Asymmetry Dependence of Spectroscopic Factors with Transfer Reactions

Juan José Manfredi Jr.
UC Berkeley
Reaction Seminar
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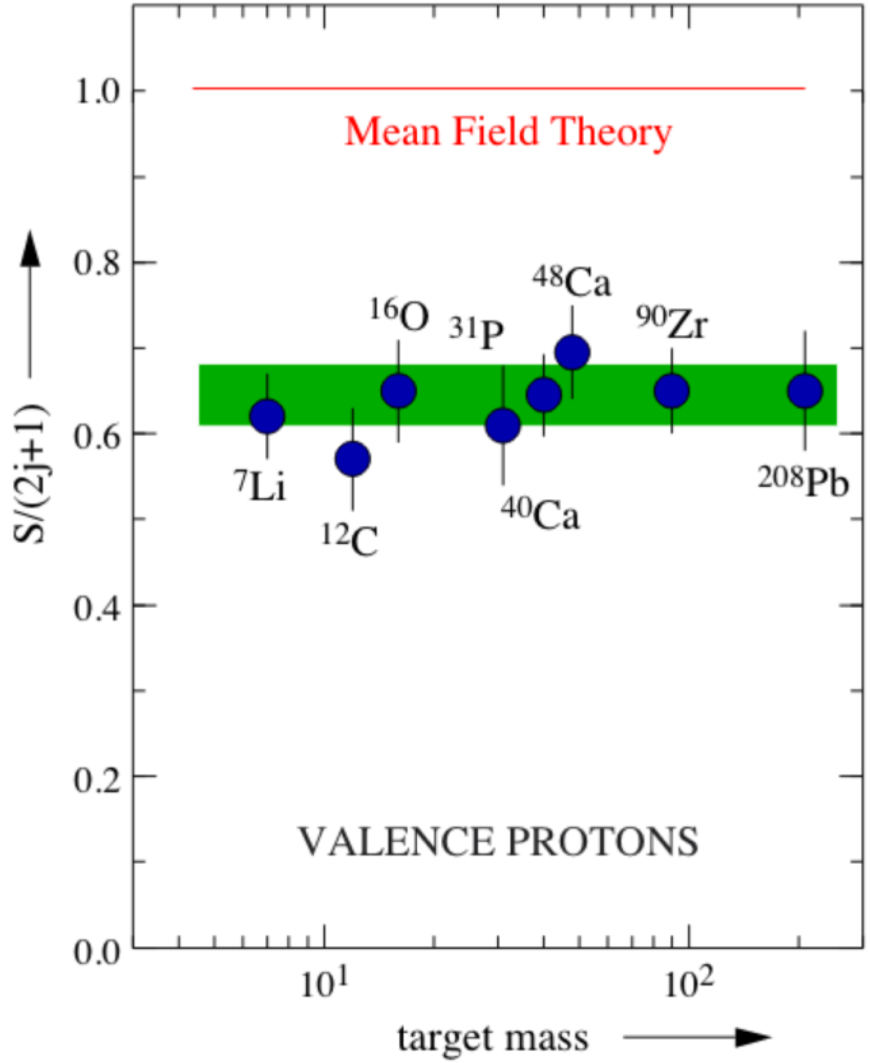
Reduced spectroscopic factors from (e,e'p)

- In the Independent Particle Model (IPM), nucleons move independently in a mean field created by other nucleons
  - ***Correlations*** between individual nucleons complicate this picture
- The spectroscopic factor (SF) quantizes the occupancy of a given single particle orbital

$$SF = \int d\vec{p}\, \left|\langle \Psi^{N-1} | a_{\vec{p}} | \Psi^{N} \rangle\right|^2$$

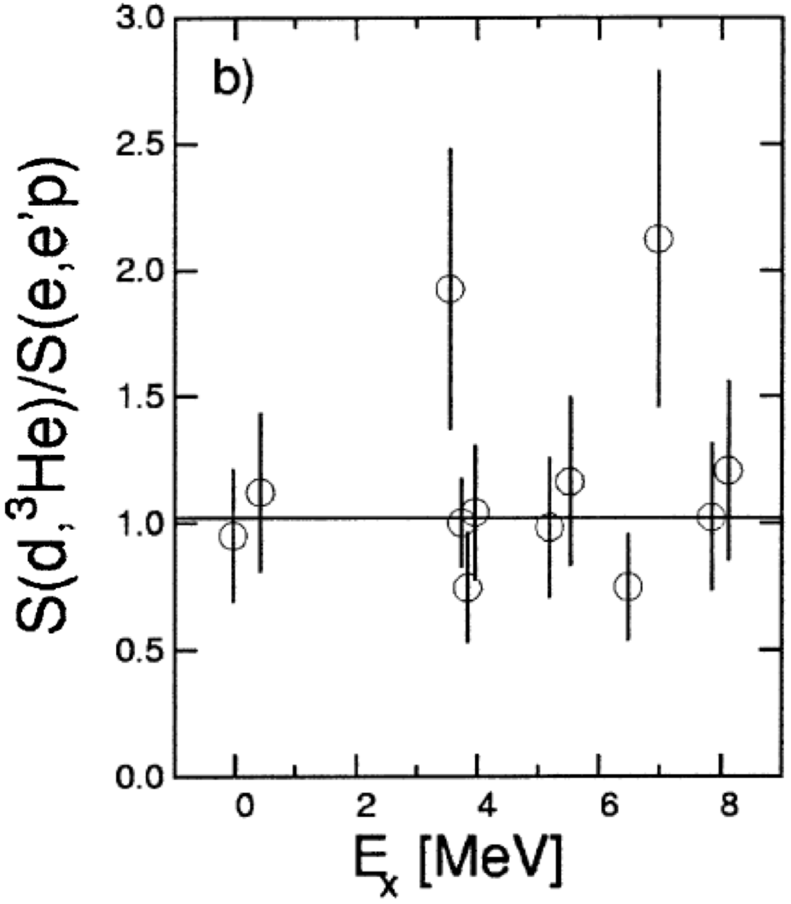
- (e,e'p) data from NIKHEF shows substantial and consistent ***reduction*** in single-particle strength compared to IPM
- \+ Electromagnetic probe, penetrates to nuclear interior
- \- Limited to stable nuclei, cannot access particle states, cannot access hole states from neutron removal

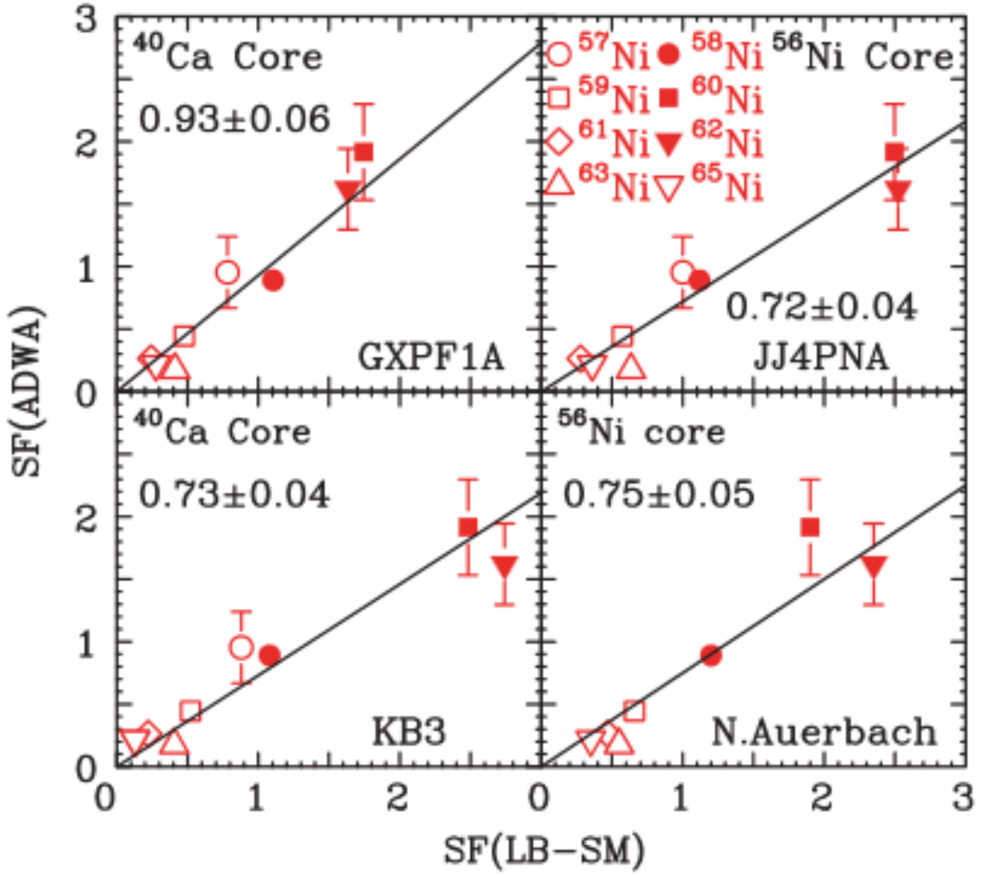


L. Lapikas Nucl. Phys. A553, 297c (1993).
W. Dickhoff and C. Barbieri, Prog. Part. Nucl. Phys. 52, 377 (2004).

Transfer reactions as a probe for nuclear structure

- Transfer reactions provide more flexibility in isotope, single-particle state
- With appropriate analysis methodology, SFs consistent with (e,e'p)
- Allows for useful nuclear structure studies
- In this talk, we will focus on single-neutron pickup, or (p,d)





G. J. Kramer, H. P. Blok, and L. Lapikas, Nucl. Phys. A679, 267 (2001).
J. Lee, et al. Phys. Rev. C 79, 054611 (2009).

Transfer reaction formalism: DWBA

- Distorted Wave Born Approximation (DWBA)
  - Split potential into two components U_1 and U_2, and treat U_2 as a perturbation
  - Prior form convenient: interaction term is V_{np}
  - For single-step DWBA, choosing spherical U_1 results in a straightforward T-matrix expression

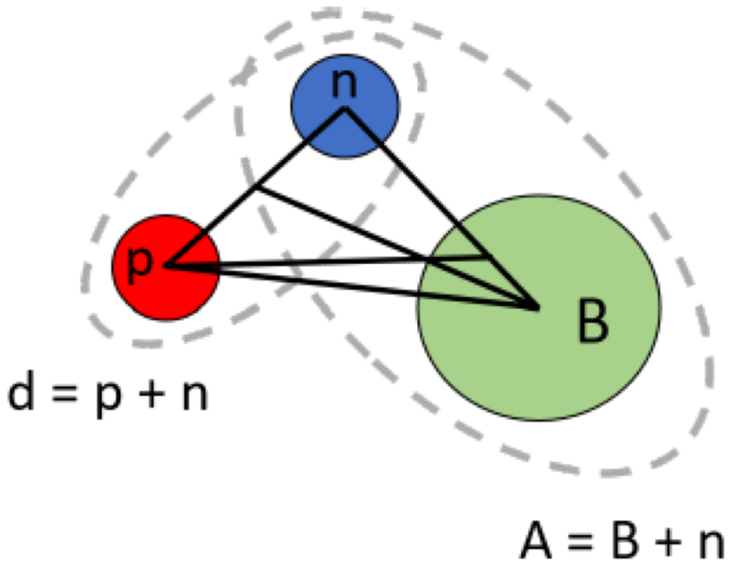
$$\mathbf{T}^{(1+2)} = \mathbf{T}^{(1)} + \mathbf{T}^{2(1)}$$

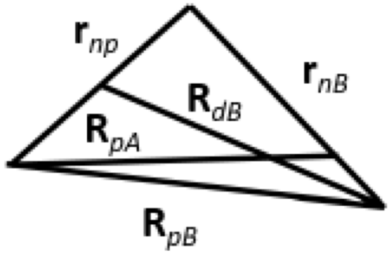
$$H = H_{\text{prior}} = T_{\mathbf{R}_{pA}} + U_i(\mathbf{R}_{pA}) + H_A(\mathbf{r}_{nB}) + \mathcal{V}_i$$

$$= H_{\text{post}} = T_{\mathbf{R}_{dB}} + U_f(\mathbf{R}_{dB}) + H_d(\mathbf{r}_{np}) + \mathcal{V}_f$$

$$\mathcal{V}_i = V_{np}(\mathbf{r}_{np}) + \overbrace{U_{pB}(\mathbf{R}_{pB}) - U_i(\mathbf{R}_{pA})}^{\sim 0}$$

$$\mathcal{V}_f = V_A(\mathbf{r}_{nB}) + U_{pB}(\mathbf{R}_{pB}) - U_f(\mathbf{R}_{dB})$$





$$\mathbf{T}^{\text{DWBA}} = \cancelto{0}{\mathbf{T}^{(1)}} - \frac{2\mu}{\hbar^2 k}\langle \chi^* | U_2 | \chi \rangle$$

$$\mathbf{T}^{\text{DWBA}}_{\alpha\beta} = -\frac{2\mu}{\hbar^2 k}\left\langle \chi^*_\alpha \phi_p \phi_A \middle| V_{np} \middle| \phi_d \phi_B \chi_\beta \right\rangle$$

Nuclear Reactions for Astrophysics. I.J. Thompson and F.M. Nunes. Cambridge University Press (2009).

Transfer reaction formalism: approximations

- Adiabatic Distorted Wave Approximation (ADWA)
  - Internal motion of n and p in d is slow compared to d → model d-target as n-target and p-target
  - Benchmarked favorably with exact Faddeev calculations for simple systems at low energies, angular mom. transfer

$$U_d(\vec{R}) = \frac{1}{D_0}\int \left\{U_n(\vec{R}+\frac{1}{2}\vec{r}) + U_p(\vec{R}-\frac{1}{2}\vec{r})\right\} V_{np}(\vec{r})\phi_d(\vec{r})d\vec{r}$$

$$D = (1 + k_b^2\beta^2)D_0$$

- Local energy approximation
  - First-order correction to our assumption that np interaction is zero-range

$$V(\mathbf{r},\mathbf{r}') = U(\tfrac{1}{2}|\mathbf{r}+\mathbf{r}'|)H(|\mathbf{r}-\mathbf{r}'|)$$

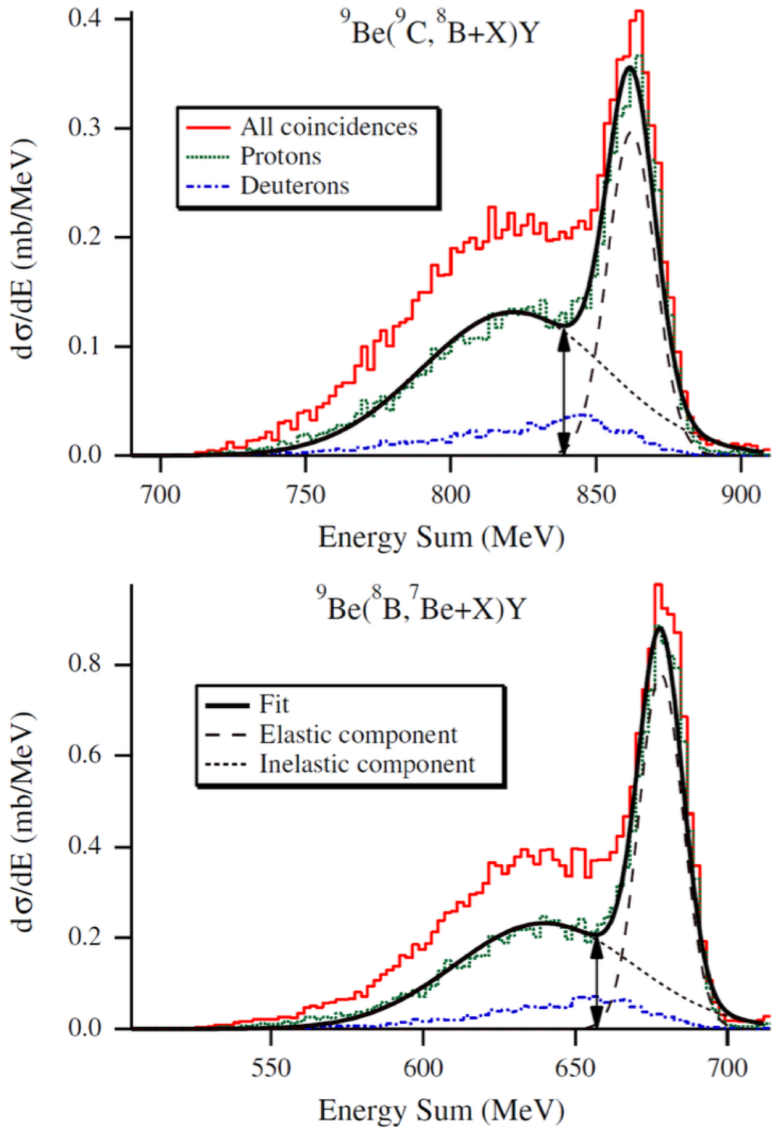
- Perey-Buck nonlocality
  - Gaussian adjustment to local potential
  - Will return to this issue in later slides

$$H(|\mathbf{r}-\mathbf{r}'|) = \frac{\exp\left[-\left(\frac{\mathbf{r}-\mathbf{r}'}{\beta}\right)^2\right]}{\pi^{\frac{3}{2}}\beta^3}$$

R.C. Johnson and P.J.R. Soper, PRC 1 976 (1970).
F.M. Nunes and A. Deltuva, PRC 84 034607 (2011).
P.J.A. Buttle and L.J.B. Goldfarb, Proc. Phys. Society 83 (1964).
Nuclear Reactions for Astrophysics. I.J. Thompson and F.M. Nunes. Cambridge University Press (2009).
F. Perey and B. Buck, Nucl. Phys. 32 (1962).

Knockout reactions offer high sensitivity

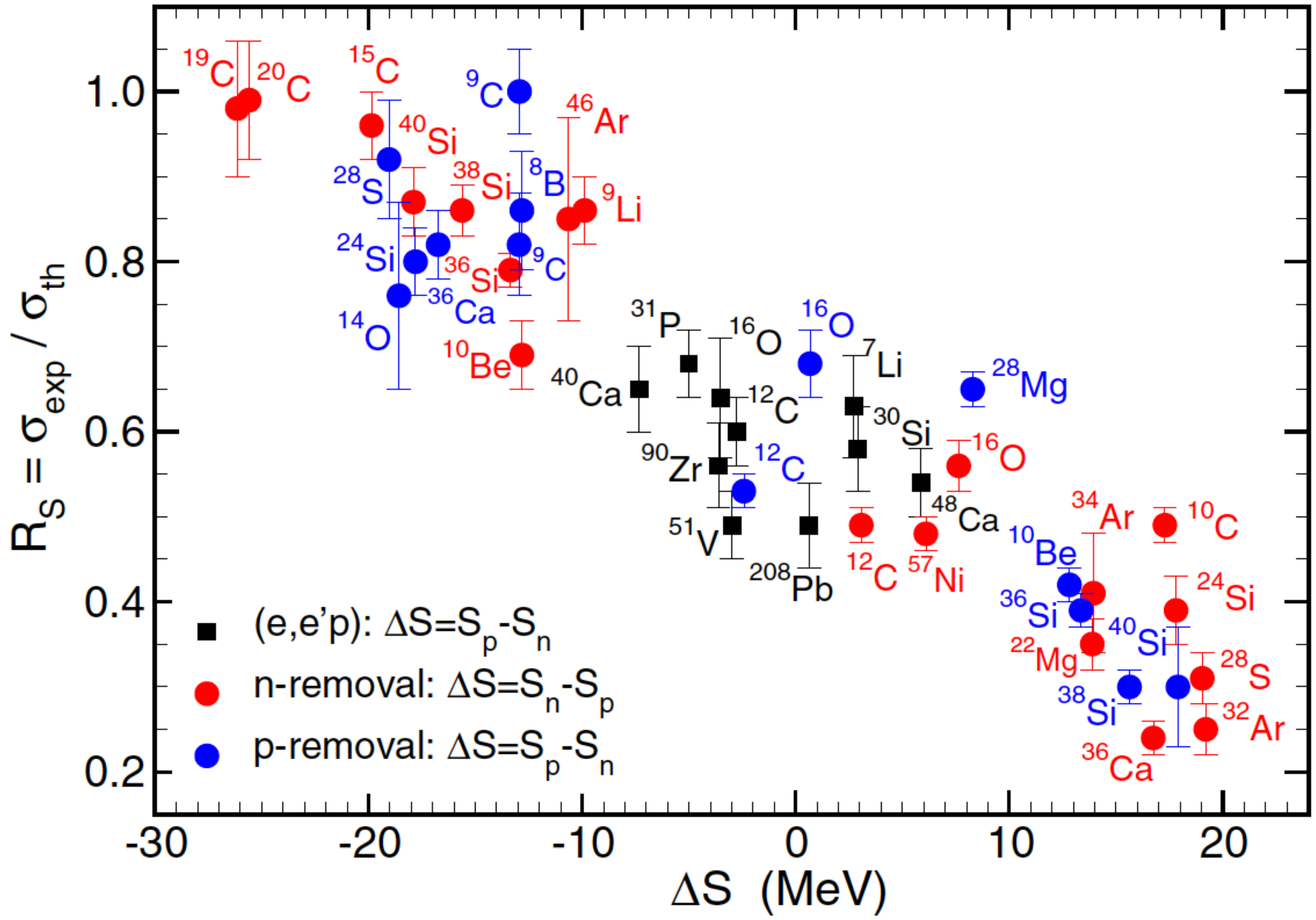
- Single-nucleon knockout works at intermediate energies and with high cross sections
  - This allows for exploration of nuclear structure at high asymmetry (i.e. low beam rates)
- Possible to separate contribution from elastic and inelastic components to constrain reaction mechanism



B.A. Brown, et al., PRC 65, 061601 (2002).
D. Bazin et al., PRL 102, 232501 (2009)

Knockout shows strong quenching at high asymmetry

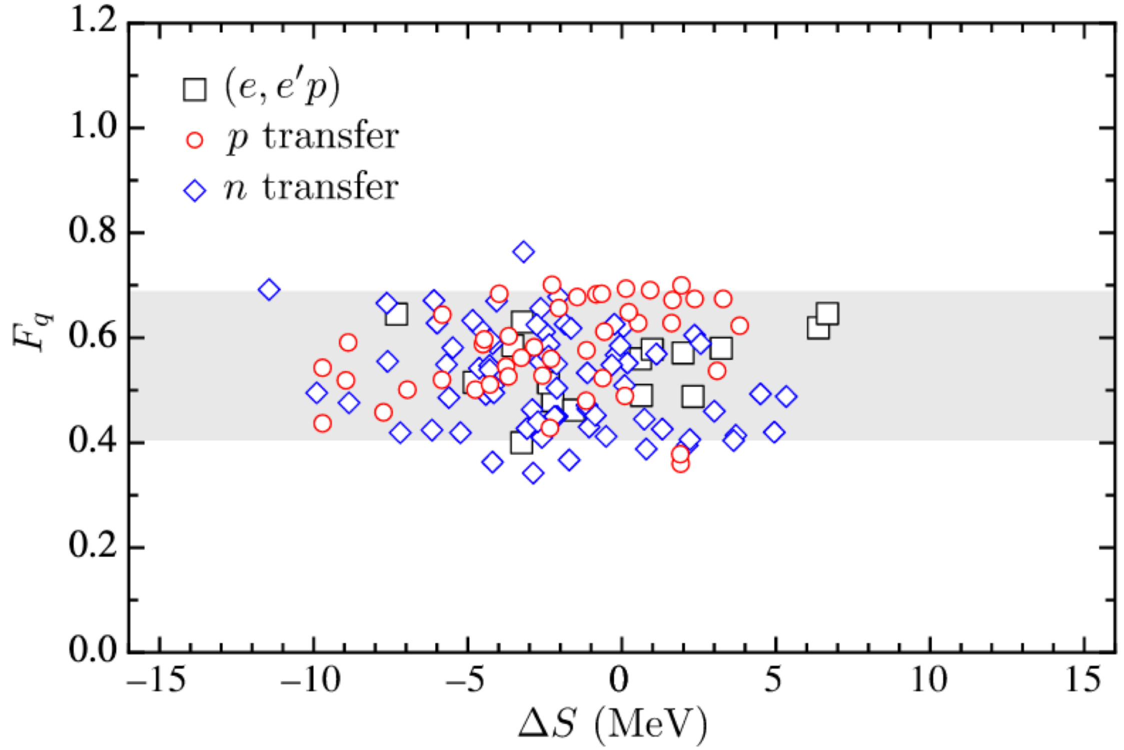
- Knockout on loosely bound nucleons in ^{8}B and ^{9}C indicated little reduction compared to SM
- First measurement of a deeply bound case 32Ar showed massive amount of reduction (*quenching*)
- Strong (and consistent) dependence of SF reduction on the *asymmetry* of the system, represented here by difference of separation energies

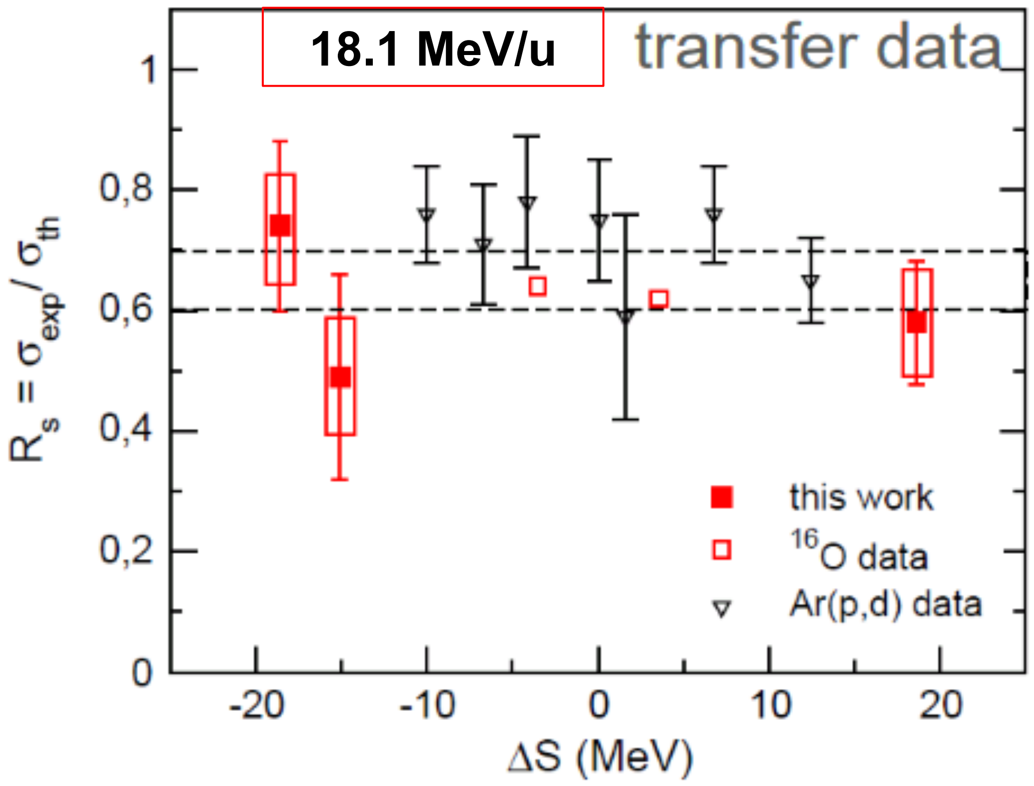


J. Enders, et al., PRC 67, 064301 (2003).
A. Gade, et al., PRL 93, 042501 (2004).
J.A. Tostevin and A. Gade. PRC 90, 057602 (2014).

Transfer shows a different asymmetry trend

- Near stability, there is no evidence from transfer or (e,e'p) of strong quenching as seen in KO
- (p,d) on argon at higher asymmetry indicates no/weak quenching
- Results on asymmetric oxygen isotopes show weak dependence





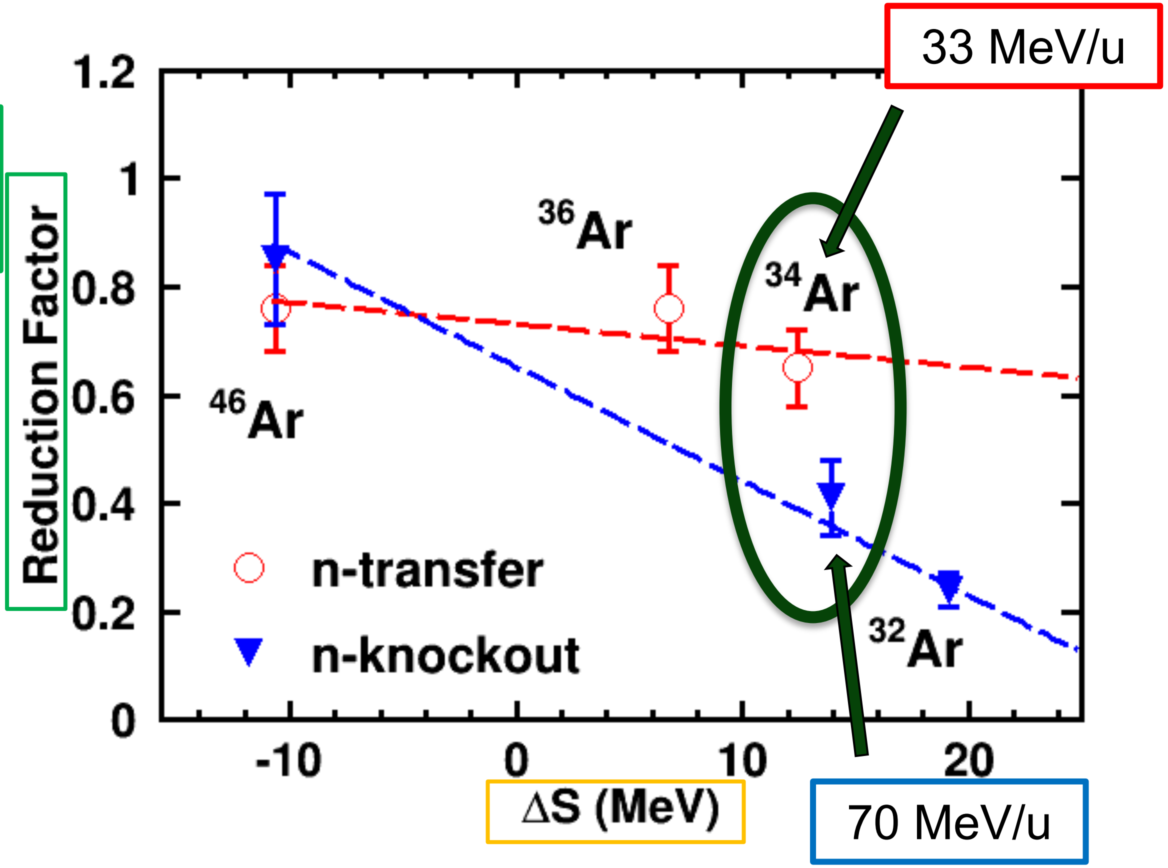
B.P. Kay, et al., PRL 111, 042502 (2013).
Lee, et al., PRL 104, 112701 (2010).
Flavigny, et al., PRL 110, 122503 (2013).
Obertelli, et al., FUSTIPEN, March 2012.

Discrepancy between transfer and knockout

- Comparing SFs from argon chain, there is discrepancy between transfer and knockout results

$$R_s = \frac{SF_{EXP}}{SF_{SM}}$$

- Why?
  - Problem with experiment? Unlikely
  - Problem with reaction model? Perhaps
  - Uncertainties are too large to say? Unlikely
- Perhaps previously described transfer reaction model is insufficient: let us try to break it
  - **Repeat argon (p,d) measurements again but with "knockout-like" beam energy of 70 MeV/u**

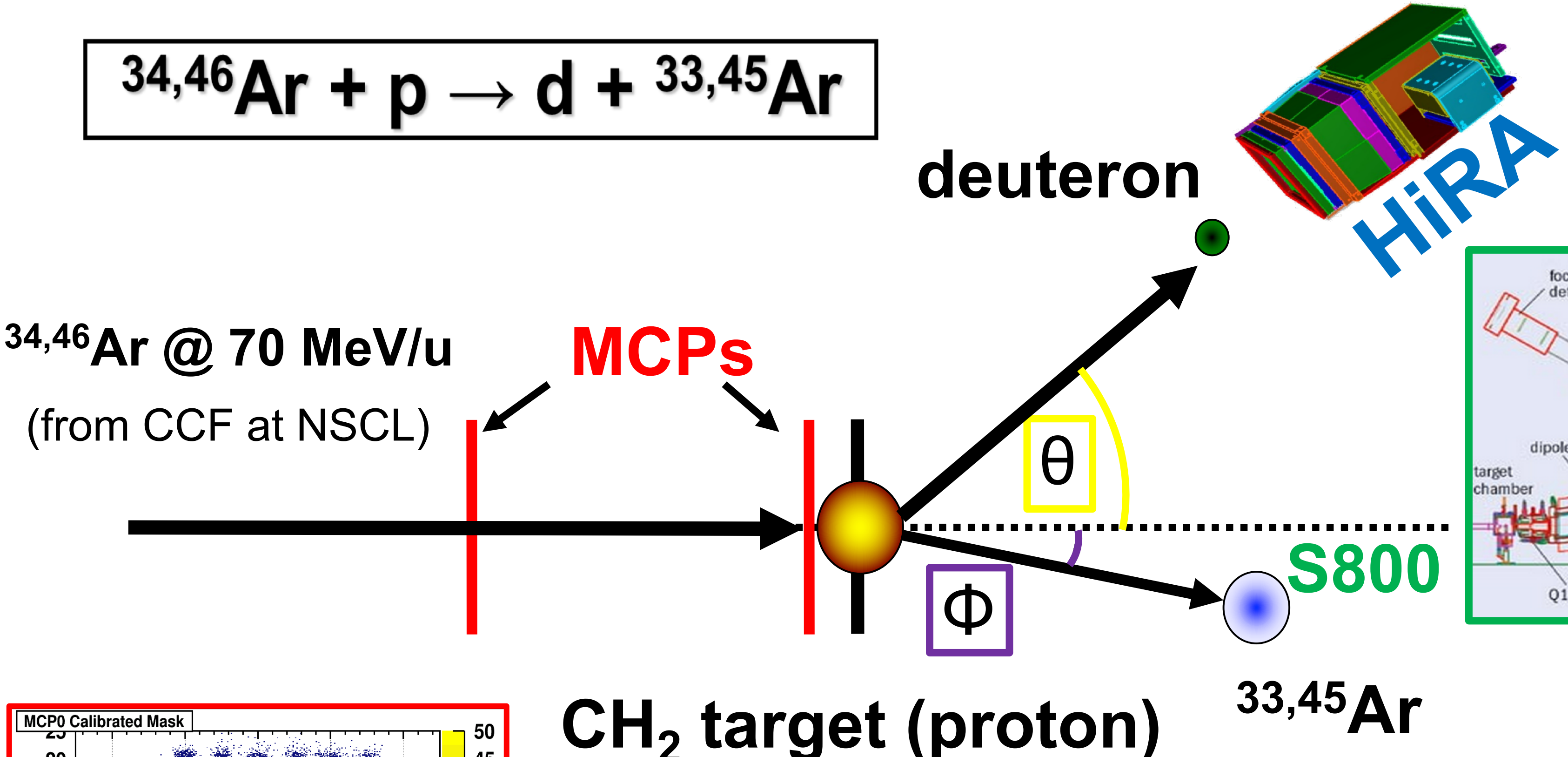


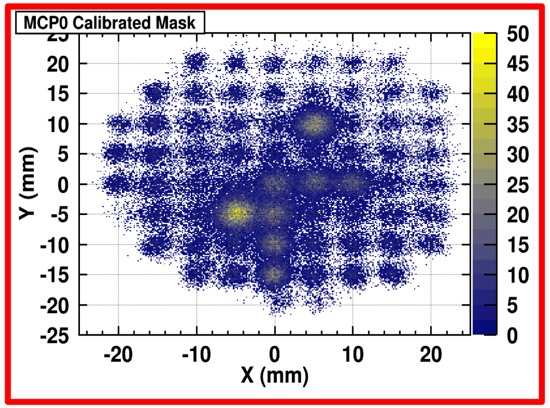
$$\Delta S = S_n - S_p$$

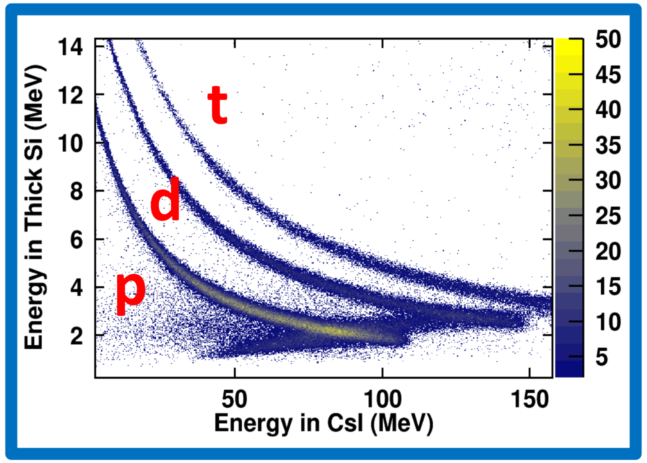
Gade, et al., Phys. Rev. C 77, 044306 (2008).
Lee, et al., Phys. Rev. Lett. 104, 112701 (2010).
Shane, et al., Phys. Rev. C 85, 064612 (2012).
Nunes, et al., PRC 83, 034610 (2011).

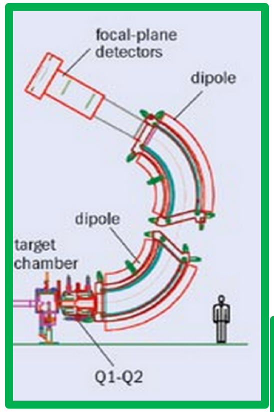
Experimental setup for (p,d) w/ complete kinematics

$^{34,46}Ar + p \rightarrow d + {}^{33,45}Ar$

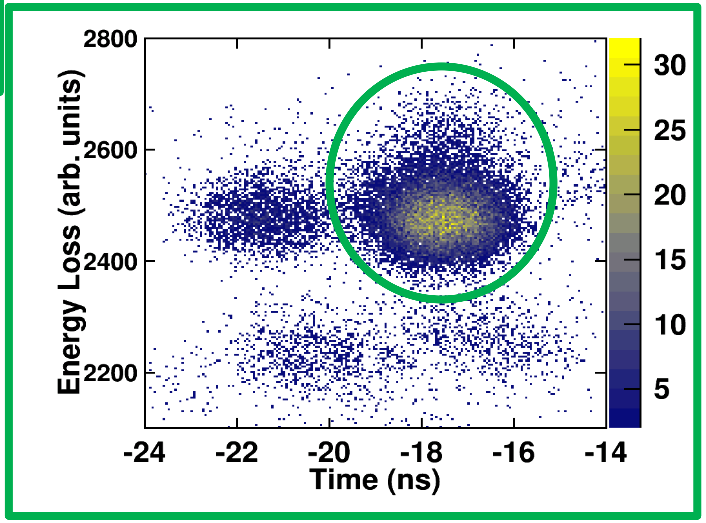






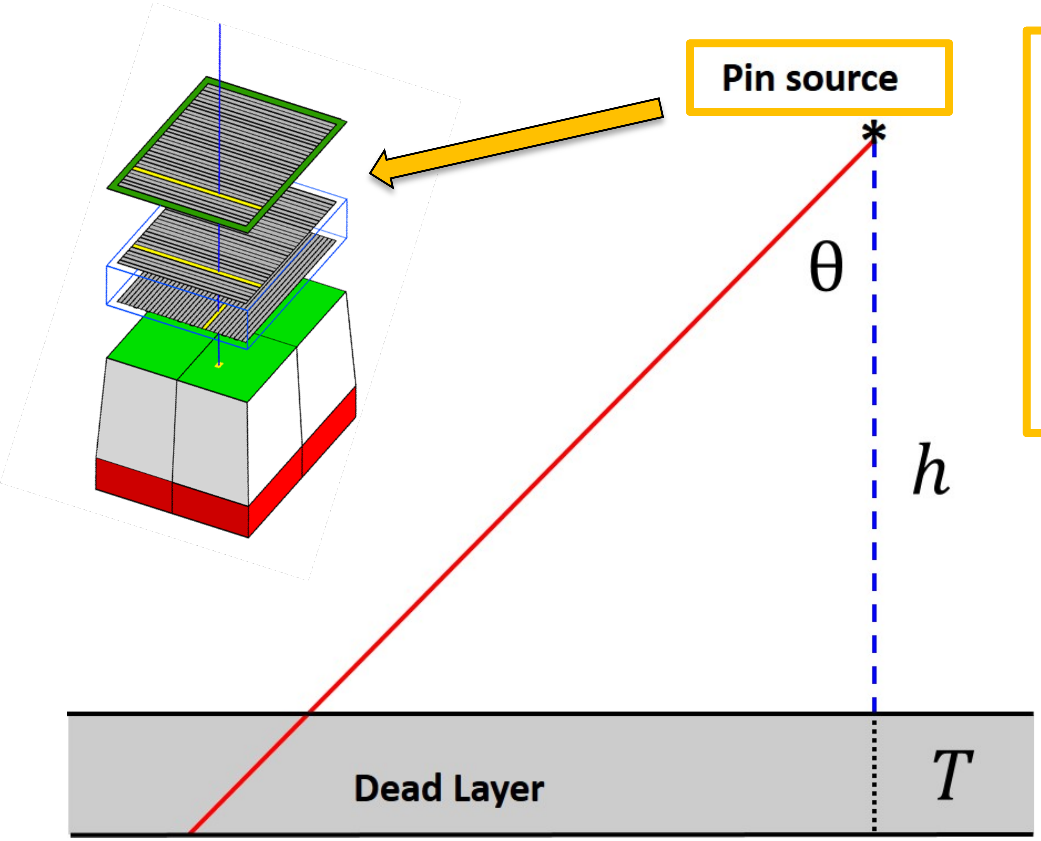


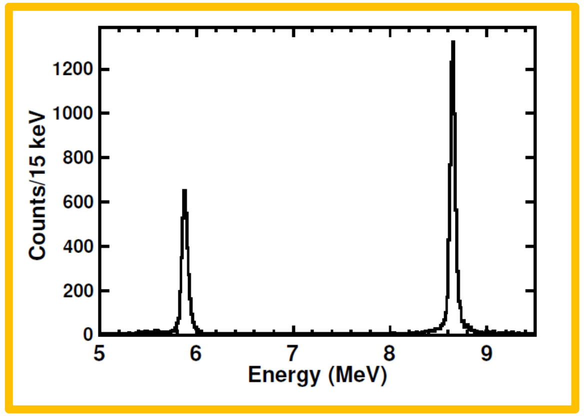
^{45}Ar

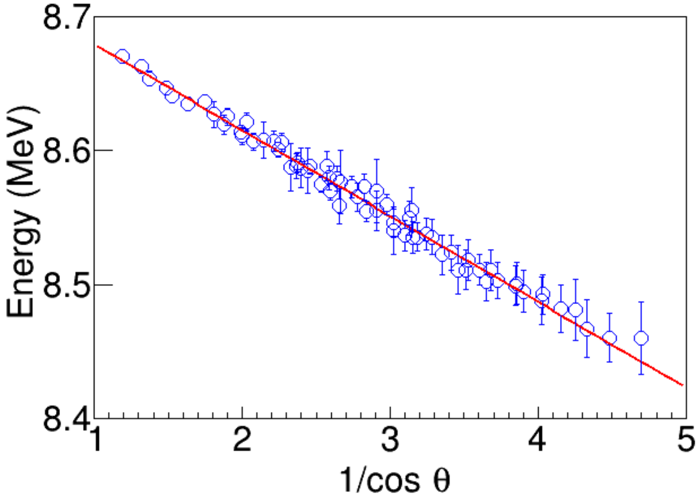


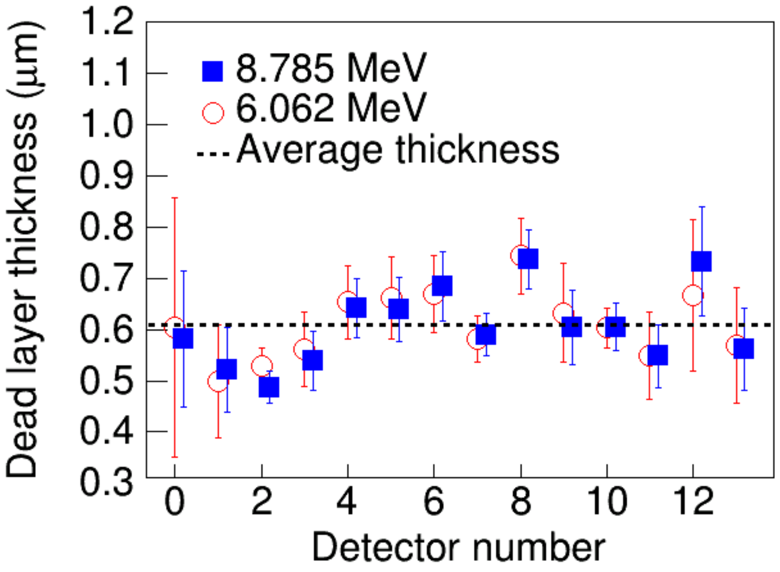
HiRA DSSD dead layer measurements

- Irradiated pin source inserted between Si detectors + position sensitivity of DSSD also allows for dead layer thickness extraction





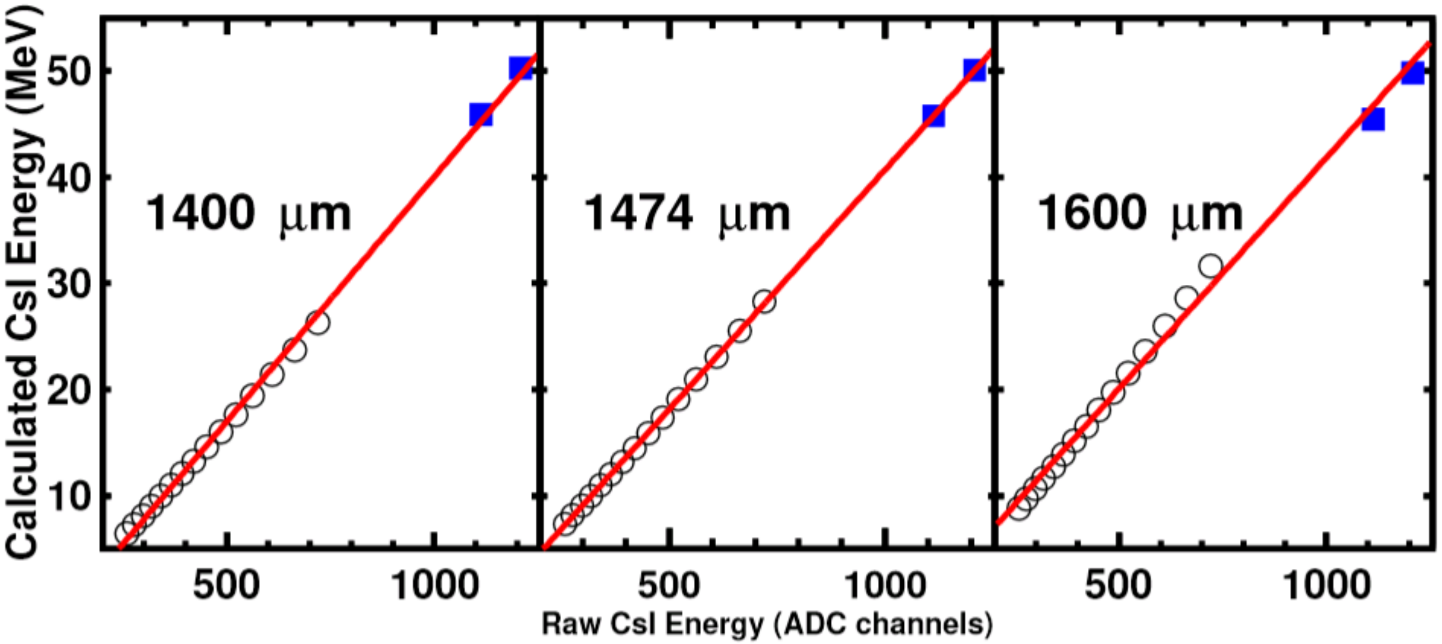


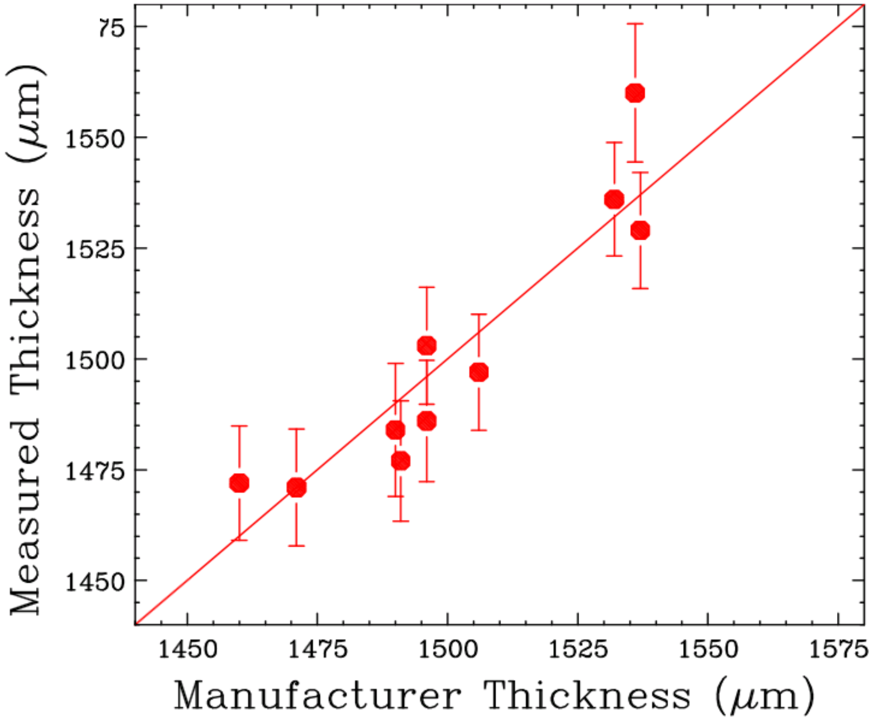


J. Manfredi et al, NIM A 888 (2018).

HiRA CsI calibration + DSSD Detector Thickness

- Calibrated E data in conjunction with energy loss tables can be used to calibrate CsI, **but detector thickness important**
- Detector thickness extracted by comparing high energy elastic scattering data (solid blue squares) with low energy points calculated using energy loss tables (open circles)
- Extracted values match manufacturer thicknesses

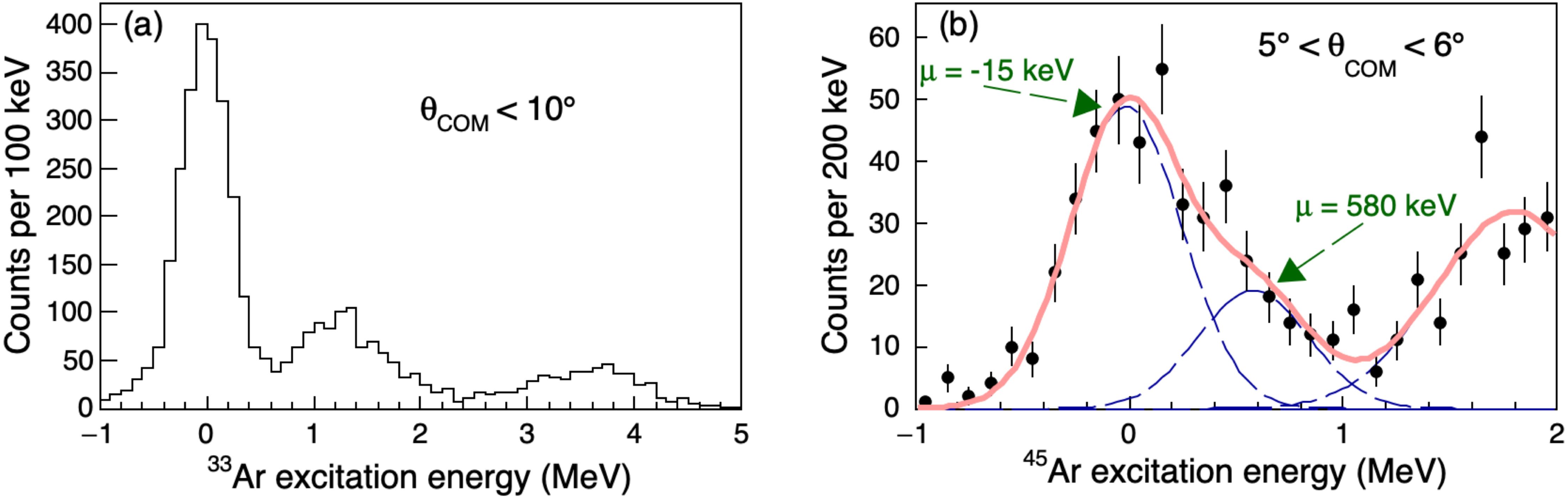




J. Manfredi et al, NIM A 888 (2018).

Excitation energy spectra for ^{33}Ar and ^{45}Ar

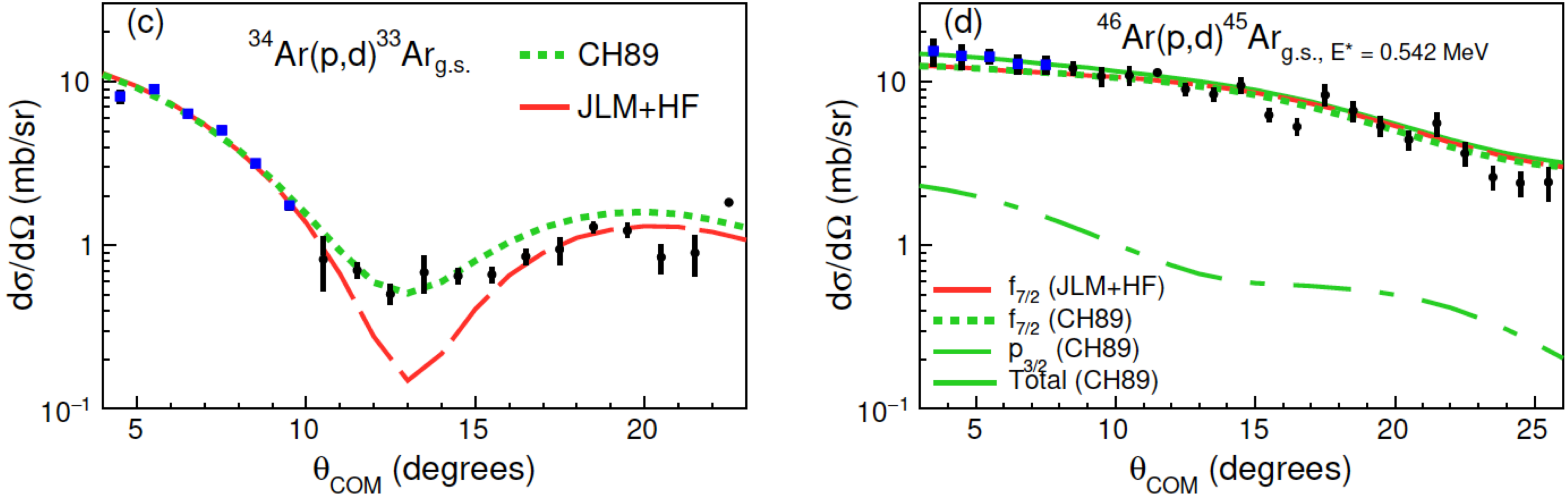
- Excitation energy spectra for heavy recoils enable exclusive g.s.-to-g.s. (p,d) measurements
- In ^{45}Ar case, contribution from $p_{3/2}$ 1st excited state ($E^* = 0.542$ MeV) separated from $f_{7/2}$ ground state by fitting spectrum with multiple Gaussians at fixed widths set to experimental uncertainty



J. Manfredi et al. (under review).

Differential cross sections and SF extraction

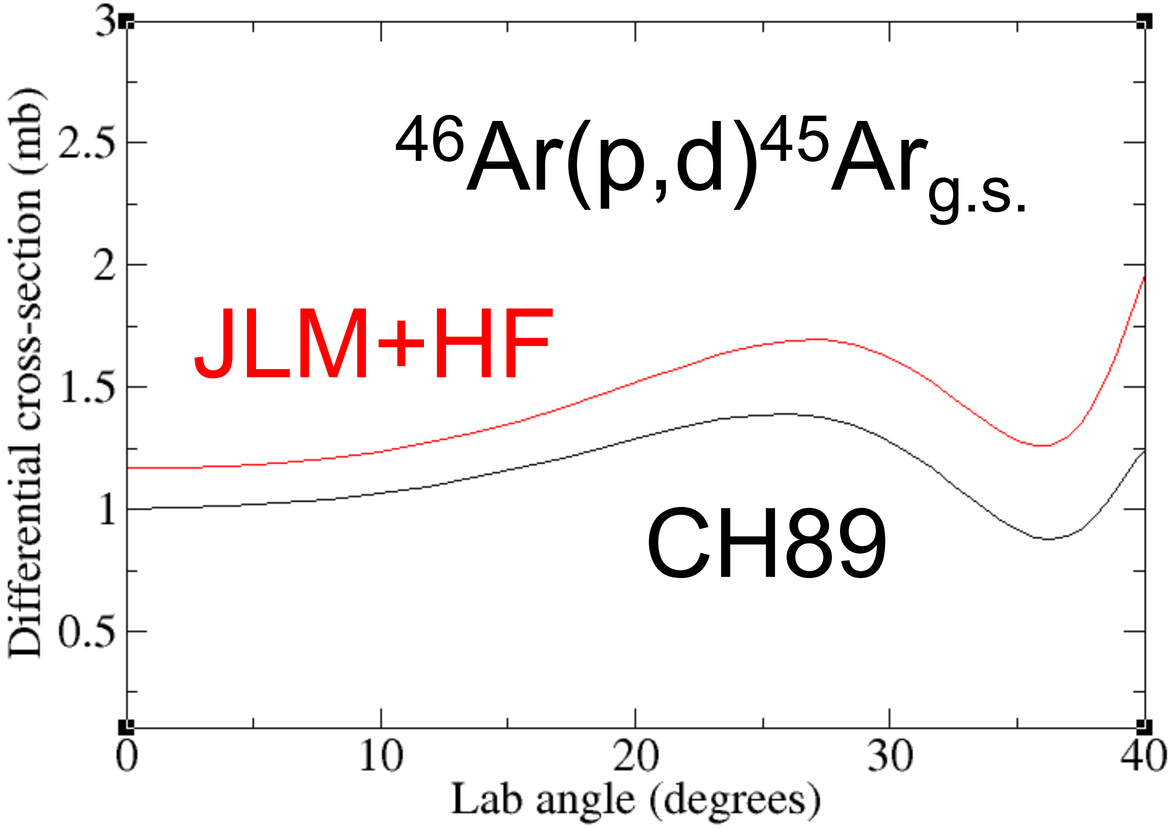
- Normalized differential cross section data compared to reaction theory calculations (see next slide) to get SFs with chi-squared minimization at forward angles (blue square points)
- Reasonable match in differential cross section shapes



J. Manfredi et al. (under review).

ADWA Calculations

- **TWOFNR** finite-range direct reaction code used for all calculations with aforementioned formalism + approximations
- Two separate approaches:
  - **CH89**: global parametrization across reaction data from many systems + conventional Woods-Saxon bound state
  - **JLM+HF**: microscopic calculation derived from effective nuclear densities (from Hartree-Fock with SkX) for individual systems
    - » Geometries determined by varying radius parameter to match HF rms radius of specific orbital
- Approaches differ by ~30% in cross section magnitude, but agree on asymmetry trend

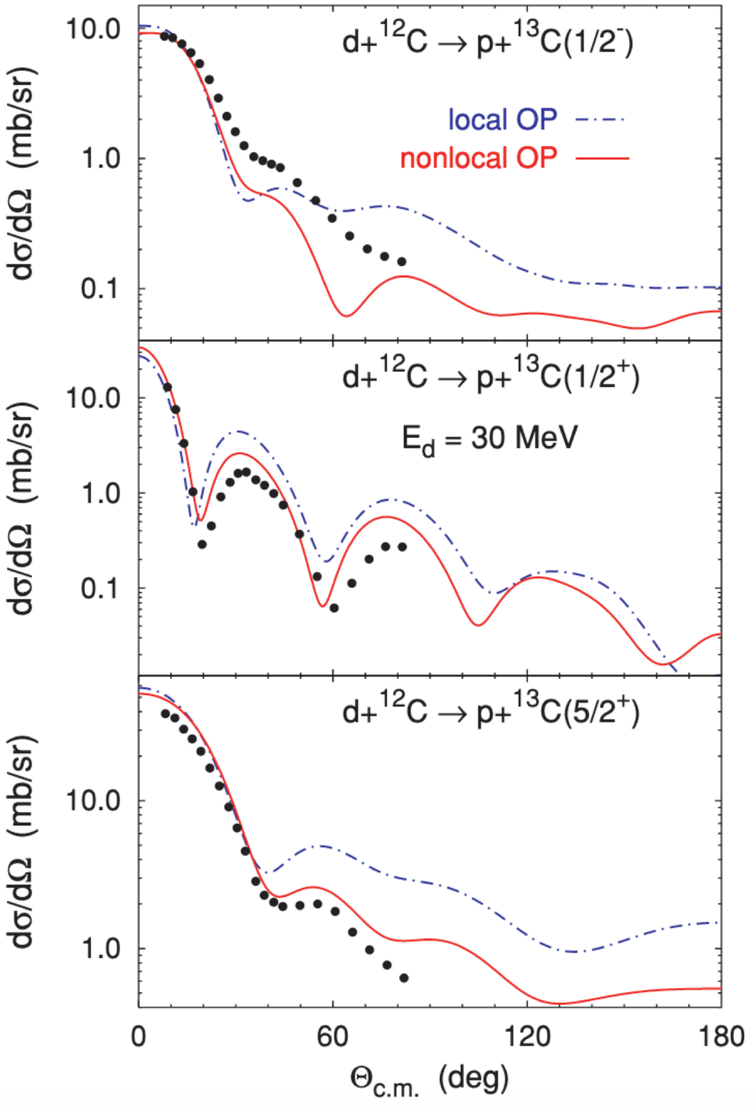


M. Igarashi et al., TWOFNR (Surrey version).
R.L.Varner et al., Phys. Rep. 201, 57 (1991).
J.-P. Jeukenne, A. Lejeune, and C. Mahaux, PRC 15, 10 (1977).
J. Lee et al., PRC 73 044608 (2006).

What about nonlocality?

- Physics is nonlocal!
  - Exchange effects, coupling to other reaction channels
- Is Perey-Buck enough?
  - Deviations from exact nonlocal treatment are well-established
- Balance between including physics and practical application to exotic systems
- Possible compromise: use local potential and add significant shift to energy at which potential is evaluated
  - Accounts for relative kinetic energy between n and p in deuteron

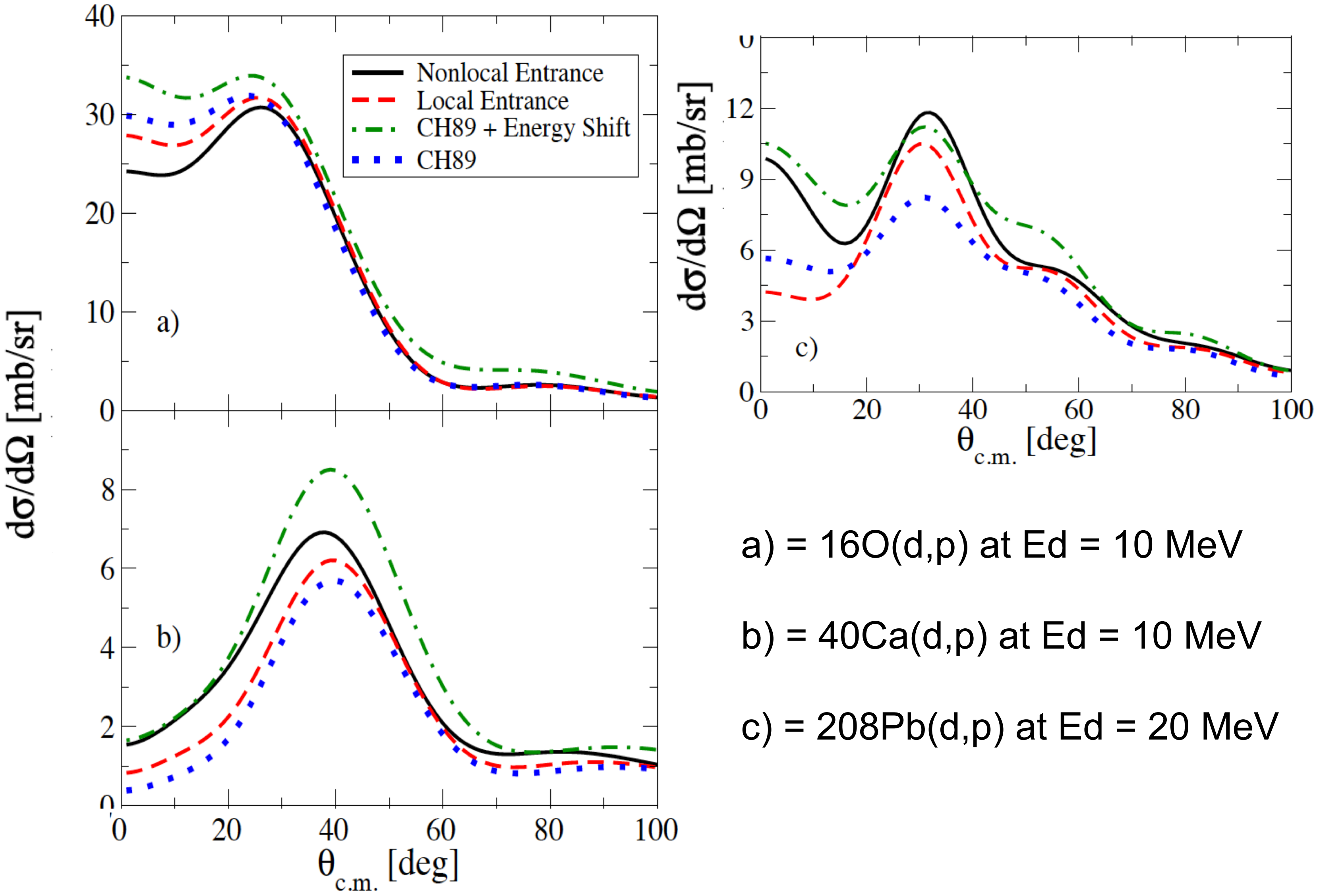
See N. Timofeyuk's talk from May 12



A. Deltuva, PRC 79, 021602 (2009).
N. Timofeyuk and R.C. Johnson, PRL 110 112501 (2012).

Effects of nonlocality in transfer reactions

- However, energy shift does not always improve the naïve local description (compared to exact nonlocal treatment)
- Because of this (and in order to best compare to previous work of Lee, et al.), we use Perey-Buck nonlocality
- This progress is still crucial to improved understanding of transfer reaction mechanism
- **Nonlocality can significantly influence individual SFs, but what is the asymmetry dependence?**



a) = 16O(d,p) at Ed = 10 MeV

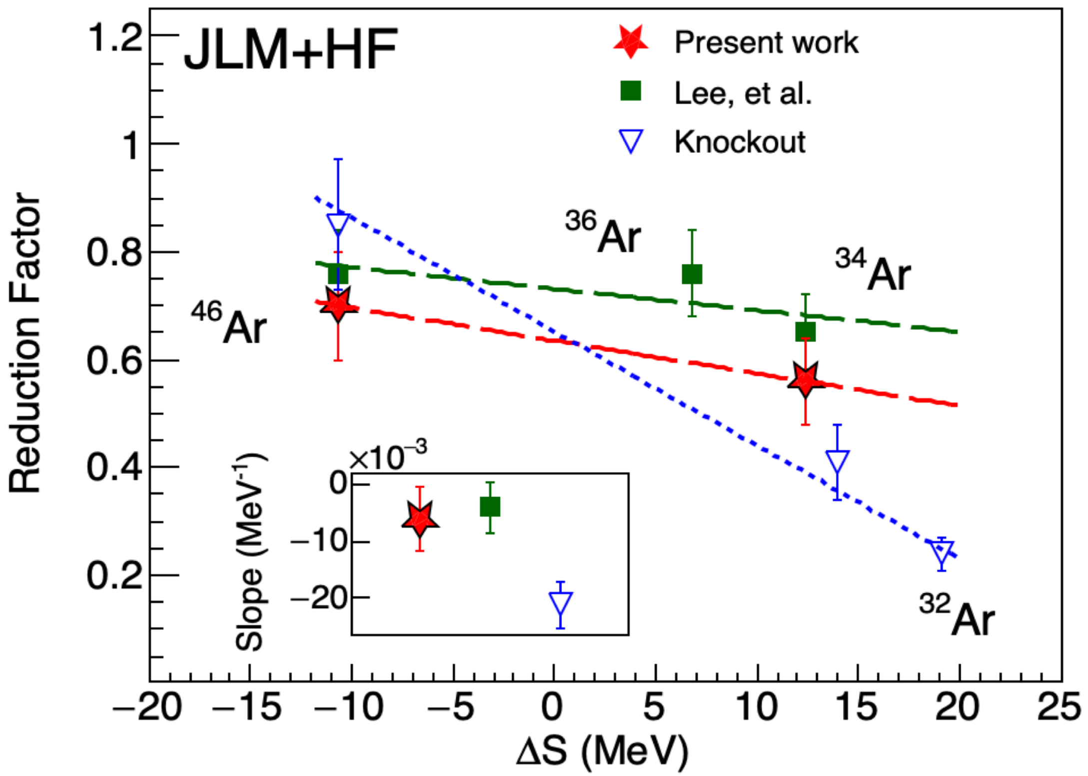
b) = 40Ca(d,p) at Ed = 10 MeV

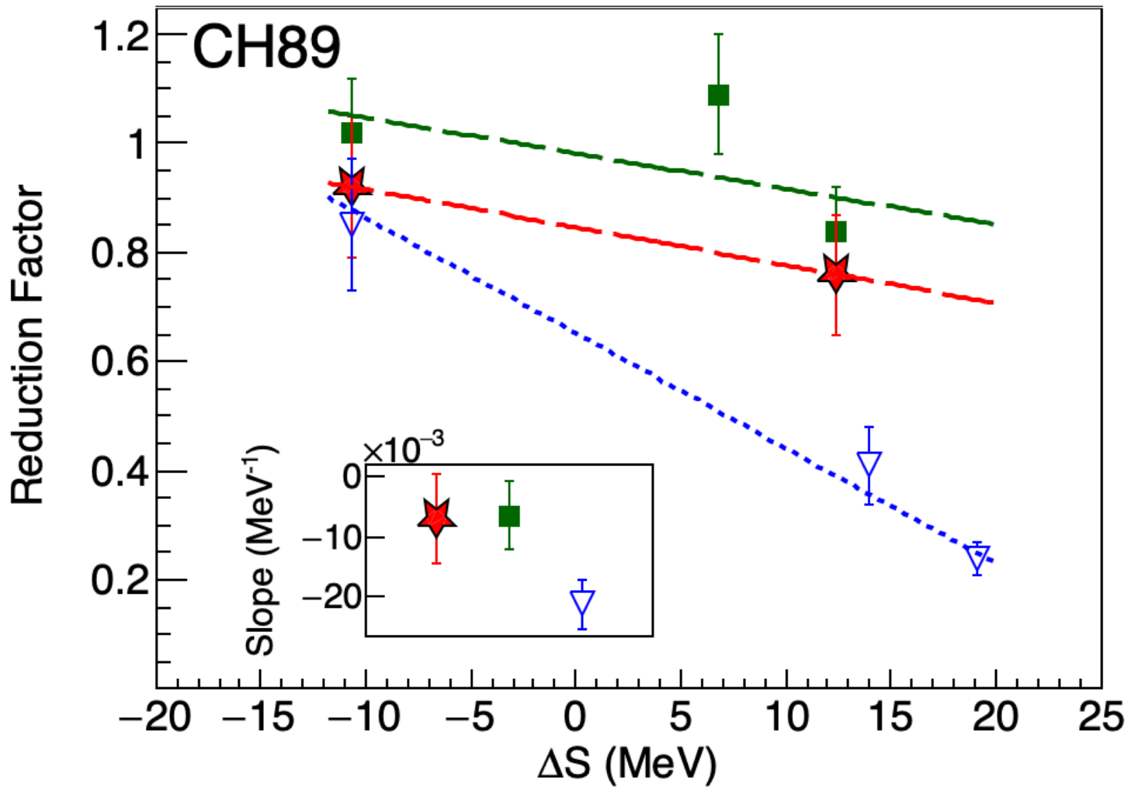
c) = 208Pb(d,p) at Ed = 20 MeV

L.J. Titus, PhD Thesis, MSU (2015).
L.J. Titus, F.M.Nunes, G.Potel, PRC 93, 014604 (2016).

Comparison with knockout and low-energy transfer

- For both CH89 and JLM+HF analysis approaches, SFs agree within error to 33 MeV/u data
- Furthermore, asymmetry dependence is weaker than that observed in beryllium-induced knockout reactions (see slope inset)

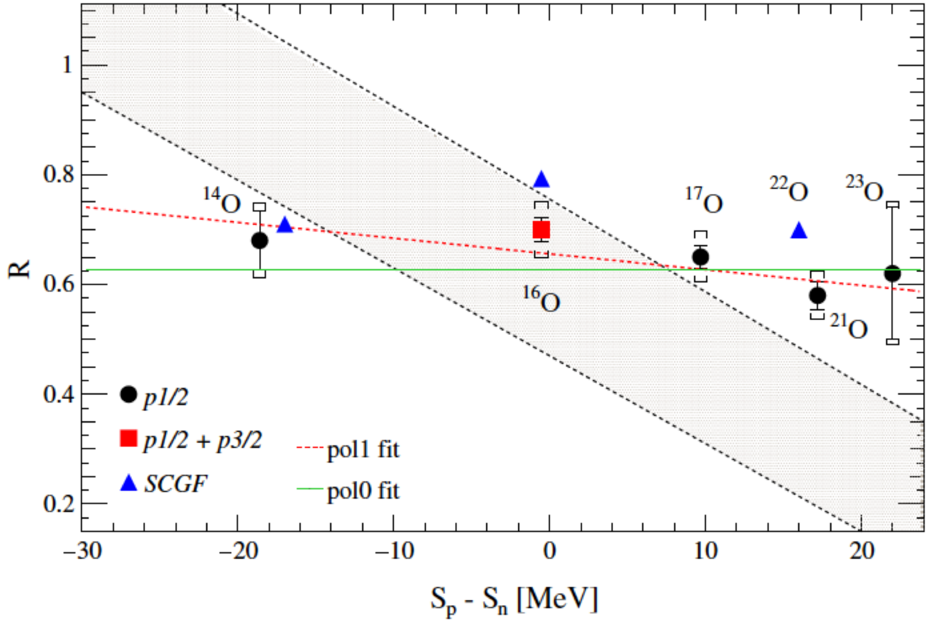


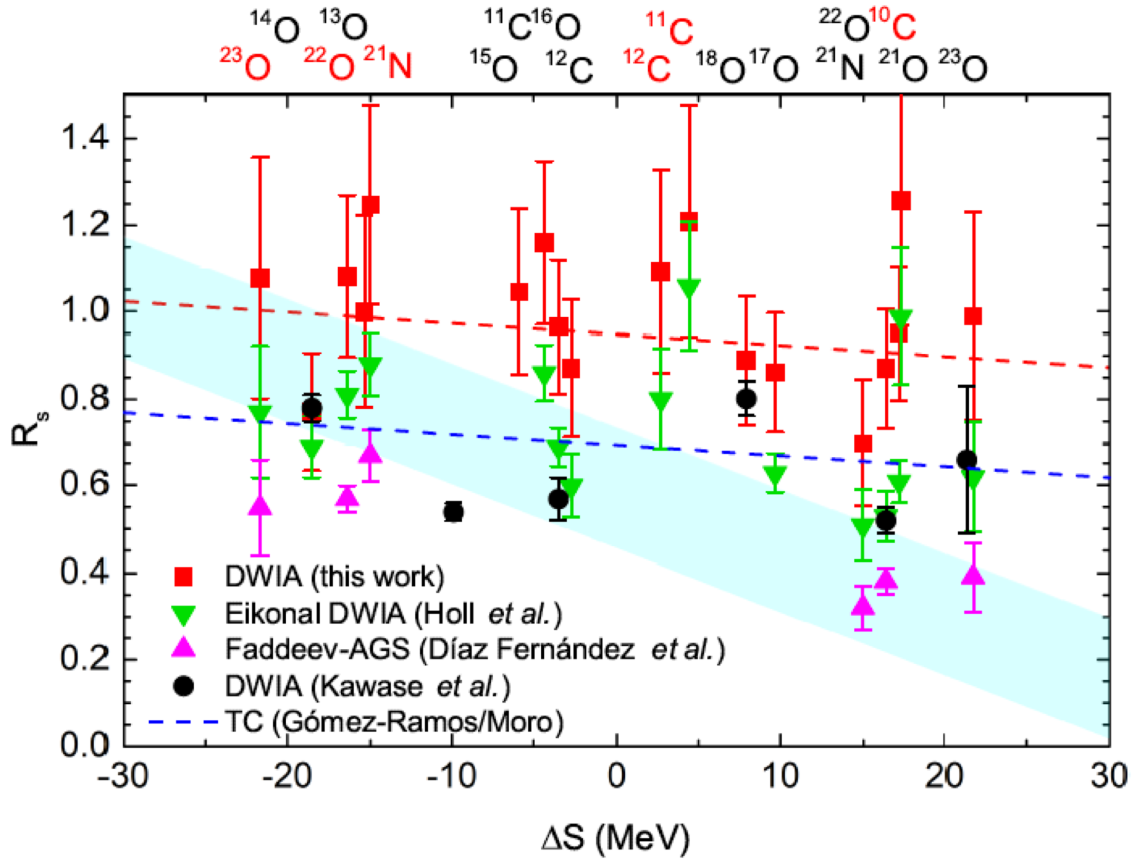


J. Manfredi et al. (under review).

Data with a new approach: (p,pN)

- *Quasifree* nucleon knockout at high energies (100s MeV/u) with proton targets
  - Probes the nuclear interior better than with intermediate energy, Be-induced knockout
  - Lots of new data and analyses coming out



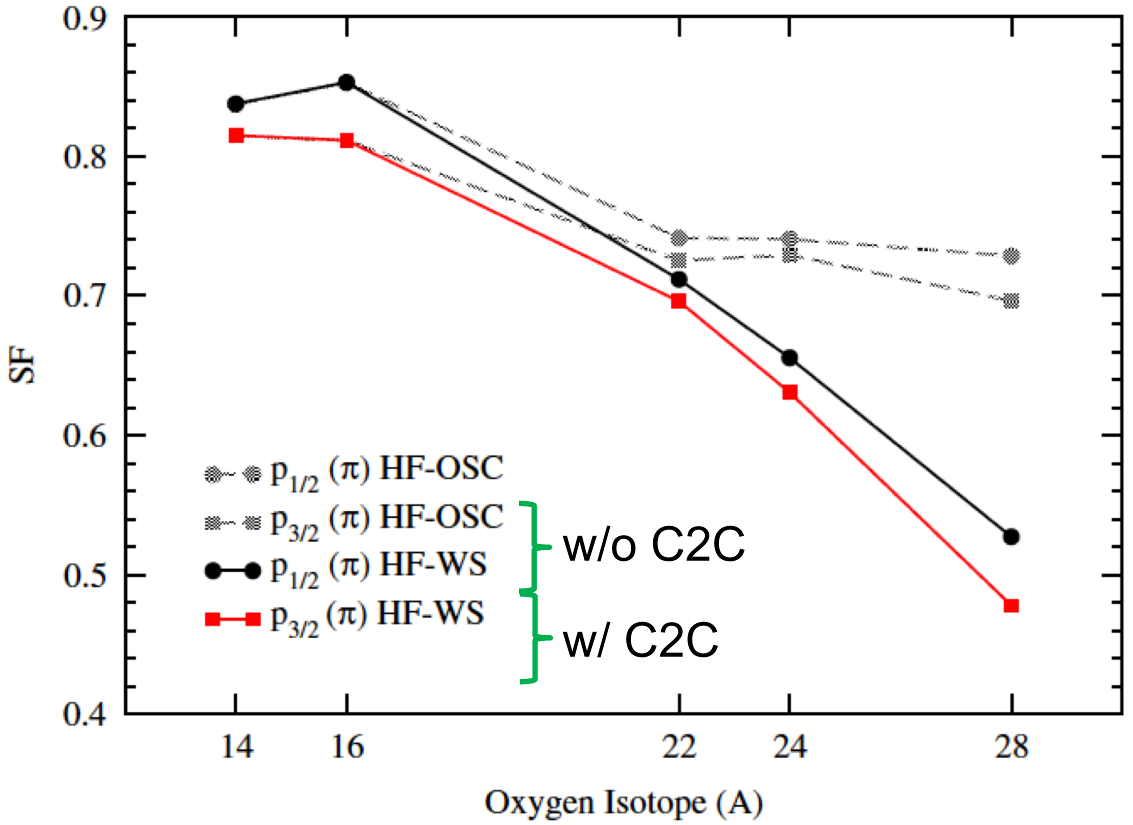


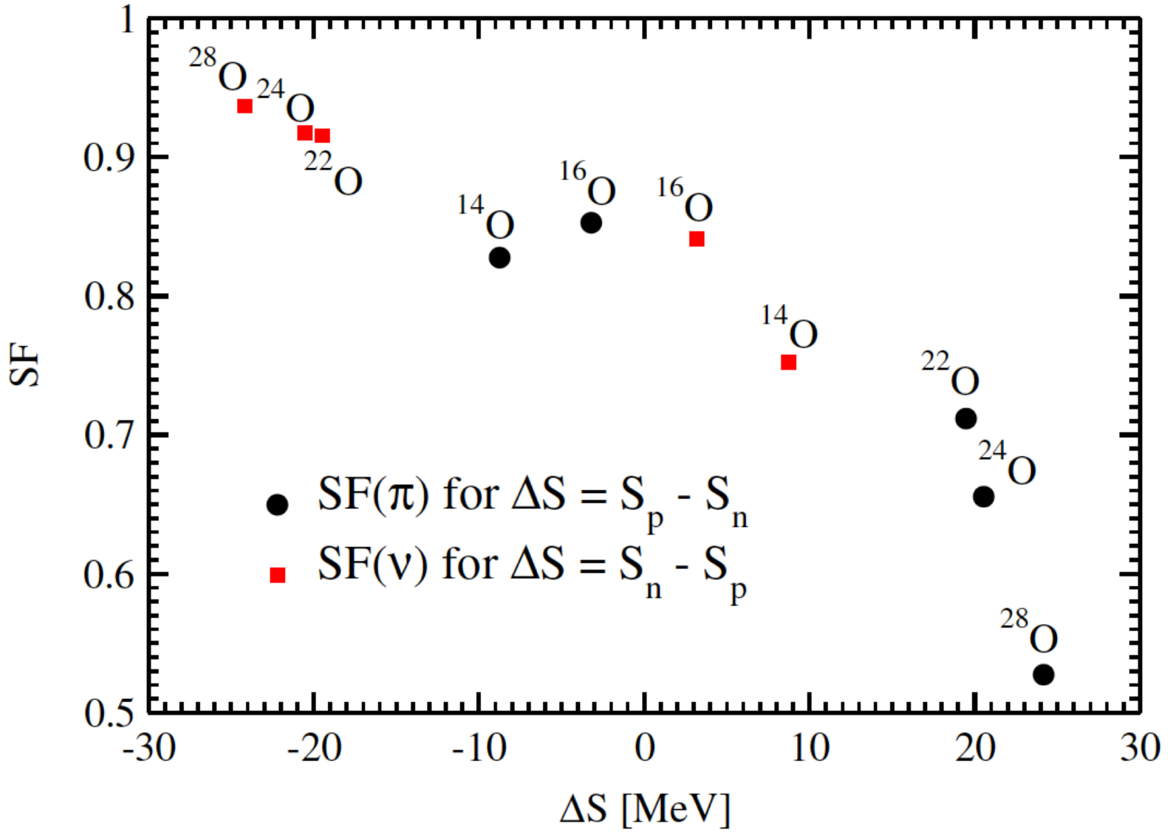
L. Atar et al., PRL 120, 052501 (2018).
M. Gómez-Ramos, A.M. Moro, PLB 785, 511 (2018).
M. Holl et al., PLB 795, 682 (2019).
N.T.T. Phuc, et al., PRC 100, 064604 (2019)

See N.T. Toan Phuc's talk from June 23

Coupled-cluster calculations across oxygen chain

- Microscopic coupled-cluster calculations explicitly treat coupling to the continuum (resulting in many-body correlations that reduce SFs)

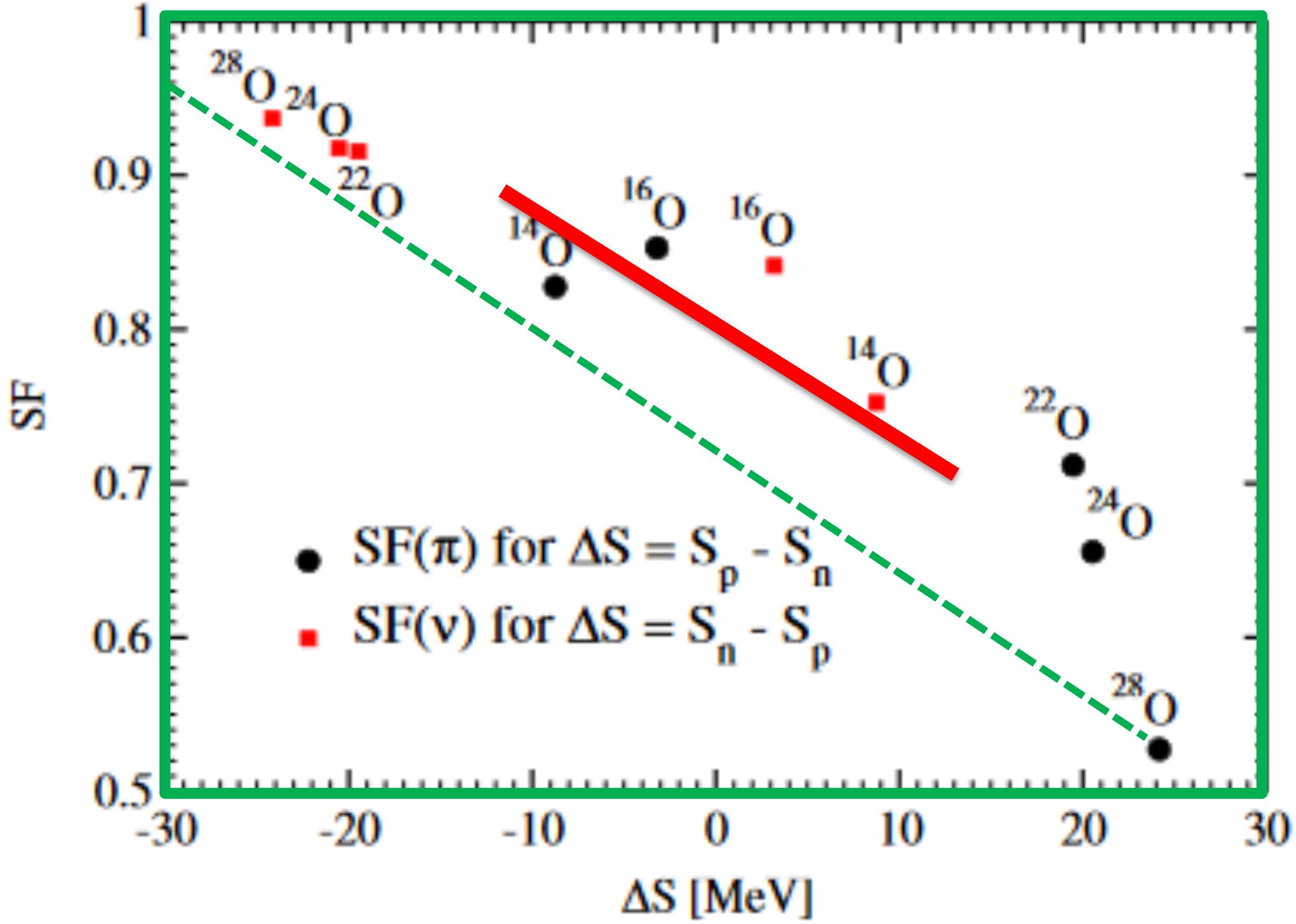




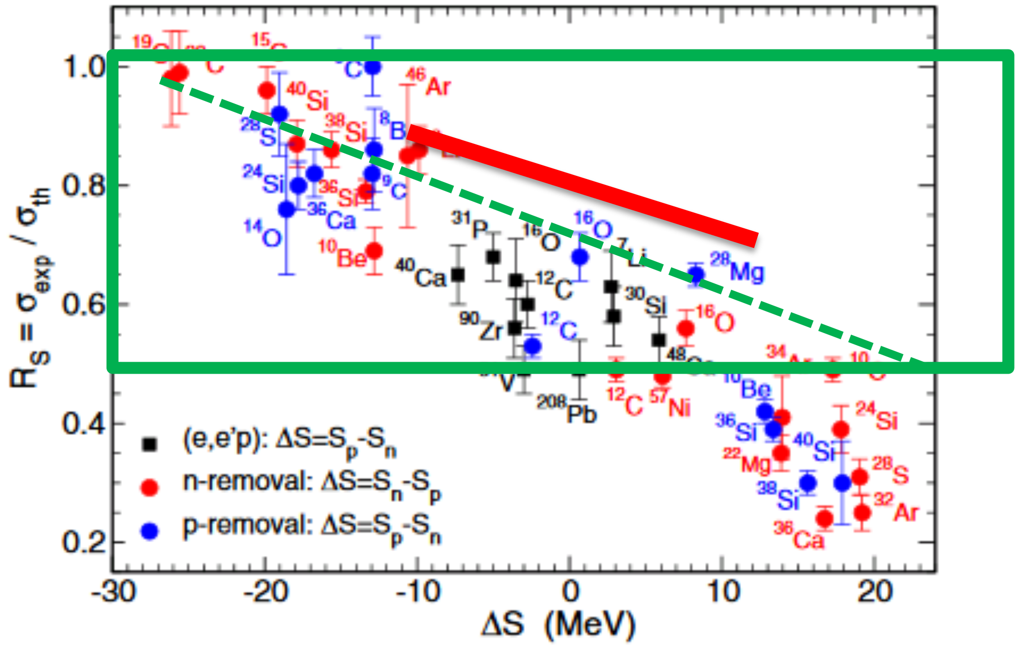
O. Jensen, et al., PRL 107, 032501 (2011)

Coupled-cluster shows weak asymmetry dependence

- Asymmetry dependence from Jensen et al. matches with **our data given by the red line**



- Axes from plot on the left **(green box)** overlaid on Tostevin and Gade systematics



O. Jensen, et al., PRL 107, 032501 (2011)
J.A. Tostevin and A. Gade. PRC 90, 057602 (2014).

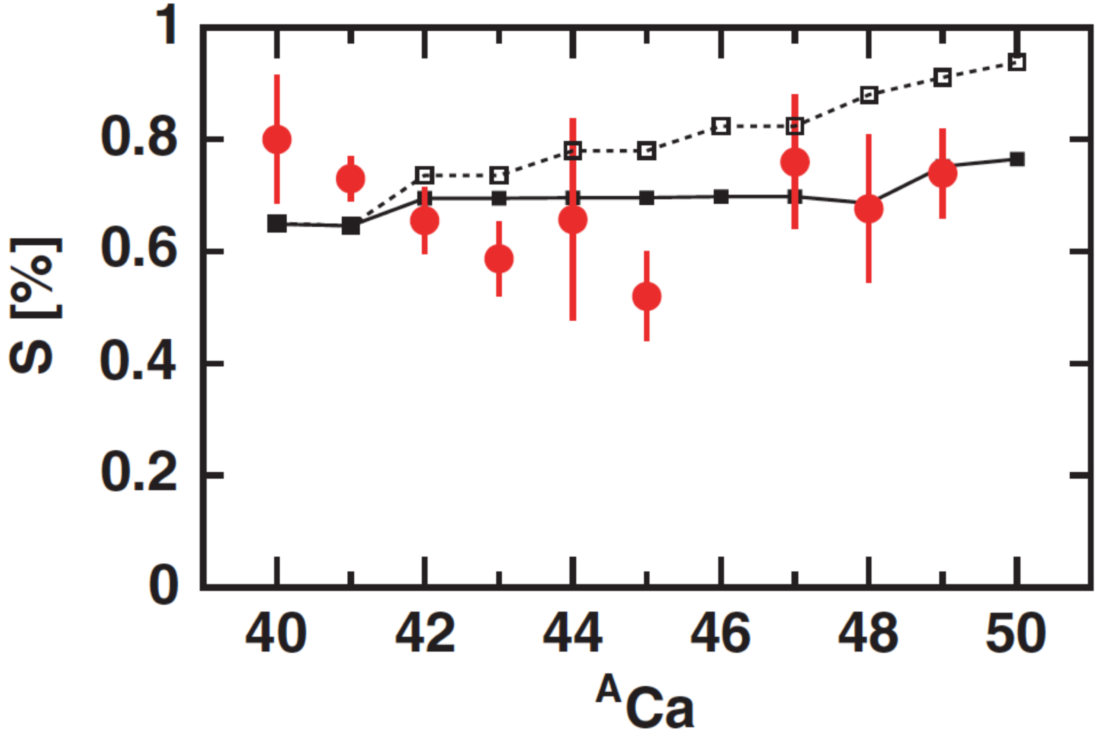
DOM also suggests weak dependence more likely

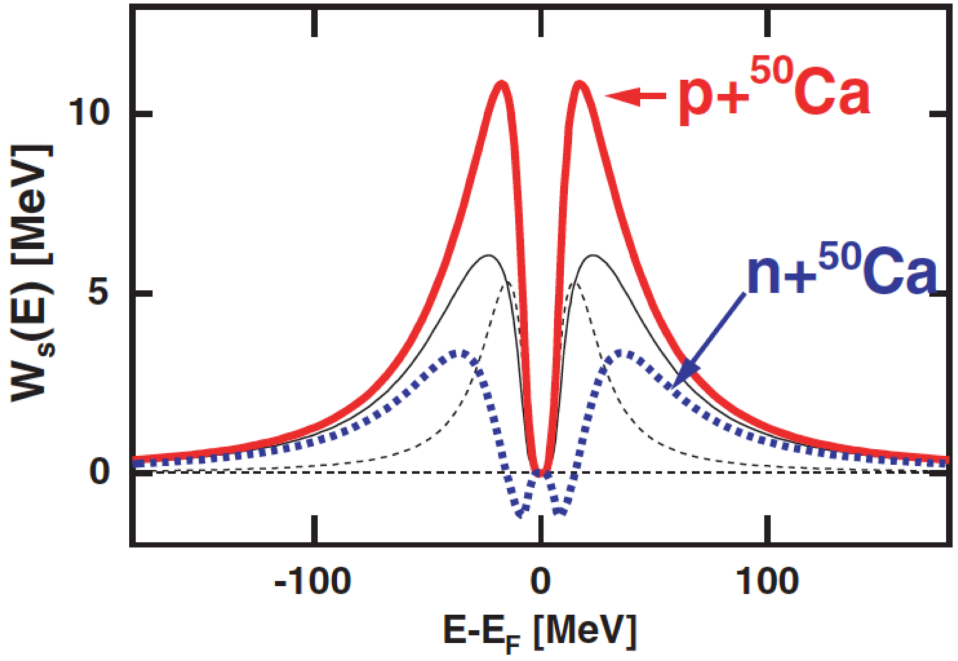
- Dispersive optical model (DOM) study used elastic scattering data on calcium isotopes to study this issue
- In imaginary surface potential, two separate asymmetry terms used (one weaker, one stronger)
- Stronger asymmetry dependence rejected

$$D_1^{p \atop n}(N,Z) = \pm \frac{N-Z}{A}.$$

$$D_2^p(N,Z) = \frac{N-Z}{A}, \quad D_2^n = 0.$$

$$W_s(E) = W_s^0(E) + D(N,Z)W_s^1(E).$$



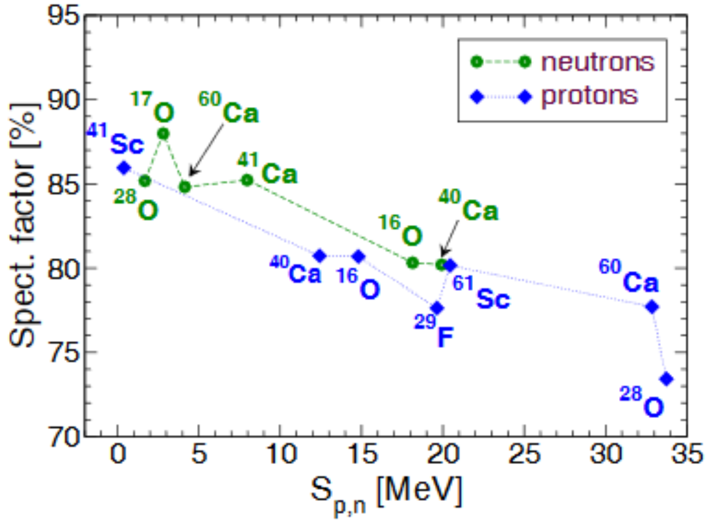


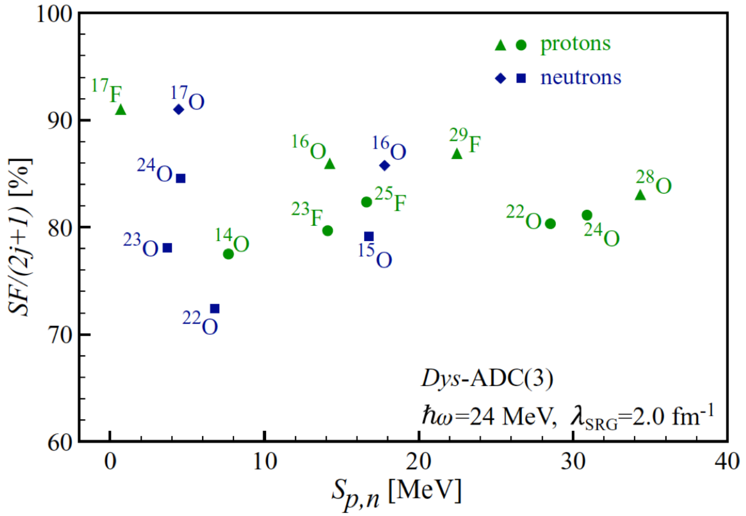
R. J. Charity et al., Phys. Rev. C 76, 044314 (2007).

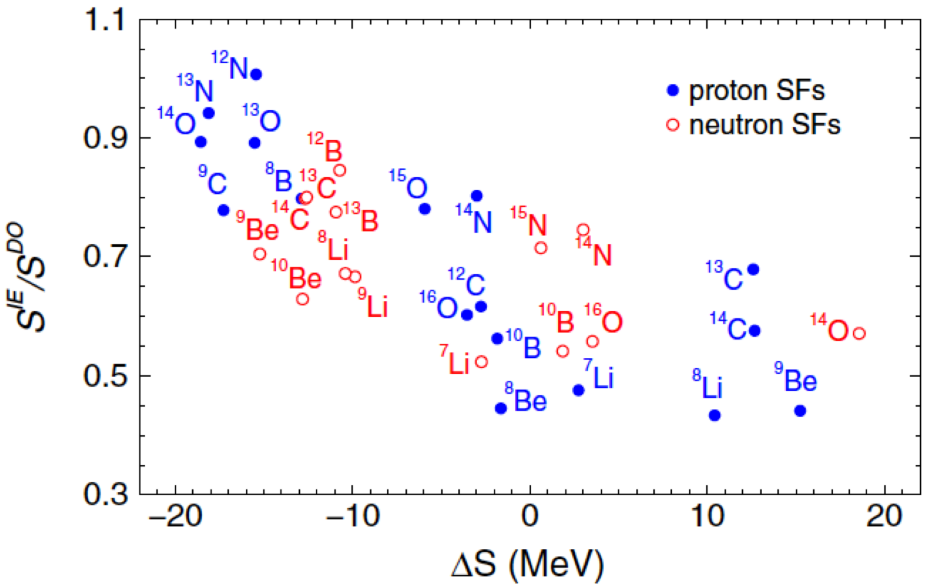
Other structure approaches weigh in, as well

- Two separate self-consistent Green's function studies: both show weak quenching
  - Barbieri, et al.: apply Faddeev Random Phase Approximation (FRPA) to account for coupling to collective excitations
    - » Long-range correlations impact quenching more than short-range
  - Cipollone, et al.: include chiral three-nucleon forces
    - » Little impact on asymmetry dependence

- Inhomogenous approach by Timofeyuk accounts for excluded shell orbits
  - Stronger asymmetry dependence than any other theoretical technique



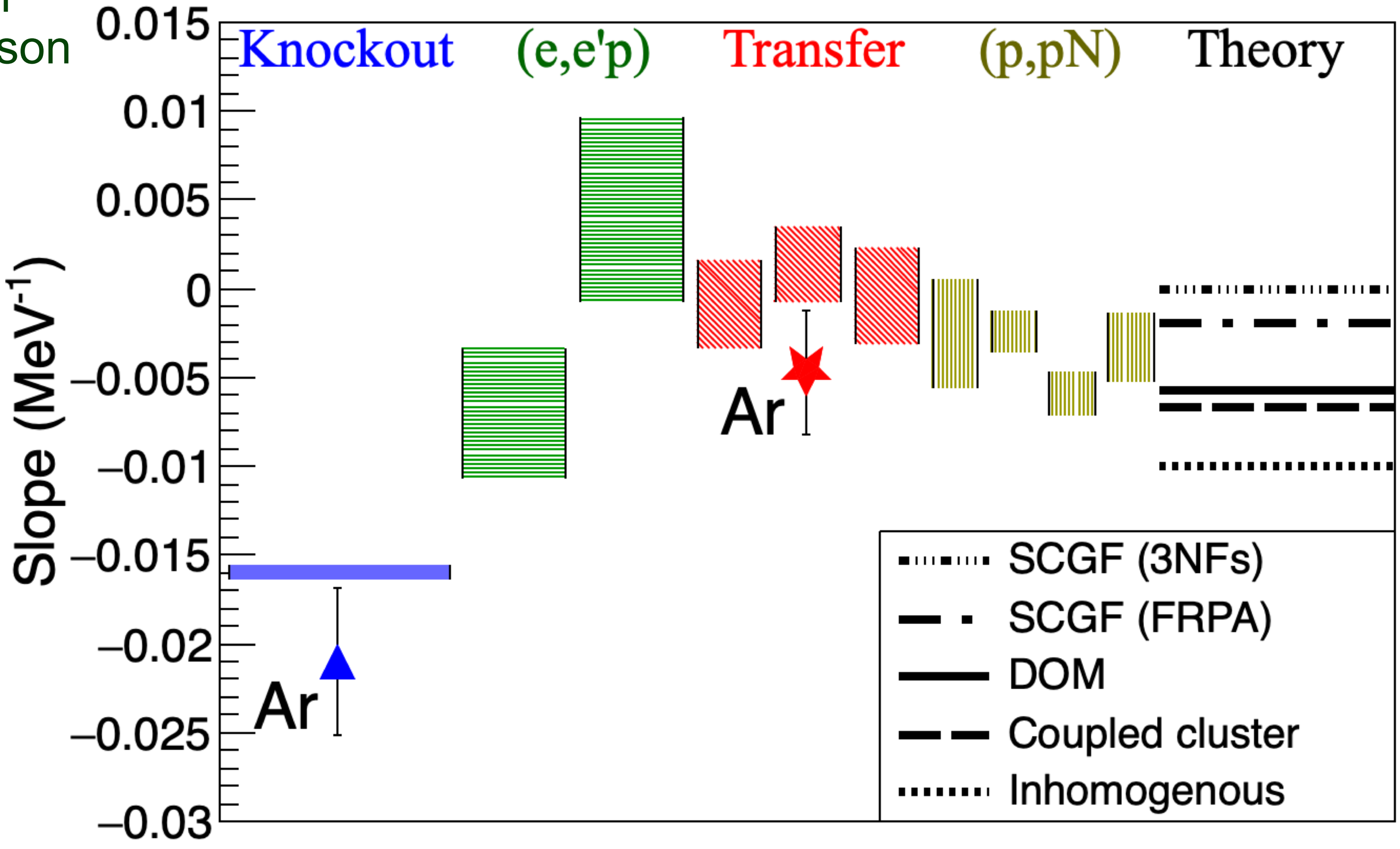




C. Barbieri and W.H. Dickhoff, Intl. Jour. Mod. Phys. 24, 2060 (2009).
A. Cipollone, et al., PRC 92, 014306 (2015).
N.K. Timofeyuk, PRL 103, 242501 (2011).

Consistent evidence for weak asymmetry dependence

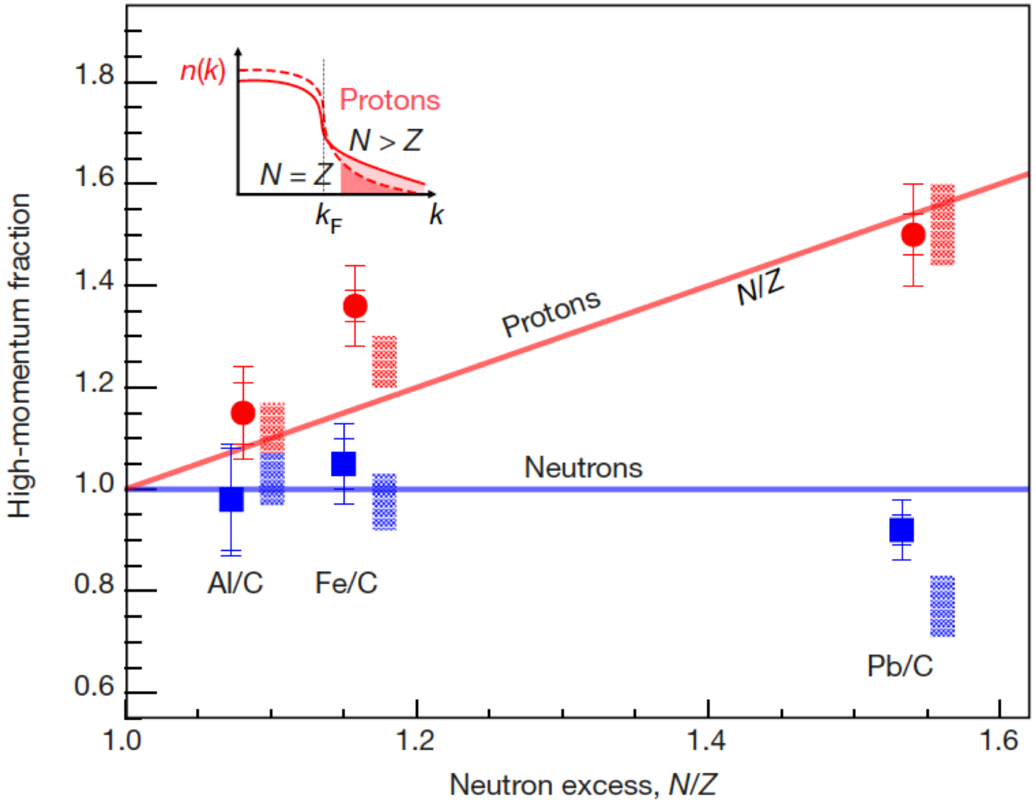
- Linear fits of reduction factor data allow for easy comparison
- Knockout band:
  - Tostevin and Gade (2014)
- (e,e'p) bands (L to R):
  - Kramer et al.
  - Lapikas et al.
- Transfer bands (L to R):
  - Xu et al.
  - Lee et al. + present work
  - Flavigny et al.
- (p,pN) bands (L to R):
  - N.T.T. Phuc et al.
  - Gomez-Ramos et al.
  - Holl et al.
  - Atar et al.

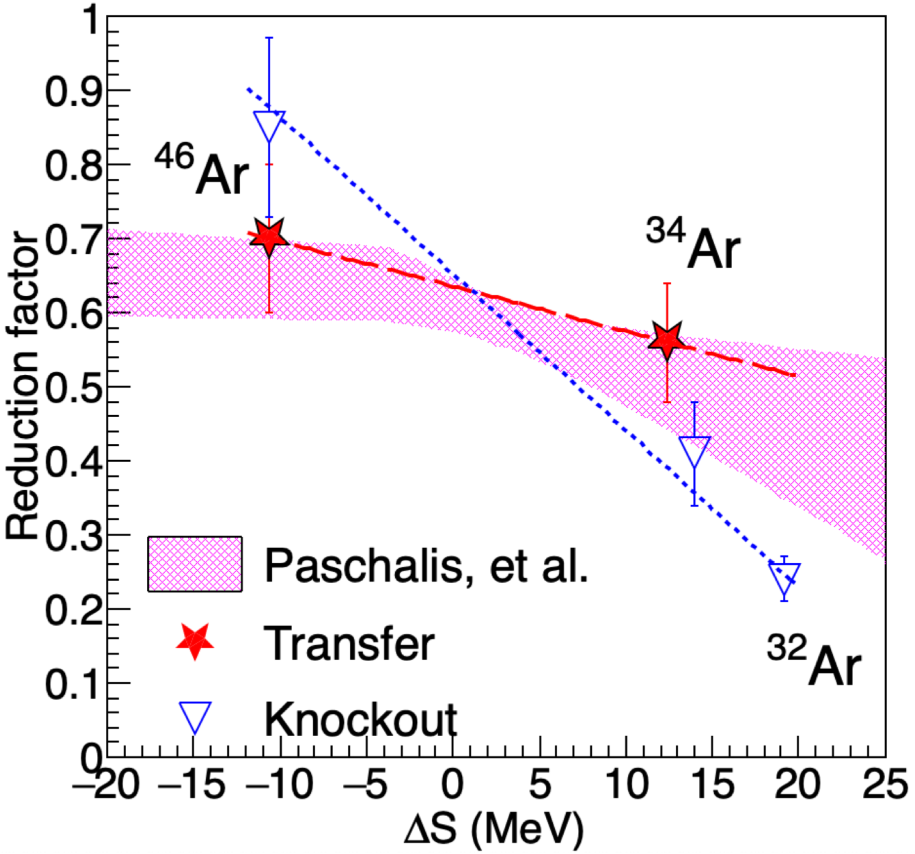


Full reference details on other slides

What about short-range correlations (SRC)?

- Electron scattering: strength shifted to high momentum (SRC)
  - Clearly indicates asymmetry effects of correlations…but to what extent?
- Paschalis, et al.: SRC (and LRC) effects combined via phenomenological approach
  - Yields weak asymmetry dependence (pink band in figure on the right)

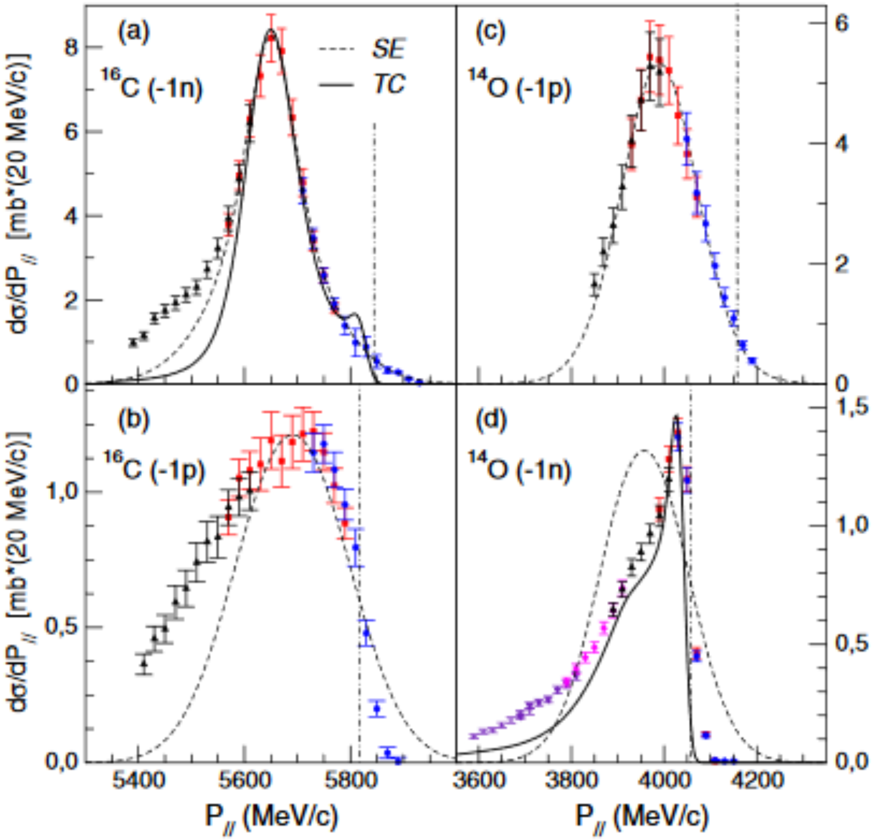


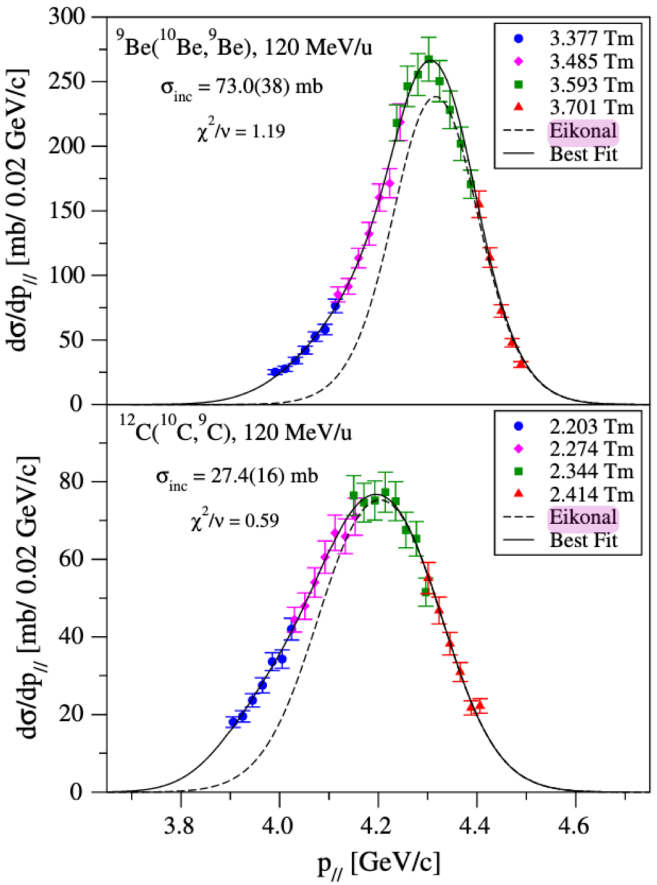


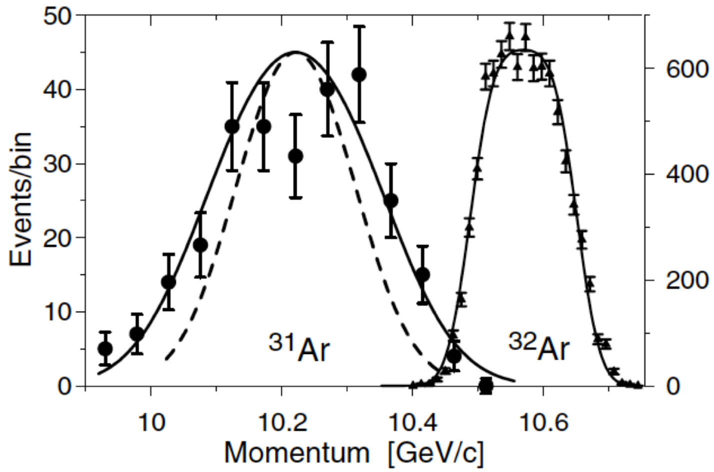
M. Duer, et al. Nature 560 (2018).
S. Paschalis, et al. Phys. Lett. B 700 (2020).

Is the eikonal approximation appropriate?

- For deeply bound systems, eikonal approximation may no longer be valid at intermediate energies
  - Distorted parallel momentum distributions sometimes (but not always) seem to indicate this





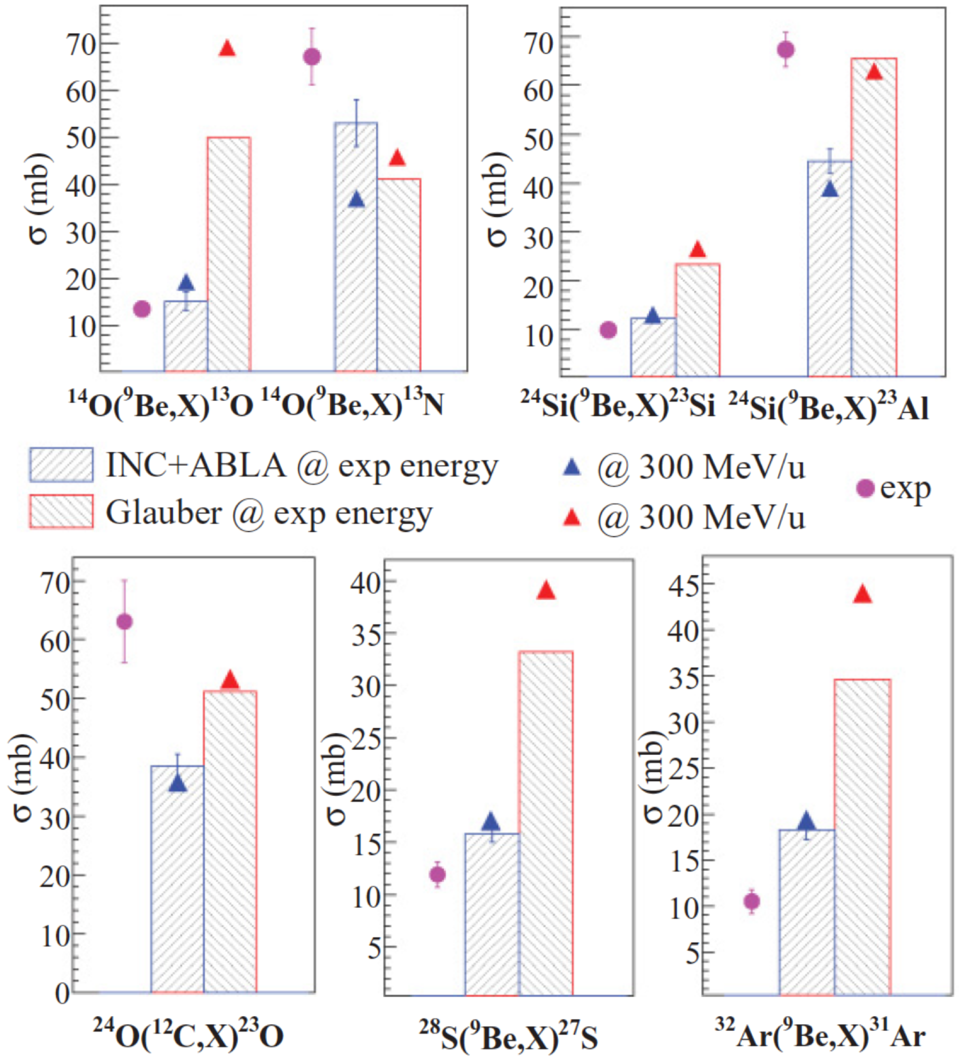


See A. Bonaccorso's talk from April 30

Flavigny, et al., PRL 108, 252501 (2012).
G. F. Grinyer et al., Phys. Rev. Lett. 106, 162502 (2011).
A. Gade, et al., PRL 93, 042501 (2004).

What about core excitations?

- Indirect effects during single-nucleon knockout studied using intranuclear cascade model (ICM)
- Trajectory of projectile influenced by target?
- Interplay between shell structure of projectile and reaction?



C. Louchart, et al., PRC 83 011601 (2011).

Conclusions

- Clear theoretical and experimental evidence for asymmetry dependence of spectroscopic factors (quenching)
  - More support for weak quenching than for strong
- (p,d) reactions on argon isotopes at 70 MeV/u agree with 33 MeV/u
- To move forward, theory is crucial
  - Effects of nonlocality
  - Uncertainty quantification
  - Core excitations
  - Non-eikonal effects (distorted momentum distributions)

Several relevant talks:
- *A. Bonaccorso (April 30)*
- *A. Lovell (April 21)*
- *M. Catacora-Rios (April 23)*

- Data from new experimental approaches, like (p,pN) and electron scattering on unstable isotopes, is important
- More exclusive knockout data may help understand contribution from indirect processes
- More transfer data at extreme asymmetry, preferably for same isotopic chains studied with knockout (higher beam energies should be okay)

T. Suda and H. Simon, Prog. Part. Nucl. Phys. 96 (2017).

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