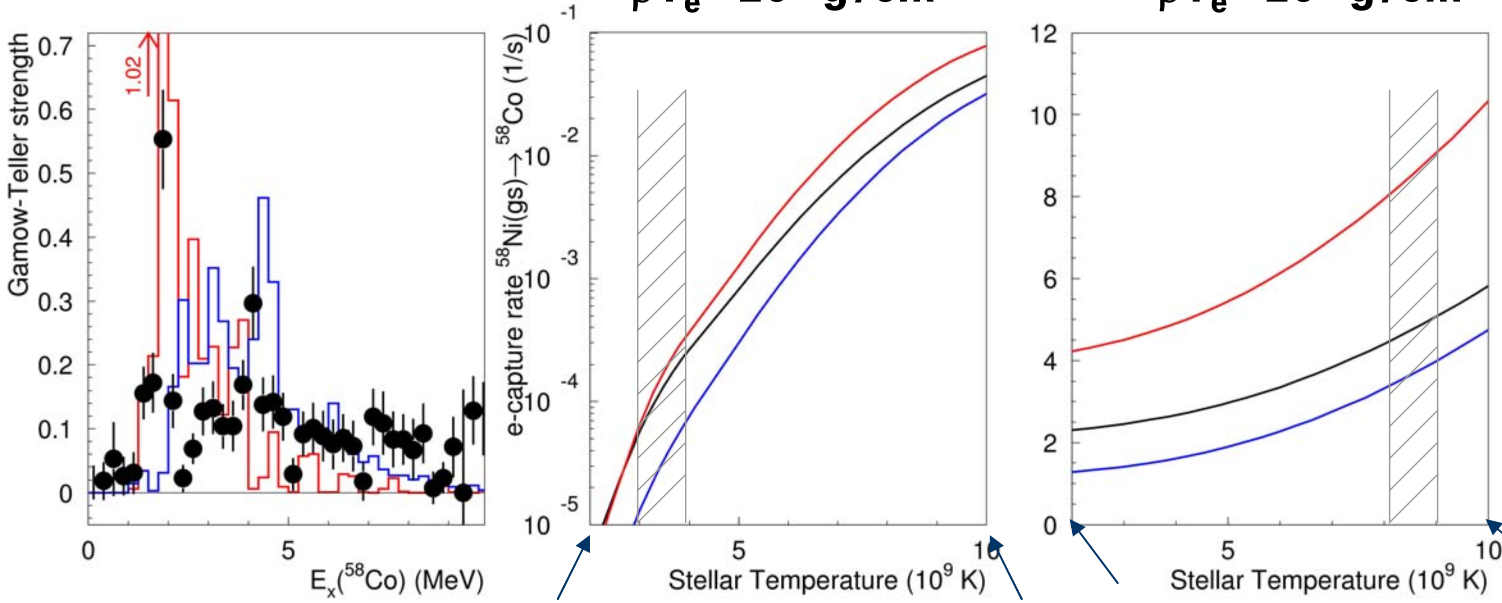
…in more detail

- At low densities & temperatures: rates sensitive to details of strength distribution
- At higher densities and temperatures and densities, rates become more sensitive to mean and width of strength distribution



… and more

early in pre-collapse $\rho Y_e = 10^7$ g/cm^3 just before collapse $\rho Y_e = 10^9$ g/cm^3



$\phi_e/(k_BT)=7$ $\phi_e/(k_BT)=-0.35$ $\phi_e/(k_BT)=52$ $\phi_e/(k_BT)=4.7$

- ($t,{}^3He$) data (syst. error in overall scale 25%)
- large-scale shell model KB3G interaction
- large-scale shell model GXPF1 interaction
- relevant temperature range at specific ρY_e

$\phi_e/(k_BT)$: degeneracy parameter: lower→lifting of degeneracy

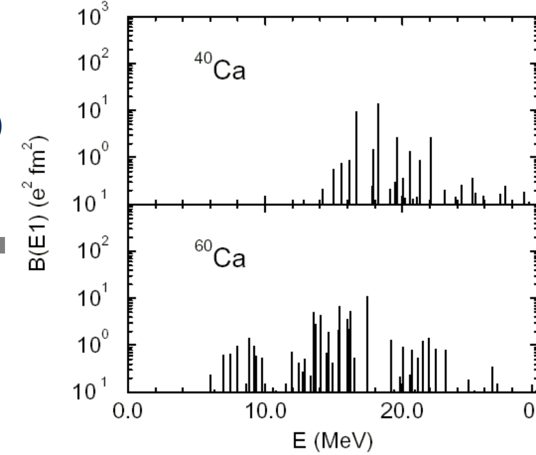
data needs?

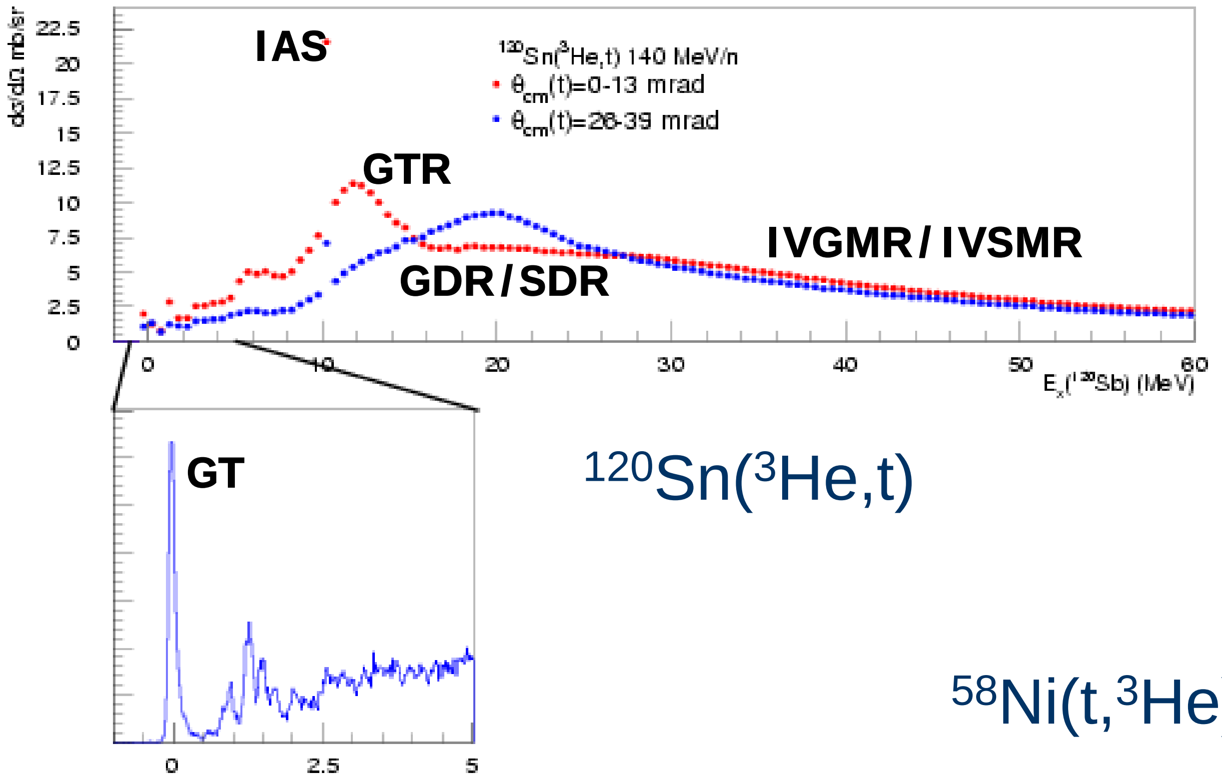
- Which nuclei are important to measure? Guidance from astrophysicists is important.
- What kind of accuracy is needed? Can we do more than ‘just’ comparing B(GT)s?
- Unstable nuclei? If measurements become feasible, which are the key nuclei? (Resolutions will likely be poor ~1 MeV) (n,p) direction will likely be more difficult than (p,n) direction. Is (p,n) sufficient to test the interactions?
- How to extract dipole strengths?

Dmitriev, Austin, Zelevinsky Phys. Rev. C **65**, 015803 (2002)

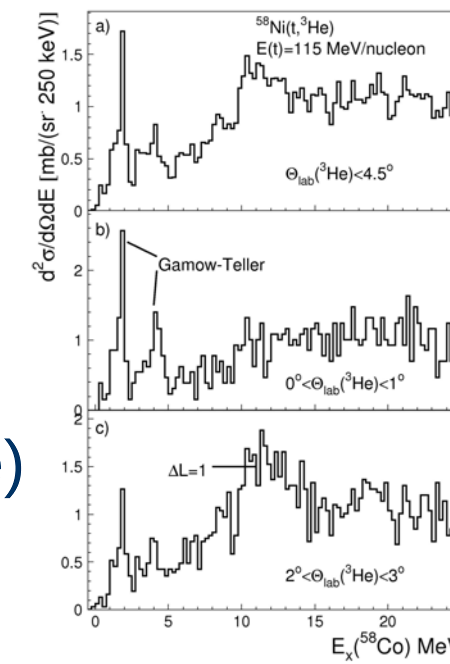
dipole strength

A. Vitturi J. Phys. G 24 1439 (1998)





^{120}Sn(^{3}He,t)



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

theory needs?

- Is it possible to improve interactions based on measured strength distributions? To what extent is it needed?
- Is it helpful to make a data base of experimental strength distributions?
- Stellar evolution simulations with strength distributions produced using KB3G and GXPF1?
- For heavier masses: test and improve large-scale shell models/QRPA
- (one-body) transition densities are needed to test systematic uncertainties in the data: normalization of exp. B(GT) and to test details of the response (now able to read in QRPA TDs in reaction codes – G. Colo, S. Fracasso, R.G.T. Zegers)
- In unstable nuclei, (non-collective) low-lying dipole (forbidden weak transitions) strength can be expected. Does it matter? (ν-process, medium enhanced ν-flavor conversion just after core-bounce$\rightarrow$energetic ν's)

Spin-isospin modes in unstable nuclei:charge-exchange in inverse kinematics

ΔT_z=-1 (p,n)

- S800
- Low-energy neutron wall

Astrophysics

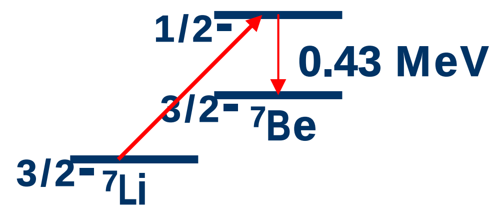
- weak rates in stellar evolution

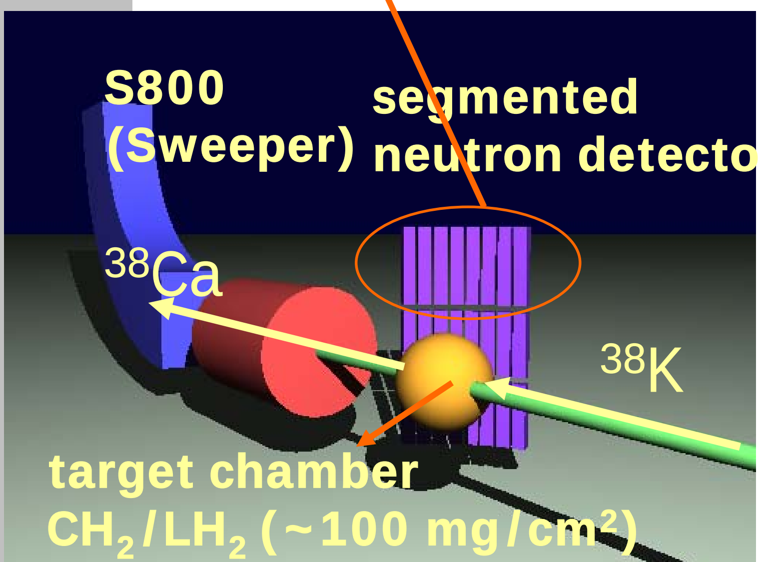
Isovector transitions ⇔ (N-Z)

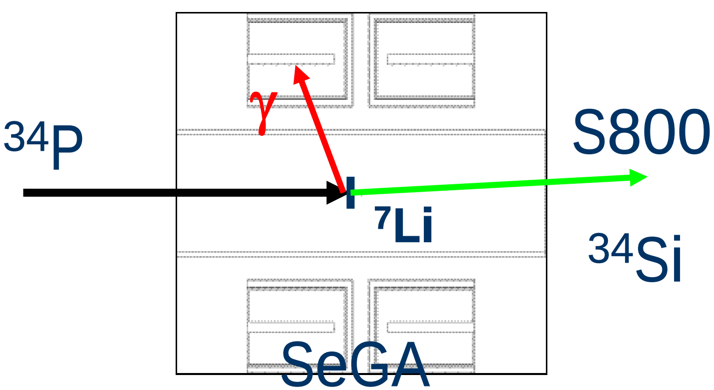
- isovector giant resonances
- spin-isospin response of (light) asymmetric systems

ΔT_z=+1: (^{7}Li,^{7}Be*)

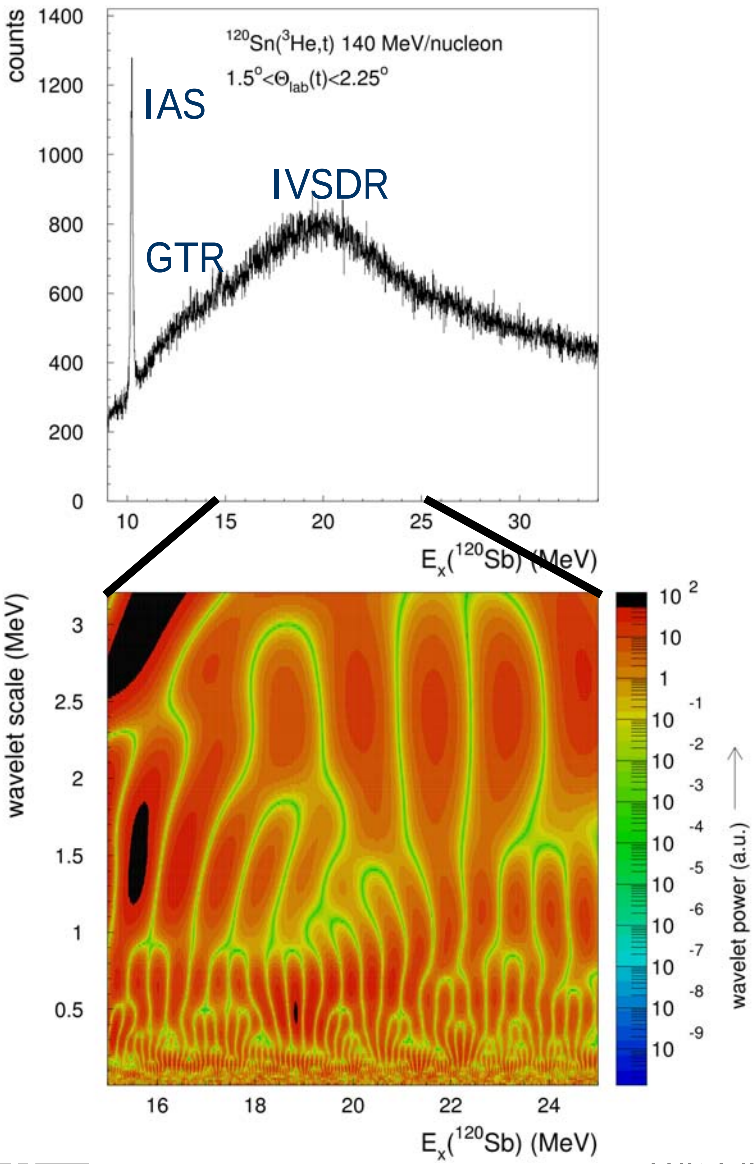
- S800
- SEGA





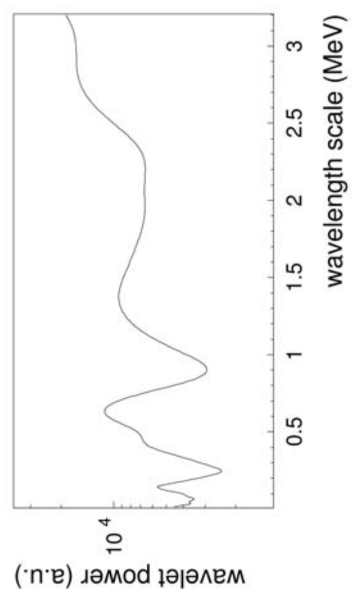


The fine structure of giant resonances



- Use Continuous Wavelet Transformation to extract the important energy scales.
- Scales test RPA,QPM… models

- Spectrum reconstruction using the Discrete Wavelet Transformation
- Model-independent construction of background and the continuum
- Extraction of level densities



Example:
CWT of the excitation energy spectrum in the region of the isovector spin-dipole resonance in ^{120}Sb