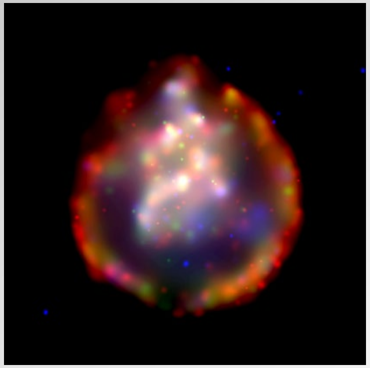

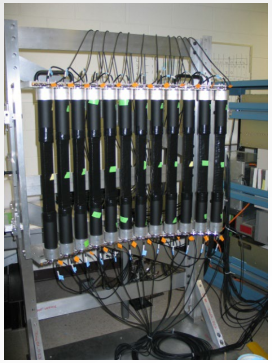

Charge-Exchange Reactions with Triton Beams

Remco G.T. Zegers

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MICHIGAN STATE UNIVERSITY

NSCL FRIB JINA-CEE GRETINA NSF U.S. DEPARTMENT OF ENERGY Office of Science

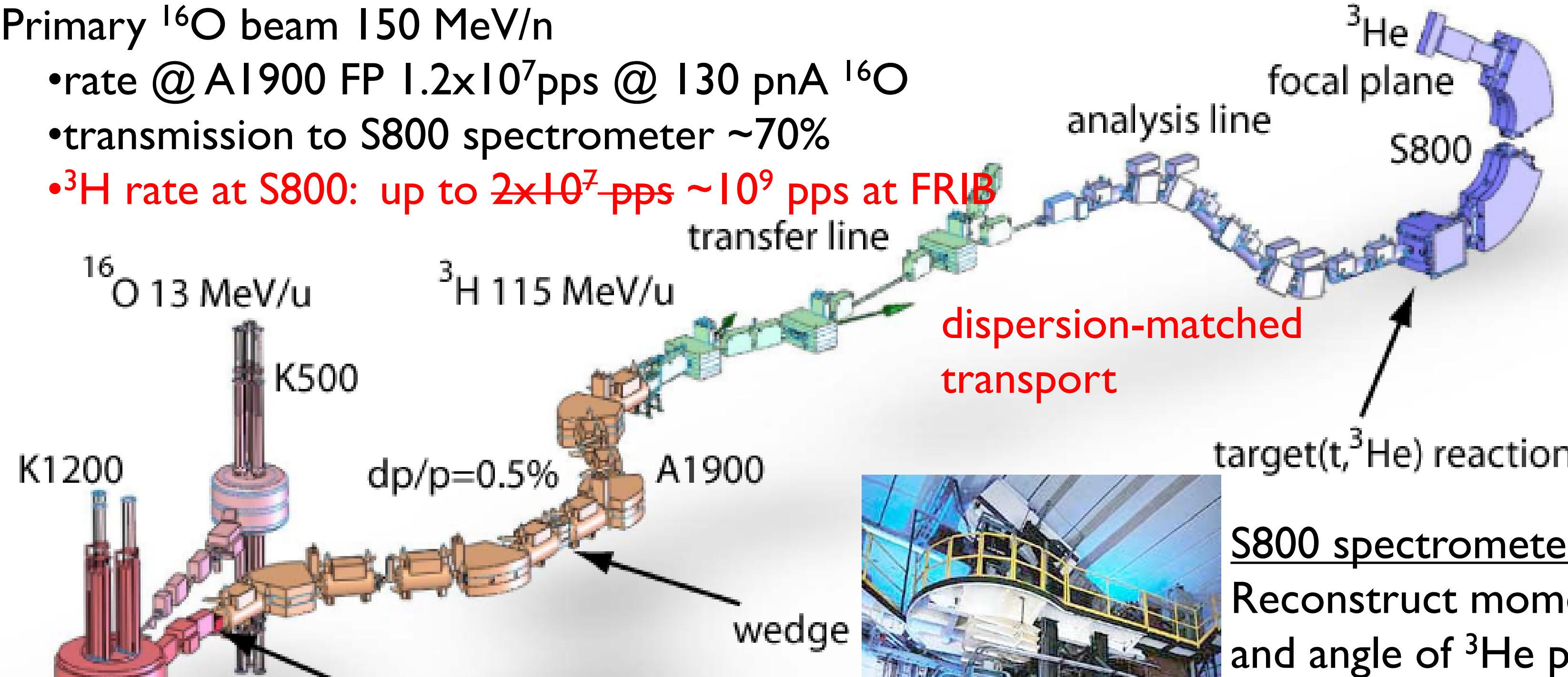
Outline

- $(t,^3He)$ experiments at ~115 MeV/u using a secondary triton beam
- Isovector response and the extraction of weak interaction strengths
- Properties of the NN interaction and the description of the $(t,^3He)$ reaction as a function of beam energy
- Opportunities for $(t,^3He)$ experiments at low beam energies

Producing a triton beam for $(t,{}^3He)$ experiments

Primary ^{16}O beam 150 MeV/n

- rate @ A1900 FP 1.2×10^7 pps @ 130 pnA ^{16}O
- transmission to S800 spectrometer ~70%
- ^3H rate at S800: up to ~~2×10^7 pps~~ ~10^9 pps at FRIB



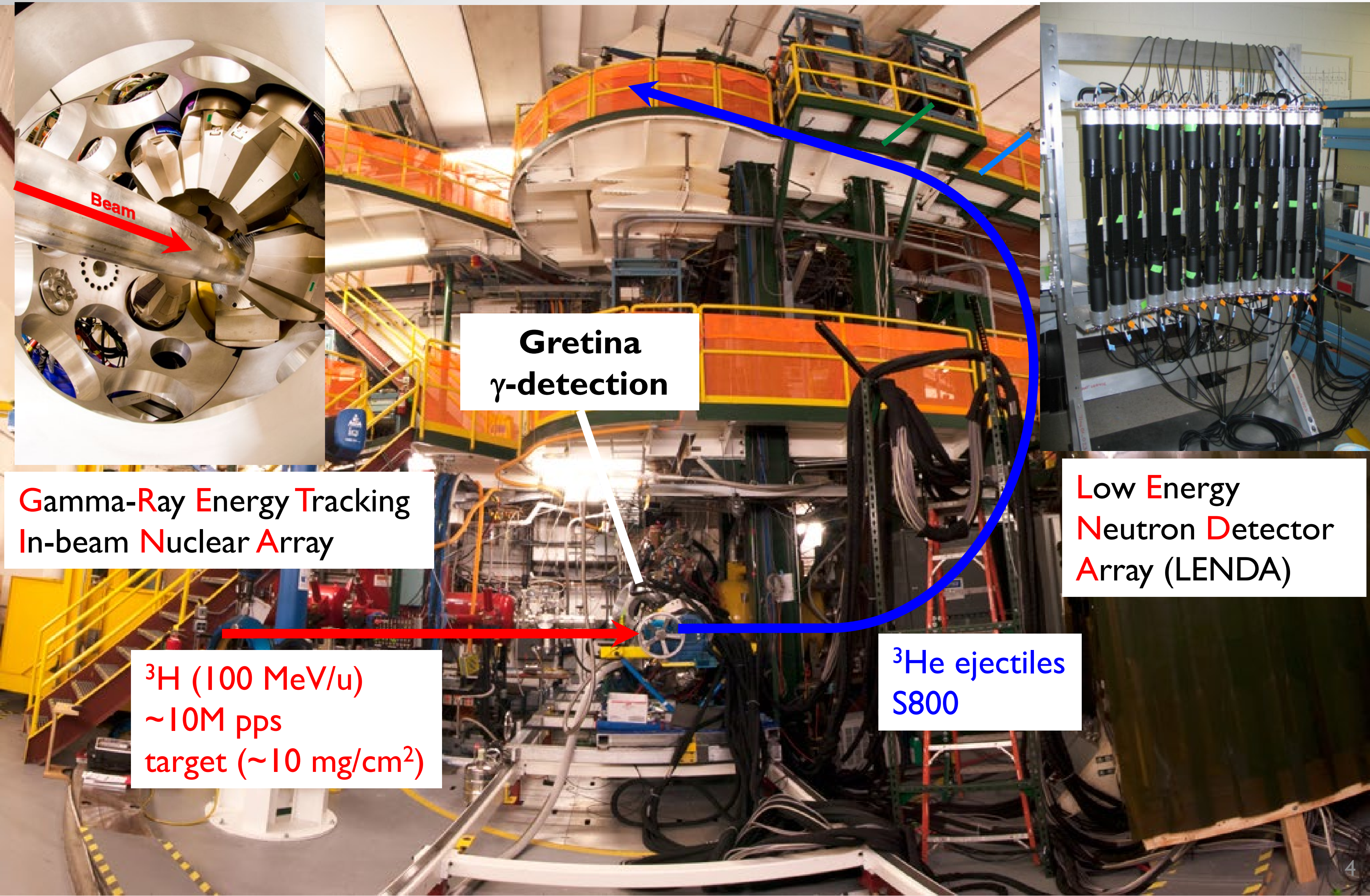
<u>S800 spectrometer</u>
Reconstruct momentum and angle of ^3He particle
→Extract excitation-energy and center-of-mass scattering angle from two-body kinematics

Thin wedge is needed to remove ^6He (^9Li)
Background channel $^6He \to {}^3He + 3n$

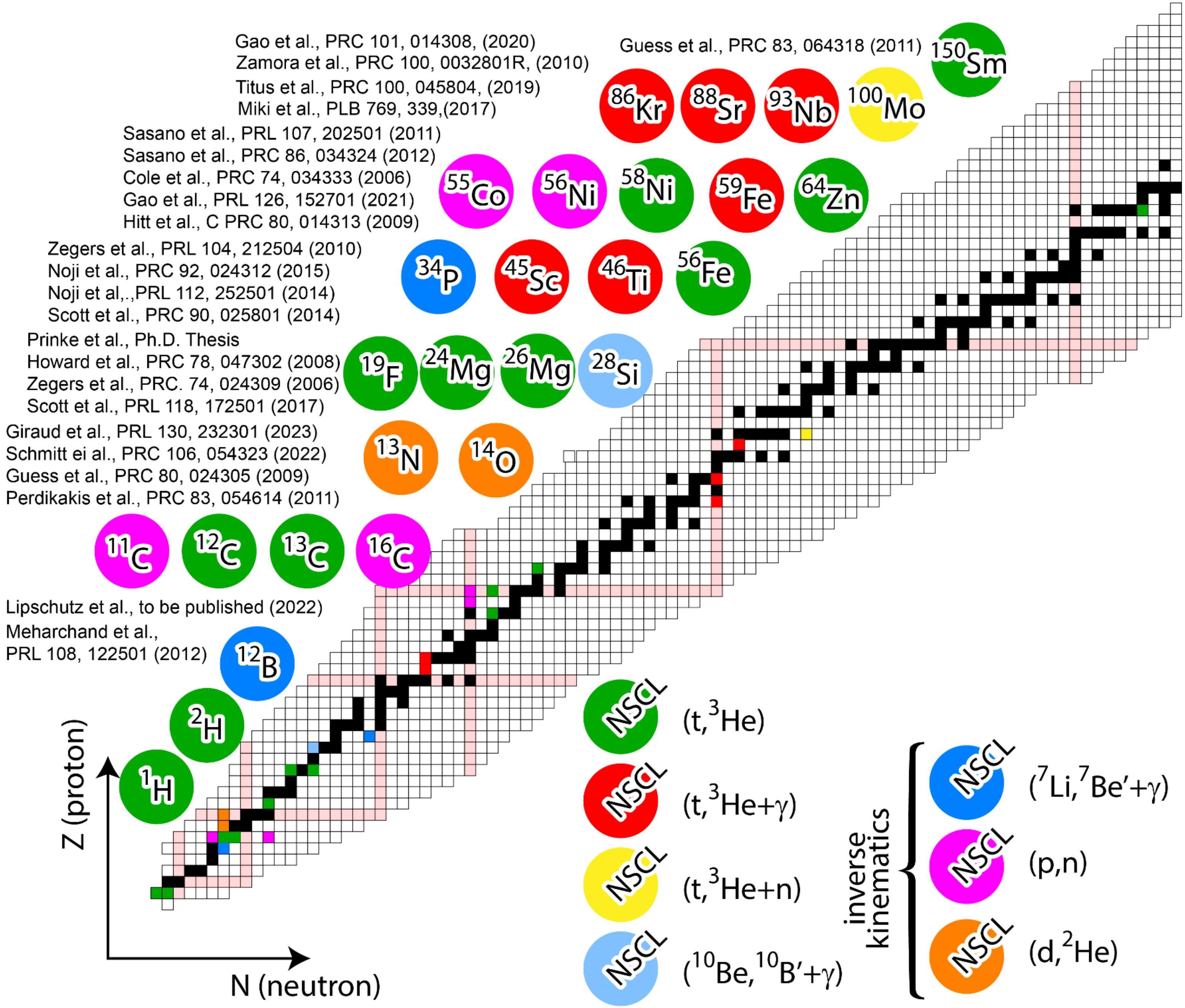
Efforts at RIKEN: Miki et al., PRL 108, 262503 (2012)
^3H rate ~10^7 pps at 300 MeV/u

G.W. Hitt Nucl. Instr. and Meth. A 566 (2006), 264.

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



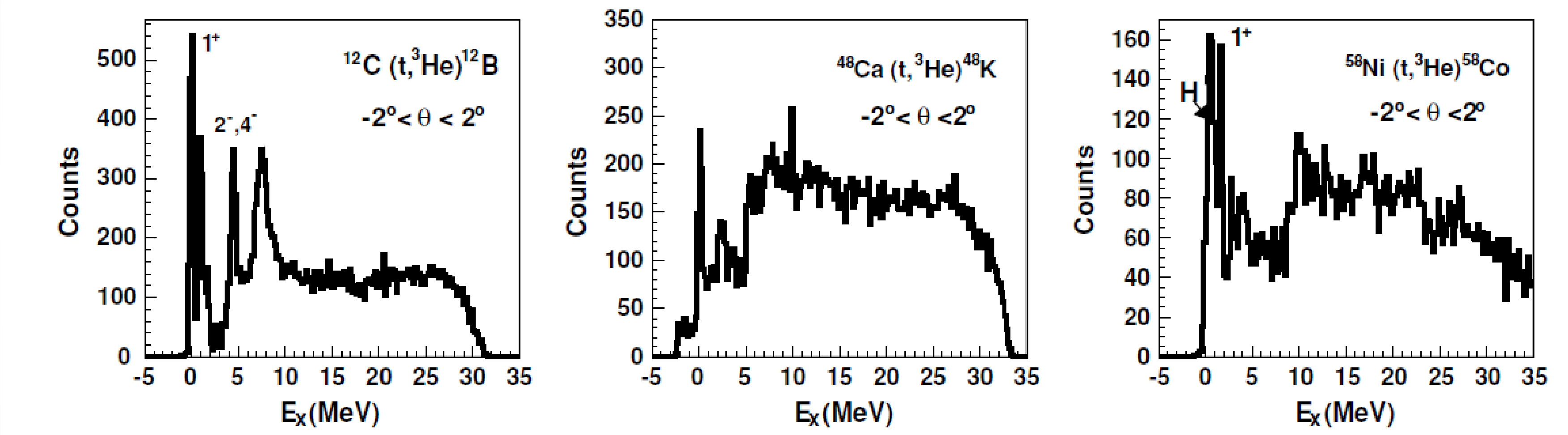
Charge-exchange reactions with unstable beams at NSCL



(t,^{3}He) at 43 MeV/u with a primary triton beam

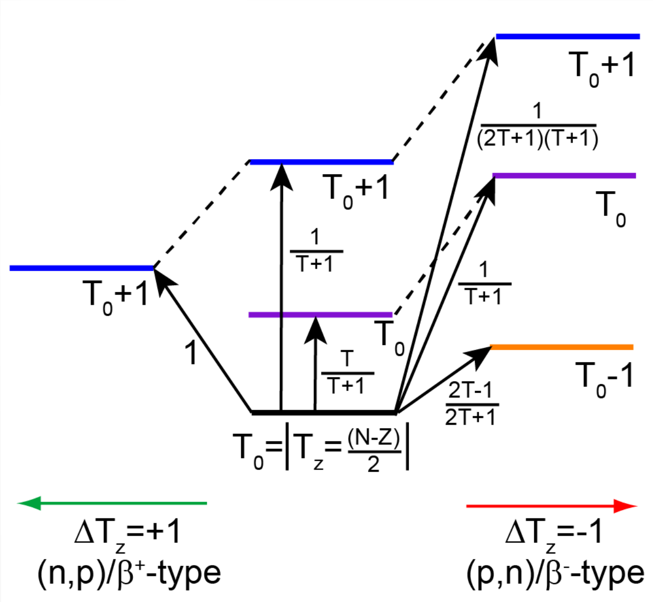
- AGOR Cyclotron at KVI
- Tritons extracted from deuterium gas (tritons~22 ppm)
- Tuning of beam lines with $^3He^{1+}$ ions
- Tritium beam intensity of 4×10^7 pps
- ^{3}He detected in Big Bite Spectrometer with resolution: 350 keV (comparable to resolution at NSCL with secondary beam)

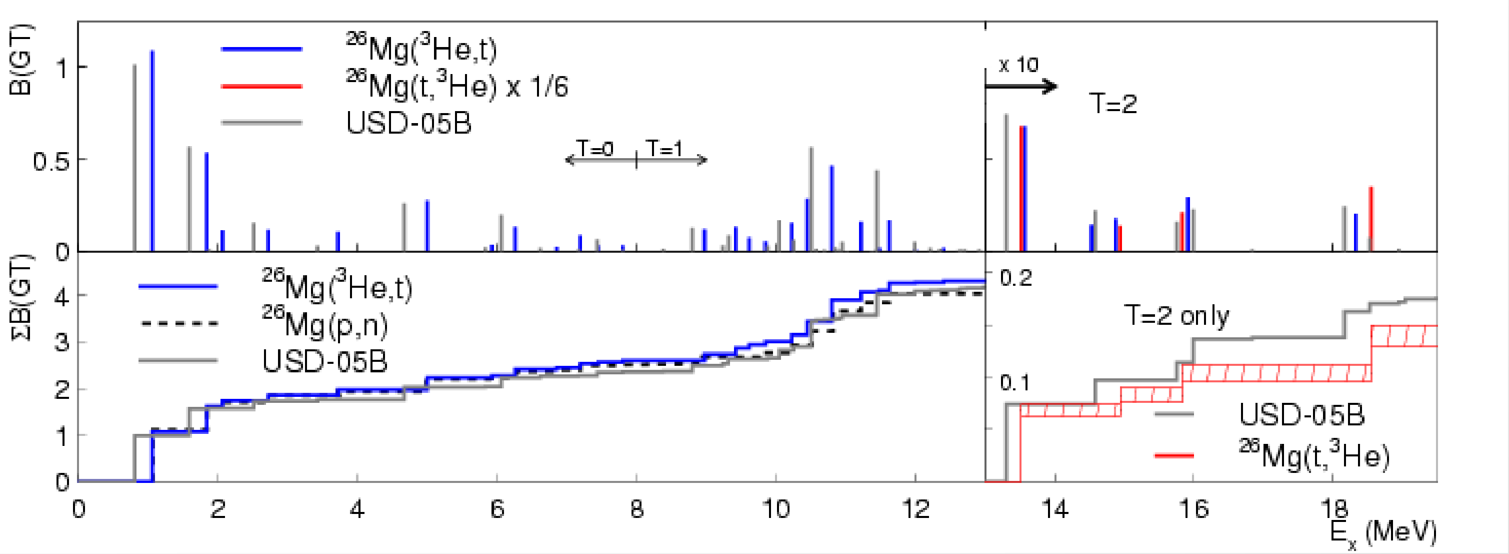
J. Guilliot et al., Phys. Rev. C **73**, 014616



The isovector response of nuclei

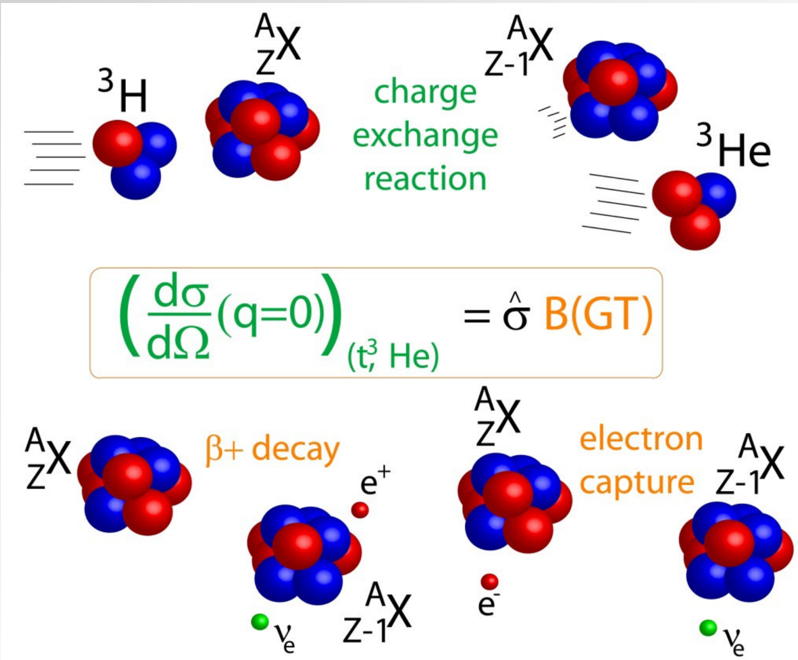
- Since the (t,^{3}He) reaction requires ΔT_z=+1, ΔT=1
- Reaction populates states with T_o+1 (T_o isospin of target)
- Populated states have analogs in the ΔT_z= 0 and -1 direction, but difficult to disentangle

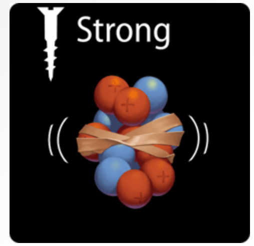


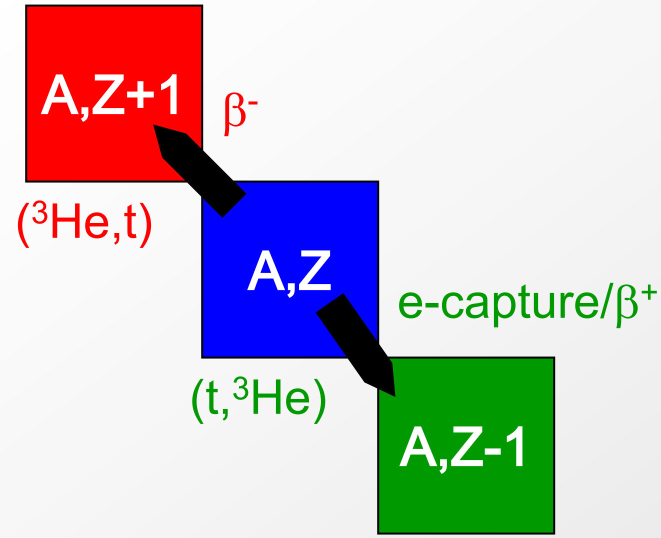


RZ et al.,
Phys. Rev. C **74**, 024309

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

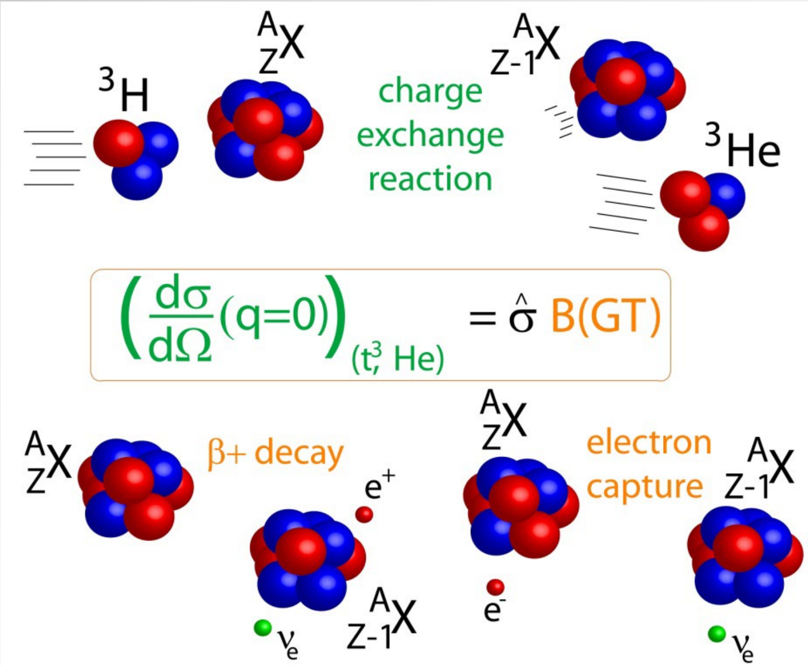




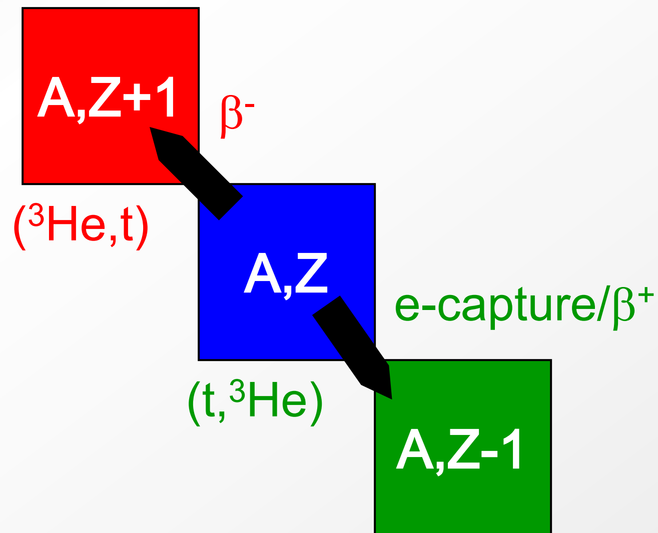


- Charge-exchange reactions connect the same initial and final states as in weak interactions and are mediated through similar spin and isospin transfer operators
- Proportionality holds at ~10% level – beam energies must be ~100 MeV/A or above
- Applied to a variety of CE probes: (p,n)/(n,p), (^{3}He,t)/(t,^{3}He),(d,^{2}He),(^{7}Li,^{7}Be) etc.
- $\hat{\sigma}$ is calibrated with a transition for which B(GT) is know from β decay half-life measurement

Gamow-Teller strengths and CE cross sections



Model-independent extraction of GT strengths

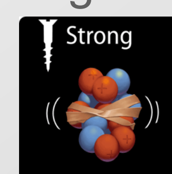


$$B(GT_{+}) = \sum_{i,f} \frac{n_i^p n_f^h}{(2j_i+1)(2j_f+1)} \boxed{\left|\left\langle f \middle| \vec{\sigma}\tau_{+} \middle| i \right\rangle\right|^2}$$

β-decay

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

charge-exchange

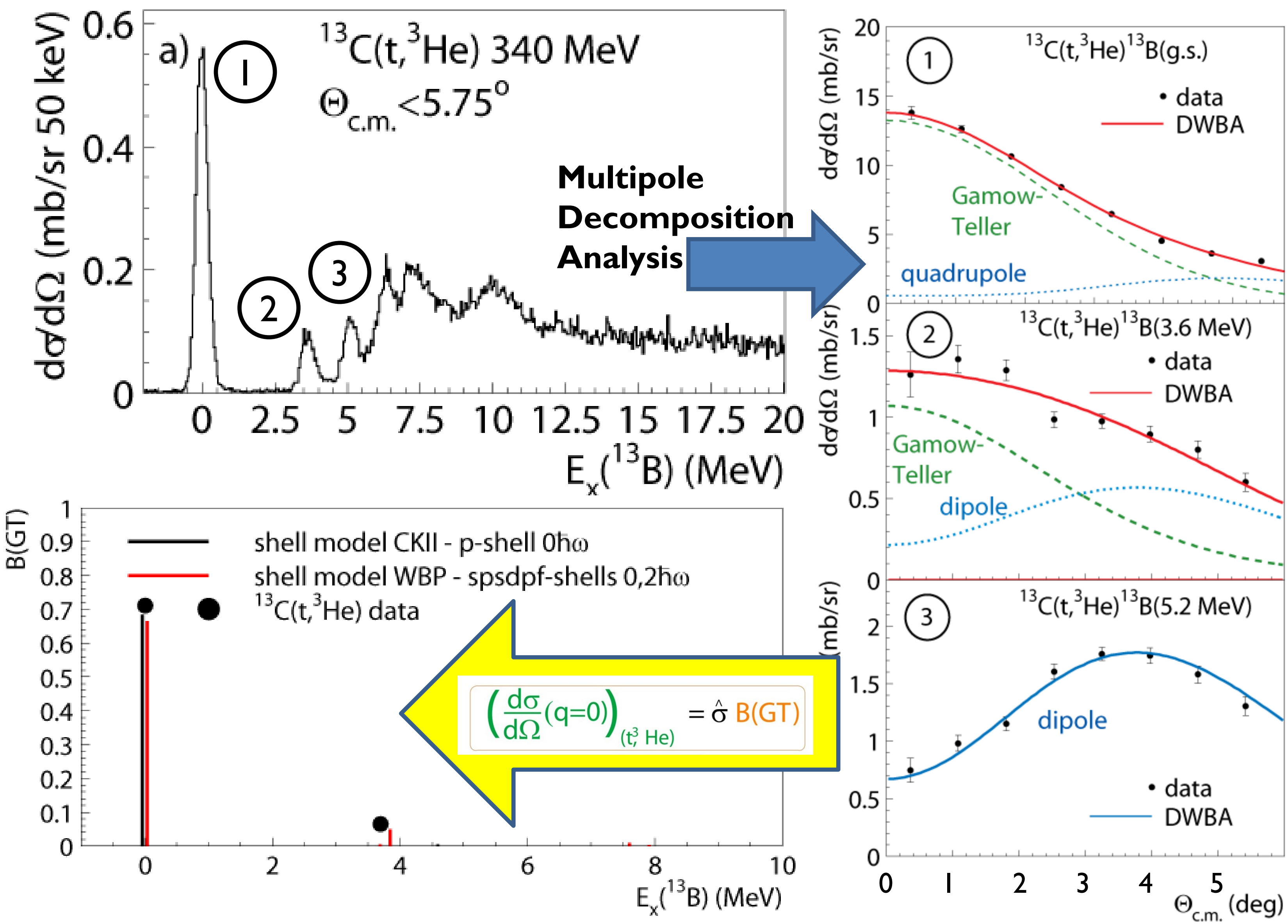


$\hat{\sigma}$ **: unit cross section**

Taddeucci et al. NPA 469, 125 (1987)

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

Extraction of GT strength



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

Extraction of Gamow-Teller strengths

Proportionality between strength and cross section requires that the differential cross section at small momentum transfers ($q \approx 0$) can be factorized in simple terms:

$$\sigma(q \approx 0) = K\, |J_{\sigma\tau}|^2\, N\, F(q,E_x)\, B(GT)$$

K: kinematic factor

$J_{\sigma\tau}$: Amplitude of the $\sigma\tau$ component of the NN interaction

N: Distortion factor (Eikonal treatment of distortion of incoming and outgoing waves

$F(q,E_x)$: correction of dependence of σ on q and E_x

B(GT): Gamow-Teller Strength

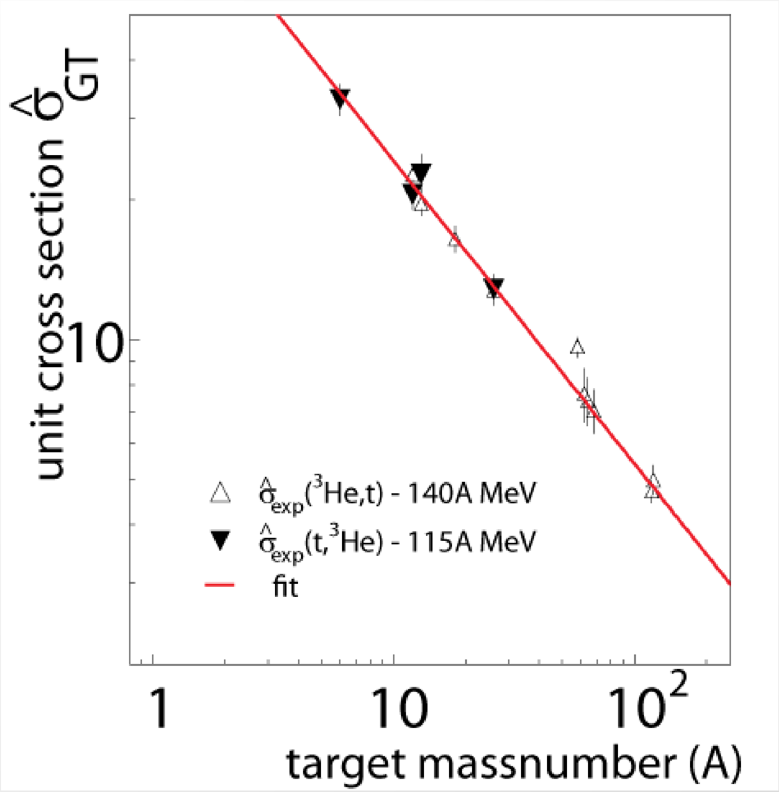
The (p,n) reaction as a probe of beta decay strength, T.N. Taddeucci et al., Nucl. Phys. A469, (1987)

Gamow-Teller Unit cross section for (^{3}He,t) and ($t,^3$He) at 115-140 MeV/u

The unit cross section has a simple dependence on mass number for A=6 and above.

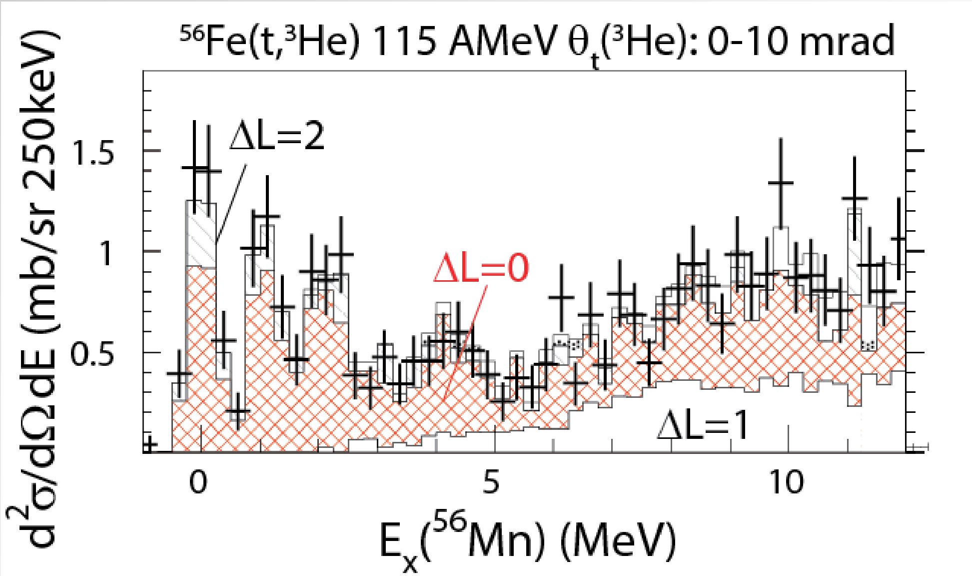
$$\left(\frac{d\sigma}{d\Omega}\right)_{q=0} = \hat{\sigma} B(GT)$$

Empirical determination allows for the extraction of GT strength even if no calibration from β/EC is available for a specific nucleus



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

$^{56}Fe(t,^{3}He)$



Result from multipole decompositions analysis

Experiment

$^{56}Fe(t,^{3}He)$ - M. Scott et al., PRC 90, 025801 (2014)

$^{56}Fe(n,p)$ - S. El-Kateb et al., PRC 49, 3128 (1994)

Theory – Shell model

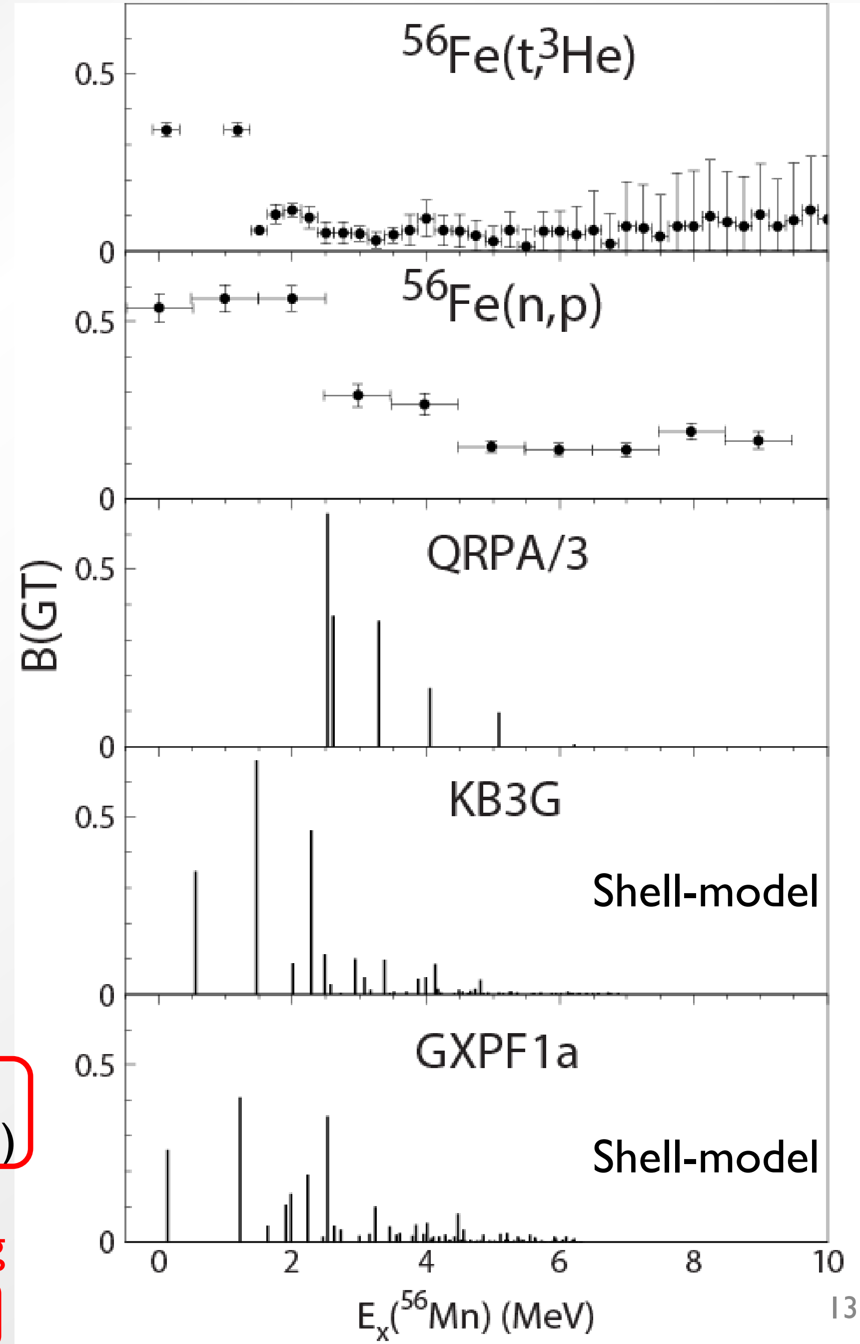
KB3G - A. Poves et al., NPA694, 157 (2001)

GXPF1a - M. Honma et al. PRC 65, 061301(R) (2002)

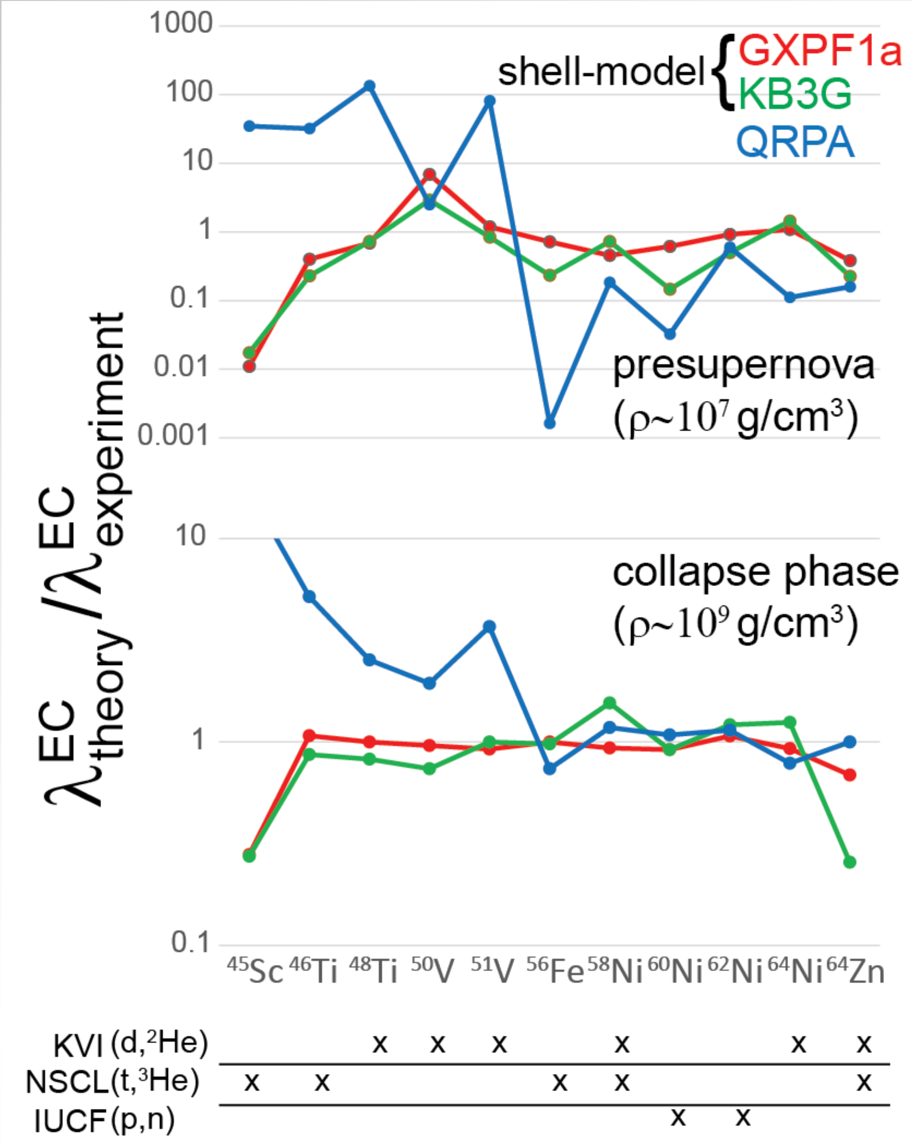
Used in astrophysical modelling

Theory – QRPA

P. Moller and J. Randrup, NPA514, 1 (1990); S. Gupta



Systematic EC rate comparisons



A.L. Cole et al., PRC 86, 015809 (2012)

Systemic comparison of EC rates calculated from theory and derived from data provide framework for error estimation of theoretical rates

($d,{}^2He$) data – KVI, the Netherlands
($t,{}^3He$) data – NSCL/MSU
(p,n) data IUCF/NSCL (isospin symmetry)

Systematic studies provide a way to benchmark and improve theoretical calculations

Experimental results from different facilities and probes are combined to perform comprehensive comparisons

Properties of the NN interaction

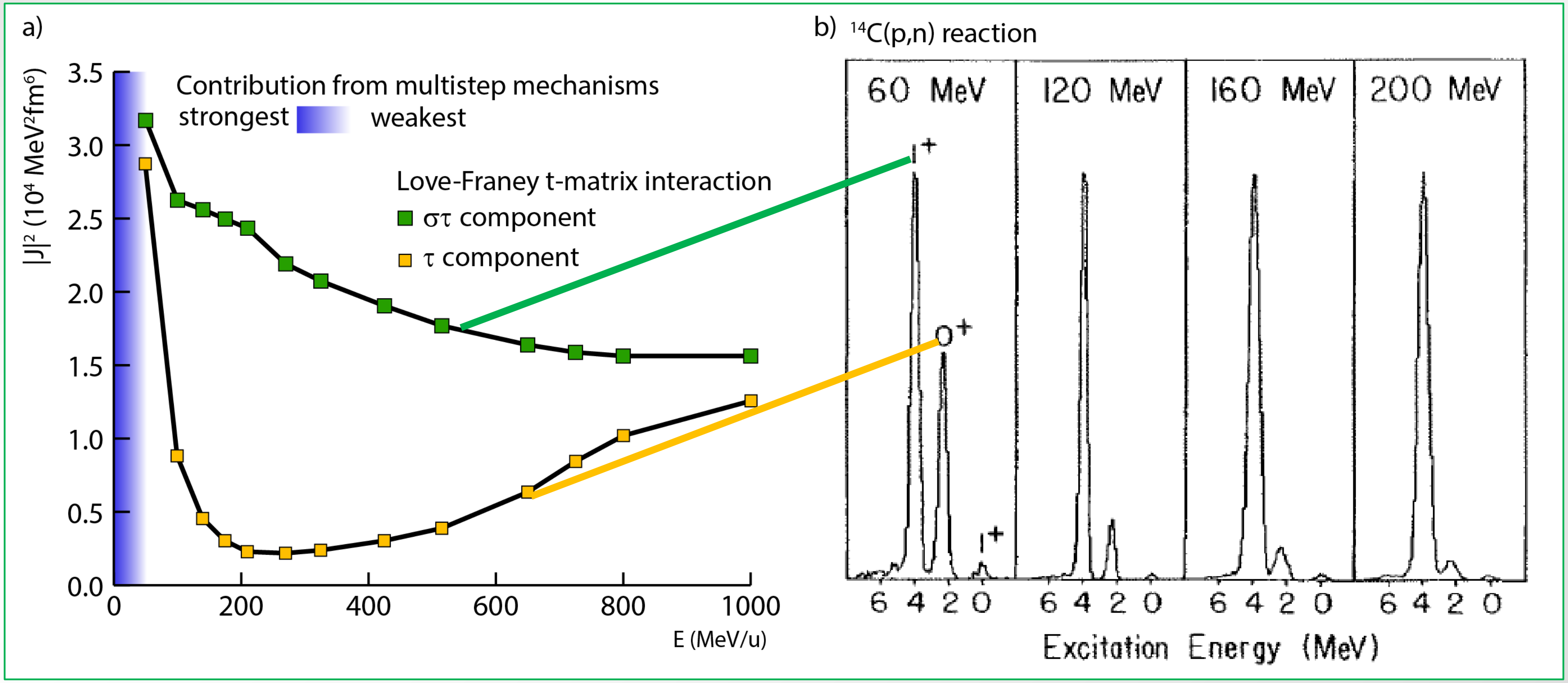
The NN interaction commonly used in DWBA/ DWIA calculations for CE (and inelastic) reactions is the Love-Franey[1,2] interaction

- Determined from NN scattering data as a function of energy
  - 50 MeV/u, 100 MeV/u, 140 MeV/u, 175 MeV/u and higher in original papers
  - 10 MeV/u, 20 MeV/u, 30 MeV/u, 40 MeV/u, 50 MeV/u: New (Horst Lenske[3])
- Easily separable in different components of the NN interaction
- Central complex terms: V_0 , $V_{\sigma\tau}$, V_τ, V_σ
- Non-central complex terms: tensor and spin-orbit terms
- Each term consists of several Yukawa potentials with different ranges representing different types of meson-exchanges
- Direct and exchange contributions are included

[1] W. G. Love and M.A. Franey, Phys. Rev. C 24, 1073 (1981)
[2] M.A. Franey and W. G. Love, Phys. Rev. C 31, 488 (1985)
[3] F. Cappuzzello, H. Lenske et al., Progress in Particle and Nuclear Physics 128, 103999 (2023); H. Lenske, priv. comm.

Above ~50 MeV/u, the response is dominated by central terms of the NN interaction

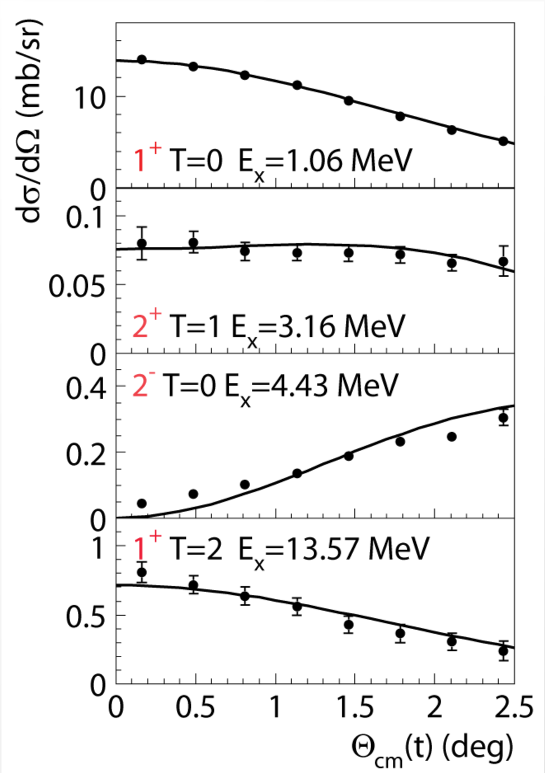
- Reaction mechanism relatively simple
- Energy dependence of excitations well-reproduced



(t,^{3}He) reactions

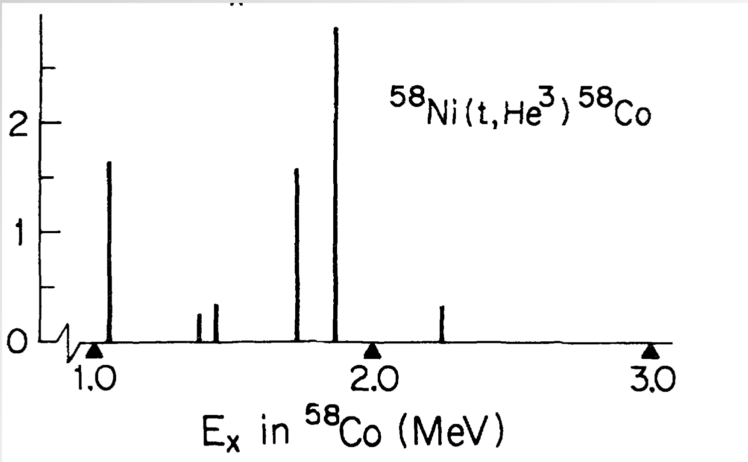
- For (t,^{3}He) (and other composite-ion CE) reactions at intermediate energies a reaction code is available: FOLD[1]
- Form factor is calculated by double-folding the Love-Franey NN interaction over the transition densities of the target-residue and projectile-ejectile systems
- ^{3}He and ^{3}H densities from Variational Monte-Carlo simulations[2]
- Microscopic inputs from shell-models, DFT, etc.
- Accurate angular distributions (at forward scattering angles), but calculated cross sections tend to be too high, due to approximate short-range treatment of exchange amplitudes that interfere with the direct amplitudes
- Alternative code is available (DCP2[3]) that treats exchange exactly, but quite difficult to use

^{26}Mg(t,^{3}He) at 115 MeV/u

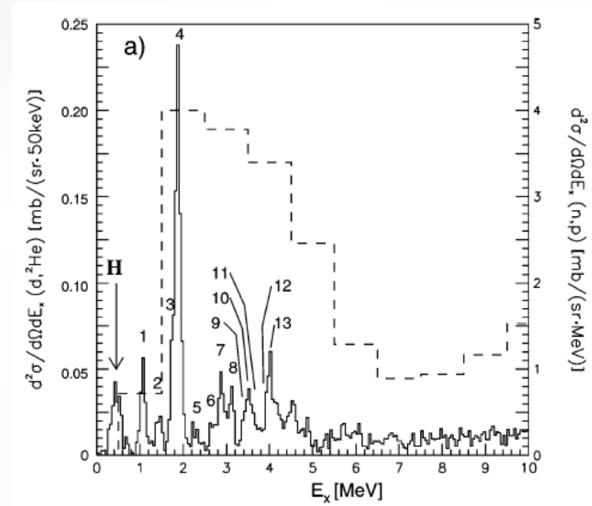


[1]J. Cook and J.A. Carr, computer program FOLD, Florida State University (unpublished), based on F. Petrovich and D. Stanley, Nucl. Phys. A 275 (1977) 487, modified as described in J. Cook *et al.* , Phys. Rev. 30 (1984) 1538 and R.G.T. Zegers, S. Fracasso and G. Colo, 2006 (unpublished).
[2] S. C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci. 51, 53 (2001), and R.B. Wiringa, private communication.
[3] T. Udagawa, A. Schulte and F. Osterfeld, Nuclear Physics, A474 (1987) 131-154, and B.T. Kim, H. Sakai, private communication

Proportionality at lower energies is broken



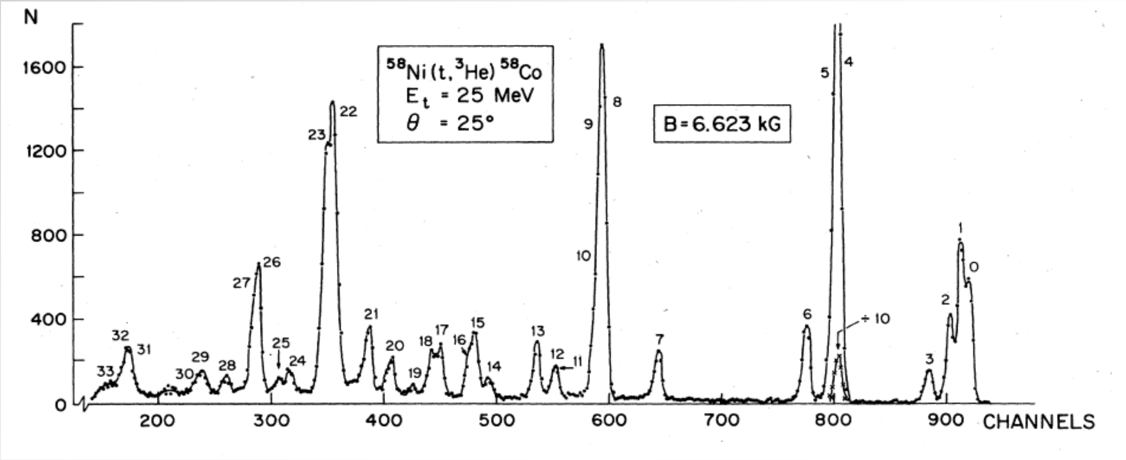
^{58}Ni(t,^{3}He) at 25 MeV
Ajzenberg-Selove et al., PRC 30, 1850 (1984)



^{58}Ni(d,^{2}He) at 170 MeV
Hagemann et al., PLB 579, 251 (2004)
(consistent with ^{58}Ni(t,^{3}He) at 345 MeV
Cole et al., PRC 74, 034333 (2006)

Ex(^{58}Co)	Strength Relative to state at 1868 KeV	
(keV)	(t,^{3}He) at 25 MeV	(d,^{2}He) at 170 MeV
1050	0.56	0.21
1435	0.08	0.13
1729	0.55	0.22
1868	**1.00**	**1.00**
2249	0.13	0.07

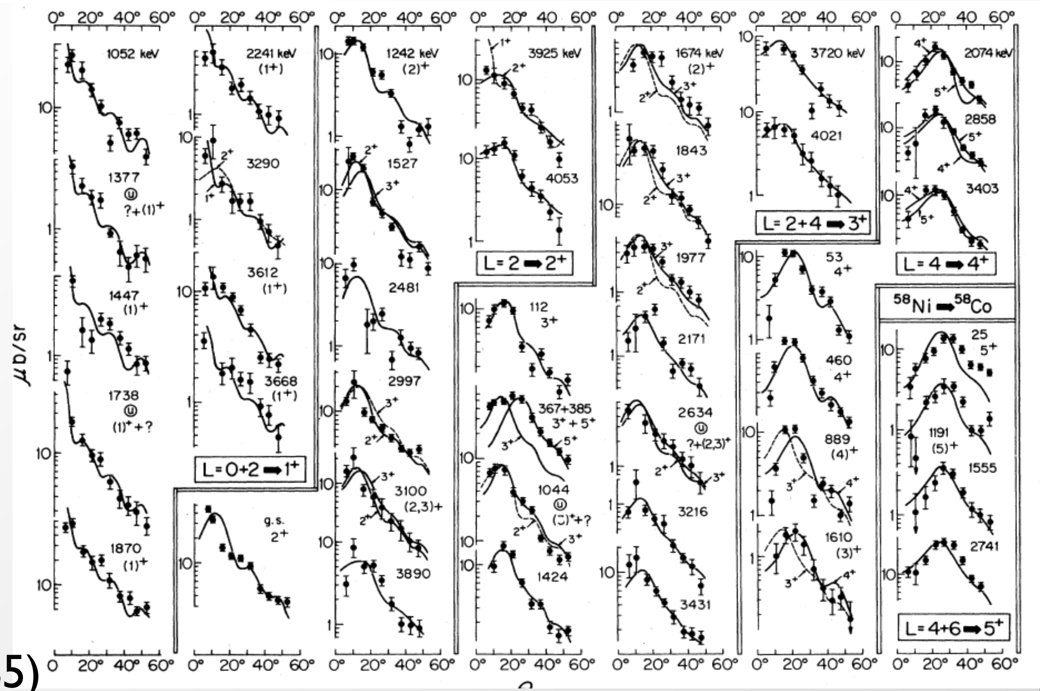
At lower energies, a lot of detailed spectroscopic information can be obtained



Access to high spin states

Comparison with Coupled-Channels Born Approximation Including:

- (t,α)-(α,^{3}He) (dominant)
- (t,d)-(d,^{3}He)



Ajzenberg-Selove et al., PRC 31, 777 (1985)

A hybrid approach – (^{3}He,t) reaction studies at E_{3He}=30-80 MeV

- First developed by R. Schaeffer et al., - Nucl. Phys. A164, 145 (1975) for (^{3}He,t) at E_{3He}=30 MeV
- Detailed development at E_{3He}~80 MeV – Van Der Werf et al., Nucl. Phys. A 496, 305 (1989)
- Used also for E_{3He}~200 MeV (IUCF, KVI)

Method assumes a single step calculation with an effective interaction that has similar terms as the Love-Franey interaction, but single Yukawa potentials are assumed.

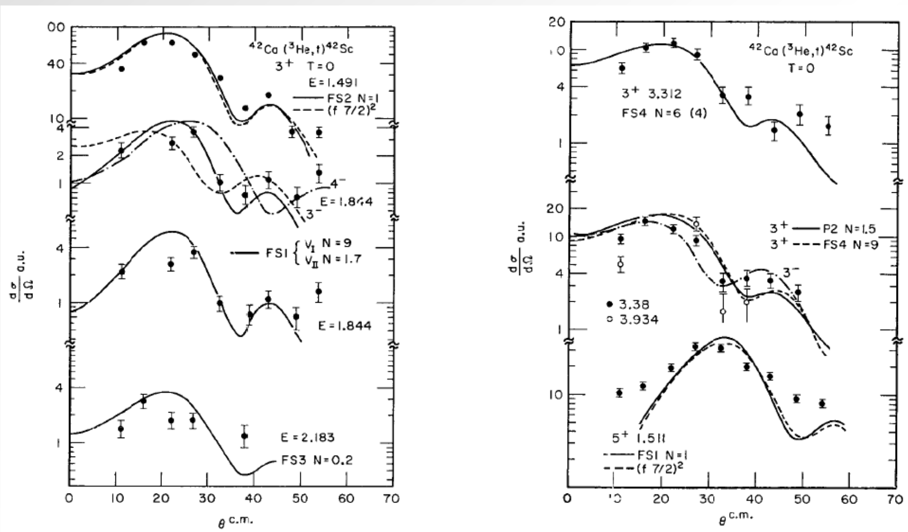
$$V_{\text{eff}} = \{V_\tau Y(r/R_c) + V_{\sigma\tau}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) Y(r/R_c) + V_{LS\tau}(\boldsymbol{L} \cdot \boldsymbol{S}) Y(r/R_{LS\tau}) + V_{T\tau} r^2 S_{12} Y(r/R_{T\tau})\}(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$$

A hybrid approach – (^{3}He,t) reaction studies at E_{3He}=30-80 MeV

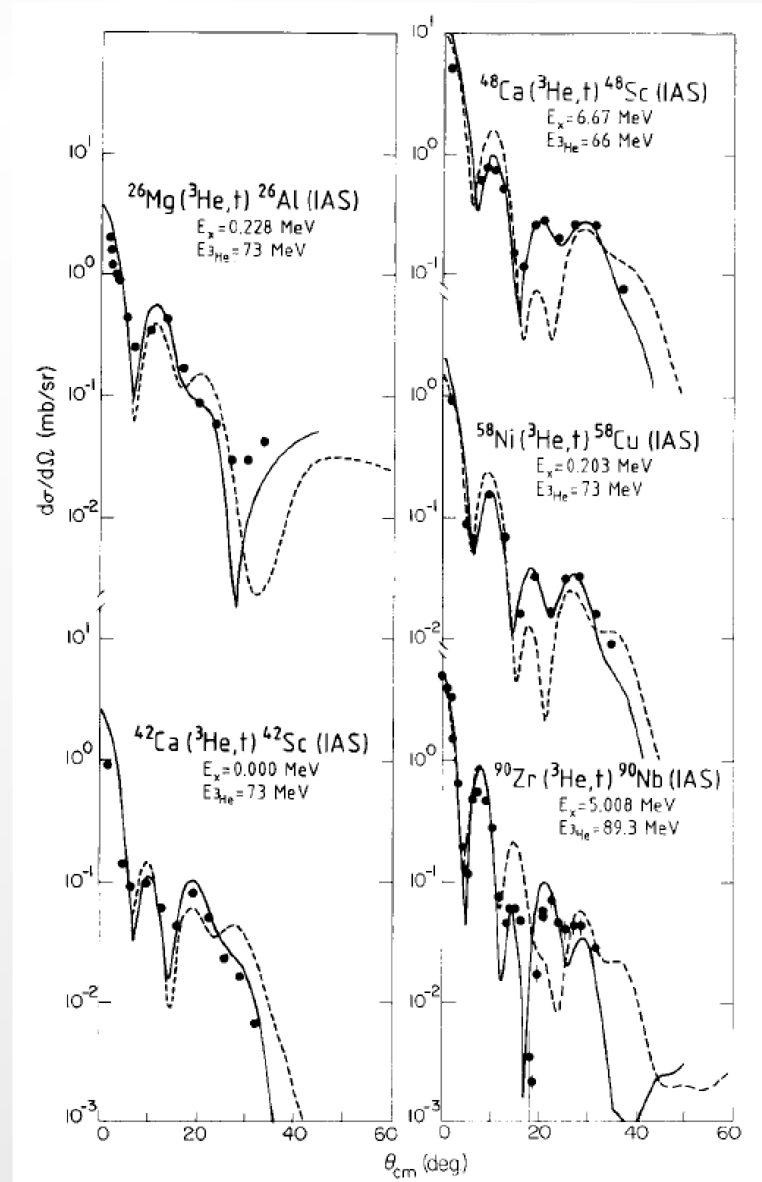
$$V_{\text{eff}} = \{V_\tau Y(r/R_c) + V_{\sigma\tau}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) Y(r/R_c) + V_{LS\tau}(\boldsymbol{L} \cdot \boldsymbol{S}) Y(r/R_{LS\tau}) + V_{T\tau} r^2 S_{12} Y(r/R_{T\tau})\}(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$$

- Only direct terms are included – amplitudes of the potentials account for exchange effects
- Two-step interactions are ignored, but were shown to not drastically change the angular distributions, so these would affect the amplitudes of the potentials
- The effective force used for the ^{3}He-n system has a bound state for S=T=0, so the two-step process (^{3}He,α)-(α,t) is effectively taken into account
- Code available: DW81

A hybrid approach – (^{3}He,t) reaction studies at E_{3He}=30-80 MeV



R. Schaeffer et al., - Nucl. Phys. A164, 145 (1975) for (^{3}He,t) at E_{3He}=30 MeV



E_{3He}~80 MeV – Van Der Werf et al., Nucl. Phys. A 496, 305 (1989)

Opportunities for (t,^{3}He) at low beam energies

- Detailed spectroscopy that is complementary to experiments at high beam energies
- Superior experimental tools compared to previous experiments with low-energy triton beams are now available
- Access to states with low and high spins
- Reaction codes exists that appear to be effective in identifying spins from angular distributions
  - Coupled channel code
  - Hybrid code based on effective interaction (DW81)
  - Might want to investigate calculations with full NN interaction newly developed down to beam energies of 10 MeV/u? (FOLD)

Thank you!