Nucleus-Informed *NN* Interaction from a Dispersive Optical Model

Mack C. Atkinson

Lawrence Livermore National Laboratory

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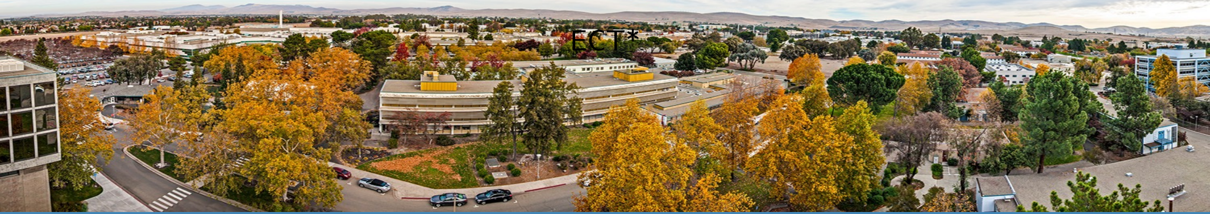
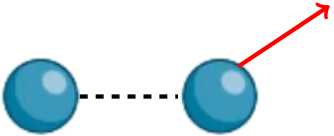


LLNL-PRESS-865739-DRAFT

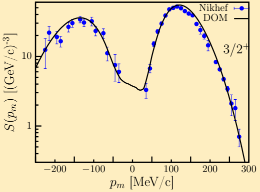
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract 24-LW-062. Lawrence Livermore National Security, LLC

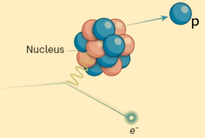
Motivation for nucleus-informed *NN* interaction

- The DOM provides consistent ingredients for knockout reactions
- Discrepancy between ^{40}Ca$(e, e'p)^{39}$K and ^{40}Ca$(p, 2p)^{39}$K

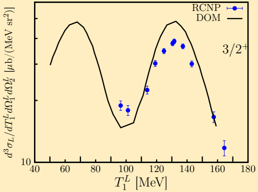


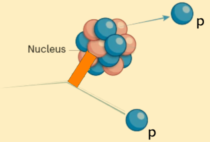
Electron probe: ^{40}Ca$(e, e'p)^{39}$K





Proton probe: ^{40}Ca$(p, 2p)^{39}$K





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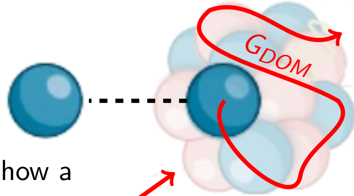

- Through Green's function formalism, the DOM can also describe how a proton propagates through the nucleus (propagator G_{DOM})

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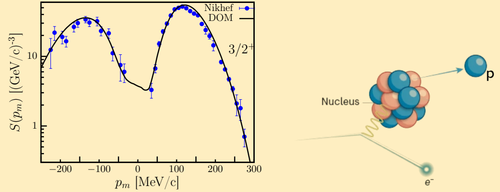

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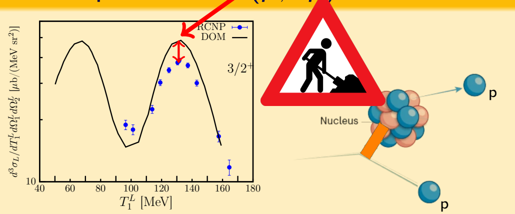
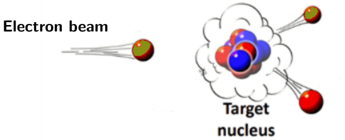


Why not just use $(e, e'p)$ for all single-knockout experiments?

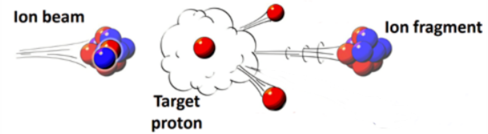
Proton knockout reactions

Experimental sketch for **stable** nuclei



Reaction mechanism well-understood

Experimental sketch for **exotic** nuclei (RIB)



Single-Particle Propagator and the Spectral Function

$$G_{\ell j}(r, r'; E) = \sum_m \frac{\langle \Psi_0^A | a_{r\ell j} | \Psi_m^{A+1} \rangle \langle \Psi_m^{A+1} | a^\dagger_{r'\ell j} | \Psi_0^A \rangle}{E - (E_m^{A+1} - E_0^A) + i\eta} + \sum_n \frac{\langle \Psi_0^A | a^\dagger_{r'\ell j} | \Psi_n^{A-1} \rangle \langle \Psi_n^{A-1} | a_{r\ell j} | \Psi_0^A \rangle}{E - (E_0^A - E_n^{A-1}) - i\eta}$$

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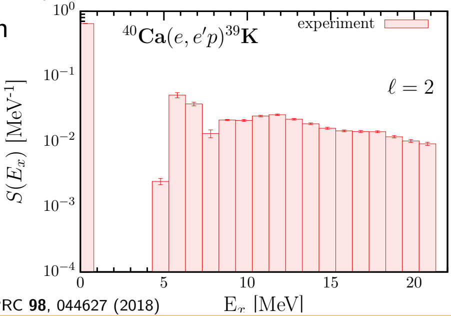

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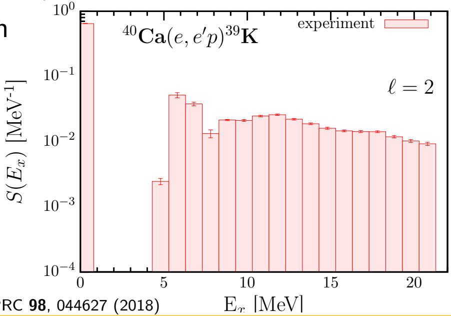
- Close connection with experimental observables



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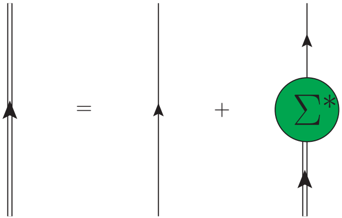
Irreducible self-energy and the Dyson equation

- Perturbative expansion of G leads to the Dyson equation



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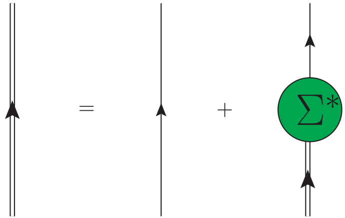

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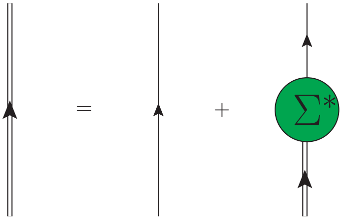

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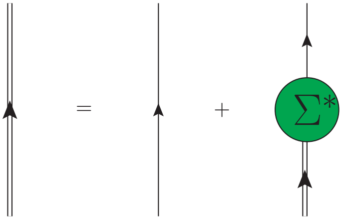

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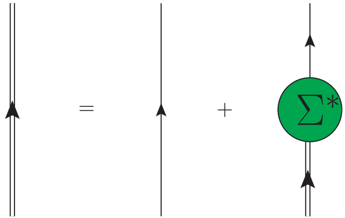

- Use the same functional form as standard optical potentials for the self-energy

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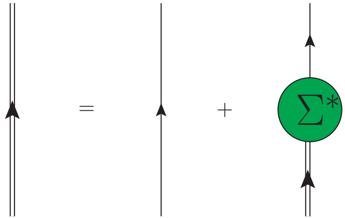

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$$\Sigma^*(\boldsymbol{r}, \boldsymbol{r'}; E) \to V_{vol}(\boldsymbol{r}, \boldsymbol{r'}; E) + V_{sur}(\boldsymbol{r}, \boldsymbol{r'}; E) + V_{so}(\boldsymbol{r}, \boldsymbol{r'}; E)$$

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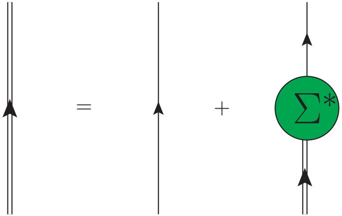

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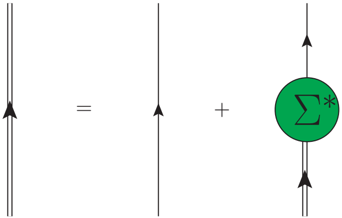

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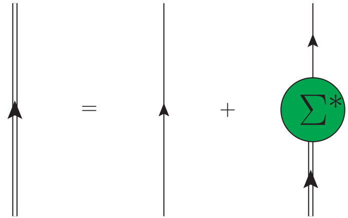

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Can this also describe negative energy observables?

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Dispersive Optical Model

- The DOM makes use of complex analysis to formulate a consistent self-energy

Dispersive Correction

$$Re\Sigma_{\ell j}(r,r';E) = Re\Sigma_{\ell j}(r,r';\epsilon_F) - \frac{1}{\pi}(\epsilon_F - E)\mathcal{P}\int_{\epsilon_T^+}^{\infty} dE'\, Im\Sigma_{\ell j}(r,r';E')\left[\frac{1}{E-E'} - \frac{1}{\epsilon_F - E'}\right]$$
$$+\frac{1}{\pi}(\epsilon_F - E)\mathcal{P}\int_{-\infty}^{\epsilon_T^-} dE'\, Im\Sigma_{\ell j}(r,r';E')\left[\frac{1}{E-E'} - \frac{1}{\epsilon_F - E'}\right]$$

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- This constraint ensures bound and scattering quantities are simultaneously described

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- Parameters of self-energy varied to minimize χ^2

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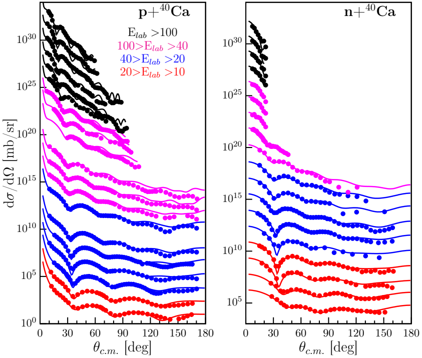

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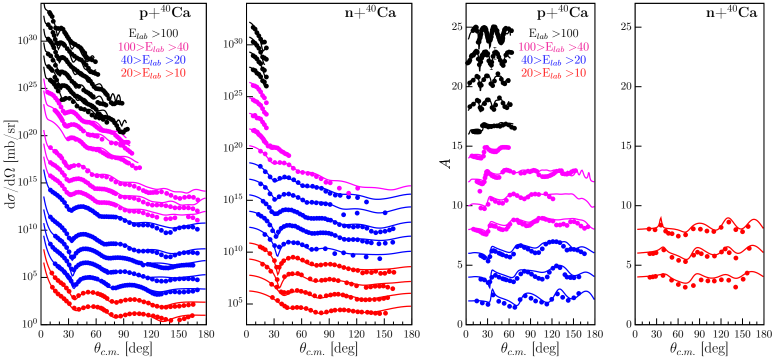

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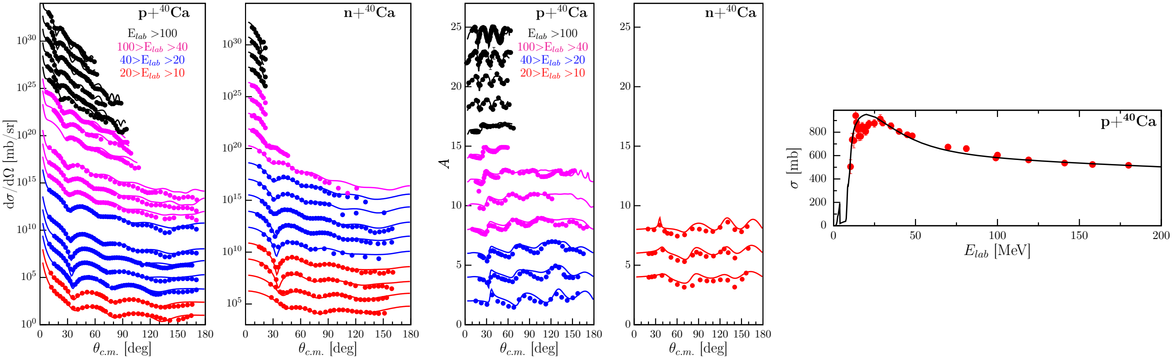

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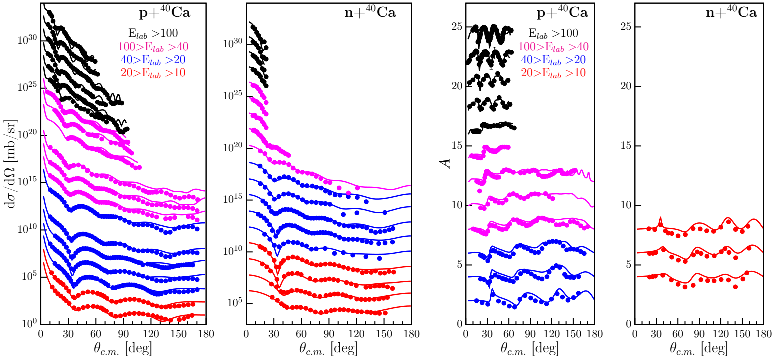

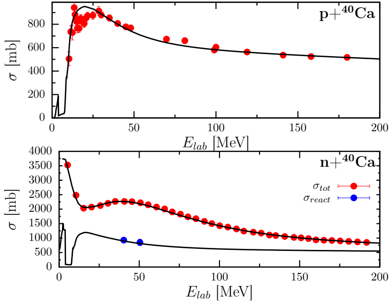

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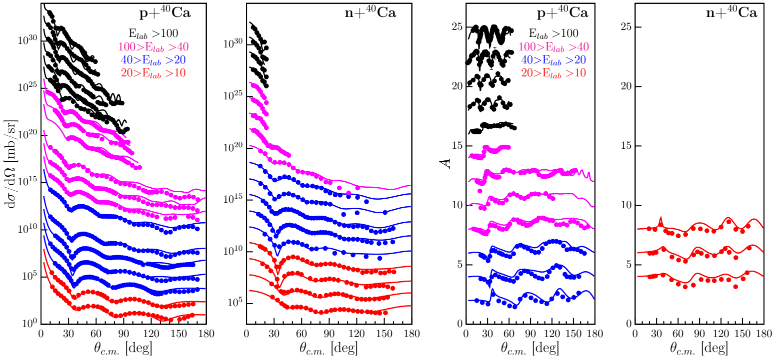
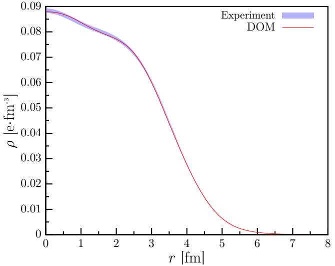
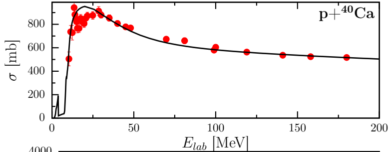
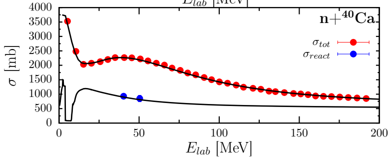
Fitting the Self-energy (^{40}Ca)

- Parameters of self-energy varied to minimize χ^2
- Reproducing the data means self-energy is found









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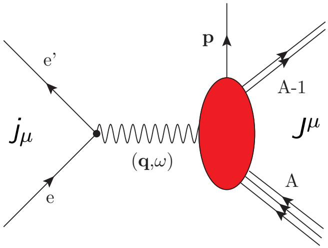
The exclusive $(e, e'p)$ reaction



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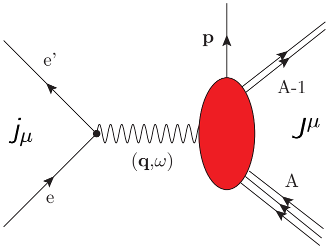

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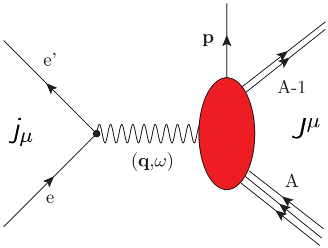

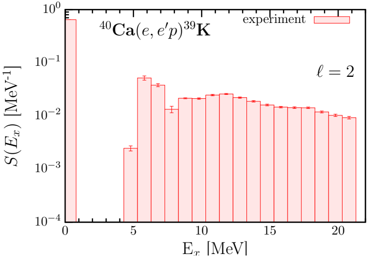

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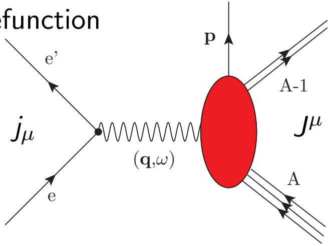
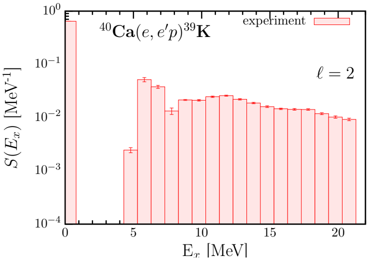
- Excitation spectrum provides evidence of many-body correlations beyond mean-field
- Momentum distribution is closely tied to the boundstate wavefunction





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- Excitation spectrum provides evidence of many-body correlations beyond mean-field
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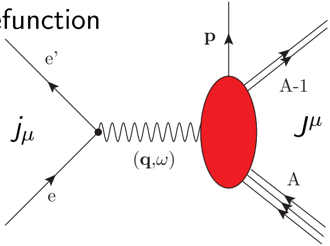

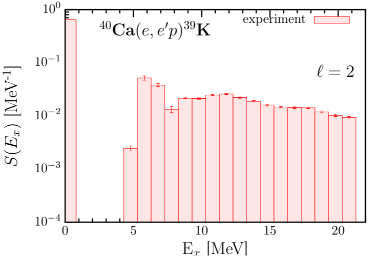

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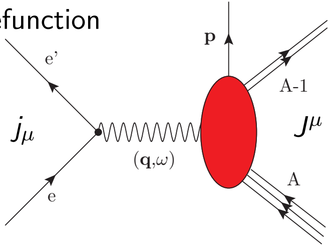
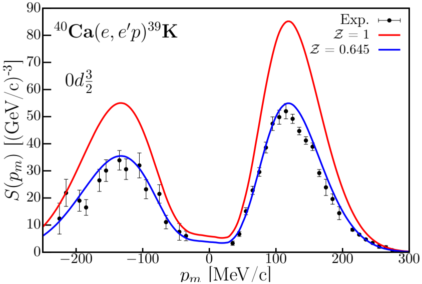
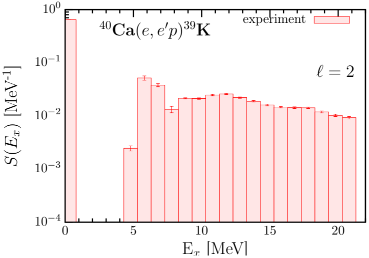


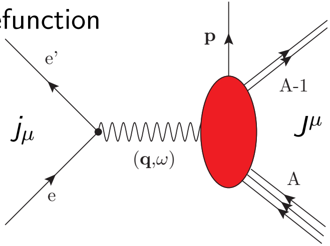


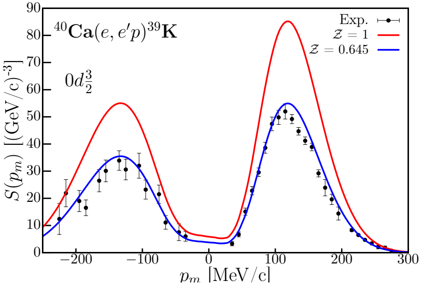


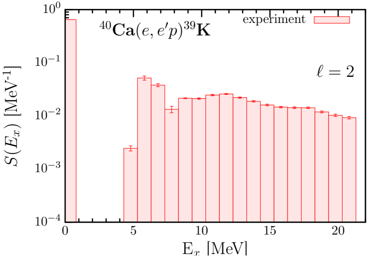
M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

The exclusive $(e, e'p)$ reaction

- Excitation spectrum provides evidence of many-body correlations beyond mean-field
- Momentum distribution is closely tied to the boundstate wavefunction
- Spectroscopic factor
- Electron interaction means clean knockout reactions

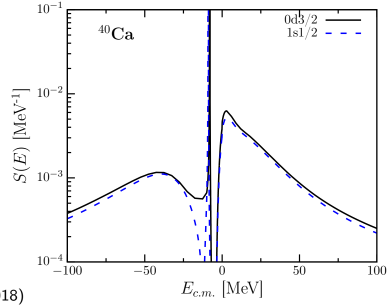






M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

Spectroscopic factor is **not** the same as Occupation



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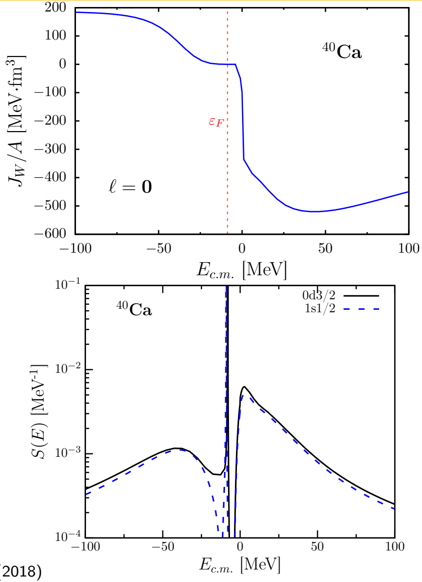

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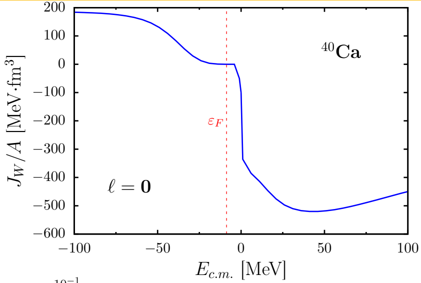

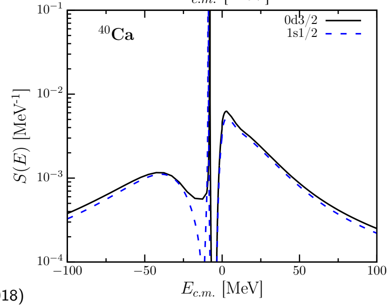

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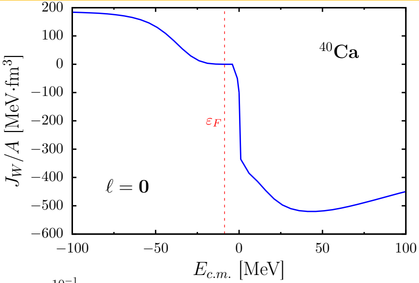
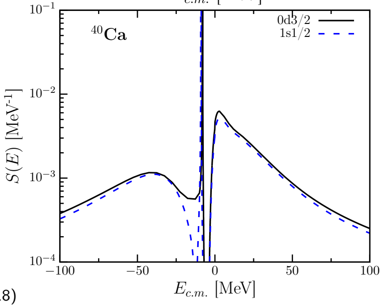
- Spectroscopic factor for states near ϵ_F is well defined from Σ^*

$$S_F = \left(1 - \left.\frac{\partial \Sigma^*(\alpha_{qh},\alpha_{qh};E)}{\partial E}\right|_\epsilon\right)^{-1}$$





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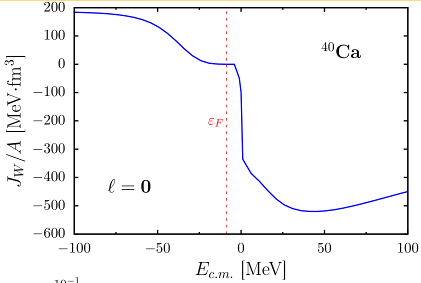

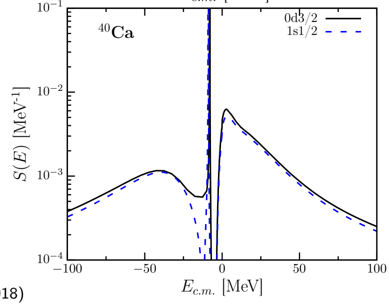

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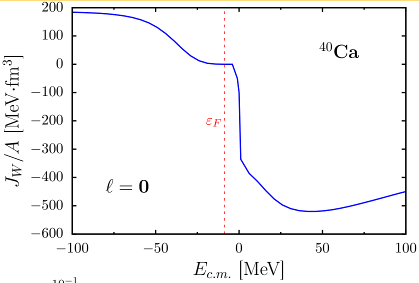

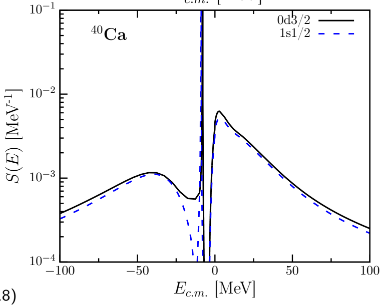

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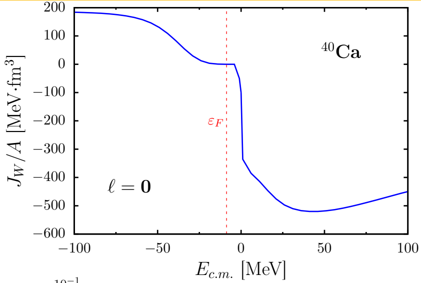
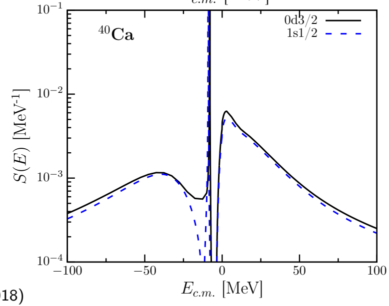
Orbital	S_F	$n_{n\ell j}$	$d_{n\ell j}$
$0d\frac{3}{2}$	0.71	0.80	0.17
$1s\frac{1}{2}$	0.60	0.82	0.15



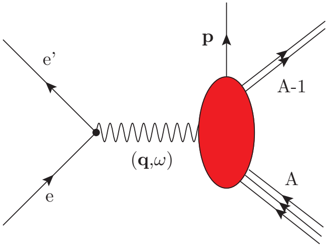


M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

DOM calculation of ^{40}Ca$(e, e'p)^{39}$K

- DWIA for exclusive reaction (C. Giusti's DWEEPY code)

$$J^{\mu}(\mathbf{q}) = \int \chi^{(-)*}_{E\alpha}(\mathbf{r}) j^{\mu}(\mathbf{r}) \phi_{E\alpha}(\mathbf{r}) [S_{F\alpha}(E)]^{1/2} e^{i\mathbf{q}\cdot\mathbf{r}} d^3r$$



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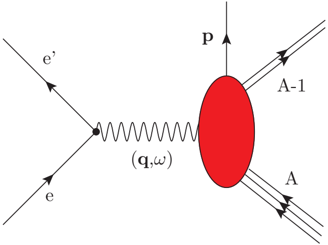
- DOM provides all ingredients



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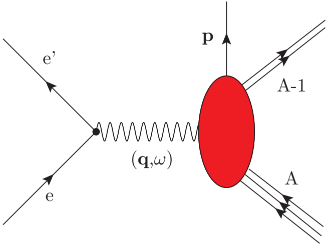
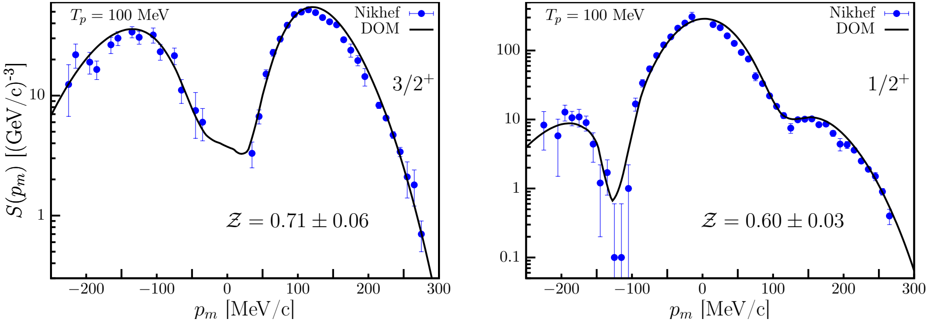
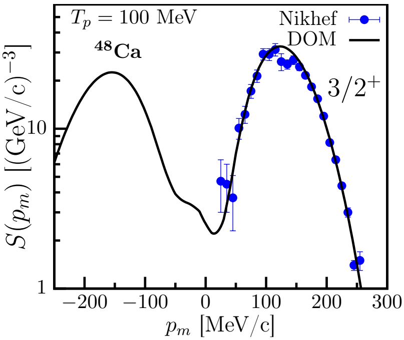
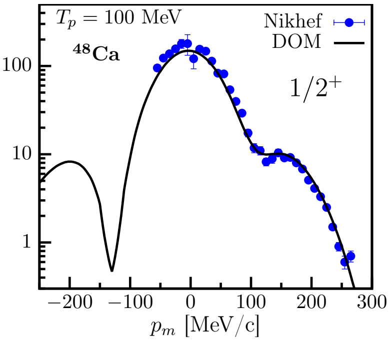




^{48}Ca(e,e'p)^{47}K Momentum Distribution





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

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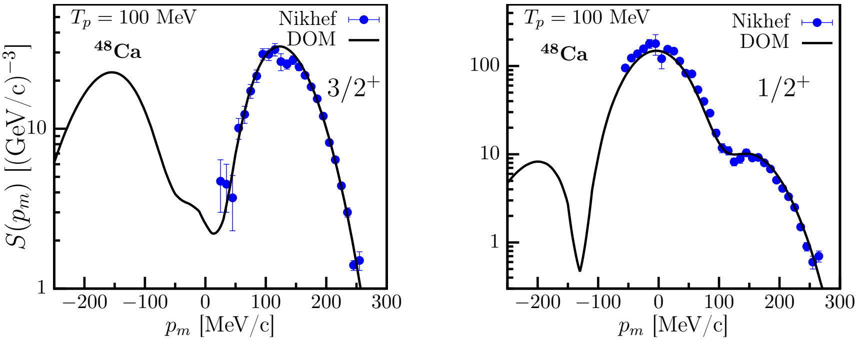

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$SF^{n}_{\ell j}$	$0d\frac{3}{2}$	$1s\frac{1}{2}$
^{40}Ca	0.71 ± 0.04	0.60 ± 0.03
^{48}Ca	0.58 ± 0.03	0.55 ± 0.03

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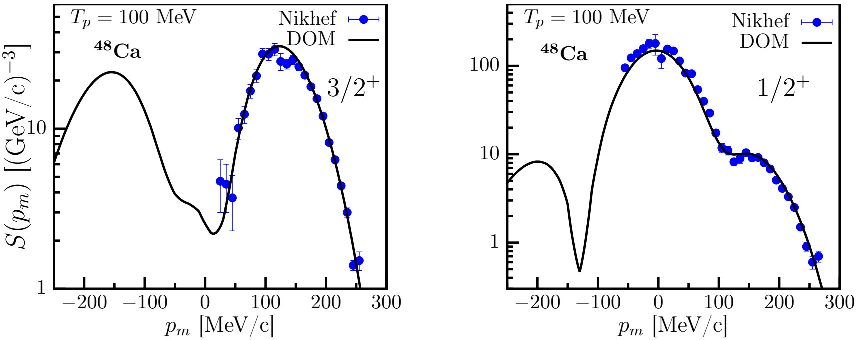

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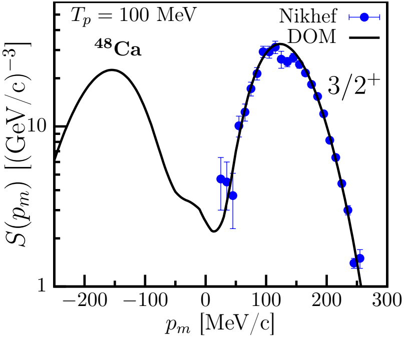

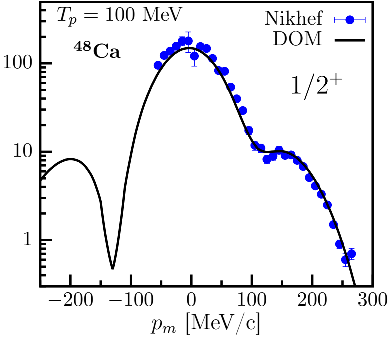

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Protons are more correlated in ^{48}Ca!

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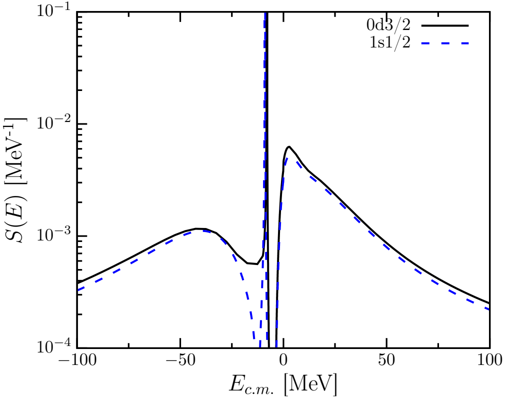
Constraints for S_F

- Dispersion relation "pulls" strength of Σ^* around



Constraints for S_F

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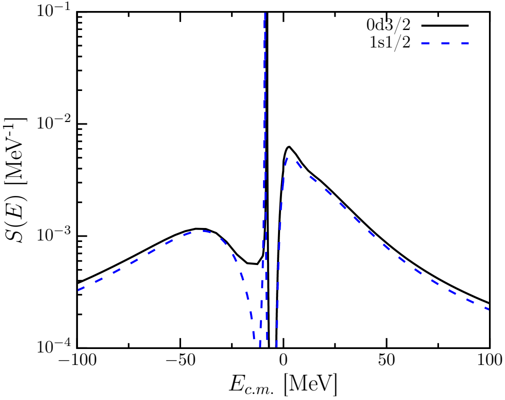

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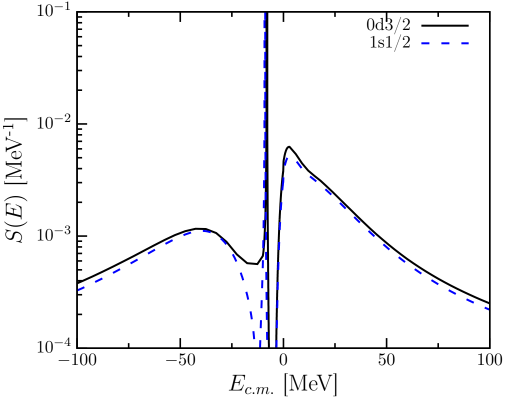

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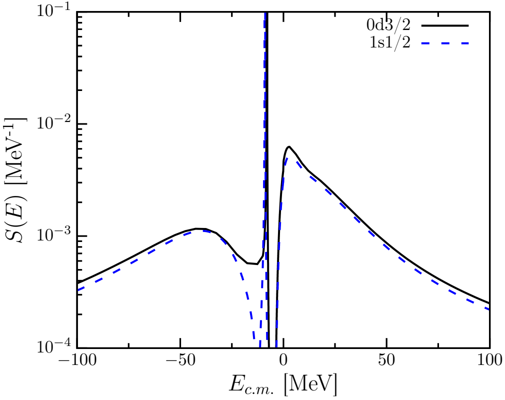

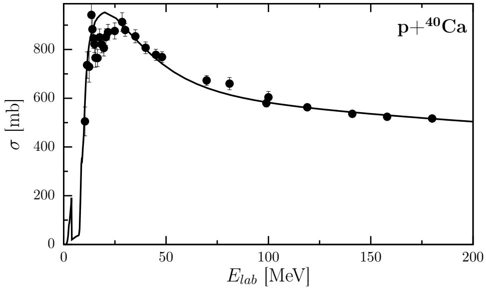

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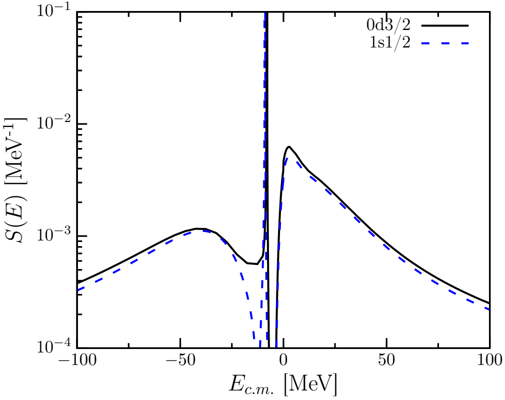

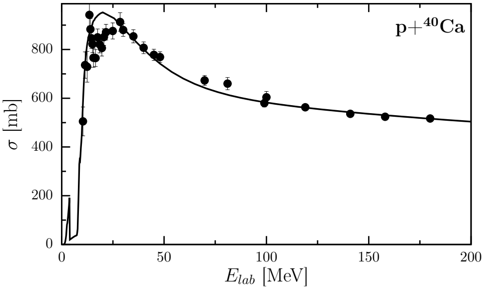

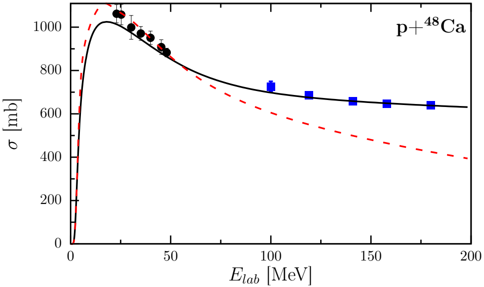

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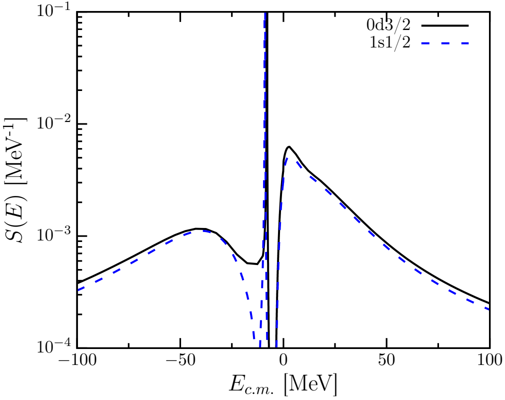
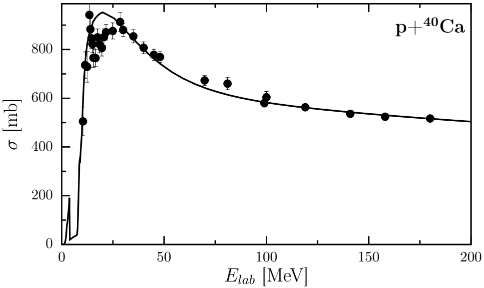
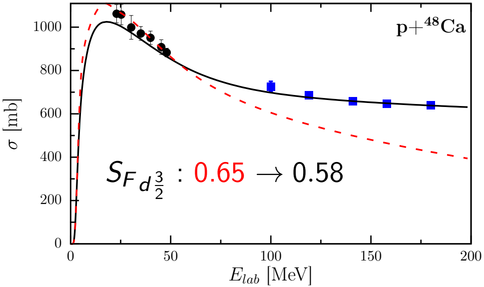
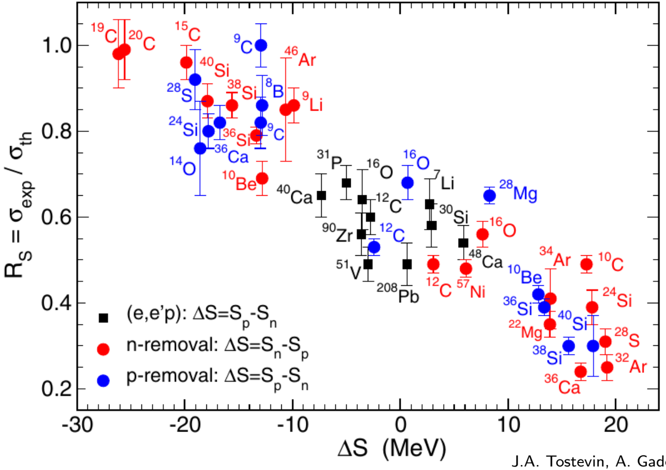






Quenching of "Spectroscopic Factors"



J.A. Tostevin, A. Gade *Phys. Rev. C* **90**, 057602 (2014)

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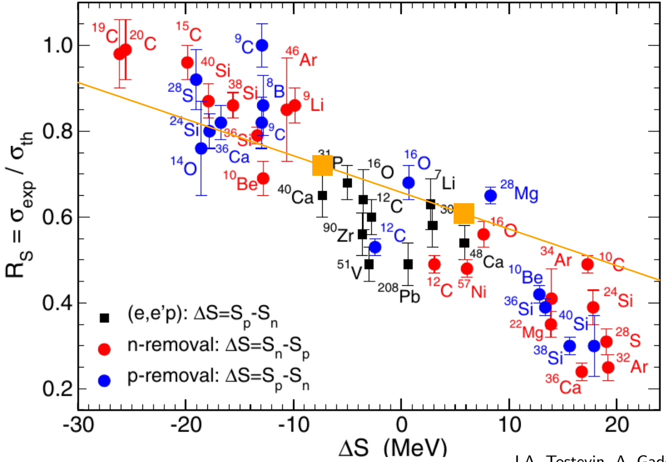
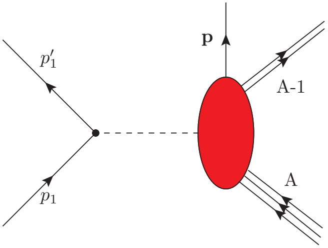


J.A. Tostevin, A. Gade *Phys. Rev. C* **90**, 057602 (2014)

Now try calculating with a hadronic probe: ^{40}Ca$(p, 2p)^{39}$K



K. Yoshida, M.C. Atkinson, K. Ogata, W.H. Dickhoff PRC **105**, 014622 (2022)

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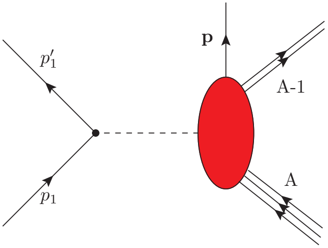

- Same DOM ingredients used

K. Yoshida, M.C. Atkinson, K. Ogata, W.H. Dickhoff PRC **105**, 014622 (2022)

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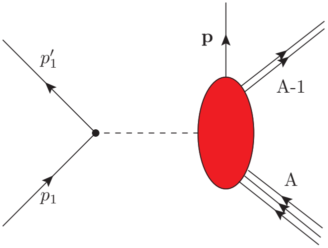

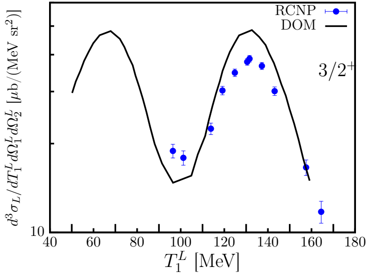

K. Yoshida, M.C. Atkinson, K. Ogata, W.H. Dickhoff PRC **105**, 014622 (2022)

Now try calculating with a hadronic probe: $^{40}\mathrm{Ca}(p,2p)^{39}\mathrm{K}$

$$T \approx \int d\boldsymbol{R}\, t_{NN}\chi_1^{(-)*}(\boldsymbol{R})\chi_2^{(-)*}(\boldsymbol{R})\chi_0^{(+)}(\boldsymbol{R})e^{-i\alpha_R \boldsymbol{K}_0\cdot\boldsymbol{R}}\phi_{ljm}^{n}(\boldsymbol{R}).$$

- Same DOM ingredients used

"S_F"	$(p,2p)$	$(e,e'p)$
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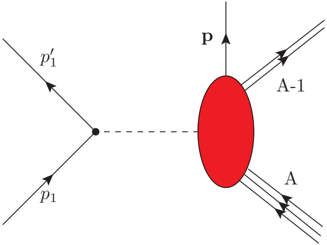

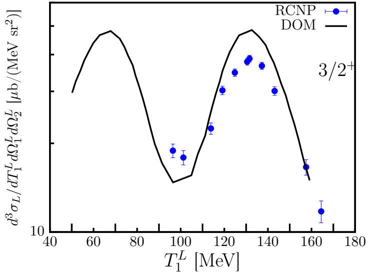

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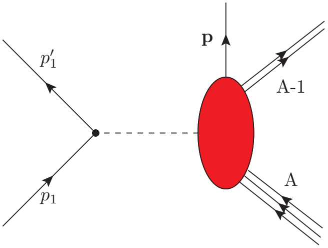

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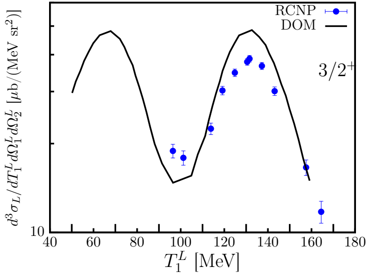

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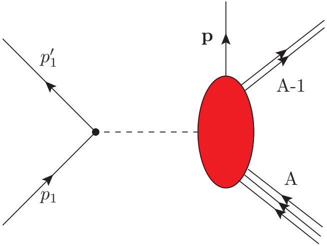

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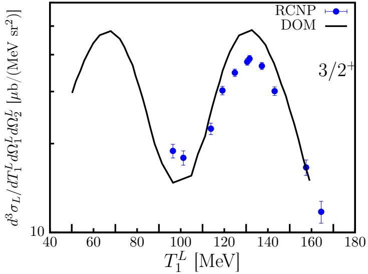

- Remember that S_F comes directly from Σ^*_{DOM}
- Main difference is the probe $\implies$ problem is likely V_{pp}

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Nucleus-informed pp interaction: $V_{pp} \rightarrow \Gamma_{pp}$

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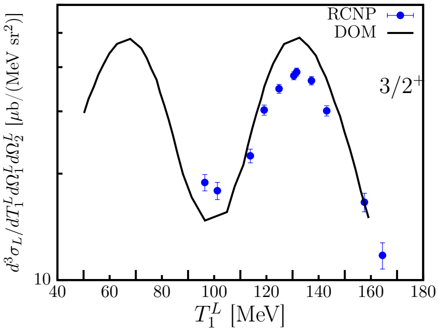

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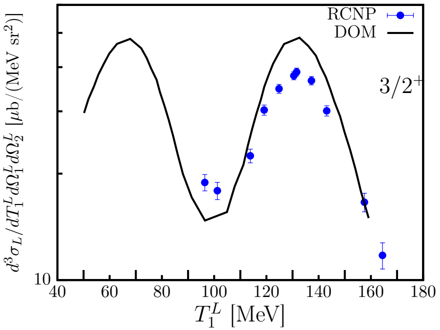

S_F	V_{NN}	$(p, 2p)$
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DOM	Mel	0.489 ± 0.05
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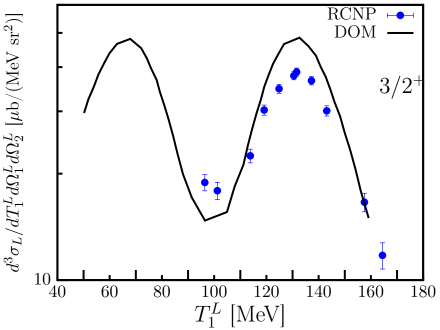

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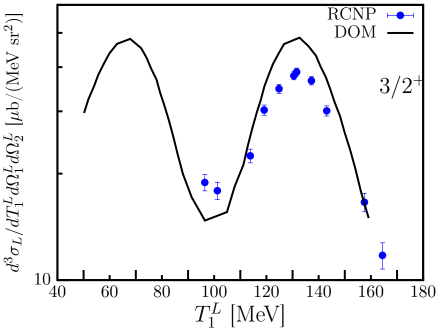

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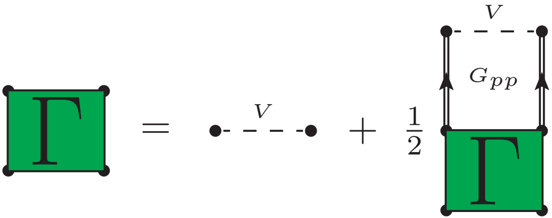

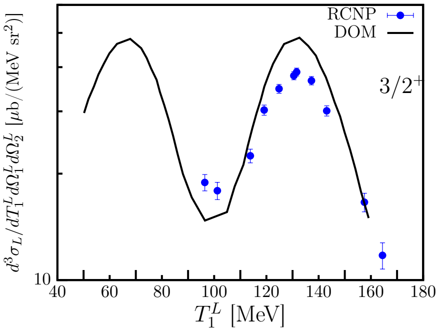

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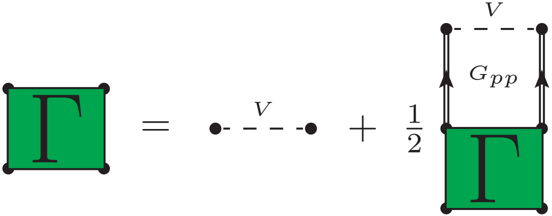
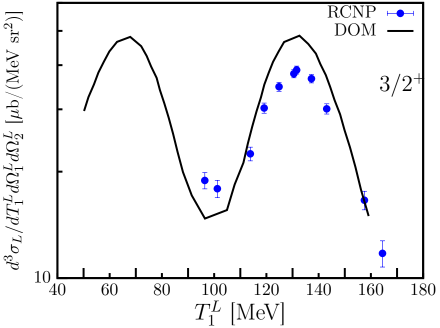


- $G_{pp} \approx \int G_{\mathrm{DOM}} \times G_{\mathrm{DOM}}$



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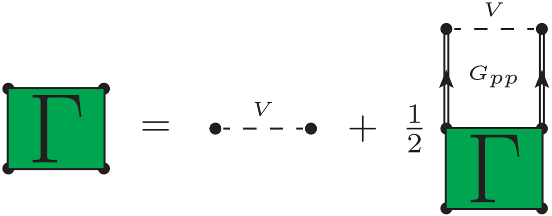

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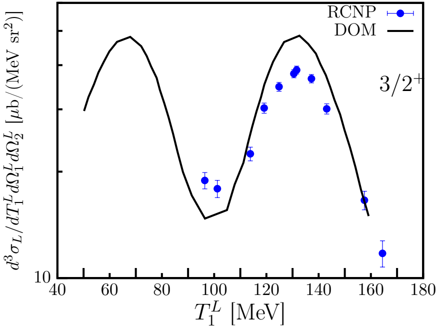

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K. Yoshida, M.C. Atkinson, K. Ogata, W.H. Dickhoff PRC **105**, 014622 (2022)

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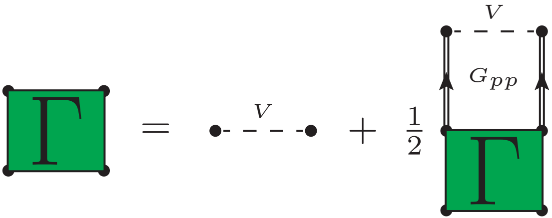
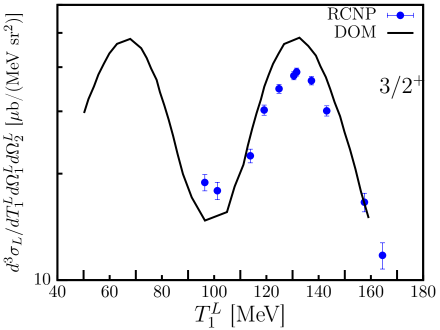


- $G_{pp} \approx \int G_{\mathrm{DOM}} \times G_{\mathrm{DOM}}$
- Similar to G-matrix, except this is calculated in finite nuclei
- Good approximation for typical $(p, 2p)$ energies



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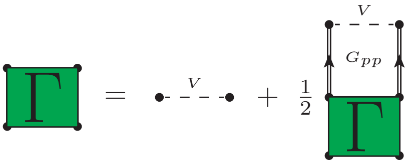

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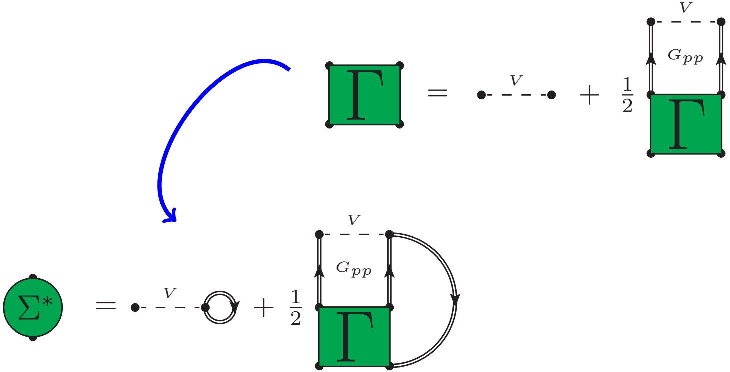

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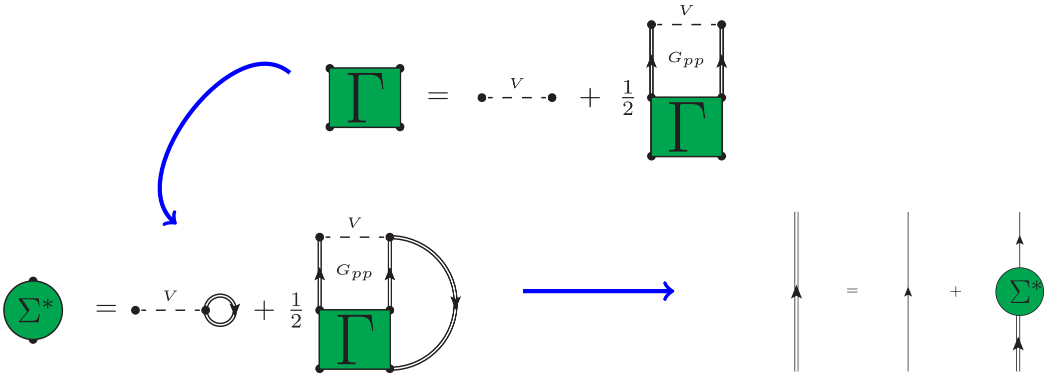

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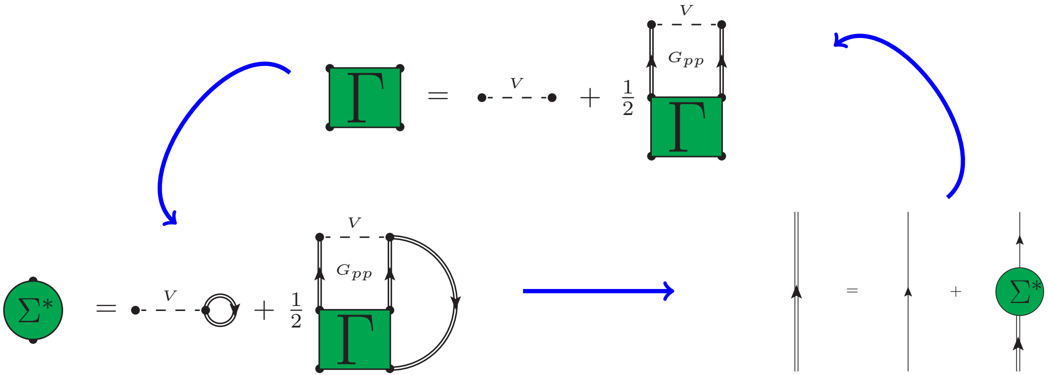
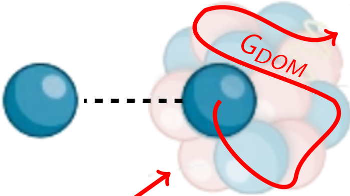
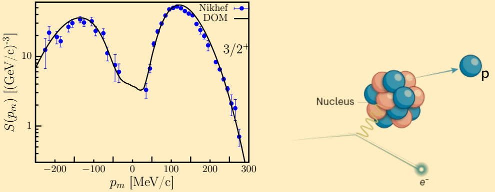


Summary

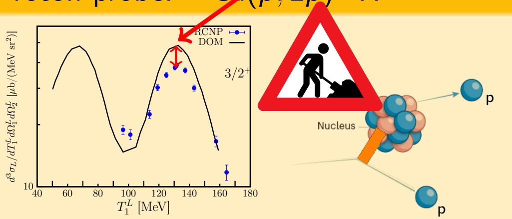
- The DOM provides consistent ingredients for knockout reactions
- Discrepancy between ^{40}Ca$(e, e'p)^{39}$K and ^{40}Ca$(p, 2p)^{39}$K
- DOM provides a path toward improvement through the nucleus-informed NN interaction Γ_{NN}



Electron probe: ^{40}Ca$(e, e'p)^{39}$K



Proton probe: ^{40}Ca$(p, 2p)^{39}$K



Thanks

- Willem Dickhoff
- Robert Charity
- Hossein Mahzoon
- Lee Sobotka
- Natalie Calleya

Cole Pruitt
Gregory Potel
Sofia Quaglioni

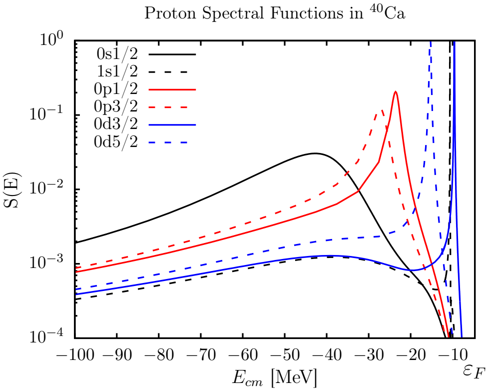
- Louk Lapikás
- Henk Blok

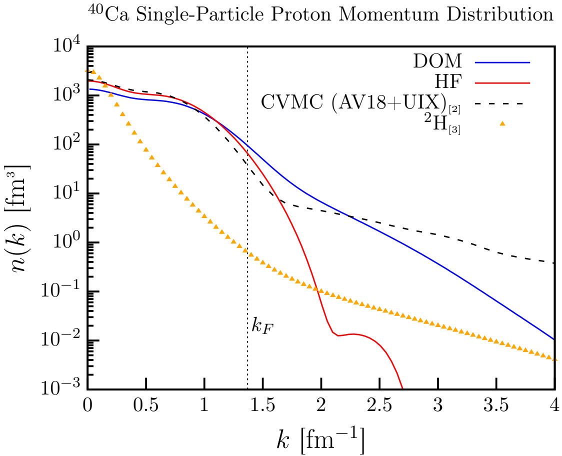
- Kazuyuki Ogata

- Kazuki Yoshida

Backup Slides

- Monte-Carlo results borrowed from Bob Wiringa's website[1]

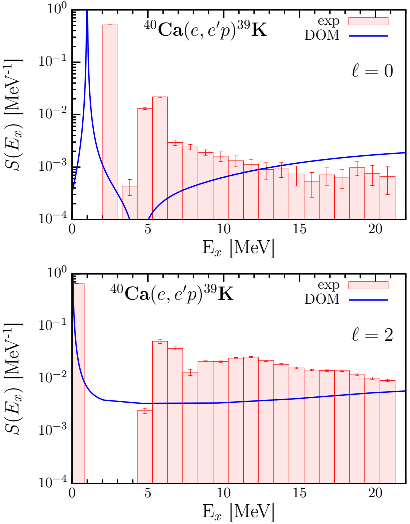




[1] https://www.phy.anl.gov/theory/research/QMCresults.html
[2] R.B. Wiringa *et al.*, PRC **89**, 024305 (2014)
[3] D. Lonardoni *et al.*, PRC **96**, 024326 (2017)

- "Smearing" of self-energy poles inflates S_F
- Renormalize with experimental excitation energy spectrum

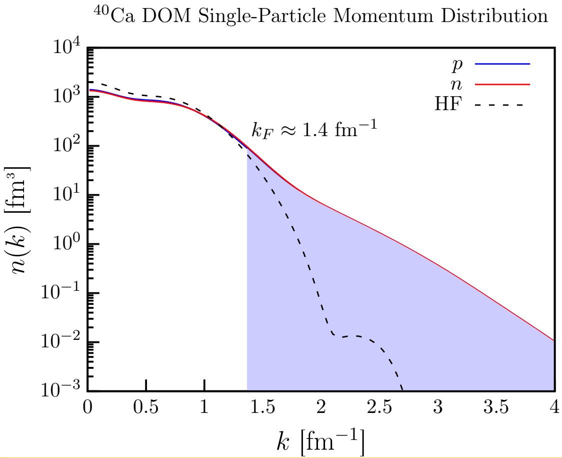
$$\frac{\mathcal{Z}_F^{\text{DOM}}}{\int dE\ S^{\text{DOM}}(E)} = \frac{\mathcal{Z}_F^{\text{exp}}}{\int dE\ S^{\text{exp}}(E)}$$



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

Momentum Distributions

$$n(\boldsymbol{k}) = \int d^3r \int d^3r' e^{i\boldsymbol{k}\cdot(\boldsymbol{r}-\boldsymbol{r}')}\rho(\boldsymbol{r},\boldsymbol{r}')$$



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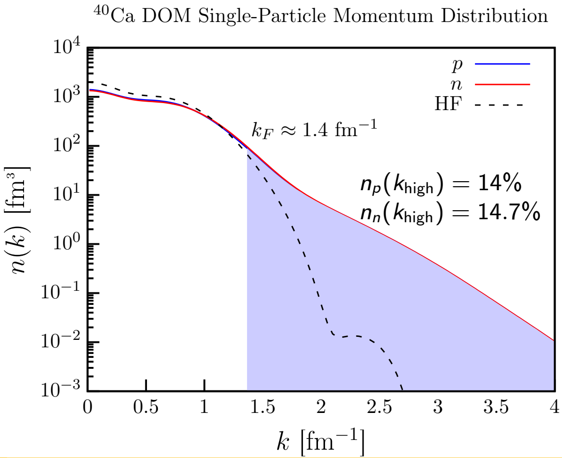

Momentum Distributions

- Short-range correlations (SRC) responsible for this high-momentum content

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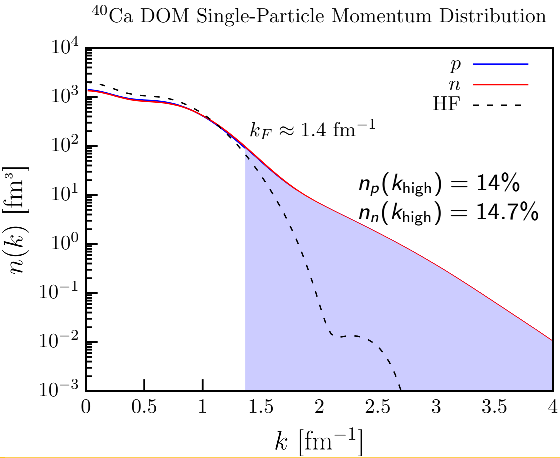

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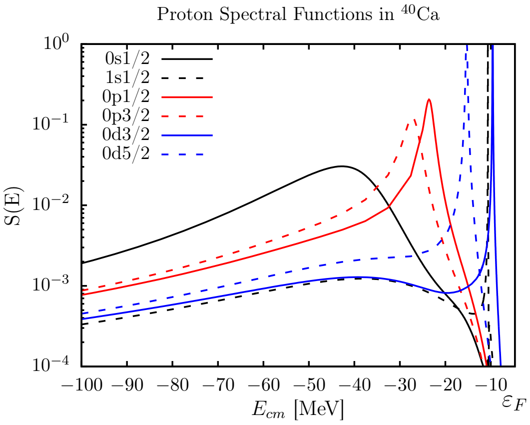

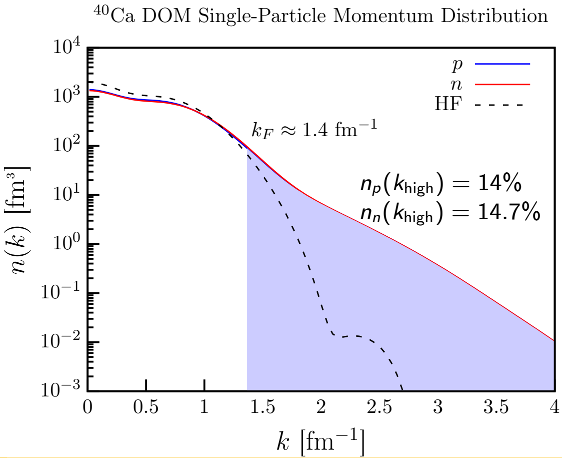

Constraints for High-Momentum Content

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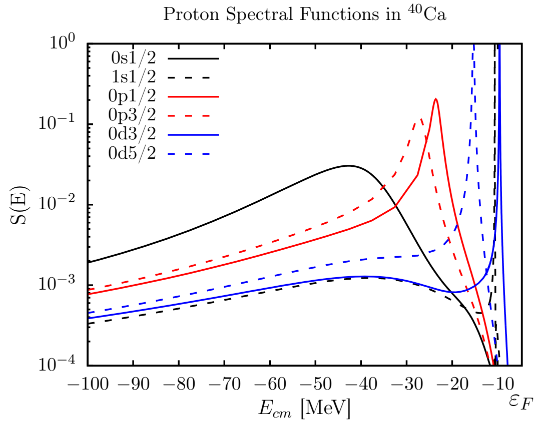

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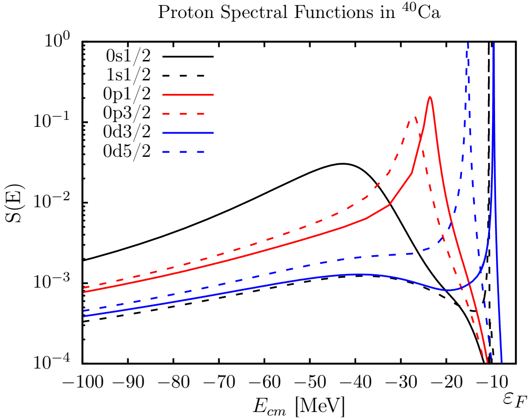

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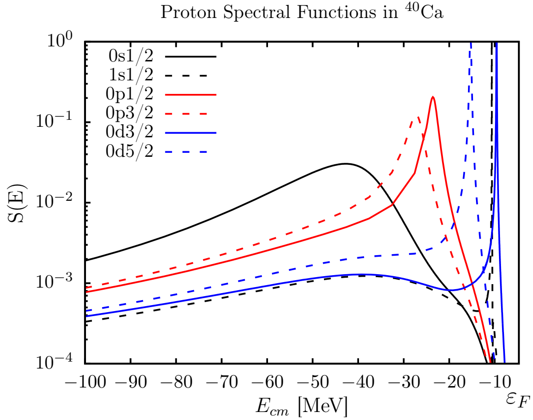

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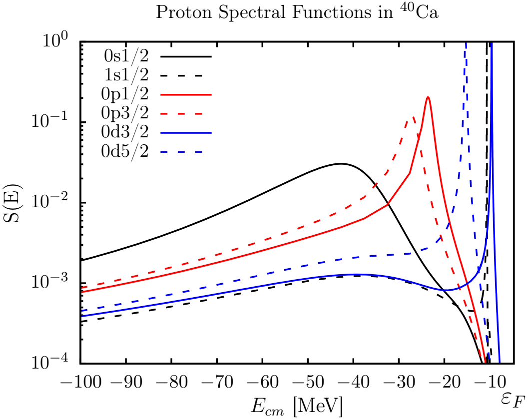

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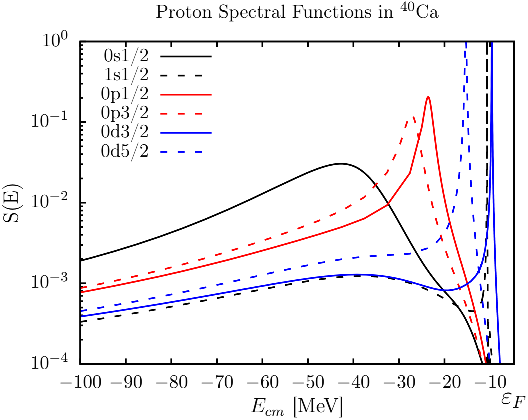
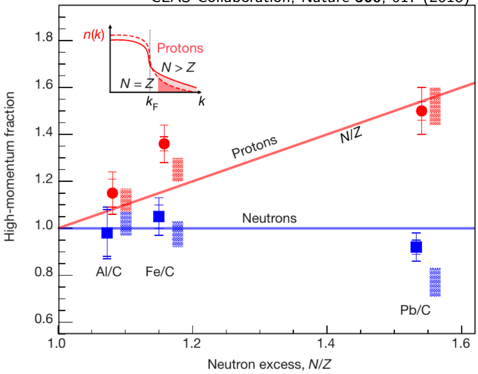
	N	Z	DOM E_0^A/A	Exp. E_0^A/A
^{40}Ca	19.9	19.8	-8.50	-8.55
^{48}Ca	27.9	19.9	-8.59	-8.66
^{208}Pb	126.2	82.1	-7.81	-7.87



Asymmetry Dependence of High-Momentum Content

CLAS Collaboration, Nature **560**, 617 (2018)



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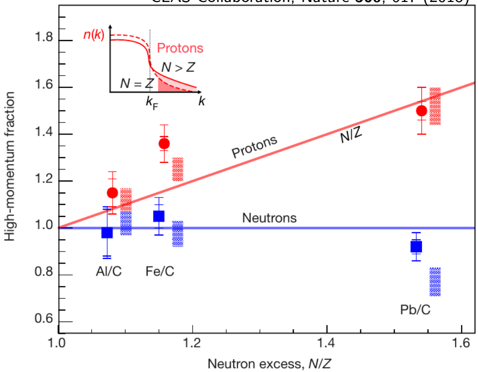

- *n*-*p* interaction stronger than *n*-*n* or *p*-*p*

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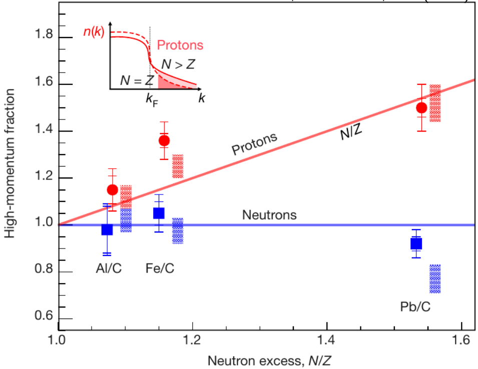

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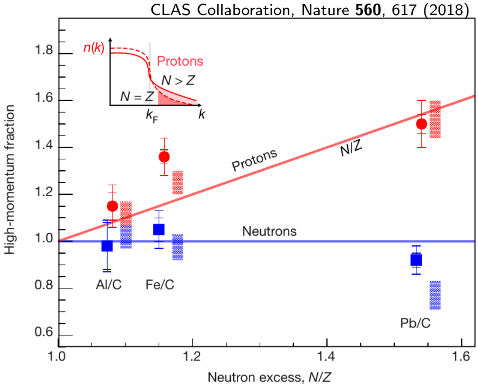

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$\Longrightarrow$ Protons more correlated (more high-momentum content)

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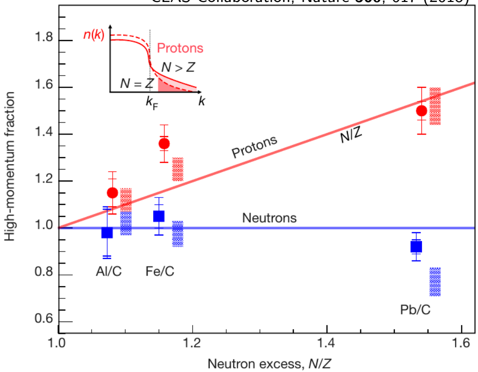
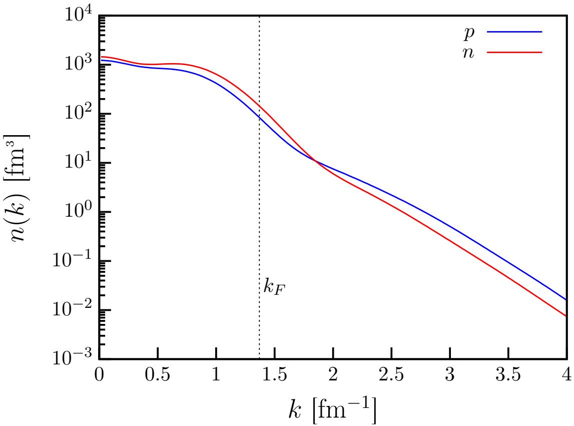


^{48}Ca DOM Single-Particle Momentum Distribution



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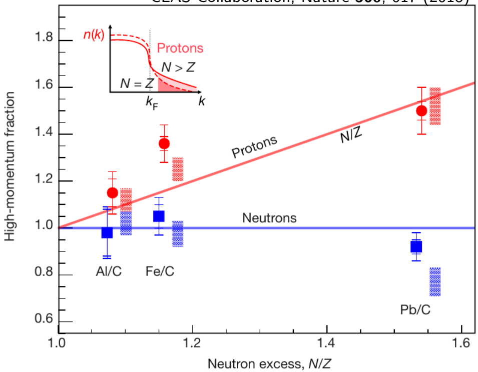

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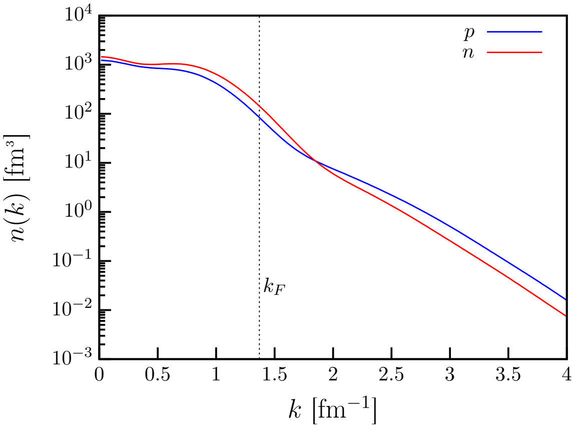

A	n_{high}	p_{high}
^{40}Ca	0.147	0.14
^{48}Ca	0.126	0.146

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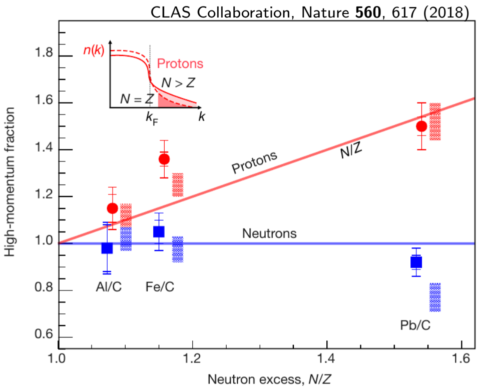

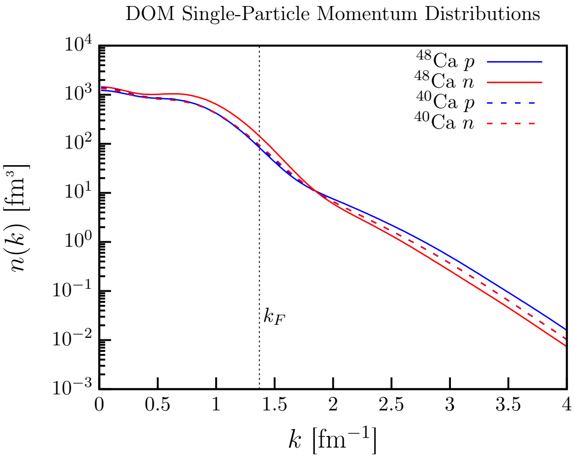

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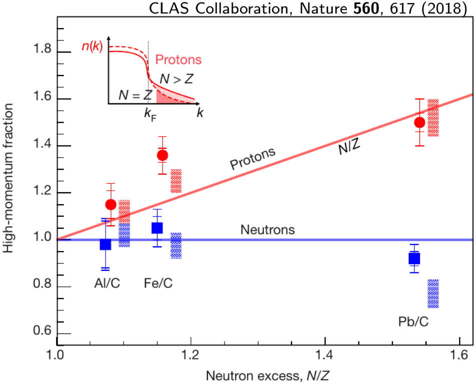

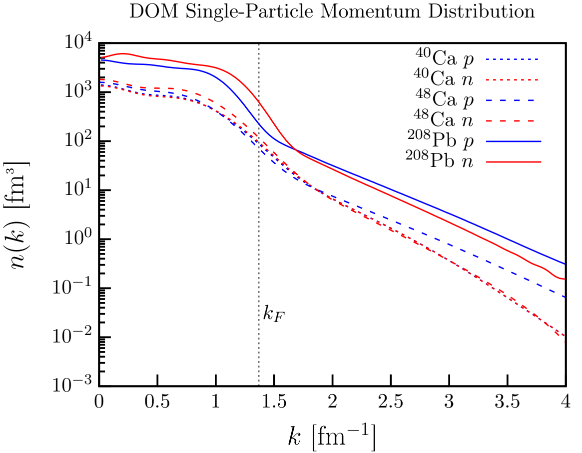

A	n_{high}	p_{high}
^{40}Ca	0.147	0.14
^{48}Ca	0.126	0.146
^{208}Pb	0.106	0.134

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