Short-range correlations in nuclei

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Outline

- Introduction – spectroscopic strength as indicator of correlations missing in shell-model or meanfield approaches
- Reduction of spectroscopic strengths for stable nuclei
  - from (e,e’p) and transfer reaction
- Reduction of spectroscopic strengths for rare isotopes
  - HI-induced knockout
  - Transfer
  - (p,2p)
- A beautiful connection
  - Anatomy of short-range correlations (SRCs) from JLab
- Challenges

Reduction of spectroscopic strength as indicator of correlations

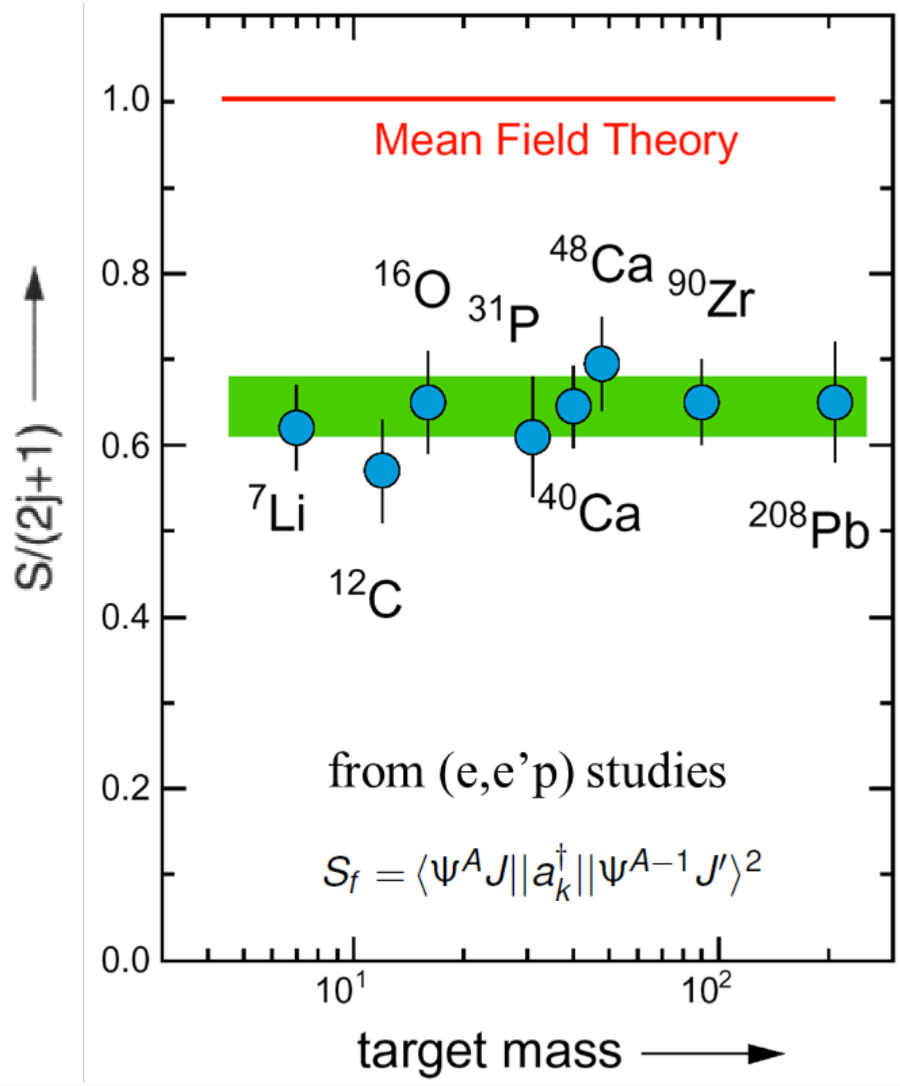
The nuclear shell model pictures deeply-bound states as fully occupied by nucleons. At and above the Fermi sea, configuration mixing leads to occupancies that gradually decrease to zero.

Correlation effects (short-range, soft-core, and long-range) are beyond the effective interactions employed in the shell model and mean-field approaches. The picture given above will be modified depending on the strength of the correlation.

V. R. Pandharipande *et al*, RMP 69, 981 (1997)

W. Dickhoff and C. Barbieri, PPNP 52, 377 (2004).

Figure from Lapikas, Dickhoff



Reduction of spectroscopic strength as indicator of correlations – Transfer consistent

- G. J. Kramer *et al.* (NIKHEF) did pioneering work on probing model dependences for transfer reactions and benchmarking with (e,e'p)
- Critical: Bound-state geometry adjusted to obtain realistic *rms* radius of bound-state wave function

Kramer *et al.*, NPA 679, 267 (2001)

A consistent analysis of (e,e′p) and (d,^{3}He) experiments

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Abstract

The apparent discrepancy between spectroscopic factors obtained in (e,e′p) and (d,^{3}He) experiments is investigated. This is performed first for ^{48}Ca(e,e′p) and ^{48}Ca(d,^{3}He) experiments and then for other nuclei. It is shown that the discrepancy disappears if the (d,^{3}He) experiments are reanalyzed with a nonlocal finite-range DWBA analysis with a bound-state wave function that is obtained from (e,e′p) experiments.

Keywords: NUCLEAR REACTIONS ^{48}Ca(e,e′p); $E = 440$ MeV; Measured $\rho(E_m, \vec{p}_m)$; Deduced spectroscopic factors; Comparison of spectroscopic factors from (e,e′p) and (d,^{3}He)

Kramer *et al.*, NPA 477, 55 (1988)

SPECTROSCOPIC FACTORS FROM THE ^{51}V(d, ^{3}He)^{50}Ti REACTION

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Received 2 September 1986
(Revised 25 August 1987)

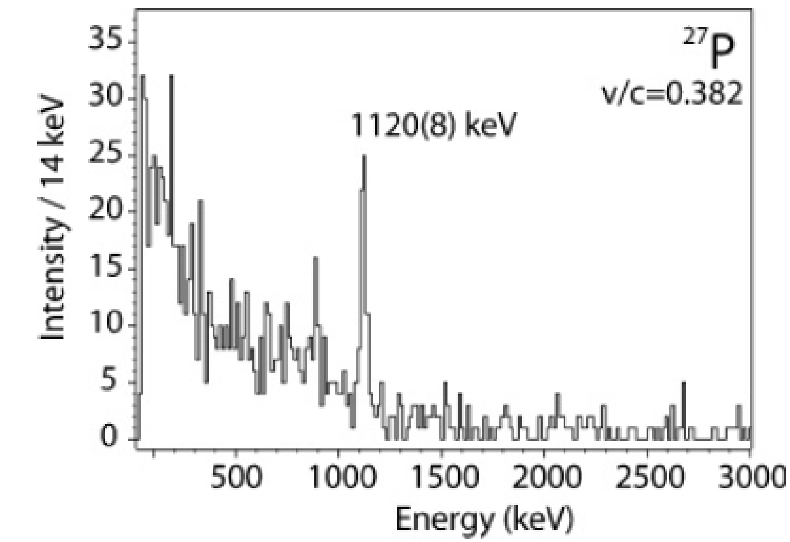
Abstract: The ^{51}V(d, ^{3}He)^{50}Ti reaction was studied at $E_d = 52.9$ MeV with an energy resolution of about 25 keV. The differential cross sections were compared with DWBA calculations. Up to 7 MeV excitation energy, 33 levels were found corresponding to $l = 3$, $l = 0$ and $l = 2$ pick-up. In addition three possible $l = 1$ transitions were observed. Realistic uncertainties to be assigned to extracted spectroscopic factors were determined by investigating the influence of different optical models, finite-range effects and different prescriptions for the bound-state wavefunction. In one of these prescriptions, electron-scattering data were used to reduce the uncertainty related to the rms radius of the bound-state wavefunction in the DWBA calculations. The experimental results are compared with the theoretical estimates.

- What about rare isotopes that have extreme ratios of neutron-to-proton numbers?

One-nucleon knockout reactions

P. G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Part. Sci. 53, 219 (2003)

- A nucleon is removed from a projectile upon fast collision with a C or Be target (>70 MeV/u)
- In conjunction with reaction theory, spectroscopic strength can be assessed (eikonal and sudden approximations, folding potentials (HF distributions), bound-state wave function constrained with input from HF calculations)

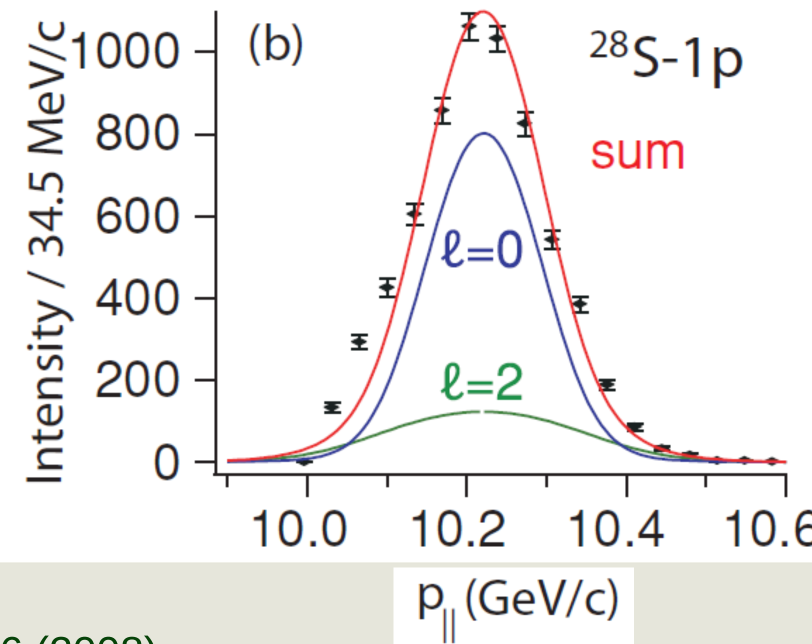


$$\sigma(j^\pi) = \left(\frac{A}{A-1}\right)^N C^2 S(j^\pi)\sigma_{\rm sp}(j, S_N + E_x[j^\pi])$$

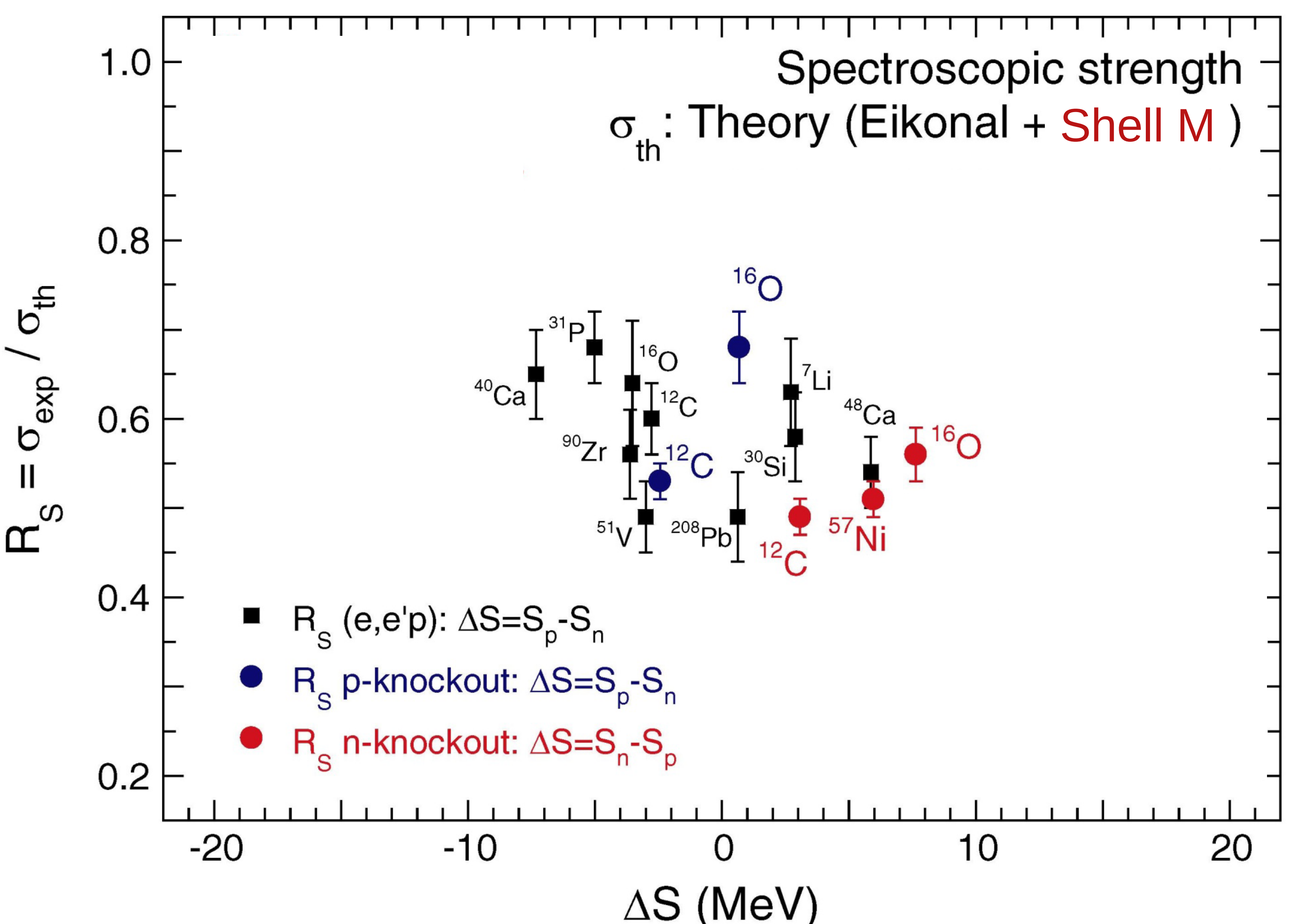
Nuclear structure

Reaction dynamics

- Final-state identification with γ-ray spectroscopy → thick targets and high luminosities (measurements can be done at a few particles per second)

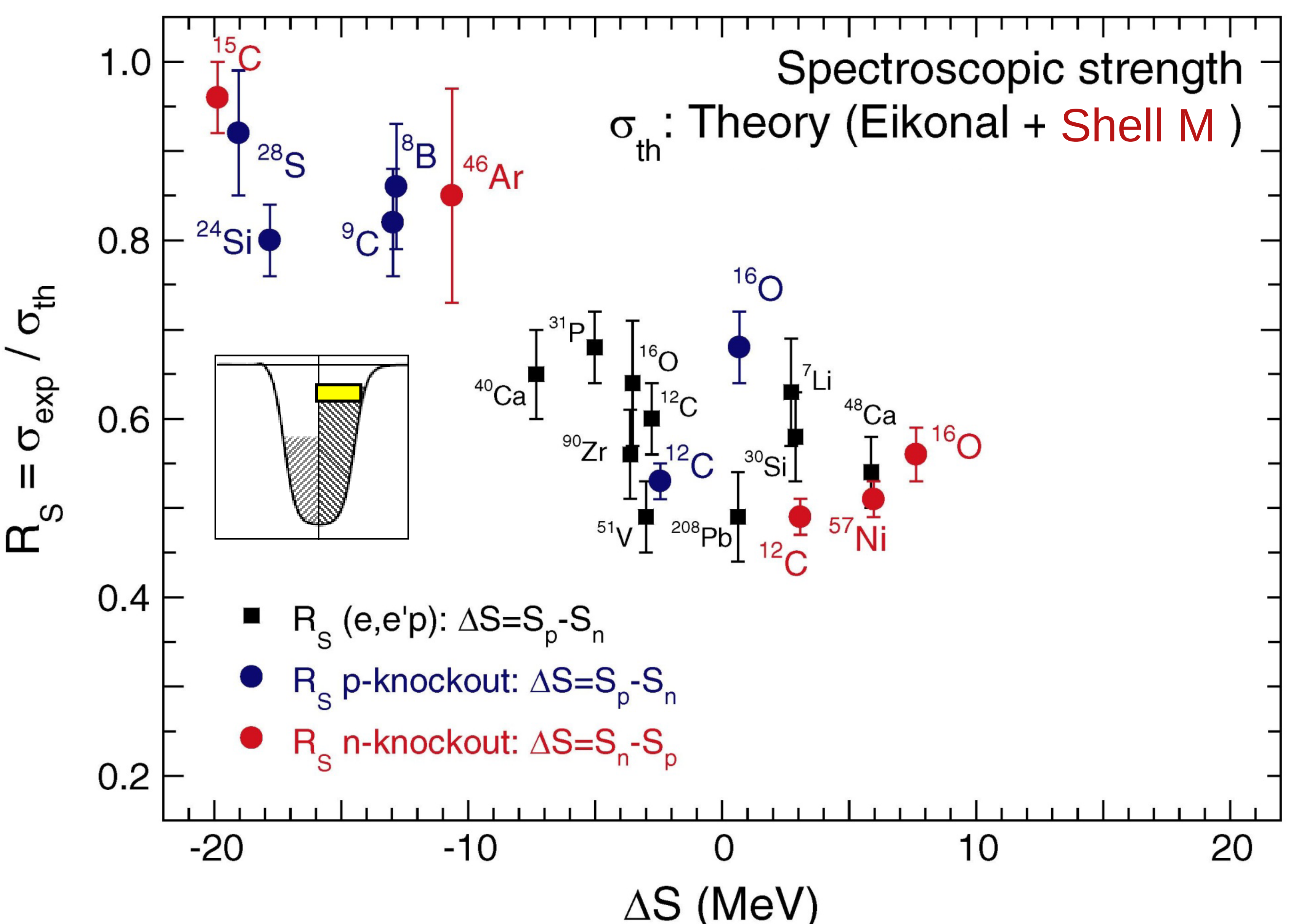


Reduction close to stability



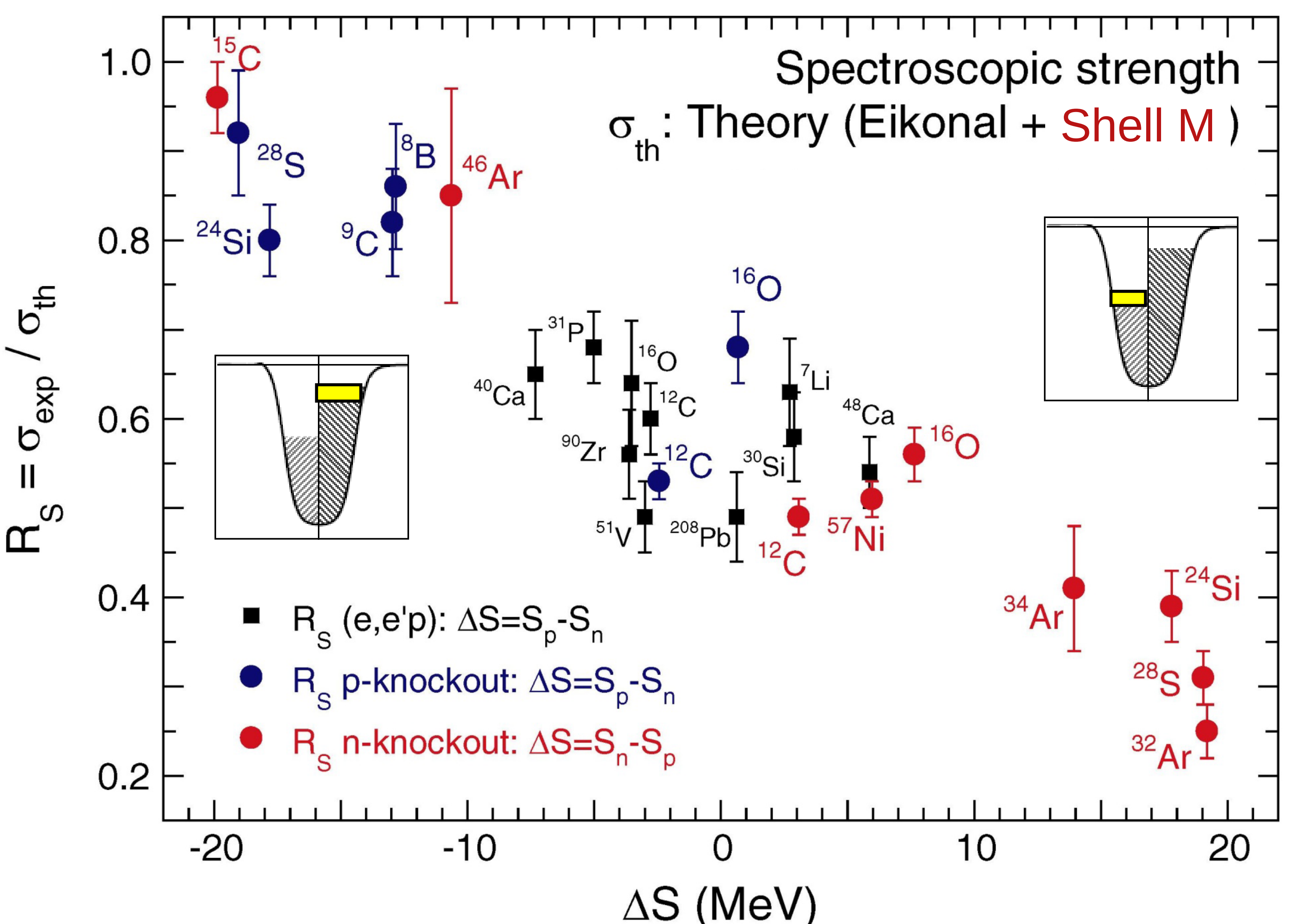
A. Gade et al., PRC 77, 044306 (2008)

Weakly-bound systems



A. Gade et al., PRC 77, 044306 (2008)

Strongly-bound systems



A. Gade et al., PRC 77, 044306 (2008)

Data today – contains data from NSCL, RIKEN, Lanzhou, Bevalac

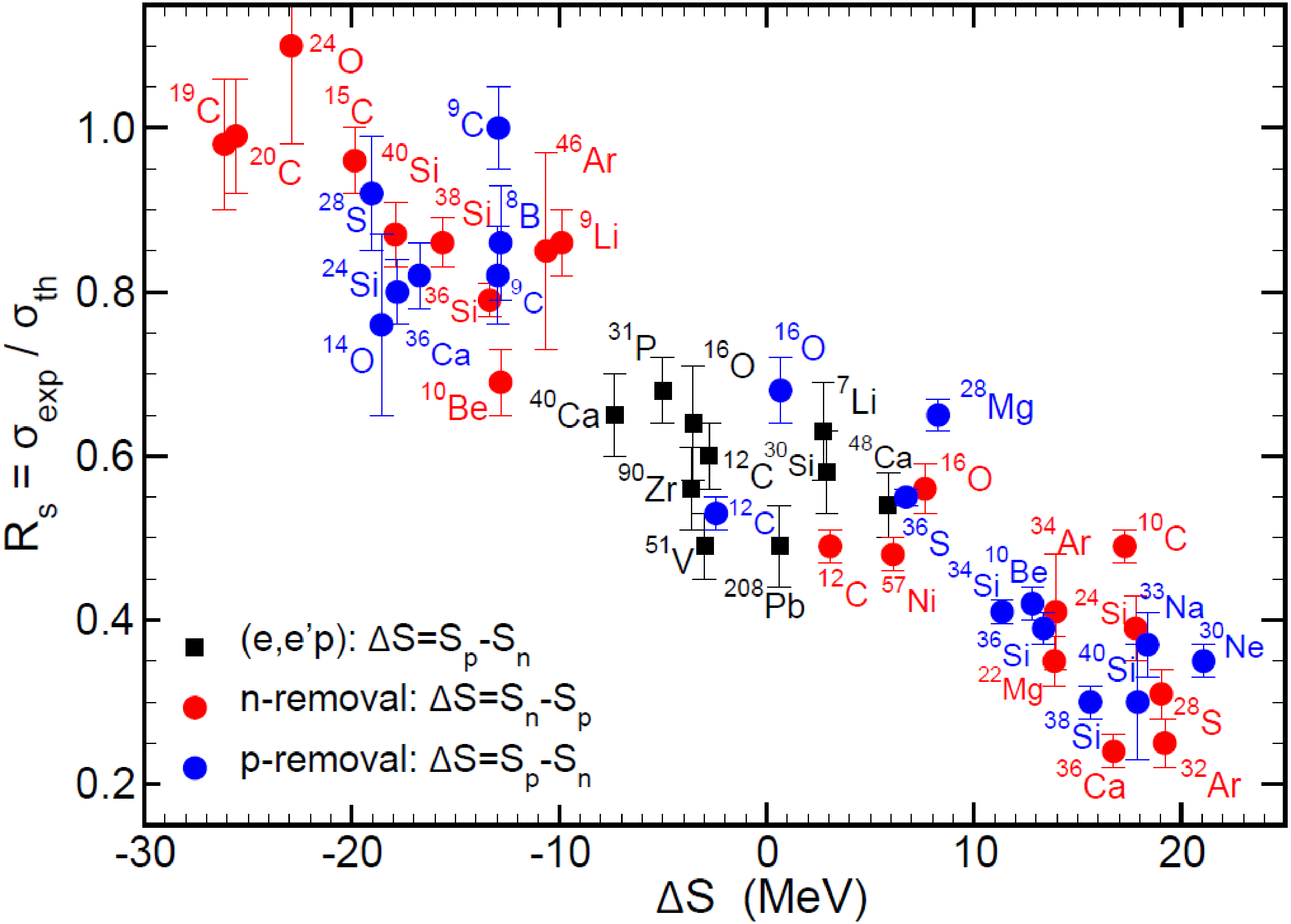


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Figure: Jeff Tostevin's 2017 update from
J. A. Tostevin and A. Gade, PRC 90, 057602 (2014)

What it may mean

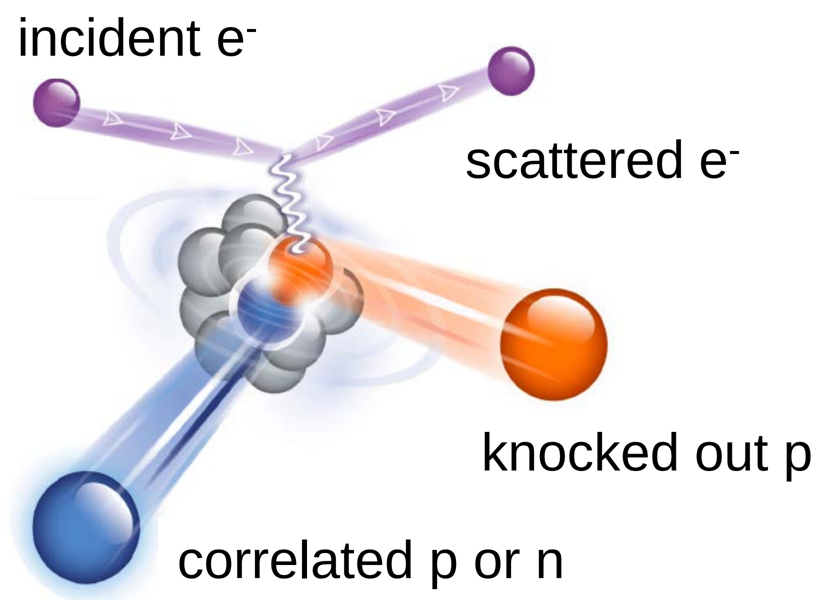
- Minority nucleons, i.e. neutrons in a proton-rich nucleus or protons in a neutron-rich nucleus, are more correlated than the majority species

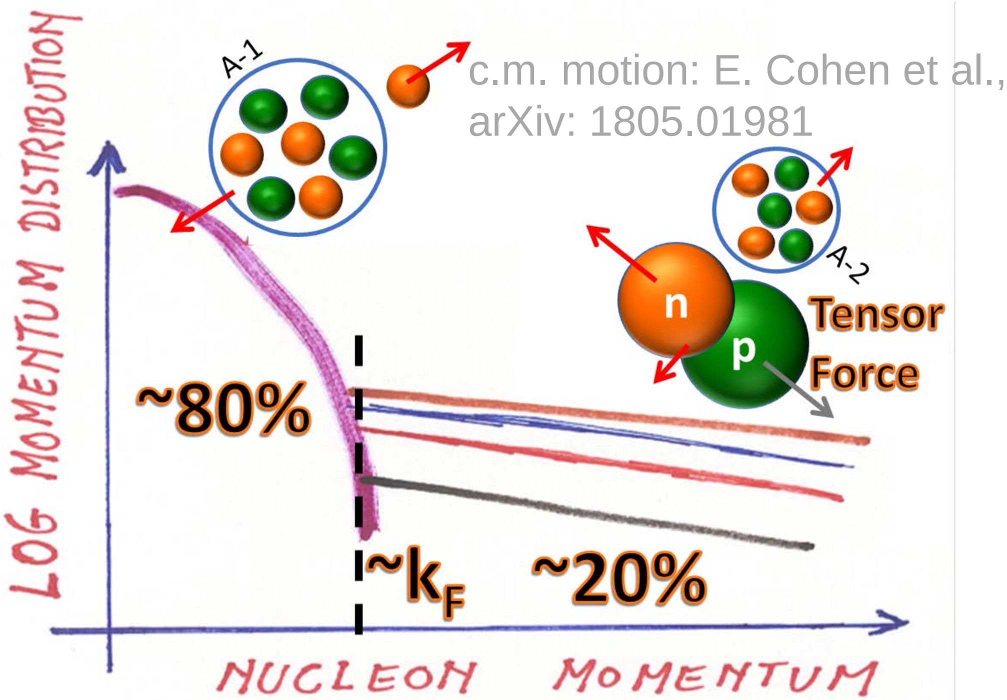
- These correlations are not captured in effective shell-model interactions and they fragment spectroscopic strength to higher-lying orbitals outside of the necessarily truncated model spaces

Direct evidence for SRC from electron-induced work

Or Hen, Gerald A. Miller, Eli Piasetzky, and Lawrence B. Weinstein

Rev. Mod. Phys. 89, 045002 (2017)

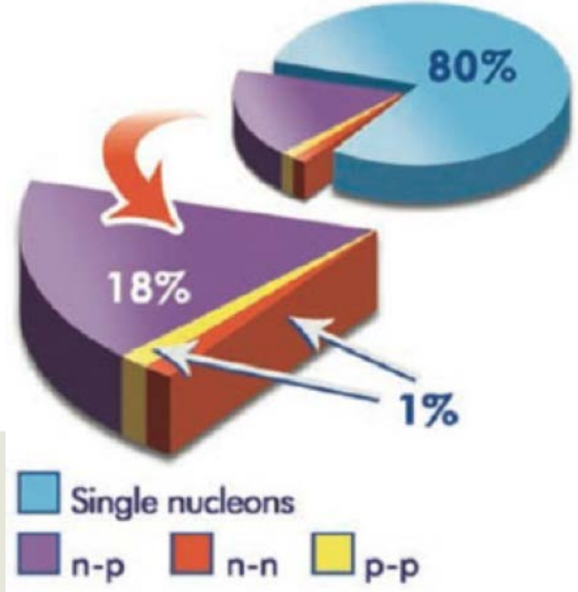




New Era in SRC Research!

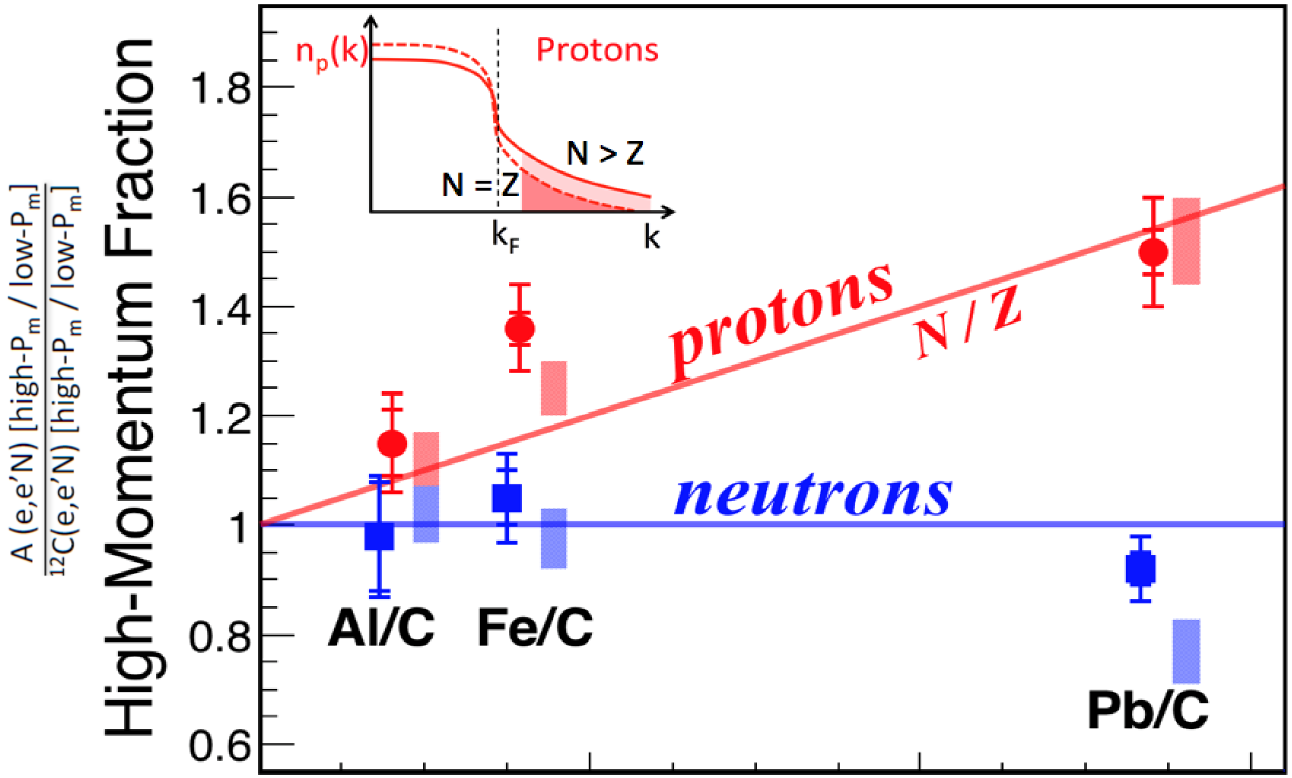
Or Hen *et al.*

1. SRC Exist in Nuclei (!) and account for:
   - ~ 20% of the nucleons in nuclei.
   - ~100% of the high-p ($k>k_F$) nucleons in nuclei.
2. Have large relative momentum and low c.m. momentum.
3. Predominantly due to np-SRC.
4. Universal for A = 4 – 208 nuclei.
5. np-SRC create a larger fraction of high-momentum protons in neutron rich nuclei!



New result – Short-range correlations and neutron excess

Correlation Probability: Neutrons saturate Protons grow



In neutron-rich nuclei, the number of protons engaged in SRC pairs increases. Minority species more correlated!

(e,e'n) vs (e,e'p) on a variety of targets

M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

Correlations of minority vs. majority species from low-energy nuclear theory

- Truncated model spaces and soft interactions can lead to an asymmetry dependence as seen in knockout

  N. K. Timofeyuk, , PRL 103, 242501 (2009)

- Trend (*not* the magnitude) of increased reduction at larger asymmetry found consistent with conclusions from dispersive optical model analyses of elastic scattering data

  R. J. Charity *et al.*, PRC 76, 044314 (2007), PRL 97, 162503 (2006)

- Continuum effects can introduce asymmetry dependence (example Oxygen isotopes from Coupled Cluster ab-initio type calculations)

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

- Asymmetry dependence expected for nuclear matter

  T. Frick *et al.*, PRC 71, 014313 (2005)

Most predict a more modest asymmetry dependence than the slope from HI-induced knockout: Consistency with other probes?

Spectroscopic factors from transfer reactions

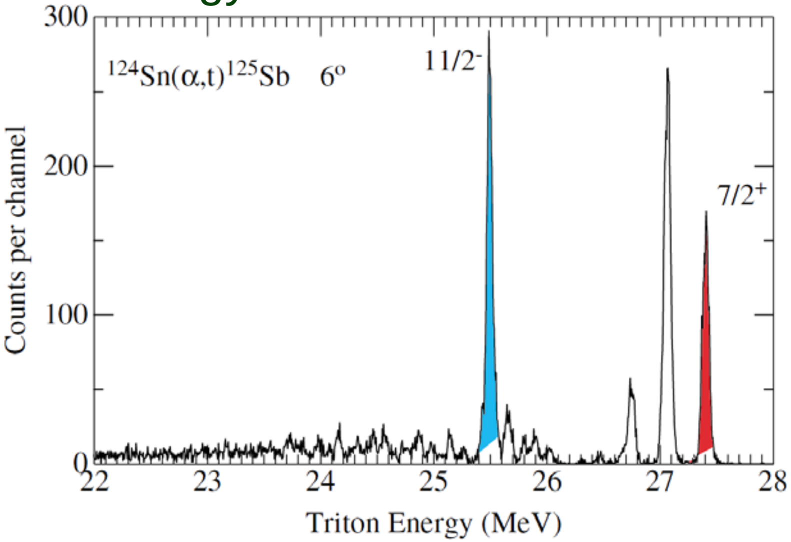
S_{JL}: Spectroscopic factor – scale factor between exp. and theory (must depend on the reaction theory used)

$$d\sigma(\theta,E)/d\Omega = S_{JL}F_{JL}(\theta,E)$$

Differential cross section measured in the experiment

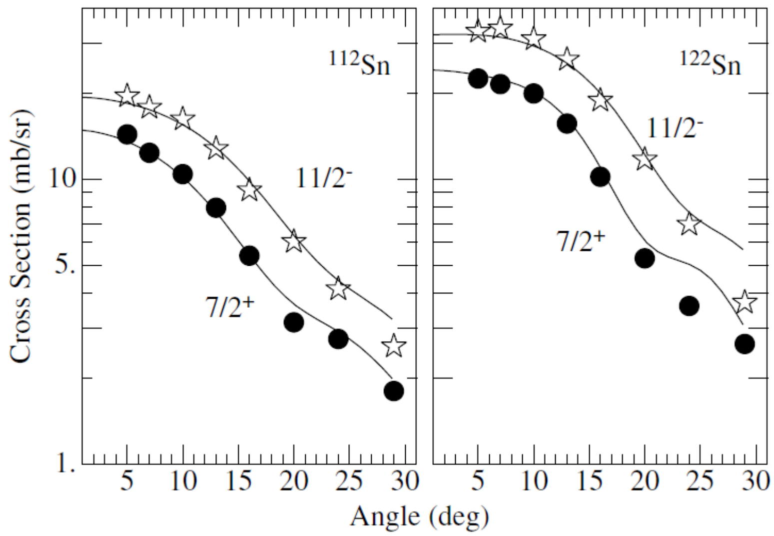
F_{JL}: Reaction theory – model dependent, many different choices, DWBA, Adiabatic Model, CCBA, CRC, … many assumptions, approximations, different optical model potentials

Observable: Excitation energy and cross section



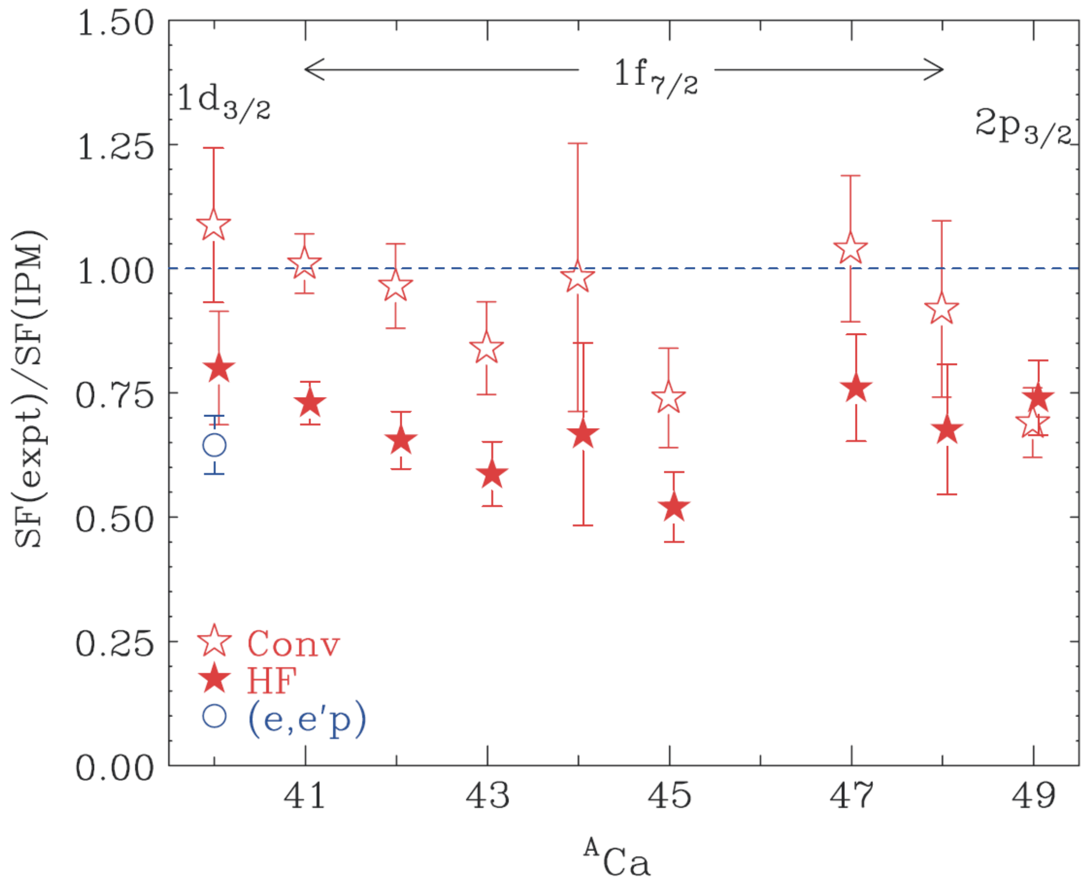
J. P. Schiffer et al., PRL 92, 162501 (2004)

Less model dependent: Shape of the angular distribution → ℓ-value of the transferred nucleon



Transfer analyzed to be consistent with (e,e'p) and HI-induced knockout - recent

- **Conventional:** Traditional, fixed bound-state geometry a=0.65 fm and r_0=1.25 fm gives the naïve IPM value
- Pioneers: Kramers et al (KVI) analyzed transfer carefully and reproduced (e,e'p) [Kramer *et al.*, NPA 679, 267 (2001) and NPA 477, 55 (1988)]
- HF: SFs deduced with the bound-state geometry constrained as well as possible with the result of mean field calculations (SkX Skyrme) agree with the magnitude in reduction observed in (e,e,'p)



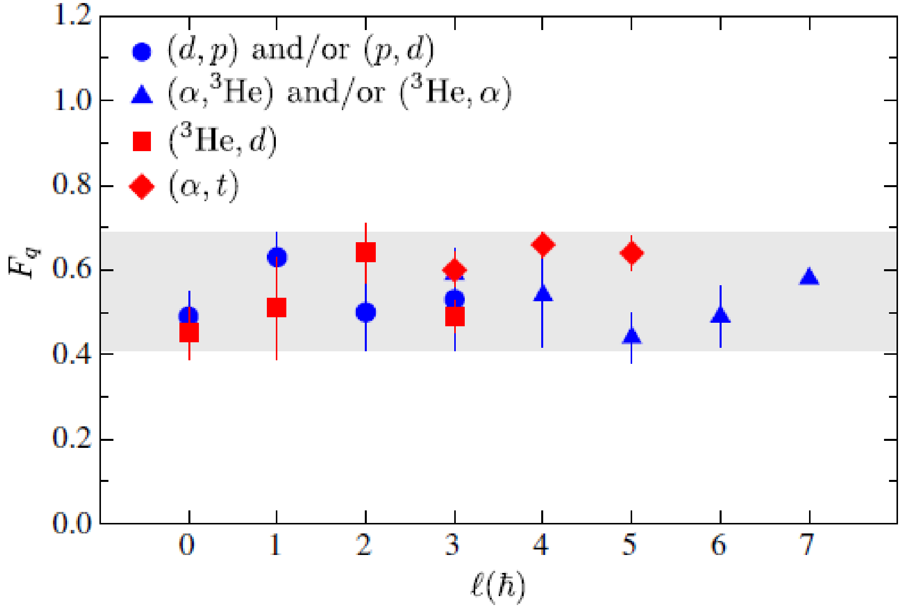
Conv: CH89 global potential, a=0.65, r_0=1.25fm

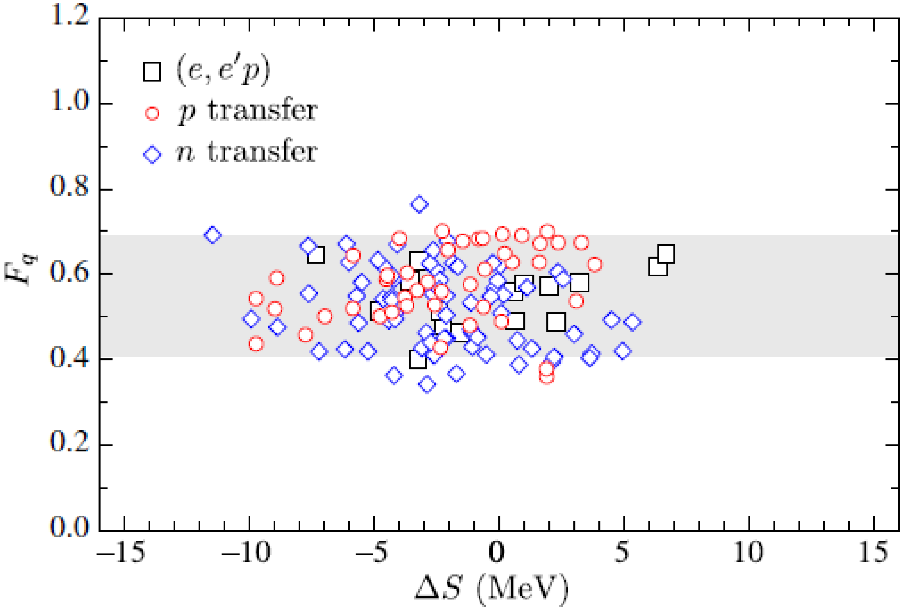
HF: JLM folding potential, densities from SkX HF a=0.65, r_0 adjusted to fit HF orbital radius

Transfer can be analyzed to be consistent

Bound-state geometry as used in (e,e'p) and ab-initio treatment of projectile

- Re-analysis of existing transfer data (nucleon-adding and -subtracting)
- Bound-state geometry adapted from (e,e'p), wave functions of d, ^{3}He, and α from AV18 (A=2) or GFMC (A=3,4)
- Use Macfarlane-French sum rule when nucleon-adding and -subtracting data exists for the same target





$F_q \sim R_s$

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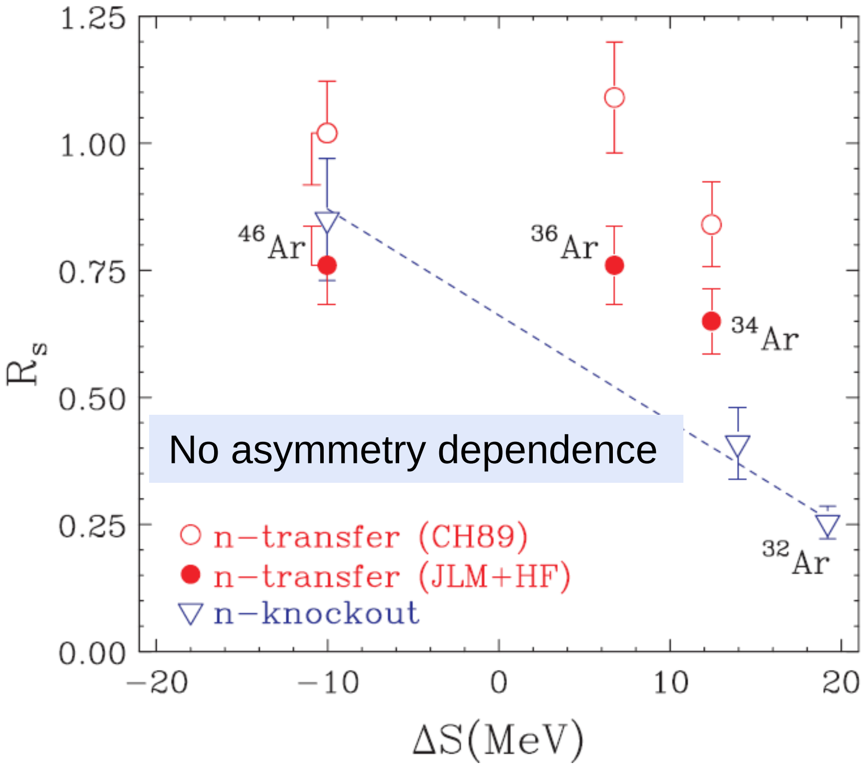
B.P. Kay, J.P. Schiffer, and S.J. Freeman, PRL 111, 042502 (2013)

Transfer at large asymmetry – one-neutron transfer from ^{46,34}Ar

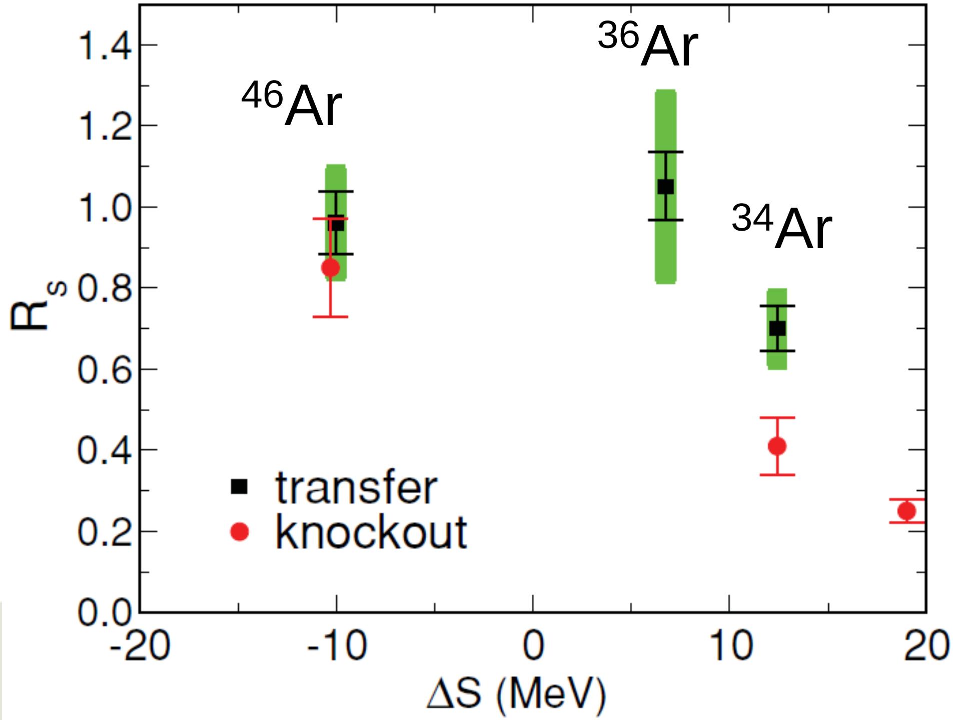
- Inverse kinematics p(^{34,36,46}Ar,d)^{33,35,45}Ar at 33 MeV/u with the HiRA Si array and the S800 at NSCL. Analyzed with bound-state geometry constrained by HF radii and standard parameters.



Jenny Lee, M.B. Tsang et al., PRL 104, 112701 (2010)

- SFs re-analyzed and uncertainty quantified. "From our new spectroscopic factors extracted from transfer, it is possible to corroborate the neutron-proton asymmetry dependence reported from knockout measurements."

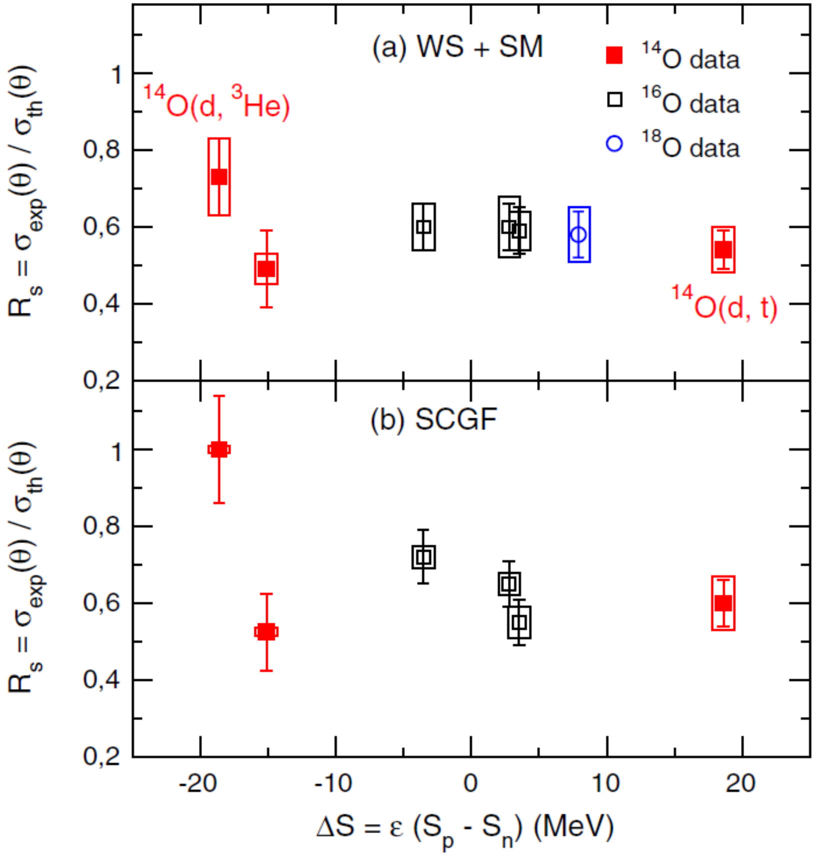
F. M. Nunes et al., PRC 83, 034610 (2011)



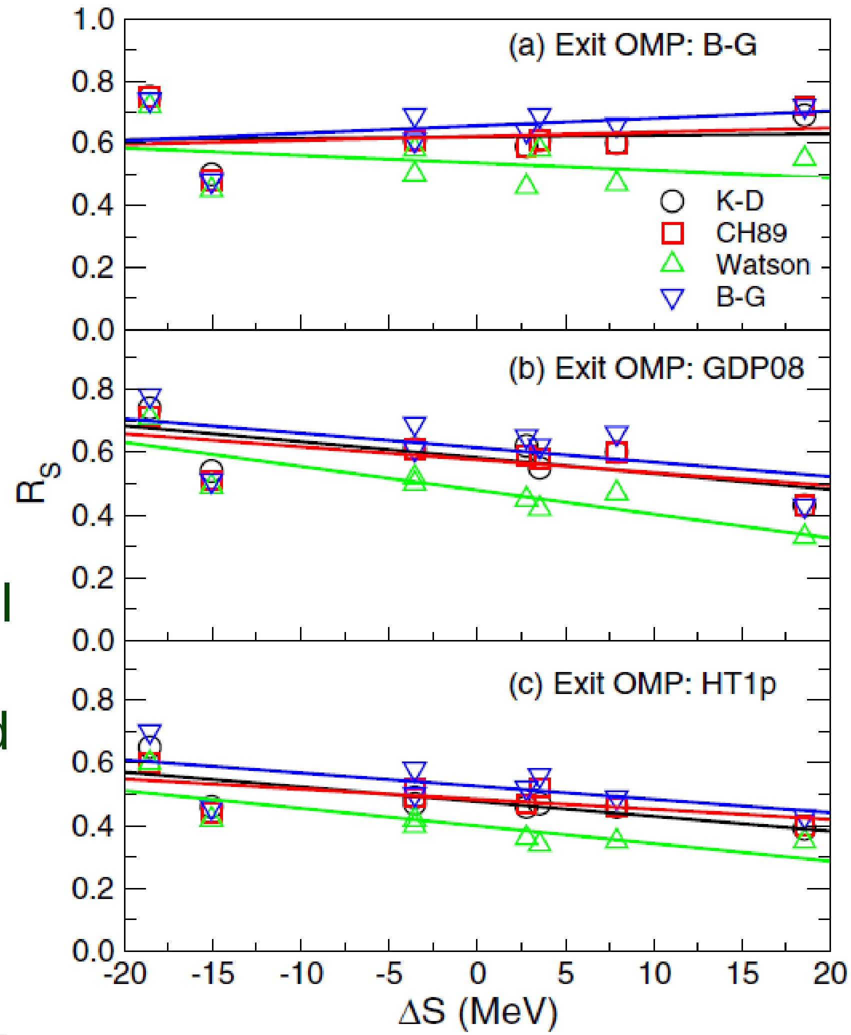
Transfer at large isospin – one-neutron transfer from ^{14}O

- d(^{14}O,^{3}He)^{13}N and d(^{14}O,^{3}H)^{13}O at MeV/u with MUST2 and VAMOS at GANIL
- Analyzed with HFB-constrained bound-state wave function geometry + shell model and SCGF overlaps. No asymmetry dependence observed (2013), reanalysis in 2018 allows for small asymmetry dependence

F. Flavigny et al., PRL 110, 122503 (2013)



Different optical model potentials in entrance and exit channel change the answer a lot



F. Flavigny et al., PRC 97, 034601 (2018)

(p,2p) and (p,pn) with rare isotopes

- This method assumes that the dominant mechanism for the knockout reaction is due to a single interaction between the incident particle and the struck nucleon (→ understanding re-scattering is critical)

PHYSICAL REVIEW C **88**, 064610 (2013)

Quasifree $(p,2p)$ and (p,pn) reactions with unstable nuclei

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(Received 28 September 2013; published 17 December 2013)

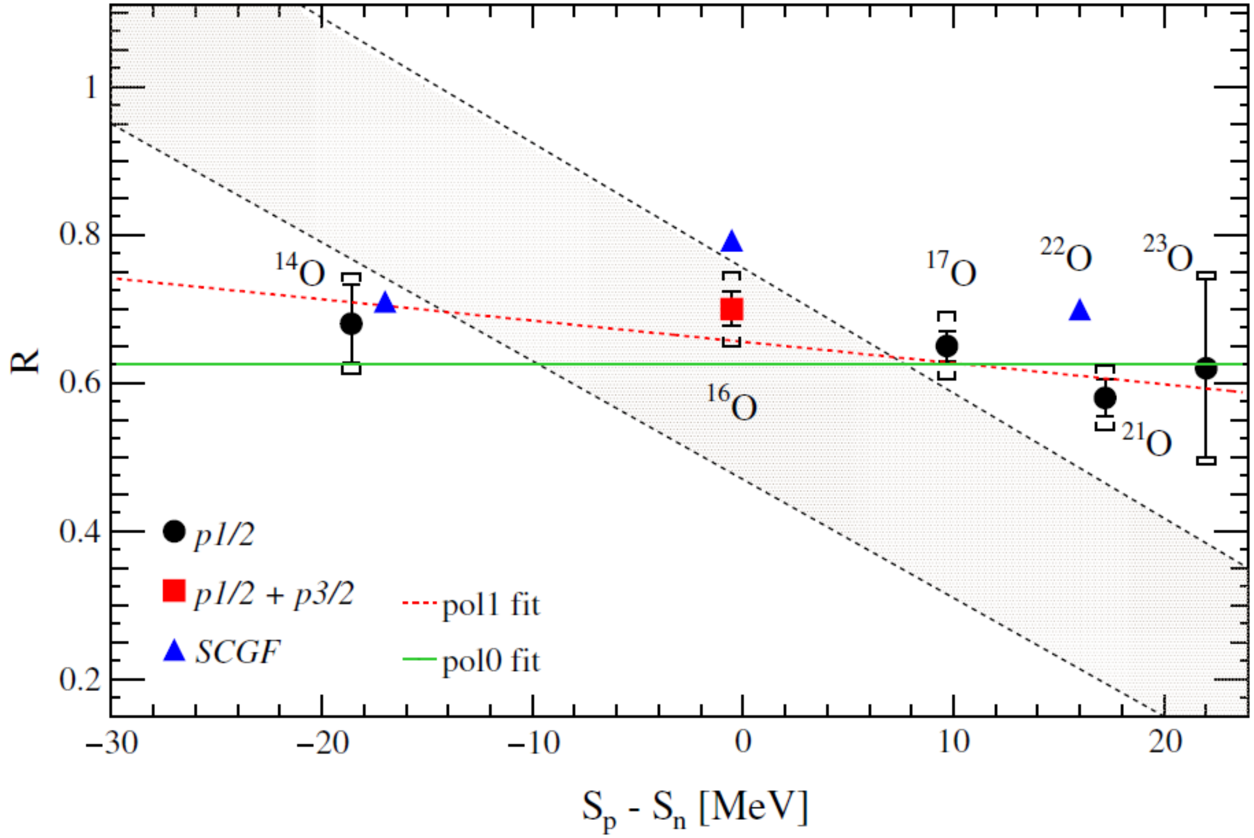
We study $(p,2p)$ and (p,pn) reactions at proton energies in the range of 100 MeV–1 GeV. Our purpose is to explore the most sensitive observables in unpolarized reactions with inverse kinematics involving radioactive nuclei. We formulate a model based on the eikonal theory to describe total cross sections and momentum distributions of the recoiled residual nucleus. The model is similar to the one adopted for knockout reactions with heavy ions. We show that momentum distributions are sensitive to the angular momentum of the ejected nucleon which can be used as an spectroscopic tool. The total cross sections are sensitive to the nucleon separation energies and to multiple scattering effects. Our calculations also indicate that a beam energy around 500 MeV/nucleon has a smaller dependence on the anisotropy of the nucleon-nucleon elastic scattering.

- Inverse kinematics (p,2p) and (p,pn) on rare isotopes are envisioned ideally at beam energies of >400 MeV/u to minimize distortions. Use of eikonal scattering waves is proposed
- Reaction theory relies of DWIA, Glauber multiple scattering is proposed to account for distortions and absorption (re-scattering is a critical effect that needs to be quantified). Same factorization: Structure x reaction theory

T. Aumann *et al.*, PRC 88, 064610 (2018)

(p,2p) on the chain of Oxygen isotopes

- ^{A}O(p,2p)$^{A-1}$N quasi-free scattering performed at GSI at the ALADIN setup for ^{14}O to ^{23}O. Data was analyzed within DWIA in eikonal approximation
- R here is relative to the independent particle model, not large-scale shell model. Data is concluded to be consistent with no (χ^2=1.91) or small asymmetry dependence (χ^2=1.29)

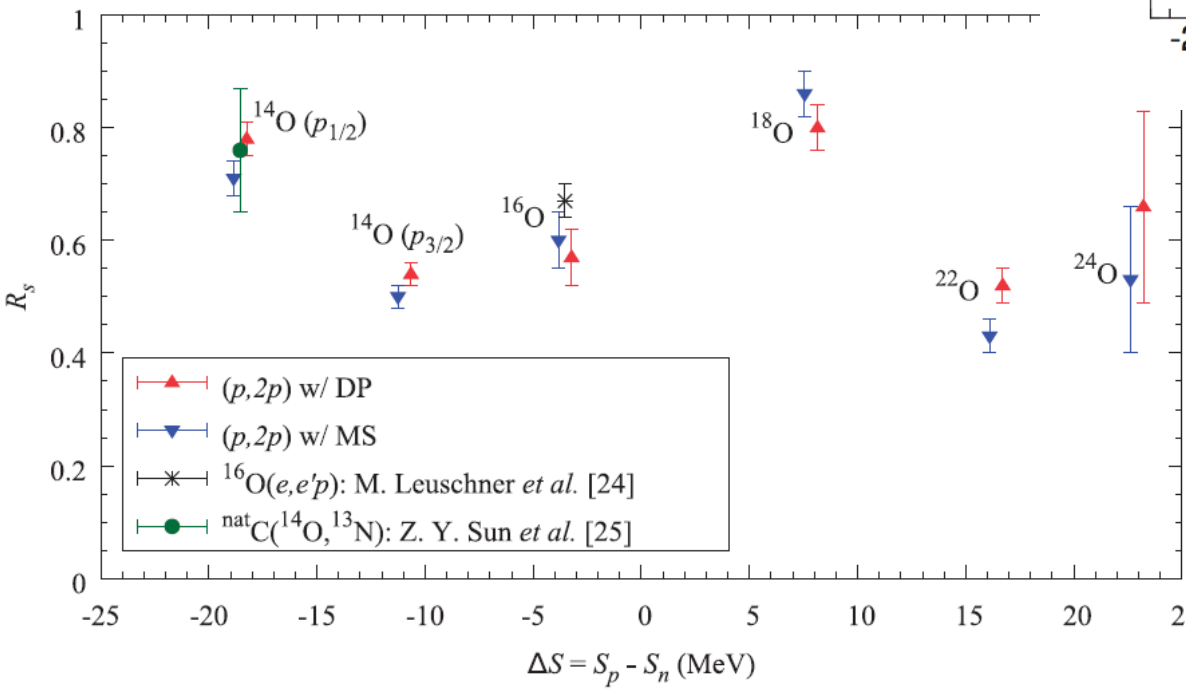


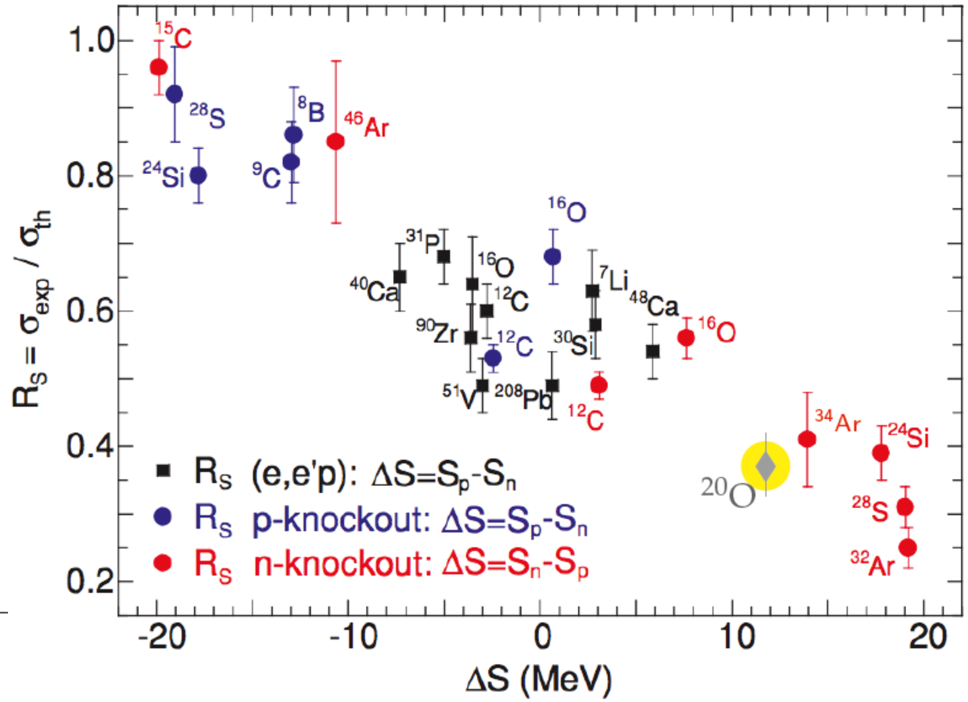
Quasi-free scattering on rare isotopes

More results from GSI/Germany and RIKEN/Japan

- Two more (p,2p) measurements on oxygen isotopes have been reported. GSI data on ^{20}O agrees with HI-induced nucleon removal systematics (PhD thesis), the RIKEN data shows large fluctuations

S. Kawase et al., PTEP 120, 052501 (2018)





M. Najafi, PhD thesis (2013) U. of Groningen

The good, the bad, and the ugly …

HI-induced knockout

- Consistent treatment of all data points, peripheral reaction with understood dependence on orbital radii, little dependence on OMP ☑
- Thought to proceed through two processes, stripping and diffraction. Predicted ratio shown to agree with experiment ☑
- Validity of eikonal and sudden approximation ~100MeV/u for deeply bound nucleons? ☒
- Effect of removing cross section via core excitations? ☒

Needed: More complete reaction theory and unification of structure and reaction formalisms

Transfer reactions

- Consistent bound-state wave function treatment gives consistent results near stability; large body of data at modest asymmetries exists ☑
- Only case at very large asymmetry (~20 MeV) is ^{14}O and huge OMP dependence ☒

Need to reign in the strong dependence of entrance and exit channel OMPs. What is right/wrong to use for rare isotopes?

The good, the bad, and the ugly … *cont.*

Quasifree scattering

- Not peripheral or surface dominated (complementary probe!) ☑
- Need to understand distortions and re-scattering (do we know exactly what a proton does inside of a neutron-rich nucleus? In-medium effects, transparency, … aka distortions) ☒

Need more experimental data, are distortions and re-scattering understood in isospin-asymmetric nuclei?

BUT: Forgetting about absolute spectroscopic factors for a moment, Hi-induced knockout, transfer reactions, and quasi-free scattering are powerful and complementary methods for studying the nuclear structure of rare isotopes as they seek out single-hole and particle strength, allow for determination of orbital angular momenta and possibly total angular momenta at modest beam intensities → track shell evolution at the extremes of the nuclear chart

Takeaways

- The reduction of spectroscopic strength, as encoded in cross sections of direct nuclear reactions relative to shell model and reaction theory, may indicate correlations beyond effective interaction theory and limited model spaces. Different experimental probes may be consistent in the trend but differ in the magnitude of the effect – but large reaction theory uncertainties exist
- From the asymmetry dependence of the reduction and consistent with expectations from some models of nuclei and nuclear matter, the minority nucleons in an asymmetric nucleus are more correlated than the majority nucleon species. This agrees with the large body of work on SRC by Hen, Weinstein *et al.*
- **Challenge:** Omission of SRC may have sizable effect on the modeling of nuclei in models with momentum cutoffs (G. A. Miller et al., arXiv:1805.12099)

Great opportunity for reaction theorists!

Thank you

… for listening

… to Or Hen for slides/figures

… to Alex Brown (NSCL/MSU) and Jeff Tostevin (Surrey) for being my theory partners in crime for >15 years