Stellar Electron-Capture Rates Accessed *via* the (t,^{3}He+γ) Reactions

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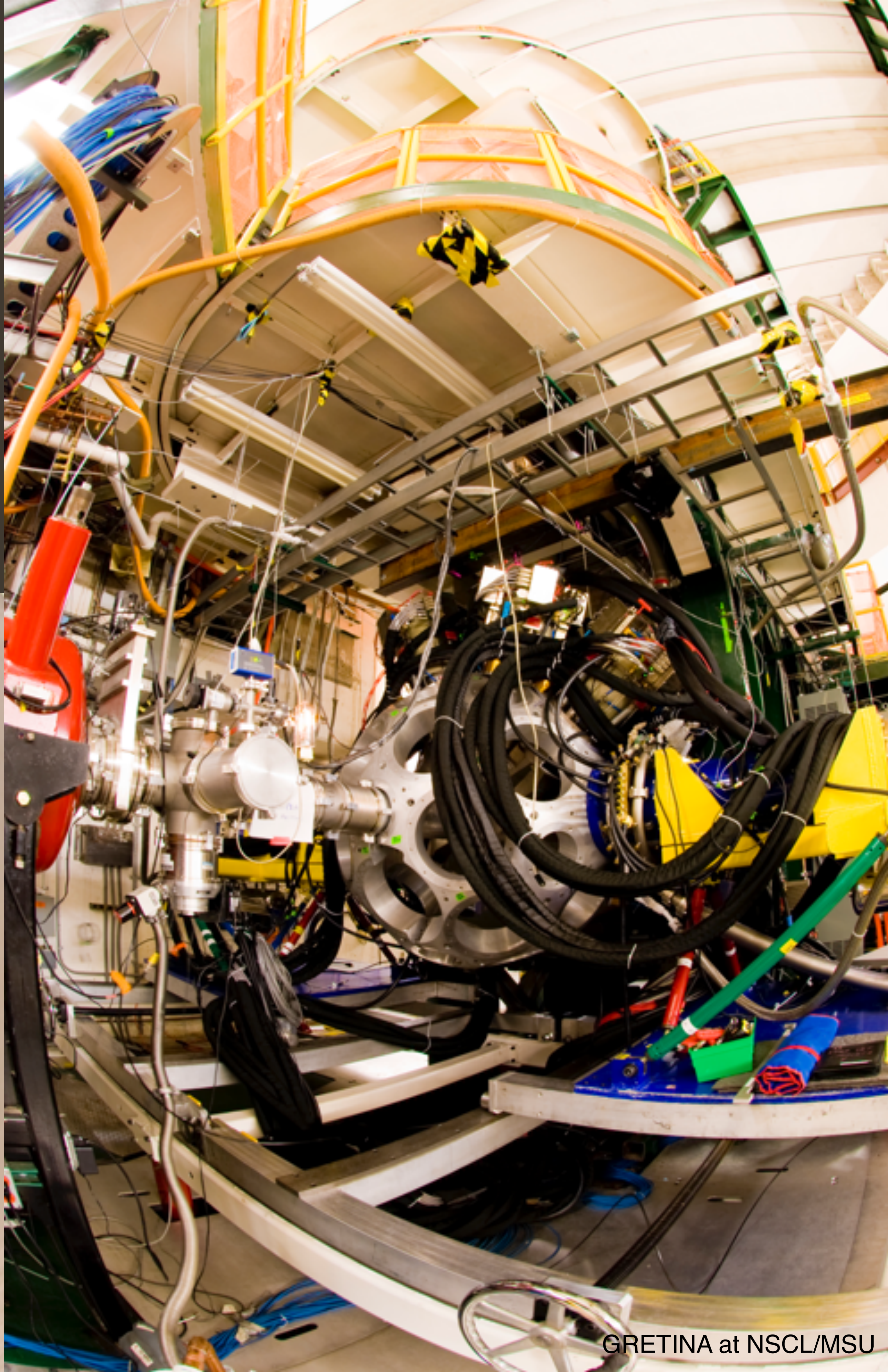

GRETINA at NSCL/MSU

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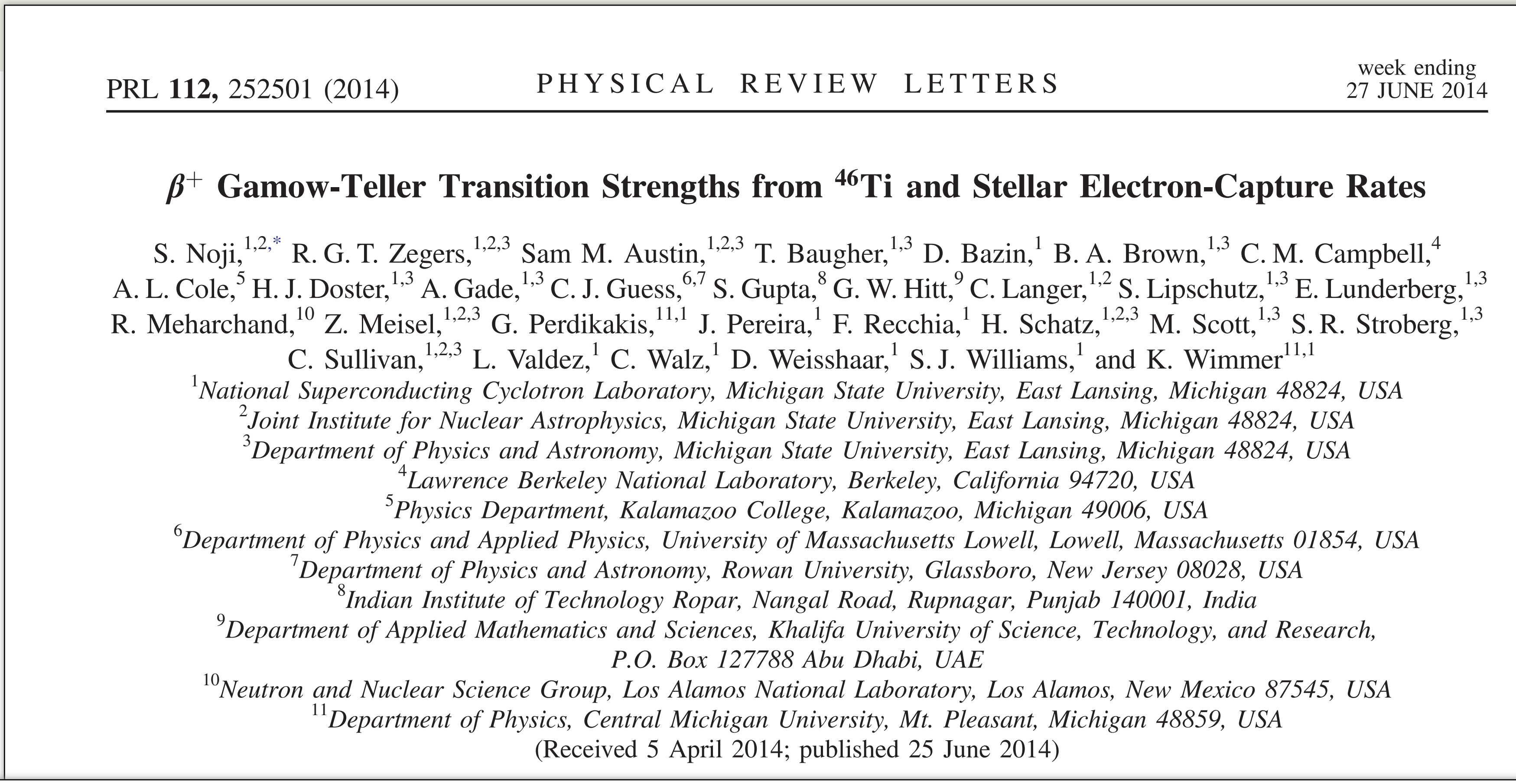

PRL **112,** 252501 (2014) PHYSICAL REVIEW LETTERS week ending 27 JUNE 2014

β^+ Gamow-Teller Transition Strengths from ^{46}Ti and Stellar Electron-Capture Rates

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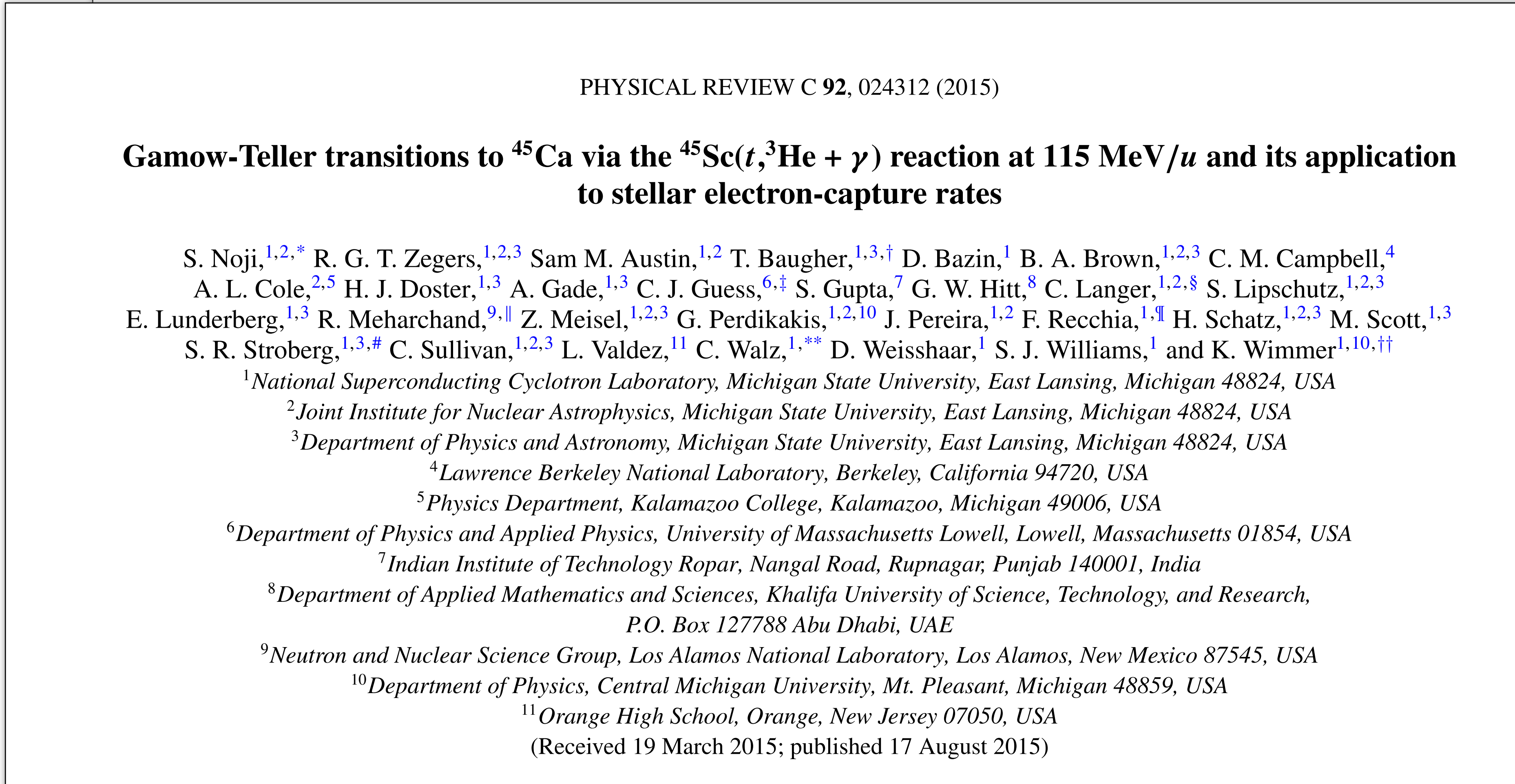

PHYSICAL REVIEW C **92**, 024312 (2015)

Gamow-Teller transitions to ^{45}Ca via the ^{45}Sc(t,^{3}He + γ) reaction at 115 MeV/u and its application to stellar electron-capture rates

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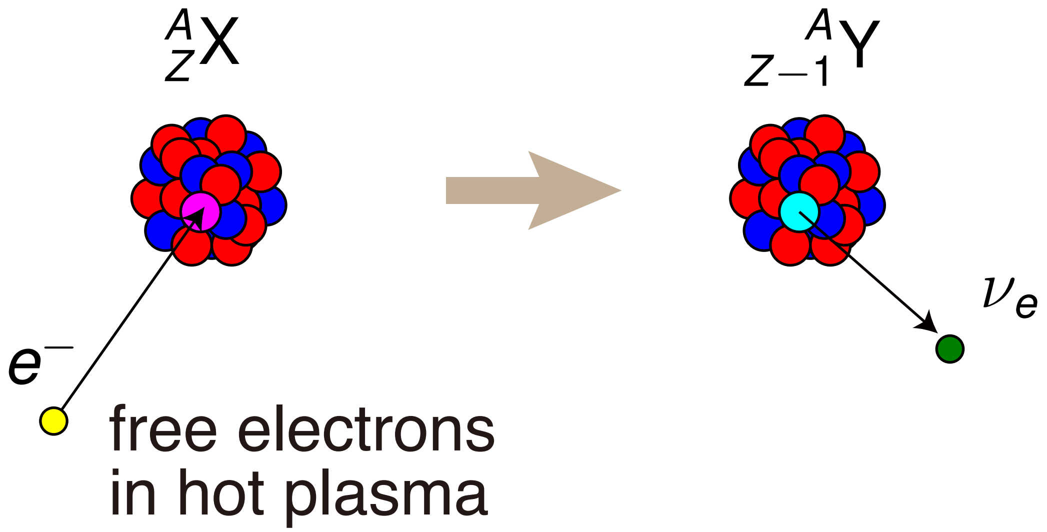
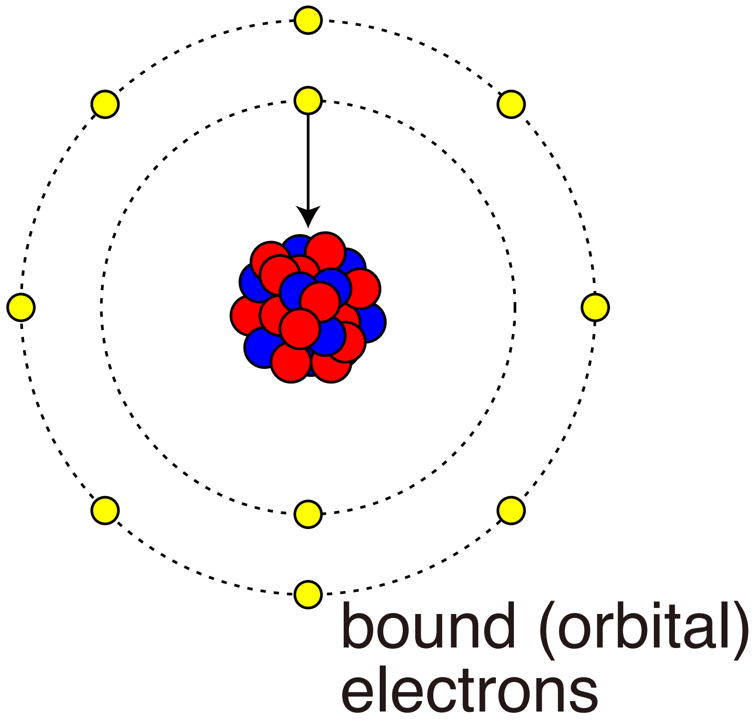
SN, et al., PRL **112**, 252501 (2014)
SN, et al., PRC **92**, 024312 (2015)

Electron Captures in Supernovæ

- **Stellar electron captures (EC)**
  - Takes place in stellar interiors: high T



cf.) Terrestrial electron capture

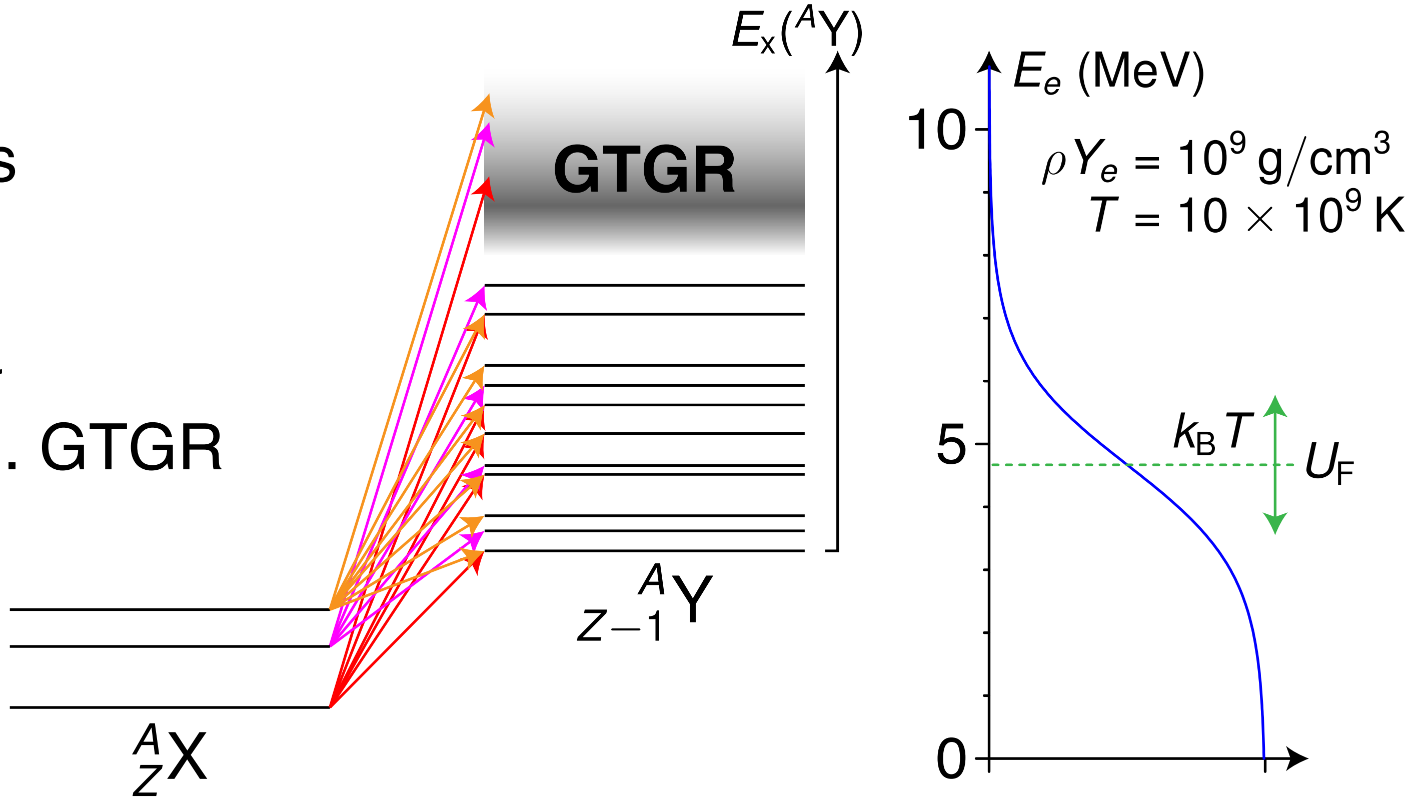


- **Important process for supernovæ (SNe)**
  - Neutronizes stellar core, decreases electron abundance
  - Reduces electron degeneracy pressure (which supports stars) → Leads to **explosion**

Stellar EC is a key to supernova evolution.

Stellar Electron Captures

- **Stellar electron captures (EC)**
  - Dominated by Gamow-Teller transitions
    - $\Delta L = 0$, $\Delta S = 1$, $\Delta T = 1$
  - Capture of free electrons in hot plasma
    - Can get excited to high E_x states incl. GTGR
    - Electrons: Fermi-Dirac distribution
  - Thermal ensemble of initial states
    - ECs take place from excited states
  - Many nuclei play an important role
    - Majority are unstable nuclei



Impossible to measure even a sizable fraction of cases

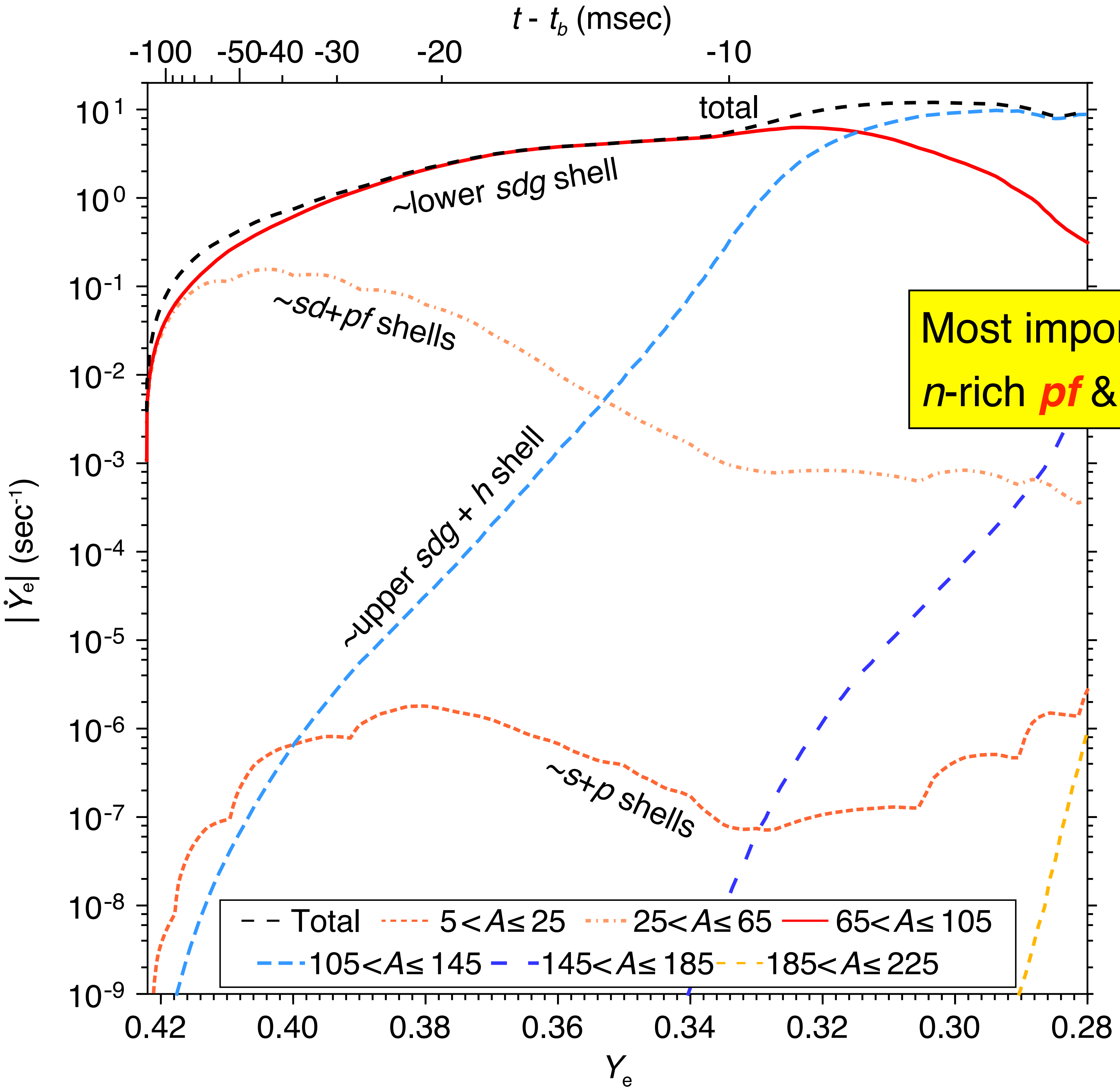
- Accurate theory that constrains key model parameters
- Experimental information for most crucial cases (importantly contributing nuclei) to guide and test development of theory

Sensitivity Study: Importance for SN Collapse

- **Time evolution of the electron fraction in CCSNe center**

arXiv:1508.07348v1, ApJ

Chris Sullivan (NSCL)
Evan O’Connor (NCSU)
Remco G. T. Zegers (NSCL)
Thomas Grubb (NSCL)
Sam M. Austin (NSCL)



Most important are
n-rich ***pf*** & ***sdg***-shell nuclei.

Sensitivity of late SN evolution
to **electron-capture rates**

↓

Identify most critical experiments
to be performed in the future

Experimental Approach to Stellar Electron Captures

- **β decays**
  - Strength $B(\mathrm{GT})$ from life time
  - Q-value restrictions
- **Charge-exchange reactions**
  - Accessible to high E_x states
  - Reliable $B(\mathrm{GT})$ extraction from cross section

→ **Proportionality**

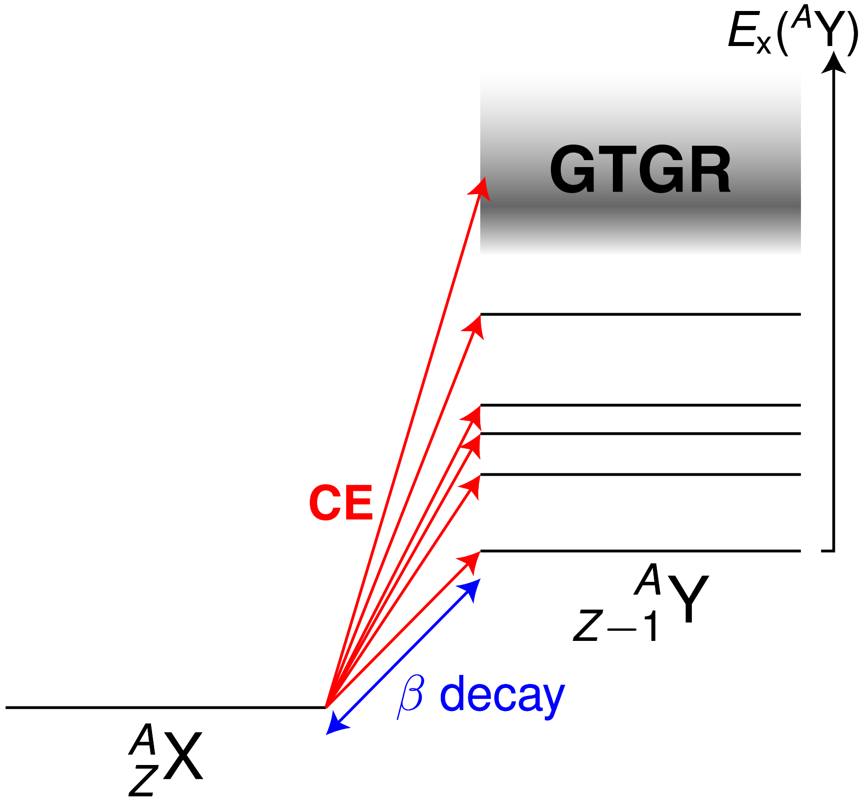
$$\boxed{\sigma_{\Delta L=0}(0^\circ) \approx \hat{\sigma}_{\mathrm{GT}} B(\mathrm{GT})}$$

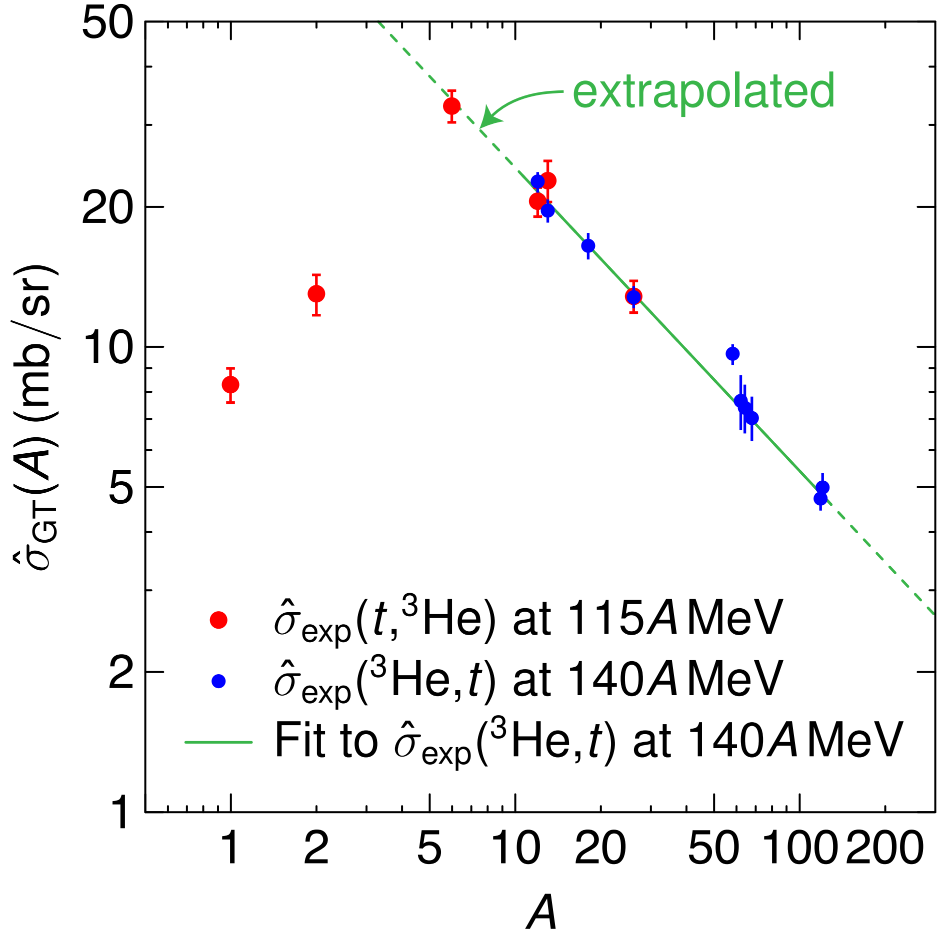
unit cross section: calibrated for (t,^{3}He)

$$\hat{\sigma}_{\mathrm{GT}} = 109/A^{0.65}$$

T. N. Taddeucci et al., Nucl. Phys. A469 (1987) 125
G. Perdikakis et al., Phys. Rev. C 83, 054614 (2011)

CE reactions on important ***pf*-shell** nuclei can be a powerful tool to study ECs





Charge-Exchange Reactions on *pf*-shell Nuclei

- ***B*(GT) in *pf*-shell nuclei**
  - Studied with intermediate-energy CE reactions in β^+ direction: (*n*,*p*), (*d*,^{2}He), (*t*,^{3}He)

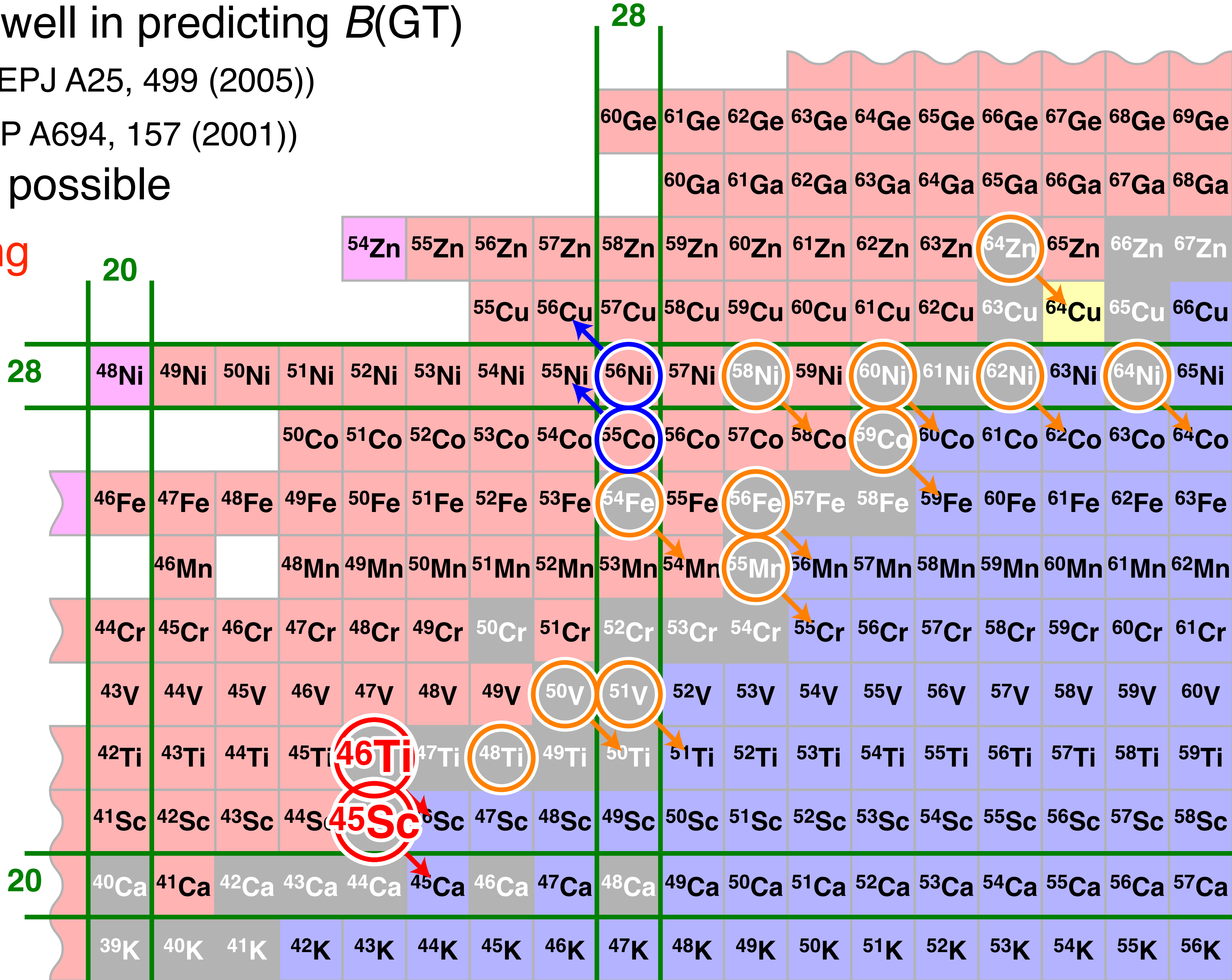
    A systematic study of EC rates: A. L. Cole *et al.*, PRC **86**, 015809 (2012)

    (*p*,*n*) inverse kinematics: M. Sasano *et al.*, PRL **107**, 202501 (2011), PRC **86**, 034324 (2012)
  - Shell models do generally well in predicting *B*(GT)

    GXPF1 (M. Honma et al., EPJ A25, 499 (2005))

    KB3G (A. Poves et al., NP A694, 157 (2001))

    but significant deficiencies possible
  - In light nuclei *pf* & *sd* mixing can affect low-lying states (not considered there)



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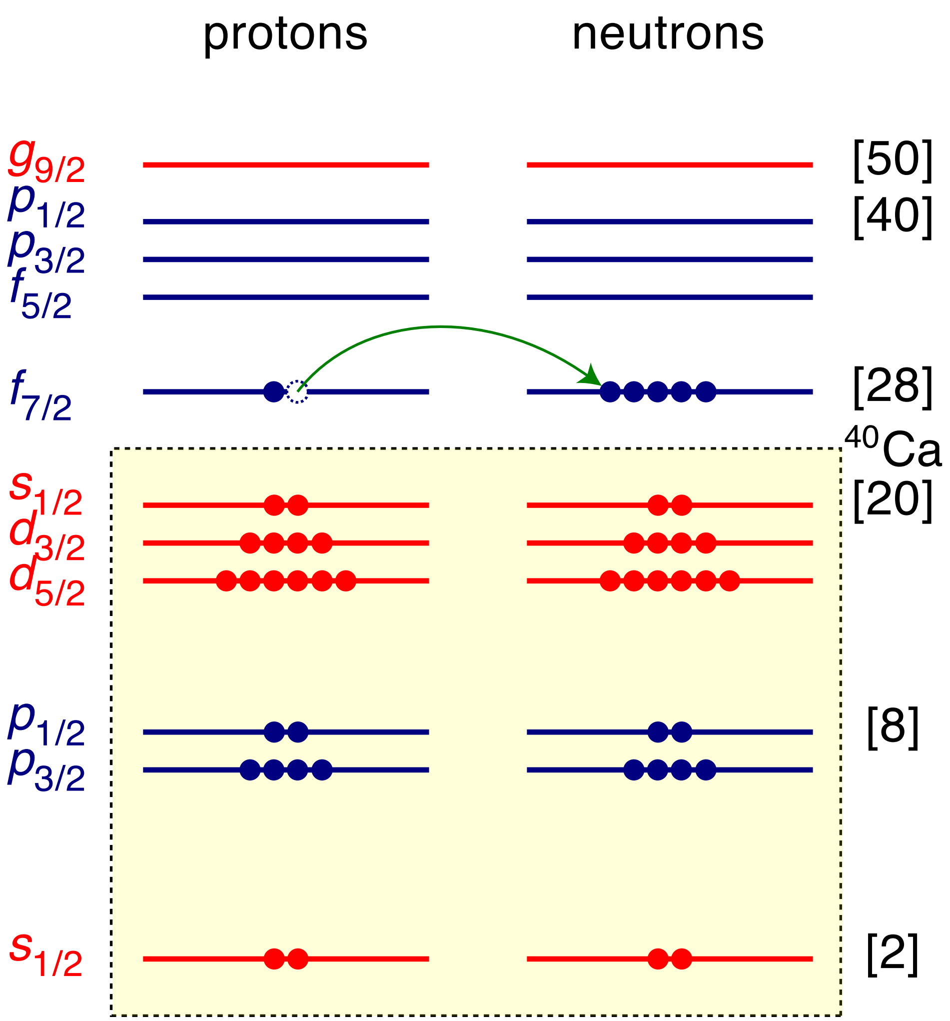
    but significant deficiencies possible
  - In light nuclei *pf* & *sd* mixing can affect low-lying states (not considered there)
- **This study**
  - Lightest *pf* nuclei **^{46}Ti & ^{45}Sc**
    - SM deficiency may be pronounced
    - Specific interests: pre-SN stars, neutron-star crustal heating
  - *B*(GT$^+$) in ^{46}Sc & ^{45}Ca *via* the (*t*,^{3}He) reaction

$^{46}_{22}$Ti → $^{46}_{21}$Sc



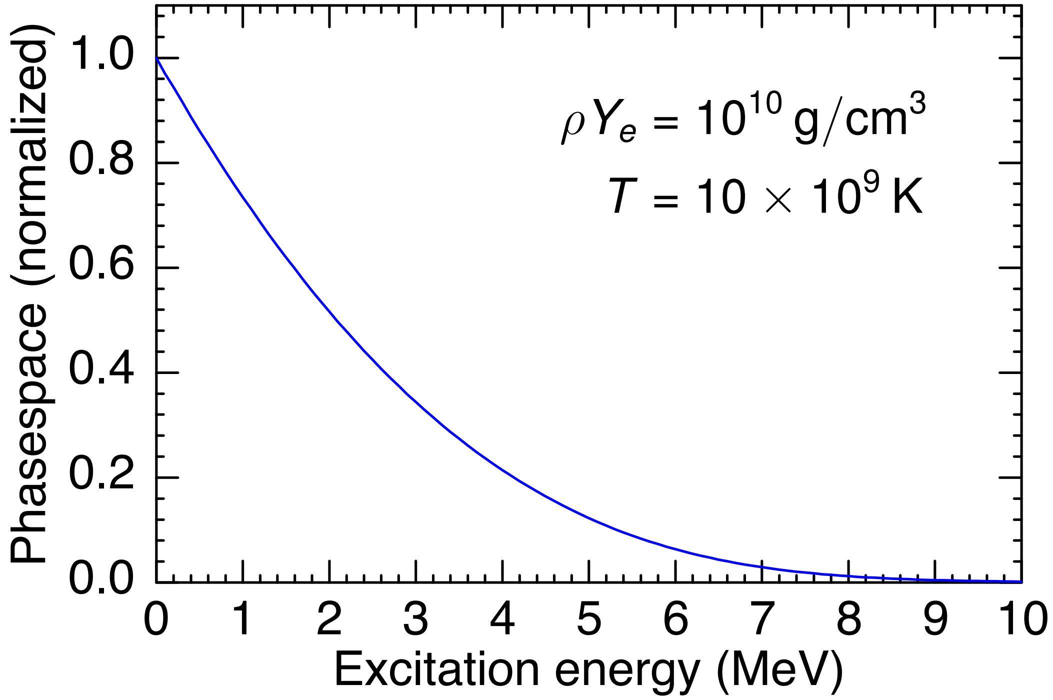
EC Rates: Importance of Detailed Low-lying Structure

- **Electron-capture rates**

transition strength

$$\lambda_{\mathrm{EC}}(T,\rho) = \text{const.} \sum_{i,j} \boxed{f_{ij}(T,\rho)}\,\boxed{B_{ij}(\mathrm{GT})}$$

- Phasespace
  - Decreases as E_{x} becomes higher
  - Increases as temp. & density become larger
  - Contrib. from low-lying strength is important
    - In particular at low temp. & density



- **This study**

“wide” E_{x} range ($E_{\mathrm{x}} \leq 25$ MeV)
“high” resolution (a few 100 keV)

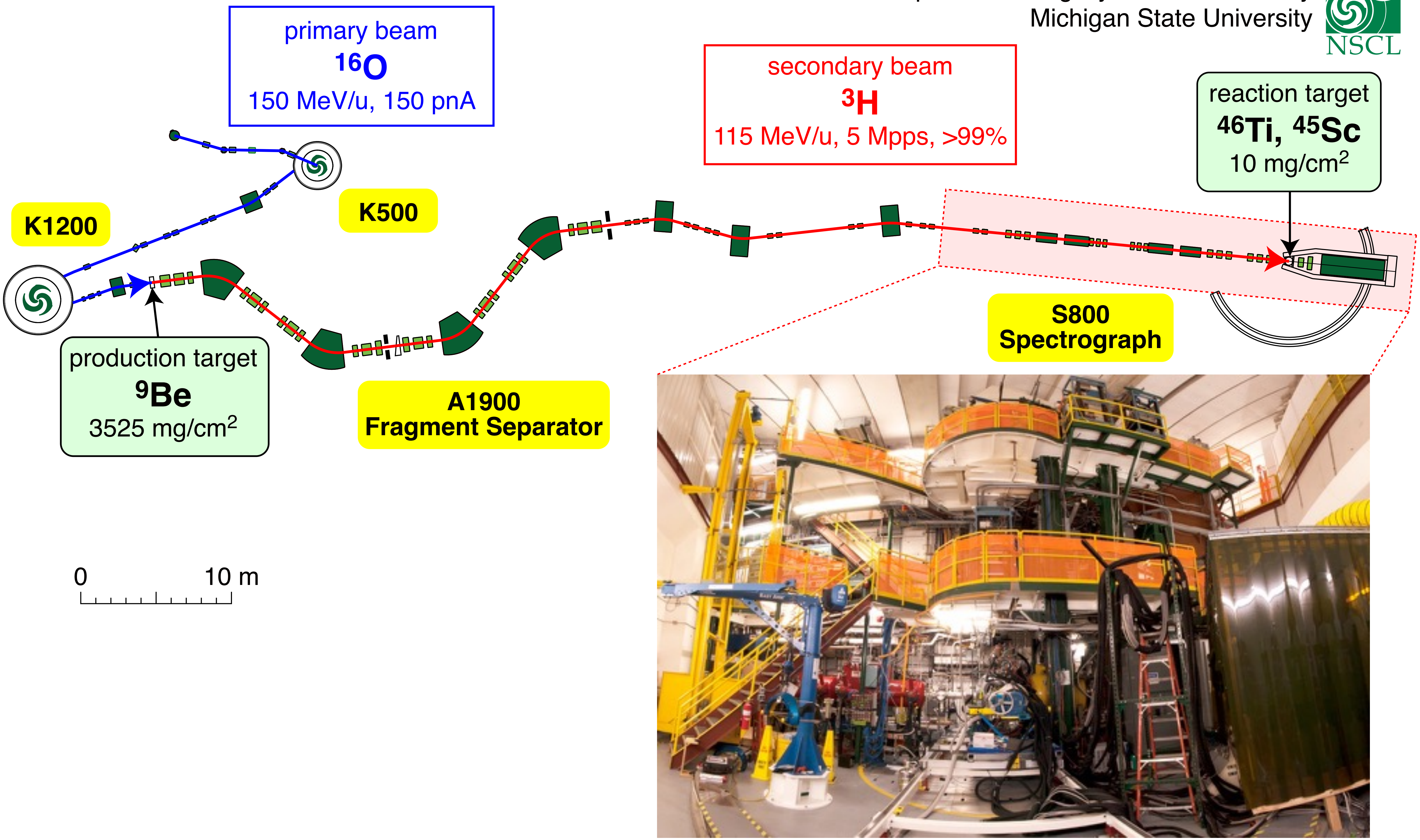
more precise* E_{x} ($\lesssim$ 10 keV)
for low-lying states ($\lesssim$ a few MeV)

* level structure may need to be known

Experiment

- ^{46}Ti, ^{45}Sc(t,^{3}He+γ)^{46}Sc at 115 MeV/u

National Superconducting Cyclotron Laboratory
Michigan State University



primary beam
^{16}O
150 MeV/u, 150 pnA

secondary beam
^{3}H
115 MeV/u, 5 Mpps, >99%

reaction target
^{46}Ti, ^{45}Sc
10 mg/cm^{2}

K1200

K500

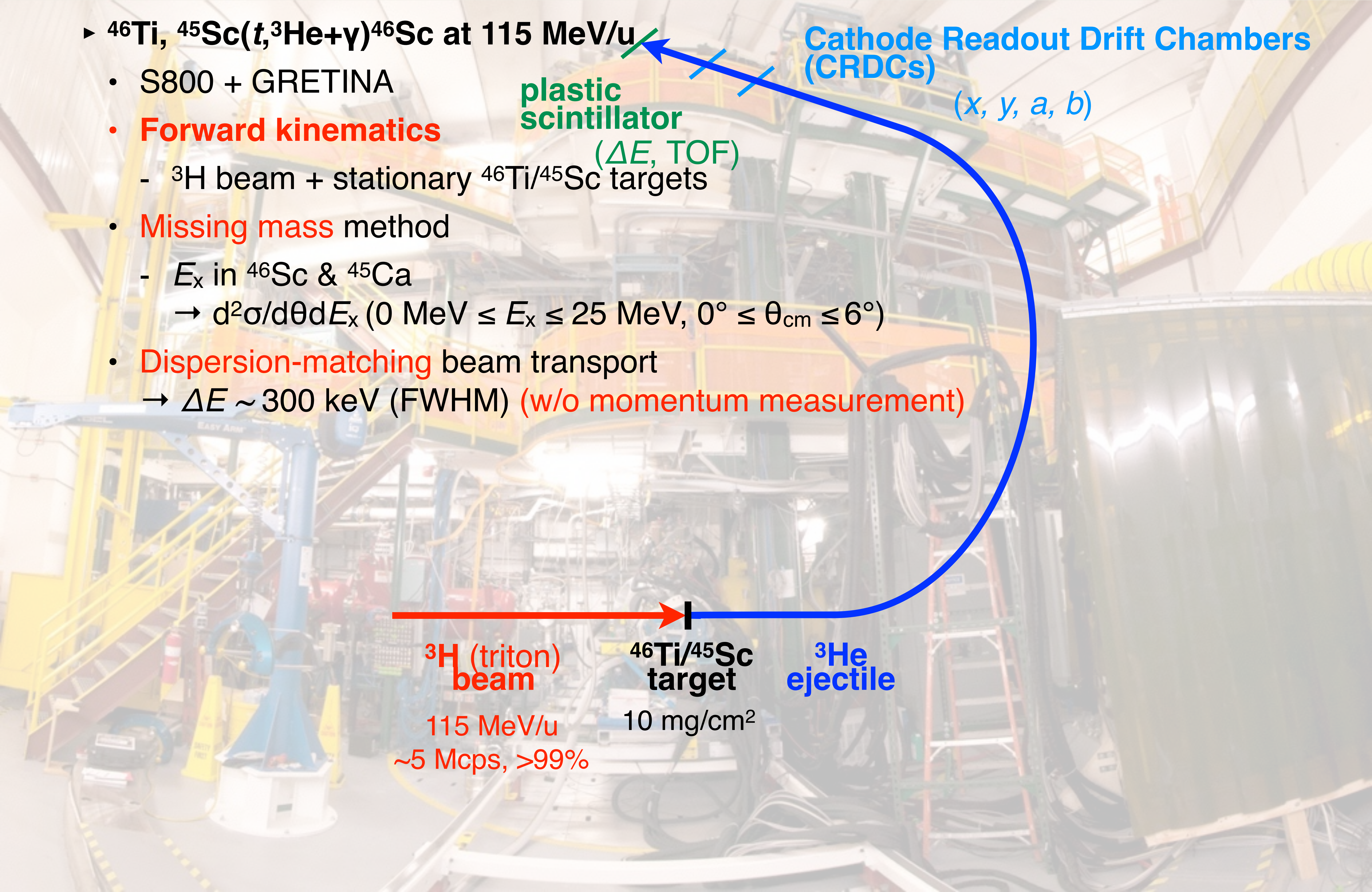
production target
^{9}Be
3525 mg/cm^{2}

A1900
Fragment Separator

S800
Spectrograph

Experiment

- **^{46}Ti, ^{45}Sc(t,^{3}He+γ)^{46}Sc at 115 MeV/u**
  - S800 + GRETINA
  - **Forward kinematics**
    - ^{3}H beam + stationary ^{46}Ti/^{45}Sc targets
  - Missing mass method
    - E_x in ^{46}Sc & ^{45}Ca
      → $d^2\sigma/d\theta dE_x$ (0 MeV ≤ E_x ≤ 25 MeV, 0° ≤ θ_{cm} ≤ 6°)
  - Dispersion-matching beam transport
    → $\Delta E \sim 300$ keV (FWHM) (w/o momentum measurement)



Cathode Readout Drift Chambers (CRDCs)

(x, y, a, b)

plastic scintillator

(ΔE, TOF)

^{3}H (triton) **beam**

115 MeV/u
~5 Mcps, >99%

^{46}Ti/^{45}Sc target

10 mg/cm^2

^{3}He ejectile

Excitation Energy Spectra

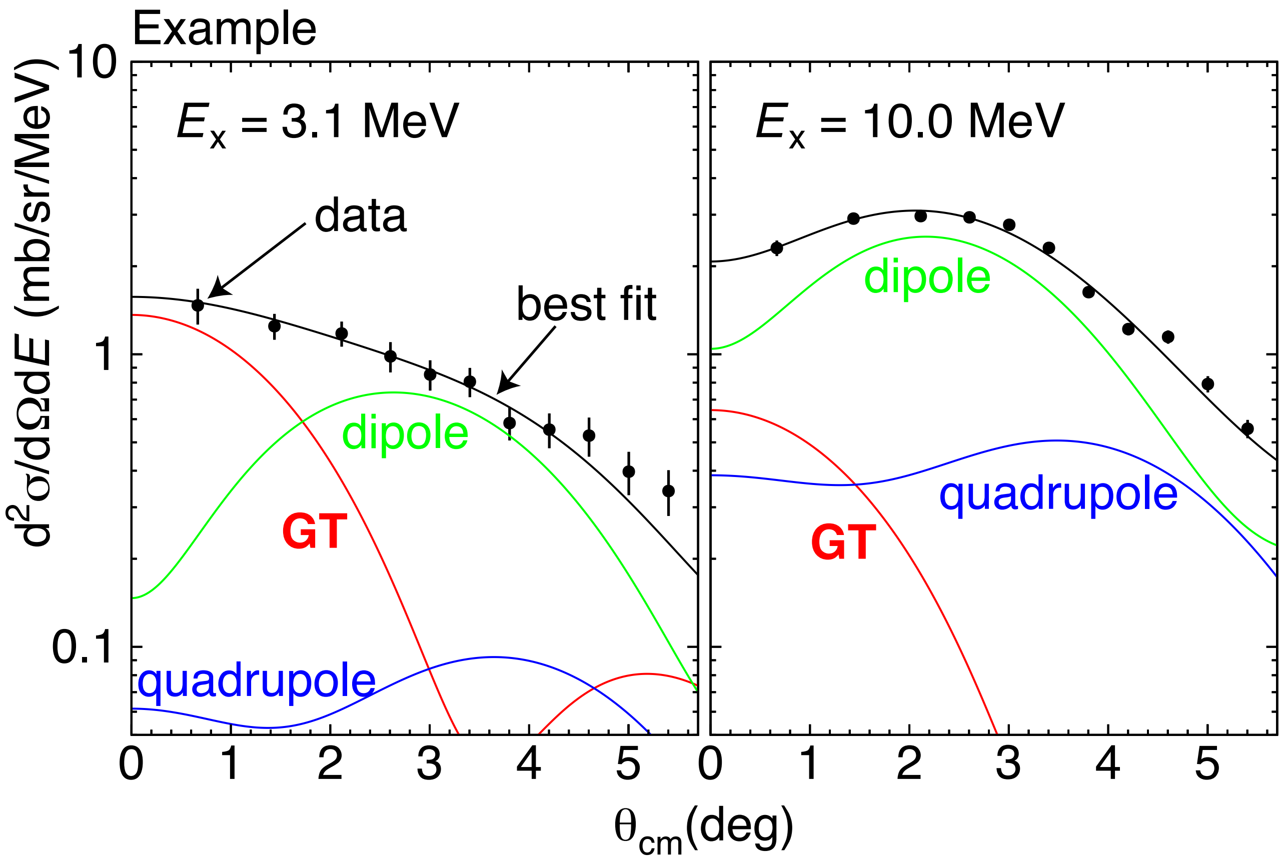
Multipole Decomposition Analysis

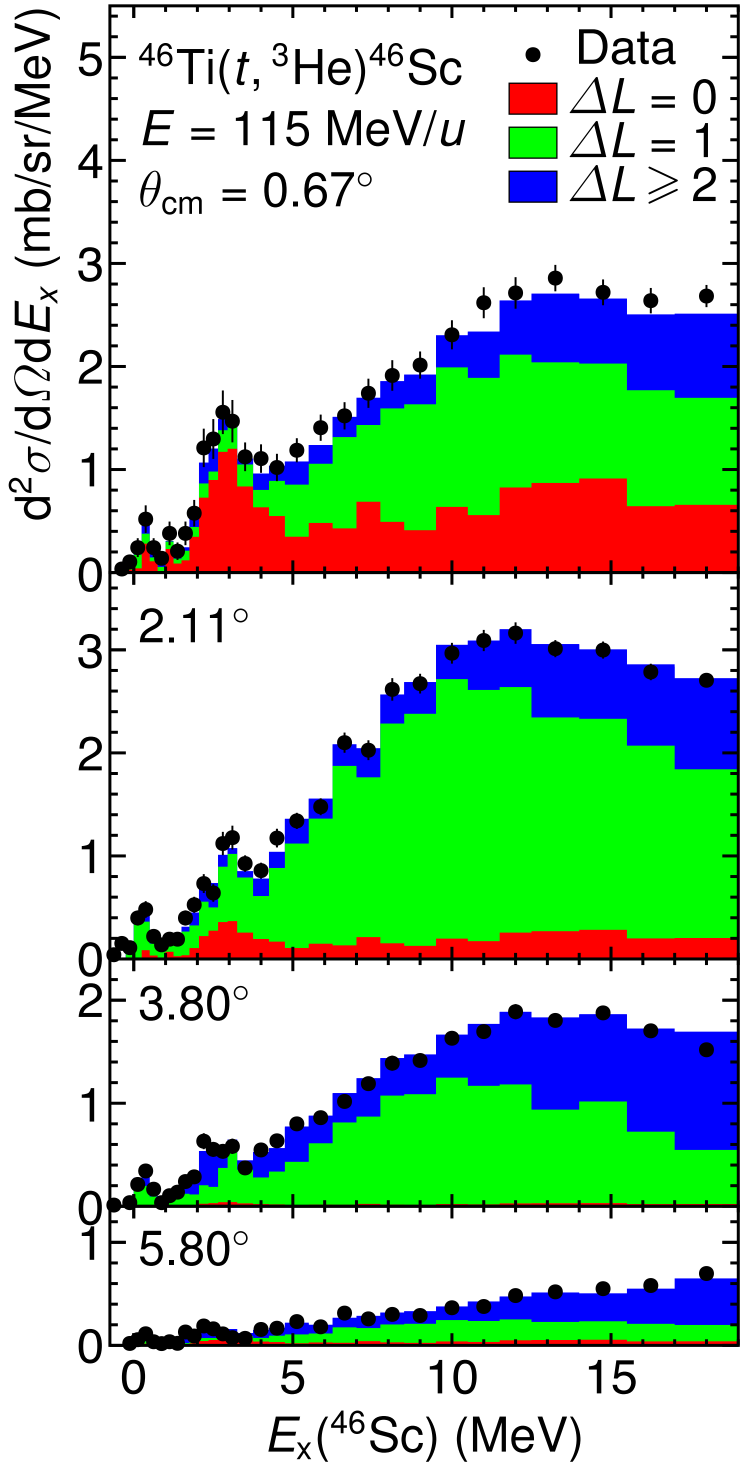
- Experimental data points fitted with sum of DWBA cross sections

$$\sigma^{\text{calc}}(\theta_{\text{cm}}, E_{\text{x}}) = \sum_{\Delta J^{\pi}} a_{\Delta J^{\pi}} \sigma^{\text{calc}}_{\Delta J^{\pi}}(\theta_{\text{cm}}, E_{\text{x}})$$

fit param.

  - DWBA code **FOLD/DWHI** for heavy-ion charge-exchange [double-folding & microscopic form factor]
- Extract each ΔJ^{π} component (**GT**, dipole, quadrupole,...)





Gamow-Teller component needs to be extracted

B(GT) Distribution

- ***B*(GT) distribution from experiment**
  - **GT Proportionality**

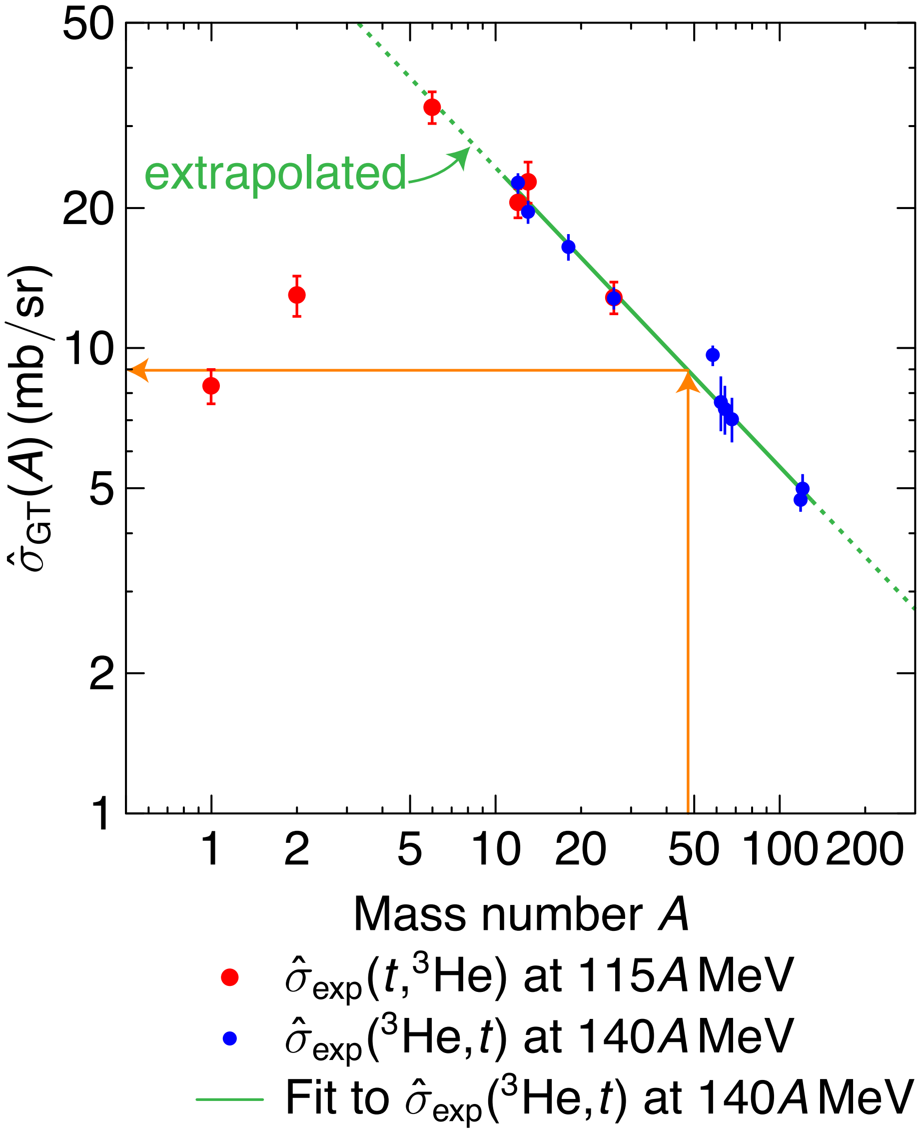
ΔL=0 cross section from MD analysis

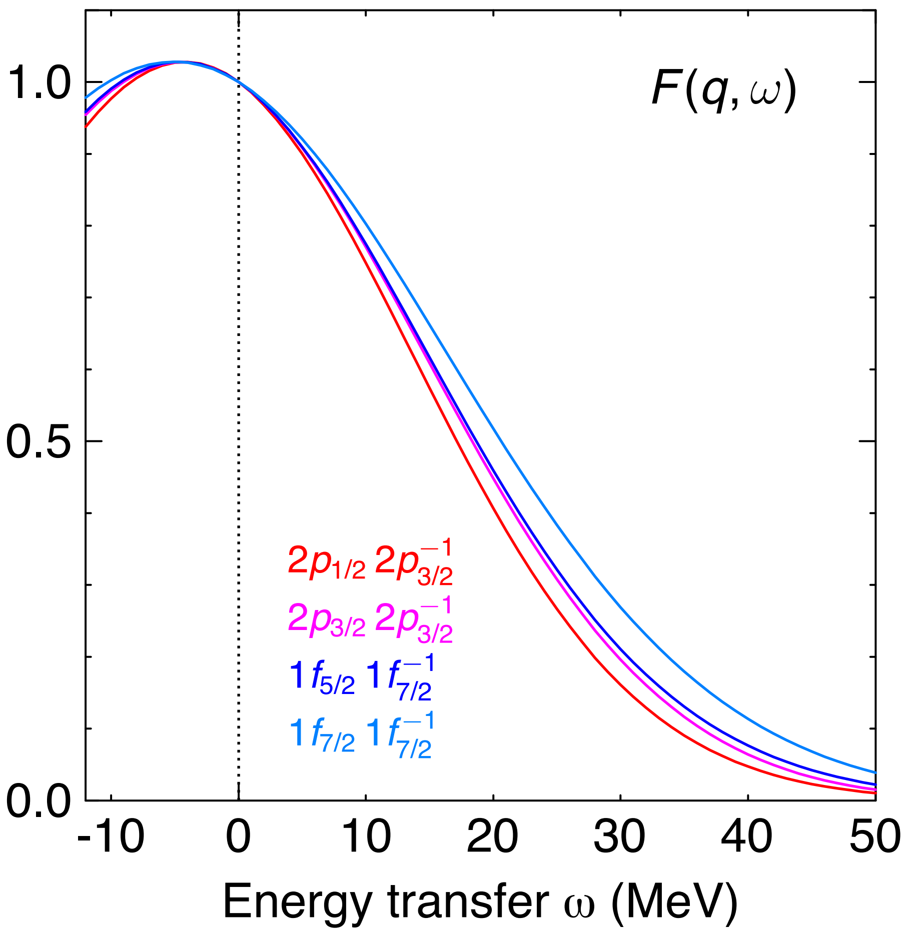
$$B(\mathrm{GT}) = \frac{\sigma_{\Delta L=0}(q,\omega)}{\hat{\sigma}_{\mathrm{GT}}\ F(q,\omega)}$$

GT unit cross section

Kinematical correction

Refs. T. N. Taddeucci et al., Nucl. Phys. A469 (1987) 125
G. Perdikakis et al., Phys. Rev. C 83, 054614 (2011)





* Kinematical correction

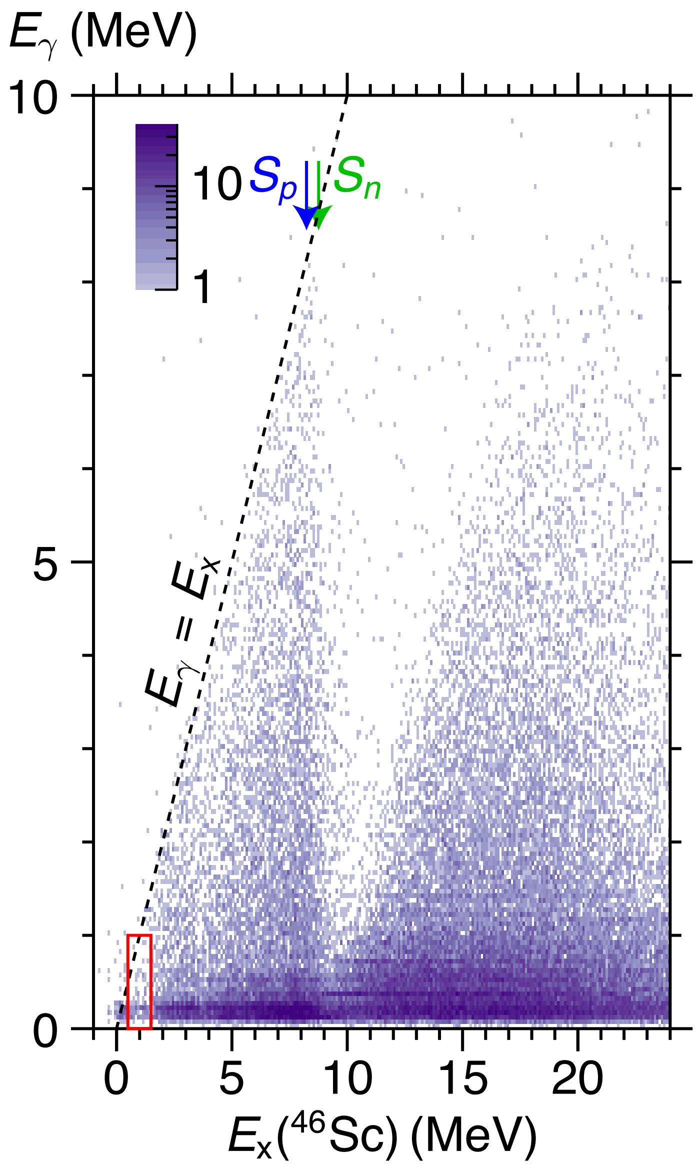
$$\boxed{F(q,\omega) = \frac{\sigma_{\Delta L=0}(q,\omega)}{\sigma_{\Delta L=0}(0,0)}}$$

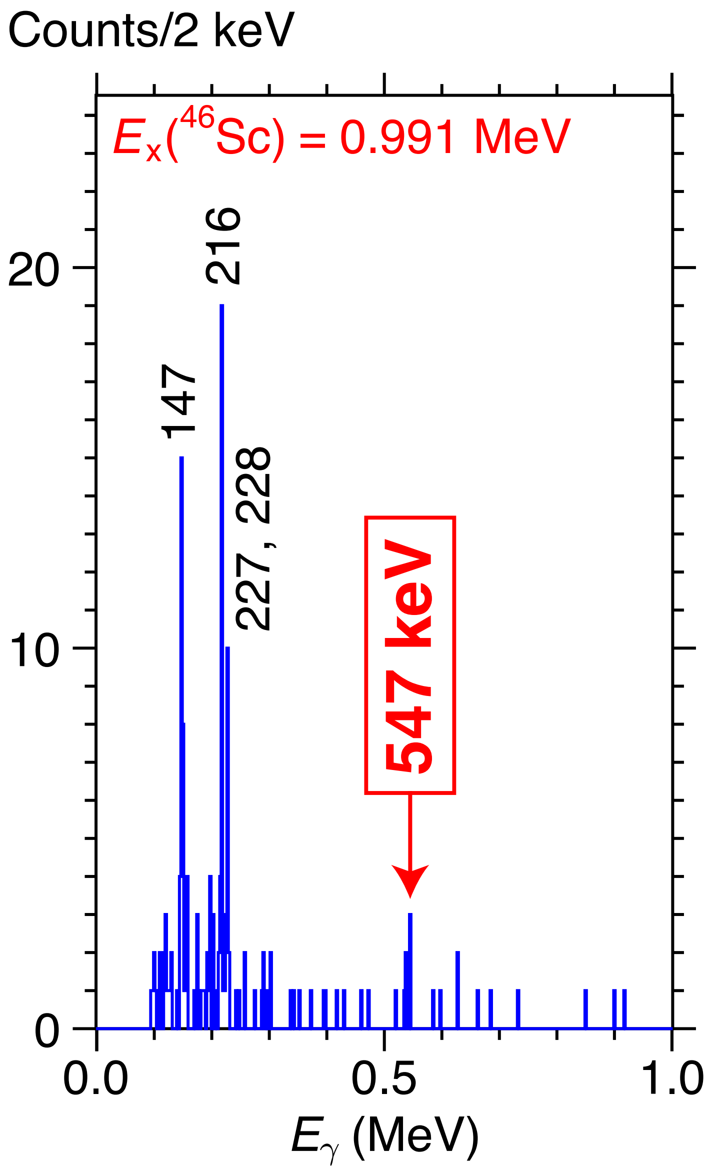
calculated by FOLD/DWHI

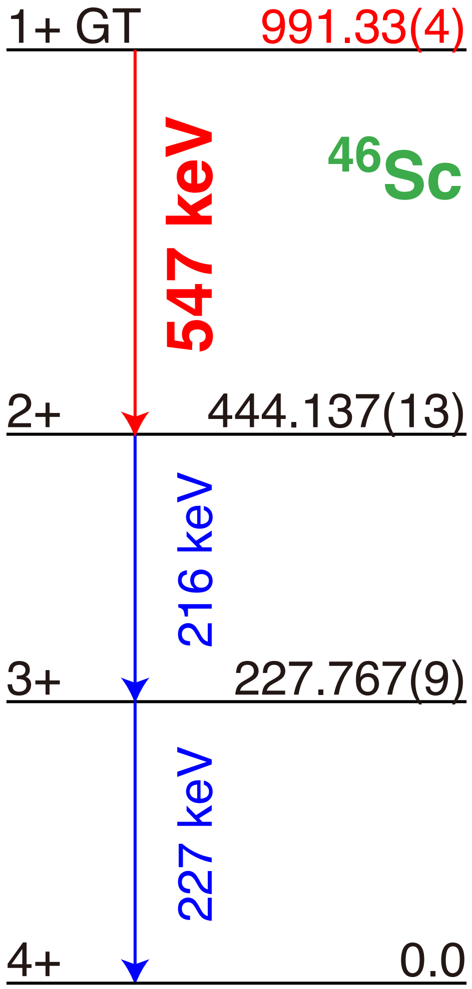
γ Rays for Detailed Information on Low-lying States

- **E_γ (GRETINA) vs E_x (S800)**
  - Distinct $E_\gamma = E_x$ line: no γ's greater than E_x → Clean E_x selection possible
  - Separation energies S_p & S_n: particle decay channels open
- **γ decays from GT states** (E_x gated E_γ spectrum)
  - Lowest known 1^+ state at 991 keV → decay with 547-keV γ ray

B(GT) = 0.009 ± 0.005 (exp.) ± 0.003 (tensor)





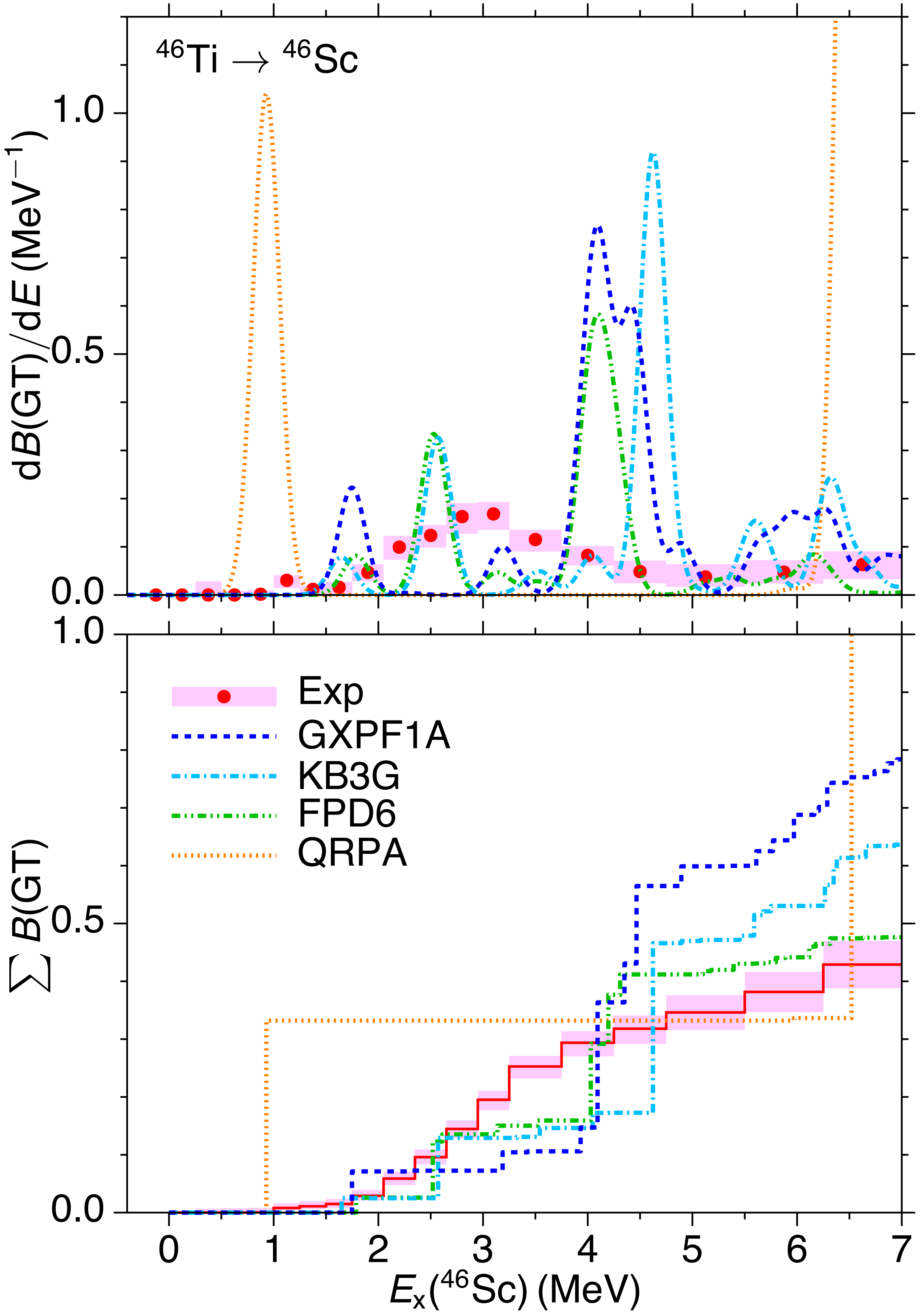


Comparison with Theory

- **Shell model**
  - Full *pf*-shell model space
    with quenched operator $(\sigma\tau_+)_{\mathrm{eff}} = 0.744\,\sigma\tau_+$
  - Interactions:
    - **GXPF1A**
      M. Honma et al., PRC **65**, 061301(R) (2002);
      PRC **69**, 034335 (2004); EPJ **A25**, 499 (2005)
    - **KB3G**
      A. Poves, et al., NP **A649**, 157 (2001)
    - **FPD6**
      W. A. Richter, et al., NP **A523**, 325 (1991)

- **QRPA** (P. Möller and J. Randrup, NP A514, 1, 1990)
  - Frequently used
    in astrophysical simulations

None of the calculations agree well with the data!

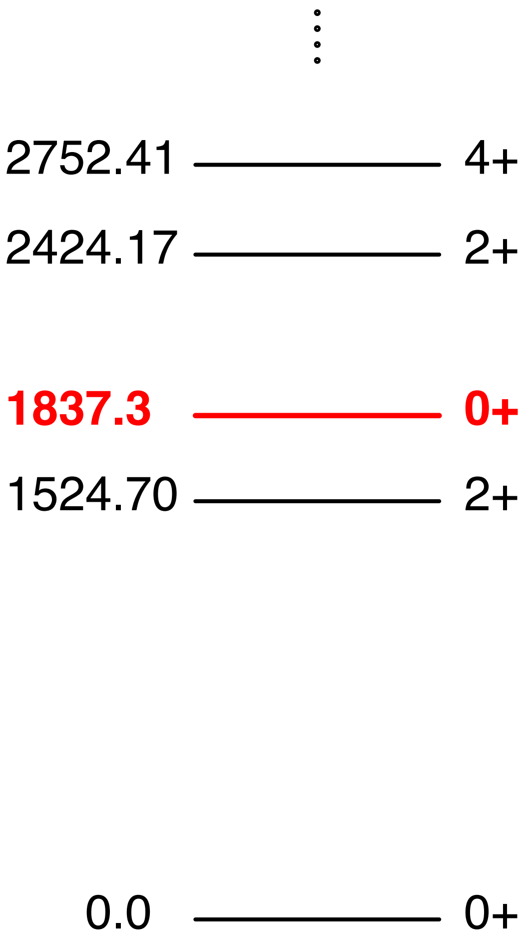


Comparison with Shell Model Calculations

- **Intruder states**
  due to admixtures with states from *sd* shell
  play an important role in the lower *pf* shell

e.g.

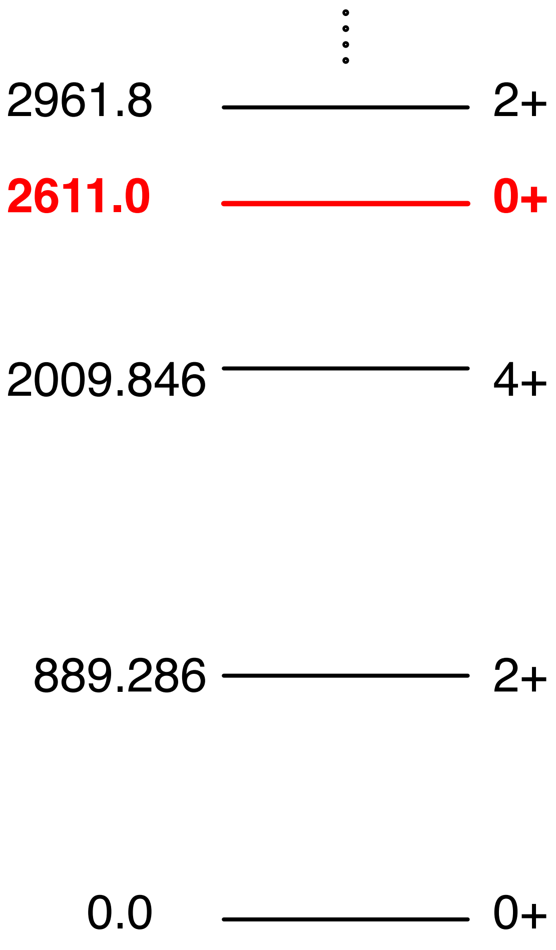
- Some low-lying levels
- Large B(E2) values for ^{42,44}Ca



Energy	J^π
⋮	
2752.41	4+
2424.17	2+
1837.3	**0+**
1524.70	2+
0.0	0+

^{42}Ca

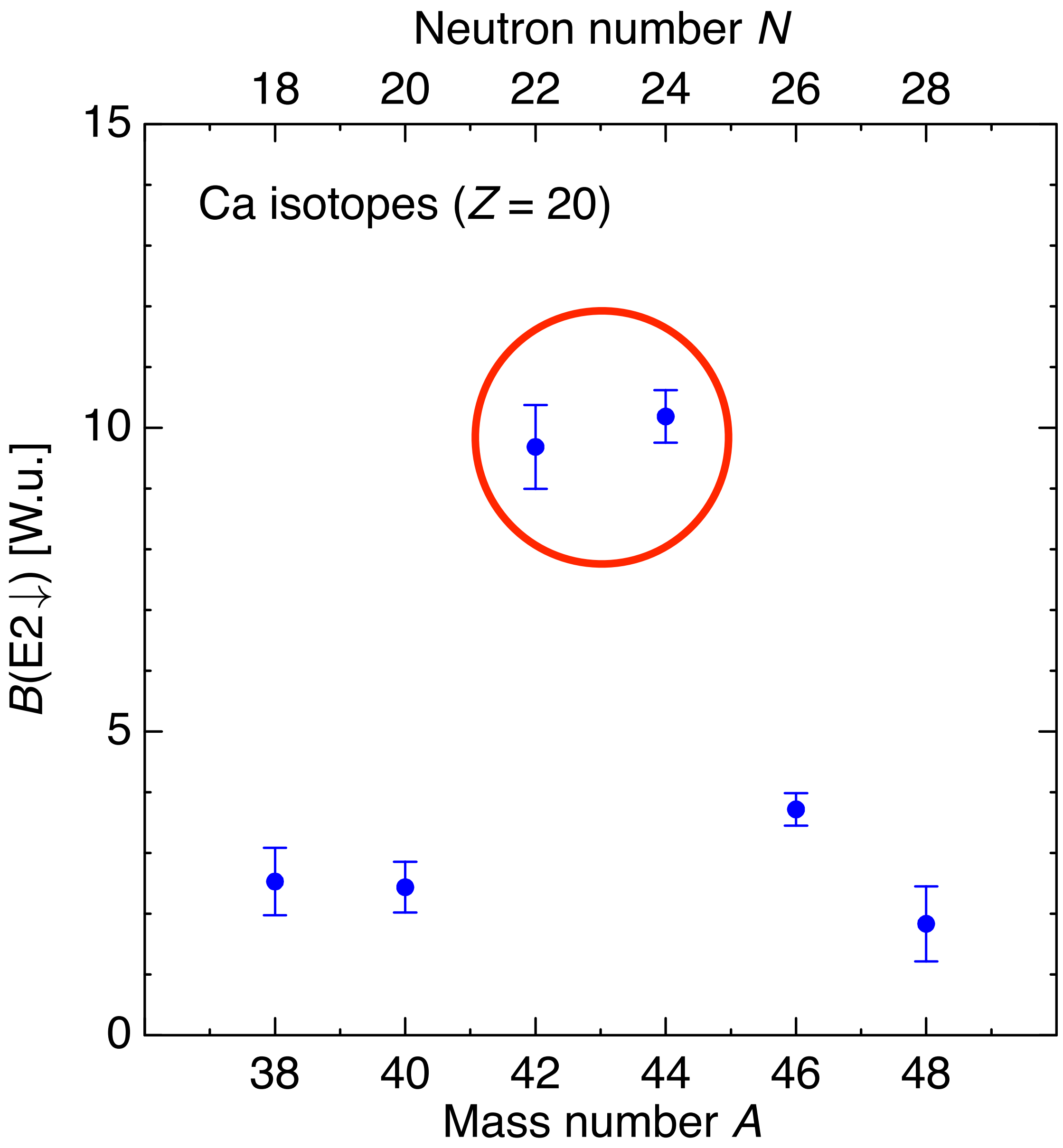
Nucl. Data Sheet **92**, 1 (2001)



Energy	J^π
⋮	
2961.8	2+
2611.0	**0+**
2009.846	4+
889.286	2+
0.0	0+

^{46}Ti

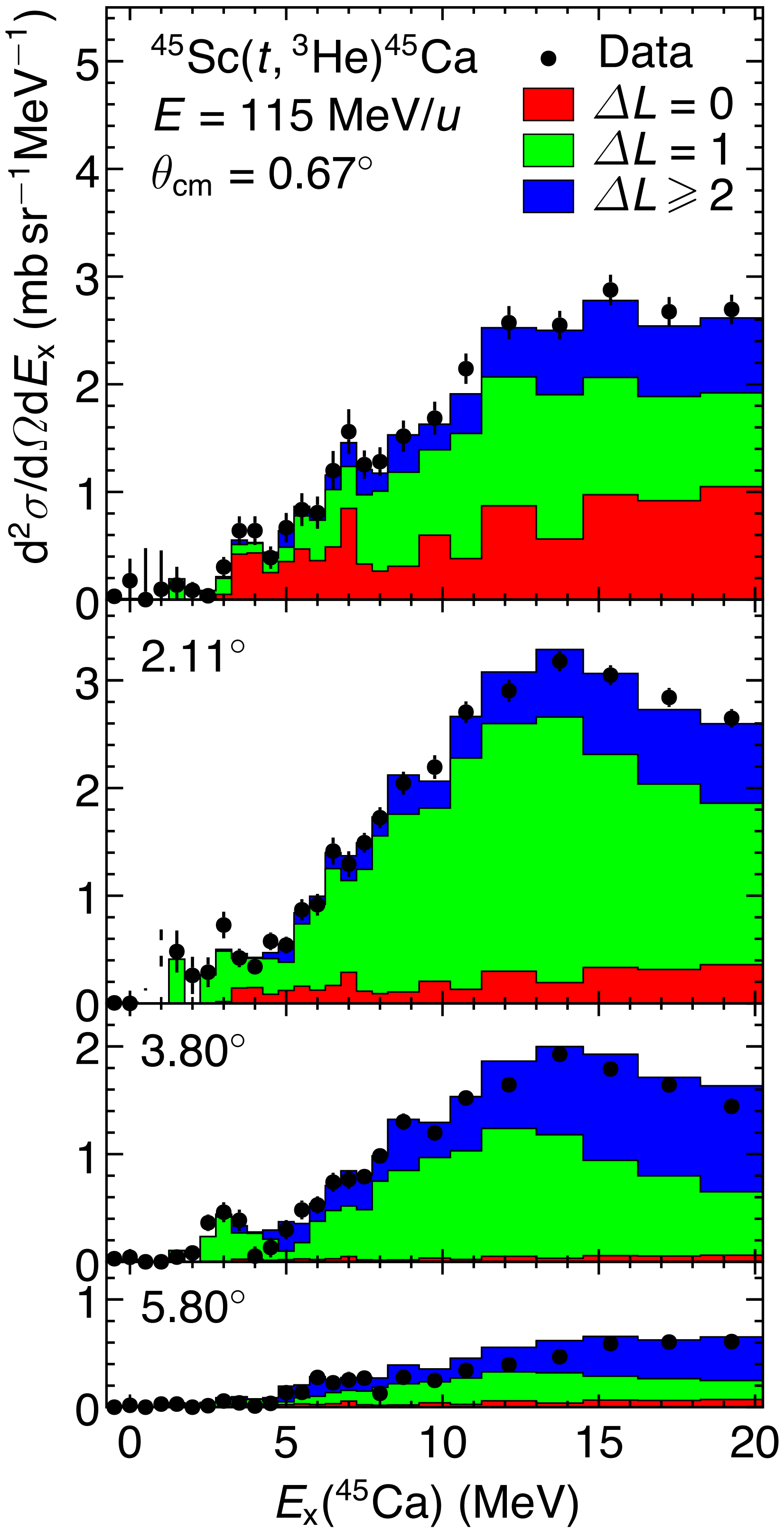
Nucl. Data Sheet **91**, 1 (2000)

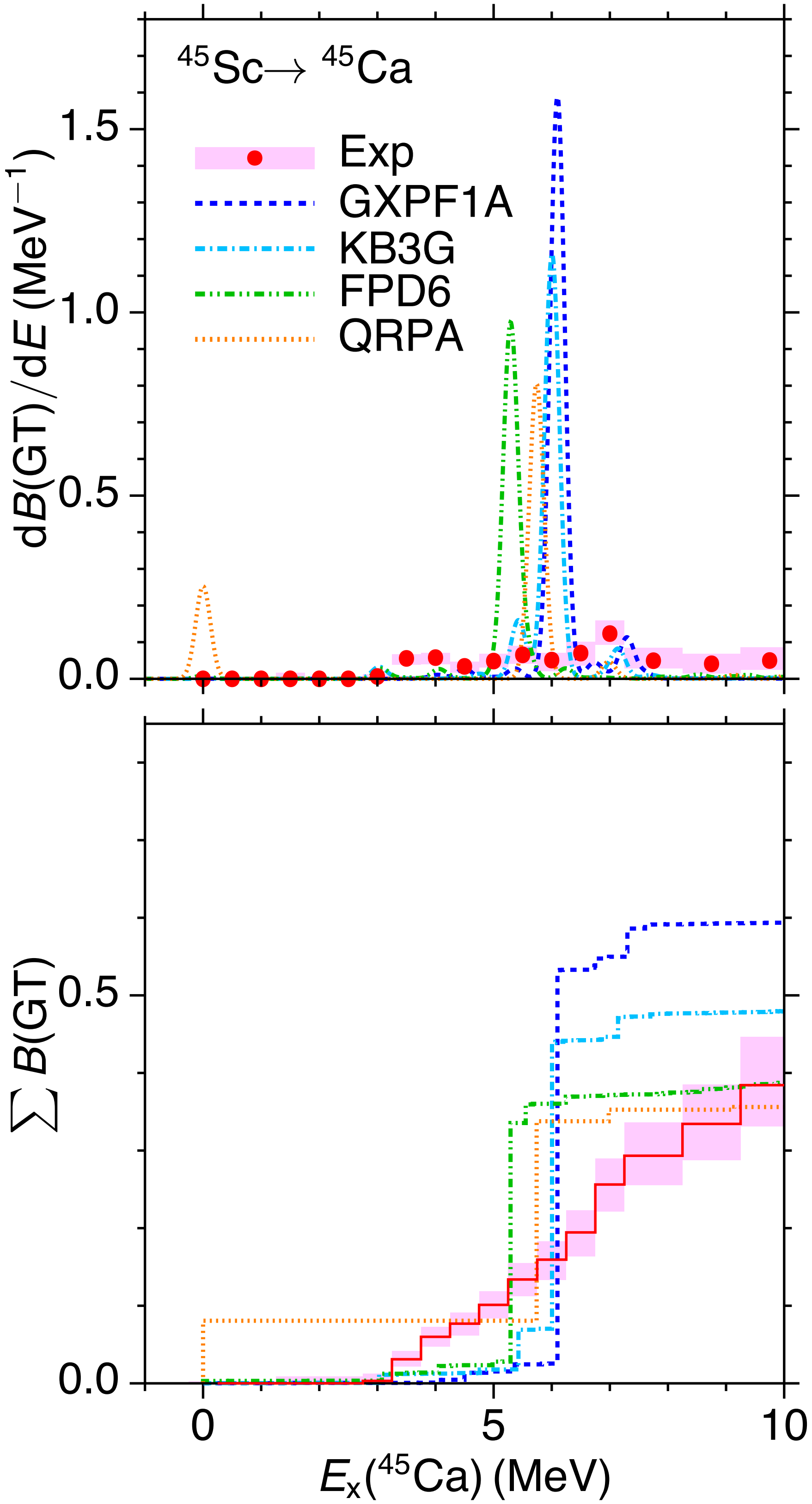


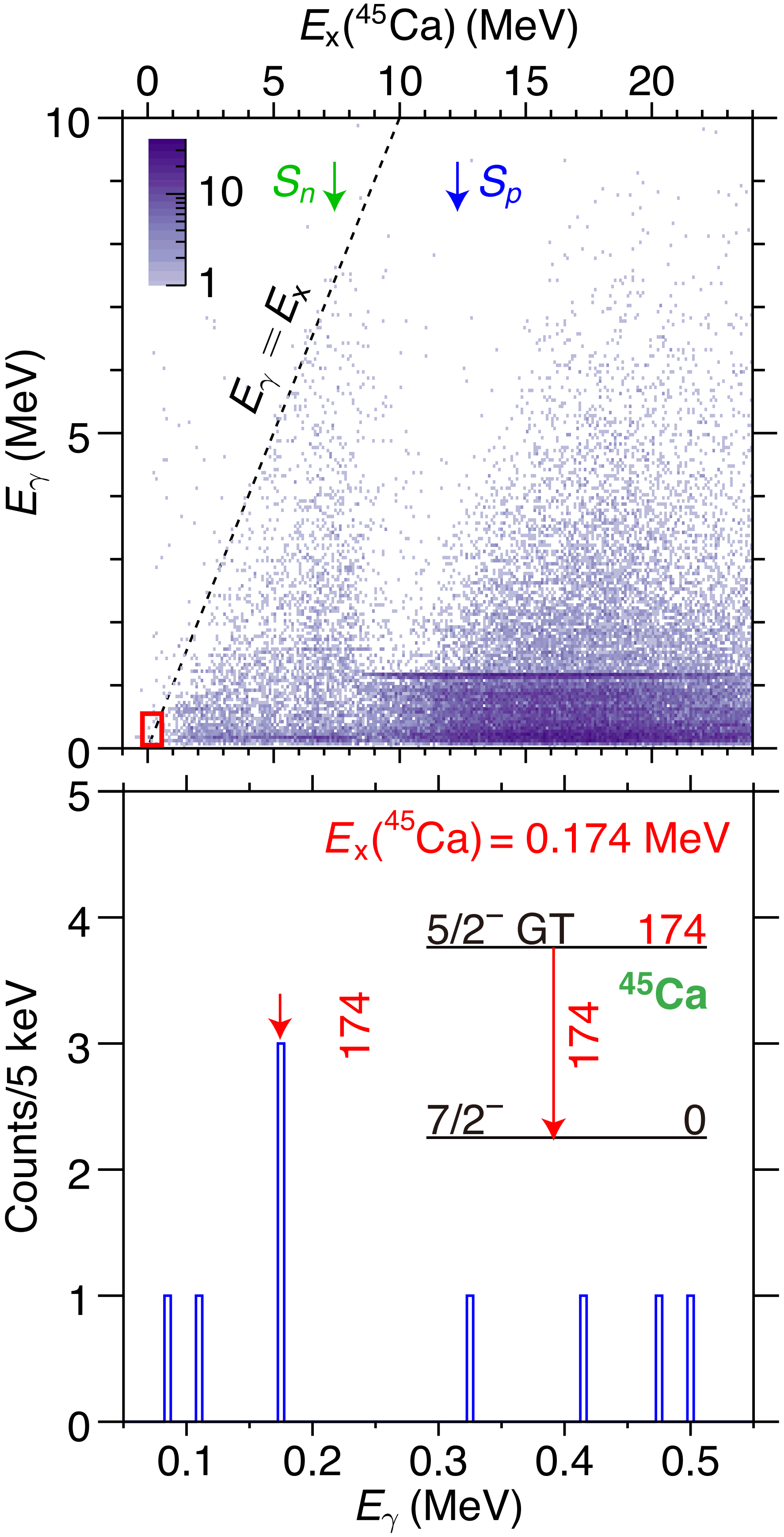
At. Data Nucl. Data Tables **78**, 1 (2001)

Results for ^{45}Sc

- **^{45}Sc(t,^{3}He) at 115 MeV/u**





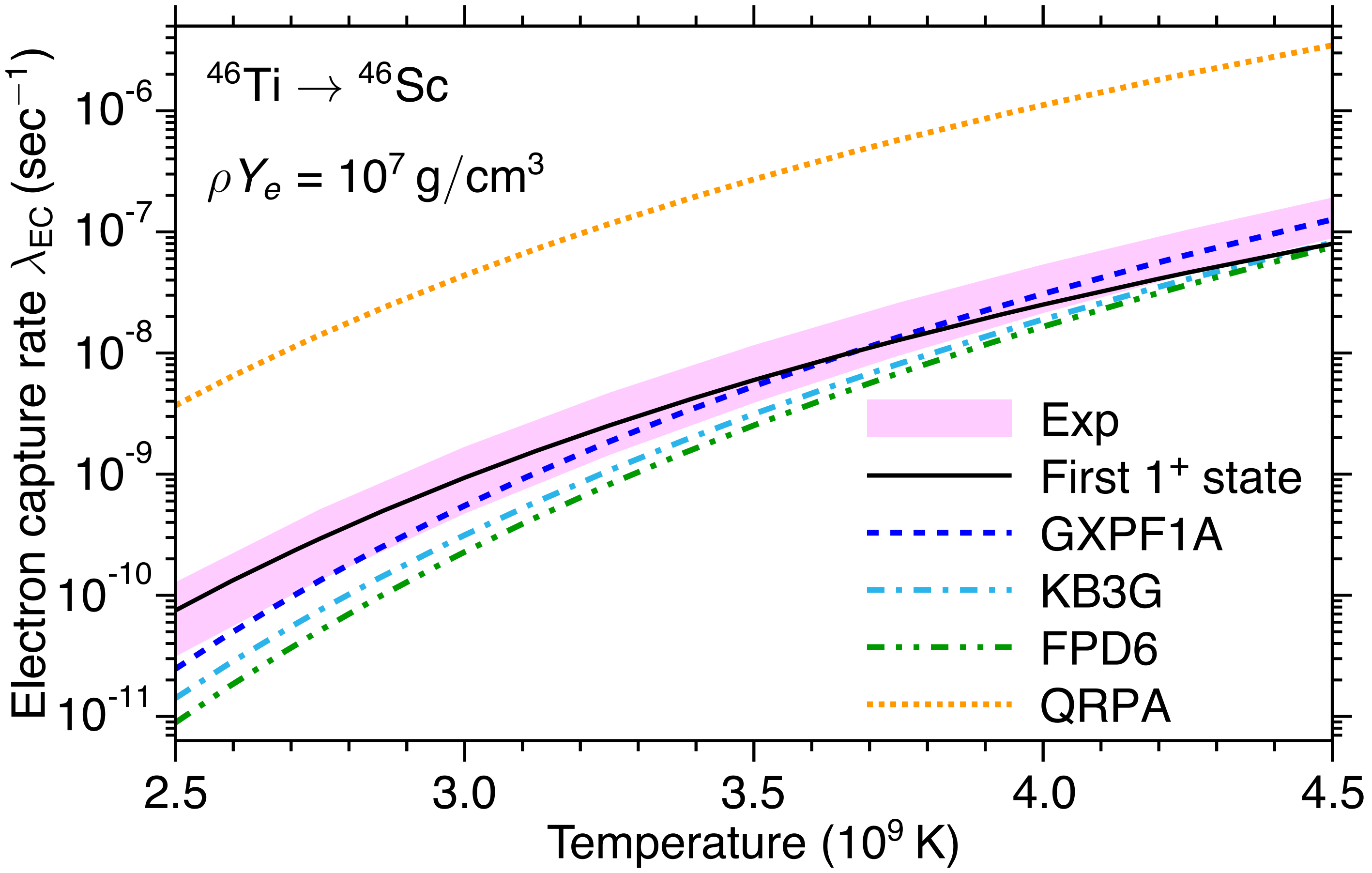


EC rates & Comparison with Theory

- **Electron-capture rate**

$$\lambda_{\mathrm{EC}}(T,\rho) = \mathrm{const.} \sum_{i,j} \overset{\text{phasespace}}{\boxed{f_{ij}(T,\rho)}} \underset{\text{transition strength}}{\boxed{B_{ij}(\mathrm{GT})}}$$

- Conditions: Pre-SN evolution of massive stars = Lower *pf*-shell nuclei are important
  - Electron density $\rho Y_e = 10^7$ g/cm^3; Temperature 2.5-4.5 GK
  - Only transitions from the ground state are included to infer the rate
  - **Low-lying strengths** dominate the total rate



Remarks:

- Strength to **the 991 keV state** *dominates the total rate* (except for the higher temps)
- SMs give lower rates as strengths locate at higher E_x
- Among SMs, GXPF1A is closest, but it is just coincidental given the overall poorer description
- QRPA overestimates the rate due to larger low-lying strengths
- Similarly for the ^{45}Sc case

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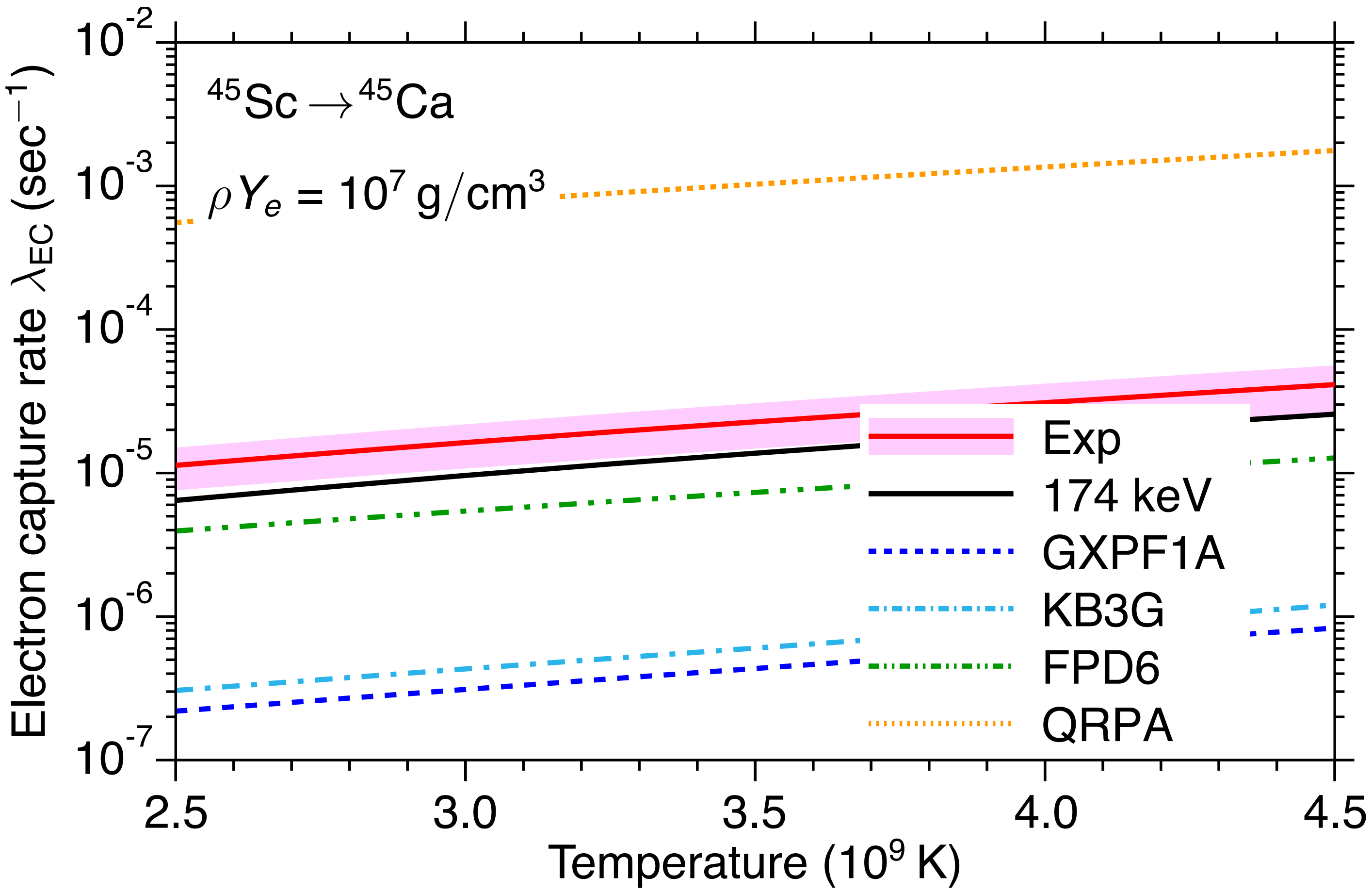

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Collaborators

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