Estimating electron-capture rates for nuclear astrophysics with charge-exchange reactions

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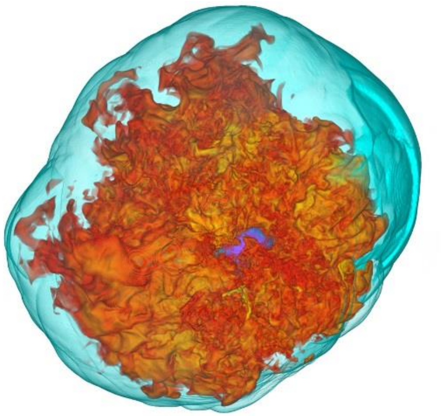
Outline

- Electron captures on nuclei for astrophysics
  - Improvement of weak-rate library
- (t,^{3}He) charge-exchange reactions to constrain Gamow-Teller strength necessary for estimating astrophysical EC rates
  - (t,^{3}He+γ) reactions on ^{88}Sr, ^{93}Nb
- Improved reaction code for calculating (t,^{3}He) charge-exchange reactions
  - Testing, completing, and optimizing code
  - Benchmarking Gamow-Teller and Fermi transition in (t,^{3}He) reactions

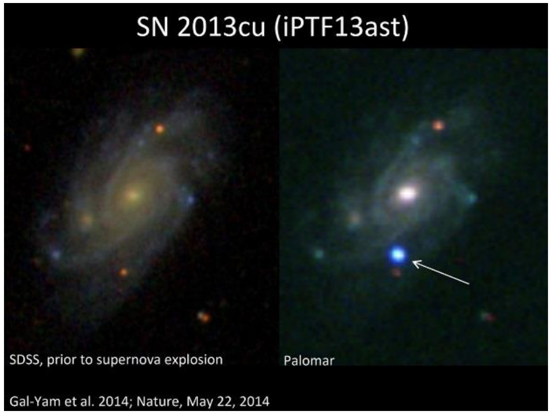
Electron captures in astrophysics

- Electron-captures on nuclei play important roles in astrophysical phenomena

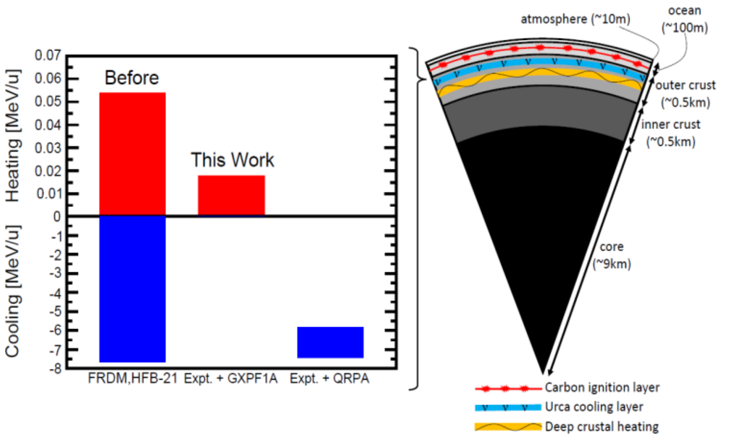
Core-collapse supernovae



Thermonuclear supernovae



Cooling & heating in accreting neutron star crusts



- Accurate electron-capture rates are vital to obtain accurate results from astrophysical simulations and to interpret observations
- Theoretical models must be used to estimate electron-capture rates. Data from charge-exchange reactions at intermediate energies benchmark, constrain, and guide the theoretical development

Electron capture rates on nuclei

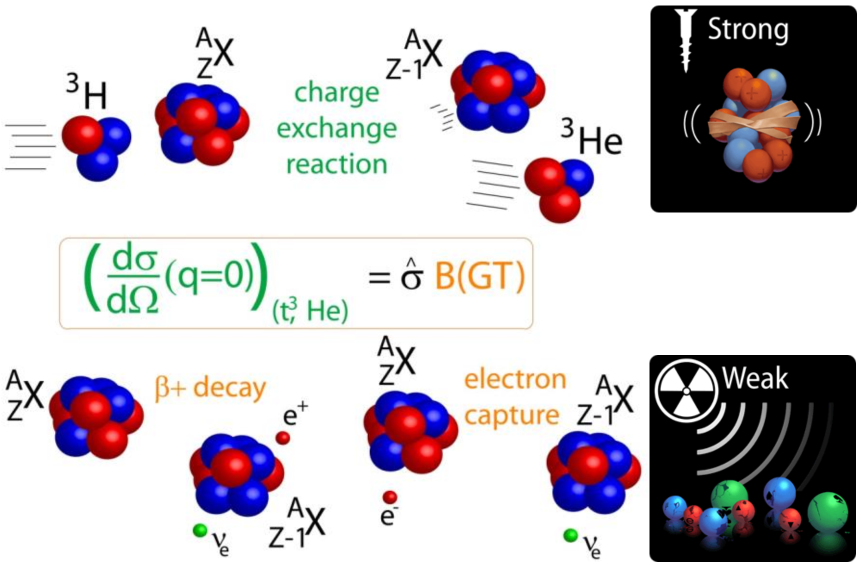
- Dominated by allowed (Gamow-Teller $\Delta L=0$, $\Delta S=1$, $\Delta T=1$) weak transitions between states in the initial and final nucleus. Each transitions is characterized by a Q-value and a strength, B(GT).

$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}$$

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

- Data from charge-exchange (CE) reactions provides information about the full GT strength distribution based on the proportionality between GT strength and CE cross section; proportionality is calibrated by using transitions for which B(GT) is known from β-decay

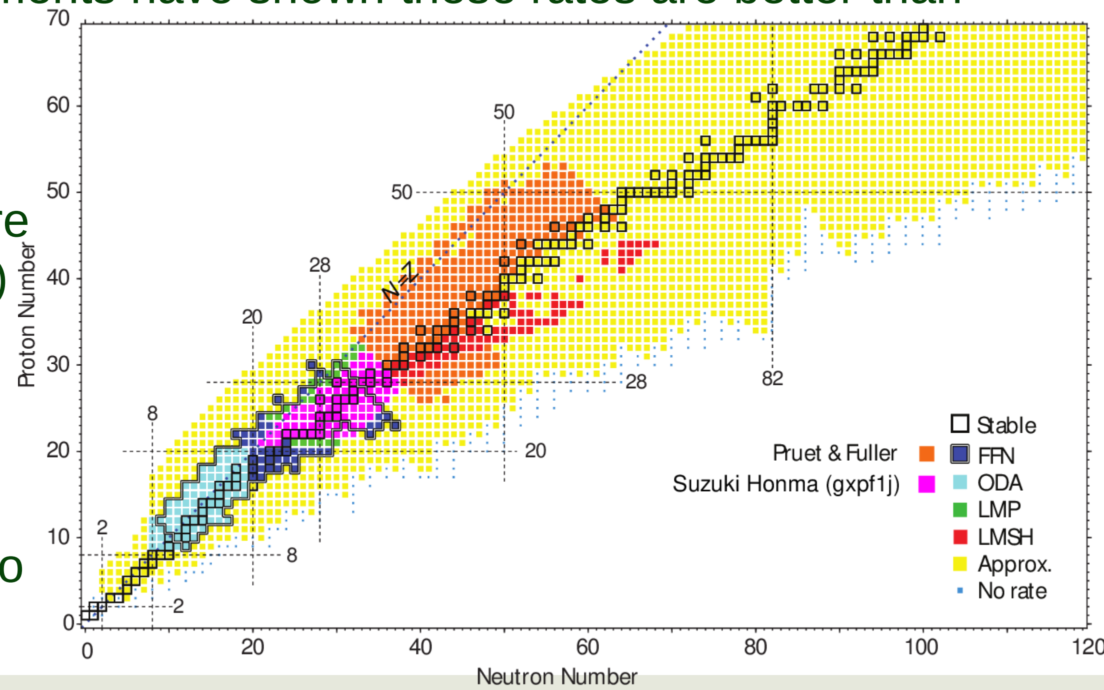
- (t,^{3}He) reaction has become an important tool for studying GT strengths



Weak rate library

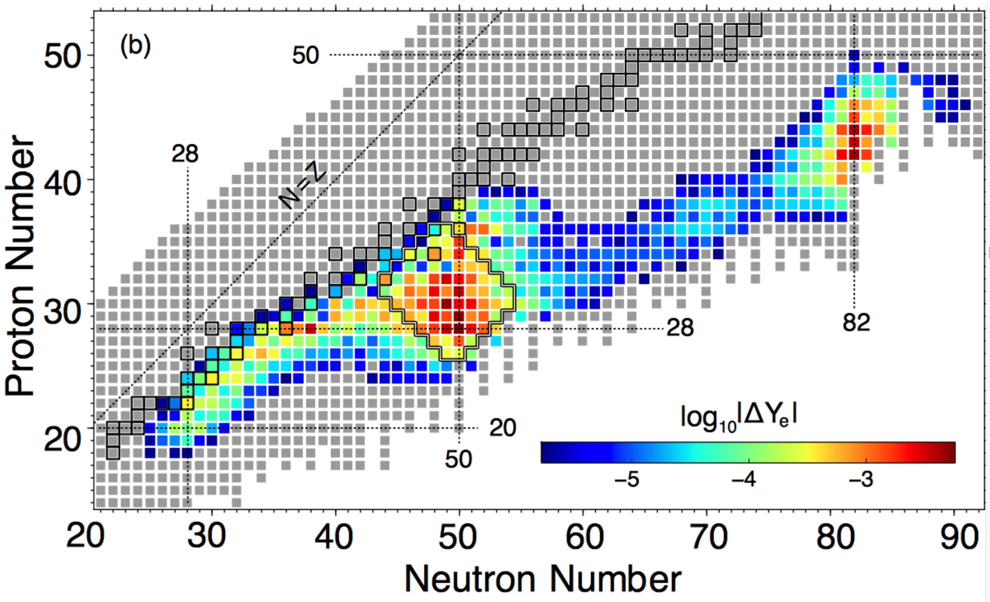
- Charge-exchange group at NSCL has created a weak-rate library which can be used in astrophysical simulations (already used in 1D, 2D, and 3D core-collapse supernovae simulations). Library integrated within NuLib library which is commonly used in astrophysical simulations (C.Sullivan, et.al. (2016) Apj 816, 44)

- Recent improvements:
  - New EC rates for pf-shell nuclei based on GXPF1J interaction (T. Suzuki, et.al. (2016). Apj 817, 163) – CE experiments have shown these rates are better than using KB3G interaction
  - Improved approximation for nuclei for which estimates based on microscopic strength information are not available (Ad. R. Raduta (2017) PRC, 95, 025805)
    - Isospin dependence
    - Even-odd staggering
    - T and ρ dependence
  - Electron-capture rate table now also available as plain text files



(t,^{3}He+γ) reactions on ^{88}Sr,^{93}Nb

- Nuclei Around N=50 contribute strongest to deleptonization of central zone in core-collapse supernovae – EC rates are poorly constrained in this region



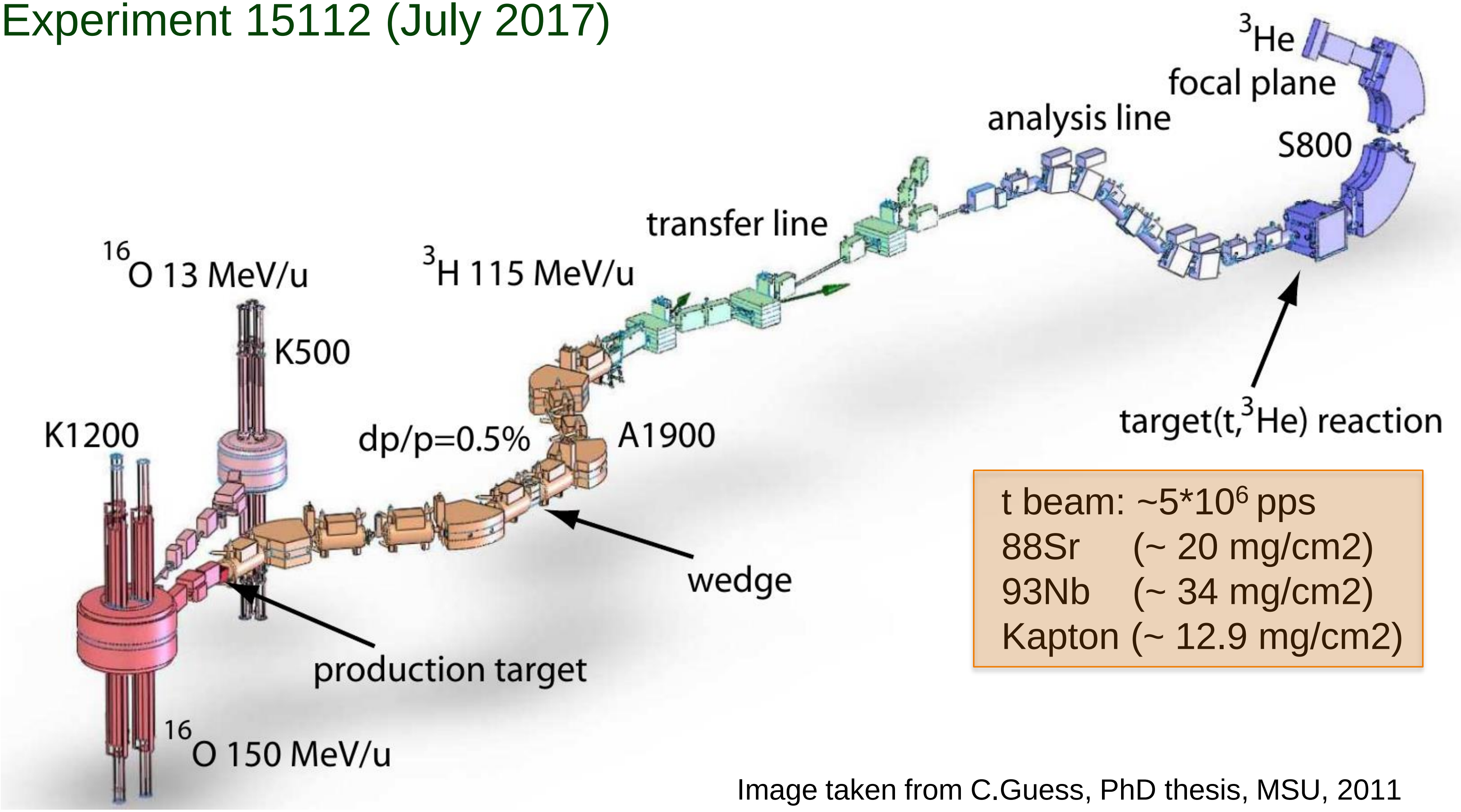
Major contributors to change in electron fraction:

- C. Sullivan et al., Ap. J., 816, 44 (2015)
- R. Titus, Bingshui Gao, et al., JPhysG to be published

- (t,^{3}He+γ) measurements on ^{88}Sr and ^{93}Nb will constrain shell-model and density-functional models

(t,^{3}He+γ) reactions on ^{88}Sr,^{93}Nb

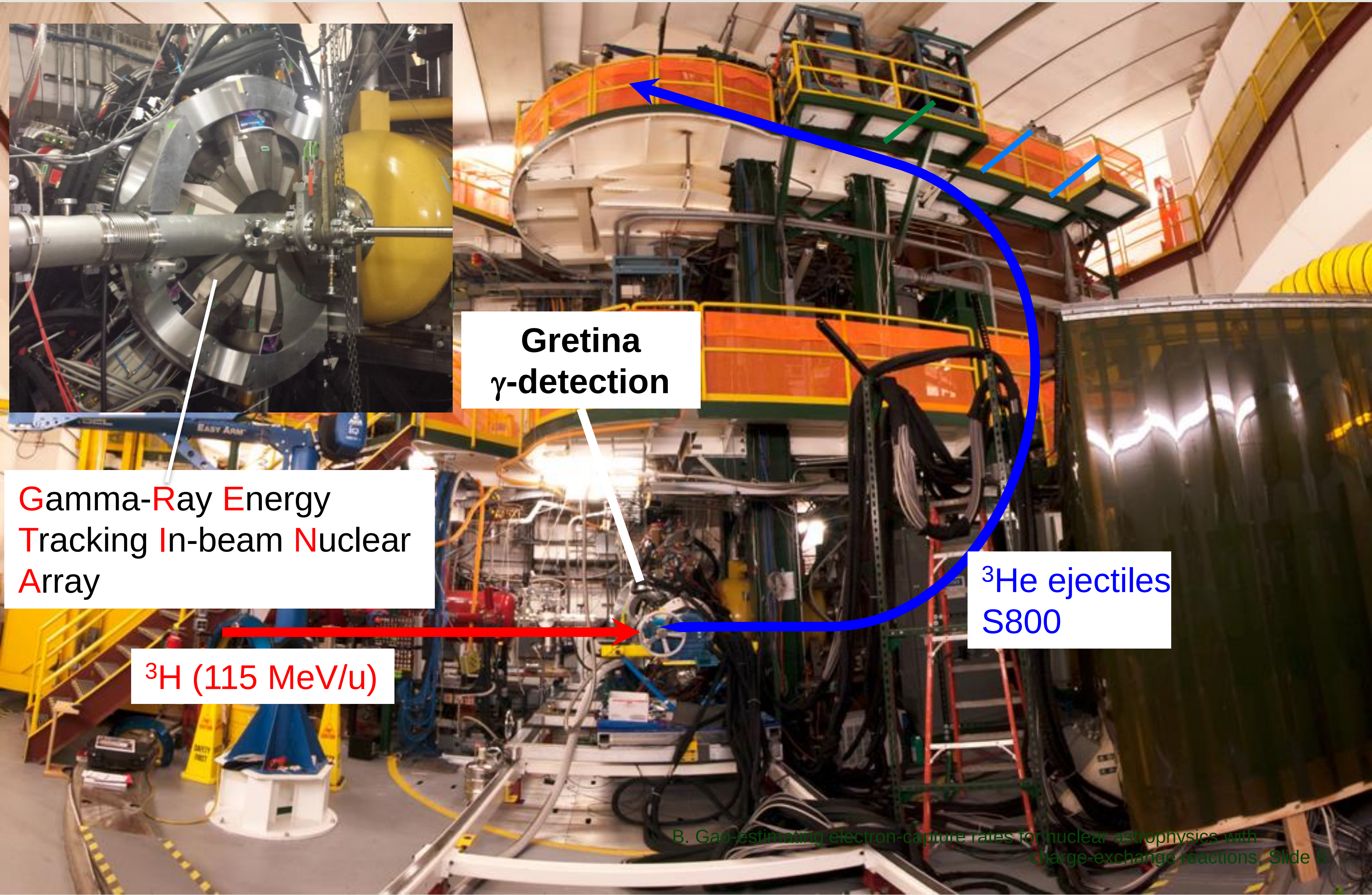
Experiment 15112 (July 2017)



t beam: ~5*10^6 pps
88Sr (~ 20 mg/cm2)
93Nb (~ 34 mg/cm2)
Kapton (~ 12.9 mg/cm2)

Image taken from C.Guess, PhD thesis, MSU, 2011

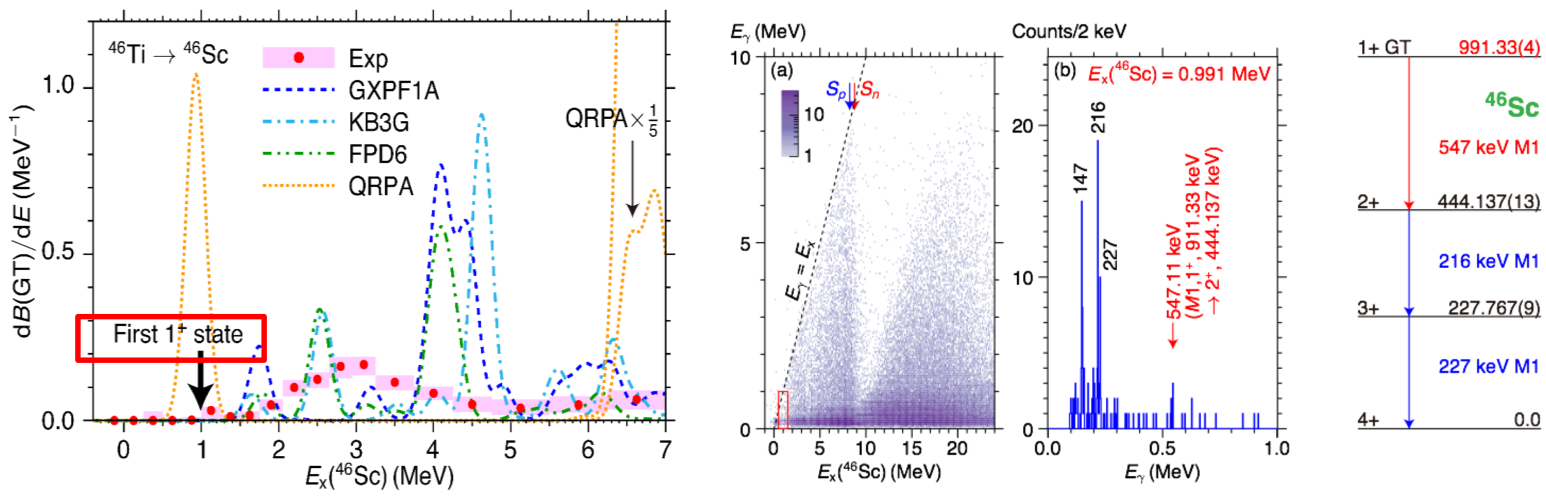
$(t,{}^{3}\mathrm{He})$ & $(t,{}^{3}\mathrm{He}+\gamma)$ S800 Spectrograph (+Gretina)



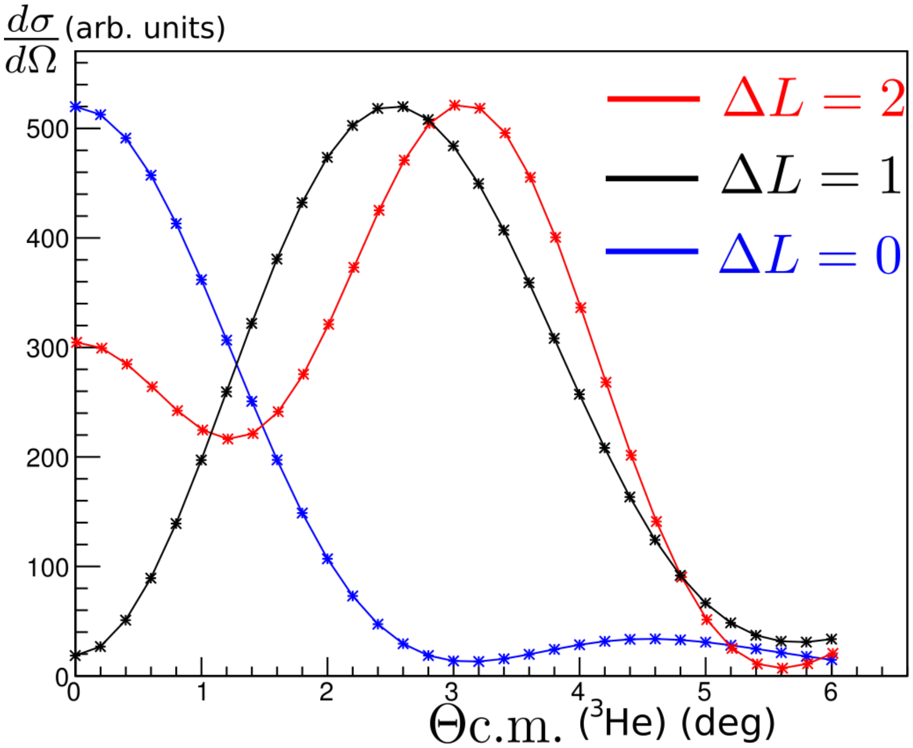
(t,^{3}He +γ) reactions on ^{88}Sr,^{93}Nb

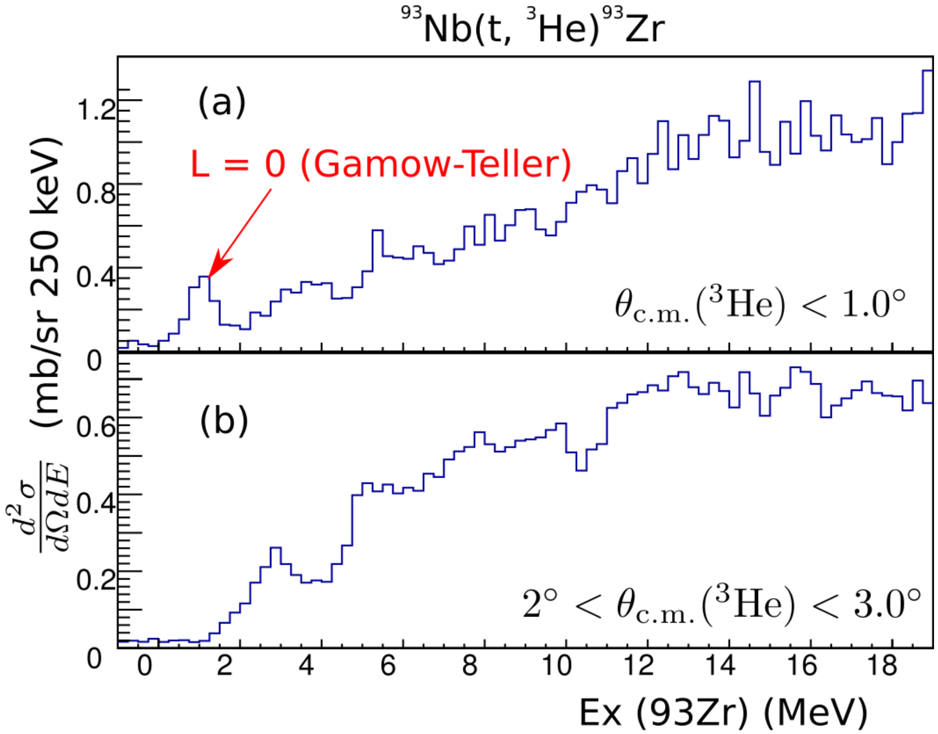
- (t,^{3}He) data provides GT strength distribution
- (t,^{3}He+γ) data provides sensitivity to very weak (B(GT)~0.01) low-lying GT transitions that can strongly impact EC rates, and that are difficult to extract from the (t,^{3}He) singles data

Example: ^{46}Ti(t,^{3}He+γ) - weak low-lying GT transition is observed in γ-coincident data:
$B(GT)_{0.991}=0.009 \pm 0.005(exp) \pm 0.003$ (sys)
S. Noji et al., Phys. Rev. C 92, 024312 (2015), Phys. Rev. Lett. 112, 252501 (2014)



(t,^{3}He +γ) reactions on ^{88}Sr,^{93}Nb





More detailed analysis on going…

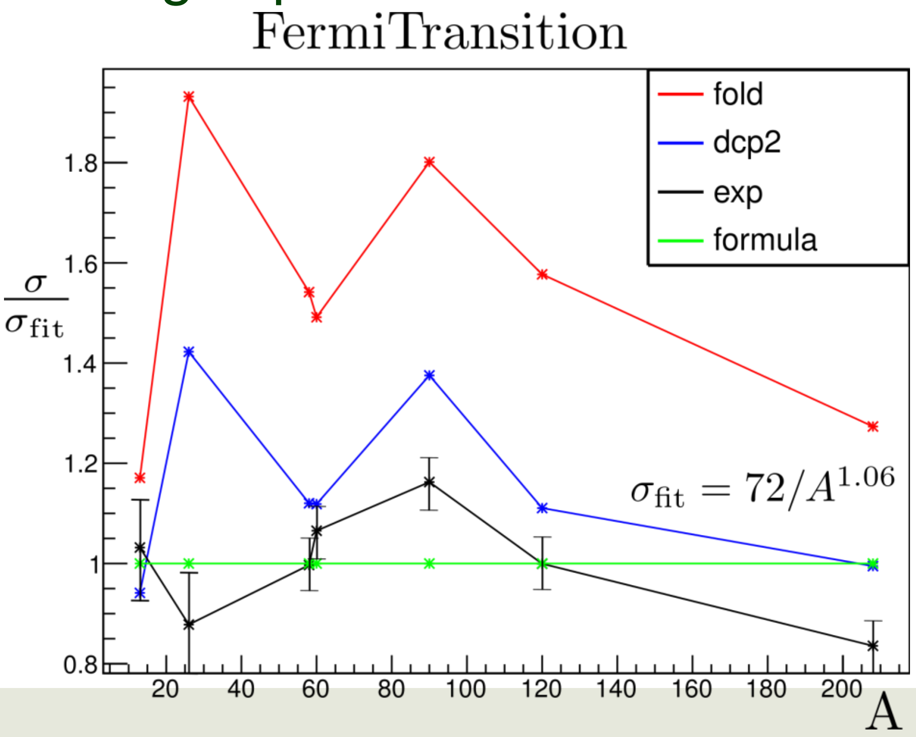
Antisymmetric Distorted Wave Impulse Approximation for Composite Particle Scattering

- Distorted-Wave Born Approximation is used for calculation of (t,^{3}He) cross sections e.g. used in multi-pole decomposition analysis for extracting GT strengths
- Presently used DWBA codes overestimate experimental cross sections, which makes it difficult to extract strength from excitations other than Gamow-Teller and Fermi type, such as first forbidden (dipole) transitions, which are important for astro and neutrino physics
- Presently used DWBA codes use short-range approximation for treatment of exchange contributions to cross section – known to lead to overestimations of cross sections
- DCP2 code addresses this: exact treatment of exchange contributions
  - DCP: T. Udagawa, A. Schulte and F. Osterfeld NPA 474, 131 (1987)
  - Updated: B. T. Kim, D. P. Knobles, S. A. Stotts, and T. Udagawa, PRC 61, 044611 (2000).
  - DCP2: by B. T. Kim et al.,
- NSCL CE group tests, completes, and optimizes code

DCP2: status

- Code operates in configuration space – convergence of calculations was identified as problematic: fixed
- Various fixes applied to ensure proper treatment of microscopic structure input
- Code is ready for first use: benchmarking in process…

(^{3}He,t) reactions @ 140 MeV:



Summary

- The weak-rate library has been improved.
  - New rate in pf shell using gxpf1j interaction;
  - Improved approximation method.
- (t,^{3}He+γ) reactions on ^{88}Sr,^{93}Nb has been carried out.
  - Constrain the EC rates in the N~50 region.
  - GRETINA+S800 proved very powerful for extracting (weak) GT strength
- A new DWBA code for charge-exchange reactions was developed.
  - Exact treatment of exchange contributions
  - Ready for first use.

This work was supported by the US NSF grant PHY-1430152 (Joint Institute for Nuclear Astrophysics – Center for the Evolution of Elements). GRETINA was funded by the US DOE Office of Science. Operation of the array at NSCL is supported by NSF under Cooperative Agreement PHY-1565546 (NSCL) and DOE under grant DE-AC02-05CH11231 (LBNL) – B.Gao is supported by the FRIB-CSC fellowship program.

Acknowledgements

- Thanks for all the kind help from the NSCL charge-exchange group: R. Zegers, J. Pereira, D. Bazin, S.Noji, J.C.Zamora, R.Titus, J.Schmitt, C.Sullivan, S.Lipschutz and S.Austin
- Thank all the collaborators in the NSCL E15112 experiment.
- Thank the organizers and everyone for your attention.

Thank you!

Direct and Exchange Contributions