Dispersive Optical Models: Acheivements and Perspectives

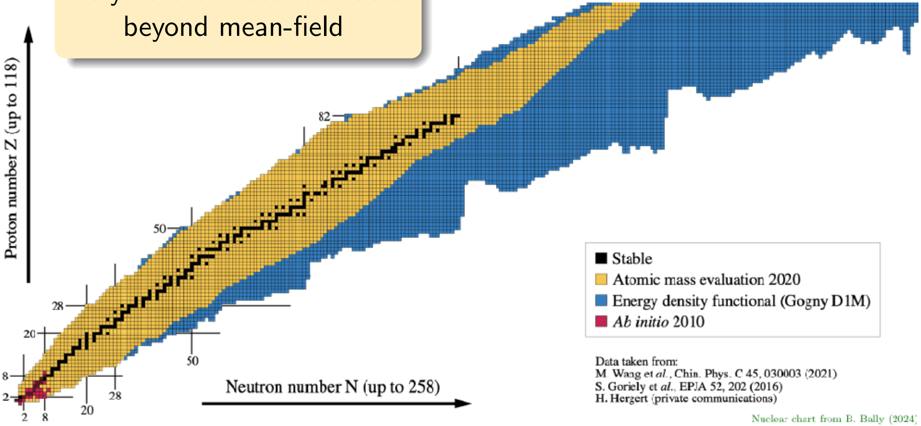
Mack C. Atkinson

Reed College

Perspectives on Nuclear Data for the Next Decade $P(ND)^2$-3

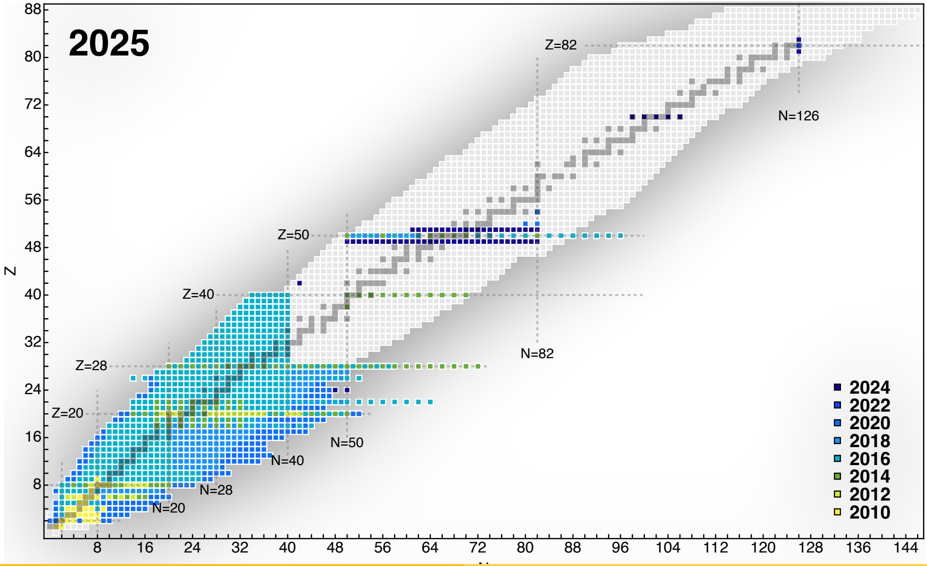
Progress in structure and reaction calculations across the nuclear chart

Very hard to describe nuclei beyond mean-field

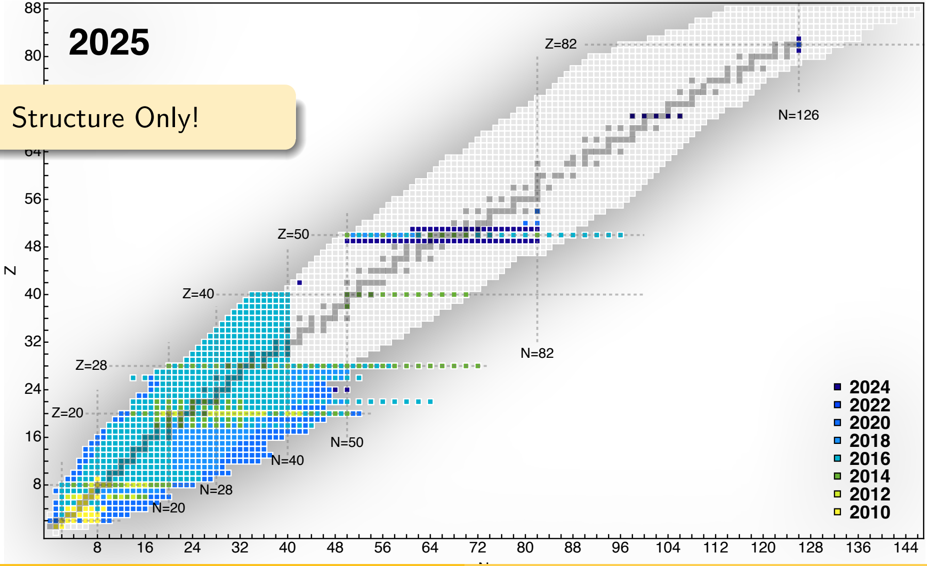


Nuclear chart from B. Bally (2024)

Progress in structure and reaction calculations across the nuclear chart

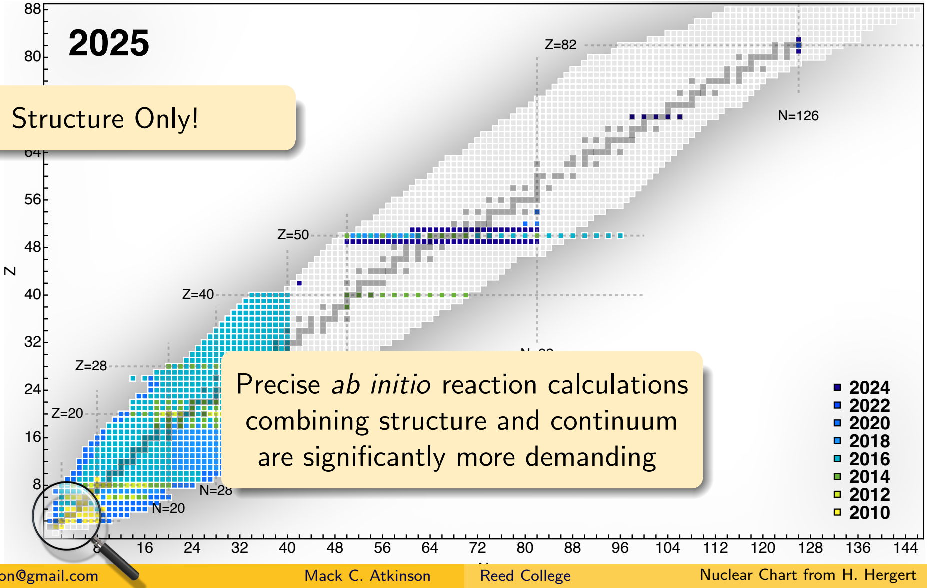


Progress in structure and reaction calculations across the nuclear chart



Structure Only!

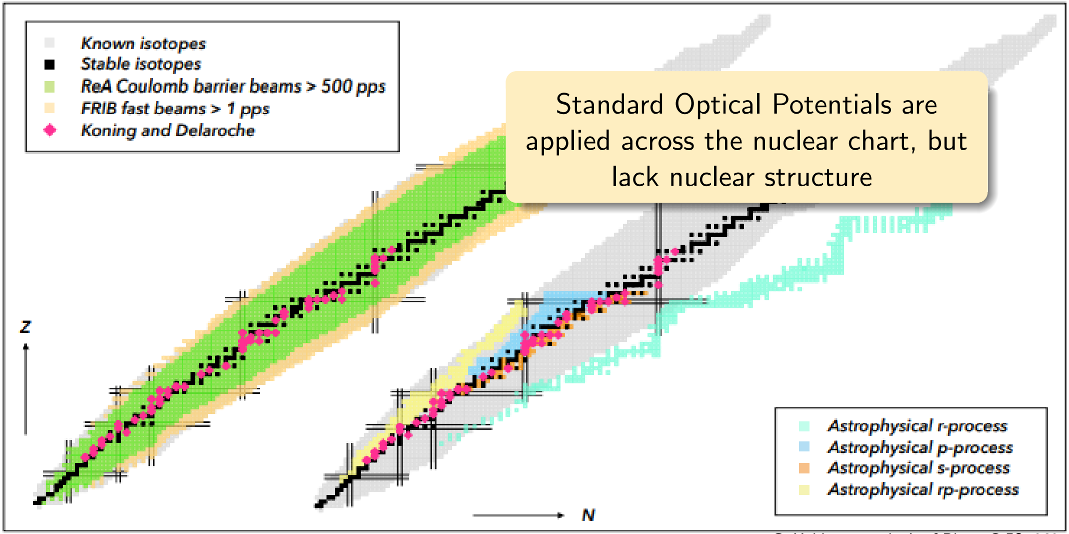
Progress in structure and reaction calculations across the nuclear chart



Structure Only!

Precise *ab initio* reaction calculations combining structure and continuum are significantly more demanding

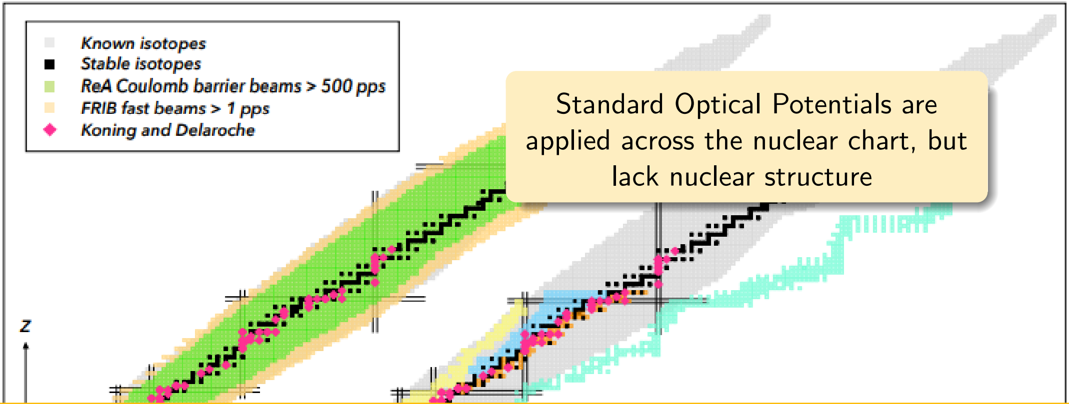
Structure and reaction calculations across the nuclear chart



Standard Optical Potentials are applied across the nuclear chart, but lack nuclear structure

C. Hebborn *et al.*, J. of Phys. G **50**, 060501 (2023)

Structure and reaction calculations across the nuclear chart



Standard Optical Potentials are applied across the nuclear chart, but lack nuclear structure

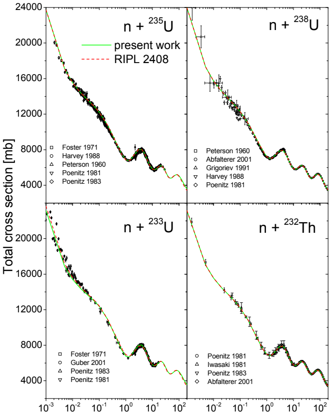
Dispersive Optical Model

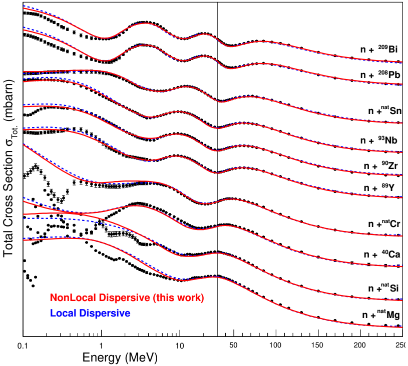
The DOM strikes a balance between computational cost and a consistent treatment of bound and continuum dynamics

C. Hebborn *et al.*, J. of Phys. G **50**, 060501 (2023)

Disclaimer

- There are several dispersive optical models
- This talk focuses on a particular DOM (Washington University in St. Louis) and its capabilities



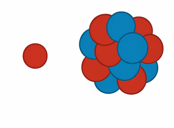


E. Sh. Soukhovitskii *et al.*, PRC **94**, 064605 (2016)

B. Morillon *et al.*, PRC **109**, 044611 (2024)

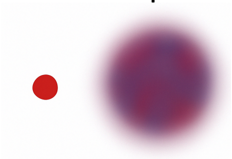
Dispersive Optical Model (DOM): uniting structure and continuum

Exact

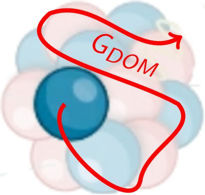


DOM

V_{opt}

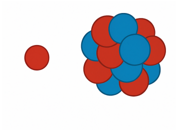


Dispersive Optical Model (DOM): uniting structure and continuum



G_{DOM}: Single-Particle Propagator

Exact



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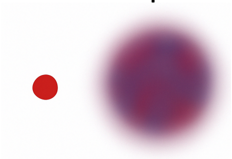

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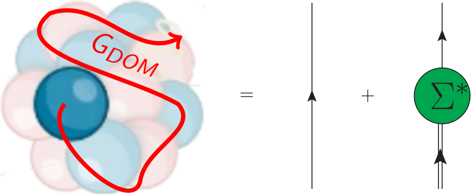

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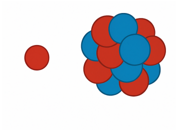

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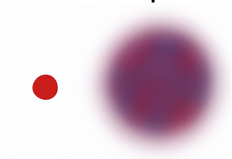
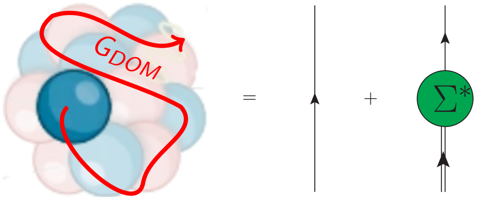


Dispersive Optical Model (DOM): uniting structure and continuum

- Self-energy: $\Sigma^*(r, r'; E) = V_{\rm opt}(r, r'; E)$



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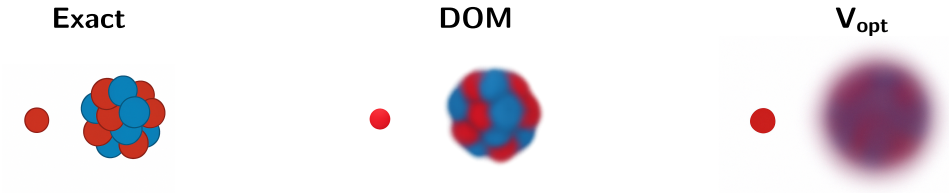
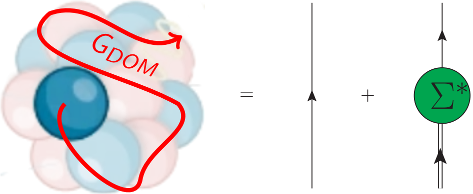


Dispersive Optical Model (DOM): uniting structure and continuum

- Self-energy: $\Sigma^*(r, r'; E) = V_{\mathrm{opt}}(r, r'; E)$

Dispersive Correction

$$Re\Sigma_{\ell j}(r, r'; E) = \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty} dE' \frac{Im\Sigma_{\ell j}(r, r'; E')}{E - E'}$$



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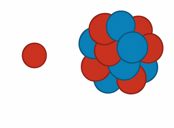

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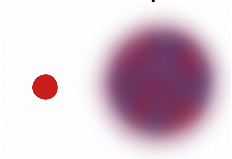

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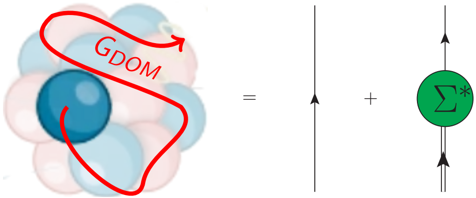
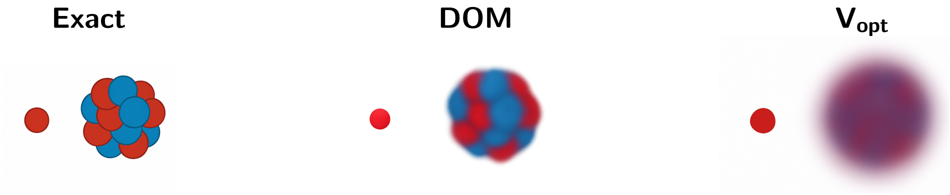


G_{DOM}: Single-Particle Propagator

- This constraint ensures bound and scattering quantities are simultaneously described



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

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

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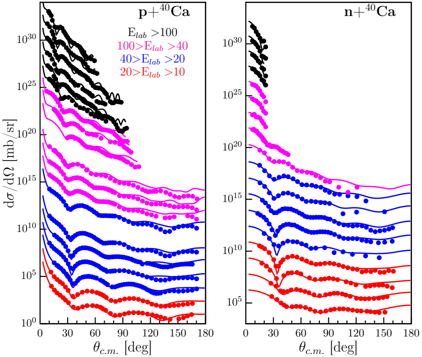

M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

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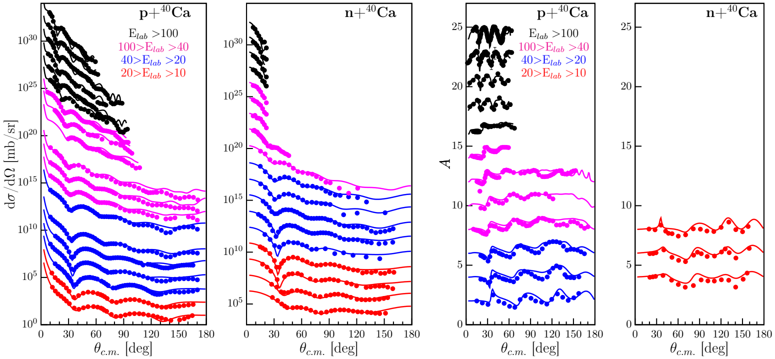

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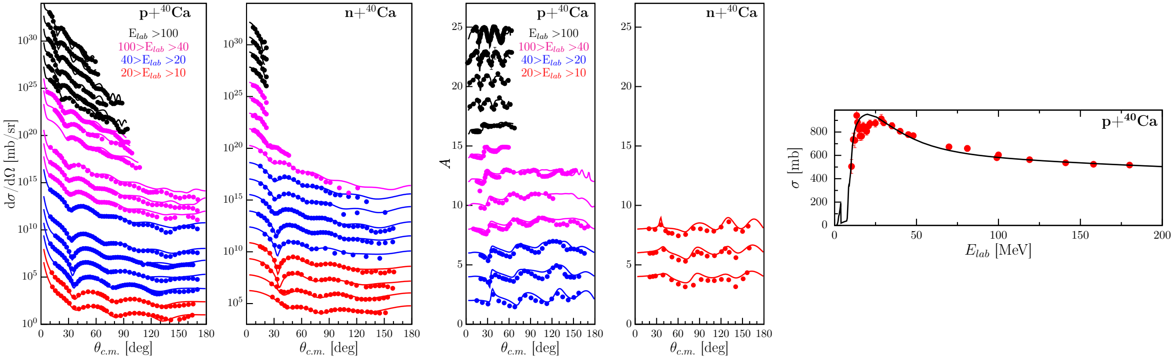

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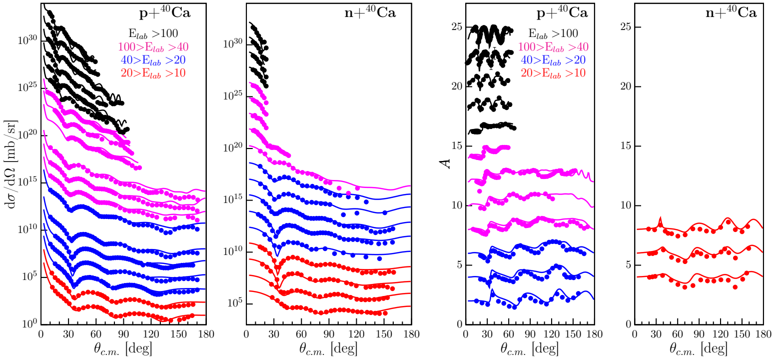
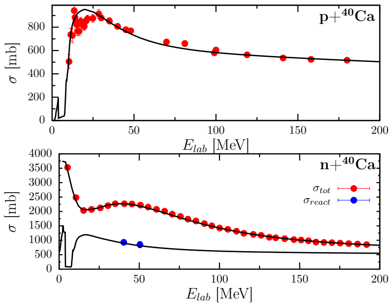
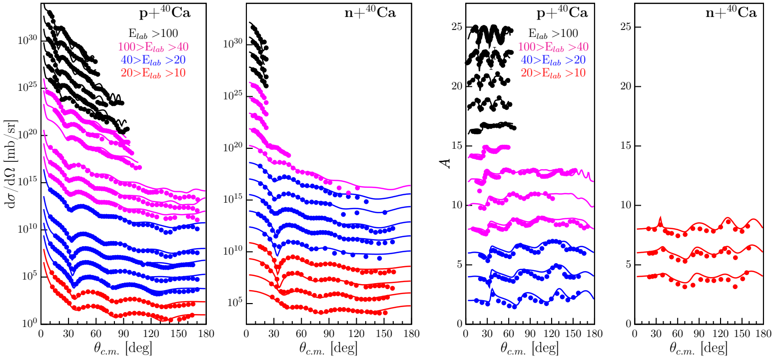


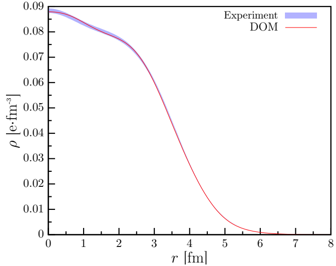


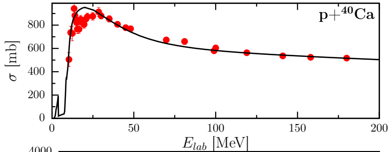
M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

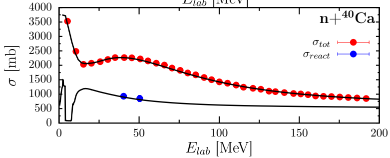
Fitting the self-energy (^{40}Ca)

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









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

Fitting the self-energy (^{48}Ca)

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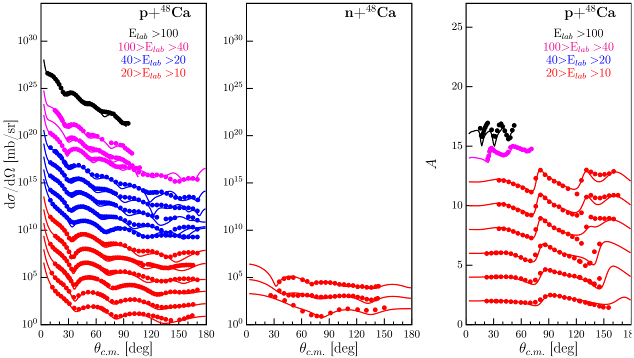

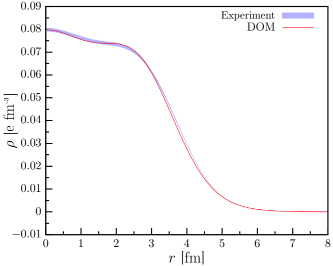

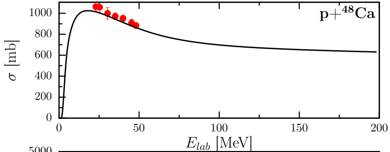

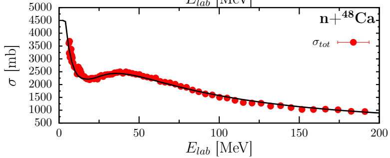

M.C. Atkinson and W.H. Dickhoff, Phys. Lett. B, **798**, 135027 (2019)

Fitting the self-energy (^{208}Pb)

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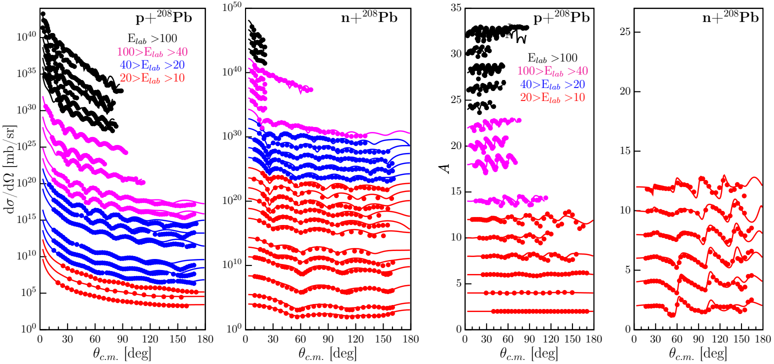
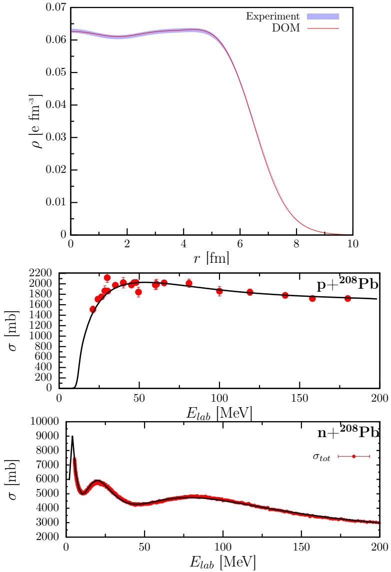
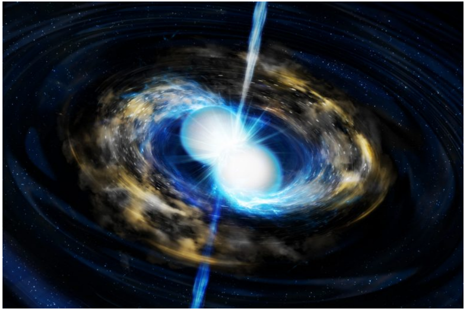




M.C. Atkinson *et al.*, PRC **101**, 044303 (2020)

Neutron skin: $R_{\text{skin}} = R_n - R_p$

- r_n can be measured through parity-violating electron scattering (weak)



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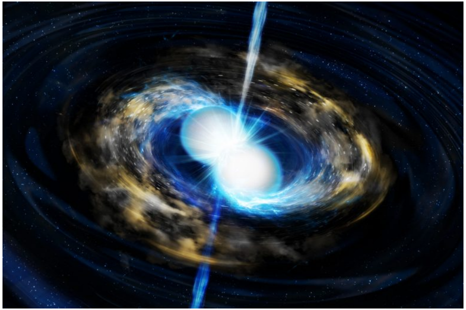

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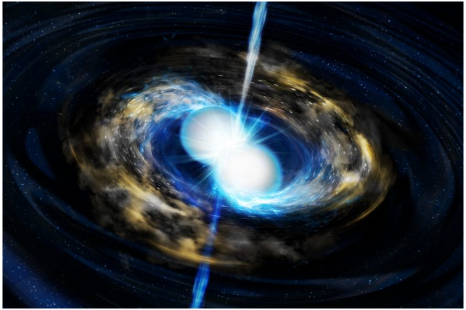

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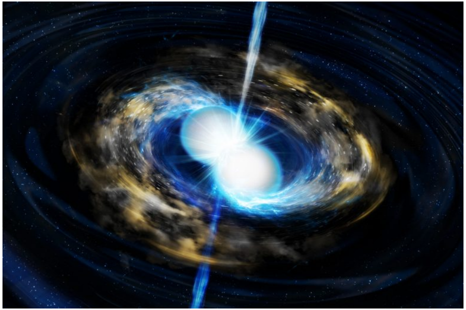
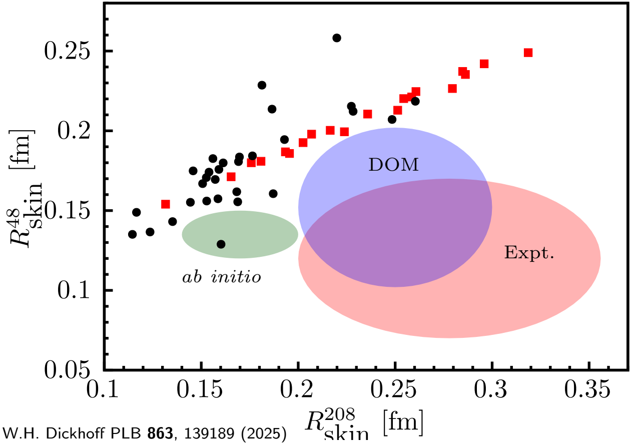
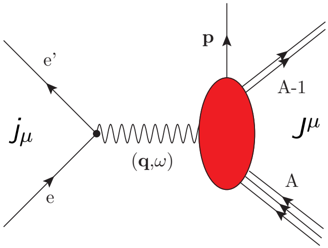
    - DOM can reproduce both skins!





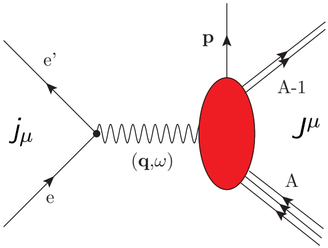
N.L Calleya, M.C. Atkinson, W.H. Dickhoff PLB **863**, 139189 (2025)

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



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

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



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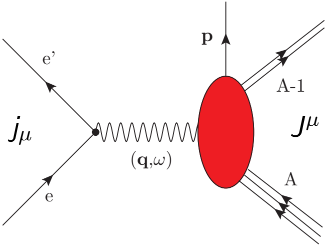
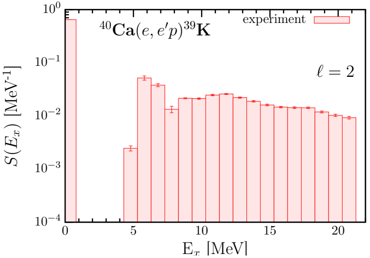
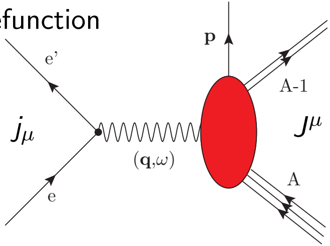


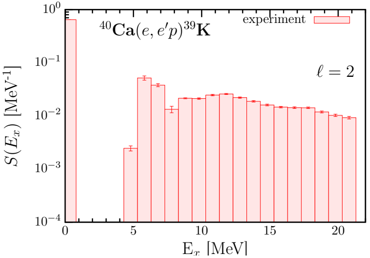


M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

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

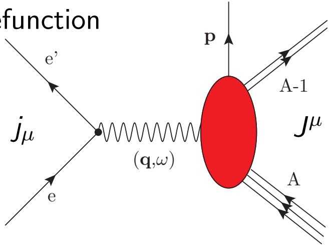


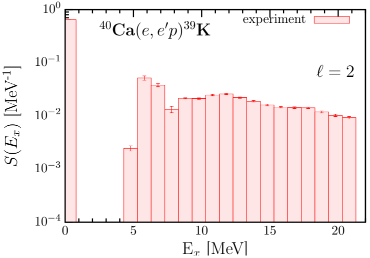


M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

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





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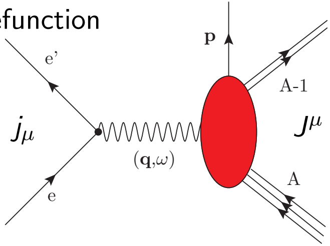
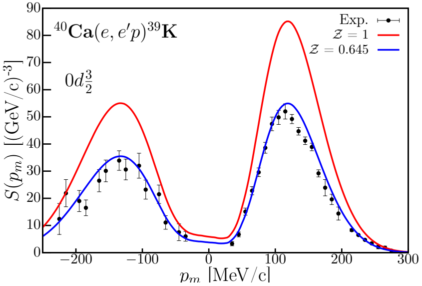
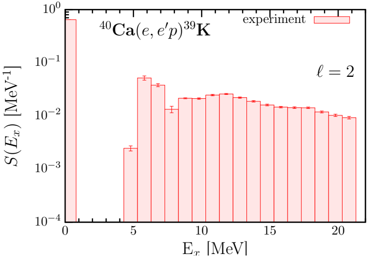


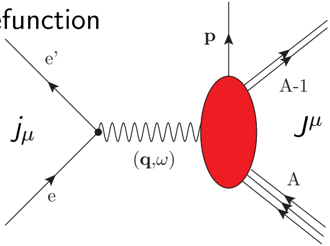


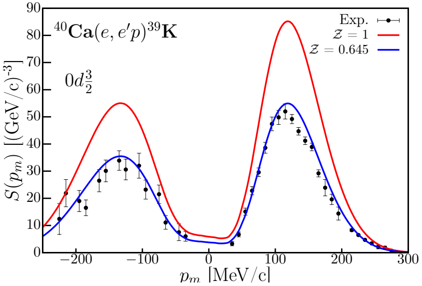


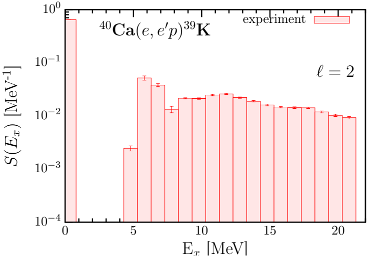
M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

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

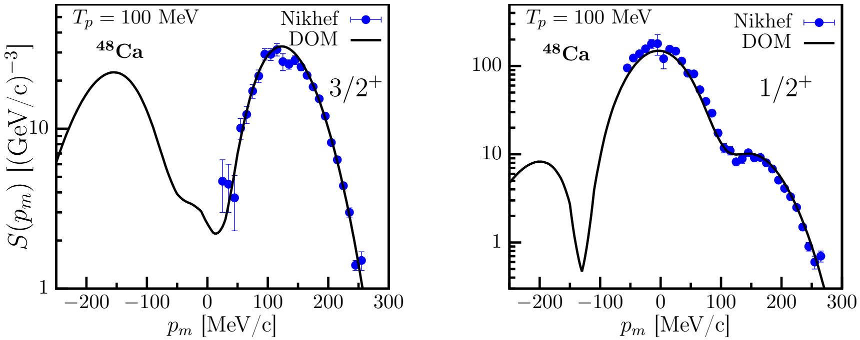






M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)

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



Data: G. J. Kramer *et. al*, Nucl. Phys. A, **679**, 267 (2001)

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

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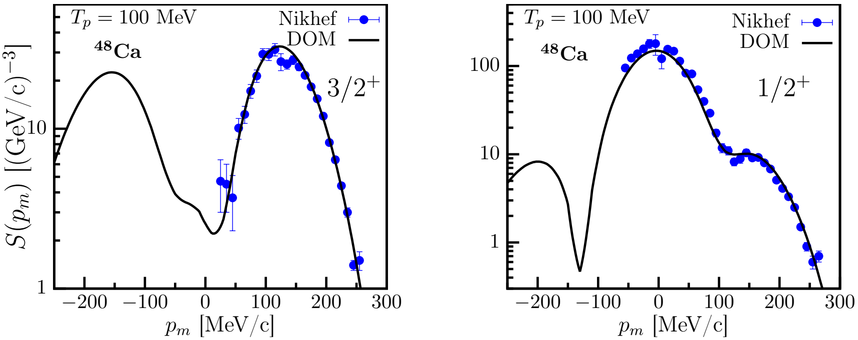
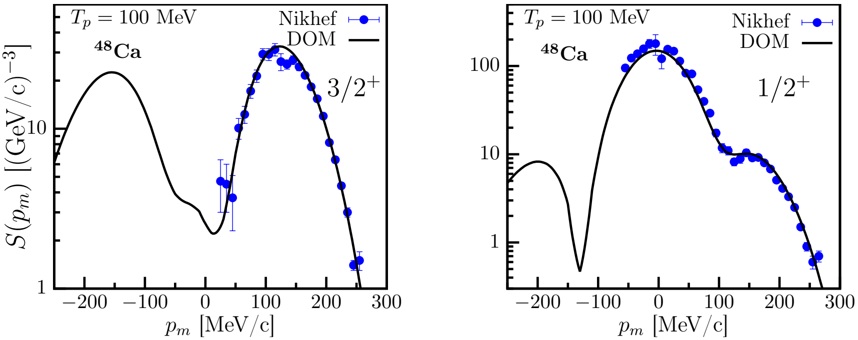


Data: G. J. Kramer *et. al*, Nucl. Phys. A, **679**, 267 (2001)

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

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

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



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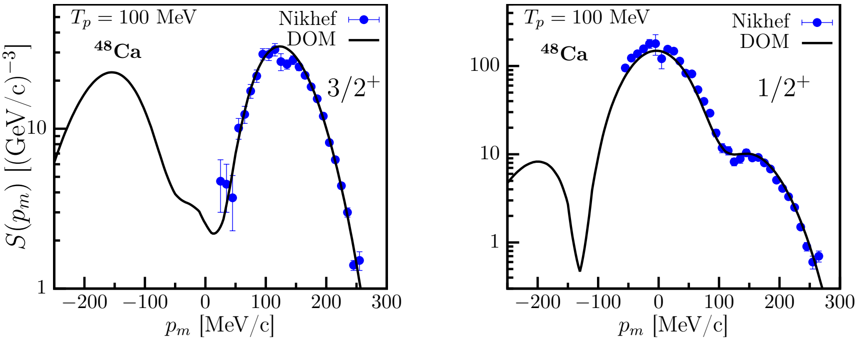

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Protons are more correlated in ^{48}Ca!

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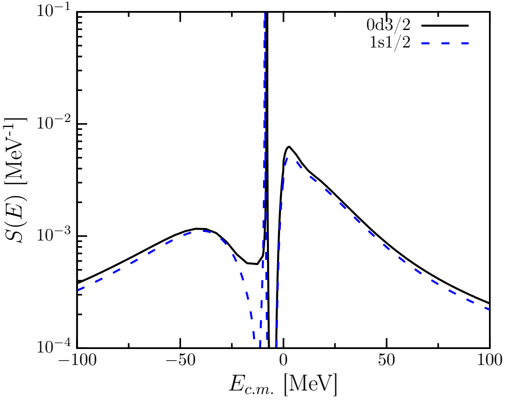
Constraints for S_F

- Dispersion distributes the energy dependence of Σ^*



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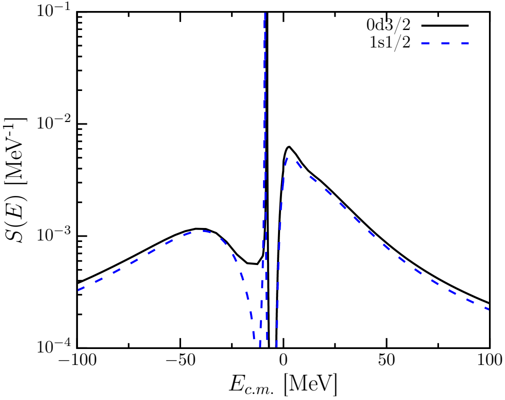

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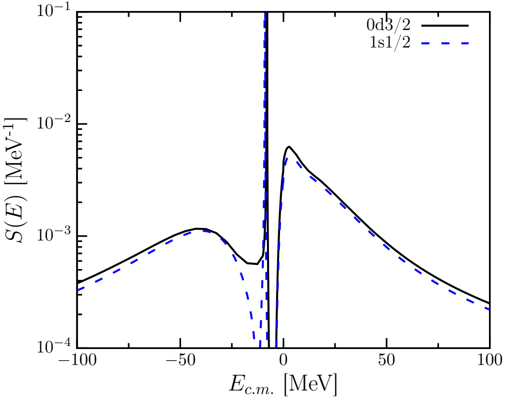

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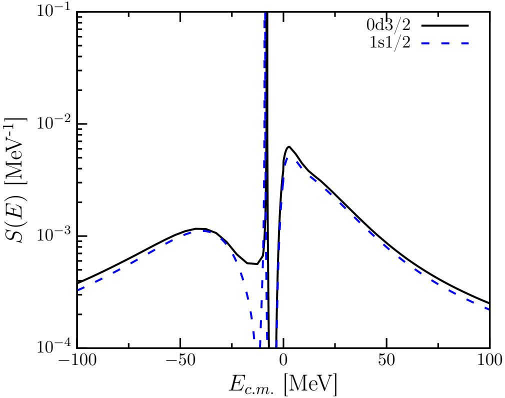

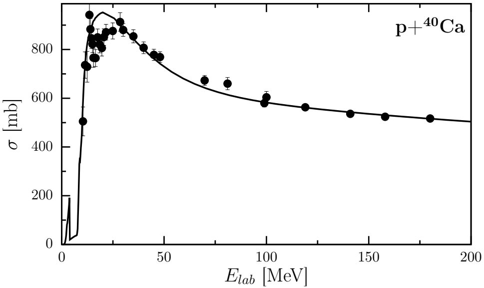

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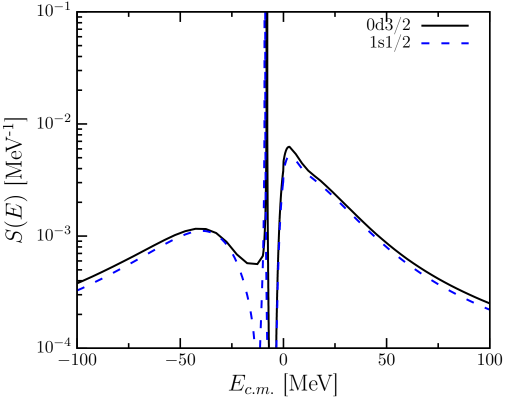

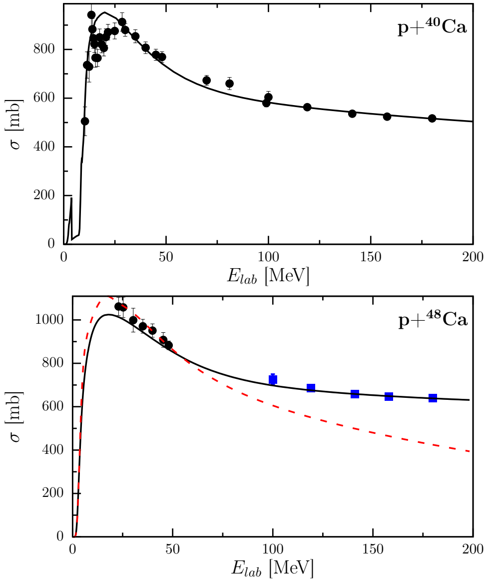

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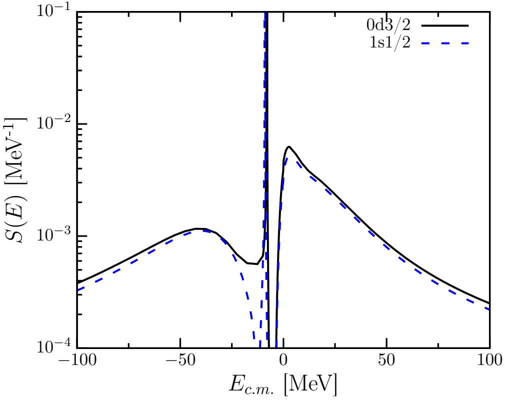
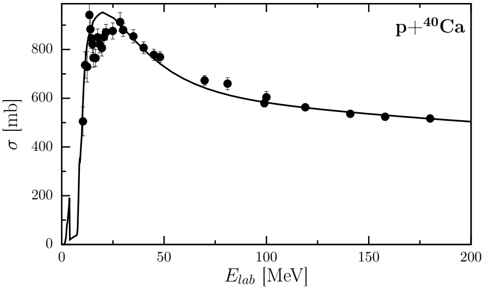
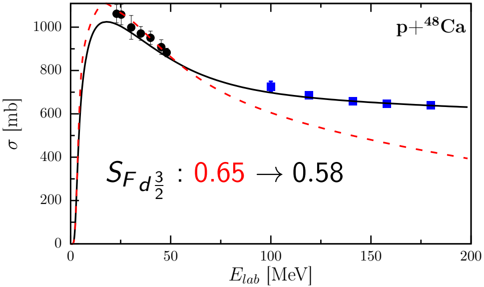
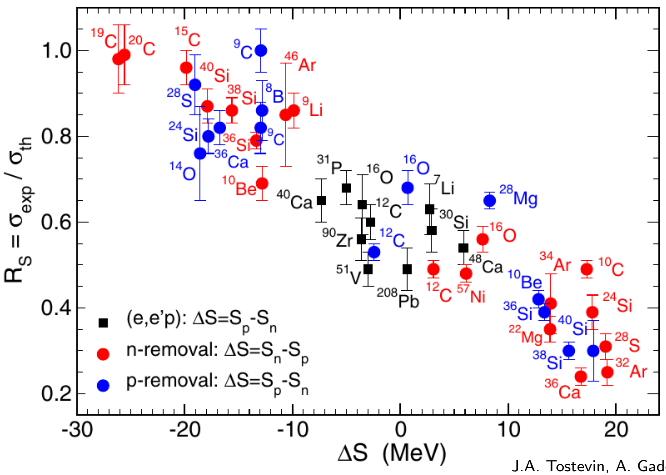






Quenching



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

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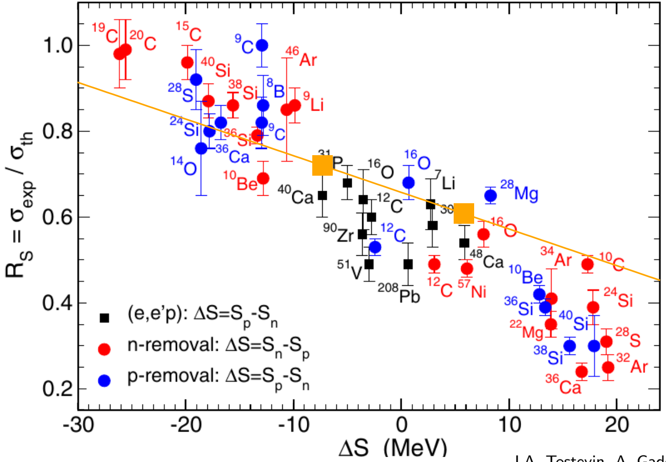

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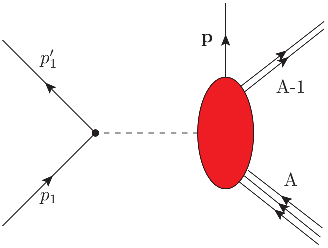
Now try calculating with a hadronic probe: ^{40}Ca$(p, 2p)^{39}$K



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

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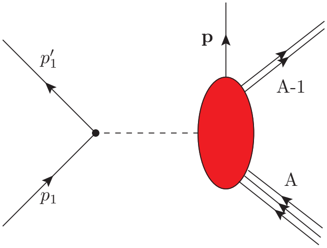
$$T \approx \int d\boldsymbol{R}\, t_{NN}\chi_1^{(-)*}(\boldsymbol{R})\chi_2^{(-)*}(\boldsymbol{R})\chi_0^{(+)}(\boldsymbol{R})e^{-i\alpha_R \boldsymbol{K}_0\cdot\boldsymbol{R}}\phi_{ljm}^{n}(\boldsymbol{R}).$$



- Same DOM ingredients used

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

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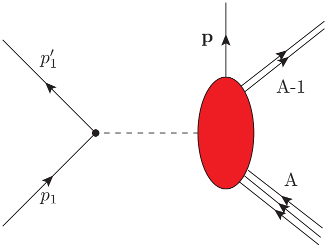

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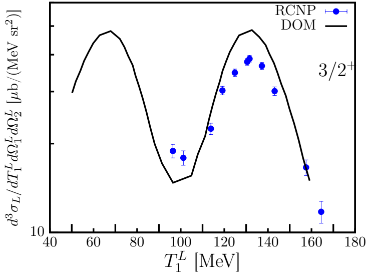

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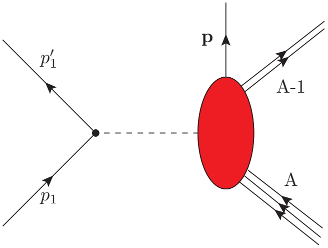

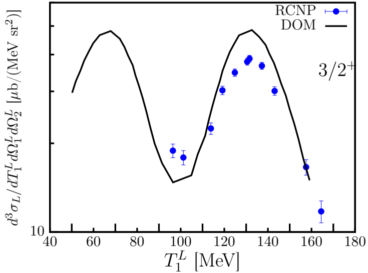

K. Yoshida, M.C. Atkinson, K. Ogata, W.H. Dickhoff PRC **105**, 014622 (2022)

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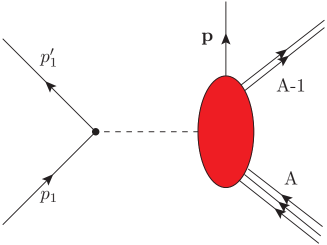

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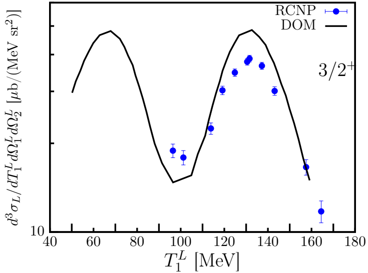
"S_F"	$(p,2p)$	$(e,e'p)$
DOM	0.560	0.71 ± 0.04

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

- Remember that S_F comes directly from Σ^*_{DOM}



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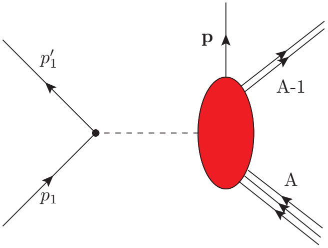

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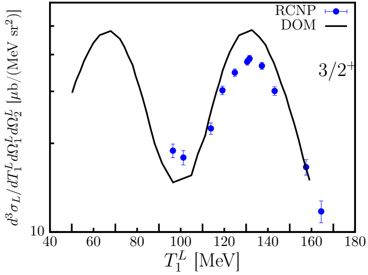

- Remember that S_F comes directly from Σ^*_{DOM}
- Main difference is the probe $\implies$ problem is likely V_{pp}

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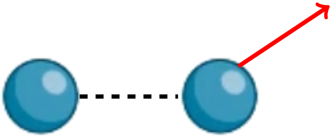
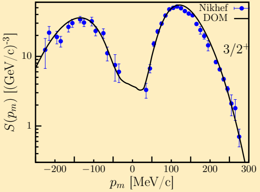
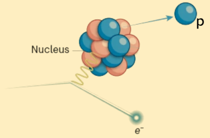
Free *NN* interaction is insufficient for knockokut

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

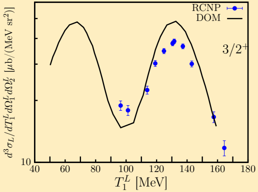


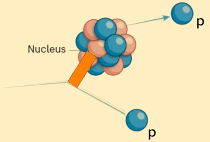
Electron probe: $^{40}\mathrm{Ca}(e, e'p)^{39}\mathrm{K}$





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





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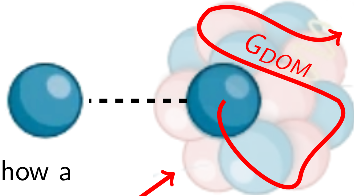
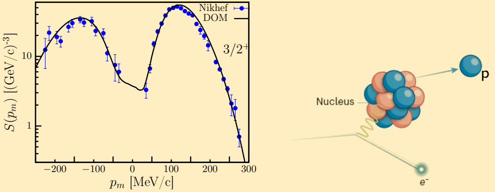


- Through Green's function formalism, the DOM can also describe how a proton propagates through the nucleus (propagator G_{DOM})

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



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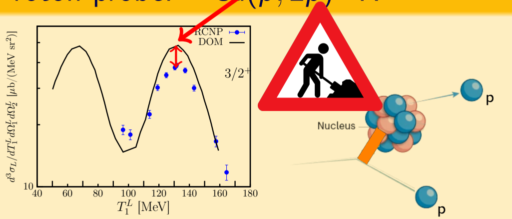
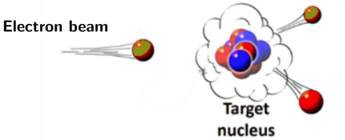


Why not just use $(e, e'p)$ for all single-knockout experiments?

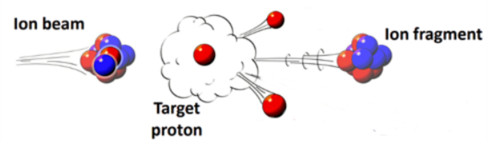
Proton knockout reactions

Experimental sketch for **stable** nuclei



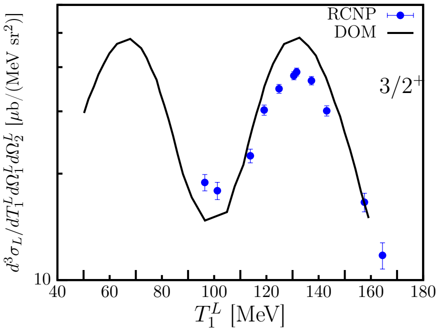
Reaction mechanism well-understood

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



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

- Try varying V_{NN} to see effect on S_F



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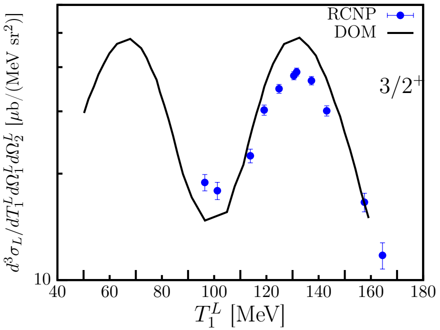

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DOM	FL	0.560 ± 0.05
DOM	Mel	0.489 ± 0.05
DOM	Mel (free)	0.515 ± 0.05

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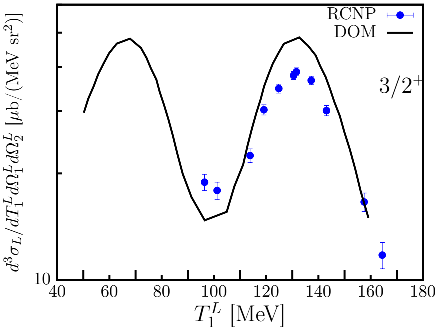

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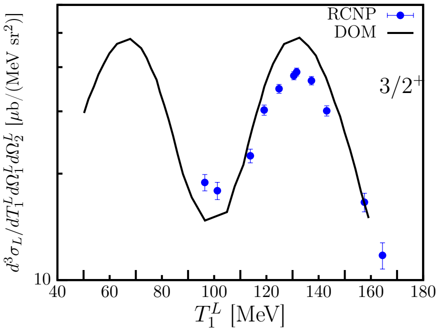

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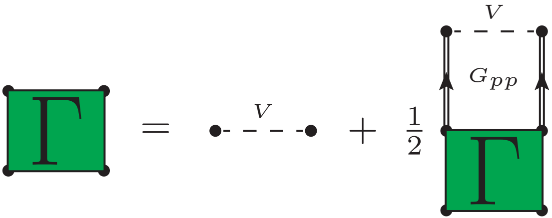

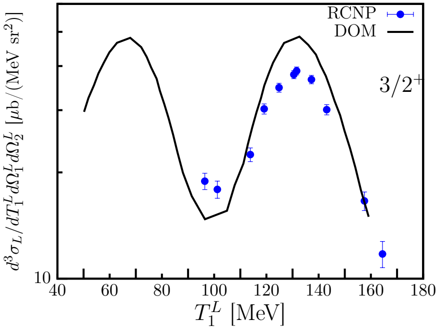

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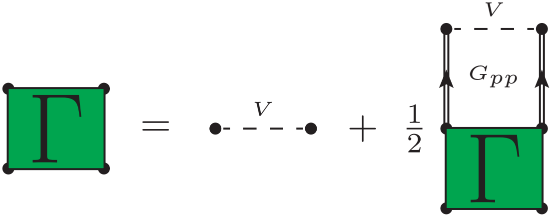
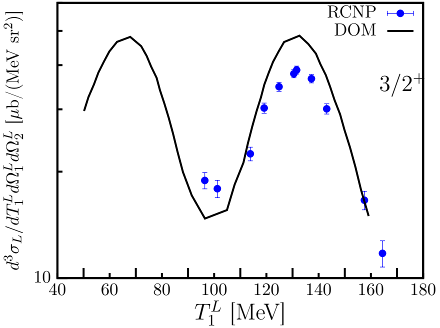


- $G_{pp} \approx \int G_{\mathrm{DOM}} \times G_{\mathrm{DOM}}$



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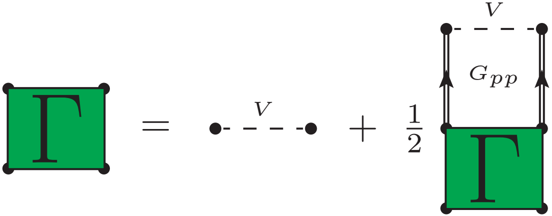
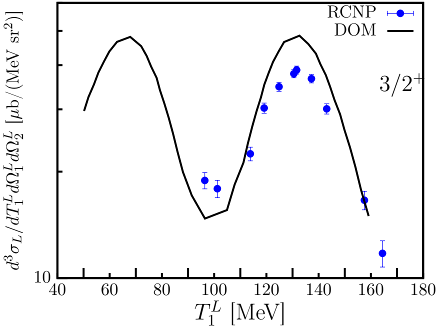


- $G_{pp} \approx \int G_{\mathrm{DOM}} \times G_{\mathrm{DOM}}$
- Similar to G-matrix, except this is calculated in finite nuclei



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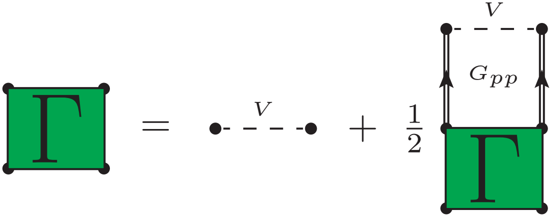
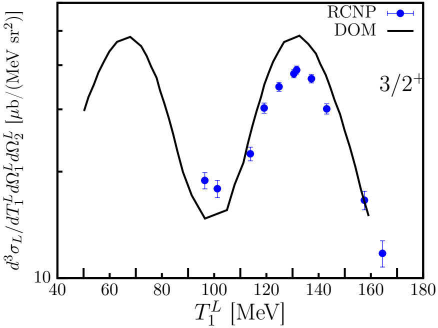
- Interactions need information about the nucleus





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

S_F	V_{NN}	$(p, 2p)$
DOM	FL	0.560 ± 0.05
DOM	MeI	0.489 ± 0.05
DOM	MeI (free)	0.515 ± 0.05

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

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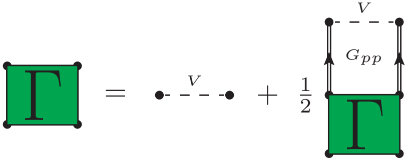

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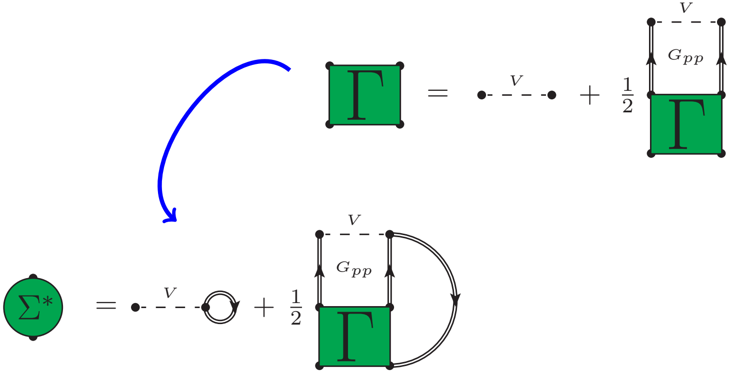

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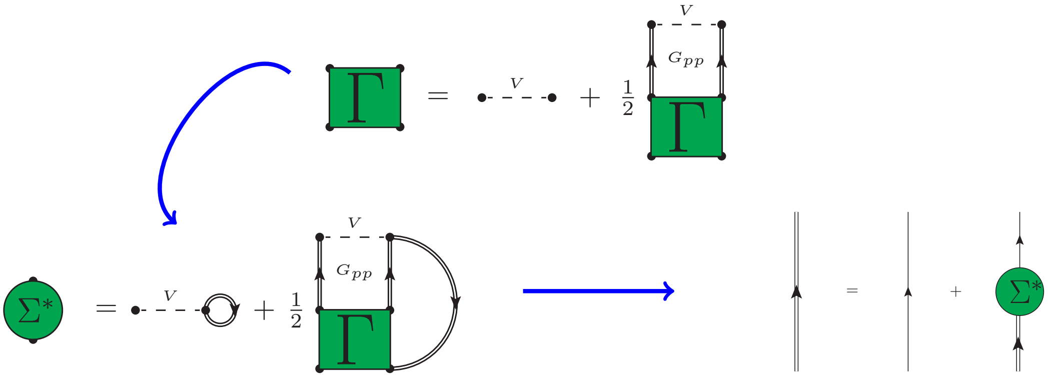

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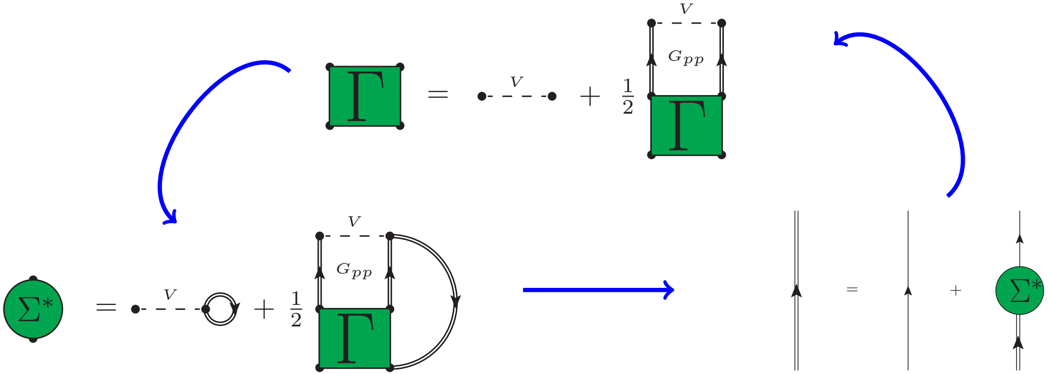
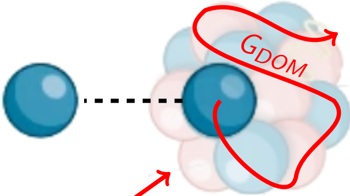
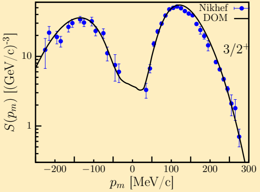


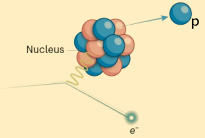
Summary

- The DOM provides consistent ingredients for knockout reactions
- The DOM provides a path toward improvement through the nucleus-informed NN interaction Γ_{NN}
- Combine this capability with a global DOM to extend the reach

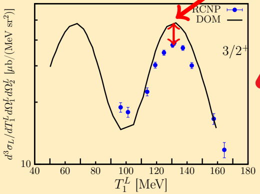


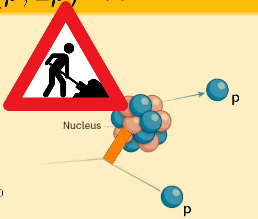
Electron probe: $^{40}\text{Ca}(e, e'p)^{39}\text{K}$





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





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