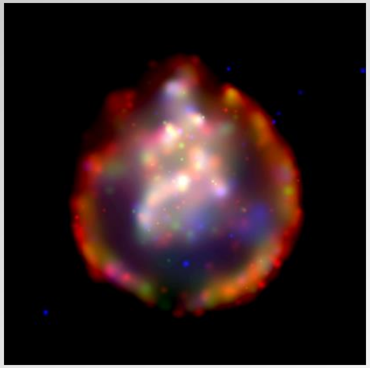
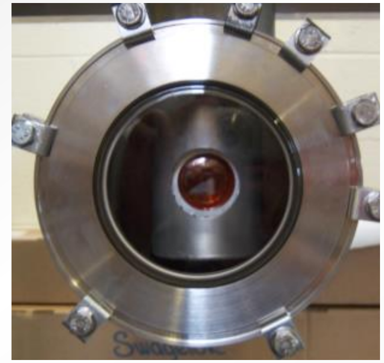



The spin-isospin response of nuclei and applications in astro- and neutrino-physics

Remco G.T. Zegers

NSCL JINA Department of Physics and Astronomy NSF MICHIGAN STATE UNIVERSITY

outline

Electron-captures in astrophysics (Core-collapse supernovae…)

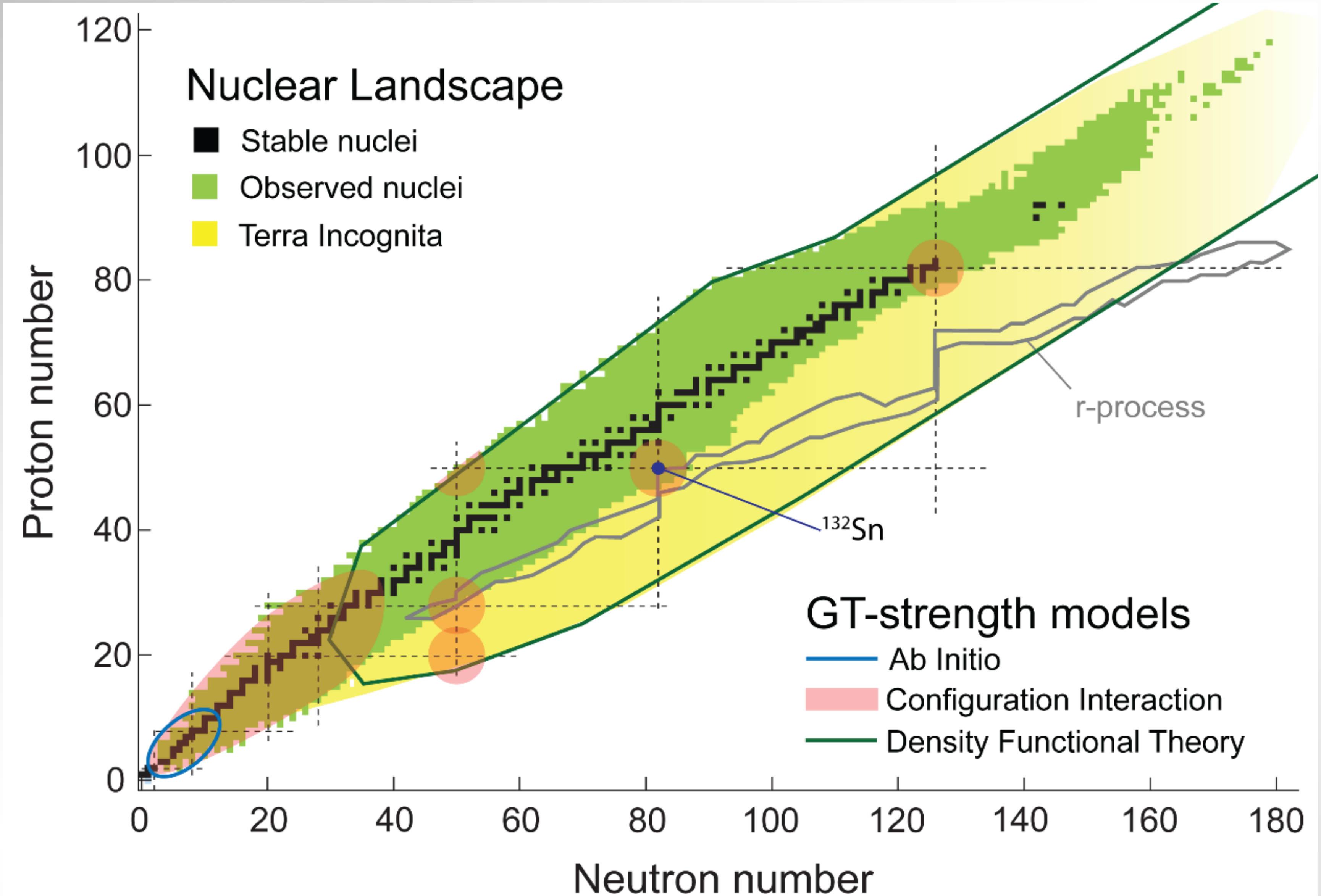
Charge-exchange reactions as a probe of weak transition strengths

Weak transition strengths and electron captures for $45<A<65$

Weak transition strengths in unstable nuclei: the case of ^{56}Ni

Matrix elements in double beta decay

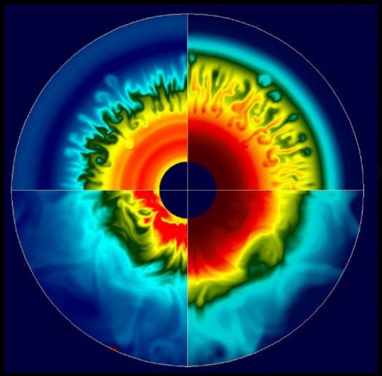
Current and future research directions in spin-isospin physics with charge-exchange reactions



Litvinova, Brown, Fang, Zegers – to be published

Multi-physics problem

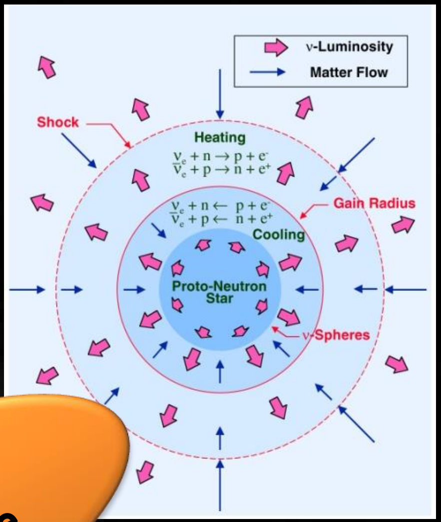
Hydrodynamics – Convection, Turbulence



Müller, E. and Janka, H.-T.
A&A 317, 140–163, (1997)

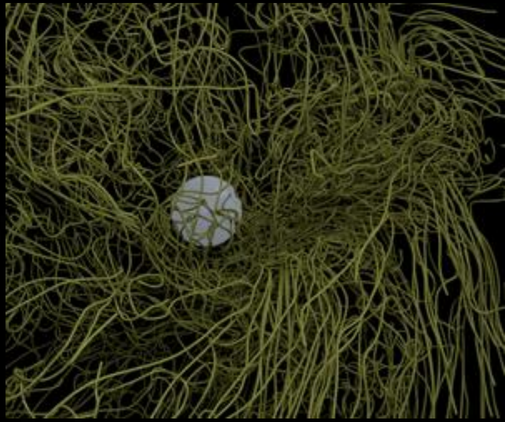
Fryer, C. L., & Warren, M. S. 2002,
ApJ, 574, L65

Multi-Dimensional Effects - Asymmetries



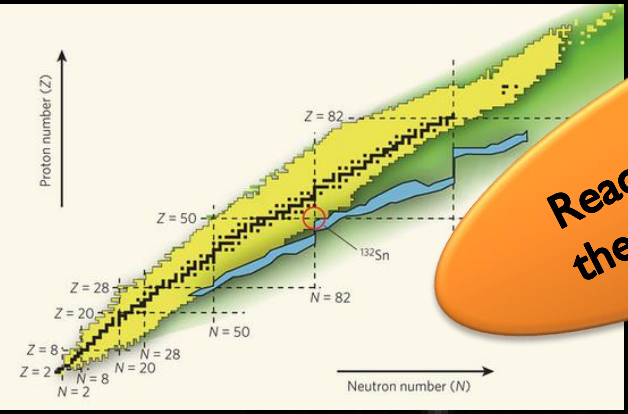
Neutrino physics
(transport/ oscillations / interactions)

Magnetic fields



Pugmire et al., ORNL

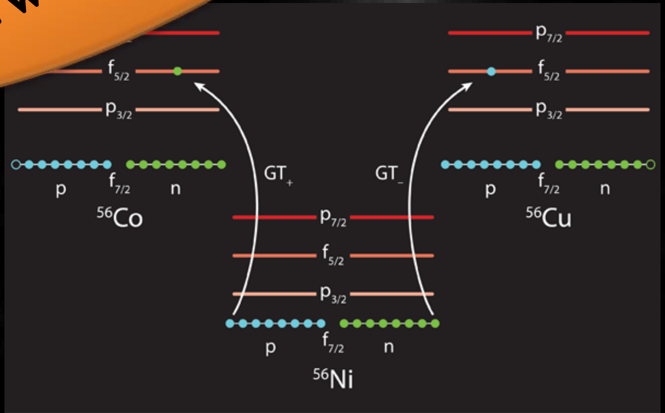
r-process



P. Cottle Nature 465, 430–431 (2010)

Reactions mediated by the weak nuclear force

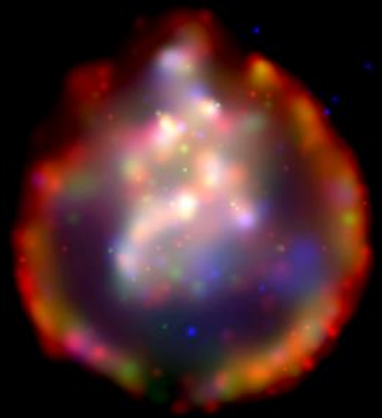
ptures



K. Langanke, Physics 4, 91 (2011)

Weak rates in astrophysical phenomena

Core-collapse (Type II) Supernovae

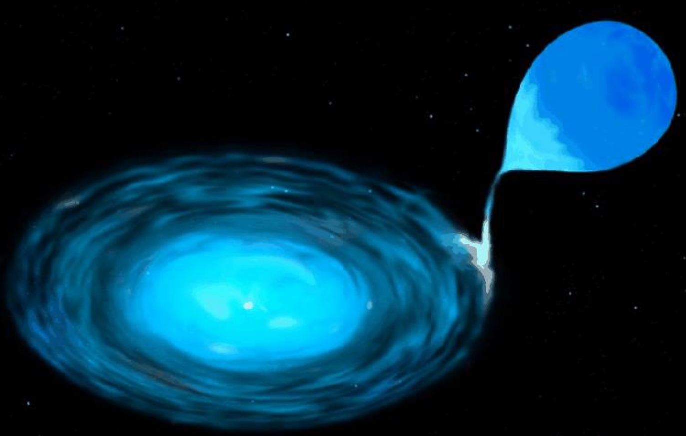


SNR 0103-72.6
Chandra observatory

Thermonuclear (Type Ia) Supernovae

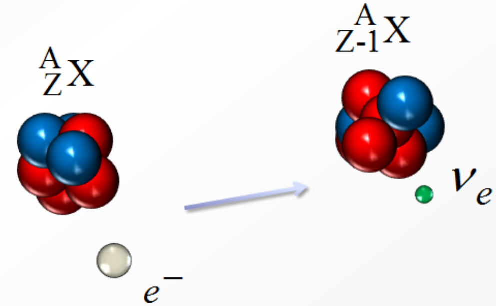
SN 1994D ESA/Hubble

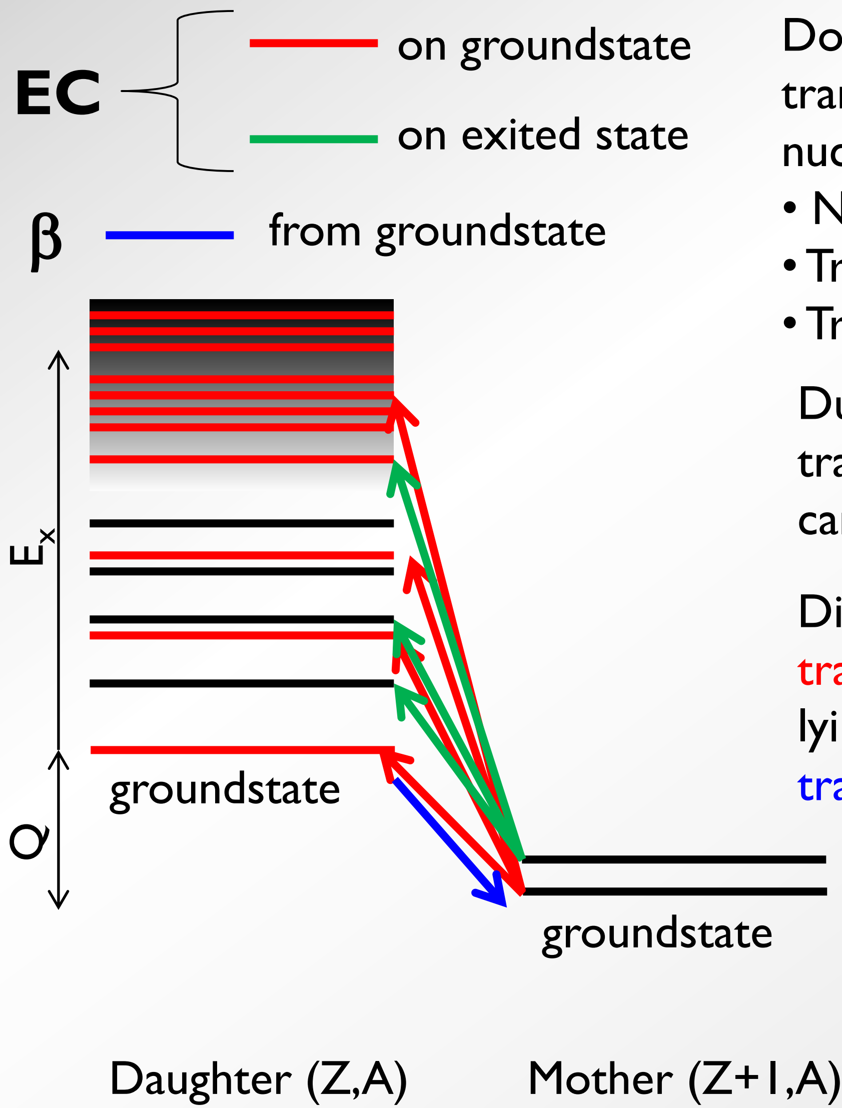
Crustal processes in accreting neutron stars



s-process
r-process
neutrino interactions
…

electron captures in supernovae





Dominated by allowed (Gamow-Teller) weak transitions between states in the initial and final nucleus:

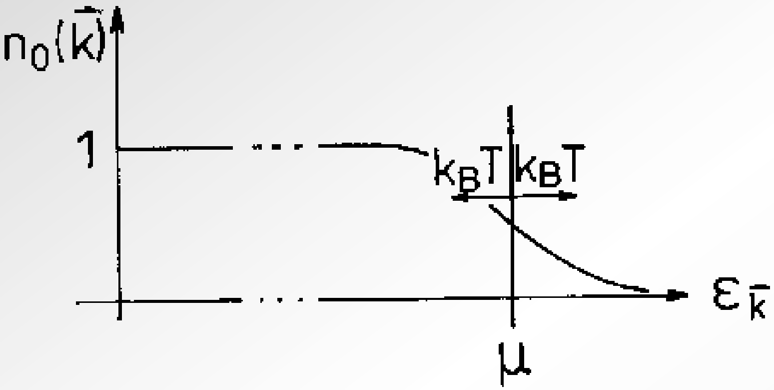
- No transfer of orbital angular momentum **(ΔL=0)**
- Transfer of spin **(ΔS=1)**
- Transfer of isospin **(ΔT=1)**

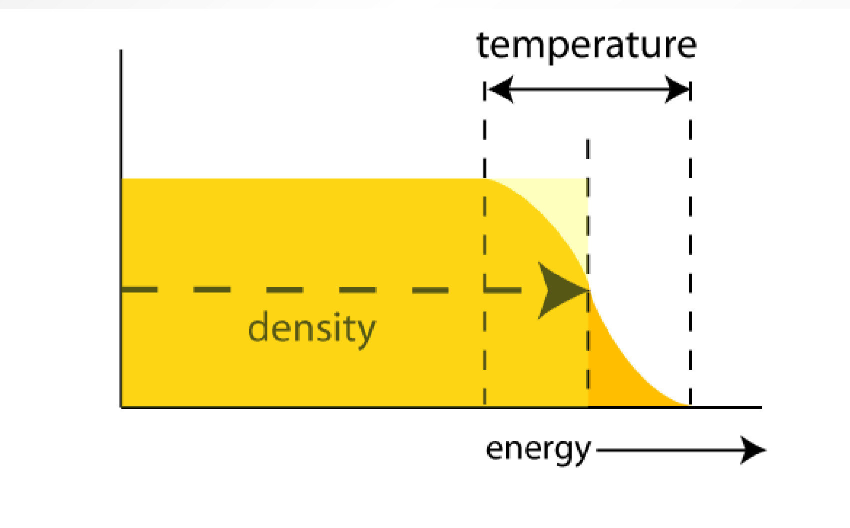
Due to finite temperature in star, Gamow-Teller transitions from excited states in the mother nucleus can occur

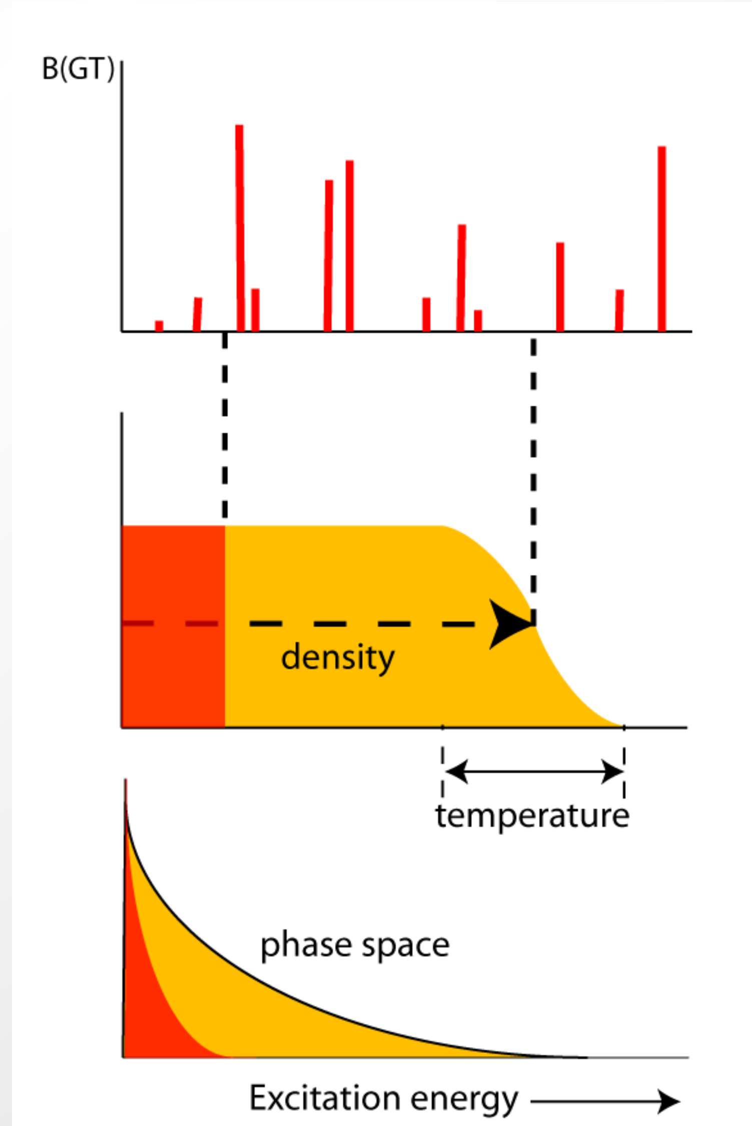
Direct empirical information on strength of transitions [B(GT)] is limited to at best a few low-lying excited states e.g. from the inverse (β-decay) transitions.

electron-captures in supernovae

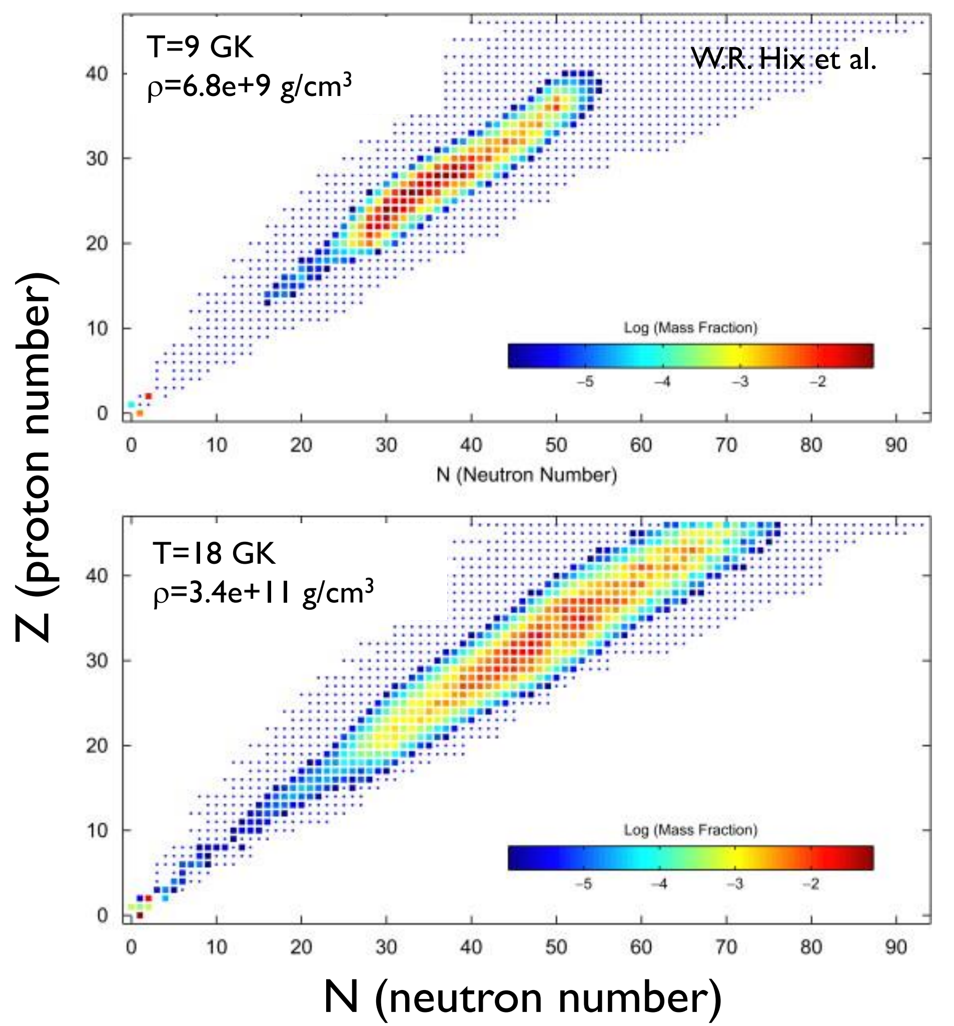
Fermi-Dirac distribution of near degenerate electron gas-function of stellar density & temperature







electron captures in supernovae



ECs on many nuclei play a role

pre-supernova – A~45-65 (pf shell)

collapse stage – A~50-120 (pf+sdg shell)

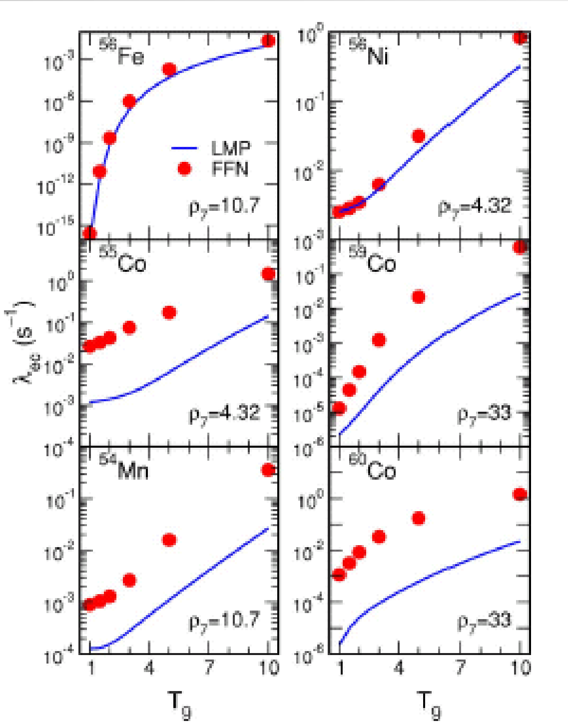
majority are unstable nuclei

Needed:

Accurate theoretical models to estimate EC rates

Experimental information to guide and test development of theory

electron captures in type II SNa

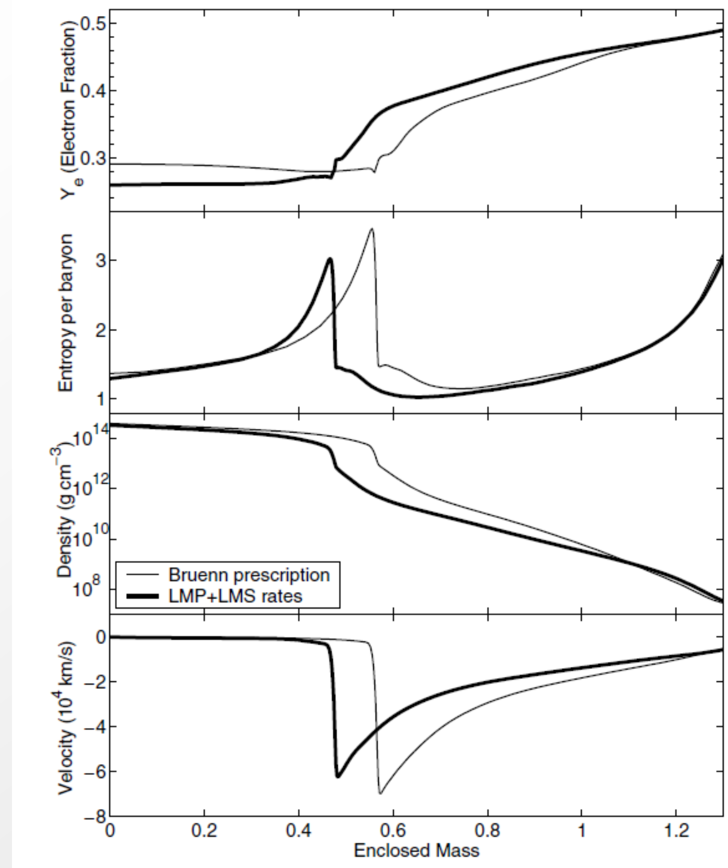


Langanke, Martinez-Pinedo
Rev.Mod. Phys. 75, 819 (2003)

EC rates based on modern microscopic nuclear models are on average lower than earlier parameterizations

Consequences:

- reduced (10%) central stellar density, entropy and electron fraction
- reduced (20%) mass behind the shock
- increased (15%) neutrino luminosity just after the bounce

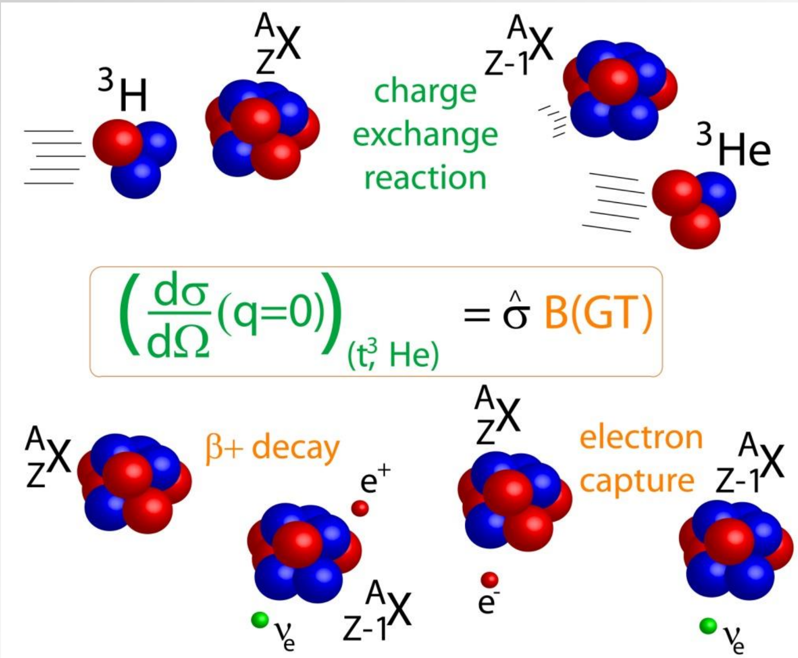


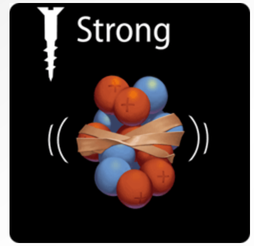
W.R. Hix Phys. Rev. Lett. 91, 201102 (2003)

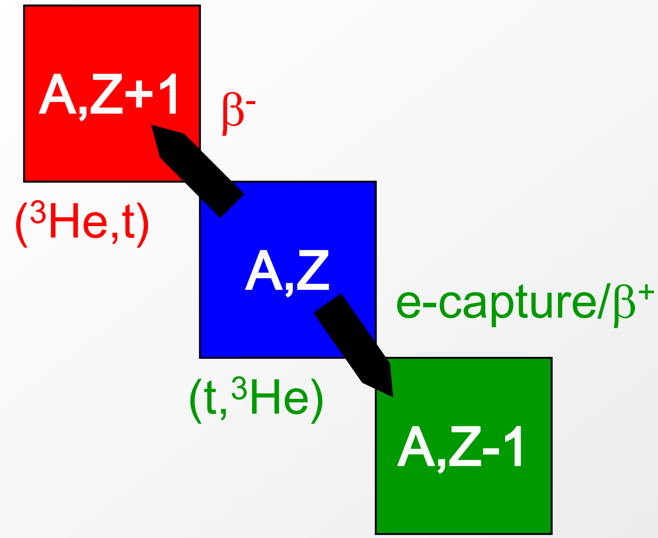
Accurate EC rates are critical for simulations of core collapse supernova

Accuracy required: ~30%

nature is kind: nuclear charge-exchange reactions as a probe of weak transition strengths





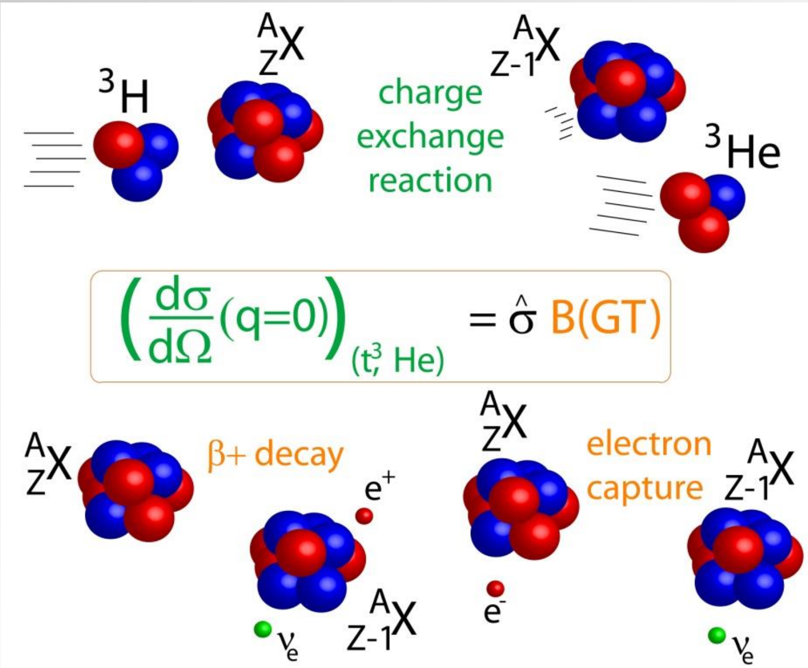


Charge-exchange reactions connect the same initial and final states as in weak interactions and are mediated through similar spin and isospin transfer operators

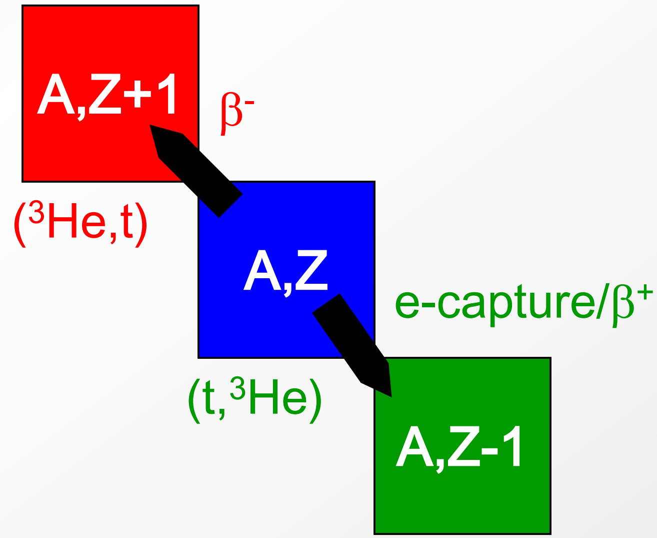
Proportionality holds at ~10% level – beam energies must be ~100 MeV/A or above

Applied to a variety of charge-exchange probes: (p,n)/(n,p), (^{3}He,t)/(t,^{3}He),(d,^{2}He),(^{7}Li,^{7}Be) etc.

Gamow-Teller strengths and CE cross sections



Model-independent extraction of GT strengths



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

β-decay weak

$$\frac{d\sigma}{d\Omega}(q=0) = \left[\frac{\mu}{2\pi\hbar}\right]^2 \frac{k_f}{k_i} N_D \left|V_{\sigma\tau}\right|^2 \left|\left\langle f \middle| \sum_k \sigma_k \tau_k \middle| i \right\rangle\right|^2$$

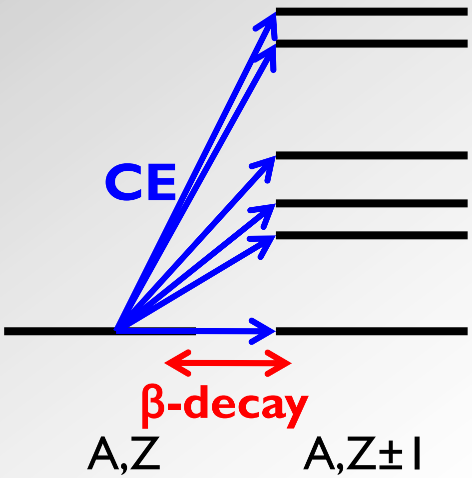
charge-exchange strong

$\hat{\sigma}$: **unit cross section**

Taddeucci et al. NPA 469, 125 (1987)

Unlike β-decay CE experiments do not suffer from Q-value restrictions

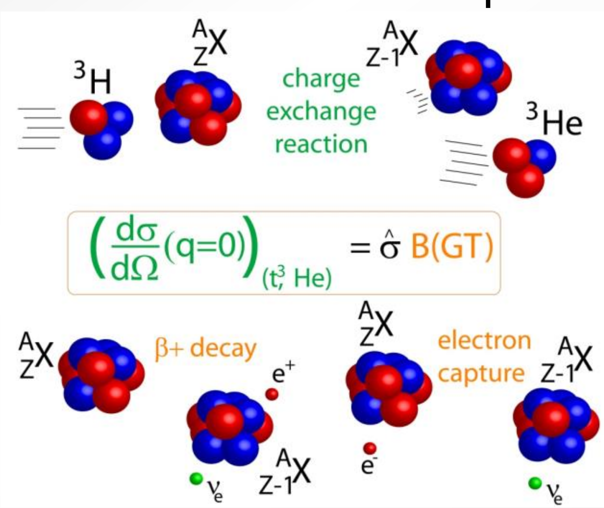
calibrating the proportionality

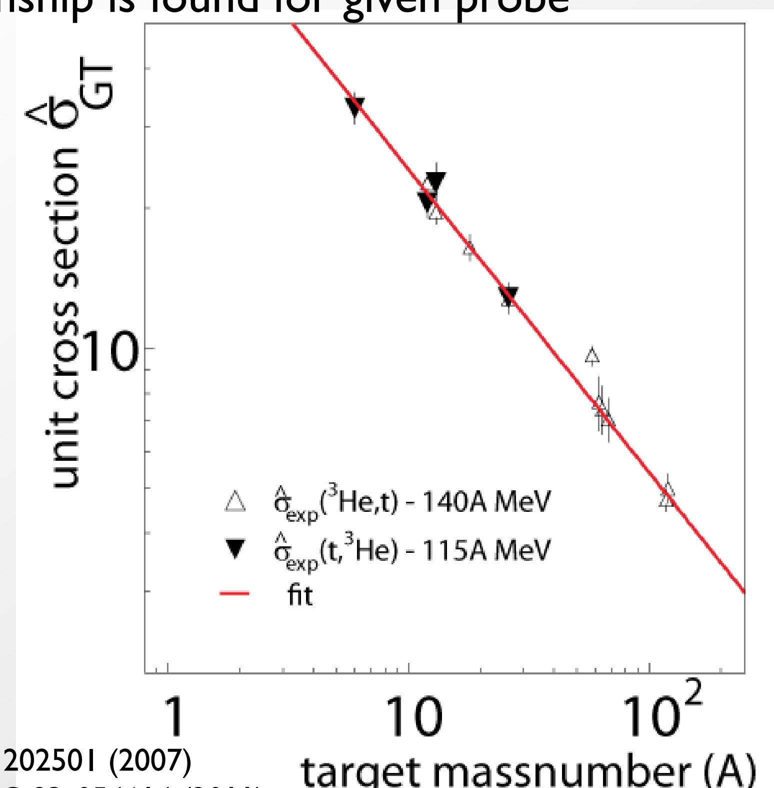


The unit cross section is conveniently calibrated using transitions for which the Gamow-Teller strength is known from β-decay.

The unit cross section depends on beam energy, charge exchange probe and target mass number: empirically, a simple mass-dependent relationship is found for given probe

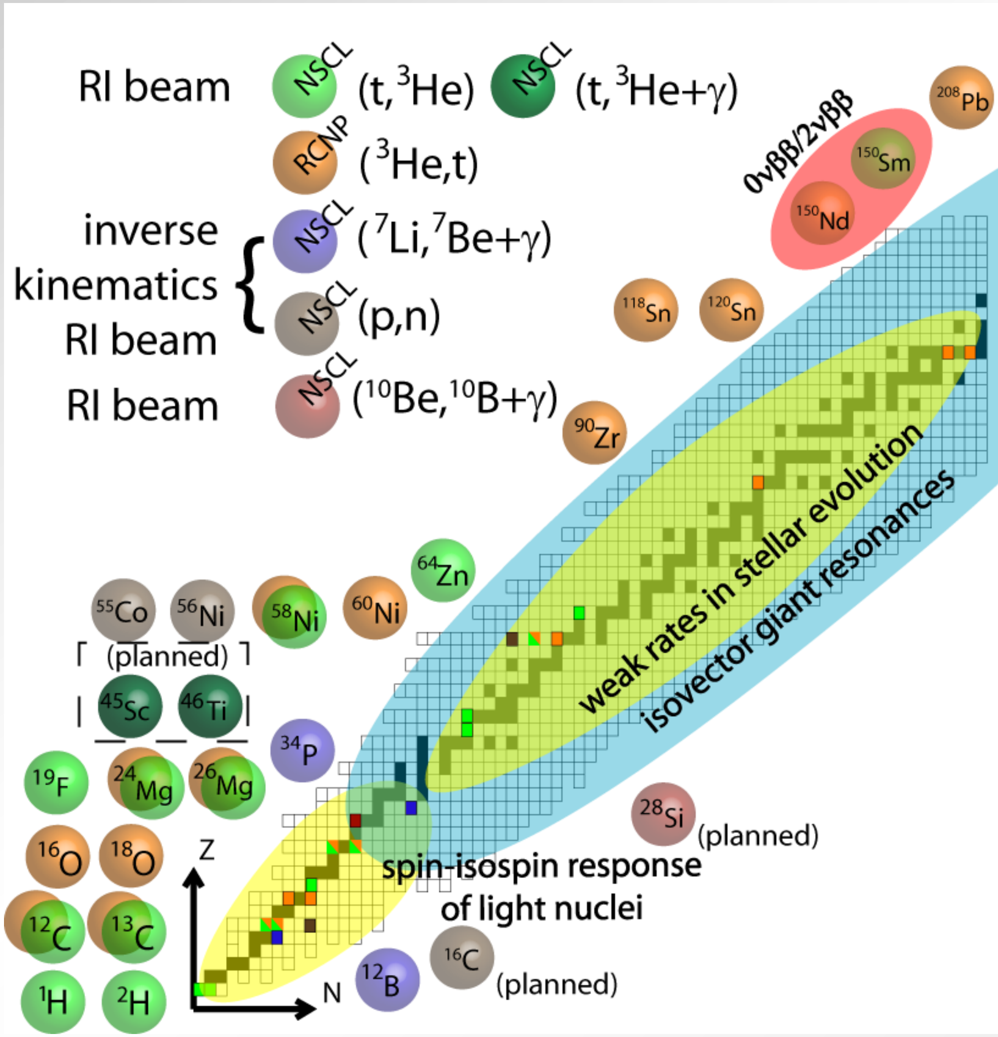
Once calibrated, Gamow-Teller strengths can be extracted model-independently.





R.Z. et al., Phys. Rev. Lett. 99, 202501 (2007)
G. Perdikakis et al., Phys. Rev. C 83, 054614 (2011)

Overview of program



Astrophysics – weak reaction rates

t,^{3}He | t,^{3}Heγ | ^{3}He,t | p,n

(Neutrinoless) Double beta decay

t,^{3}He | ^{3}He,t

Shell evolution in light systems

t,^{3}He | ^{3}He,t | ^{7}Li,^{7}Beγ

Giant resonances and the macroscopic properties of nuclear matter

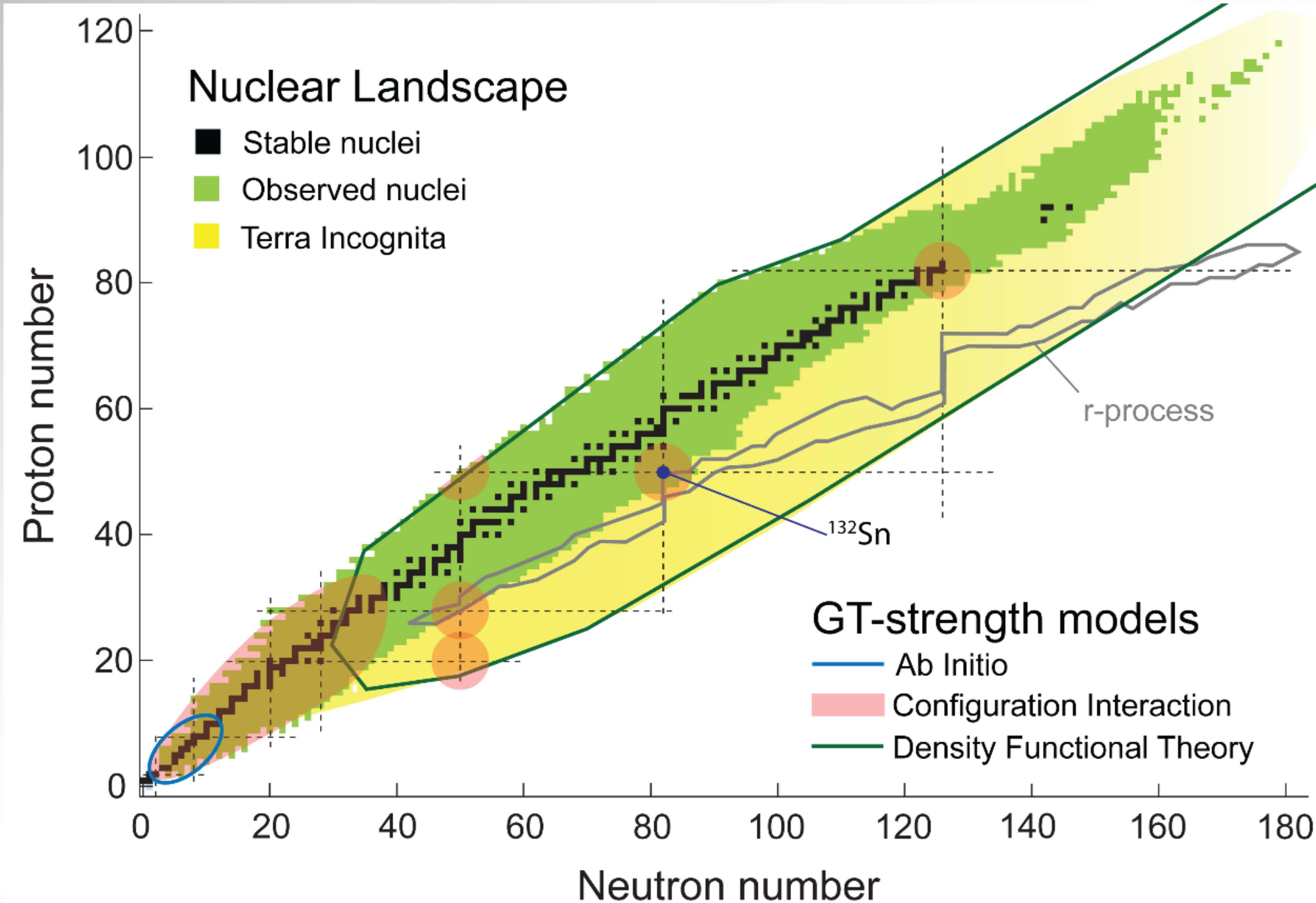
t,^{3}He | ^{3}He,t | p,n | ^{10}Be,^{10}Bγ

Novel probes for isolating particular responses

^{7}Li,^{7}Beγ | ^{10}Be,^{10}Bγ | t,^{3}Heγ

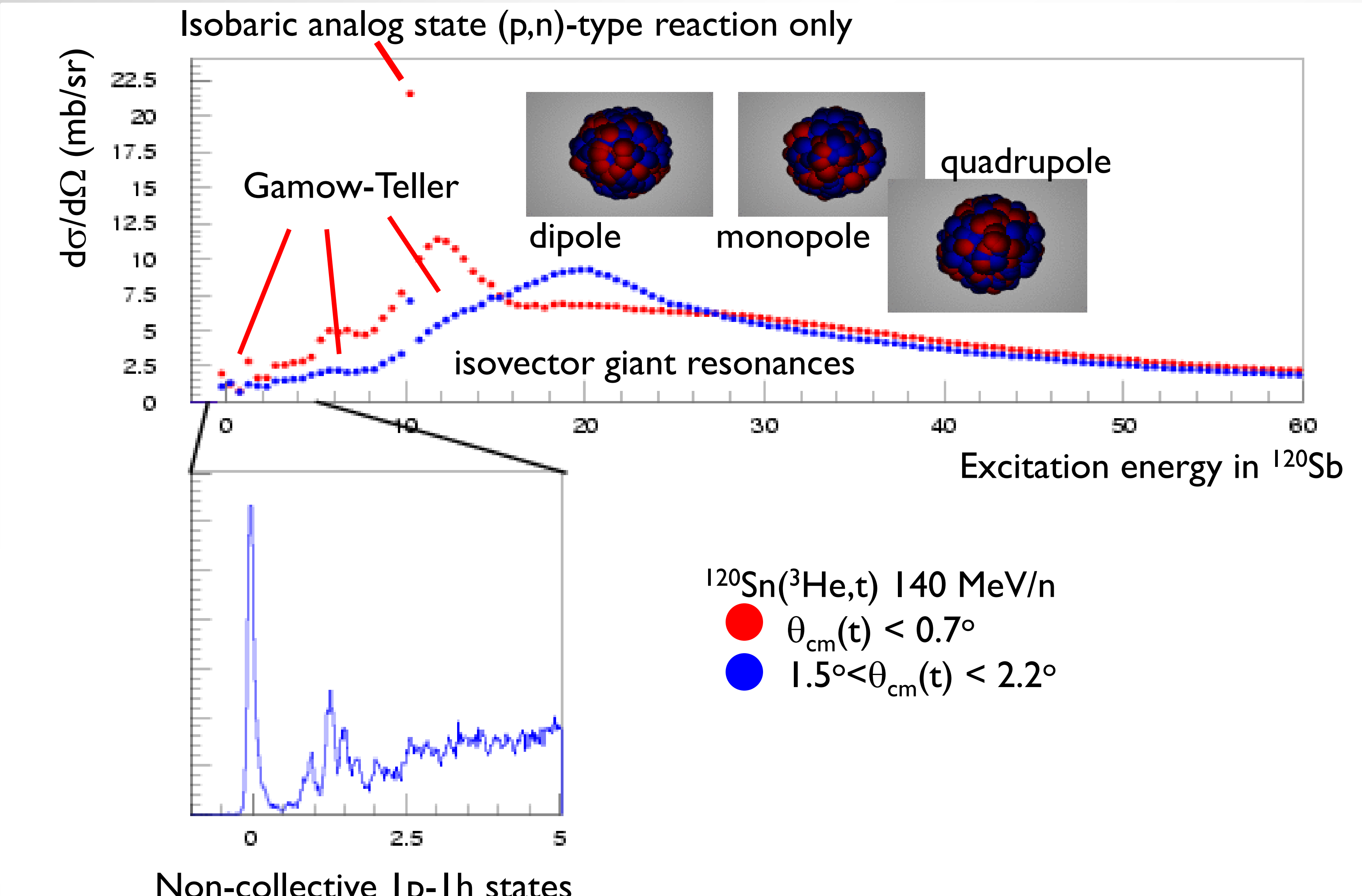
Studies of the charge-exchange reaction mechanism

t,^{3}He | ^{3}He,t



Litvinova, Brown, Fang, Zegers – to be published

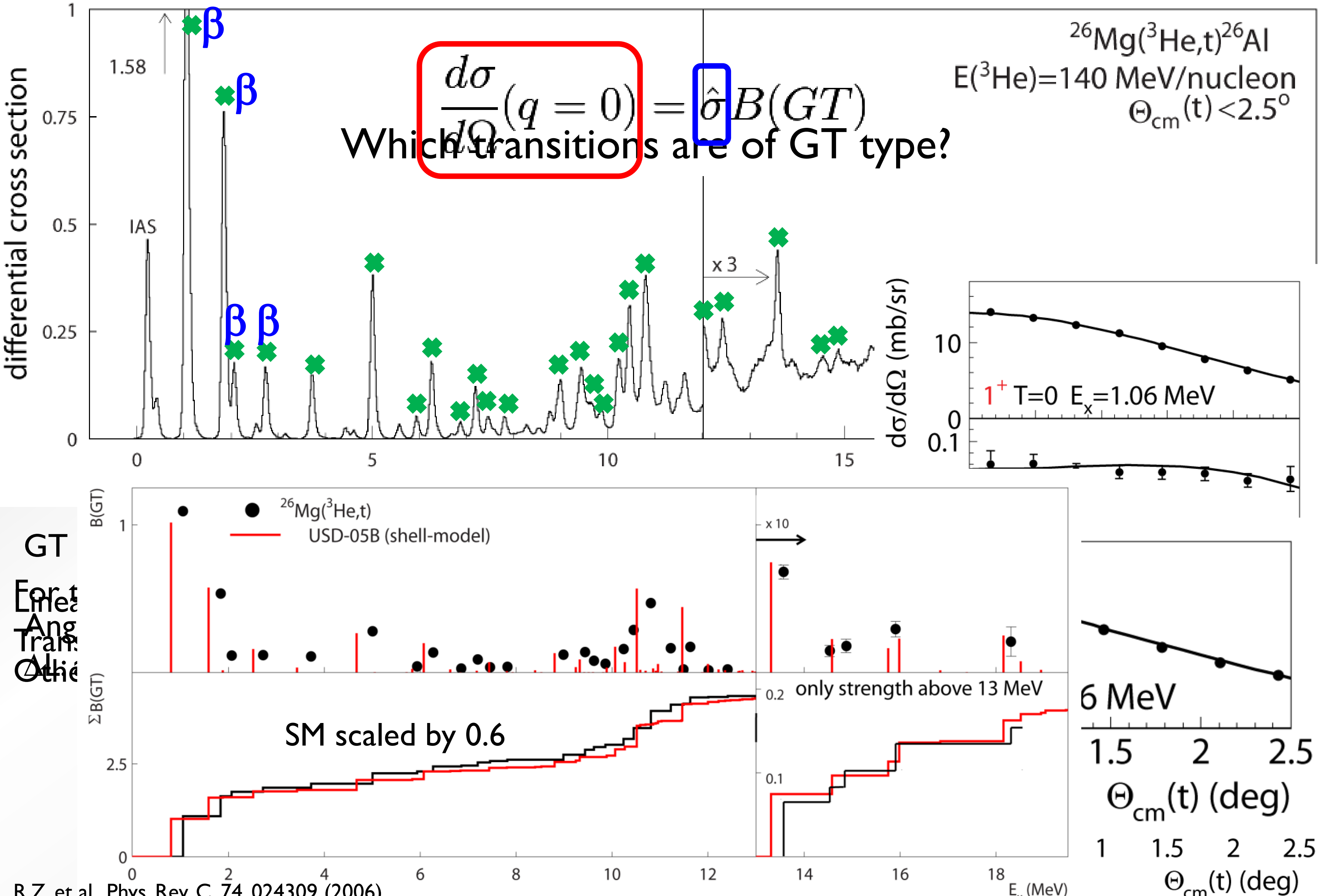
General spin-isospin response



Extracting GT strength from scattering data

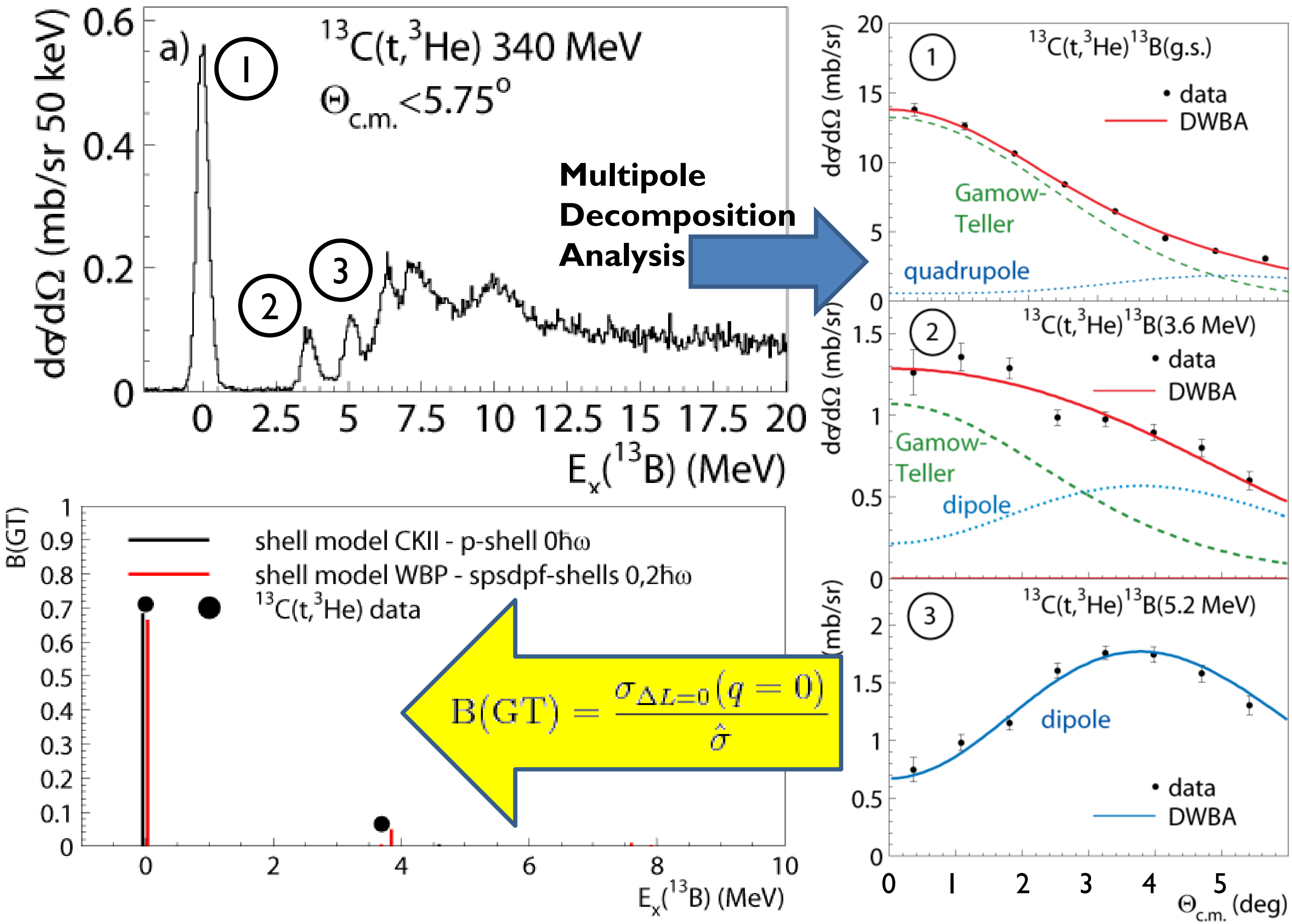
$$\frac{d\sigma}{d\Omega}(q=0) = \hat{\sigma} B(GT)$$

Which transitions are of GT type?



R.Z. et al., Phys. Rev. C. 74, 024309 (2006)

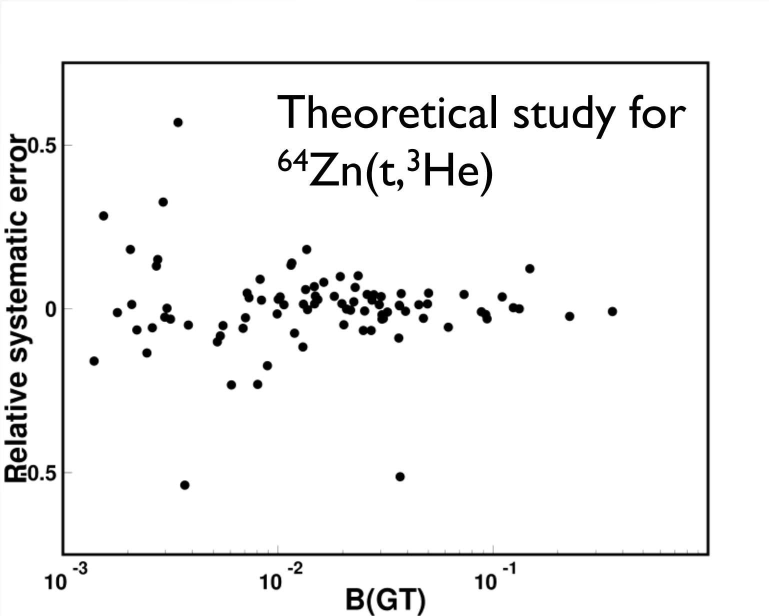
Multipole decomposition

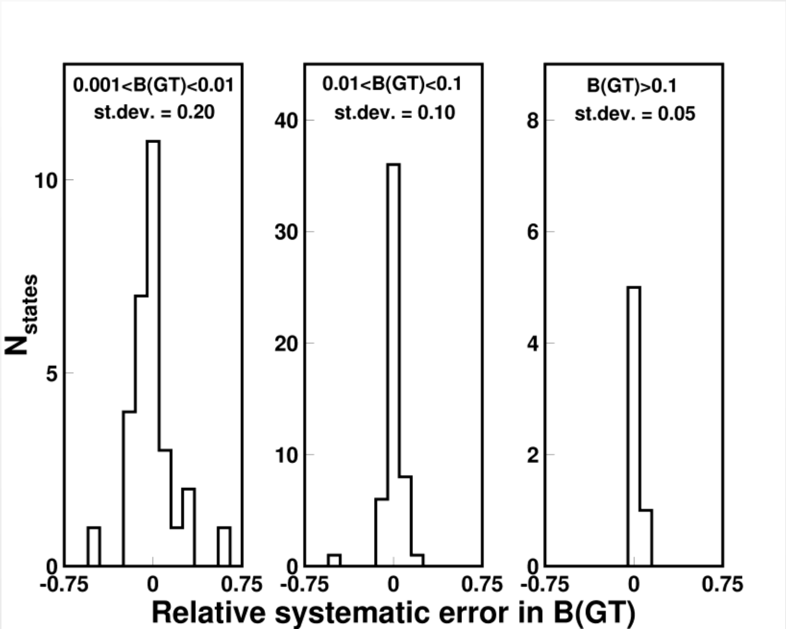


C. Guess et al., Phys. Rev. C 80, 024305 (2009)

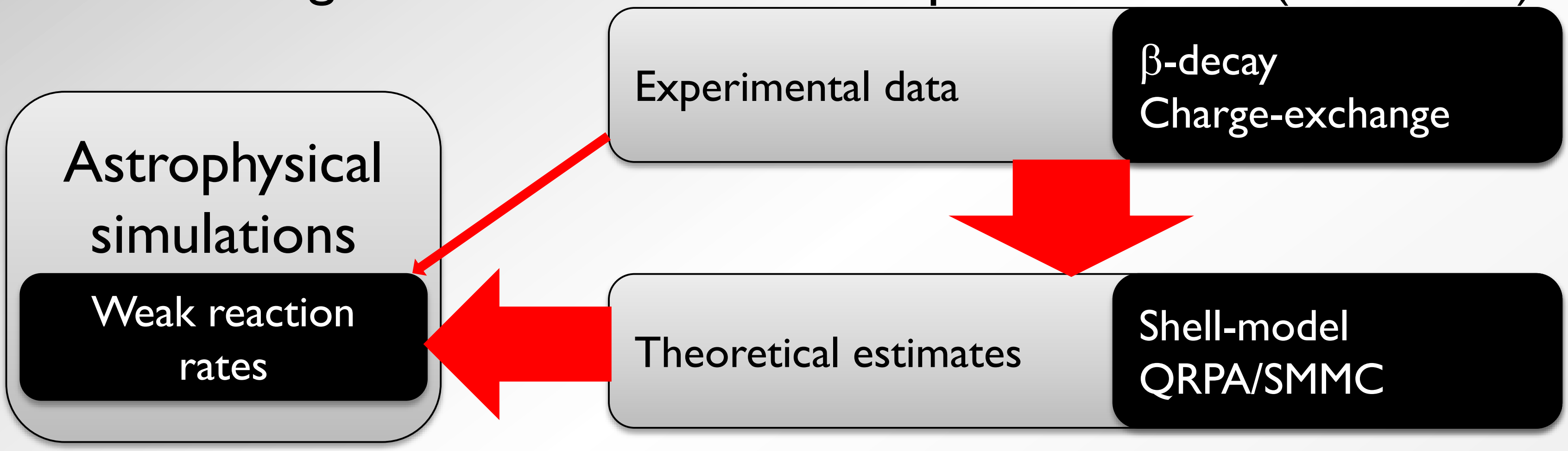
Systematic error in extraction of B(GT)

- Leading uncertainty comes from interference between ΔL=0 and ΔL=2 amplitudes mediated by the στ and Tτ parts of the NN-interaction that drives the CE reaction
- Uncertainty increases for small B(GT)
- Can be studied statistically, but corrections on a state-by-state basis are only possible if the transition densities are well-known (some success have been achieved, e.g. ^{58}Ni, ^{13}C)
- Difference between B(GT)s extracted from different probes (e.g. (p,n) and (^3He,t) are indicative of strong L=2 amplitudes mediated via Tτ





Generating weak reaction rates for pf-shell nuclei ($45<A<65$)



Charge-Exchange Data

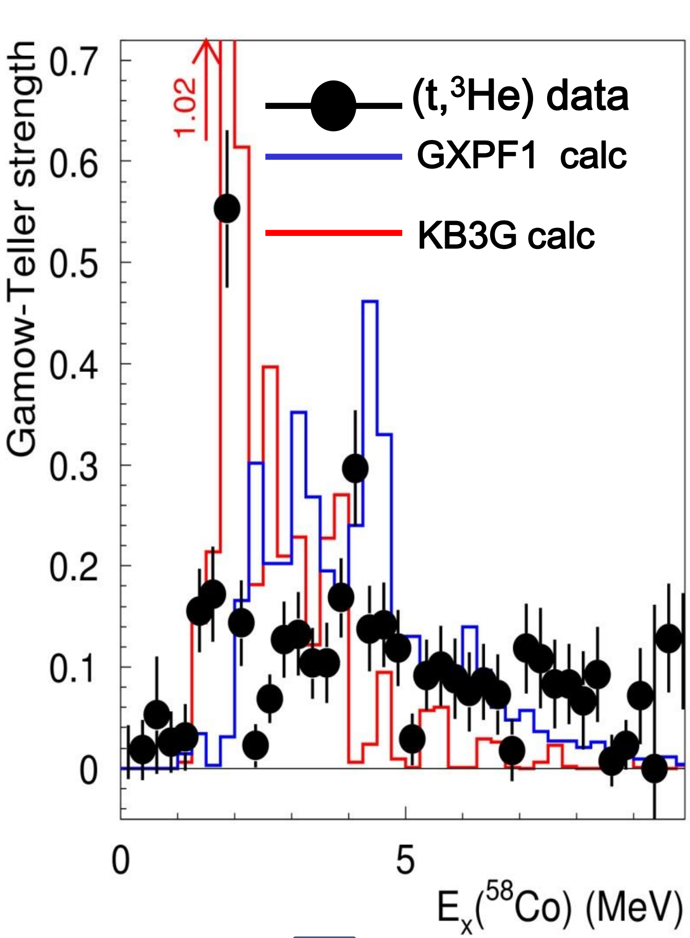
- (n,p) – TRIUMF/RCNP
- (d,^{2}He) – KVI
- (t,^{3}He) - NSCL

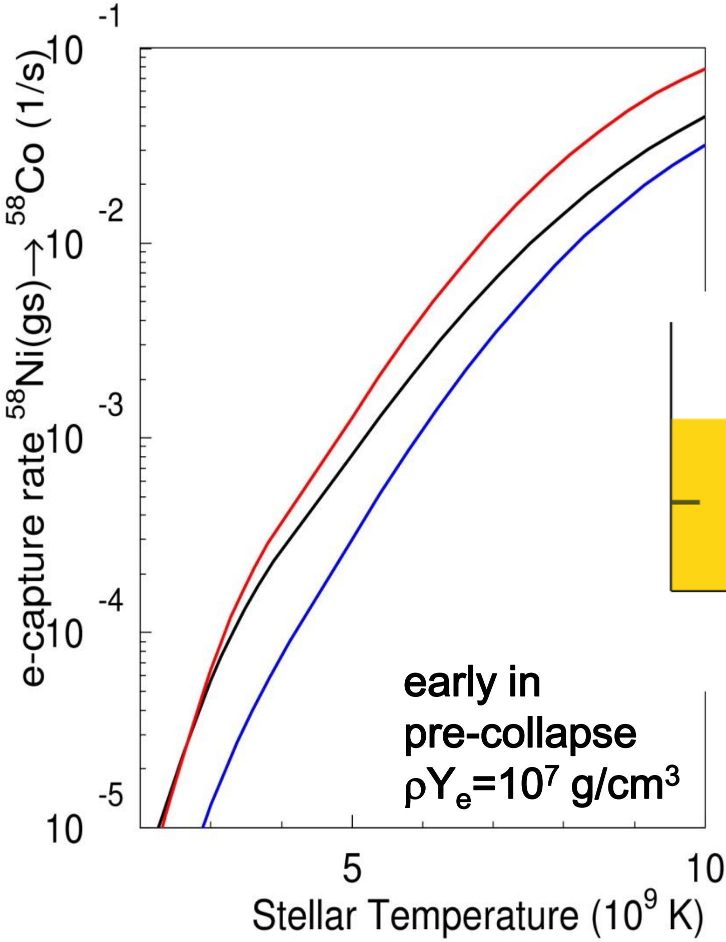
Theory

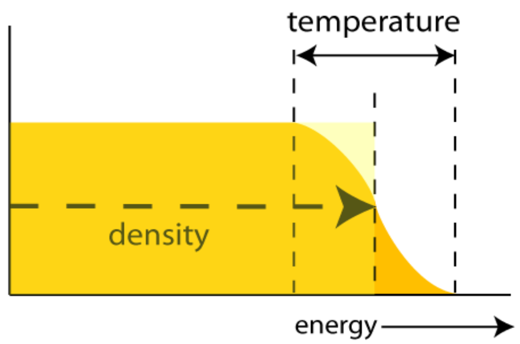
- Configuration-interaction (shell) models
  - **KB3G** (Poves et al.)
  - GXPF1 (Honma et al.)
- Mean-field (Quasi-particle Random Phase Approximation) – P. Möller et al.
- Hybrid (RPA+Shell-model Monte Carlo)

Used in most sophisticated weak reaction rate library used in astrophysical simulations

Example $^{58}Ni \rightarrow ^{58}Co$







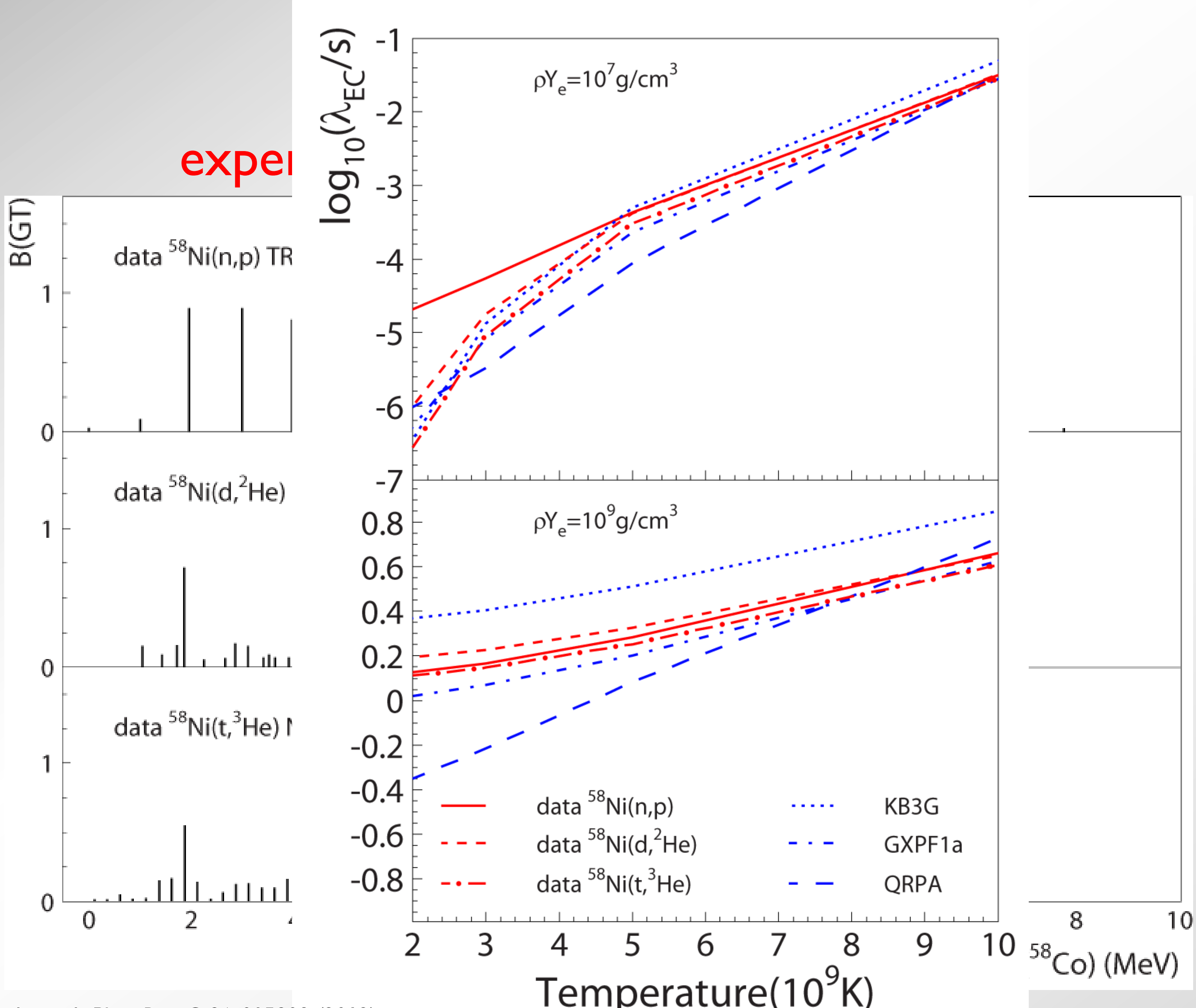
$$\lambda = \sum_i \sum_f \ln 2 \frac{f_{ij}(T,\rho)}{ft_{ij}}$$

Phase-space

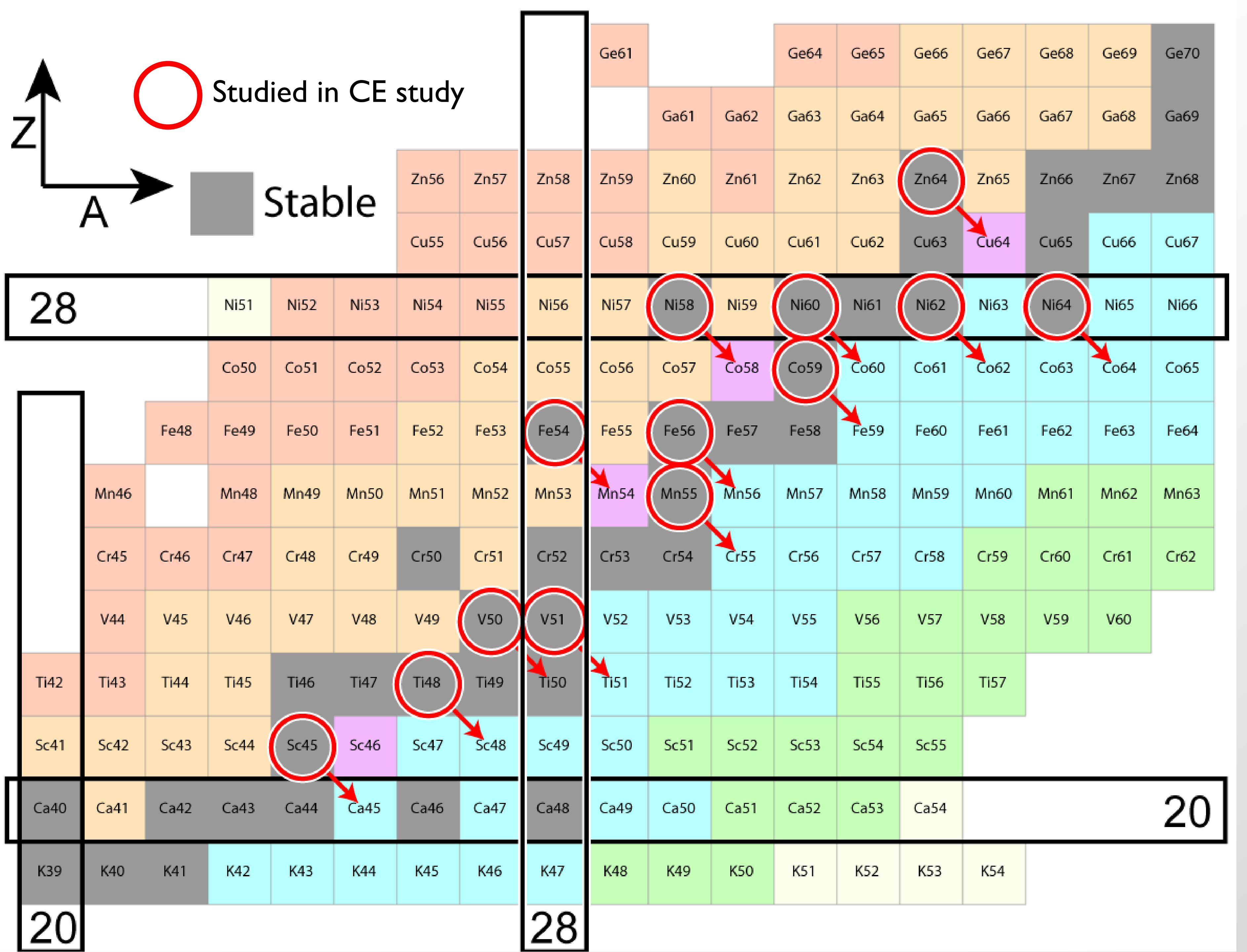
Transition strength

A. L. Cole et al., Phys. Rev. C. 74, 034333 (2006)

exper

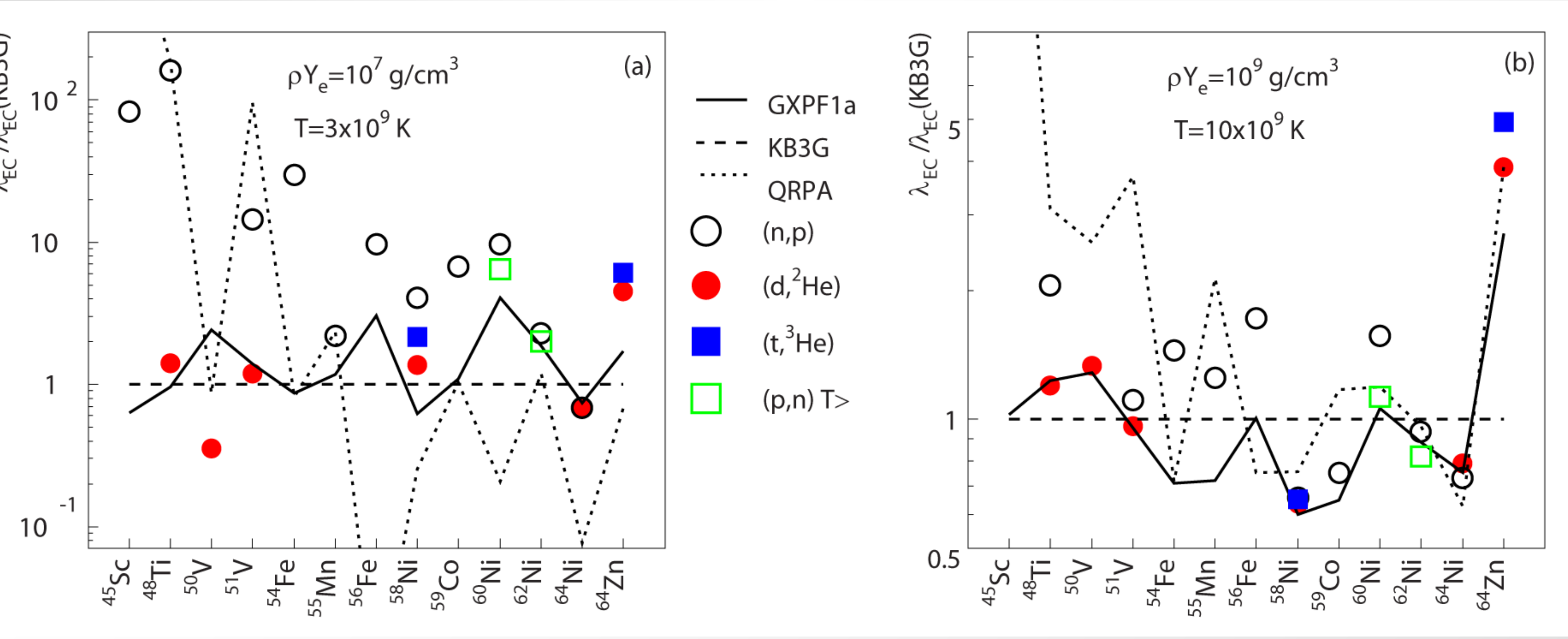


A.L. Cole et al., Phys. Rev. C 86, 015809 (2012)



Z
A
Studied in CE study
Stable
Ge61 Ge64 Ge65 Ge66 Ge67 Ge68 Ge69 Ge70
Ga61 Ga62 Ga63 Ga64 Ga65 Ga66 Ga67 Ga68 Ga69
Zn56 Zn57 Zn58 Zn59 Zn60 Zn61 Zn62 Zn63 Zn64 Zn65 Zn66 Zn67 Zn68
Cu55 Cu56 Cu57 Cu58 Cu59 Cu60 Cu61 Cu62 Cu63 Cu64 Cu65 Cu66 Cu67
28
Ni51 Ni52 Ni53 Ni54 Ni55 Ni56 Ni57 Ni58 Ni59 Ni60 Ni61 Ni62 Ni63 Ni64 Ni65 Ni66
Co50 Co51 Co52 Co53 Co54 Co55 Co56 Co57 Co58 Co59 Co60 Co61 Co62 Co63 Co64 Co65
Fe48 Fe49 Fe50 Fe51 Fe52 Fe53 Fe54 Fe55 Fe56 Fe57 Fe58 Fe59 Fe60 Fe61 Fe62 Fe63 Fe64
Mn46 Mn48 Mn49 Mn50 Mn51 Mn52 Mn53 Mn54 Mn55 Mn56 Mn57 Mn58 Mn59 Mn60 Mn61 Mn62 Mn63
Cr45 Cr46 Cr47 Cr48 Cr49 Cr50 Cr51 Cr52 Cr53 Cr54 Cr55 Cr56 Cr57 Cr58 Cr59 Cr60 Cr61 Cr62
V44 V45 V46 V47 V48 V49 V50 V51 V52 V53 V54 V55 V56 V57 V58 V59 V60
Ti42 Ti43 Ti44 Ti45 Ti46 Ti47 Ti48 Ti49 Ti50 Ti51 Ti52 Ti53 Ti54 Ti55 Ti56 Ti57
Sc41 Sc42 Sc43 Sc44 Sc45 Sc46 Sc47 Sc48 Sc49 Sc50 Sc51 Sc52 Sc53 Sc54 Sc55
Ca40 Ca41 Ca42 Ca43 Ca44 Ca45 Ca46 Ca47 Ca48 Ca49 Ca50 Ca51 Ca52 Ca53 Ca54
20
K39 K40 K41 K42 K43 K44 K45 K46 K47 K48 K49 K50 K51 K52 K53 K54
20
28

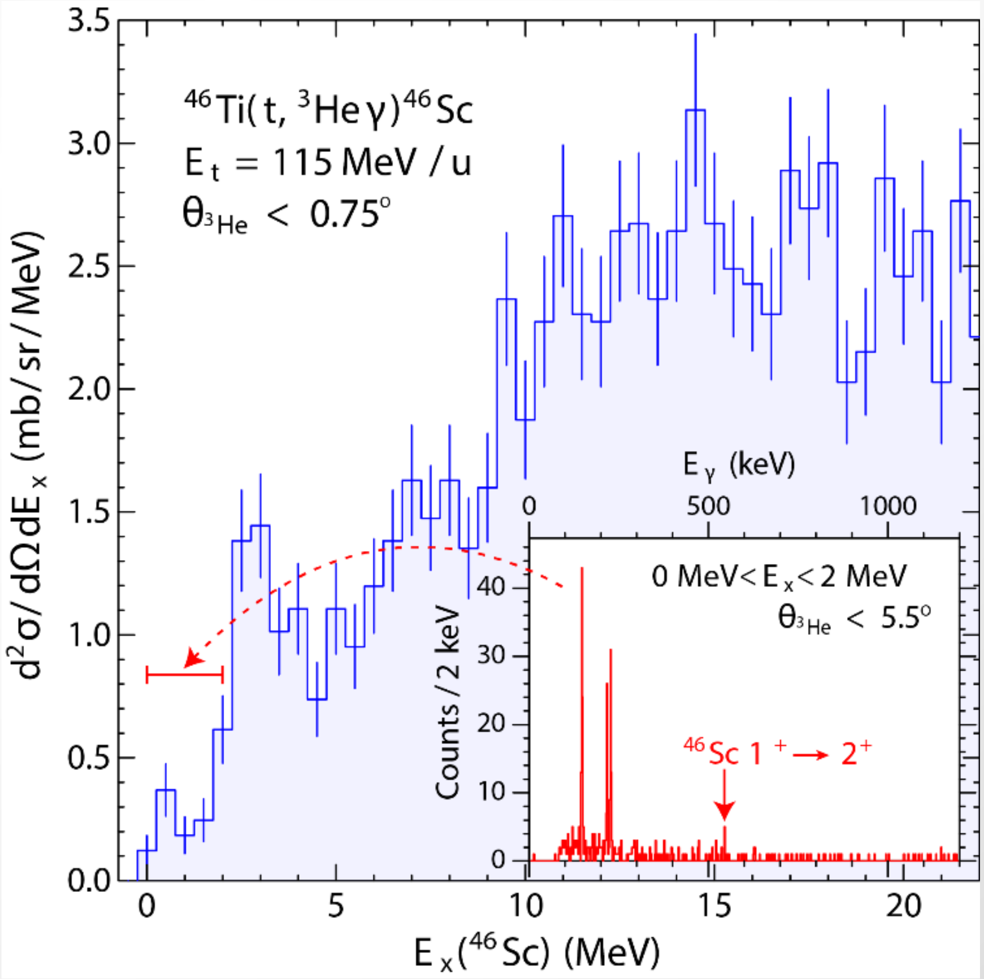
EC rate comparisons



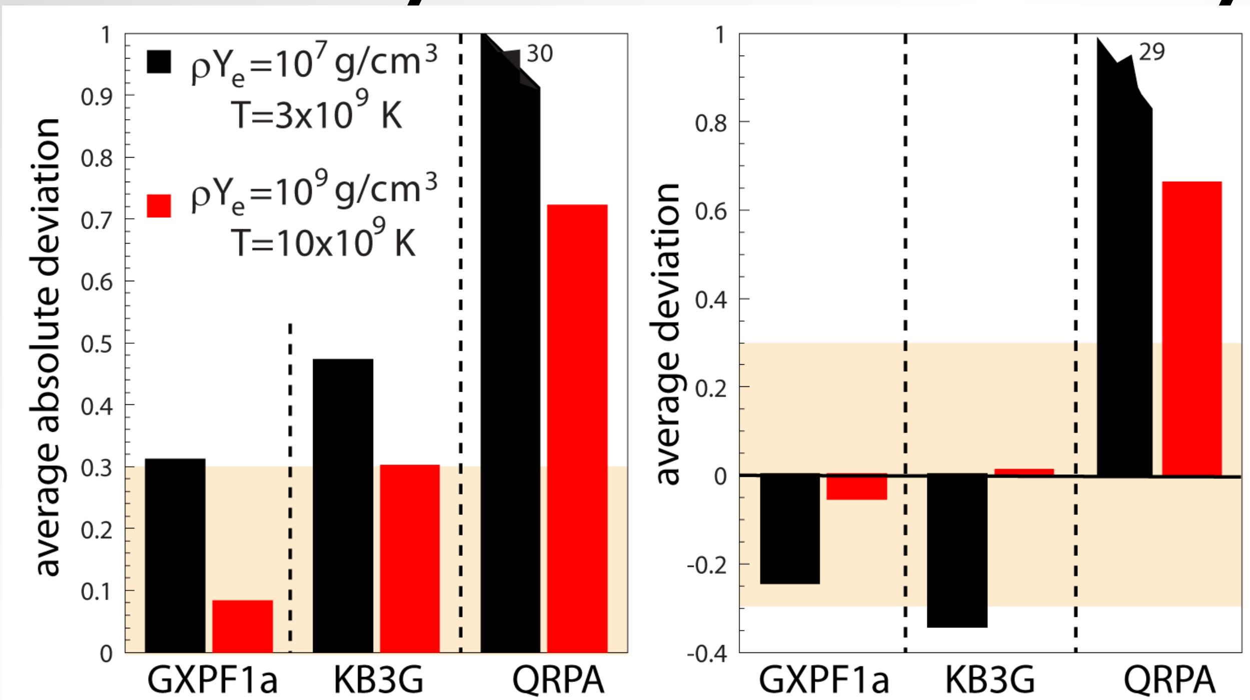
(t,^{3}He+γ)-for high precision

- ^{45}Sc and ^{46}Ti measured
- Using Gretina+S800 Spectrometer
- Resolutions of a few keV
- Helpful for identification and accurately measuring the location of the low-lying GT transitions

Very preliminary…



Summary of EC rate study

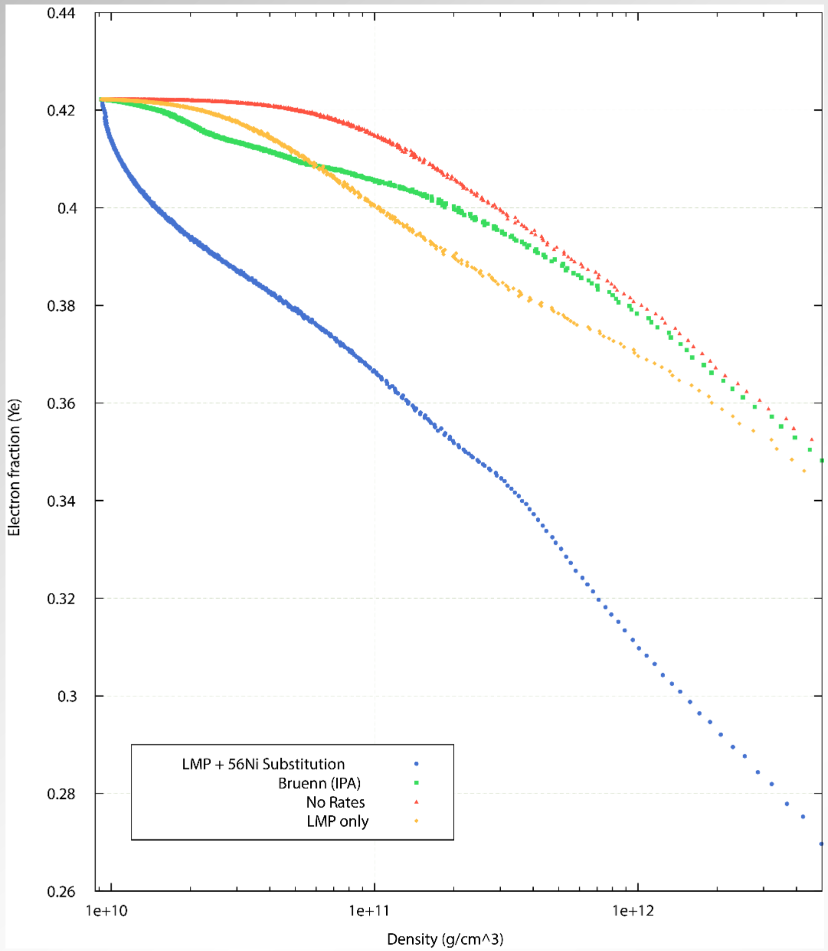


$$\overline{|\Delta_{EC}|} = \frac{1}{N}\sum_{i=1}^{N}\frac{|\lambda_i^{th} - \lambda_i^{exp}|}{\lambda_i^{exp}}$$

$$\overline{\Delta_{EC}} = \frac{1}{N}\sum_{i=1}^{N}\frac{\lambda_i^{th} - \lambda_i^{exp}}{\lambda_i^{exp}}$$

EC rates based on configuration interaction (shell-model) calculations underestimate the rates based on experimental strengths by about 30%, - GXPF1a interaction is slightly better than KB3G

EC rates based on QRPA calculations are strongly overestimate the rates based on experiment – even at high densities/temperatures, where the fine structure of the strength distribution is of little relevance



Weak processes in CCSNe

- GR1D is an open source spherically symmetric general relativistic hydrodynamics code
- Implements two moment Boltzmann neutrino transport with analytic closure for all six neutrino species via NuLib
- Designed to study core collapse supernovae (Type Ib/c, Type II)
- Currently using 15 solar mass, solar metalicity star from Woosley & Weaver 1995, but can simulate massive stars with M>8Msol
- Rigorous implementation of neutrino/weak interaction microphysics, including:
  - Absorption of nu_e and anti nu_e on neutrinos and protons (resp.)
  - Scattering on neutrons, protons, and heavy nuclei for all species of neutrino
  - Thermal emission of all species from electron-positron annihilation
- Most recently: electron capture on heavy nuclei
  - Full NSE distribution of nuclei using the FRDM mass model for use in calculating neutrino emissivities and opacities.

Chris Sullivan (NSCL), Remco Zegers (NSCL), Evan O'Connor (CITA), Christian Ott (CalTech)

Similar studies have been performed in the past – the goal of the present study is to perform detailed sensitivity studies to motivate experiments (with rare isotope beams)

strategy

Given that one can only do so many experiments, what is the best strategy for testing theories used to calculate weak reaction rates for astrophysics?

1) Perform experiments on nuclei that are particularly abundant in the stellar environment

2) Perform experiments on nuclei that can tell us something fundamental about the theorertical calculations

^{56}Ni – satisfies both conditions!

However, ^{56}Ni is unstable ($T_{1/2}$=6 days)

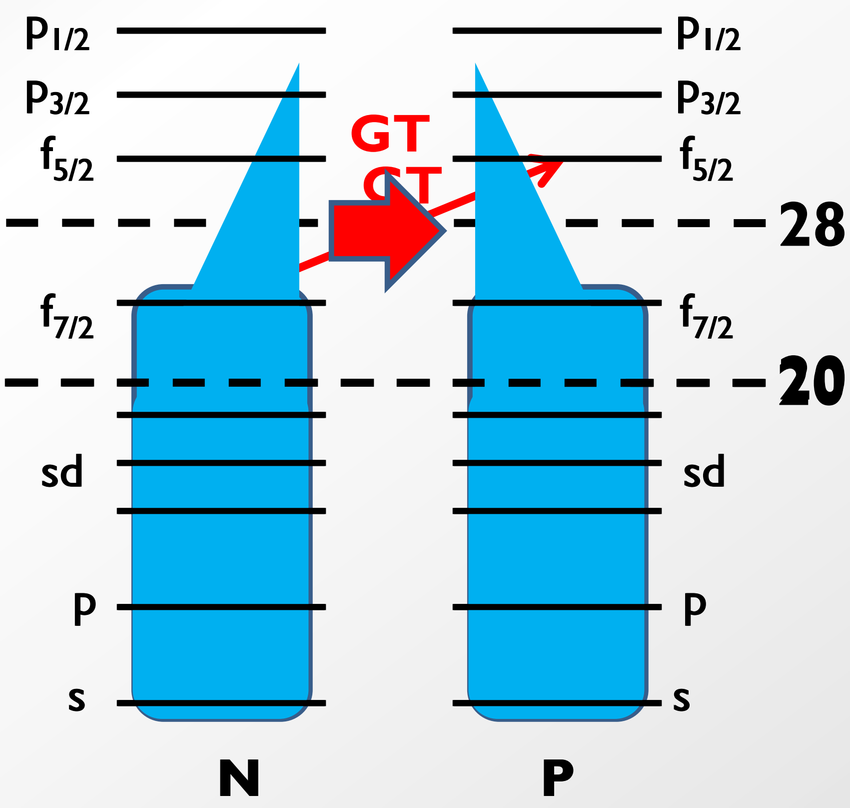
^{56}Ni

Independent particle model:

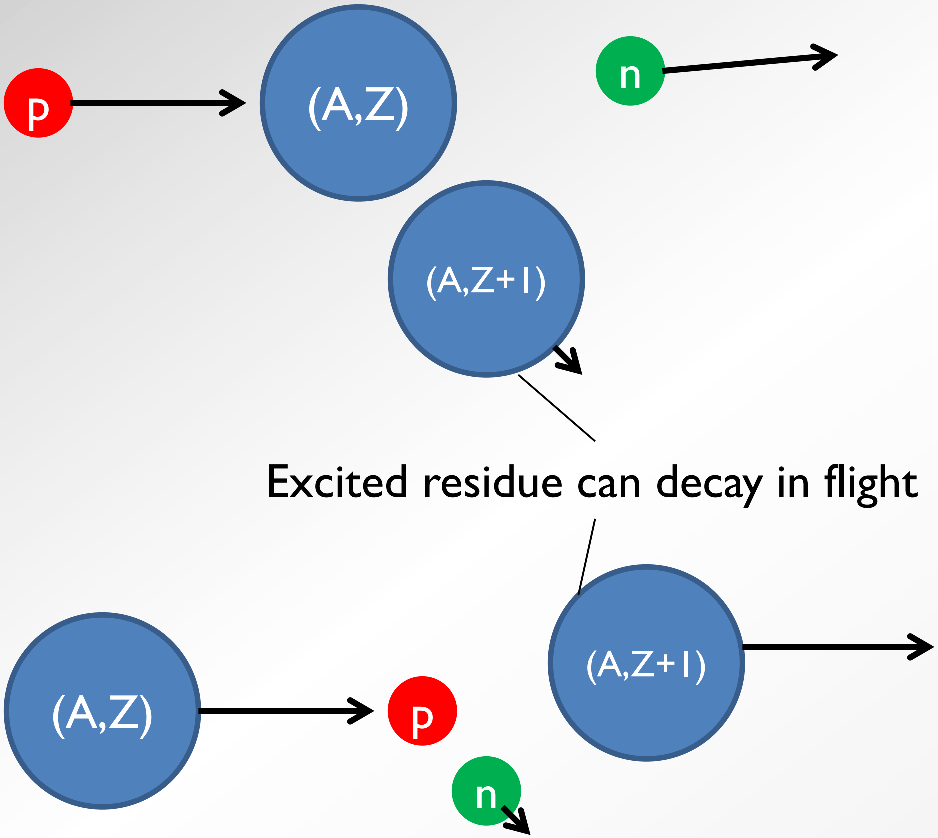
- ^{56}Ni is doubly magic
- GT involves $f_{7/2} \rightarrow f_{5/2}$

Due to large p-n residual interaction, ^{56}Ni is not magic

Shell-model calculations with the KB3G interaction and the GXPF1a interaction both predict that the probability of a closed $(f_{7/2})^{16}$ configuration is ~65%.



kinematics



Normal kinematics

At q~0, outgoing neutron is fast.

From its properties (angle, energy) one can "easily" determine the excitation energy and center-of-mass scattering angle.

Residual is not detected (two-body kinematics)

Inverse kinematics

At q~0, outgoing residue is fast – almost impossible to detect its properties with sufficient precision.

Neutron is very slow – hard to detect. However, if feasible one can reconstruct the excitation energy and center-of-mass scattering angle.

Advantage: neutron is not stopped in target

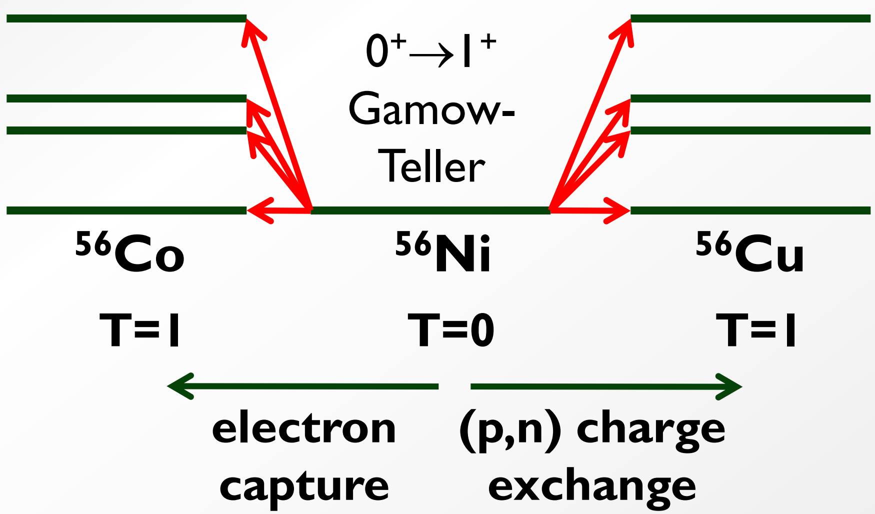
Problem…

To extract the Gamow-Teller strength of relevance for electron-captures, we need an (n,p)-type charge-exchange experiment in inverse kinematics with rare-isotope beams….

The charge-exchange group at NSCL has successfully developed the ^{7}Li,^{7}Be reaction in inverse kinematics for that purpose – but not suitable for experiments with A>35 (In the future, (d,^{2}He) in inverse kinematics might become feasible

However: because of isospin symmetry, one can use a (p,n)-type probe instead!

isospin symmetry

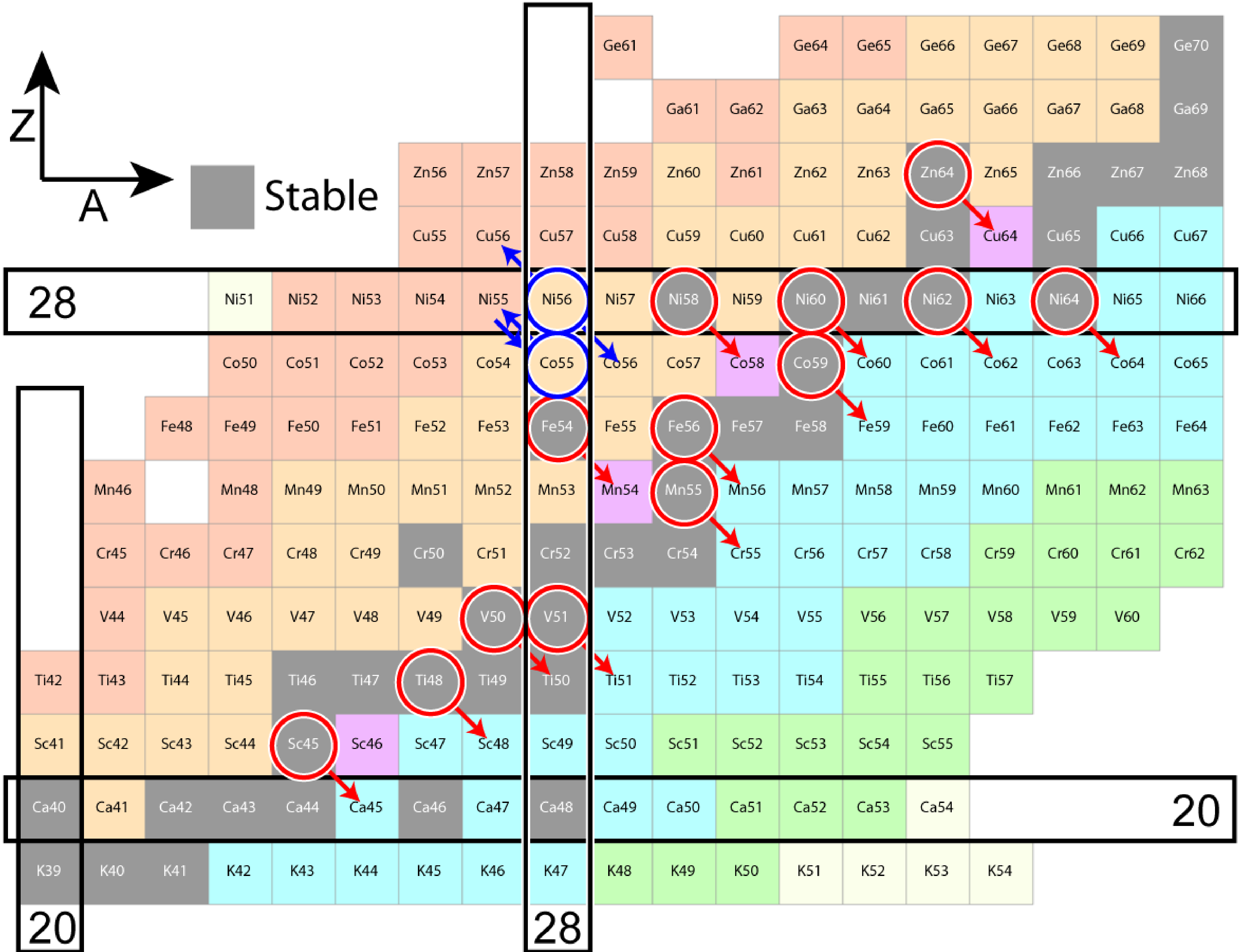


^{56}Ni isospin T=0

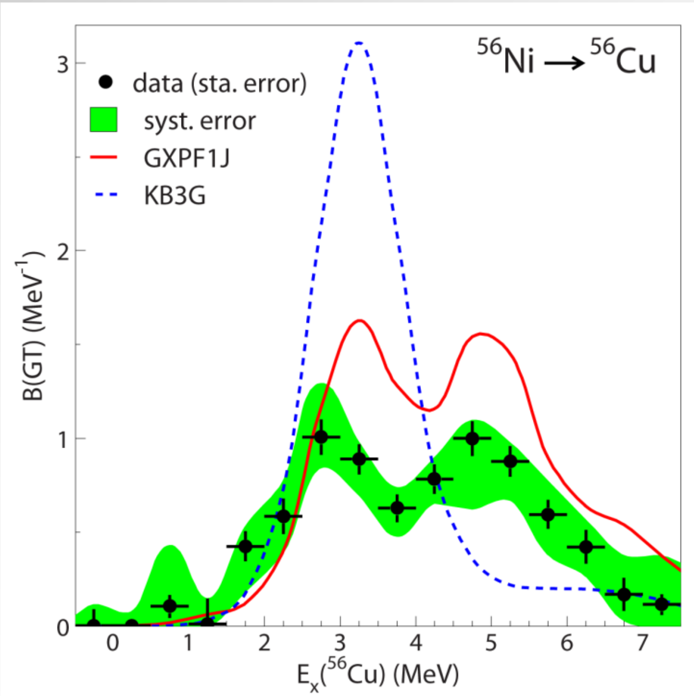
$$B(GT)_{56Ni \rightarrow 56Cu} = B(GT)_{56NI \rightarrow 56Co}$$

^{56}Ni(p,n) CE

^{56}Ni EC


Z
A
Stable
28
20
Ge61 Ge64 Ge65 Ge66 Ge67 Ge68 Ge69 Ge70
Ga61 Ga62 Ga63 Ga64 Ga65 Ga66 Ga67 Ga68 Ga69
Zn56 Zn57 Zn58 Zn59 Zn60 Zn61 Zn62 Zn63 Zn64 Zn65 Zn66 Zn67 Zn68
Cu55 Cu56 Cu57 Cu58 Cu59 Cu60 Cu61 Cu62 Cu63 Cu64 Cu65 Cu66 Cu67
Ni51 Ni52 Ni53 Ni54 Ni55 Ni56 Ni57 Ni58 Ni59 Ni60 Ni61 Ni62 Ni63 Ni64 Ni65 Ni66
Co50 Co51 Co52 Co53 Co54 Co55 Co56 Co57 Co58 Co59 Co60 Co61 Co62 Co63 Co64 Co65
Fe48 Fe49 Fe50 Fe51 Fe52 Fe53 Fe54 Fe55 Fe56 Fe57 Fe58 Fe59 Fe60 Fe61 Fe62 Fe63 Fe64
Mn46 Mn48 Mn49 Mn50 Mn51 Mn52 Mn53 Mn54 Mn55 Mn56 Mn57 Mn58 Mn59 Mn60 Mn61 Mn62 Mn63
Cr45 Cr46 Cr47 Cr48 Cr49 Cr50 Cr51 Cr52 Cr53 Cr54 Cr55 Cr56 Cr57 Cr58 Cr59 Cr60 Cr61 Cr62
V44 V45 V46 V47 V48 V49 V50 V51 V52 V53 V54 V55 V56 V57 V58 V59 V60
Ti42 Ti43 Ti44 Ti45 Ti46 Ti47 Ti48 Ti49 Ti50 Ti51 Ti52 Ti53 Ti54 Ti55 Ti56 Ti57
Sc41 Sc42 Sc43 Sc44 Sc45 Sc46 Sc47 Sc48 Sc49 Sc50 Sc51 Sc52 Sc53 Sc54 Sc55
Ca40 Ca41 Ca42 Ca43 Ca44 Ca45 Ca46 Ca47 Ca48 Ca49 Ca50 Ca51 Ca52 Ca53 Ca54
K39 K40 K41 K42 K43 K44 K45 K46 K47 K48 K49 K50 K51 K52 K53 K54
20
28

Gamow-Teller strengths

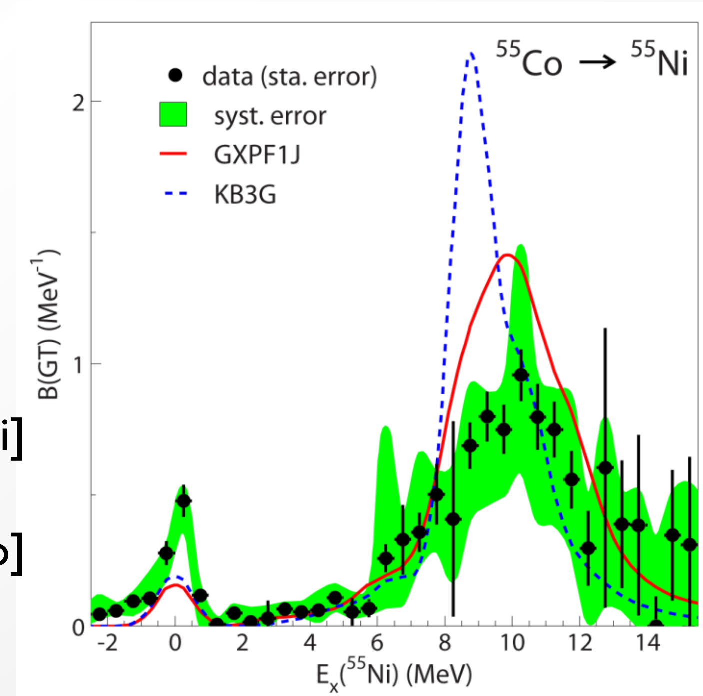


Isospin symmetry:

$B(GT)[^{56}Ni \rightarrow ^{56}Cu] = B(GT)[^{56}Ni \rightarrow ^{56}Co]$

and

$B(GT)[^{55}Co \rightarrow ^{55}Ni] = B(GT)[^{55}Ni \rightarrow ^{55}Co]$



GT strengths from GXPF1A/J provide better results than from KB3G for ^{56}Ni (^{55}Co)

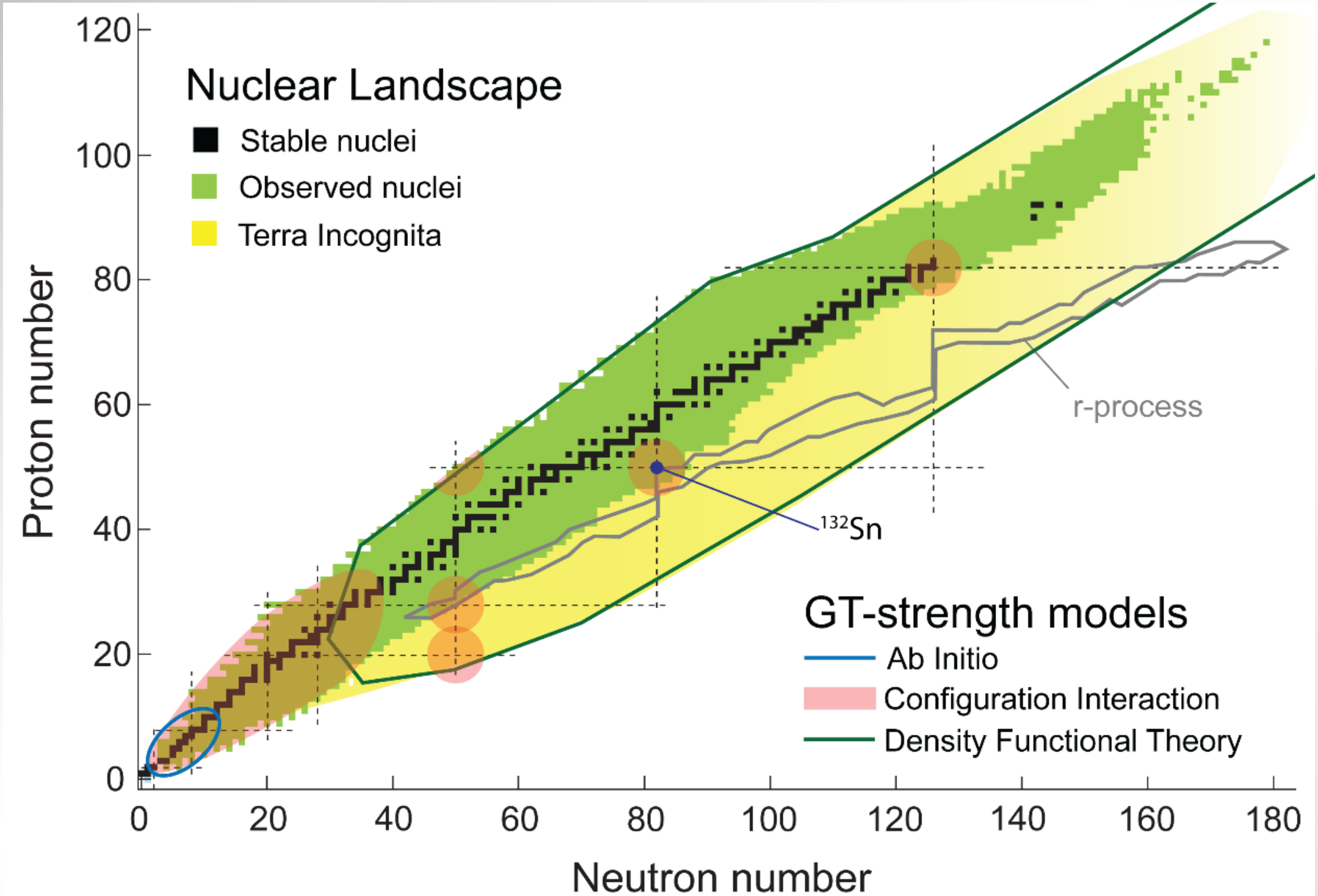
Difference between KB3G and GXPF1A:

- KB3G weaker spin-orbit and pn-residual interactions→GT strength resides at lower E_x
- KB3G lower level density→GT strength less spread
- Improvements to the most up-to-date weak reaction rate library based on calculations with the KB3G interaction are possible, probably at the level of ~30%.

M. Sasano et al., Phys. Rev. Lett. 107, 202501 (2011),Phys. Rev. C 86, 034324 (2012)

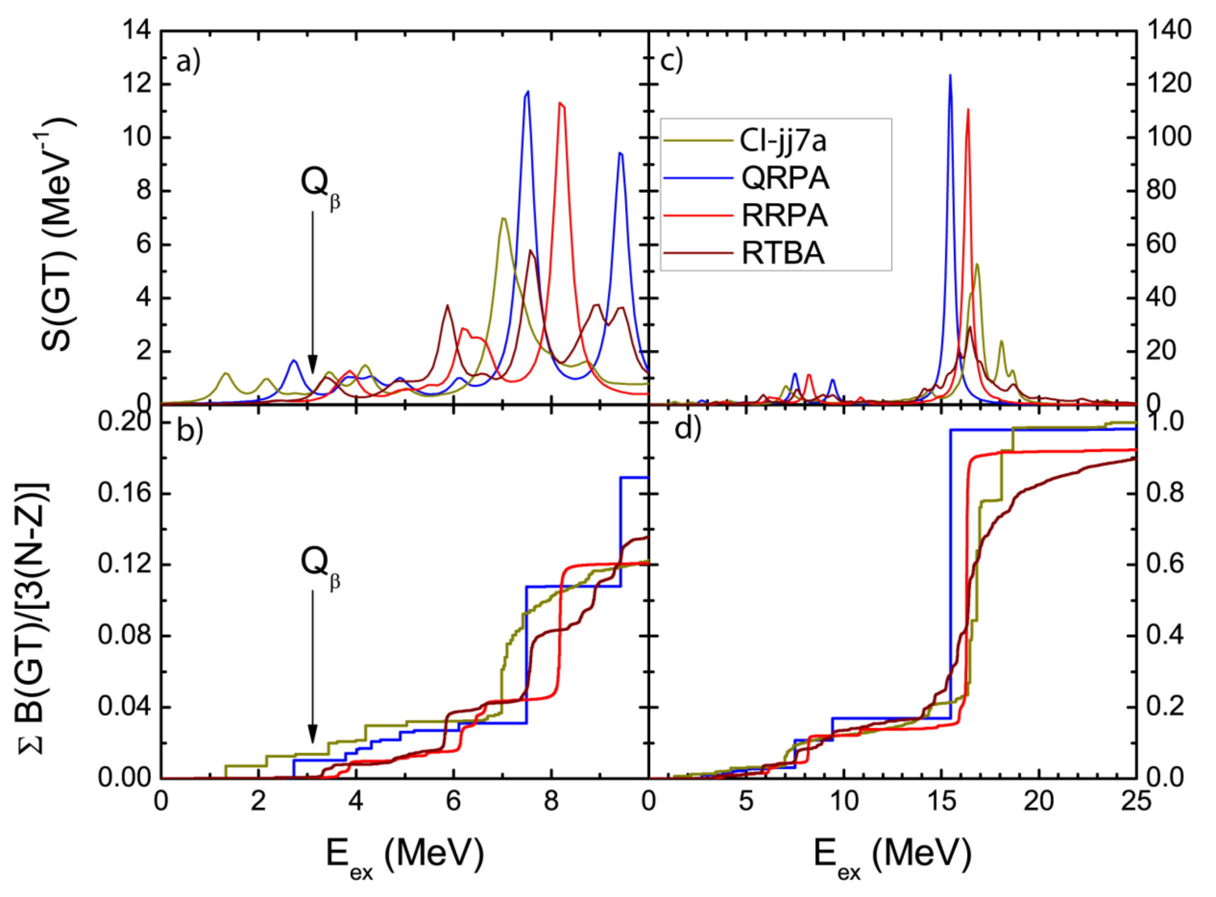
K. Langangke, Physics 4, 91 (2011)

CERN Courier, Jan/Feb 2012



Litvinova, Brown, Fang, Zegers – to be published

$^{132}Sn(p,n)$ planned



CI-jj7a: Configuration Interaction model in $0g_{9/2}$, $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2}$ and $0h_{7/2}$ space (Alex Brown)

QRPA: two quasiparticle pn-QRPA following procedure by Tubingen group for many double beta decay cases (D.L. Fang)

RRPA: self-consistent relativistic RPA (RRPA) calculation (E. Litvinova)

RTBA: relativistic (quasiparticle) time blocking approximation (RTBA) including 1p1h+phonon couplings (E. Litvinova)

Electron-capture rates on nuclei – summary/outlook

Validity of various theoretical approaches has been tested through a variety of charge-exchange experiments. The ^{56}Ni(p,n) experiment in inverse kinematics was critical in pinpointing the strengths and weaknesses of different models.

The development of different weak rate libraries to more accurately test sensitivities in astrophysical models is an important next step-effort started

The next frontiers: : nuclei with mass A>65 and nuclei far from the valley of stability – experiments with unstable nuclei are critical

With the successful development of the (p,n) reaction in inverse kinematics a new tool to study the spin-isospin response of unstable nuclei has been created with applications in astrophysics and beyond-various other proposals planned/carried out, e.g. ^{132}Sn.

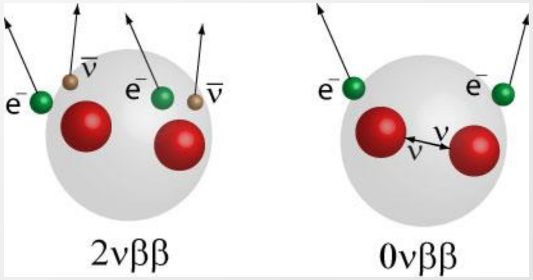
Double beta decay

$$[T^{2\nu}_{1/2}(0^+ \rightarrow 0^+)]^{-1} = G^{2\nu}(Q_{\beta\beta}, Z)|M^{2\nu}_{GT}|^2$$

$$M^{2\nu}_{GT} = \sum_j \frac{\langle 0^+_f \parallel \sum_k \sigma_k \tau^-_k \parallel 1^+_j \rangle \langle 1^+_j \parallel \sum_k \sigma_k \tau^-_k \parallel 0^+_i \rangle}{E_j - E_0 + Q_{\beta\beta}/2}$$

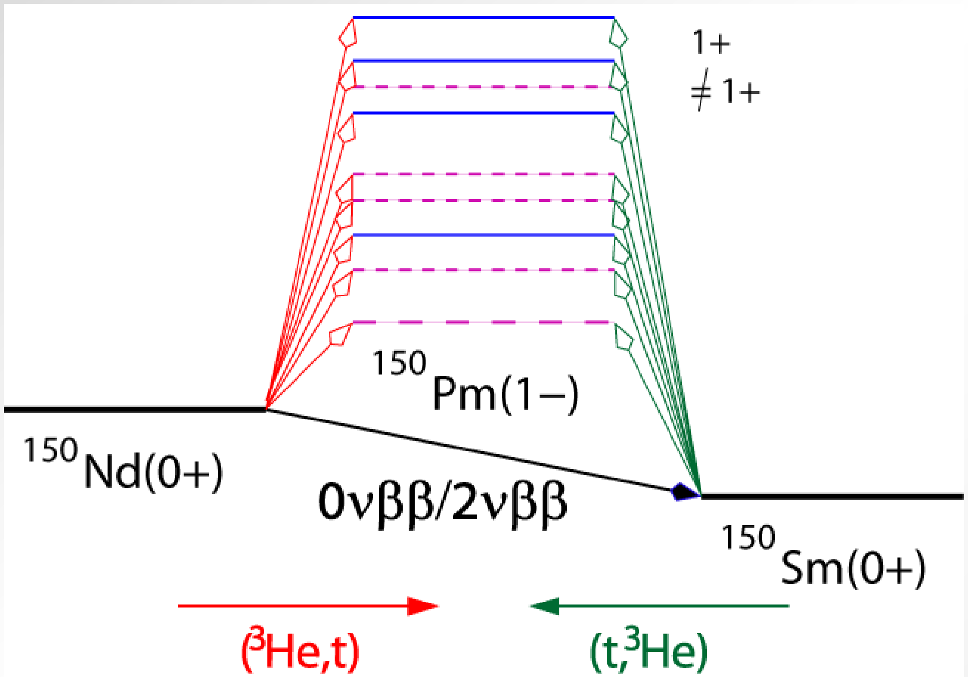
Phases?

$$|M_j(\mathrm{GT}^\pm)|^2 = B_j(\mathrm{GT}^\pm)$$



$$[T^{0\nu}_{1/2}(0^+ \rightarrow 0^+)]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

The case of ^{150}Nd



RCNP
Osaka U.

NSCL
MSU

SNO+

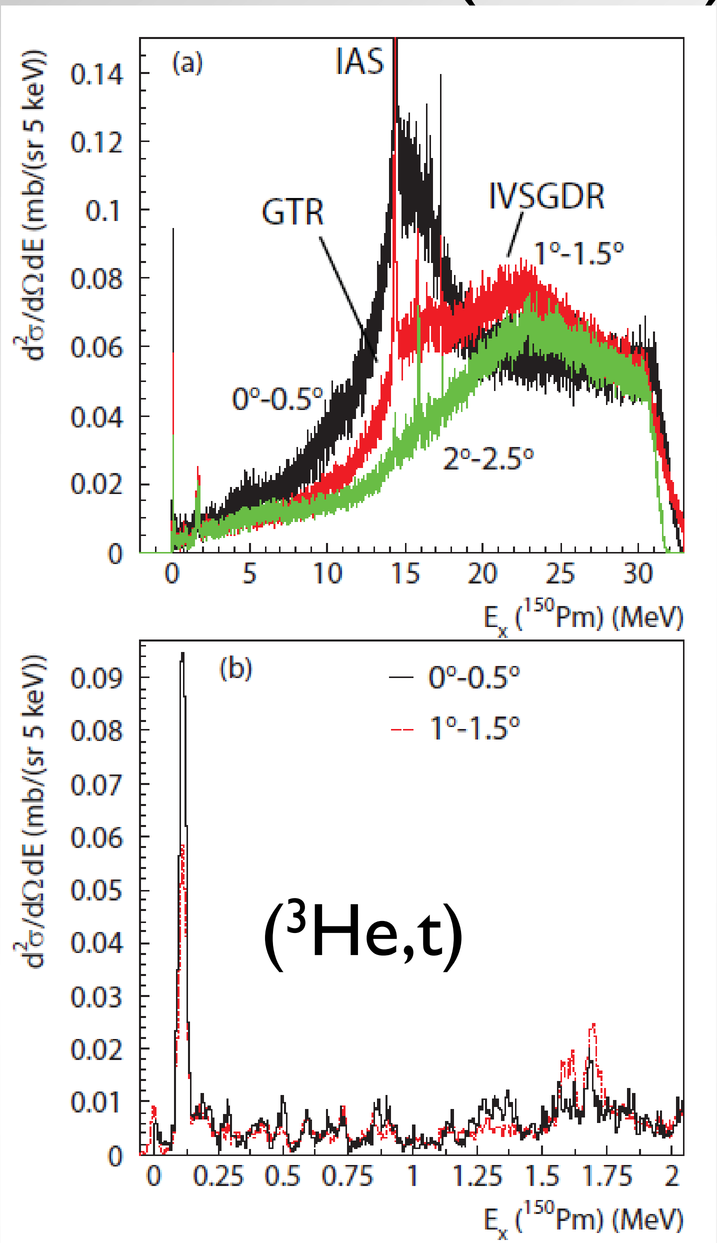
High Q-value

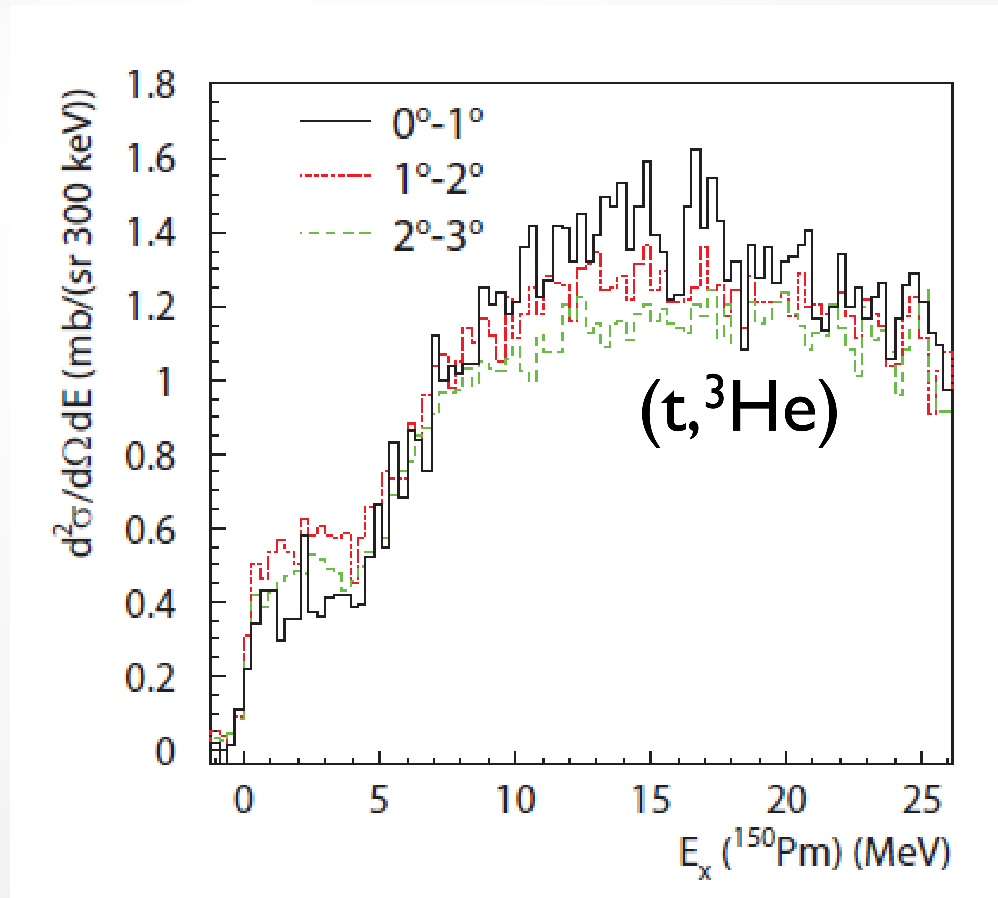
High Z

Deformed

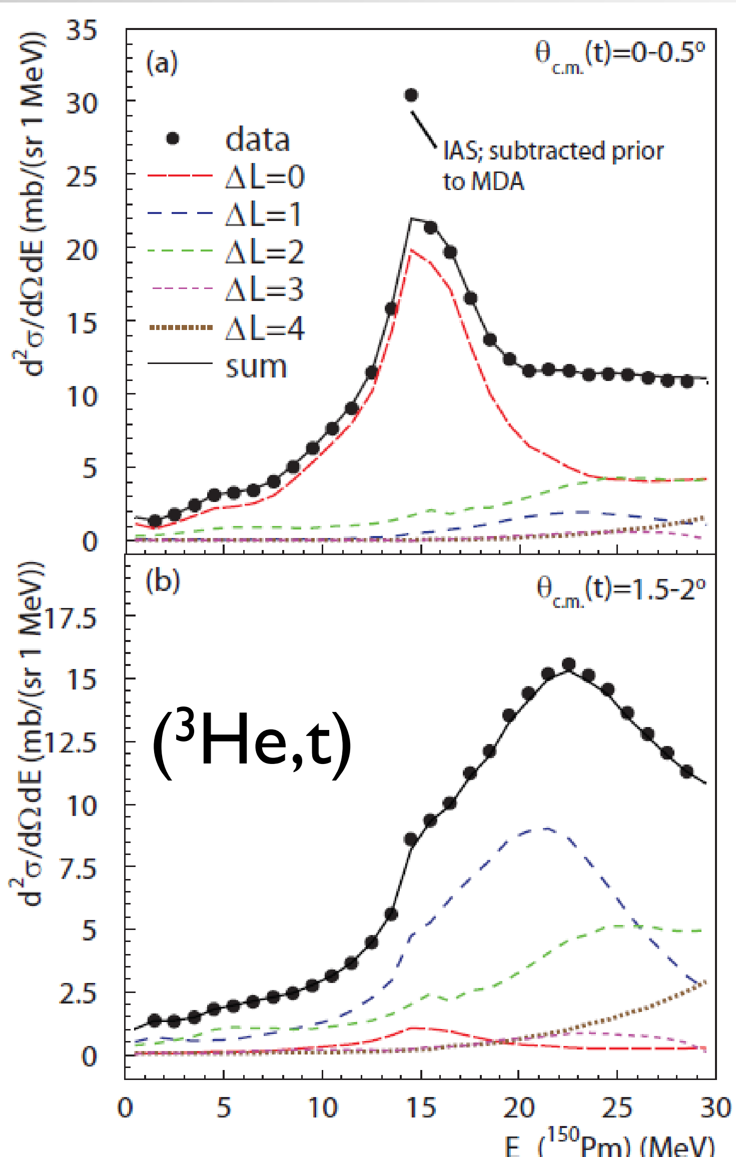
Complex structure

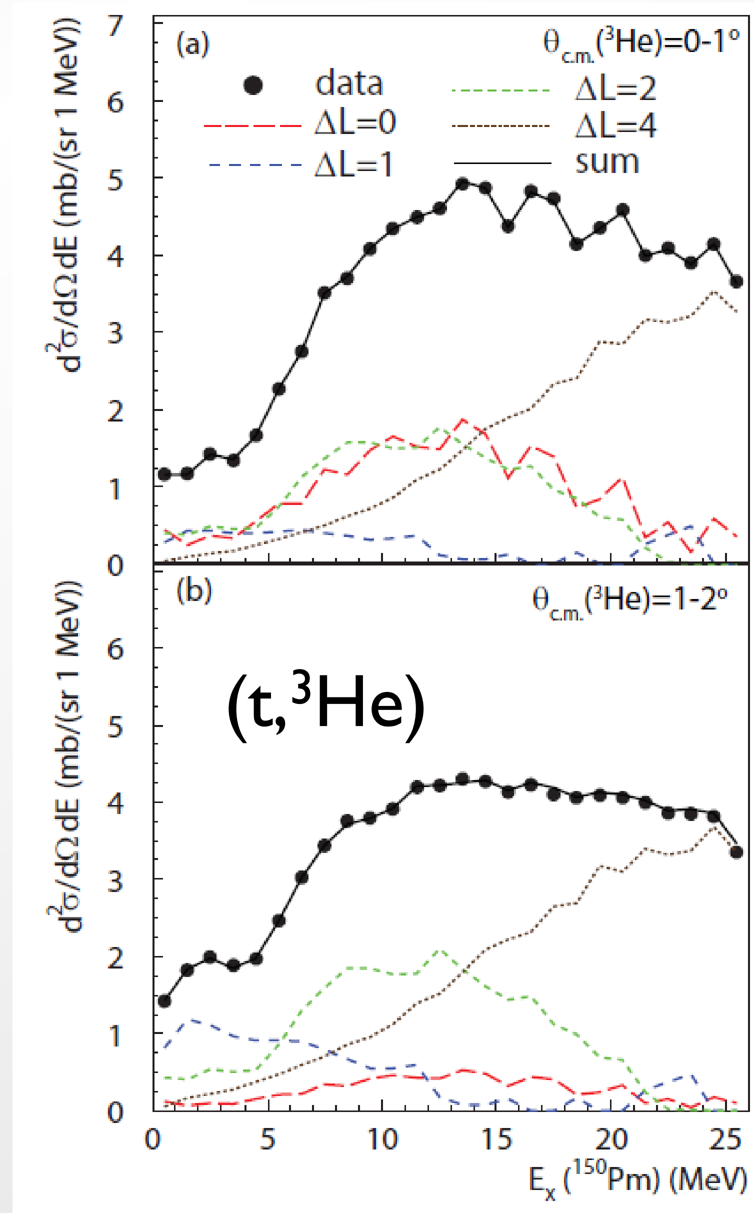
^{150}Nd(^{3}He,t) and ^{150}Sm(t,^{3}He) data



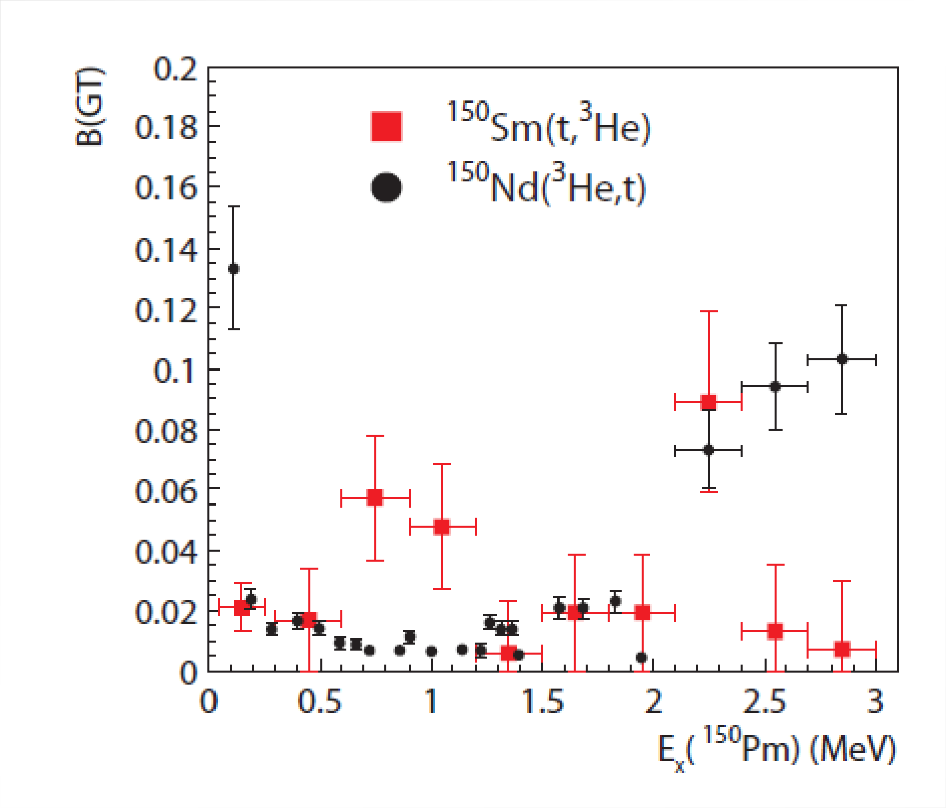


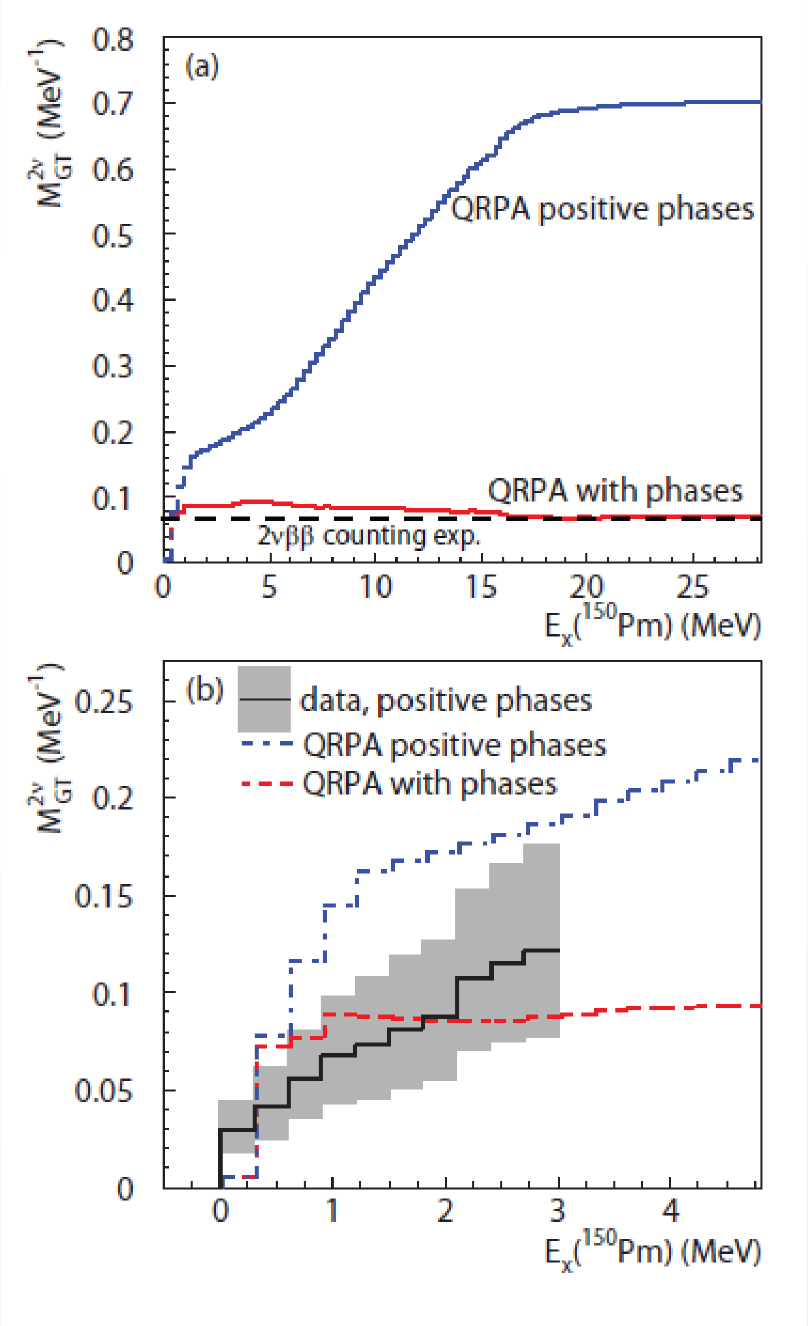
Multipole Decomposition



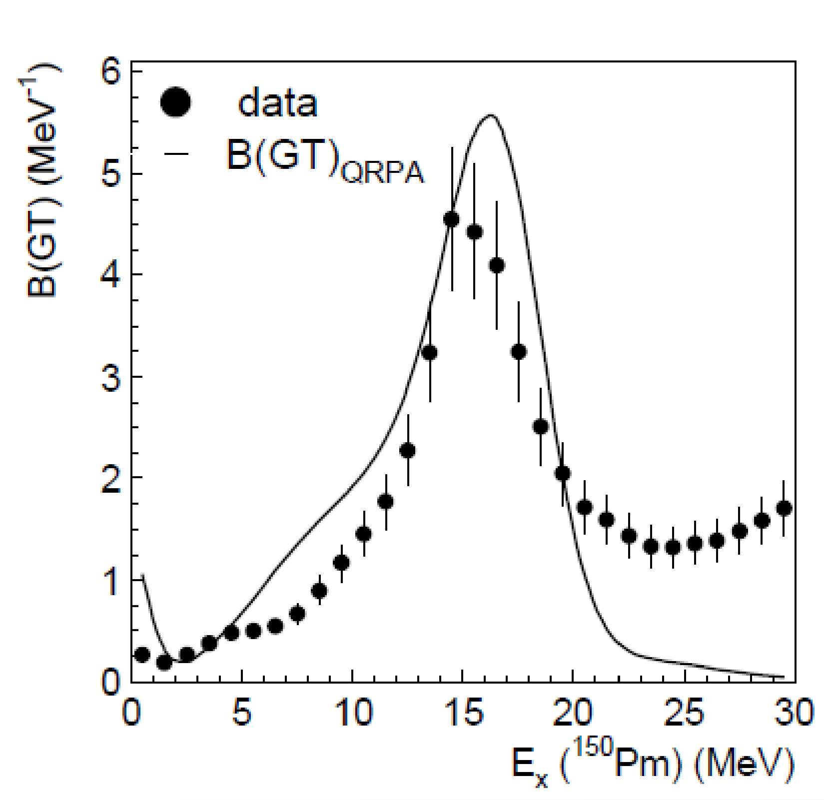


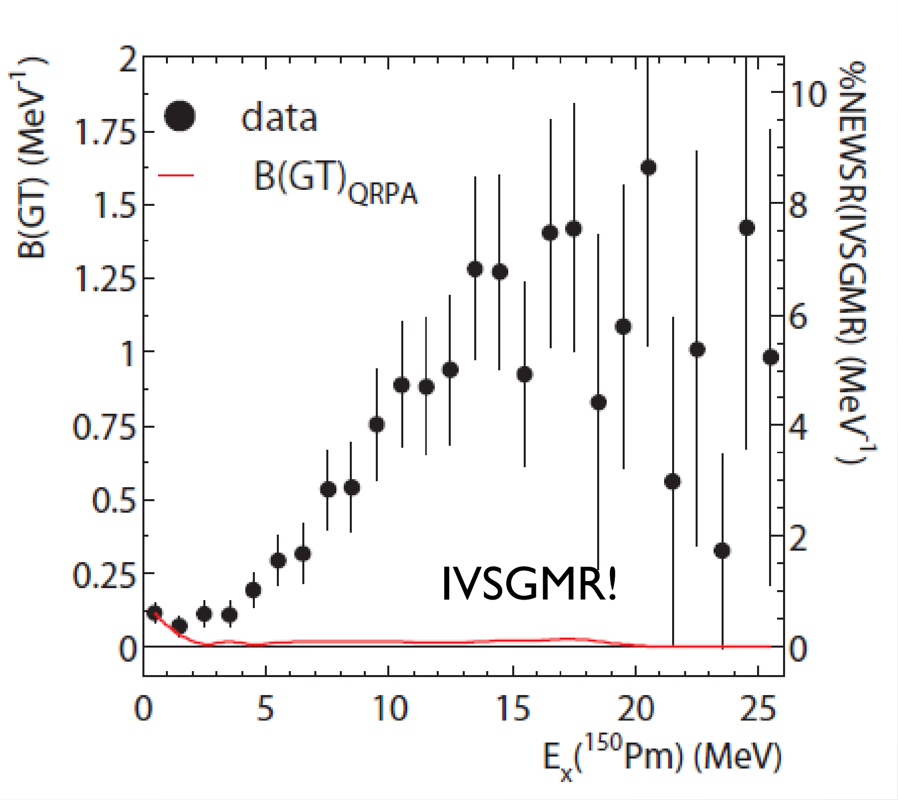
2νββ matrix element





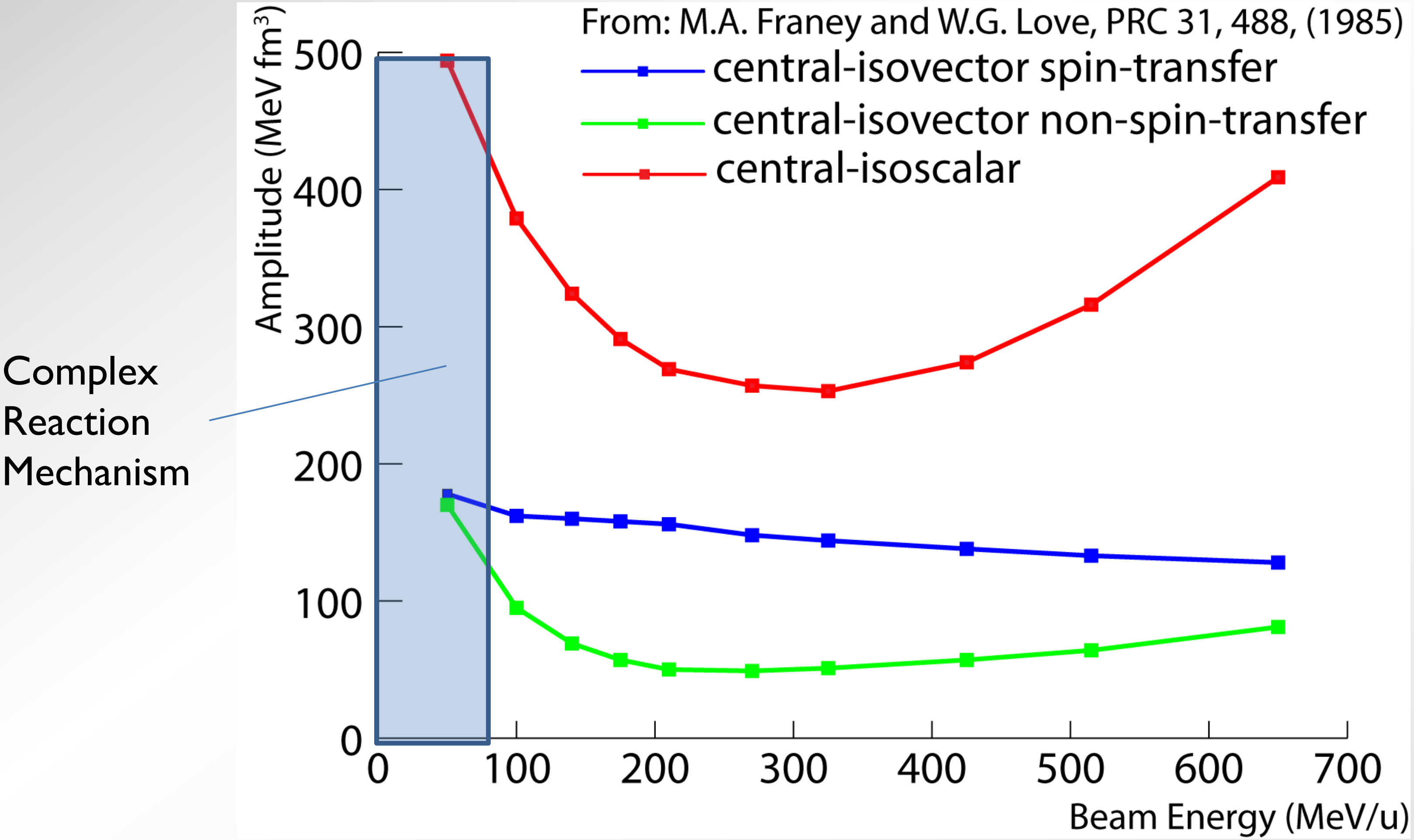
Comparison with QRPA calculations





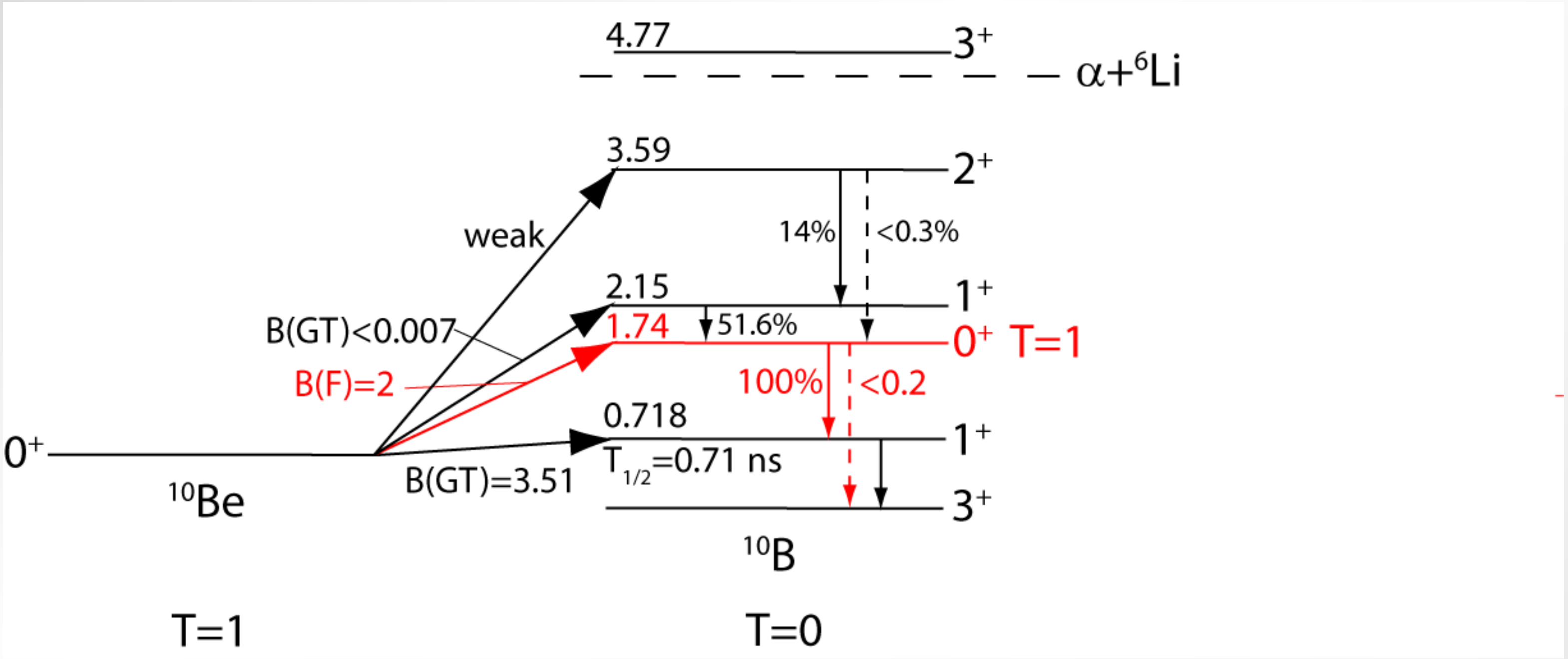
Calculations by Fang, Rodin et al.

New probes to achieve channel selectivity



How to isolate isovector non-spin transfer channels?

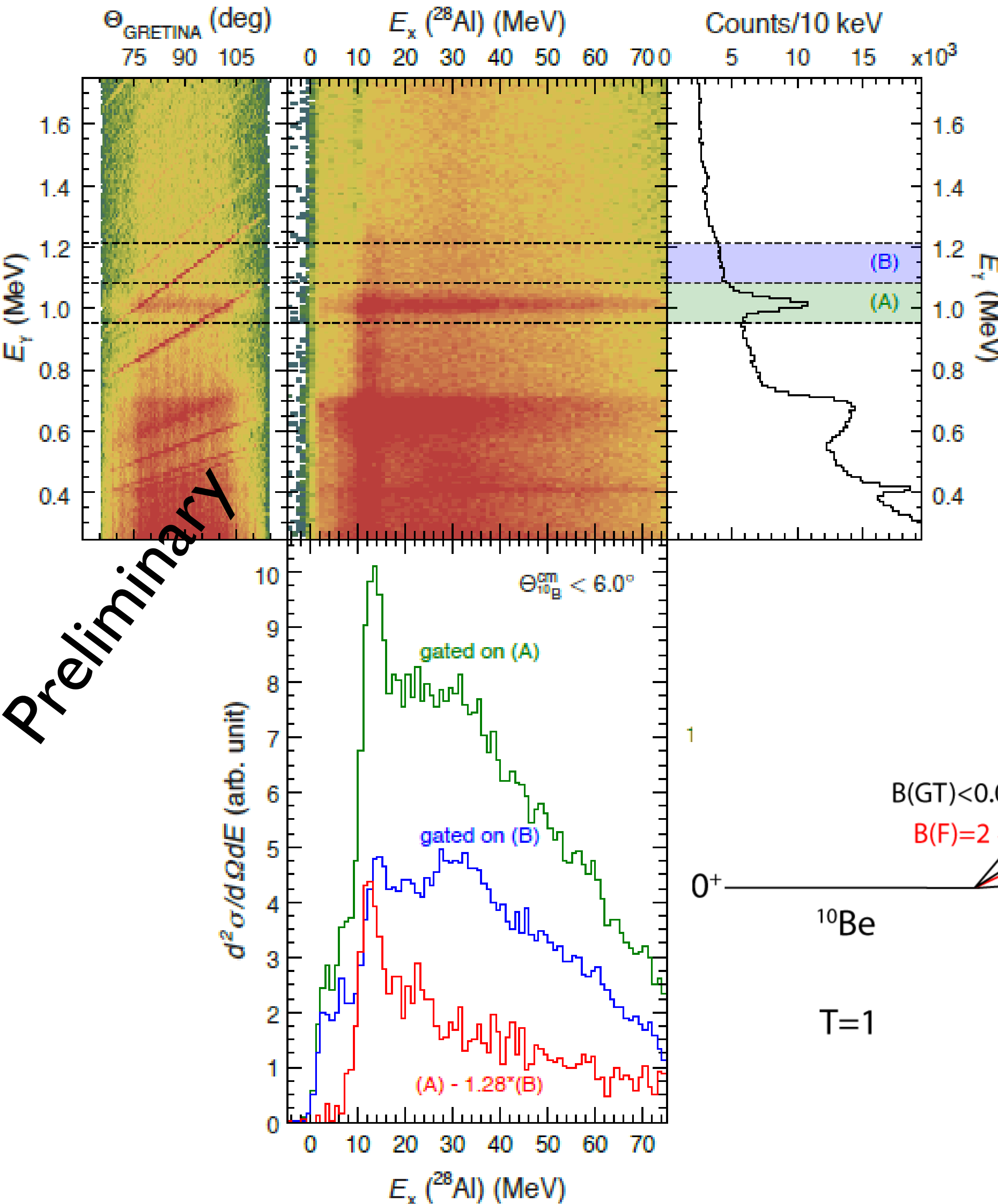
$^{10}Be, ^{10}B+\gamma$ reaction

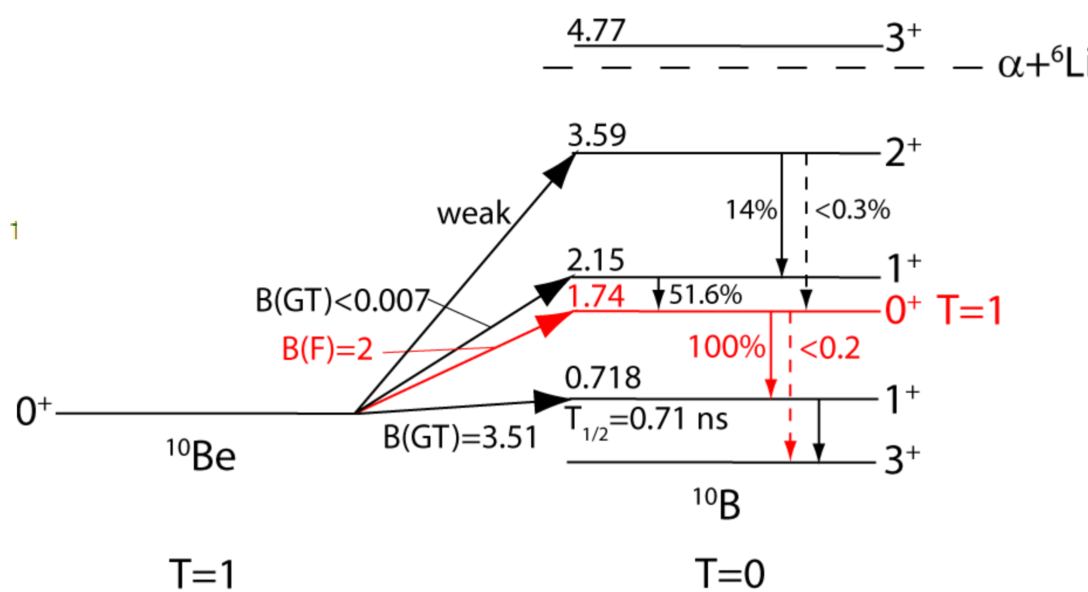


By gating on the 1.74→0.718 MeV transition after the ^{10}Be, ^{10}B reaction, one can isolate **non spin transfer reactions**

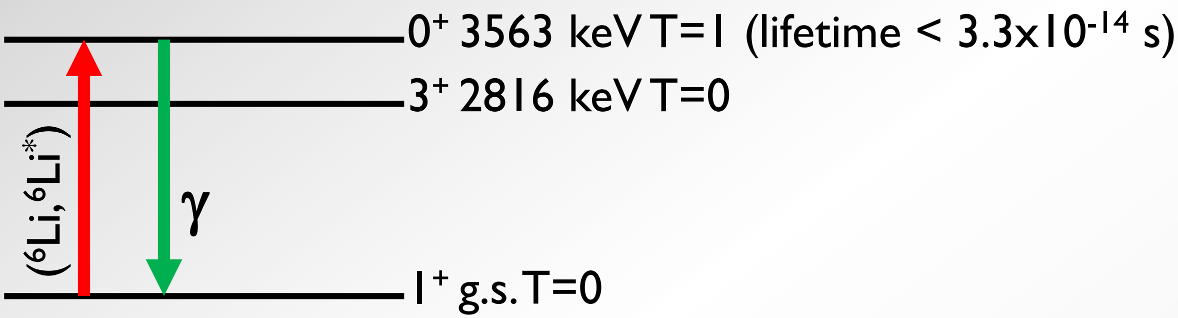
$^{28}Si(^{10}Be,^{10}B+\gamma)$ reaction

- S800+Gretina
- Goal was to measure the IVGMR
- Experiment ran in June 2013





(^{6}Li,^{6}Li*+γ) reaction



Alternative to p,p' reaction but with the additional advantage that only isovector amplitudes contribute, instead of isovector and isoscalar amplitudes. In addition, one would avoid orbital contributions.

Application would not only be limited the $\Delta L=0$ strengths, but also focus on $\Delta L=1$ strengths which is important for neutral-current neutrino interactions in astrophysical scenario

Preliminary plans for experiments at RCNP using Grand-Raiden+Clover Array

See e.g. Austin et al., NPA 719, 233c (2003)

Thanks!

The NSCL Charge-Exchange Club*

Graduate students
Jared Doster
Sam Lipschutz
Amanda Prinke
Michael Scott
Chris Sullivan
LeShawna Valdez
Rhiannon Meharchand
Jenna Deaven
Carol Guess
Wes Hitt
Meredith Howard

Postdocs
Shumpei Noji

Masaki Sasano
George Perdikakis
Arthur Cole
Cedric Simenel
Yoshihiro Shimbara

Other group members
Sam Austin
Daniel Bazin

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**Current members in italics*