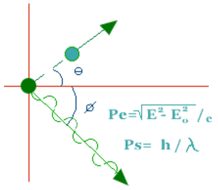
The influence of weak charge data on the optical potential

Washington University in St.Louis

Towards a consistent approach for nuclear structure
and reactions: microscopic optical potentials 6/17/2024



- Optical potential <—> nucleon self-energy
- Motivation —> meaningful link between structure and reactions essential for the physics of rare isotopes
- Green’s functions/propagator method <—> Causality by employing dispersion relations <—> dispersive optical model (DOM)
- Correlations implied by elastic scattering data <—> sum rule
  - Framework to link data at positive and negative energy (and to generate predictions for exotic nuclei as well as neutron skins)
- Revisiting the Nikhef results and analysis of (e,e’p) using the DOM
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- Conflict with guidance from ab initio in asymmetric matter & experiment?
- Conclusion and outlook

DOM

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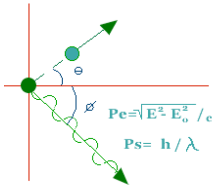
DOM activities: Wim Dickhoff
Bob Charity
Lee Sobotka
Louk Lapikas (e,e'p)
Henk Blok (e,e'p)
Kazuyuki Ogata (p,2p)
Kazuki Yoshida (p,2p)
Hossein Mahzoon (Ph.D.2015)
Mack Atkinson (Ph.D. 2019)
Natalya Calleya (Grad)
Ragib Ramon (Grad)
Cole Pruitt (Ph.D. 2019)
Bob Wiringa
Maria Piarulli
Arnau Rios



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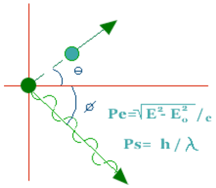

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DOM

Optical potential <--> nucleon self-energy <—> DOM

- relate dynamic (energy-dependent) real part to imaginary part
- employ subtracted dispersion relation
- contributions from the hole (structure) and particle (reaction) domain

General dispersion relation for self-energy:

$$\mathrm{Re}\ \Sigma(E) = \Sigma^{HF} - \frac{1}{\pi}\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\mathrm{Im}\ \Sigma(E')}{E-E'} + \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\mathrm{Im}\ \Sigma(E')}{E-E'}$$

Calculated at the Fermi energy

$$\mathrm{Re}\ \Sigma(\varepsilon_F) = \Sigma^{HF} - \frac{1}{\pi}\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\mathrm{Im}\ \Sigma(E')}{\varepsilon_F-E'} + \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\mathrm{Im}\ \Sigma(E')}{\varepsilon_F-E'}$$

$$\varepsilon_F = \tfrac{1}{2}\left\{(E_0^{A+1}-E_0^A) + (E_0^A - E_0^{A-1})\right\}$$

Subtract

$$\mathrm{Re}\ \Sigma(E) = \mathrm{Re}\ \Sigma^{\widetilde{HF}}(\varepsilon_F)$$

$$- \quad \frac{1}{\pi}(\varepsilon_F - E)\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\mathrm{Im}\ \Sigma(E')}{(E-E')(\varepsilon_F-E')} + \frac{1}{\pi}(\varepsilon_F - E)\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\mathrm{Im}\ \Sigma(E')}{(E-E')(\varepsilon_F-E')}$$

Propagator in principle generates

- Elastic scattering cross sections for p and n
- Including all polarization observables
- Total cross sections for n
- Reaction cross sections for p and n
- Overlap functions for adding p or n to bound states in Z+1 or N+1
- Plus normalization --> spectroscopic factor
- p and n distorted waves
- Overlap function for removing p or n with normalization
- Hole spectral function including high-momentum description
- One-body density matrix; occupation numbers; natural orbits
- Charge density
- Neutron distribution
- Contribution to the energy of the ground state from V_{NN}

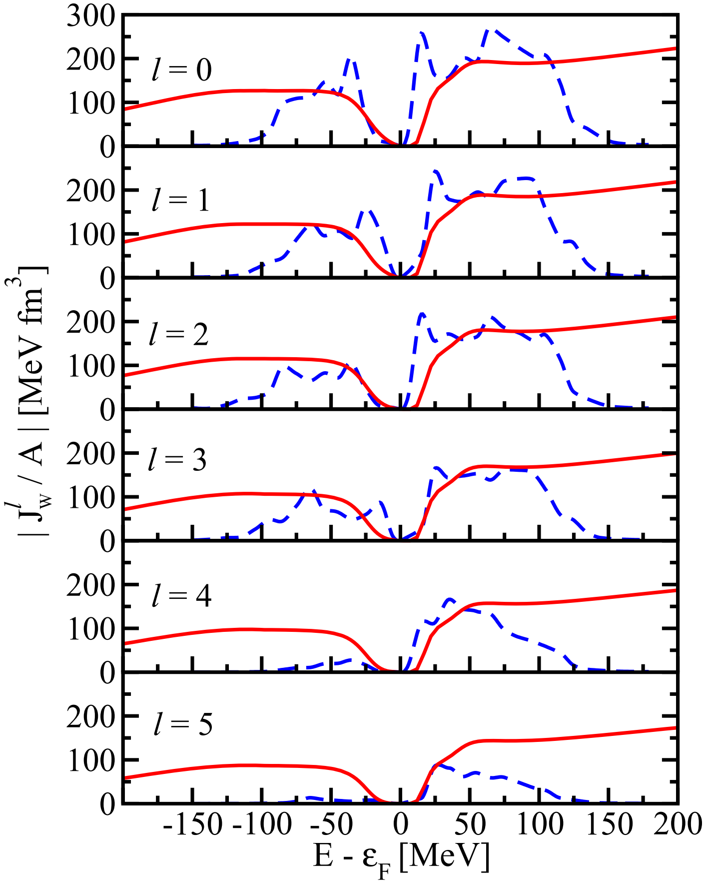
reactions and structure

Causality <—> 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
  - Requires fully **nonlocal** treatment
  - Reviewed in J. Phys. G: Nucl. Part. Phys. **44** (2017) 033001, Prog. Part. Nucl. Phys. 105 (2019), 252, and Prog. Part. Nucl. Phys. **118** (2021) 103847
  - Generates a consistent description of Nikhef data in parallel kinematics

Perspective: DOM <—> ab initio

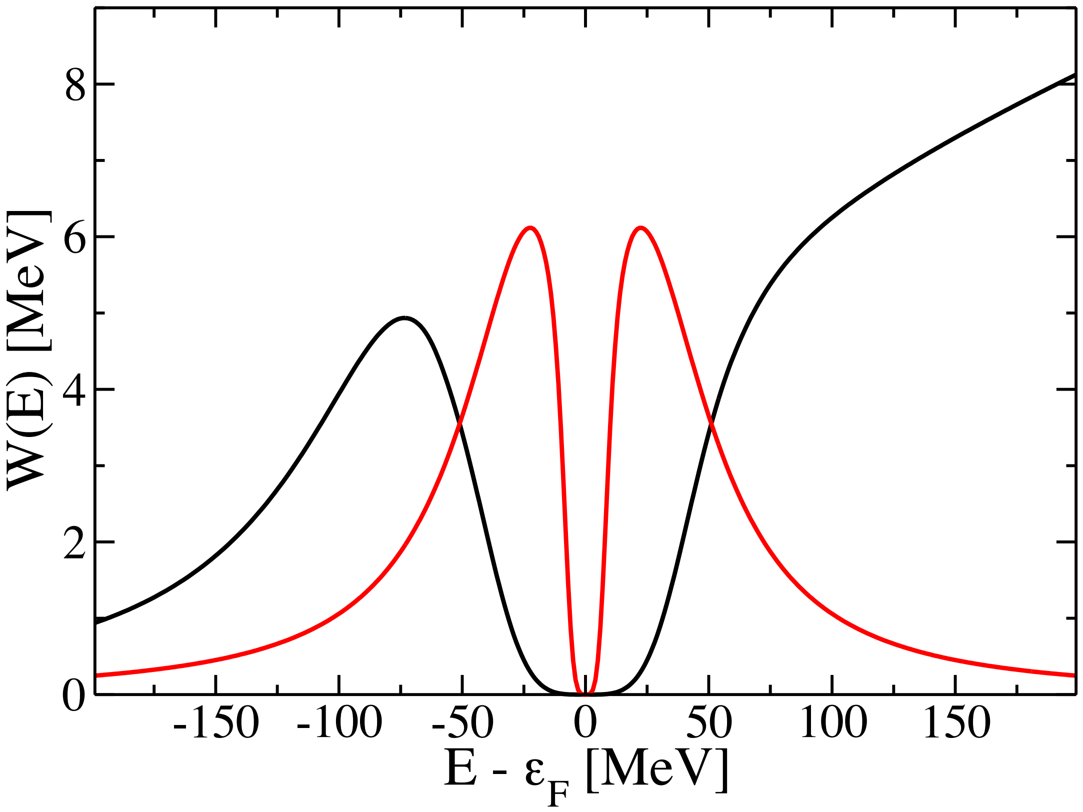
- Volume integrals of imaginary potential ^{40}Ca
- Dashed FRPA/SCGF
- Solid DOM



J. Phys. G: Nucl. Part. Phys. **44** (2017) 033001

Energy dependence of typical surface and volume imaginary potentials

- Generates compression of the single-particle spectrum around the Fermi energy
- Strength is moved from below to above the Fermi energy
- Strength is moved from above to below the Fermi energy (high momenta)
- Valence spectroscopic factors < 1



Do elastic scattering data tell us about correlations?

- Scattering T-matrix (neutrons)

$$\Sigma_{\ell j}(k,k';E) = \Sigma^*_{\ell j}(k,k';E) + \int dq q^2 \Sigma^*_{\ell j}(k,q;E) G^{(0)}(q;E) \Sigma_{\ell j}(q,k';E)$$

- Free propagator $G^{(0)}(q;E) = \dfrac{1}{E - \hbar^2 q^2/2m + i\eta}$
- Propagator

$$G_{\ell j}(k,k';E) = \frac{\delta(k-k')}{k^2} G^{(0)}(k;E) + G^{(0)}(k;E)\Sigma_{\ell j}(k,k';E)G^{(0)}(k;E)$$

- Spectral representation

$$G^p_{\ell j}(k,k';E) = \sum_n \frac{\phi^{n+}_{\ell j}(k)\left[\phi^{n+}_{\ell j}(k')\right]^*}{E - E^{*A+1}_n + i\eta} + \sum_c \int_{T_c}^{\infty} dE' \, \frac{\chi^{cE'}_{\ell j}(k)\left[\chi^{cE'}_{\ell j}(k')\right]^*}{E - E' + i\eta}$$

- Spectral density for $E > 0$

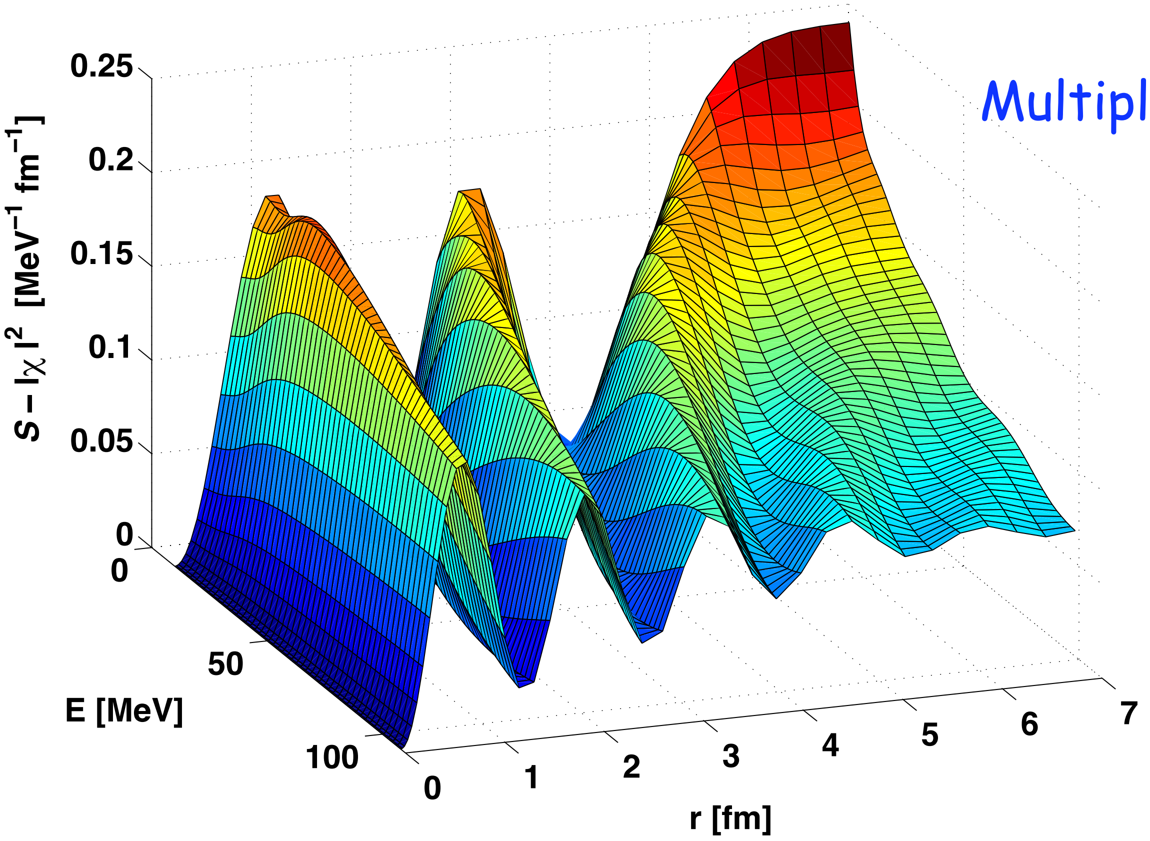
$$\boxed{S^p_{\ell j}(k,k';E) = \frac{i}{2\pi}\left[G^p_{\ell j}(k,k';E^+) - G^p_{\ell j}(k,k';E^-)\right] = \sum_c \chi^{cE}_{\ell j}(k)\left[\chi^{cE}_{\ell j}(k')\right]^*}$$

- Coordinate space $S^p_{\ell j}(r,r';E) = \sum_c \chi^{cE}_{\ell j}(r)\left[\chi^{cE}_{\ell j}(r')\right]^*$
- Elastic scattering also explicitly available

$$\chi^{elE}_{\ell j}(r) = \left[\frac{2mk_0}{\pi\hbar^2}\right]^{1/2} \left\{ j_\ell(k_0 r) + \int dk k^2 j_\ell(kr) G^{(0)}(k;E)\Sigma_{\ell j}(k,k_0;E) \right\}$$

Adding an $s_{1/2}$ neutron to ^{40}Ca

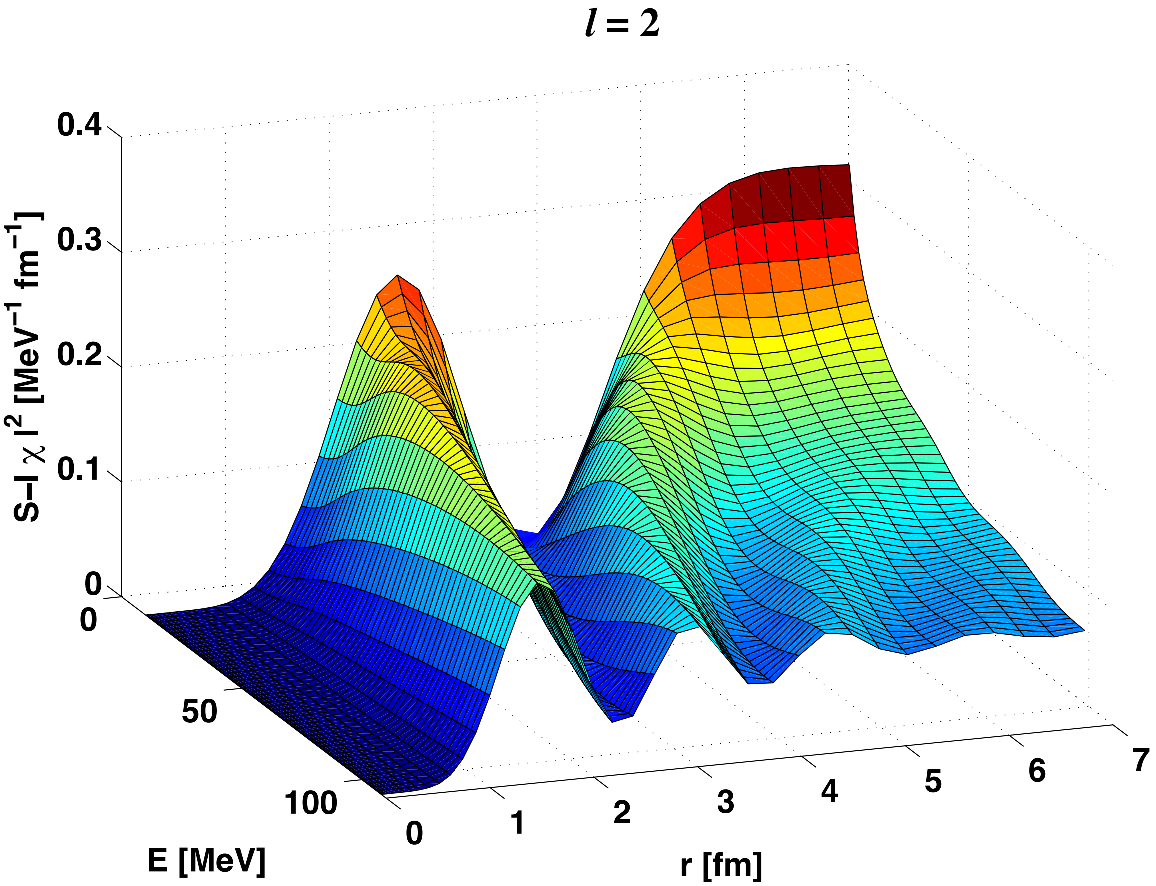
- Inelastically!
- Zero when there is no absorption!



Multiplied by r^2

$d_{3/2}$

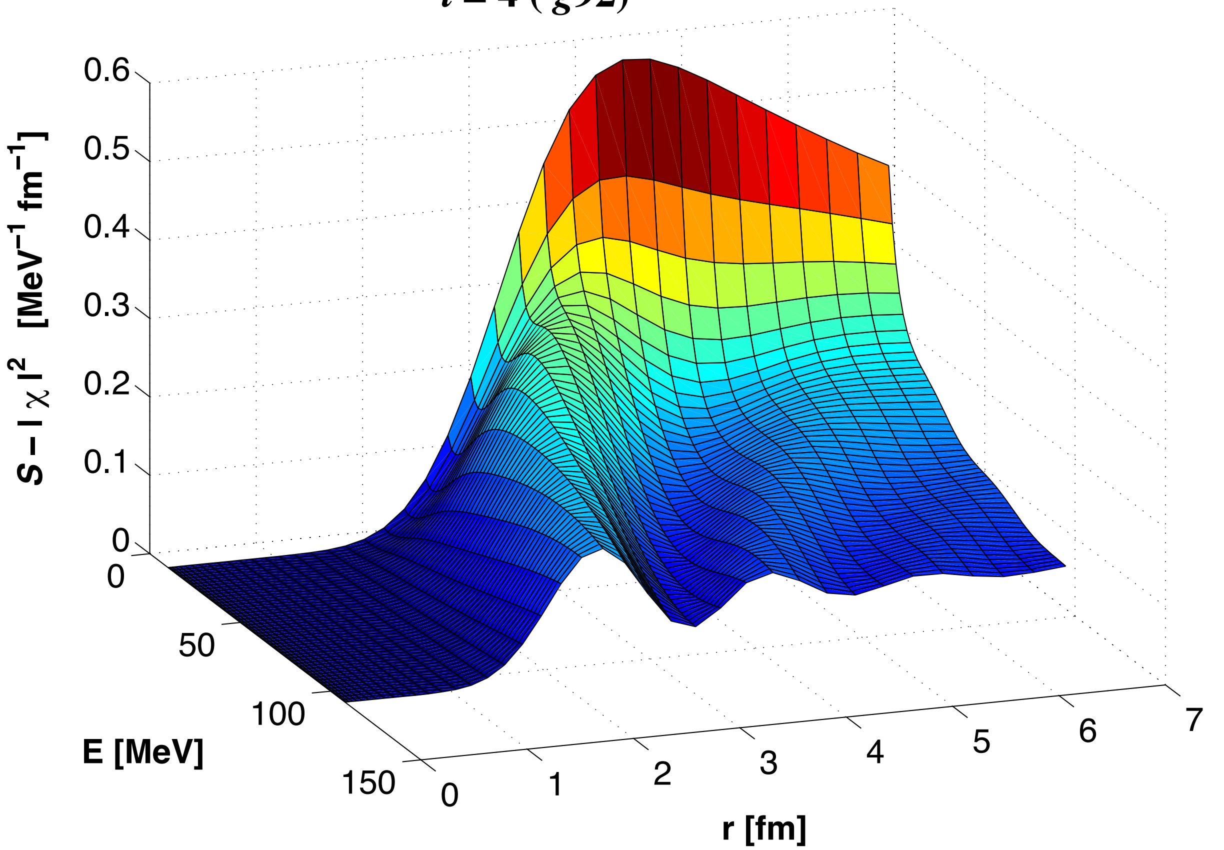
- One node now



No nodes

- Asymptotically determined by inelasticity

$l = 4$ ($g92$)



Determine location of bound-state strength

- Fold spectral function with bound state wave function

$$S_{\ell j}^{n+}(E) = \int dr\ r^2 \int dr'\ r'^2 \phi_{\ell j}^{n-}(r) S_{\ell j}^{p}(r,r';E) \phi_{\ell j}^{n-}(r')$$

- —> Addition probability of bound orbit
- Also removal probability

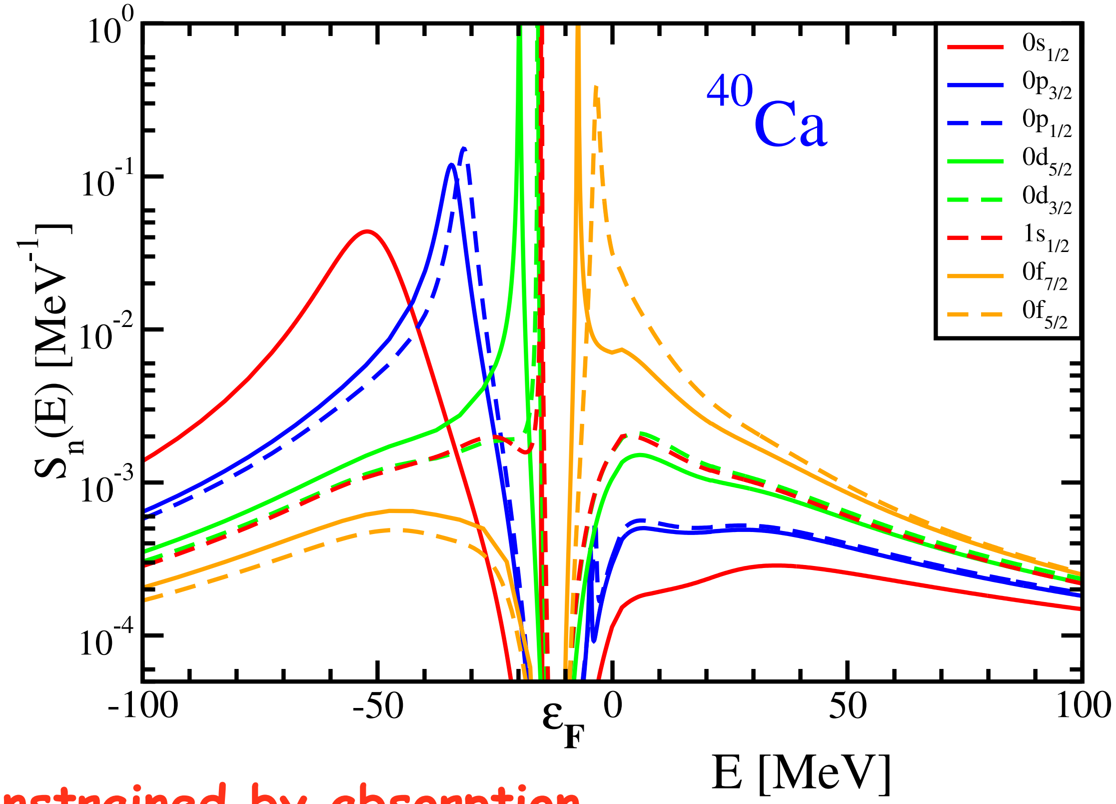
$$S_{\ell j}^{n-}(E) = \int dr r^2 \int dr' r'^2 \phi_{\ell j}^{n-}(r) S_{\ell j}^{h}(r,r';E) \phi_{\ell j}^{n-}(r')$$

- Overlap function $\sqrt{S_{\ell j}^{n}}\phi_{\ell j}^{n-}(r) = \langle \Psi_n^{A-1} | a_{r\ell j} | \Psi_0^A \rangle$

- Sum rule $1 = n_{n\ell j} + d_{n\ell j} = \int_{-\infty}^{\varepsilon_F} dE\ S_{\ell j}^{n-}(E) + \int_{\varepsilon_F}^{\infty} dE\ S_{\ell j}^{n-}(E)$

Spectral function for bound states from DOM analysis

- [0,200] MeV —> constrained by elastic scattering data



Emptiness constrained by absorption necessary to describe elastic scattering!

PRC90, 061603(R) (2014)

Quantitatively

- Orbit closer to the continuum —> more strength in the continuum
- Note "particle" orbits
- Drip-line nuclei have valence orbits very near the continuum

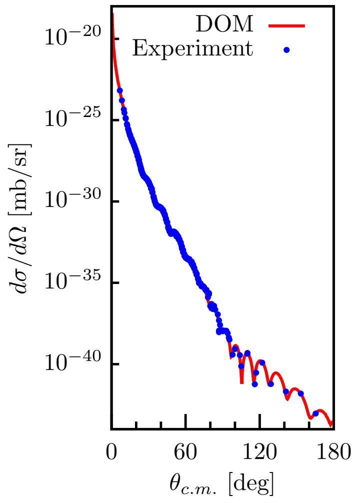
Table 1: Occupation and depletion numbers for bound orbits in ^{40}Ca. $d_{nlj}[0,200]$ depletion numbers have been integrated from 0 to 200 MeV. The fraction of the sum rule that is exhausted, is illustrated by $n_{n\ell j} + d_{n\ell j}[\varepsilon_F, 200]$. Last column $d_{nlj}[0,200]$ depletion numbers for the CDBonn calculation.

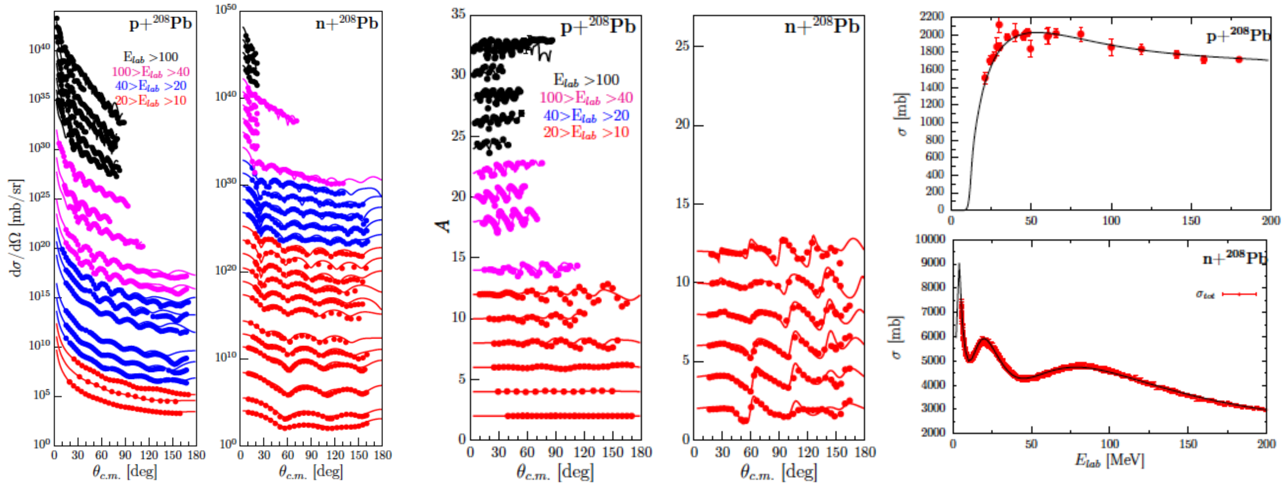
orbit	$n_{n\ell j}$ DOM	$d_{n\ell j}[0,200]$ DOM	$n_{n\ell j} + d_{n\ell j}[\varepsilon_F, 200]$ DOM	$d_{n\ell j}[0,200]$ CDBonn
$0s_{1/2}$	0.926	0.032	0.958	0.035
$0p_{3/2}$	0.914	0.047	0.961	0.036
$1p_{1/2}$	0.906	0.051	0.957	0.038
$0d_{5/2}$	0.883	0.081	0.964	0.040
$1s_{1/2}$	0.871	0.091	0.962	0.038
$0d_{3/2}$	0.859	0.097	0.966	0.041
$0f_{7/2}$	0.046	0.202	0.970	0.034
$0f_{5/2}$	0.036	0.320	0.947	0.036

PRC90, 061603(R) (2014)

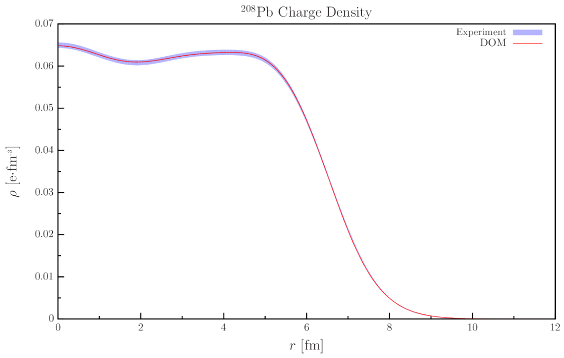
Dispersive Optical Model (St. Louis group)

- Mahaux & Sartor 1991
- Washington University group since 2006 now fully nonlocal
- ^{208}Pb





E<0 —>



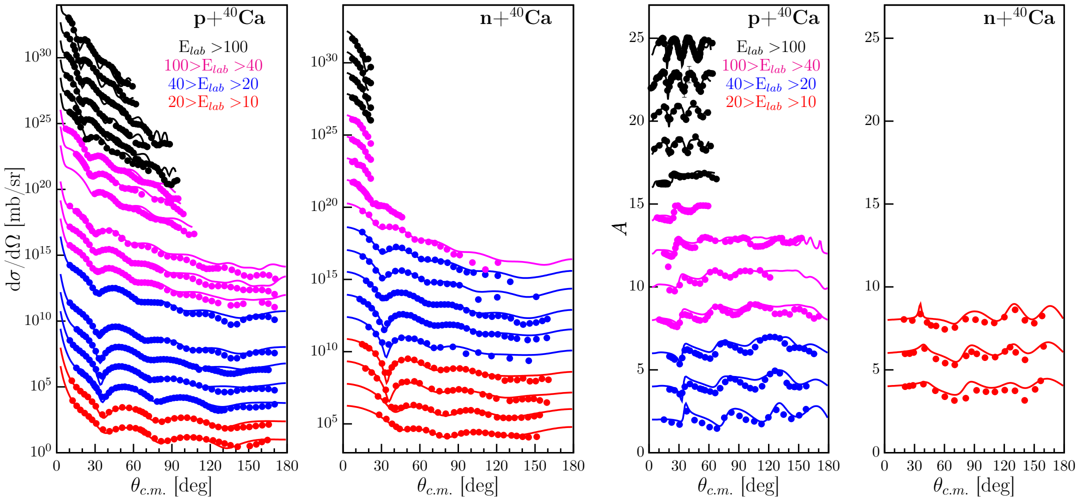
Indirectly:

- Predict neutron distribution —> skin

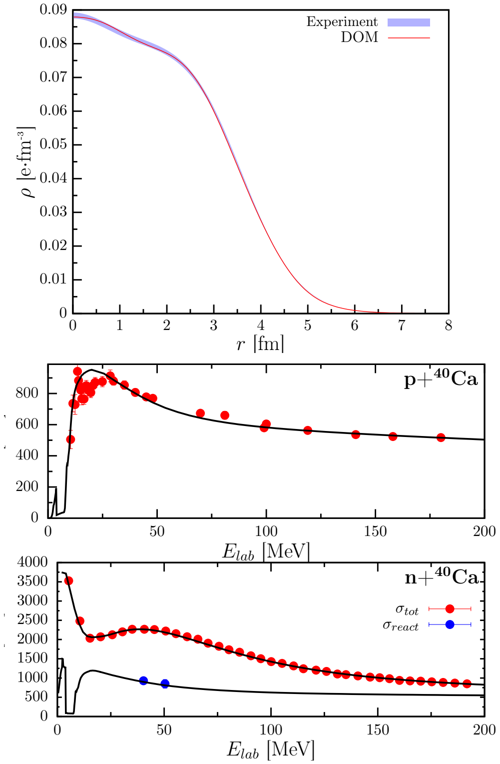
M. C. Atkinson, M. H. Mahzoon, M. A. Keim, B. A. Bordelon, C. D. Pruitt, R. J. Charity, and W. H. Dickhoff
Phys. Rev. C 101, 044303 (2020), 1-15. [arXiv:1911.09020]

DOM

^{40}Ca

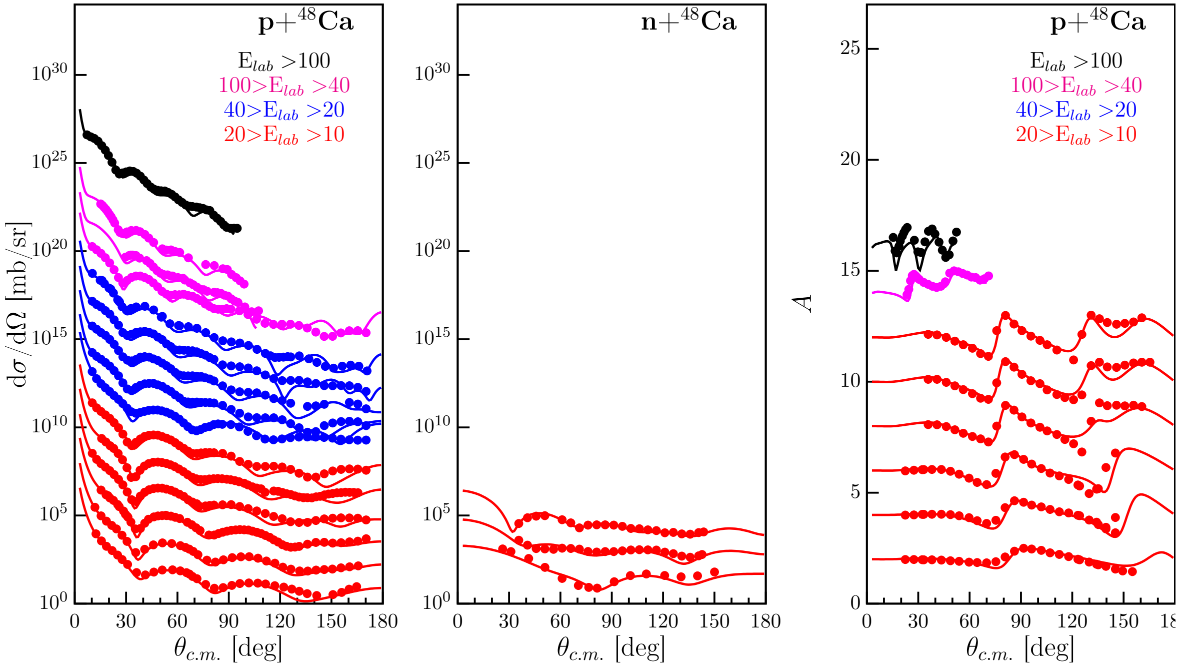


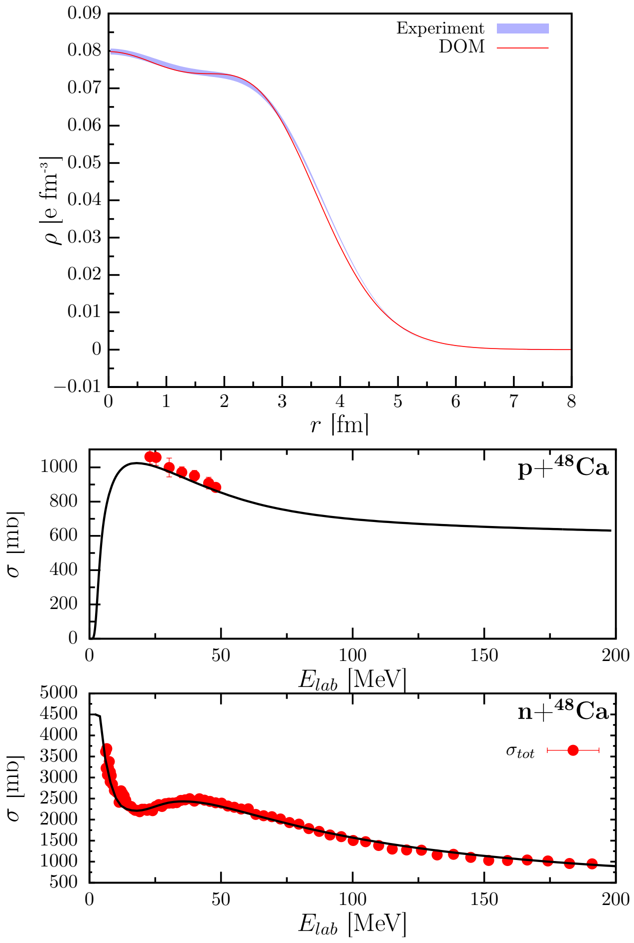
M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)



^{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 and spectroscopic factors

- 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? —> transfer information to (p,pN) in inverse kinematics

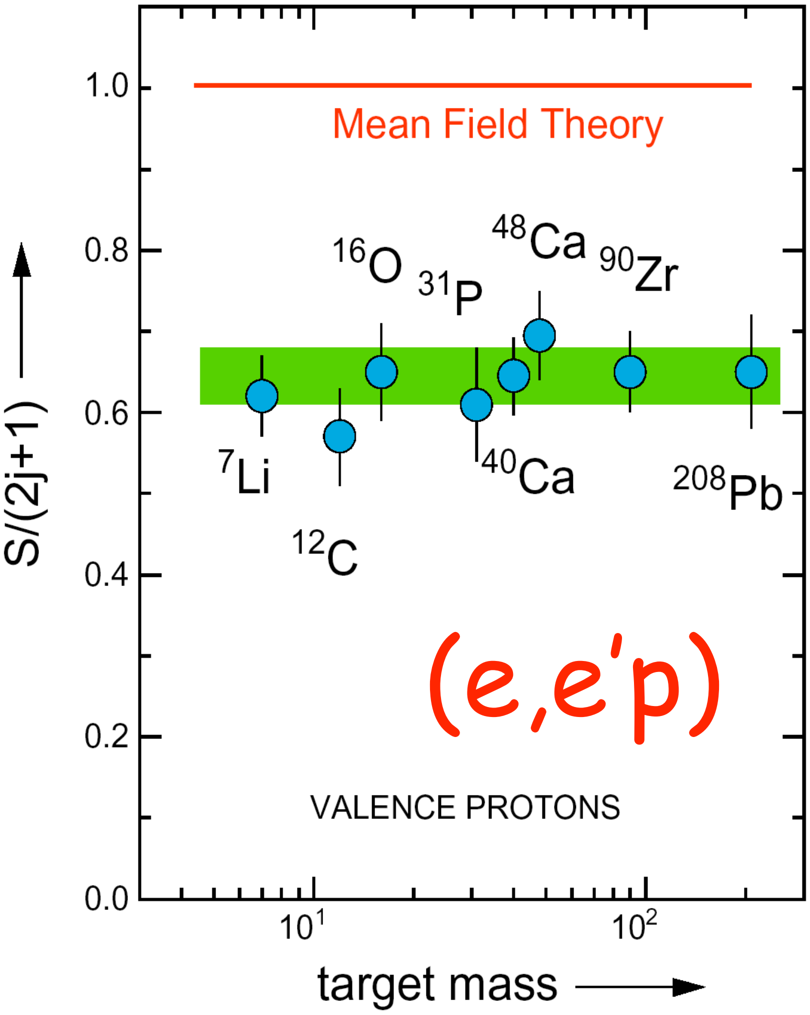
Removal probability for valence protons from NIKHEF data

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

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

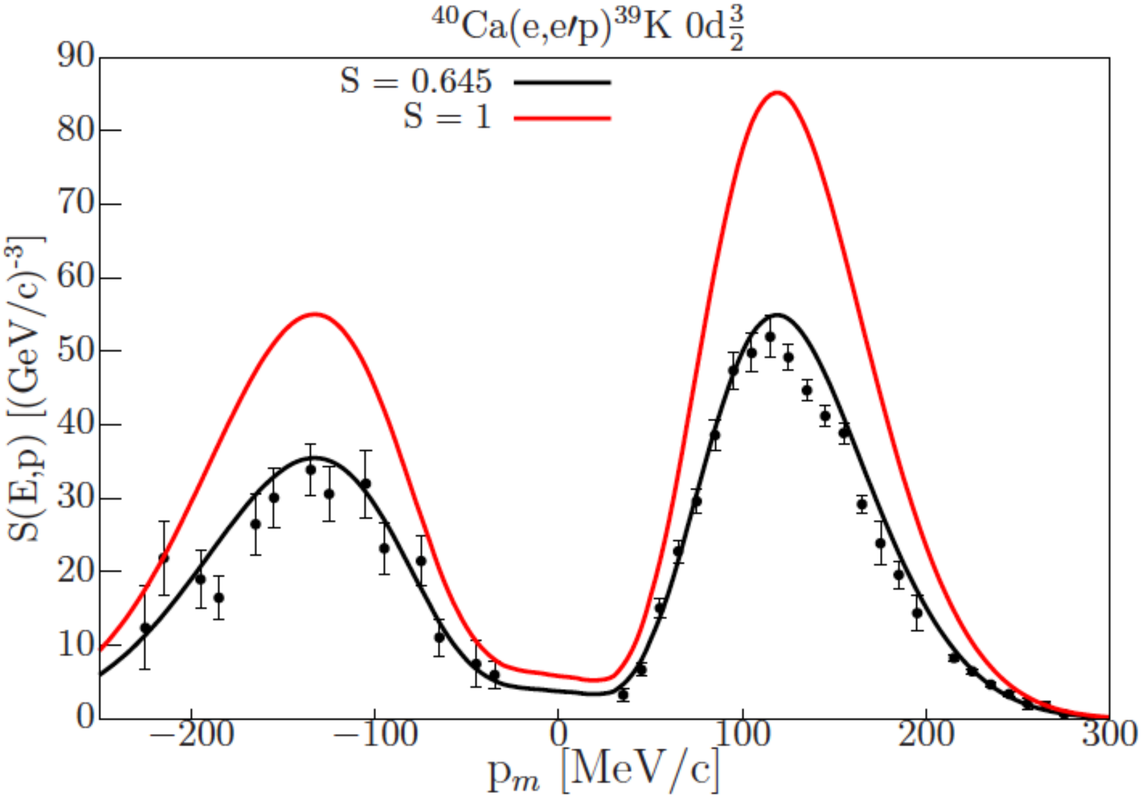
Weak probe but propagation in the nucleus of removed proton using standard optical potentials to generate distorted wave --> associated uncertainty ~ 5-15%

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

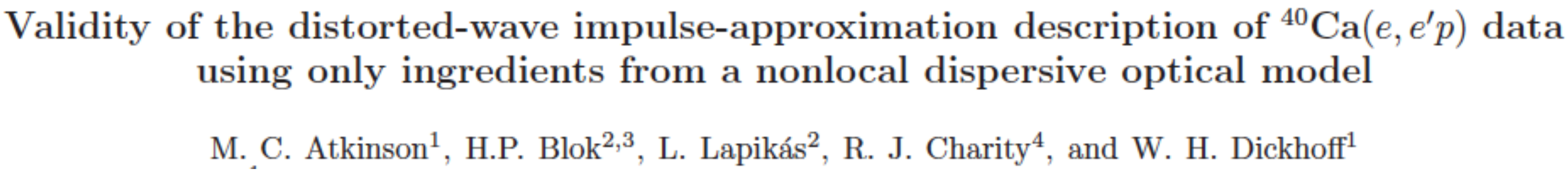


NIKHEF analysis PLB227,199(1989)

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



Two papers ^{40}Ca and ^{48}Ca



Validity of the distorted-wave impulse-approximation description of $^{40}\mathrm{Ca}(e,e'p)$ 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)

NIKHEF data PLB227,199(1989)

- NIKHEF: $S(d_{3/2})=0.65\pm0.06$
- Only DOM ingredients

NIKHEF data PLB227,199(1989)

- NIKHEF: S($d_{3/2}$)=0.65±0.06
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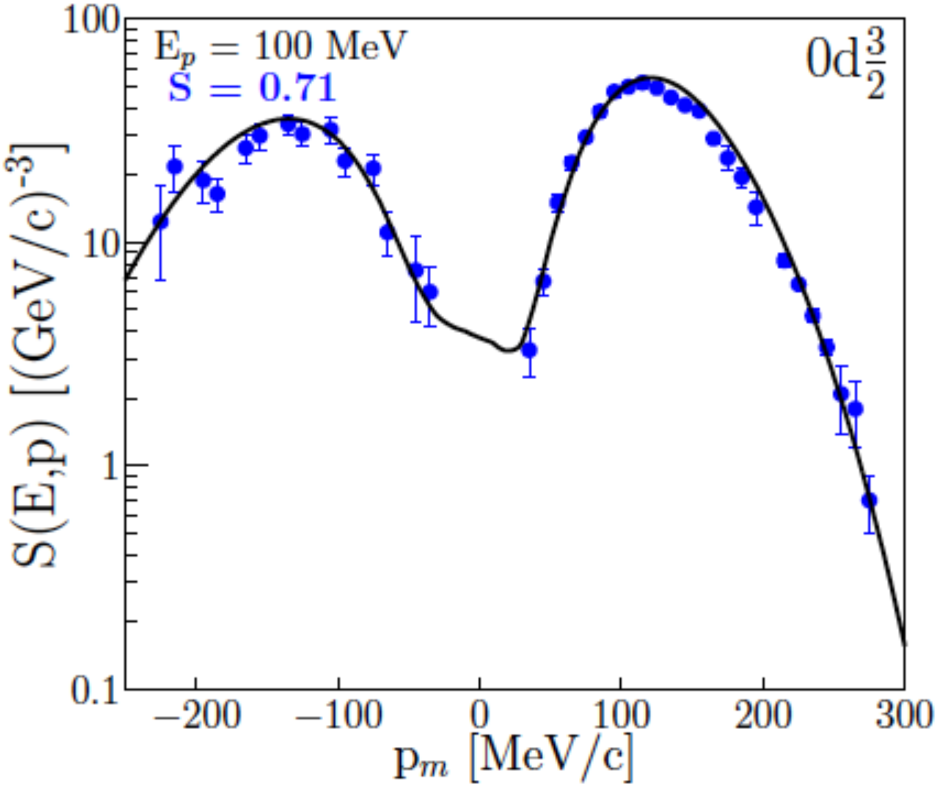

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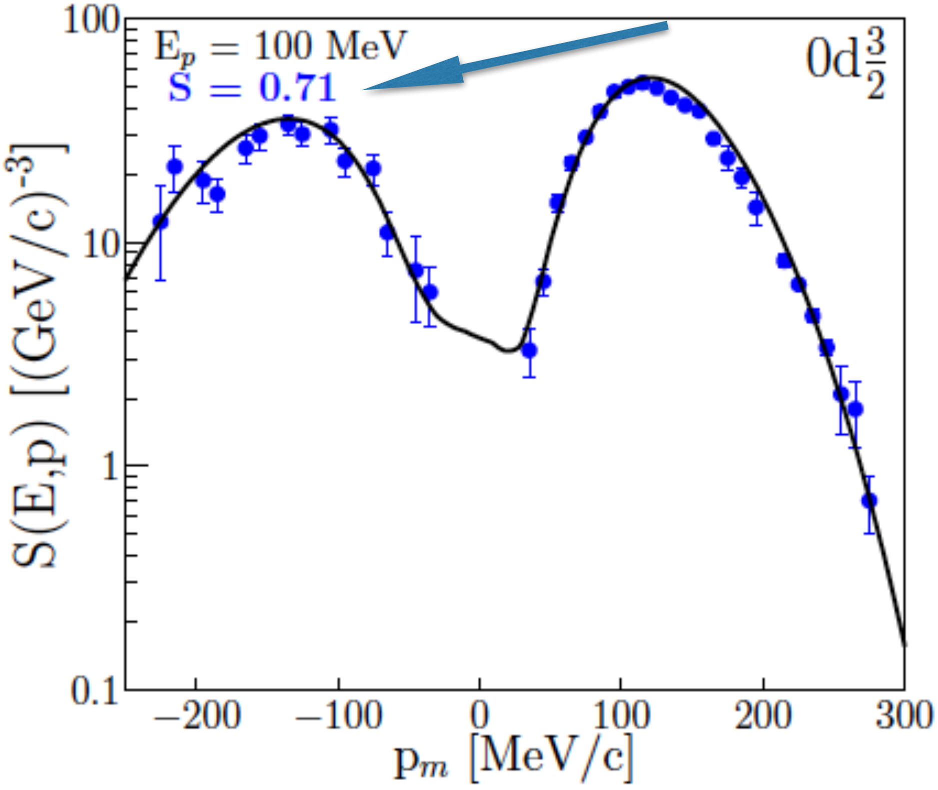

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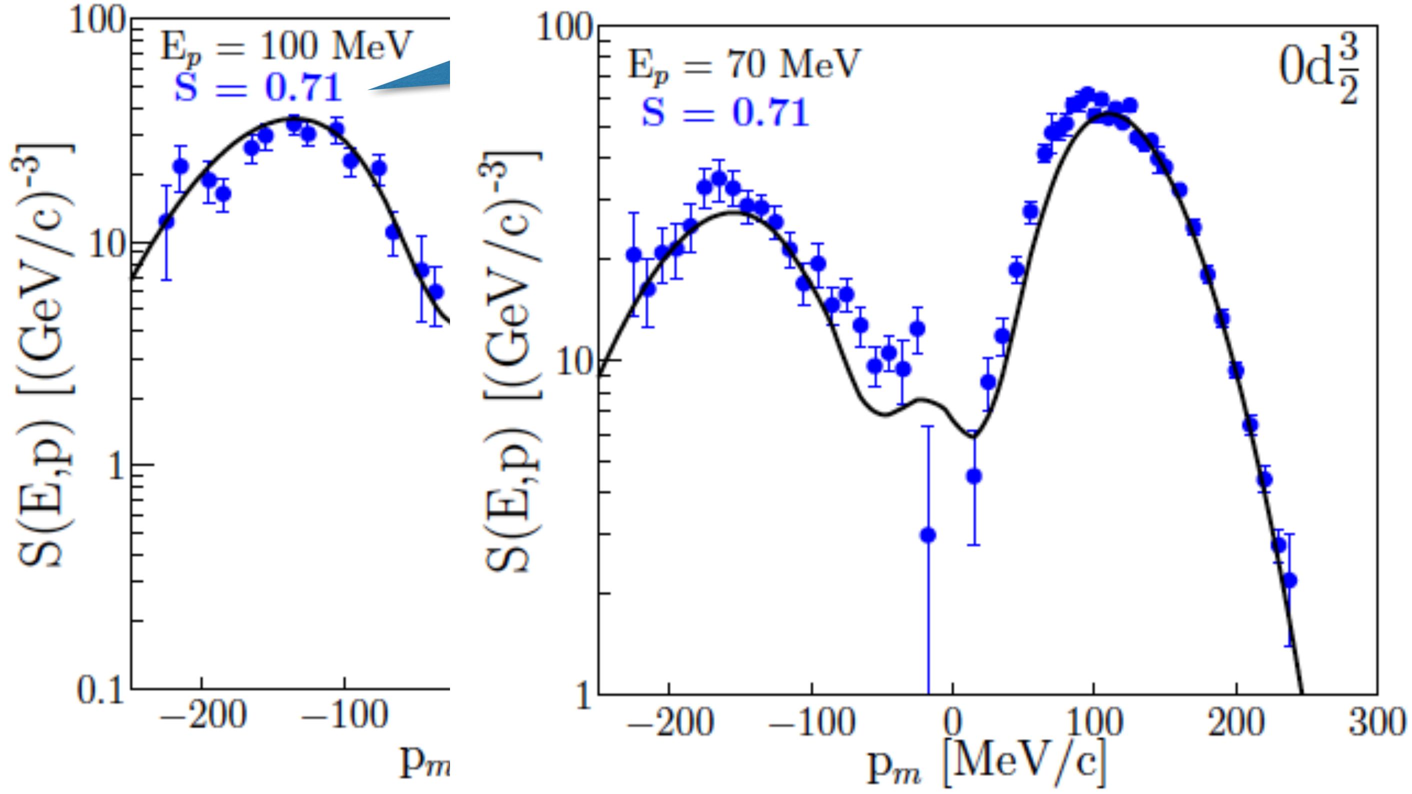

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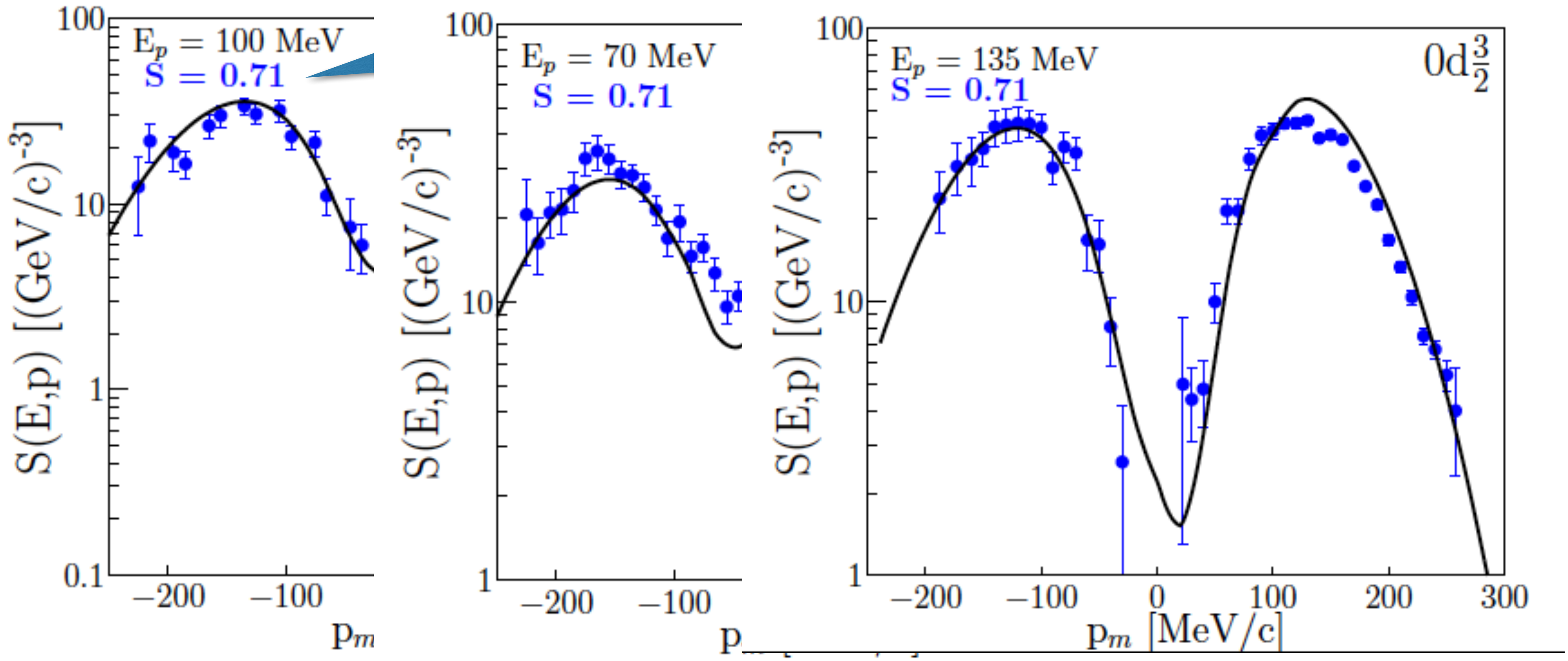
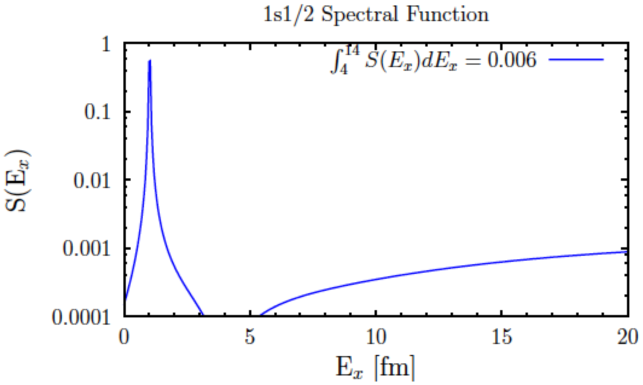
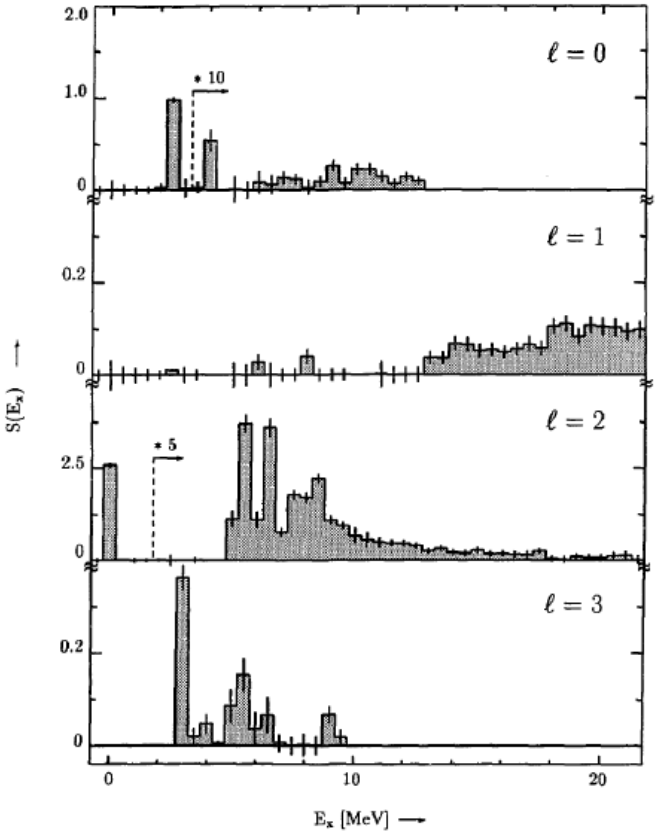


Thesis G. J. Kramer (1990)

- $s_{1/2}$ strength fragmented

- Not yet included in DOM





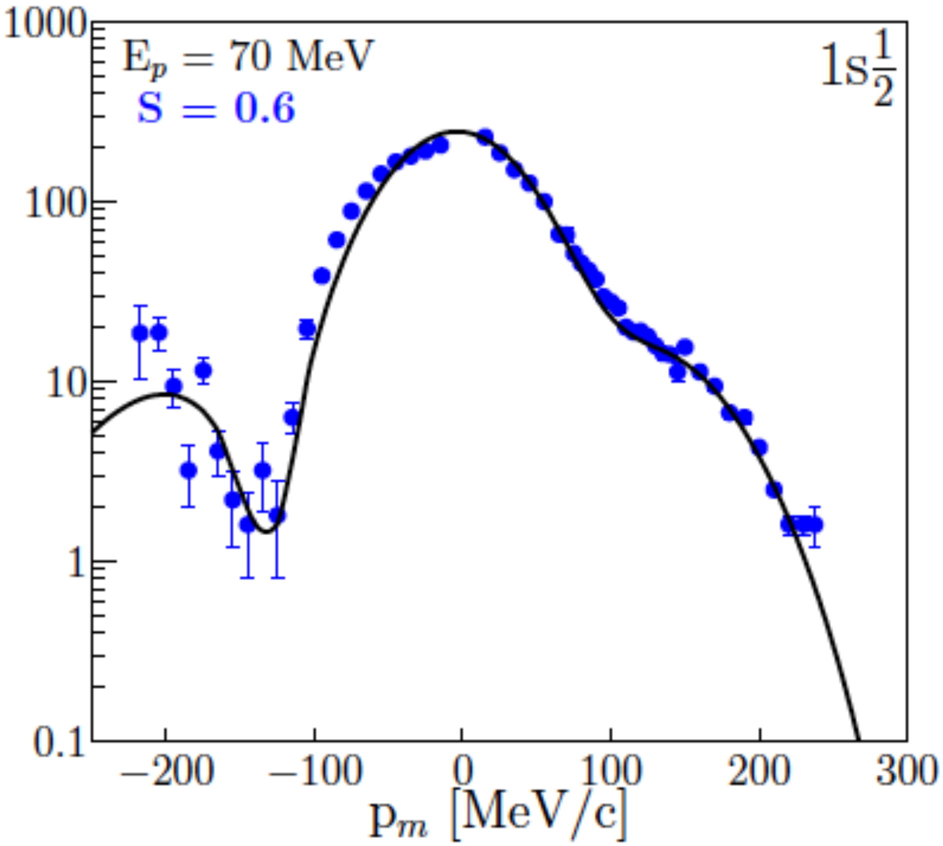
- Corrects DOM spectroscopic factor
- Low-energy fragmentation —> shell model description possible

Includes NIKHEF data published for the first time

- Only DOM ingredients

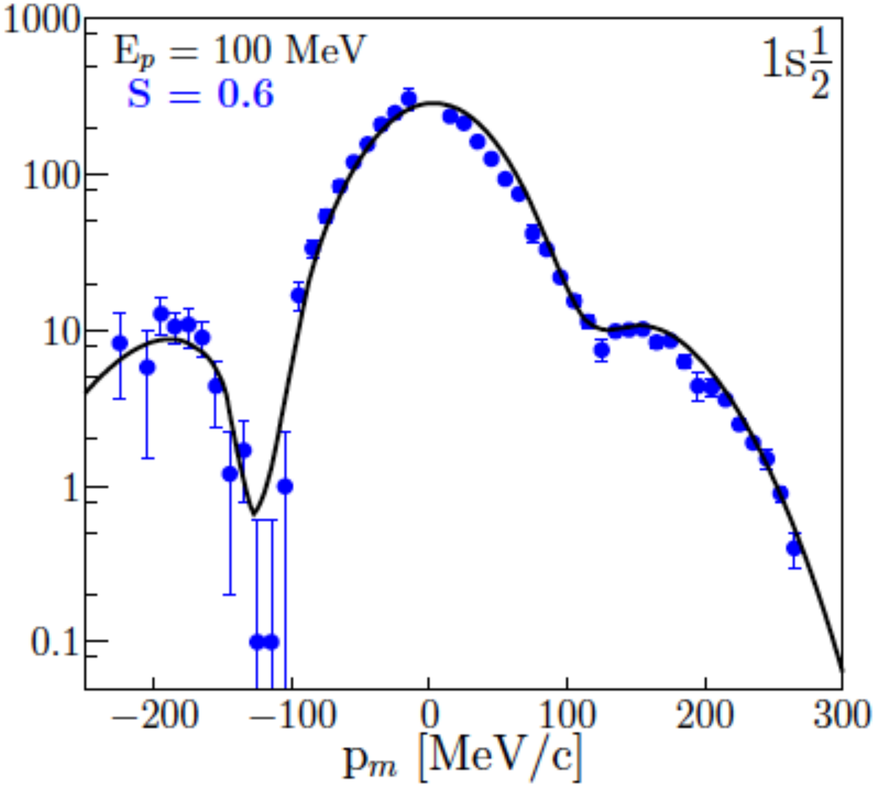
Includes NIKHEF data published for the first time

- Only DOM ingredients



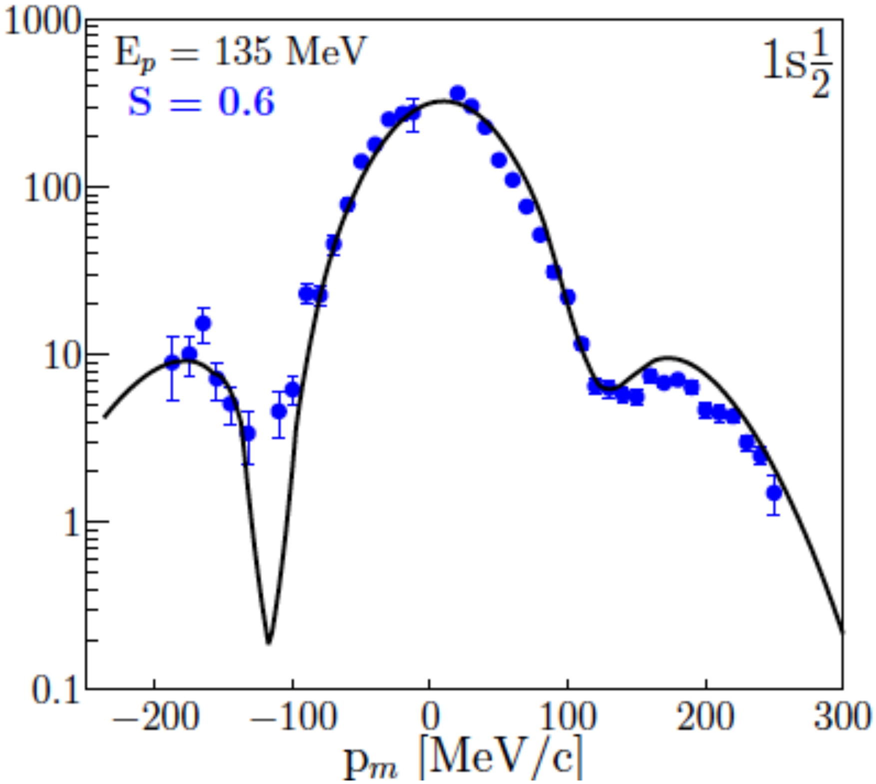
NIKHEF data PLB227,199(1989)

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



NIKHEF data unpublished

- Only DOM ingredients



Message

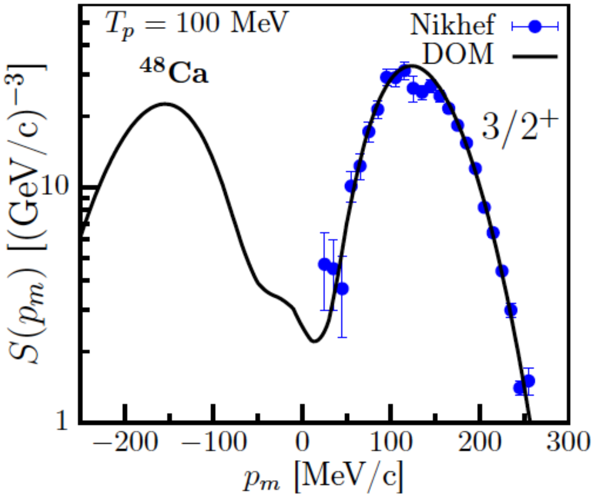
- Nonlocal dispersive potentials yield consistent input but are constrained by **other** experimental data

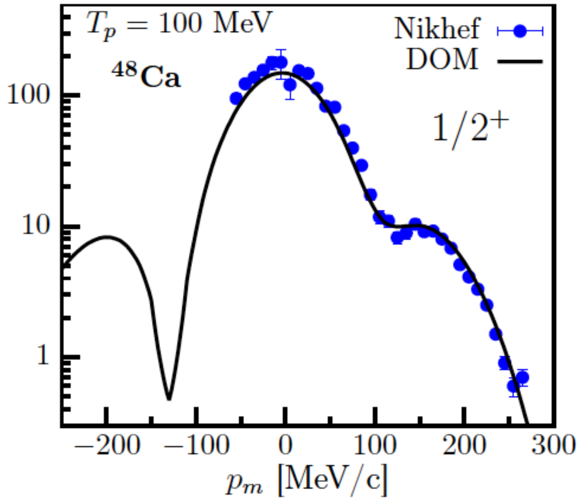
- Constraints from these other data generate spectroscopic factor —> $S(d_{3/2})=0.71$ in ^{40}Ca for ground state transition
- Using experimental $s_{1/2}$ strength distribution: 2.5 MeV state —> $S(s_{1/2})=0.60$

- 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

^{48}Ca(e,e′p)

- $d_{3/2}$ spectroscopic factor 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

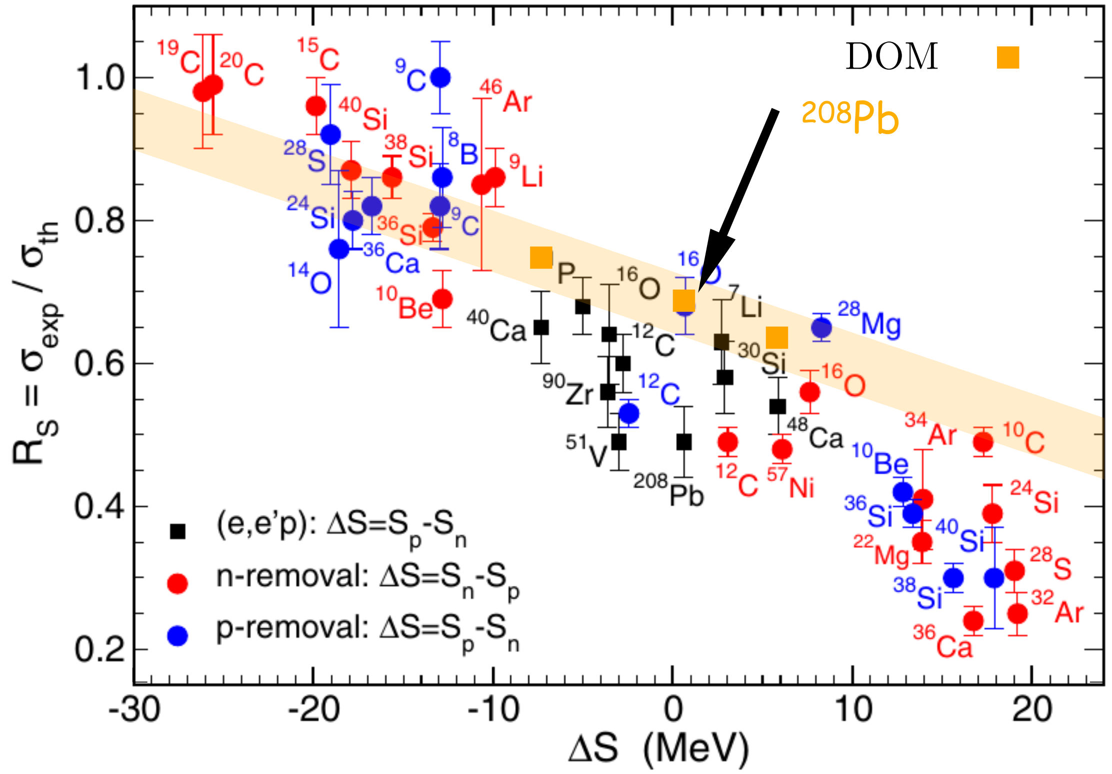




- No further adjustments! All ingredients provided by DOM
- **Both structure and reaction properties allowed to change when 8 n added**

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)

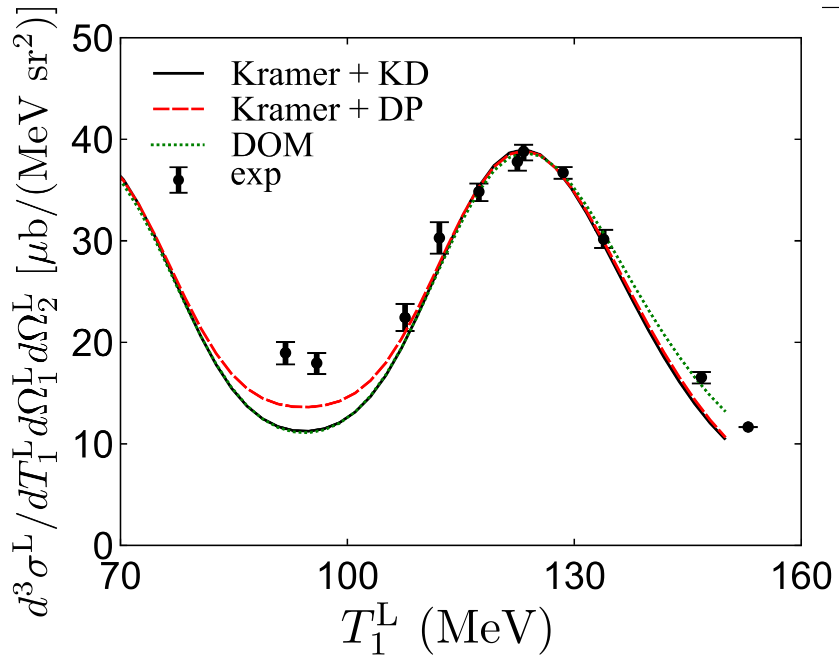
DOM

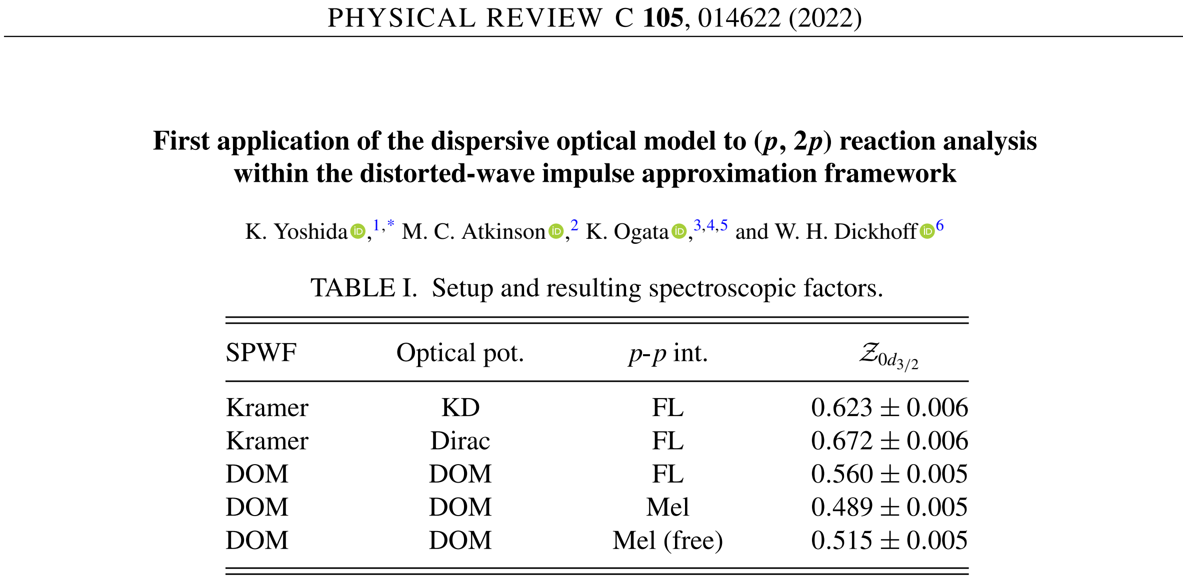
(p,2p) stable targets (RCNP)

- 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.

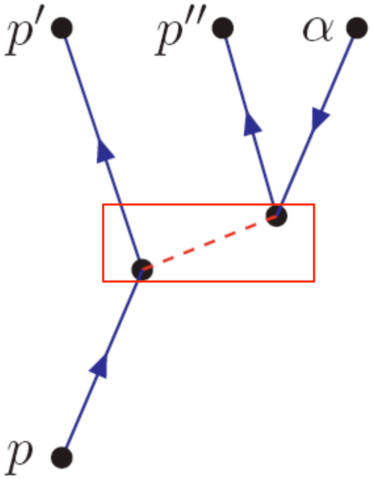
SPWF	Optical pot.	*p*-*p* int.	$\mathcal{Z}_{0d_{3/2}}$
Kramer	KD	FL	0.623 ± 0.006
Kramer	Dirac	FL	0.672 ± 0.006
DOM	DOM	FL	0.560 ± 0.005
DOM	DOM	Mel	0.489 ± 0.005
DOM	DOM	Mel (free)	0.515 ± 0.005

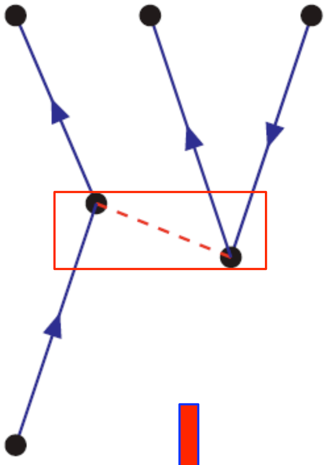
?

- DOM spectroscopic factor 0.71±0.05

Observations for (p,2p)

Born terms
already different!





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

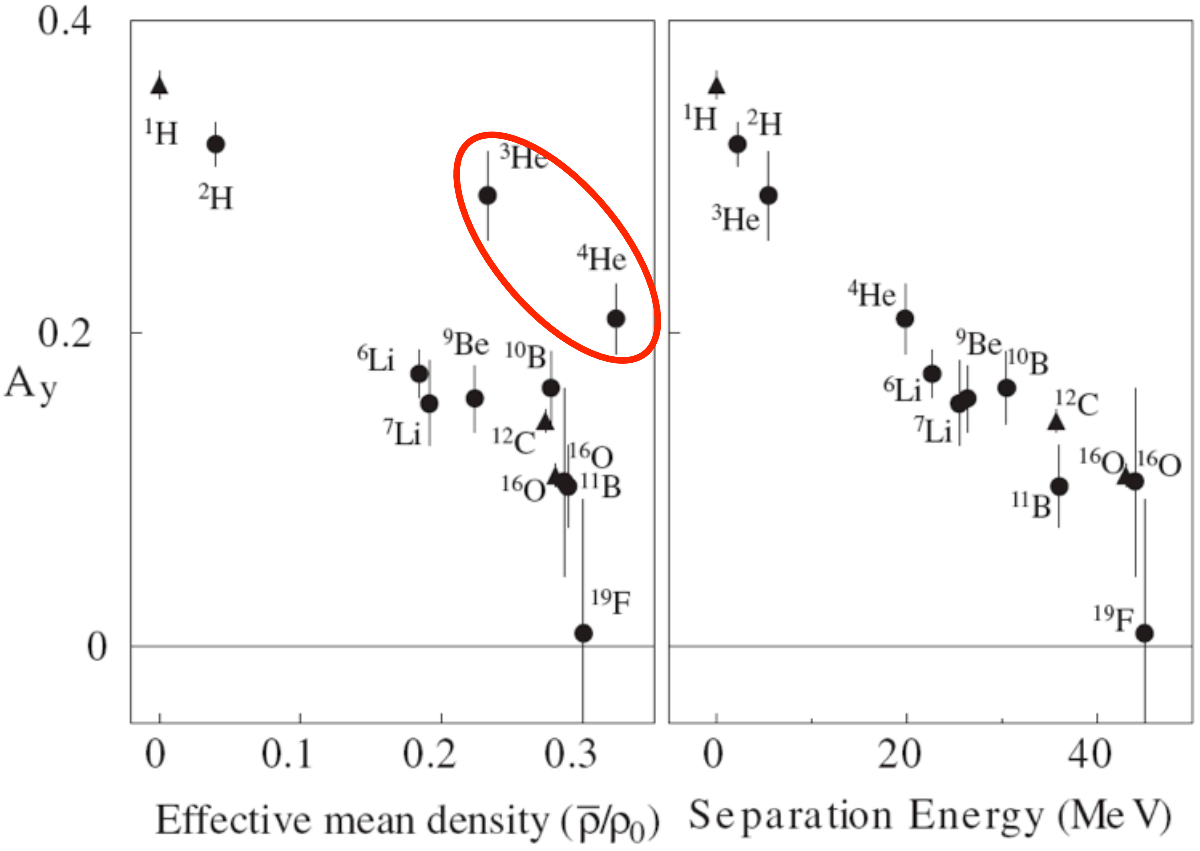
$$\frac{1}{2\sqrt{m_\pi^2+q^2}}\,\frac{1}{\varepsilon_\alpha-\varepsilon(p')-\sqrt{m_\pi^2+q^2}}$$

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

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

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

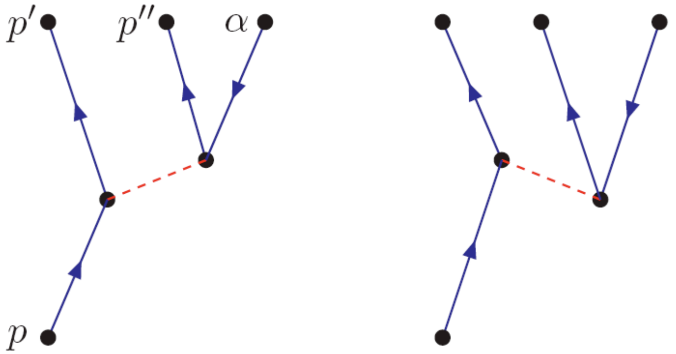
A_y puzzle in (p,2p) [first QFS-RB 2008]



Noro et al.
RCNP data

DWIA
almost like
free A_y...

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



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

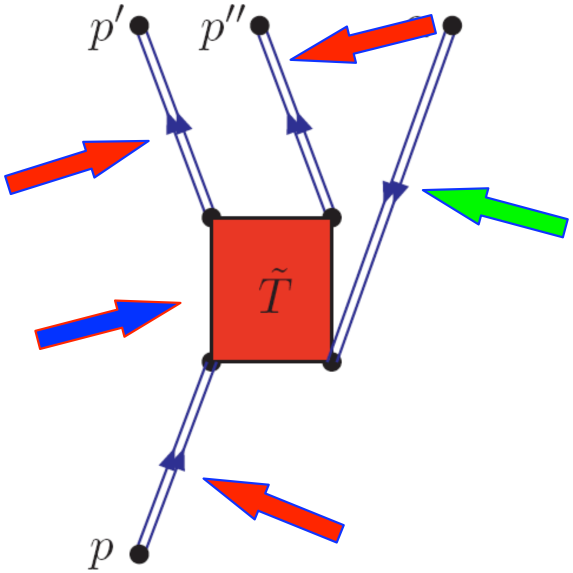
⇒ Pion carries 124 MeV or

304 MeV (exchange term)

contrast with NN T-matrix
⇒ 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.



Status of "reduction" factors/spectroscopic factors

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

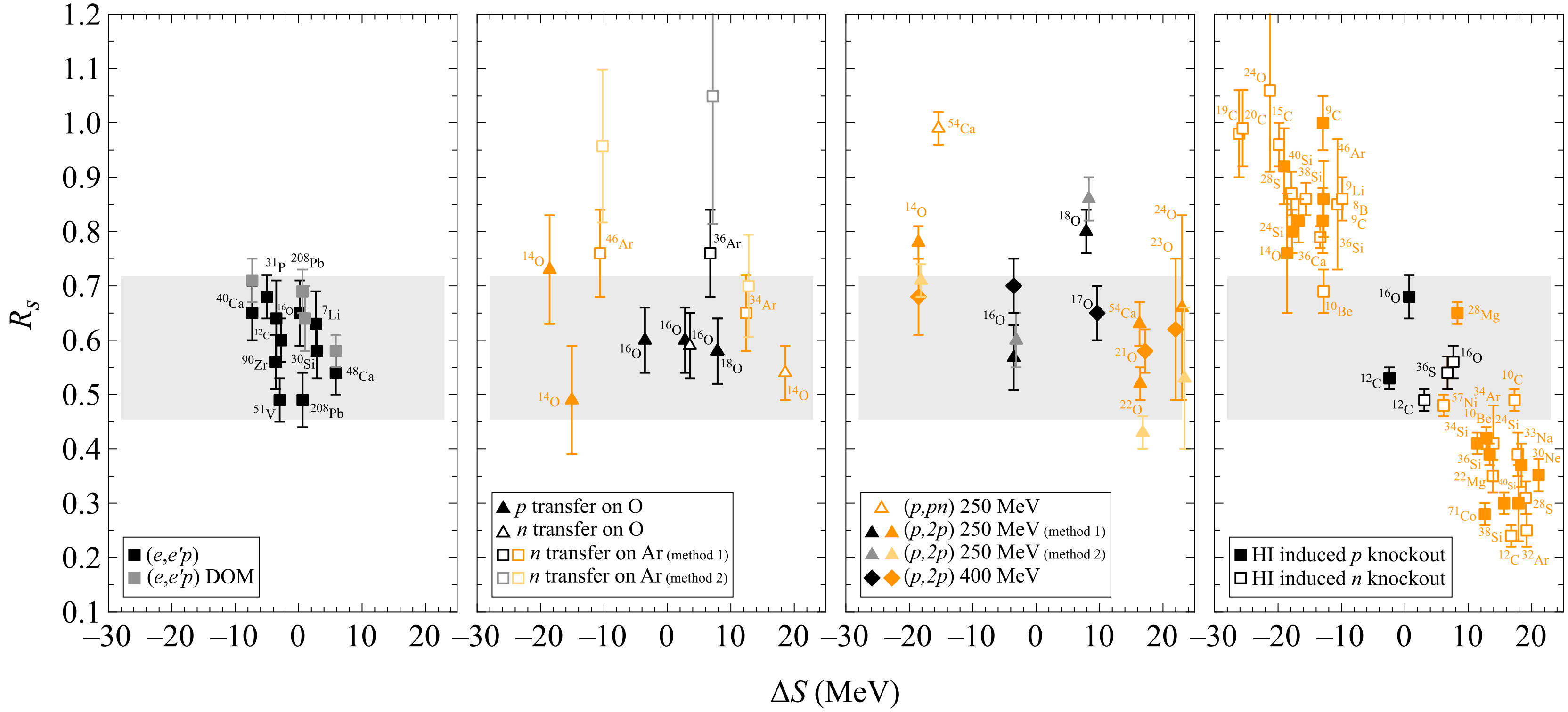


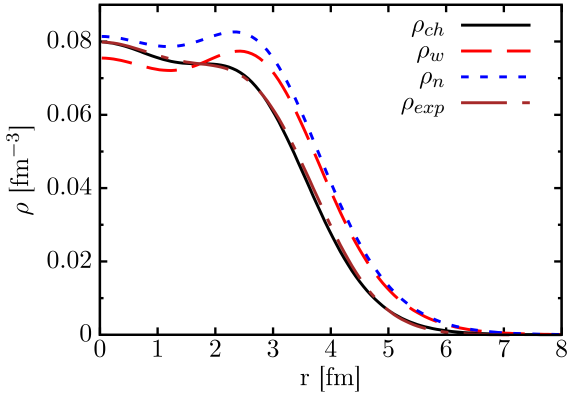
Fig. 56. The four panels of this plot show the quenching (reduction) factors for (a) electron-induced knockout reactions [87,172,237,376], (b) transfer reactions with radioactive ion beams [55,57,203], (c) quasifree $(p, 2p)$ proton knockout on stable nuclei (from the compilation in [239]) and radioactive 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.

But....

- What about CREX?

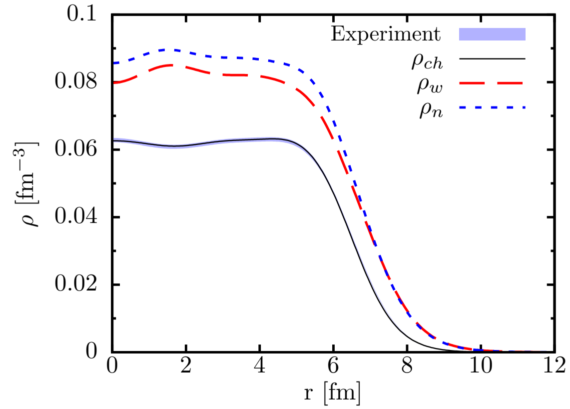
Neutron skins in ^{48}Ca and ^{208}Pb from DOM predictions

- DOM 2017



M. H. Mahzoon, M. C. Atkinson, R. J. Charity, and W. H. Dickhoff
Phys. Rev. Lett. **119,** 222503 (2017), 1-5.

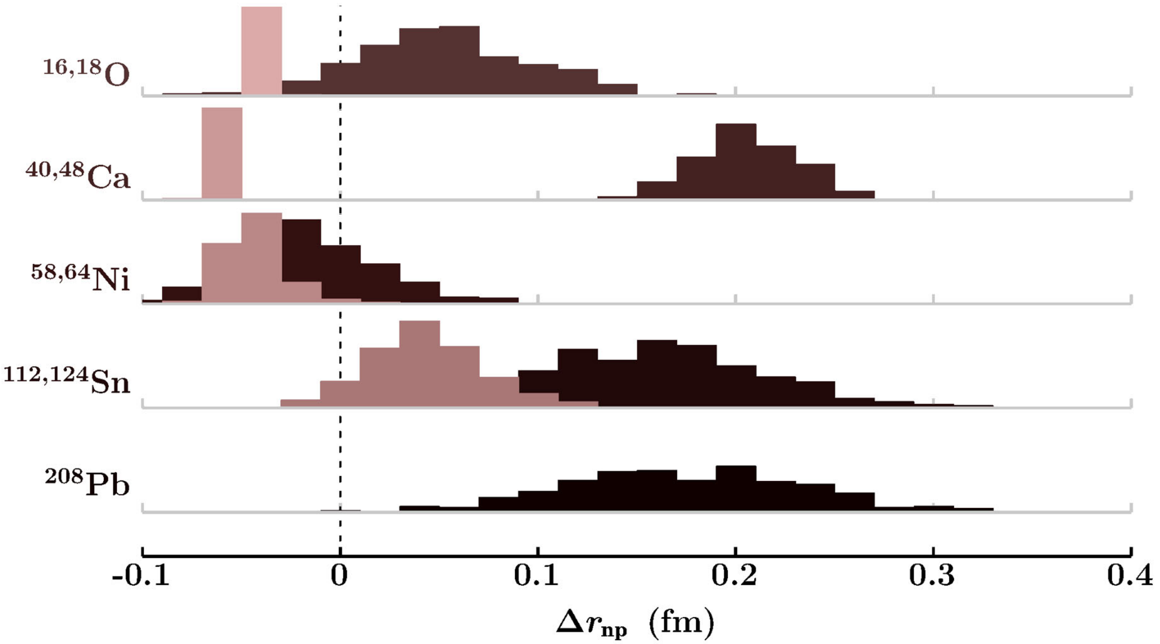
- DOM 2020



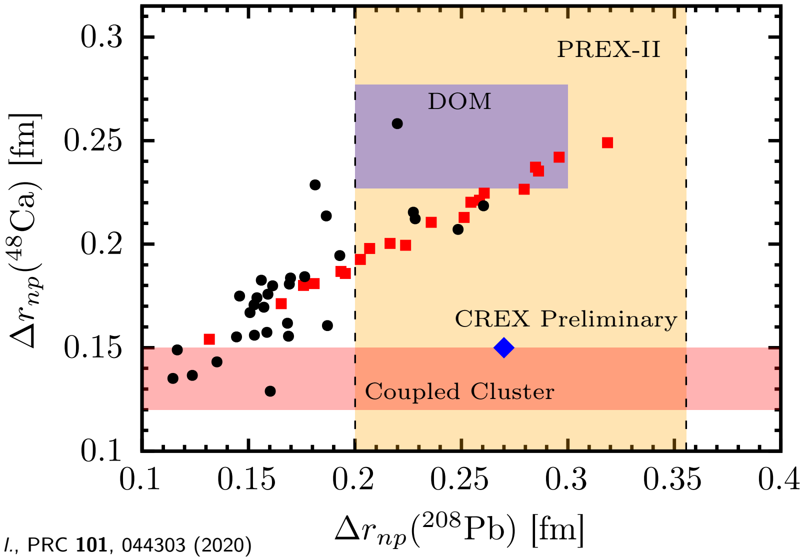
M. C. Atkinson, M. H. Mahzoon, M. A. Keim, B. A. Bordelon, C. D. Pruitt, R. J. Charity, and W. H. Dickhoff
Phys. Rev. C 101, 044303 (2020), 1-15.

MCMC and standard DOM prediction of neutron skins

- Markov Chain Monte Carlo



Standard



l., PRC **101**, 044303 (2020)

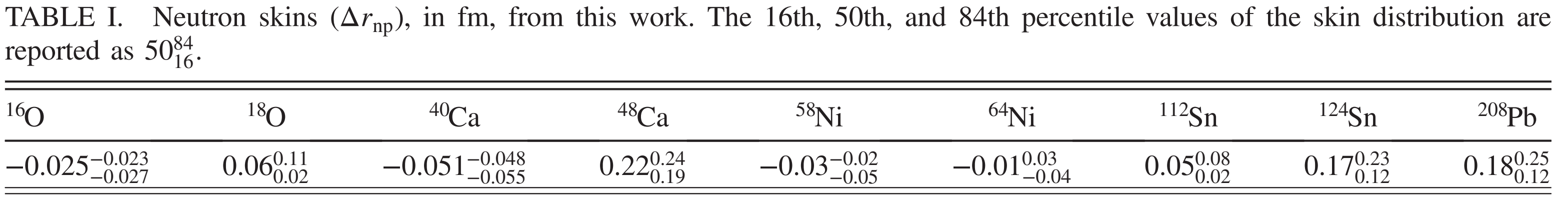


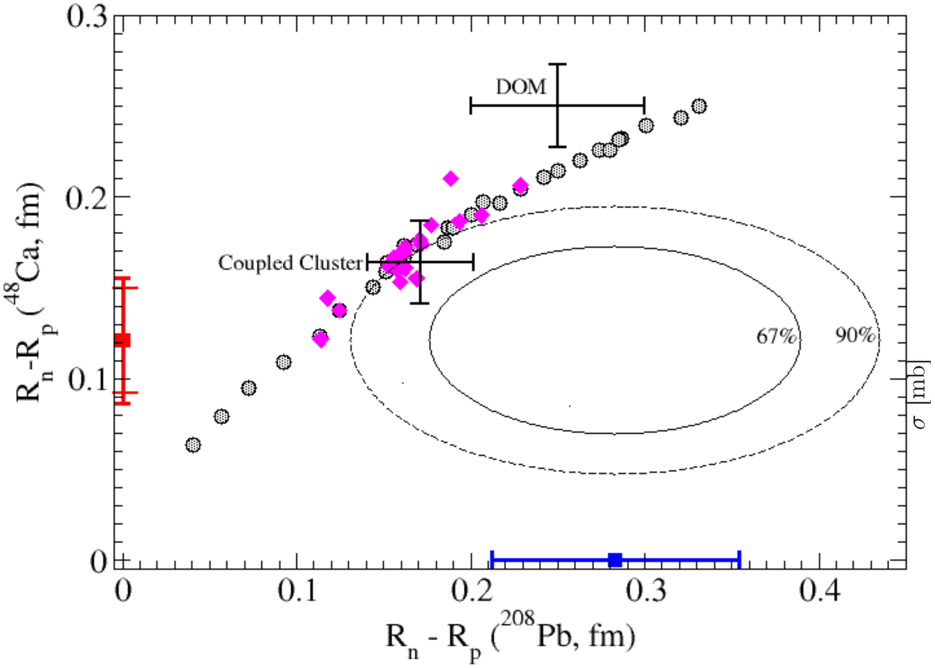
TABLE I. Neutron skins (Δr_{np}), in fm, from this work. The 16th, 50th, and 84th percentile values of the skin distribution are reported as 50^{84}_{16}.

^{16}O	^{18}O	^{40}Ca	^{48}Ca	^{58}Ni	^{64}Ni	^{112}Sn	^{124}Sn	^{208}Pb
$-0.025^{-0.023}_{-0.027}$	$0.06^{0.11}_{0.02}$	$-0.051^{-0.048}_{-0.055}$	$0.22^{0.24}_{0.19}$	$-0.03^{-0.02}_{-0.05}$	$-0.01^{0.03}_{-0.04}$	$0.05^{0.08}_{0.02}$	$0.17^{0.23}_{0.12}$	$0.18^{0.25}_{0.12}$

C. D. Pruitt, R. J. Charity, L. G. Sobotka, M. C. Atkinson, and W. H. Dickhoff
Phys. Rev. Lett. 125, 102501 (2020), 1-6.

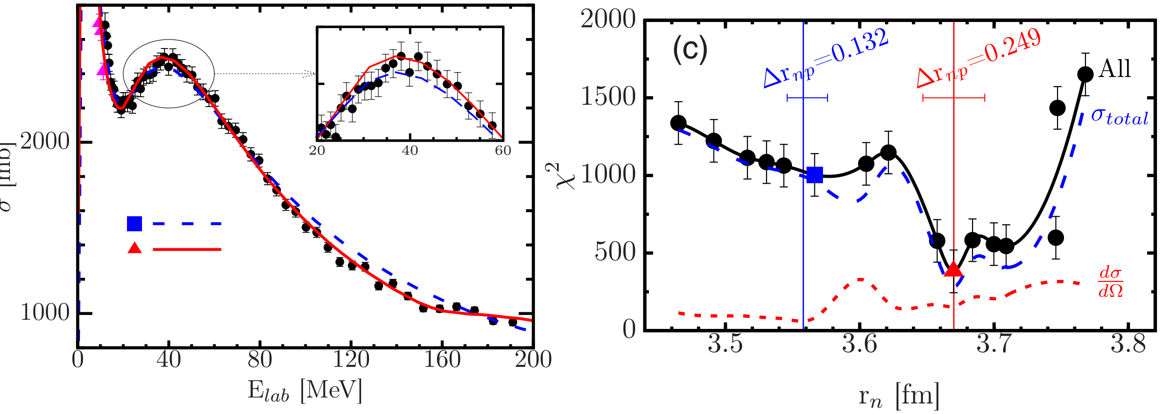
CREX surprise Phys. Rev. Lett. 129, 042501 (2022)

Precision Determination of the Neutral Weak Form Factor of ^{48}Ca
(The CREX Collaboration)



Mean field description cannot accommodate both

How about DOM?



Phys. Rev. Lett. **119,** 222503 (2017)

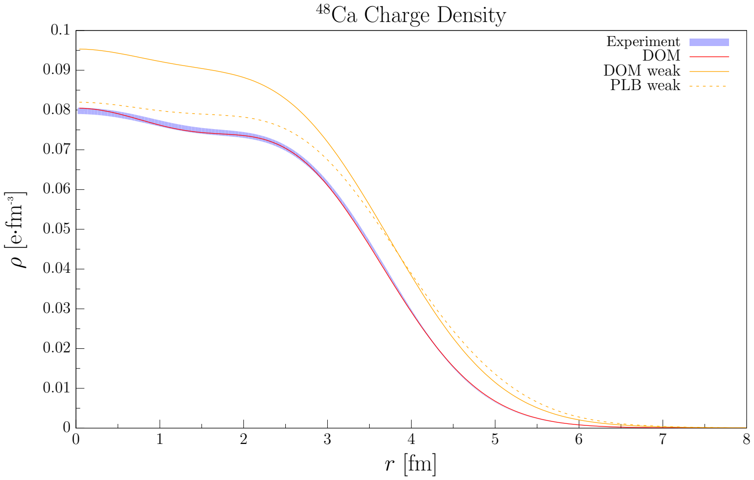
- But…

DOM

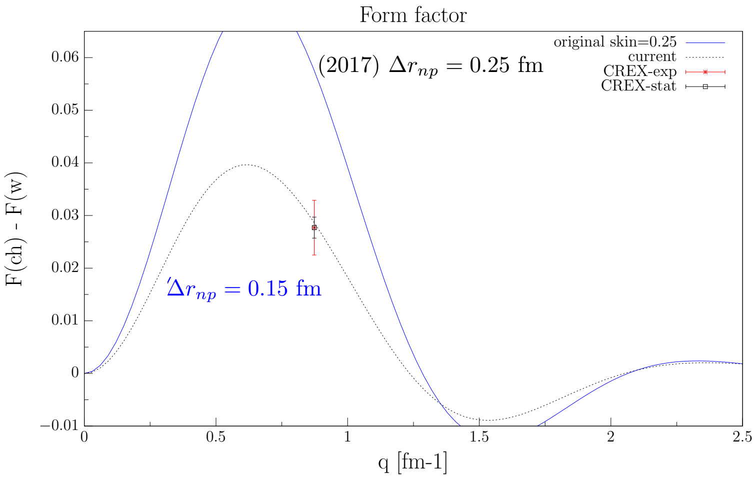
Can the DOM describe CREX form factor?

- 2017 result relied on assumed accuracy of experimental total neutron cross sections…however
- New fit includes CREX result
  - Form factor OK
  - Skin 0.15 fm
- One form factor point doesn't make a density and certainly doesn't unambiguously determine the radius (q too high)

- More ^{48}Ca data needed



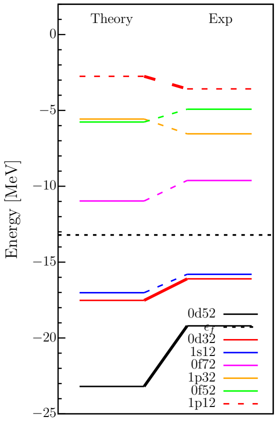
Natalia Calleya & Mack Atkinson



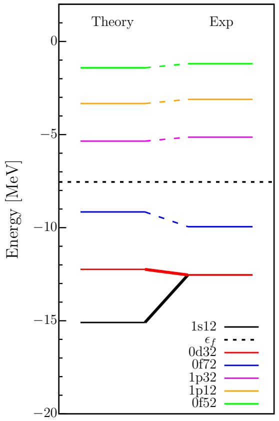
Preliminary

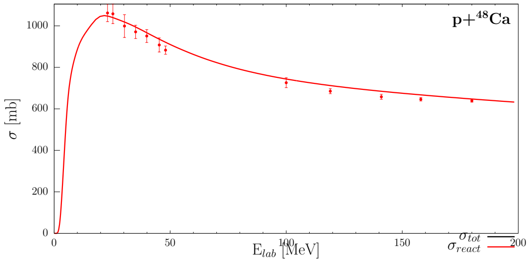
Current ^{48}Ca results generate some concerns

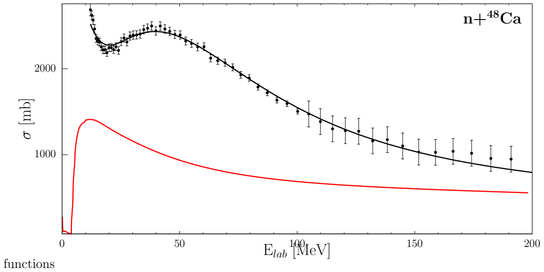
Proton Single-Particle Energy Levels

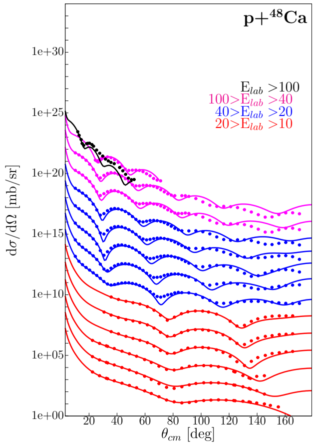


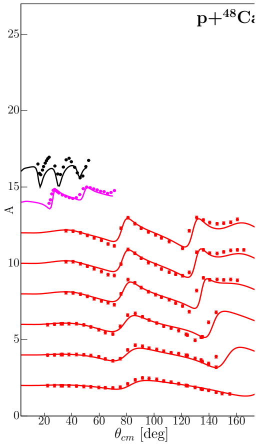
Neutron Single-Particle Energy Levels



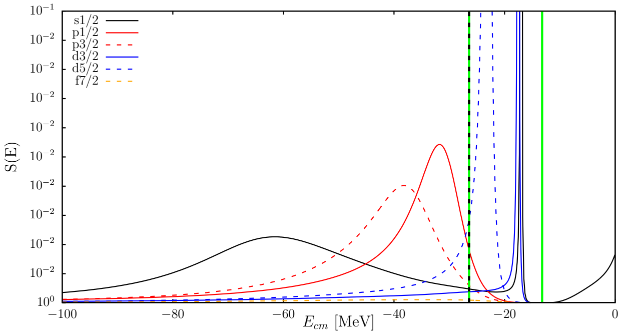




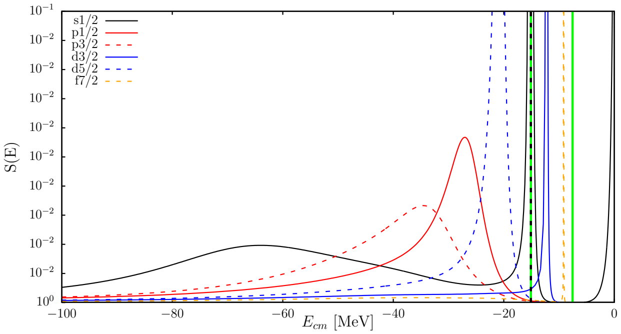




Proton Spectral functions



Neutron spectral functions

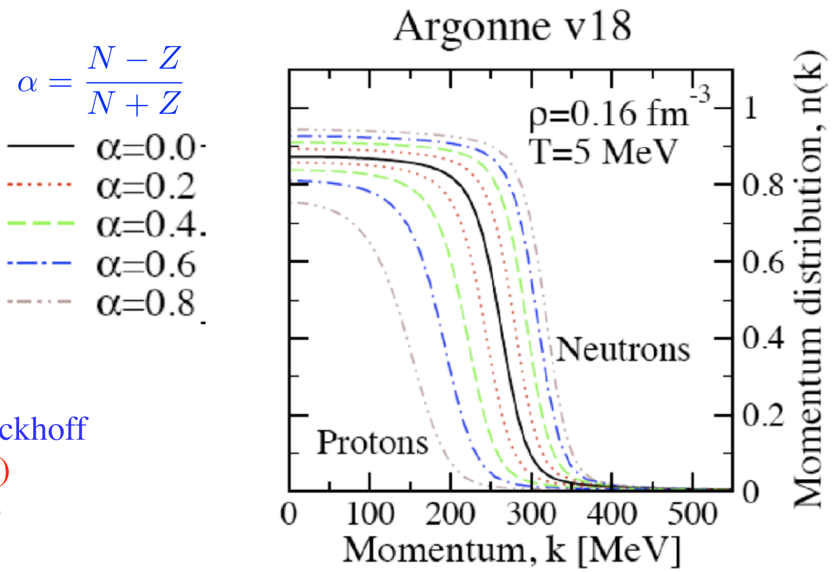


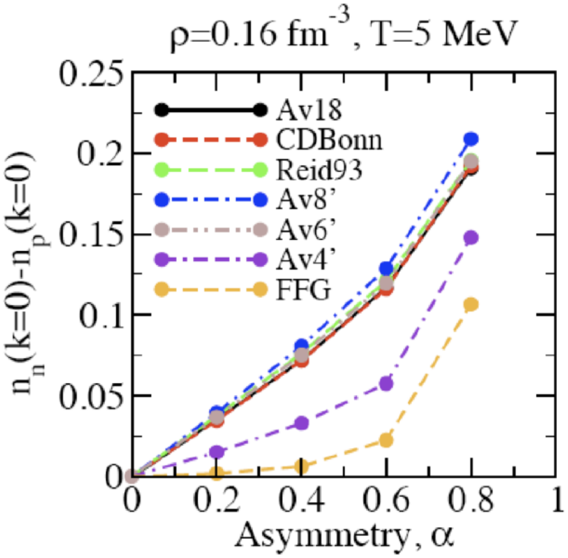
Guidance from ab initio: depletion as a function of asymmetry

- Asymmetry dependence

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

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

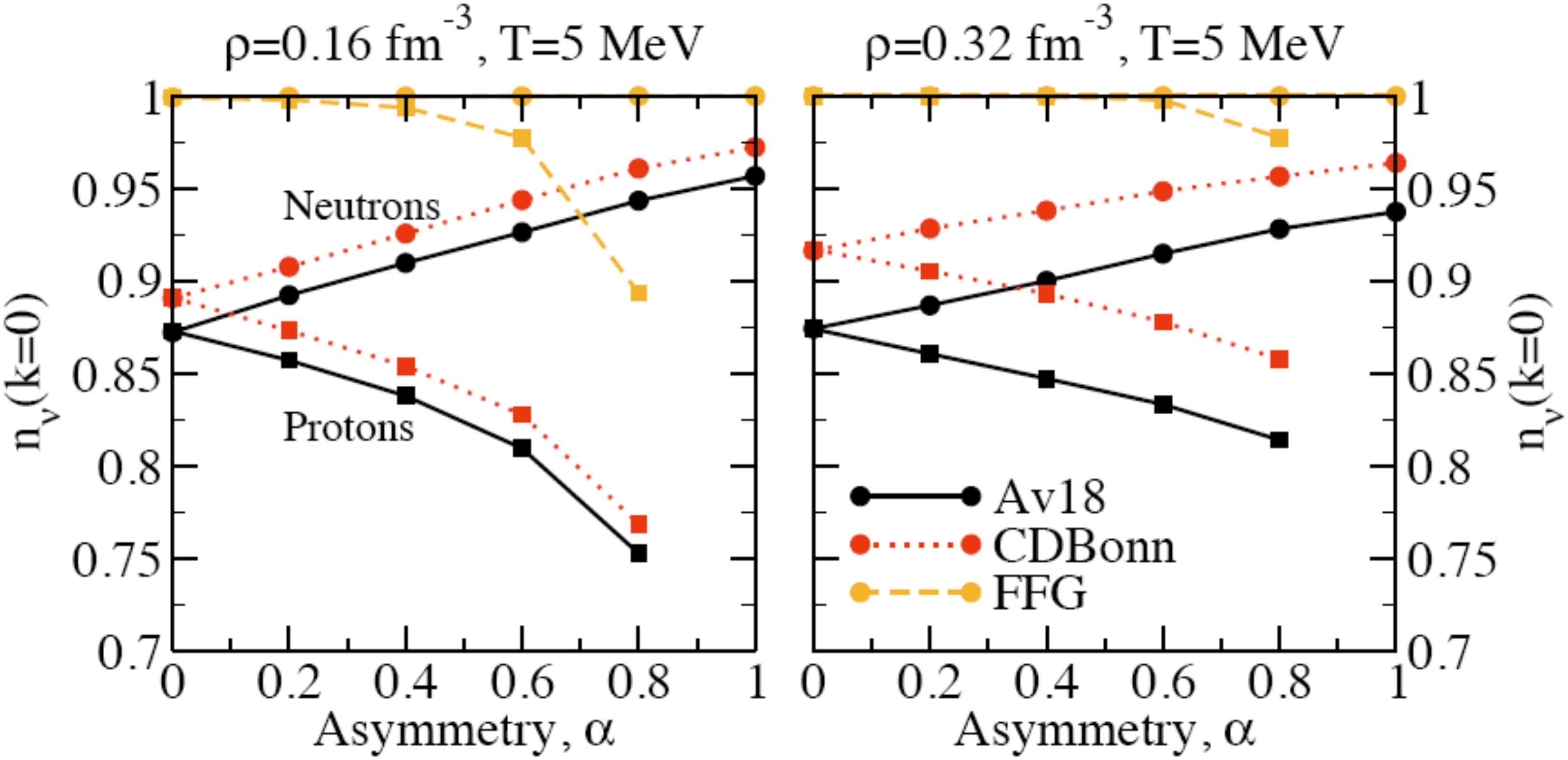




A. Rios, A. Polls, and W. H. Dickhoff
Phys. Rev. C89, 044303 (2014)
Phys. Rev. C79, 064308 (2009)

- 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})

Guidance from ab initio: Depletion as a function of asymmetry in matter treating short-range and tensor correlations



A. Rios, A. Polls, and W. H. Dickhoff
Depletion of the nuclear Fermi sea.
Phys. Rev. C79, 064308 (2009).

Conclusions

- Empirical Green's function method —> DOM
- Scattering data described by DOM generate positive energy spectral function and complement the occupation/depletion sm rule
- 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**
- DOM describes lots of data and can predict hard to access experimental data —> neutron skin
- CREX result can be described but more ^{48}Ca data are needed
- Ab initio guidance in asymmetric matter (2N knockout experiments): Minority species more correlated quantitatively determined by tensor force and constrained by NN interaction <—> CREX some tension?