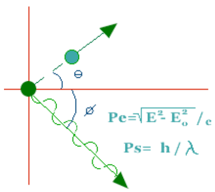
Comparison of (e,e'p) and (p,2p) reactions: similarities and differences

SRC-EMC workshop
1/31/2023

Washington University in St. Louis



DOM activities: Wim Dickhoff
Bob Charity
Lee Sobotka
Louk Lapikas (e,e'p)
Henk Blok (e,e'p)
Kazuyuki Ogata (p,2p)
Kazuki Yoshida (p,2p)
Hossein Mahzoon (Ph.D.2015)
Mack Atkinson (Ph.D. 2019)
Natalya Calleya (Grad)
Cole Pruitt (Ph.D. 2019)
Bob Wiringa
Maria Piarulli
Arnau Rios

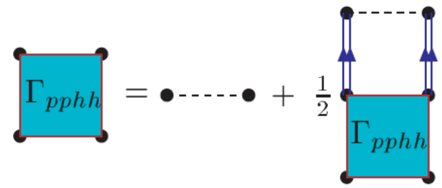
- Motivation —> meaningful link between structure and reactions
- Green's functions/propagator method
  - vehicle for ab initio calculations —> matter & finite nuclei
  - as a framework to link data at positive and negative energy (and to generate predictions for exotic nuclei as well as neutron skins)

    —> Dispersive optical model (DOM <- started by Claude Mahaux)
- Revisiting the Nikhef results and analysis of (e,e'p) using the DOM
- Discussion of (p,2p) and its difficulties to emulate (e,e'p)
- Conclusion and outlook

DOM

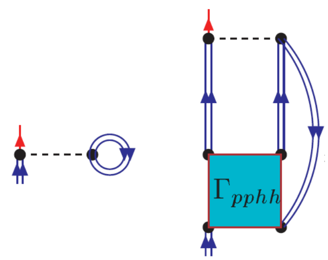
Full off-shell propagation in infinite matter at finite T

SCGF:
self-consistent
Green's functions
for SRC and tensor
effects



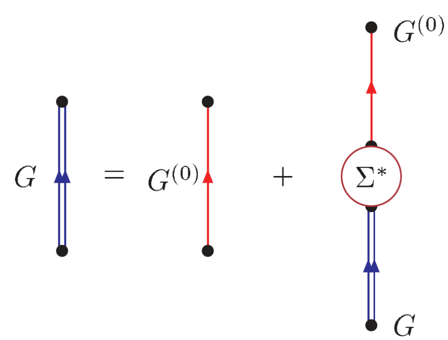
Interaction in the medium properly treating **short-range and tensor correlations**

self-consistency
=> thermodynamically consistent



Self-energy = complex potential in nuclear matter

Arnau Rios
Arturo Polls
W.D.
finite T avoids pairing
standard for AV18, CDBonn, N3LO, etc



Dyson equation $\Rightarrow$ Schrödinger equation for dressed nucleons

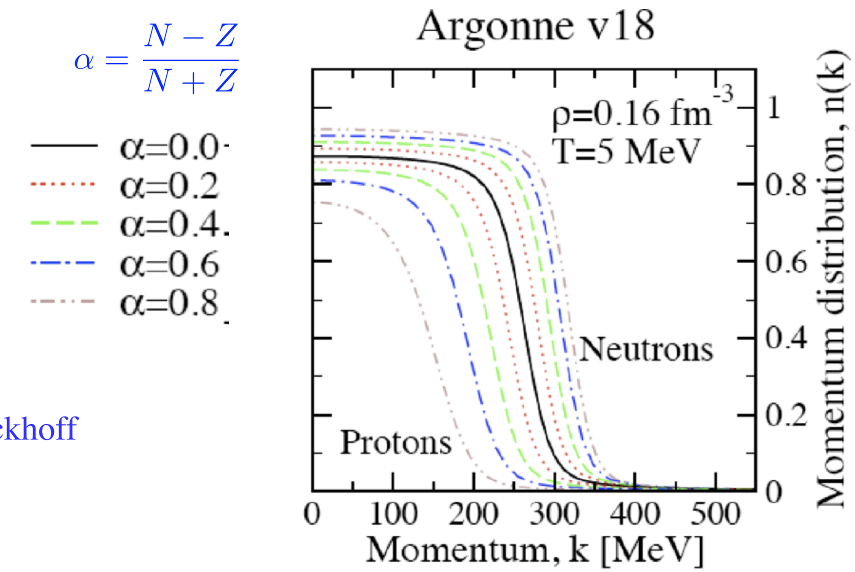
reactions and structure

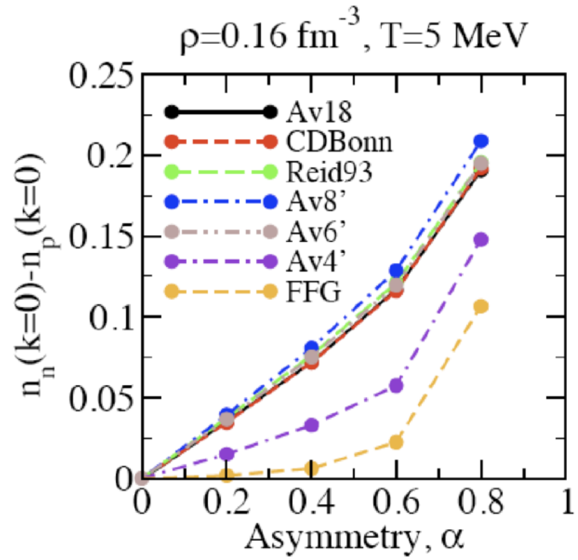
Example momentum distribution SCGF asymmetric matter

- Asymmetry dependence

$$\alpha = \frac{N - Z}{N + Z}$$

SCGF:
self-consistent
Green's functions
for SRC and tensor effects





A. Rios, A. Polls, and W. H. Dickhoff
Phys. Rev. C89, 044303 (2014)
Phys. Rev. C79, 064308 (2009)

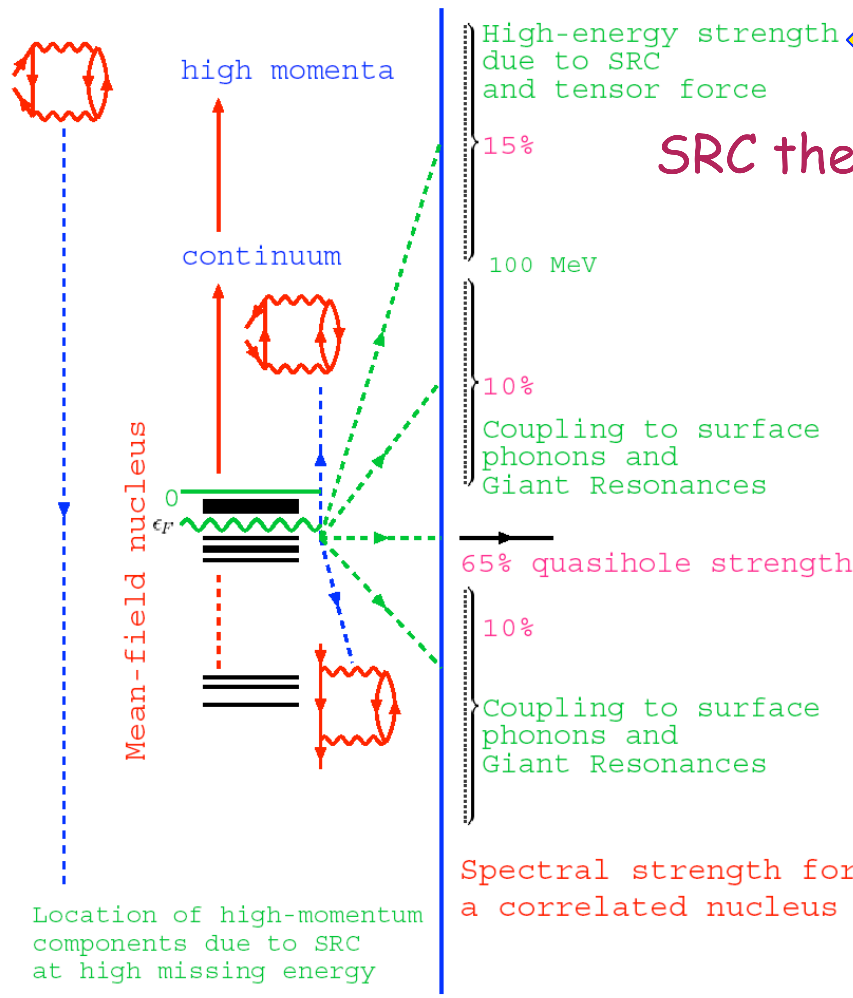
- Full treatment of short-range and tensor correlations
- Incorporates/represents np dominance <—> influence of tensor force
- So more correlations for minority species
- EOS available as a function of T and asymmetry (and several V_{NN} + V_{NNN})

Reviewed in Prog. Part. Nucl. Phys. 52 (2004) 377-496

Location of single-particle strength in closed-shell (stable) nuclei

For example: protons in ^{208}Pb

SRC



SRC theory

Elastic nucleon scattering

NIKHEF (e,e'p) data

L. Lapikás

Nucl. Phys. A553,297c (1993)

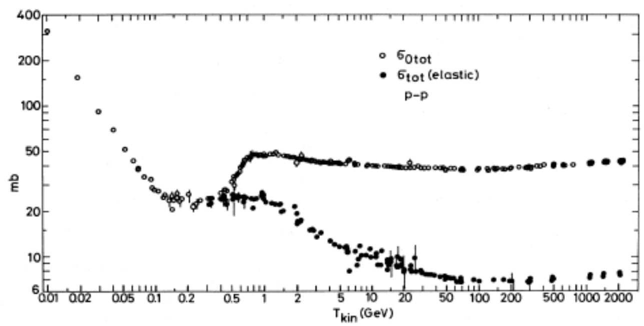
JLab E97-006

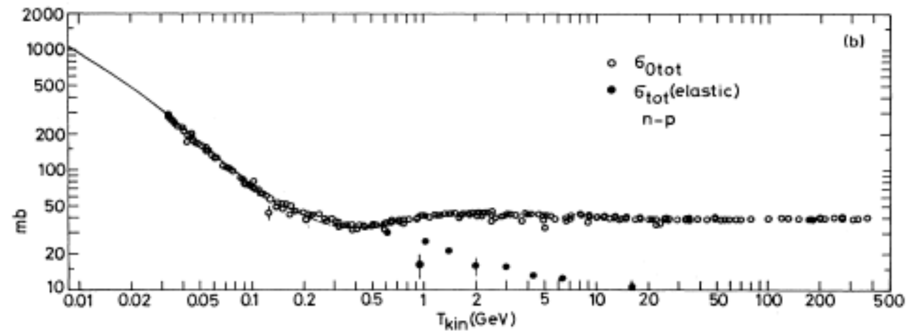
Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.

reactions and structure

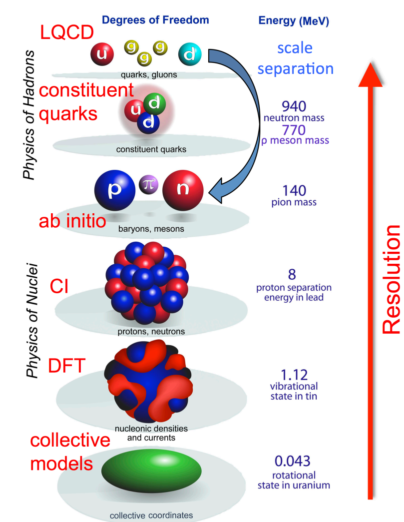
Short-range correlations and NN cross sections

- NN total cross sections





- NN —> coupled to anything at higher energy
- simulate by a strong core
- better to use dispersion relations (not much has been done)



- traditional approach: deal with repulsion as in Monte Carlo
- or SCGF with ladders —> high-momentum tails & removal of strength near the Fermi energy

Dispersive Optical Model

- Claude Mahaux 1980s
  - connect traditional optical potential to bound-state potential
  - crucial idea: use the dispersion relation for the nucleon self-energy
  - employed traditional volume and surface absorption potentials and a local energy-dependent Hartree-Fock-like potential
  - Reviewed in Adv. Nucl. Phys. **20**, 1 (1991)

- Radiochemistry group at Washington University in St. Louis: Charity and Sobotka propose to use the DOM for a sequence of Ca isotopes —> data-driven extrapolations to the drip line
  - First results PRL 97, 162503 (2006)
  - Subsequently —> include data **below** the Fermi energy related to ground-state properties

DOM

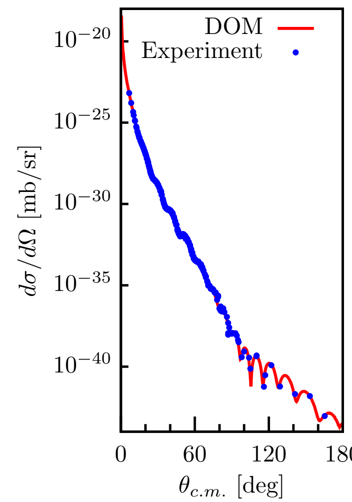
- Nonlocal and dispersive optical potential

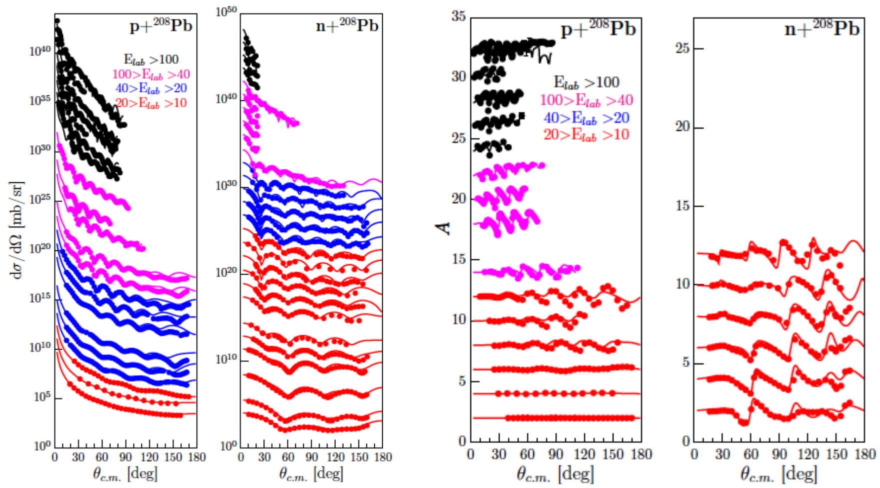
$$
\begin{aligned}
\mathrm{Re}\ \Sigma_{\ell j}(r,r';E) = &\ \mathrm{Re}\ \Sigma_{\ell j}(r,r';\varepsilon_F) \\
- &\ \mathcal{P}\int_{\varepsilon_T^+}^{\infty} \frac{dE'}{\pi}\, \mathrm{Im}\ \Sigma_{\ell j}(r,r';E') \left[\frac{1}{E-E'} - \frac{1}{\varepsilon_F - E'}\right] \\
+ &\ \mathcal{P}\int_{-\infty}^{\varepsilon_T^-} \frac{dE'}{\pi}\, \mathrm{Im}\ \Sigma_{\ell j}(r,r';E') \left[\frac{1}{E-E'} - \frac{1}{\varepsilon_F - E'}\right]
\end{aligned}
$$

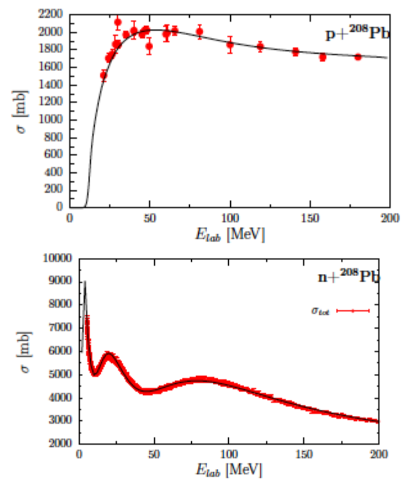
- Allows consideration of negative energy experimental information [charge density]
- Subtracted dispersion relation emphasizes influence of energies close to the Fermi energy
- Empirical information constrains binding potential at the Fermi energy as well as volume integrals of the imaginary part at positive energy

Dispersive Optical Model (St. Louis group)

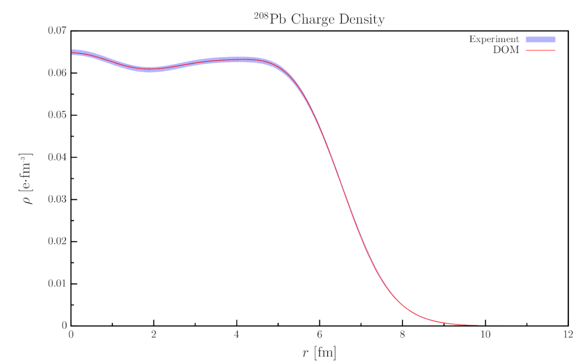
- Mahaux & Sartor 1991 —> Washington University group since 2006
- Use experimental data to constrain the nucleon self-energy while linking structure and reaction domain using dispersion relations







E<0 —>



Indirectly:

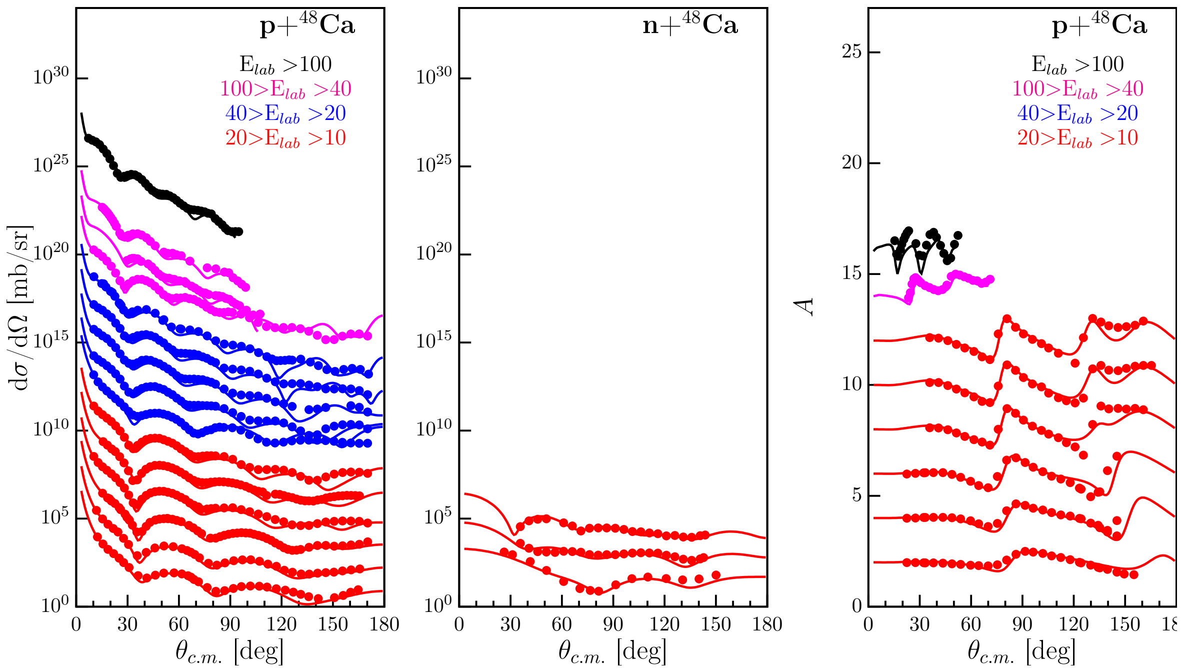
- Predict neutron distribution —> skin

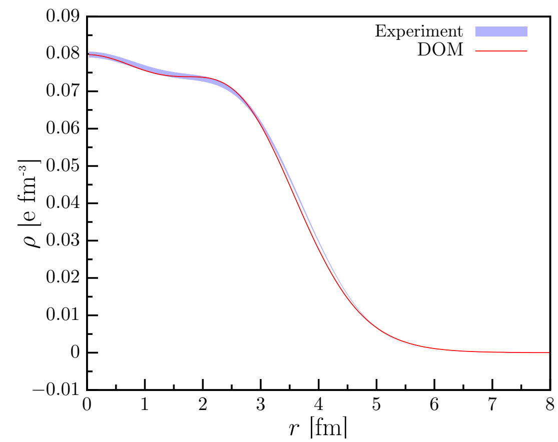
M. C. Atkinson, M. H. Mahzoon, M. A. Keim, B. A. Bordelon, C. D. Pruitt, R. J. Charity, and W. H. Dickhoff
Phys. Rev. C 101, 044303 (2020), 1-15. [arXiv:1911.09020]

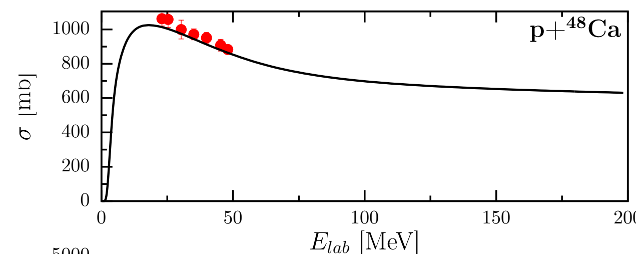
DOM

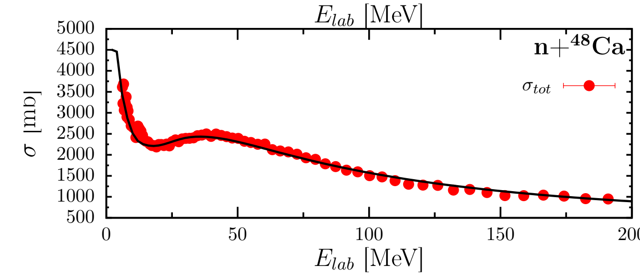
^{48}Ca

- *Allows prediction of neutron properties*









M. C. Atkinson and W. H. Dickhoff
Phys. Lett. B 798, 135027 (2019), 1-6.

Another look at (e,e'p) data

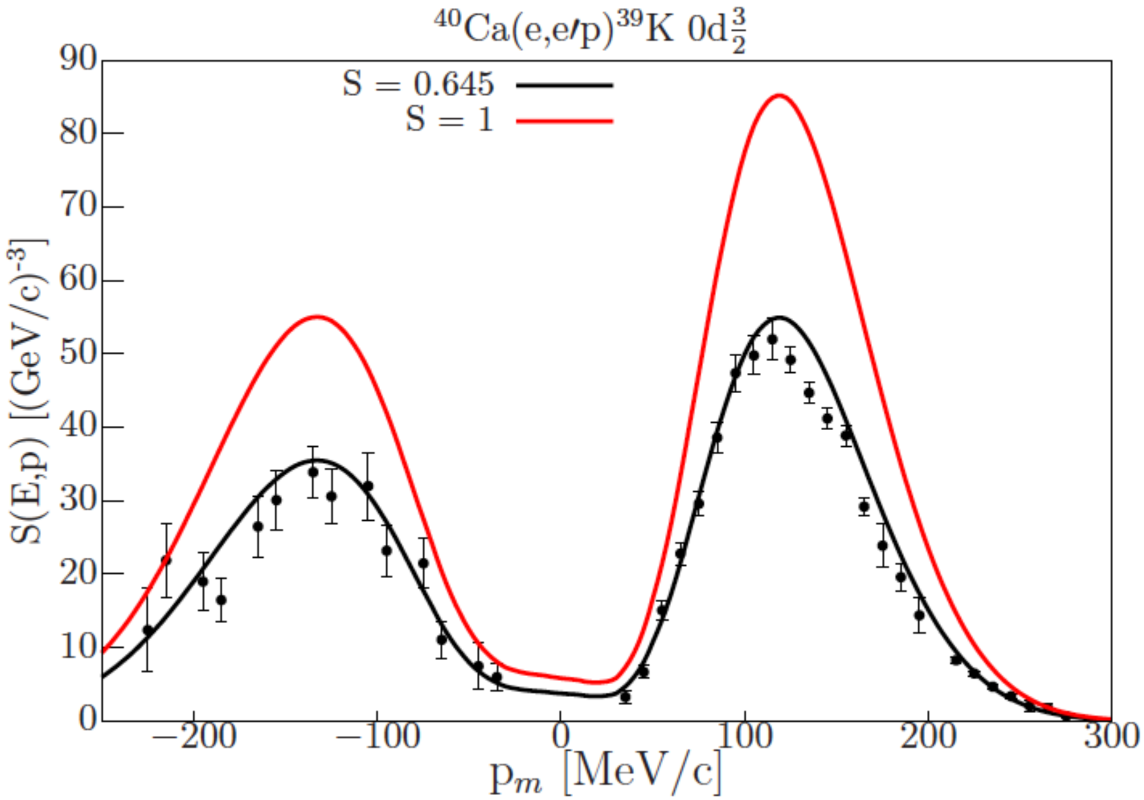
- Collaboration with Louk Lapikás and Henk Blok from Nikhef
- Data published at E_p = 100 MeV Kramer thesis Nikhef for $^{40}Ca(e,e'p)^{39}K$ Phys. Lett. B227, 199 (1989)
  Results: $S(d_{3/2})$=0.65 and $S(s_{1/2})$=0.51
- More data at 70 and 135 MeV (only in a conference paper)
- What do these spectroscopic factor numbers really represent?
  - Assume DWIA for the reaction description
    - Use kinematics (momentum transfer parallel to initial proton momentum) favoring simplest part of the excitation operator (no two-body current) & sufficient energy for the knocked out proton
  - Overlap function:
    - WS with radius adjusted to shape of cross section
    - Depth adjusted to separation energy
  - Distorted proton wave from standard local non-dispersive "global optical potential"
  - Fit normalization of overlap function to data -> spectroscopic factor

Why go back there?

reactions and structure

NIKHEF analysis PLB227,199(1989)

- Schwandt et al. (1981) optical potential
- BSW from adjusted WS



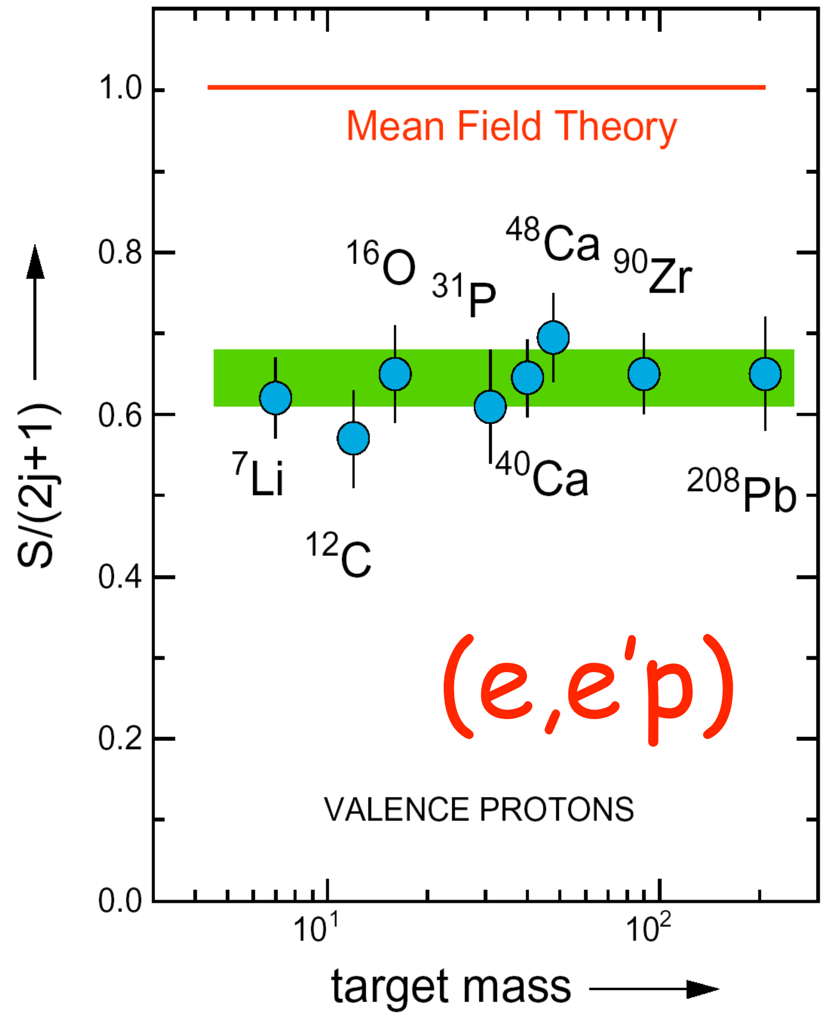
Removal probability for valence protons from NIKHEF data

L. Lapikás, Nucl. Phys. A553,297c (1993)

S ≈ 0.65 for valence protons
Reduction ⇒ both SRC and LRC

Weak probe but propagation in the nucleus of removed proton using standard optical potentials to generate distorted wave --> associated uncertainty ~ 5-15%

Why: details of the interior scattering wave function uncertain since non-locality is not constrained (so far.....)
but now available for ^{40}Ca etc!



reactions and structure

Two recent papers

Validity of the distorted-wave impulse-approximation description of ^{40}Ca$(e, e'p)$ data using only ingredients from a nonlocal dispersive optical model

M. C. Atkinson[1], H.P. Blok[2,3], L. Lapikás[2], R. J. Charity[4], and W. H. Dickhoff[1]

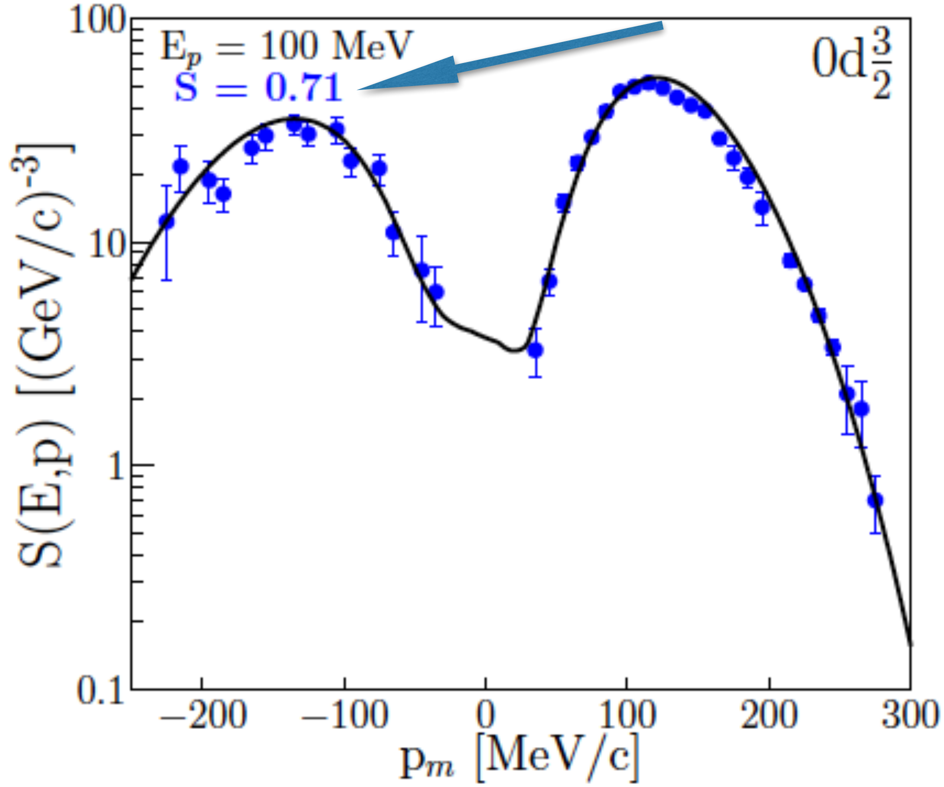
Mack Atkinson et al., Phys. Rev. C98, 044627 (2018)

M. C. Atkinson and W. H. Dickhoff, Phys. Lett. B 798, 135027 (2019)

reactions and structure

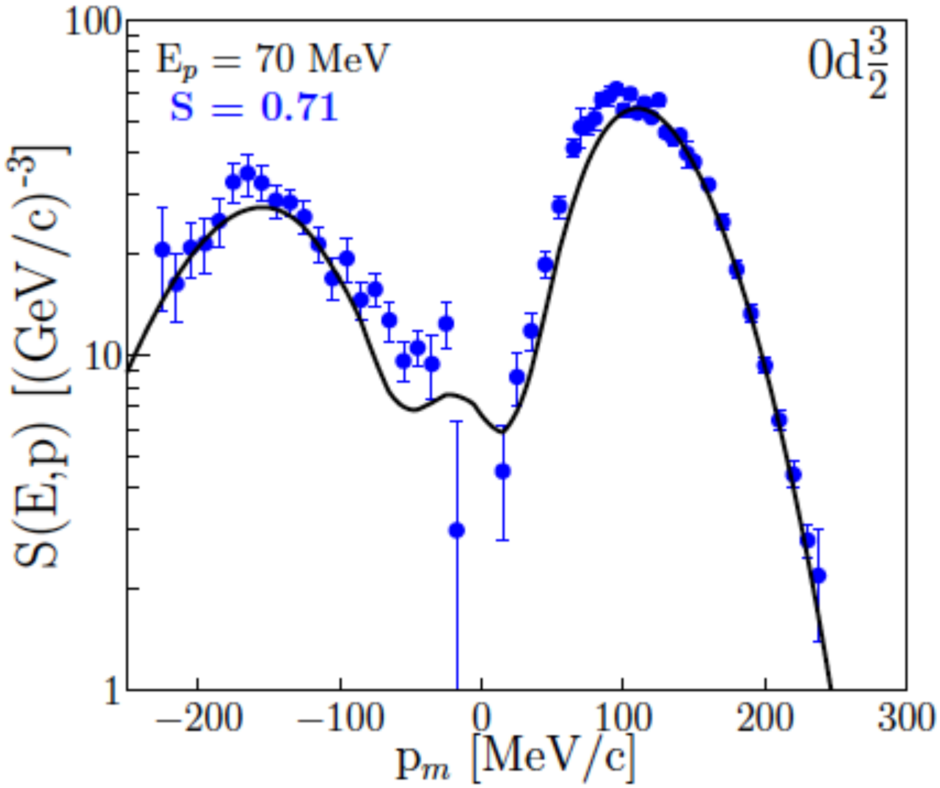
NIKHEF data PLB227,199(1989)

- NIKHEF: $S(d_{3/2})$=0.65±0.06
- Only DOM ingredients



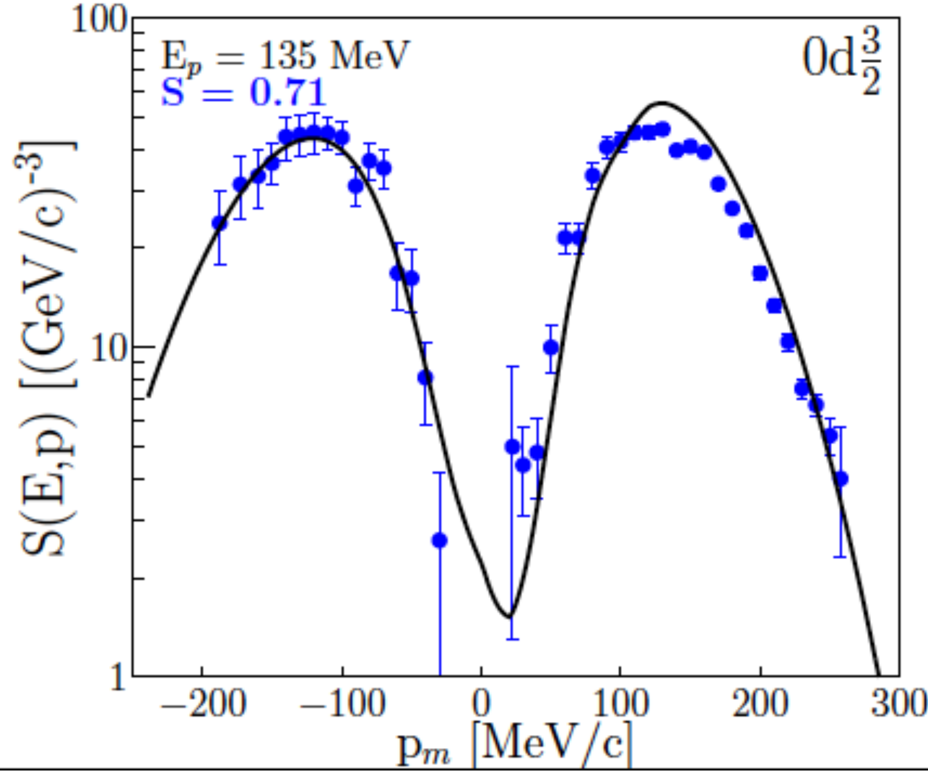
NIKHEF data unpublished so far

- Only DOM ingredients
- DWEEPY code C. Giusti



NIKHEF data unpublished so far

- Only DOM ingredients

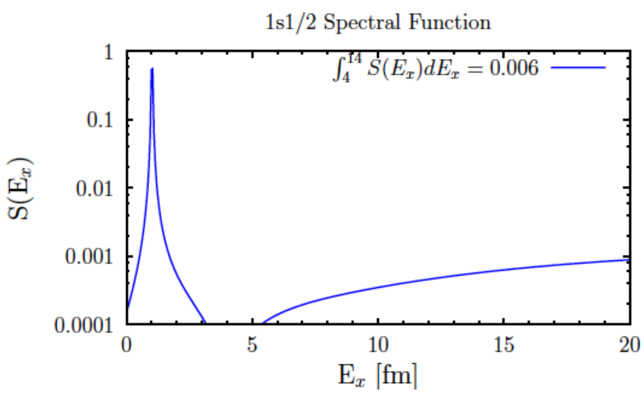


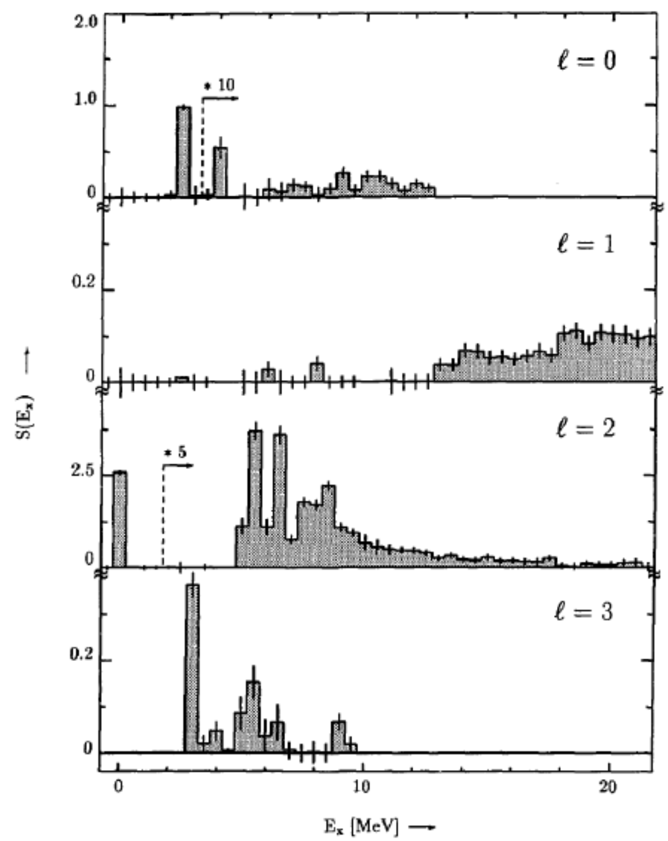
- at this energy DWIA may no longer be the whole story

Thesis G. J. Kramer (1990)

- $s_{1/2}$ strength fragmented

- Not yet included in DOM

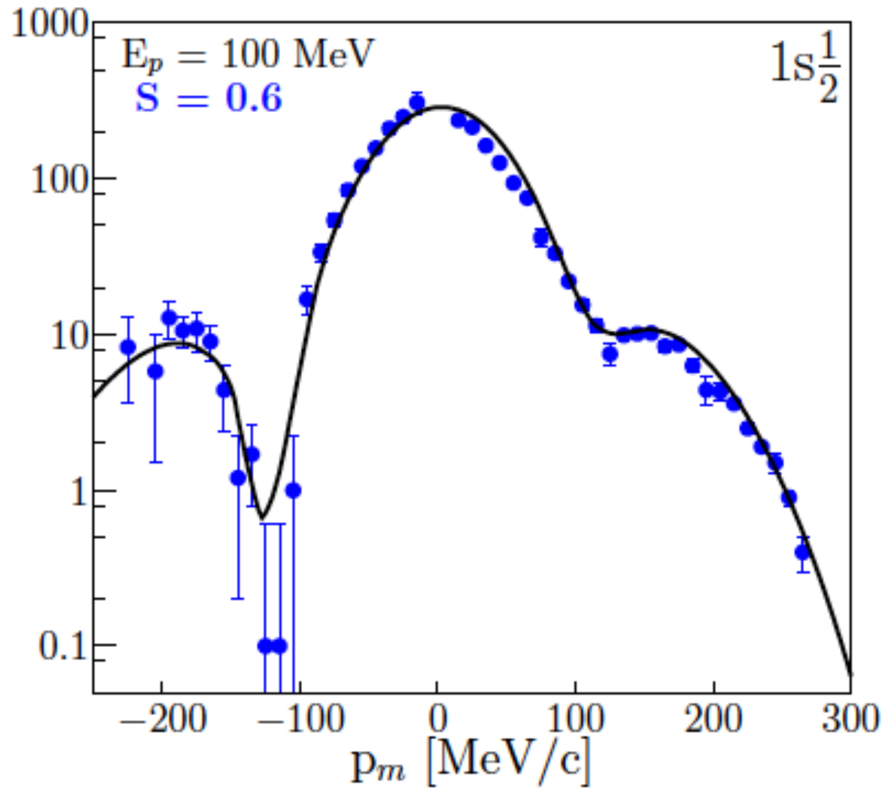




- Corrects DOM spectroscopic factor
- Low-energy fragmentation —> shell model description possible

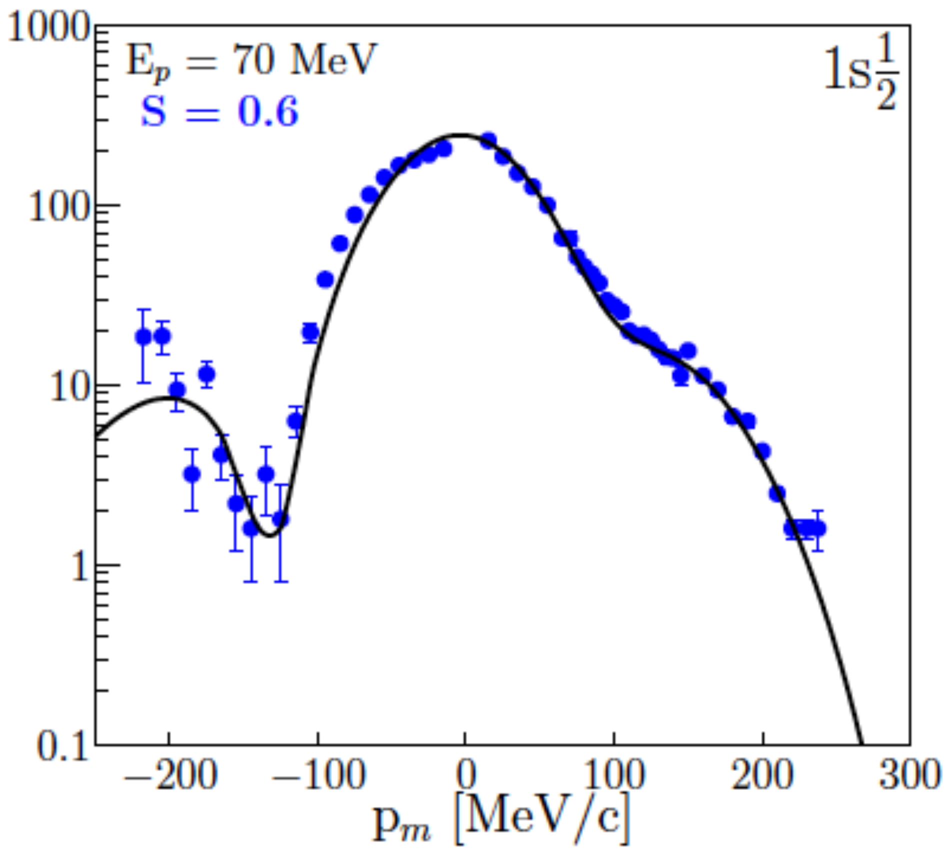
NIKHEF data PLB227,199(1989)

- NIKHEF: $S(s_{1/2})=0.51\pm0.05$



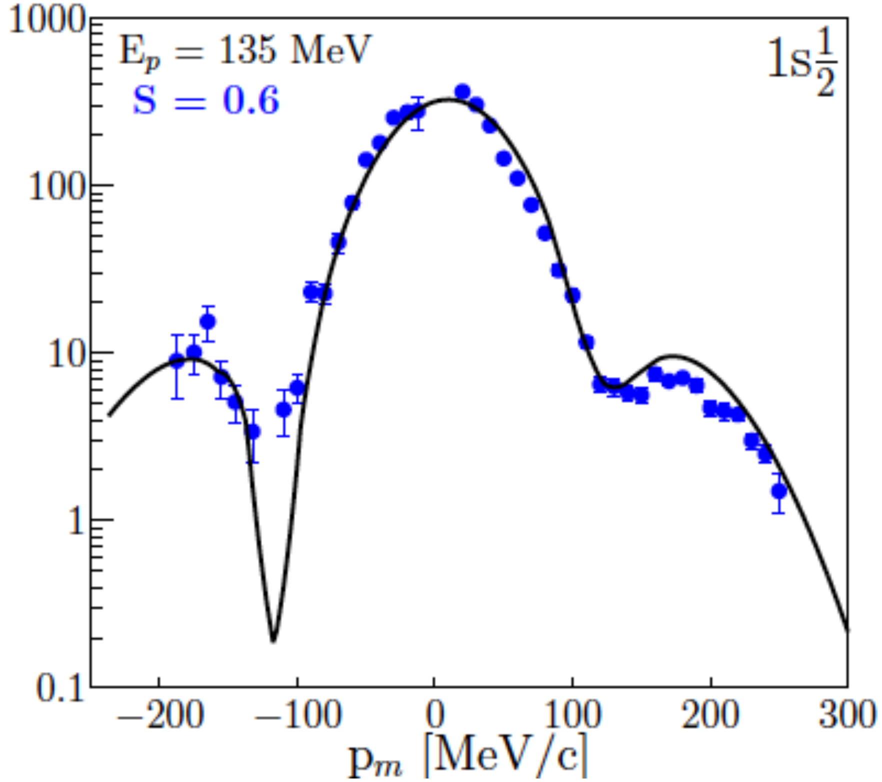
Includes NIKHEF data published for the first time

- Only DOM ingredients



NIKHEF data unpublished

- Only DOM ingredients



Message

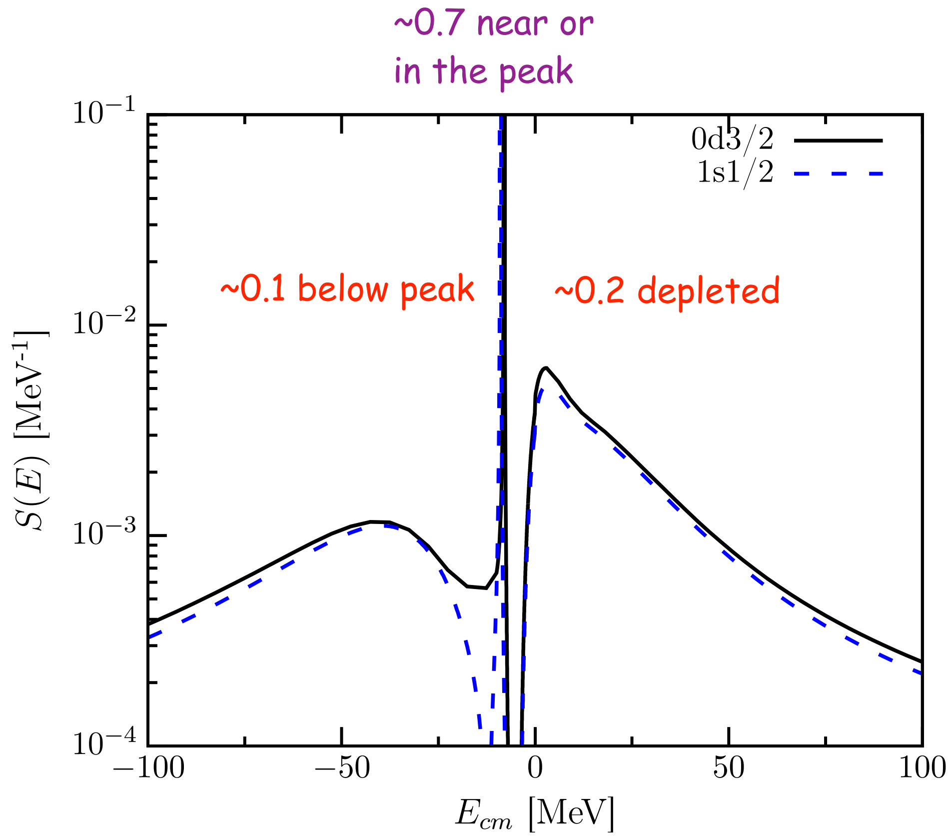
- Nonlocal dispersive potentials yield consistent input but are constrained by **other** experimental data

- Constraints from these other data generate spectroscopic factor —> $S(d_{3/2})=0.71$ in ^{40}Ca for ground state transition
- Using experimental $s_{1/2}$ strength distribution: 2.5 MeV state —> $S(s_{1/2})=0.60$

- NIKHEF 0.65±0.06 and 0.51±0.05, respectively (local)
- DWIA validated for (e,e'p) including the choice of kinematics and energy domain as implemented at Nikhef

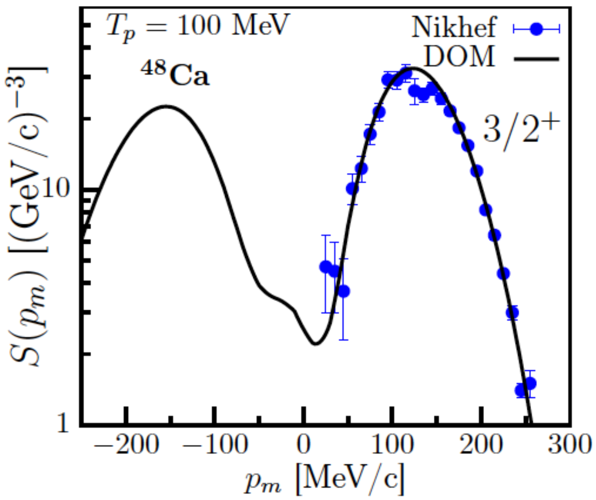
^{40}Ca spectral distribution

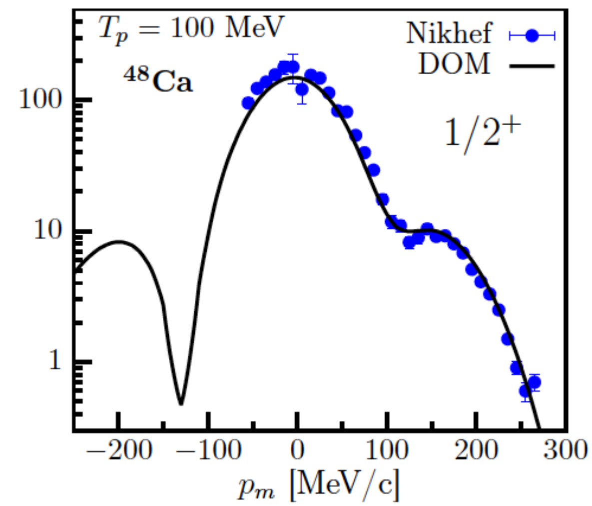
- 0d3/2 and 1s1/2



$^{48}Ca(e,e'p)$

- Reduced to 0.60 from 0.71 in ^{40}Ca
- after local energy correction —> from 0.60 to $S(d_{3/2})$=0.58
- and from 0.64 —> $S(s_{1/2})$ = 0.55

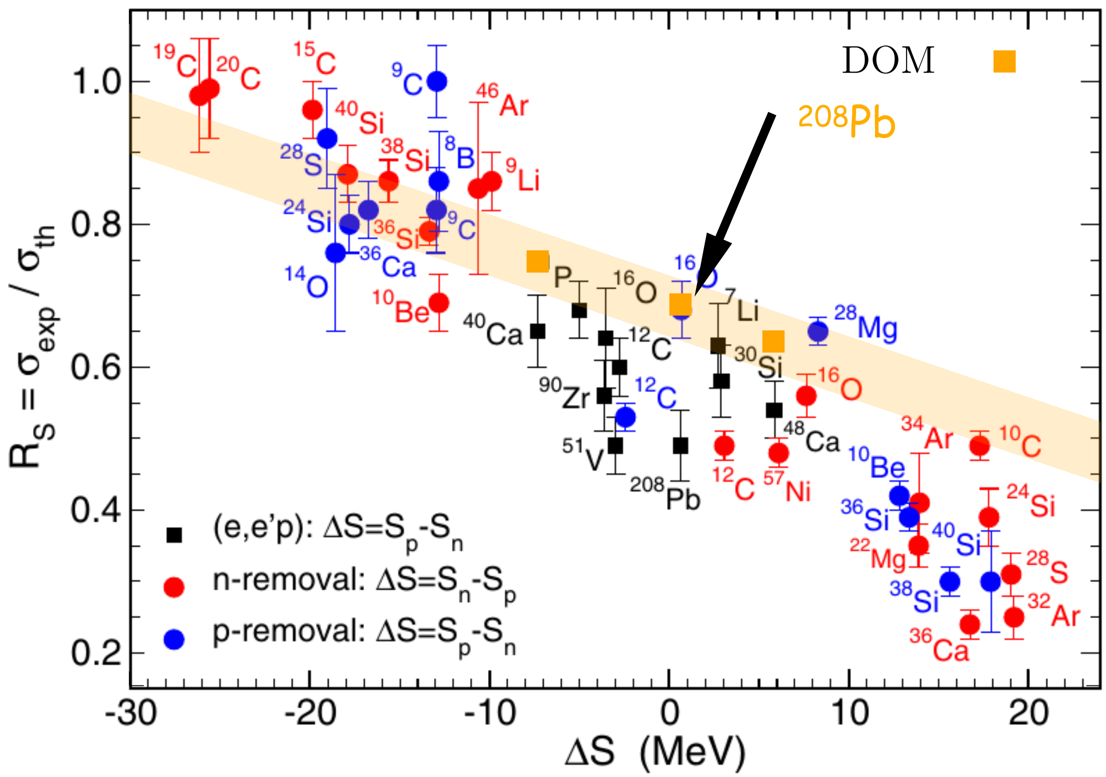




- No further adjustments! All ingredients provided by DOM
- **Both structure and reaction properties allowed to change when 8 n added**

Compare with Gade plot

Very near the Fermi energy in ^{40}Ca and ^{48}Ca from (e,e'p) —> error band



Quenching sp strength review: Aumann et al, Prog. Part. Nucl. Phys. 118, 103847 (2021)

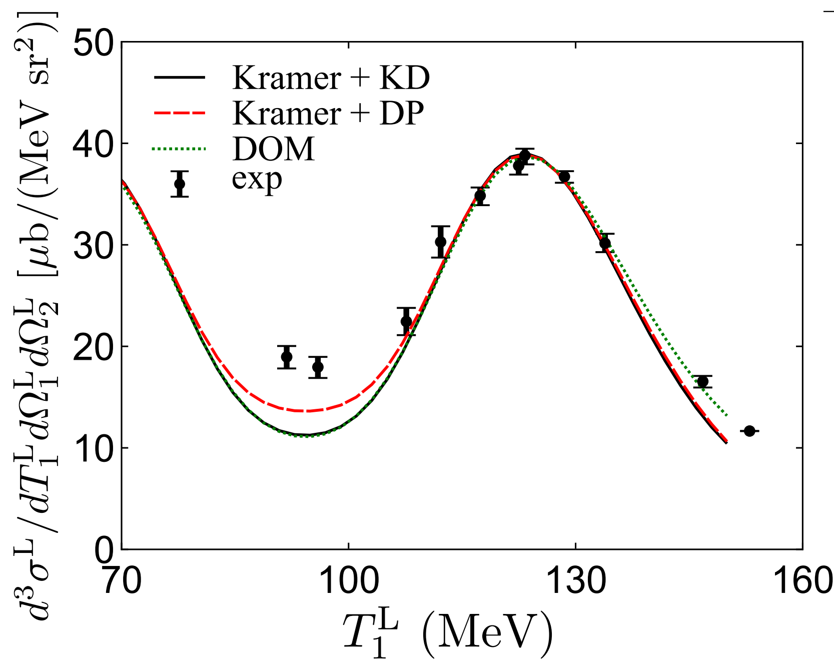
DOM

(p,2p) stable targets (RCNP)

- Can "emulate" (e,e'p) results for orbits near the Fermi energy (Noro et al. RCNP data)
- But: there is an unresolved A_y puzzle…
- DOM ingredients + standard DWIA (Ogata & Yoshida)
- —> Requires NN interactions with pions etc. that can carry energy!

First results identify a problem

- Using the same ingredients as for (e,e'p) standard (p,2p) DWIA interaction —> inconsistent for ^{40}Ca(p,2p) at 200 MeV



PHYSICAL REVIEW C **105**, 014622 (2022)

First application of the dispersive optical model to (*p*, 2*p*) reaction analysis within the distorted-wave impulse approximation framework

K. Yoshida[1,*] M. C. Atkinson[2] K. Ogata[3,4,5] and W. H. Dickhoff[6]

TABLE I. Setup and resulting spectroscopic factors.

SPWF	Optical pot.	*p*-*p* int.	$\mathcal{Z}_{0d_{3/2}}$
Kramer	KD	FL	0.623 ± 0.006
Kramer	Dirac	FL	0.672 ± 0.006
DOM	DOM	FL	0.560 ± 0.005
DOM	DOM	Mel	0.489 ± 0.005
DOM	DOM	Mel (free)	0.515 ± 0.005

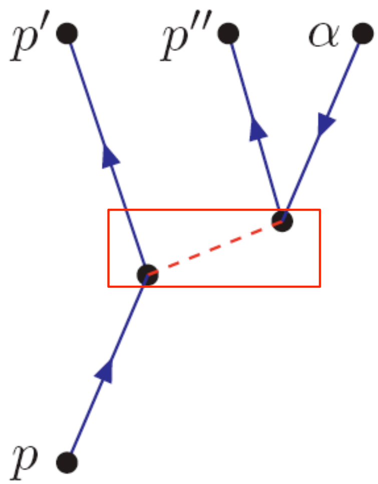
- DOM spectroscopic factor 0.71±0.05

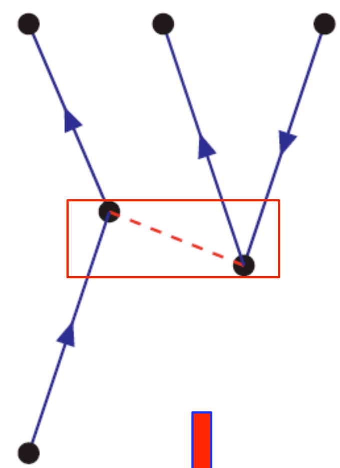
?

reactions and structure

Observations for (p,2p)

Born terms already different!





$$\frac{1}{2\sqrt{m_\pi^2+q^2}}\,\frac{1}{E-\varepsilon(p')-\sqrt{m_\pi^2+q^2}+i\eta}$$

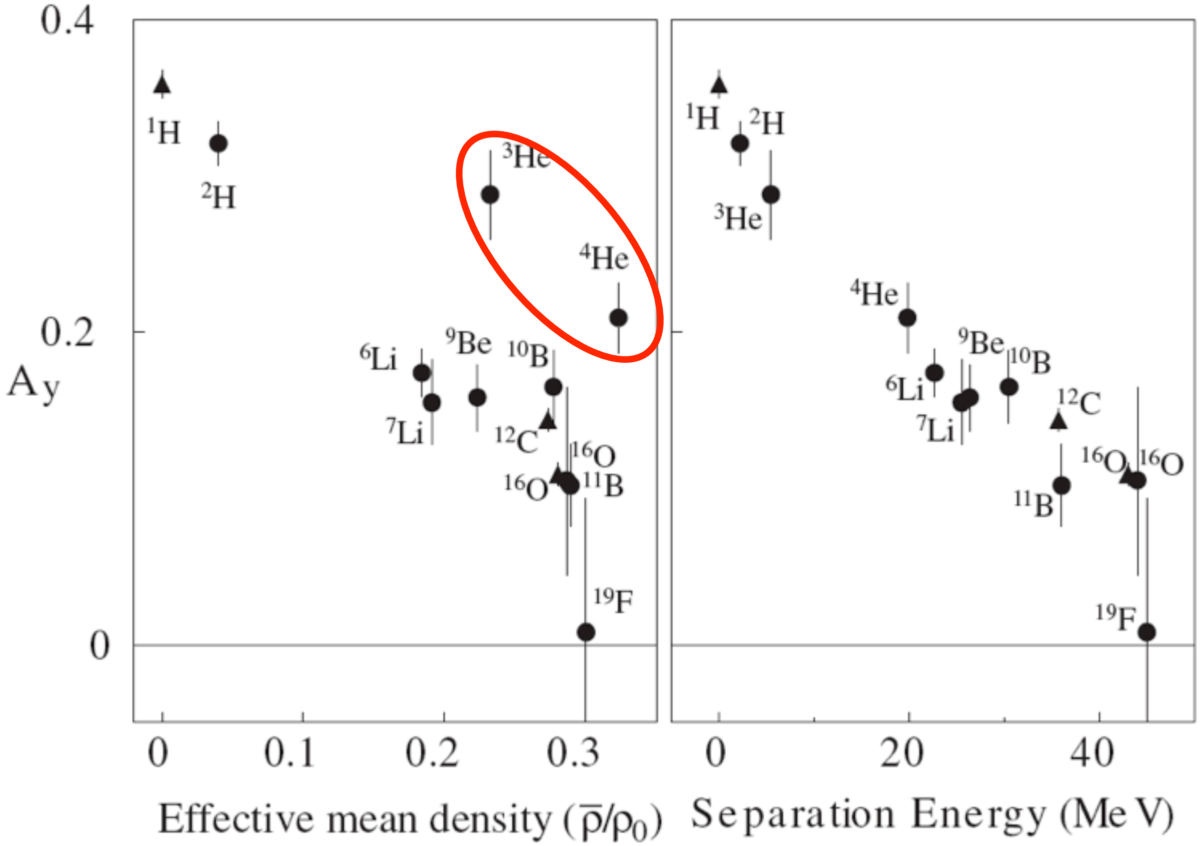
$$\frac{1}{2\sqrt{m_\pi^2+q^2}}\,\frac{1}{\varepsilon_\alpha-\varepsilon(p')-\sqrt{m_\pi^2+q^2}}$$

$$\frac{1}{2\sqrt{m_\pi^2+q^2}}\,\frac{-1}{\sqrt{m_\pi^2+q^2}}$$

$$\frac{1}{2\sqrt{m_\pi^2+q^2}}\,\frac{-1}{\sqrt{m_\pi^2+q^2}}$$

$$\frac{-1}{m_\pi^2+q^2}$$

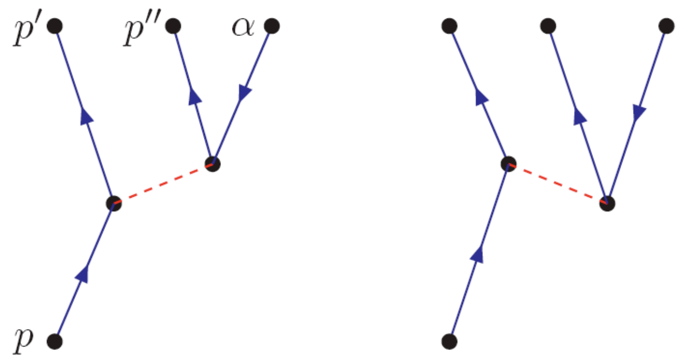
A_y puzzle in (p,2p)



Noro et al.
RCNP data

DWIA
almost like
free A_y...

Typical energies ^{12}C $s_{1/2}$ removal



$$E_p = 392 \text{ MeV}$$
$$E_{p'} = 268 \text{ MeV}$$
$$E_{p''} = 88 \text{ MeV}$$
$$\varepsilon_\alpha = -36 \text{ MeV}$$

$\Rightarrow$ Pion carries 124 MeV or

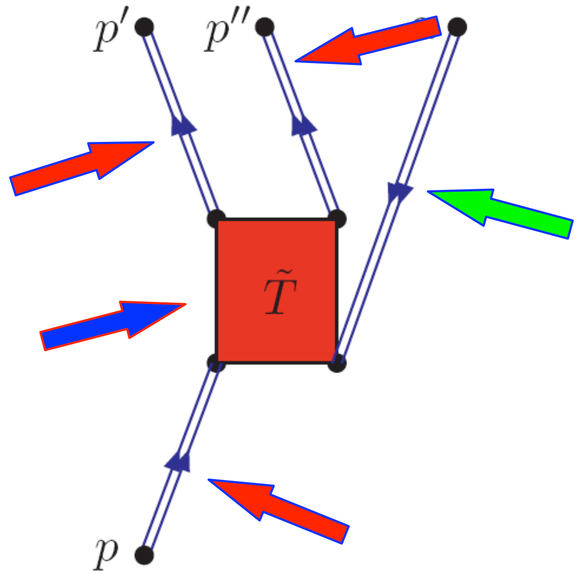
304 MeV (exchange term)

contrast with NN T-matrix

$\Rightarrow$ Pion carries 0 MeV

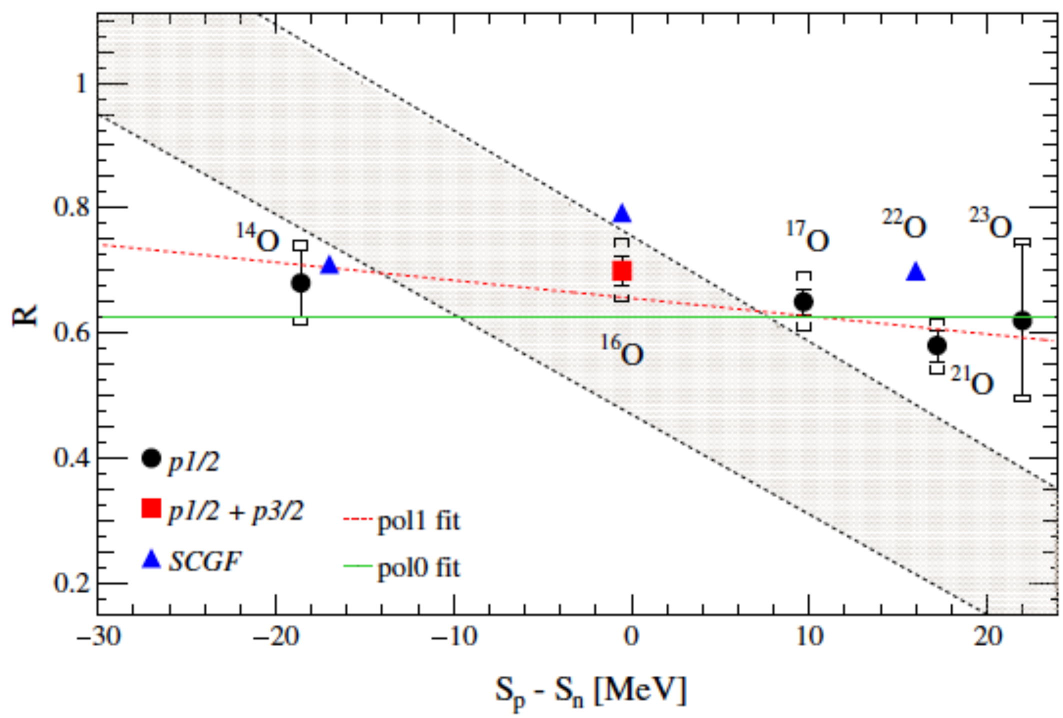
Analysis of (p,2p)/(p,pn) and other reactions

- DOM distorted waves and removal amplitude
- Modified T-matrix with dynamic π-exchange etc.



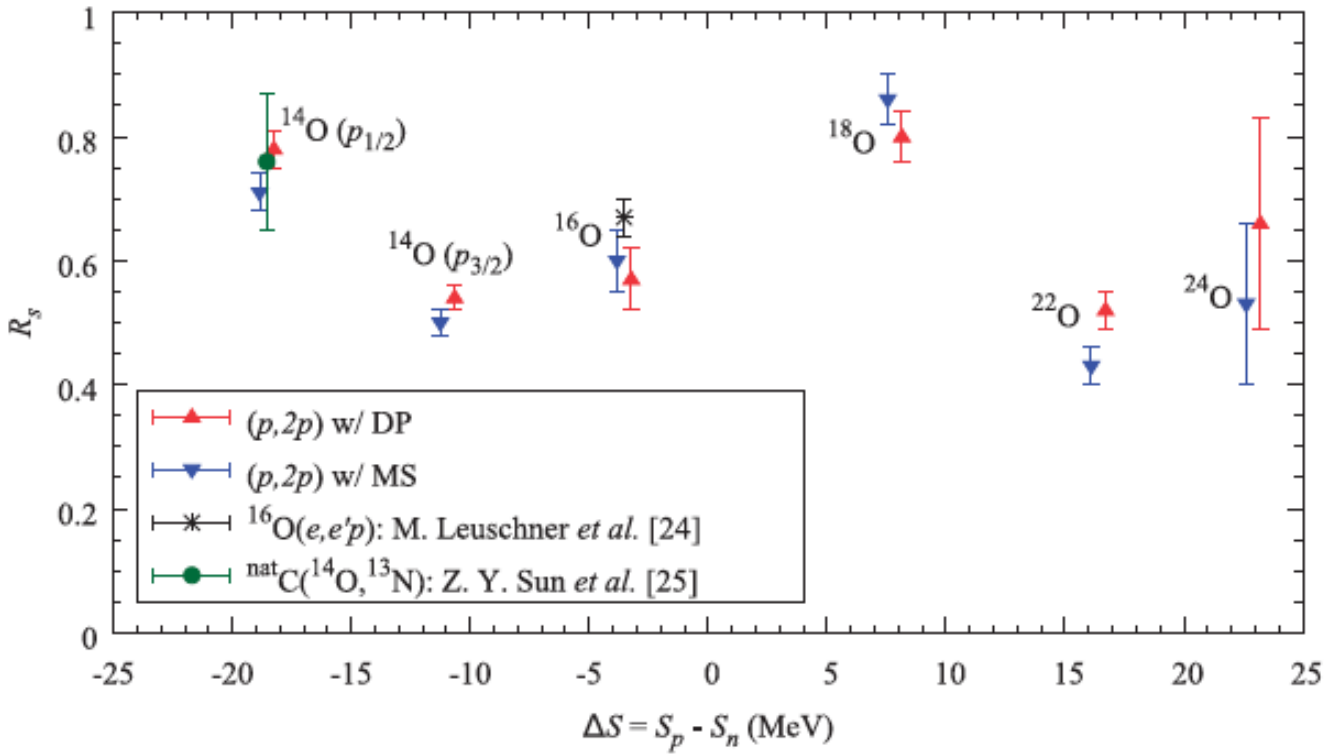
O(p,2p) L. Atar et al. Phys. Rev. Lett. 120, 052501 (2018)

- "Ab initio" interaction has "no" tensor force —> spectroscopic factors?
- Reaction model: distorted waves not constrained by experiment as a function of nucleon asymmetry
- Inconsistent with np dominance observed in 2N knockout reactions (Or et al.)
- Energy transfer completely neglected



O(p,2p)

- S. Kawase et al. Prog. Theor. Exp. Phys. 2018, 021D01
- DWIA uses optical potentials not constrained by scattering data for unstable nuclei



Status of “reduction” factors/spectroscopic factors

T. Aumann, C. Barbieri, D. Bazin et al. Progress in Particle and Nuclear Physics 118 (2021) 103847

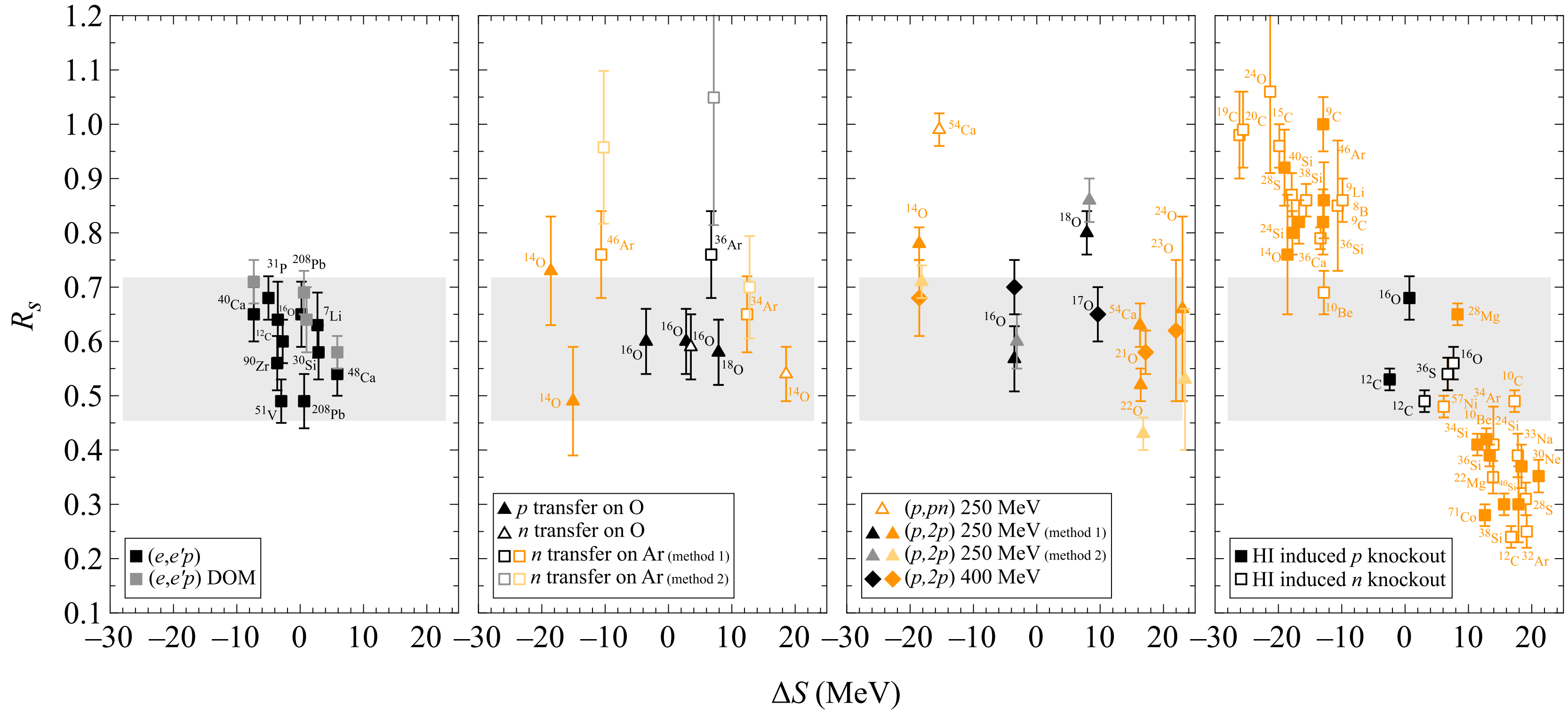


Fig. 56. The four panels of this plot show the quenching (reduction) factors for (a) electron-induced knockout reactions [87,172,237,376], (b) transfer reactions with radioactive ion beams [55,57,203], (c) quasifree $(p, 2p)$ proton knockout on stable nuclei (from the compilation in [239]) and radioactive nuclei [58,59], and (d) the inclusive intermediate-energy knockout data [46]. The measurements are compared to predictions based on effective-interaction shell-model SFs while, in the case of $(e, e'p)$, the integrated strength is compared to the independent-particle expectation.

Conclusions

- Ab initio Green's function method at finite T —> asymmetric matter <—> tensor force
- Asymmetric matter: Minority species more correlated quantitatively determined by tensor force

- Empirical Green's function method —> DOM
- DOM describes lots of data and can predict hard to access experimental data —> neutron skin
- DOM ingredients confirm validity of DWIA for (e,e'p) —> spectroscopic factors but in specific kinematics and a definite energy window for the outgoing proton ~ 100 MeV

- Same DOM ingredients utilized in standard (p,2p) analysis do not yield agreement for spectroscopic factors **BUT note that substantial energy is transferred in this reaction**
- **—> Requires further development**