Nuclear structure-based optical potentials for the era of rare isotope beams

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Towards a consistent approach for nuclear structure and reactions: microscopic optical potentials
ECT*, Trento, Italy
19 June 2024

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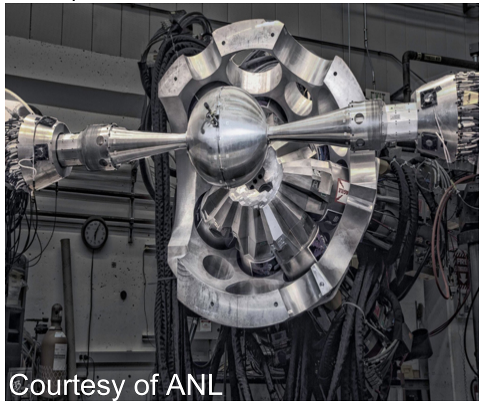
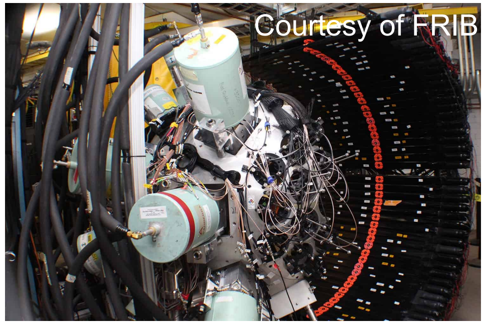
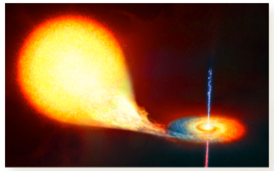
The era of rare isotope beams

Experiments at RIB facilities





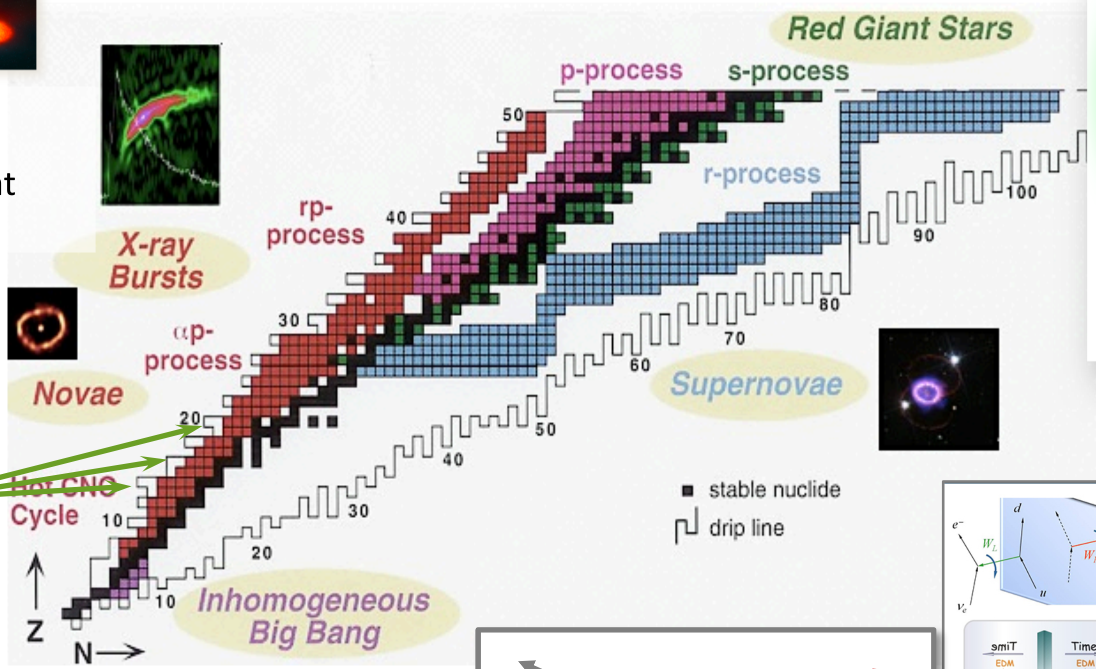


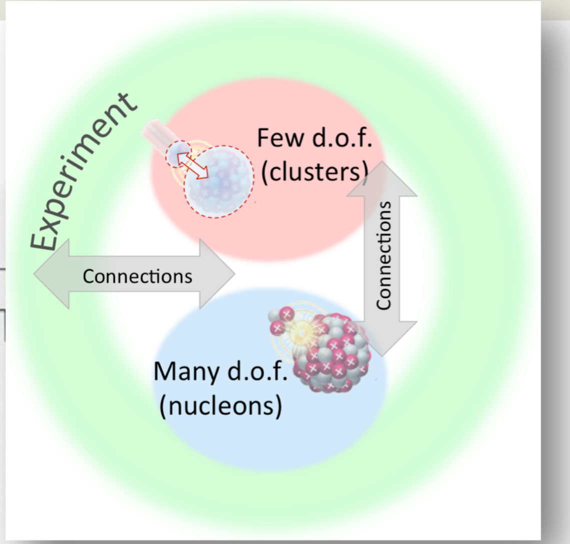
X-ray burst nucleosynthesis

Alpha widths

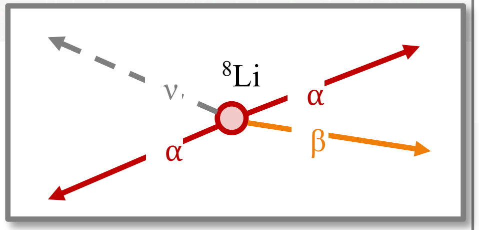
Reaction rates at low energies

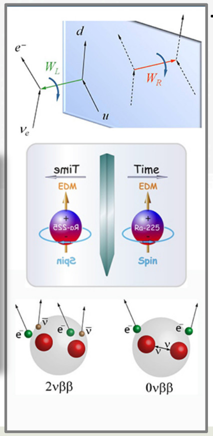
Close proximity of the drip lines





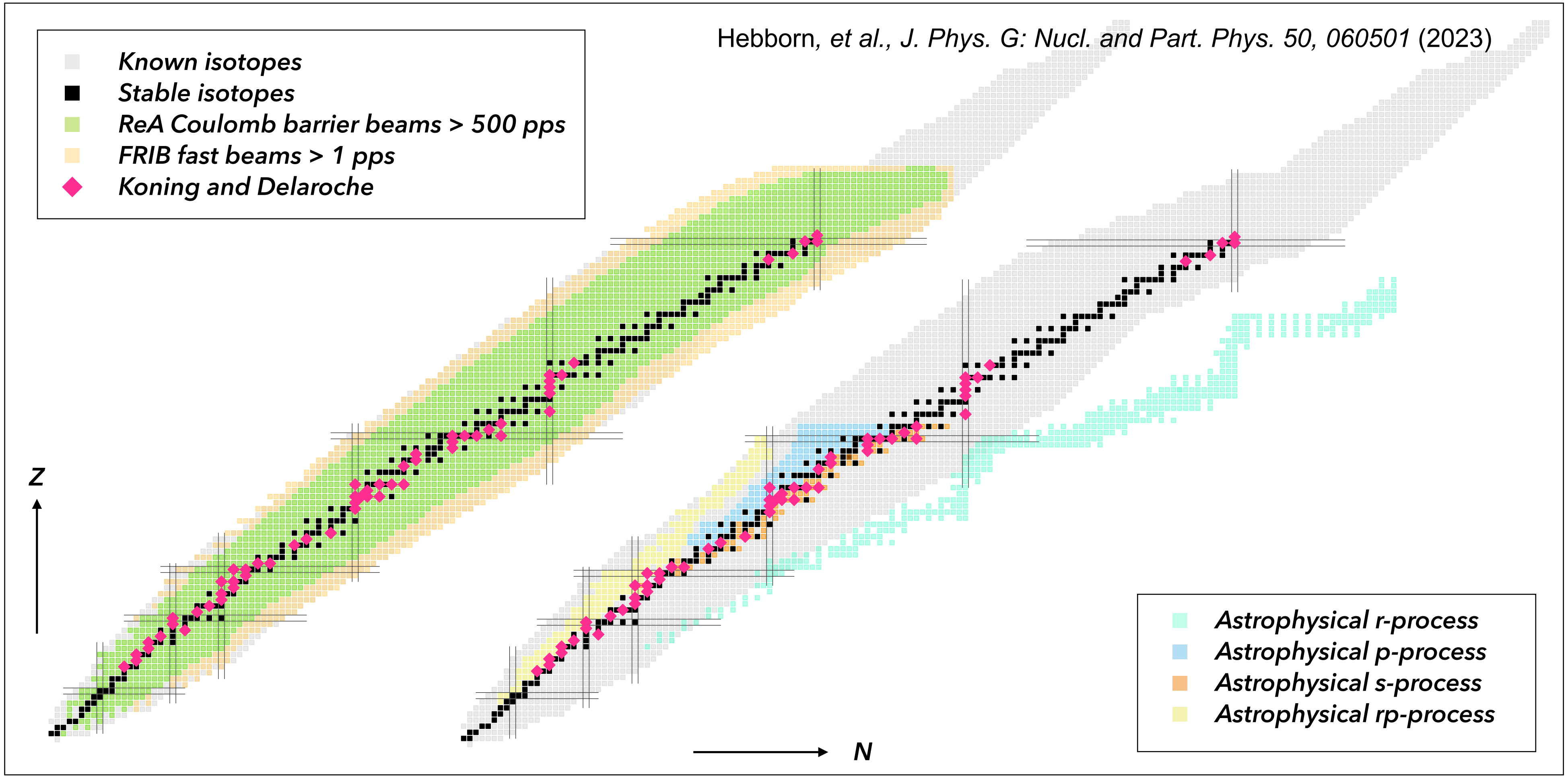
FRIB Theory Alliance topical program (2018) “From bound states to the continuum“ (C. Johnson et al.)

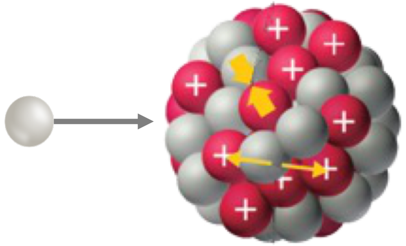




Fundamental symmetries

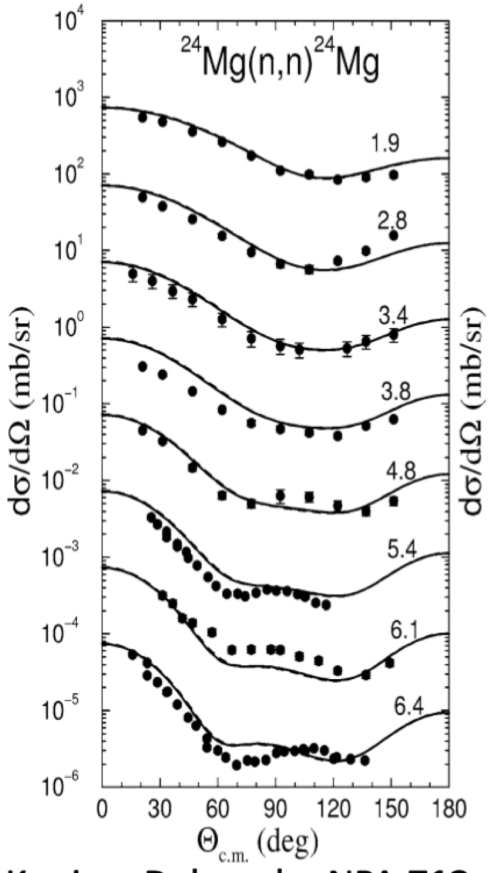
Our current knowledge of optical potentials (OP) is very limited





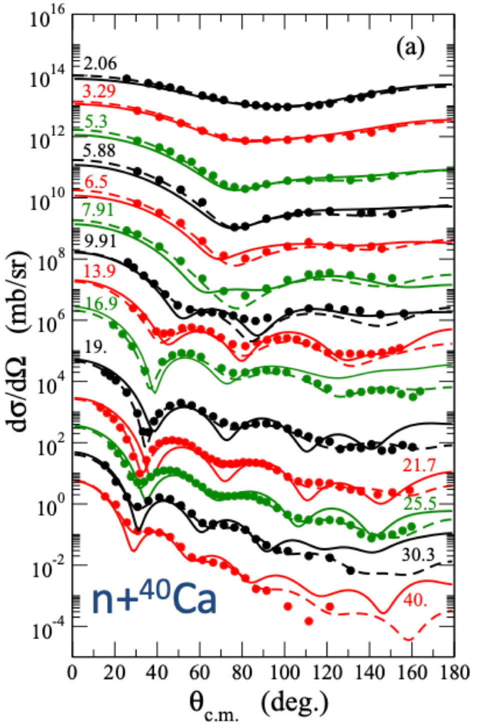
Different strategies for calculating the nucleon-nucleus optical potential (OP)

phenomenological fit



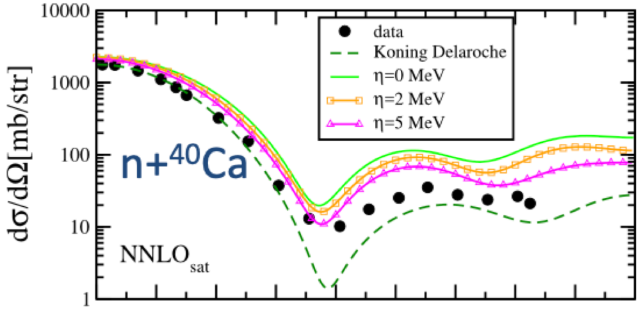
Koning, Delaroche NPA **713** (2003) 231

RPA calculation with added imaginary part



Blanchon *et al*. PRC **91** 014612 (2015)

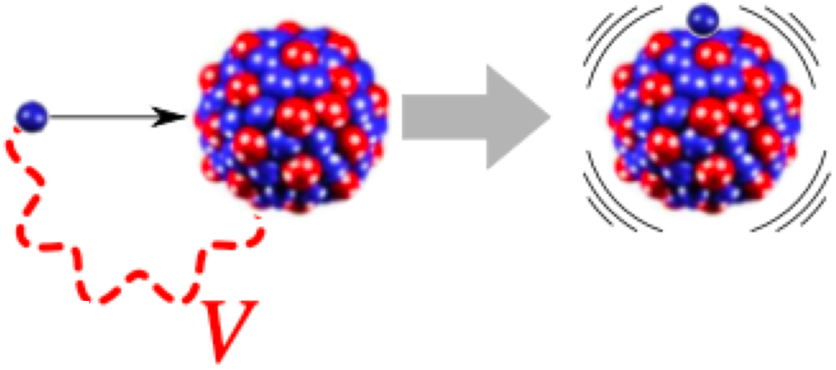
coupled-cluster ab initio with non-zero η parameter



Rotureau *et al*. PRC **98** 044625 (2018)

- Phenomenological fits are widely used, but are disconnected from the structure, and extrapolation away from stability is risky
- Microscopic theories often struggle to get absorption right
- Ab initio approaches are mainly feasible for light or near closed-shell nuclei

Embedding nuclear structure information within OP



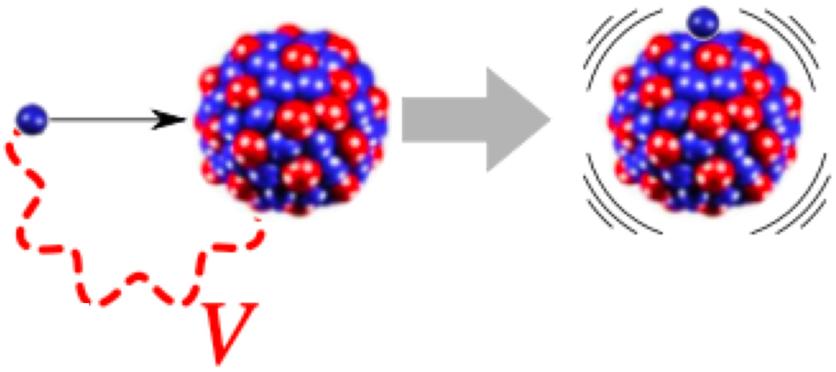
Feshbach formalism

$$V(\mathbf{r},\mathbf{r}',E) = U_0(\mathbf{r}) + V_{PO}(\mathbf{r},\mathbf{r}',E-E_i)$$
$$= U_0(\mathbf{r}) + \sum_i U_{0i}(\mathbf{r})G_i(\mathbf{r},\mathbf{r}',E-E_i)U_{0i}(\mathbf{r}')$$

Static, energy-independent potential

Polarization potential: Requires input from nuclear structure

Embedding nuclear structure information within OP



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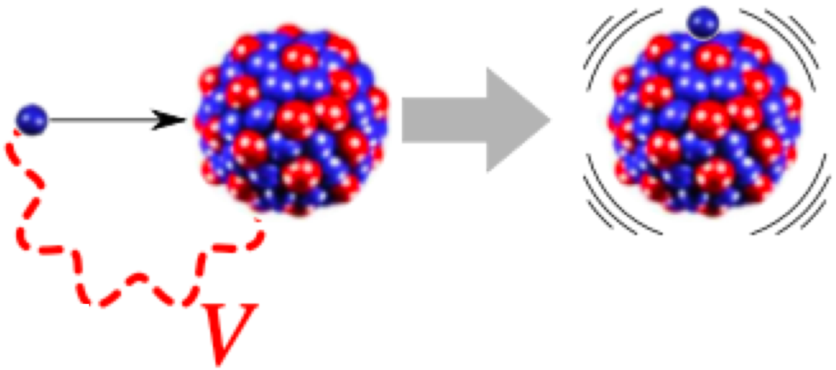
Static, energy-independent potential

Polarization potential: Requires input from nuclear structure

Can be applied to any mass range as long as nuclear structure calculations are available

Embedding nuclear structure information within OP



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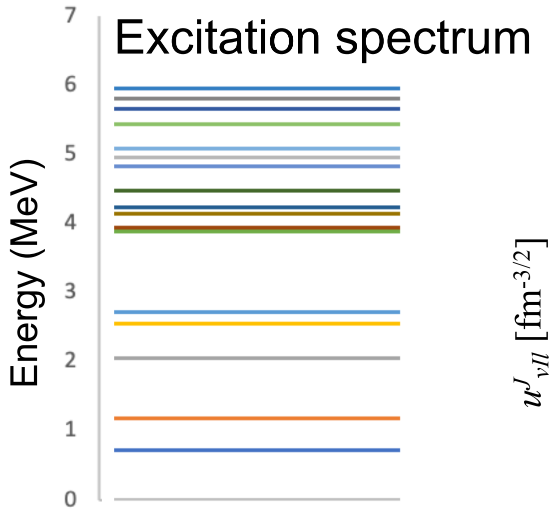
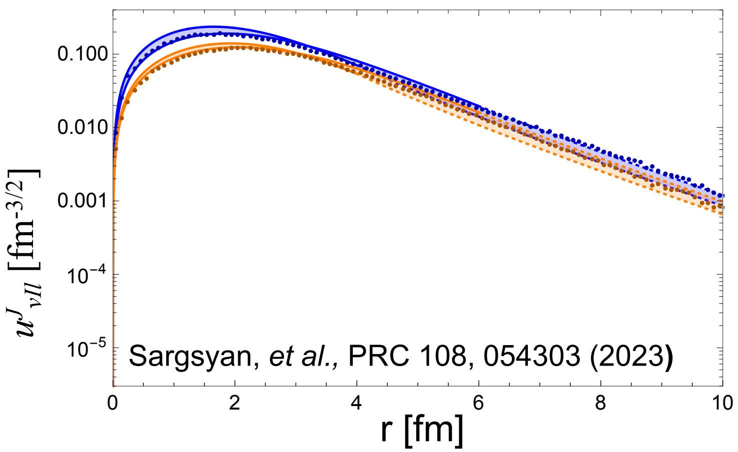
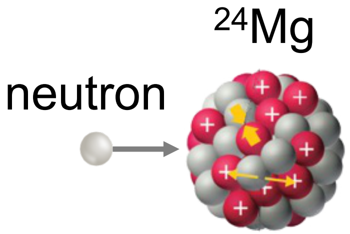
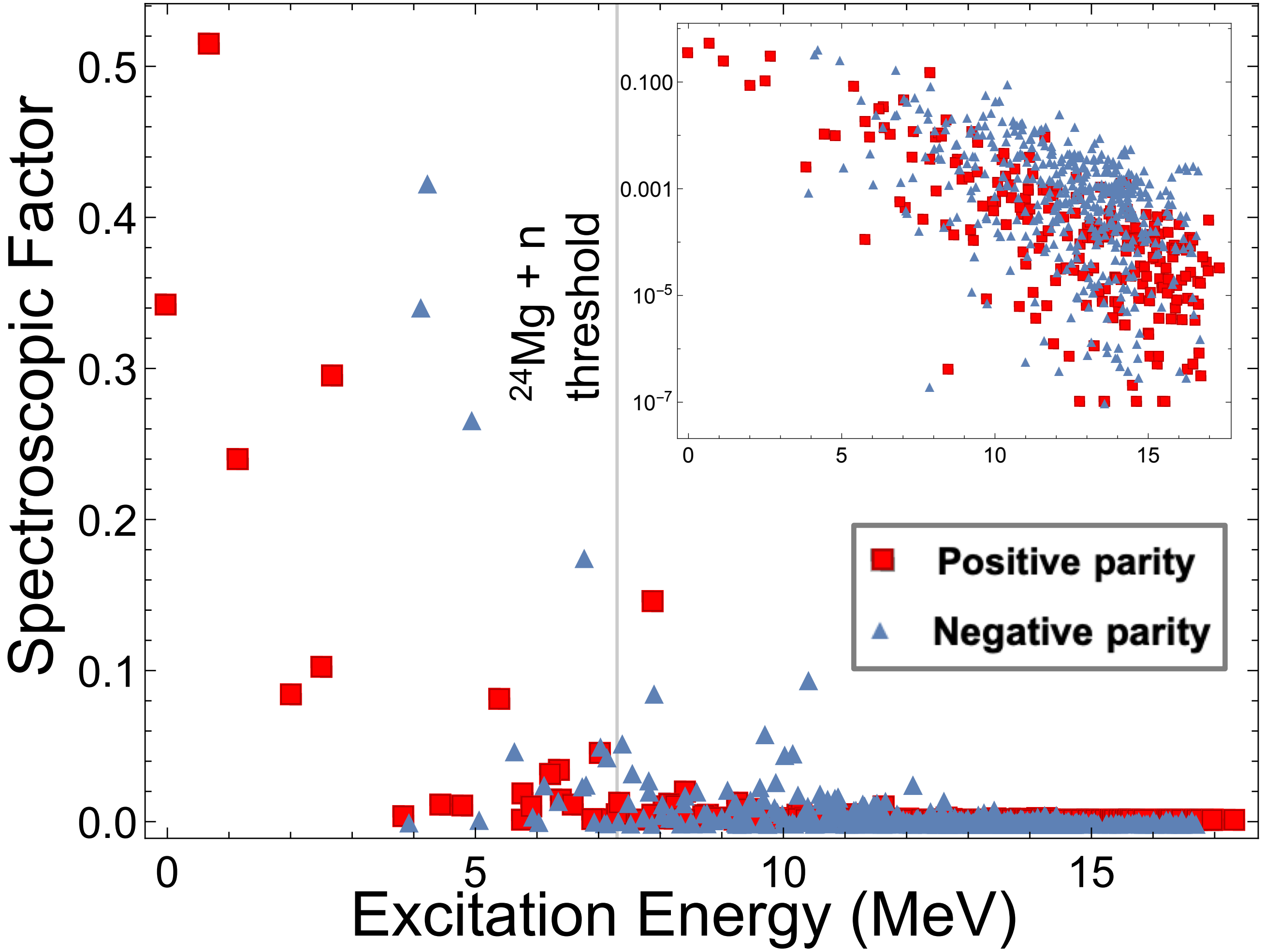




e.g., **shell model, RPA, ab initio models, ...**

1st ingredient for constructing OP: shell model input



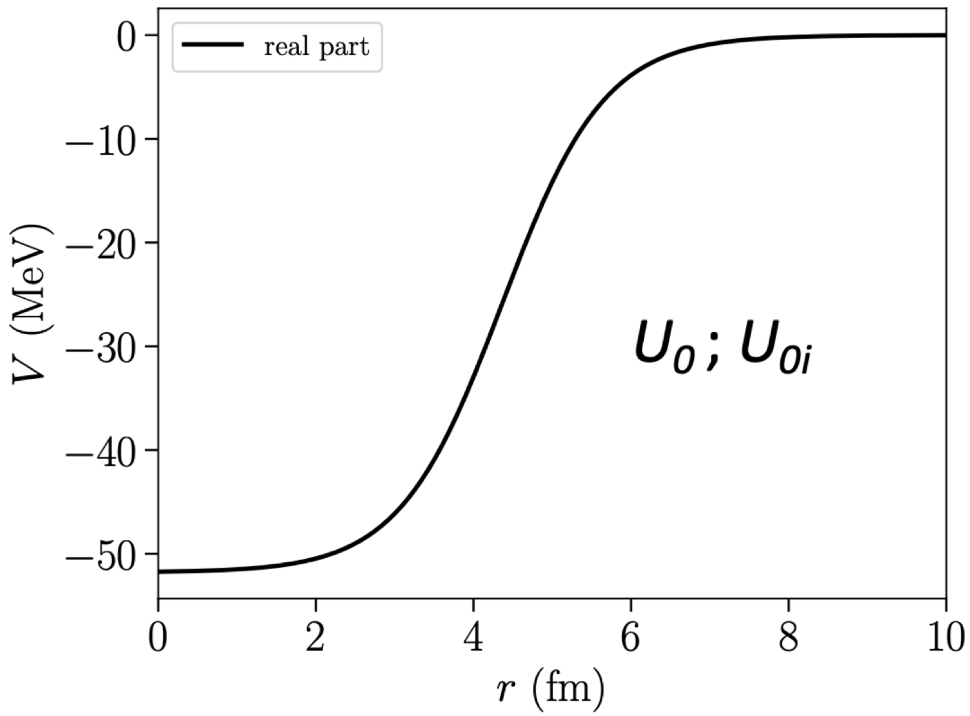


Around 600 intrinsic states

Shell model calculations with PSDPF potential M Bouhelal, *et al.*, Nucl. Phys. A 864 (2011)

2^{nd} ingredient: static potential and couplings

$$V(\boldsymbol{r},\boldsymbol{r}',E) = U_0(\boldsymbol{r}) + \sum_i U_{0i}(\boldsymbol{r}) G_i(\boldsymbol{r},\boldsymbol{r}',E - E_i) U_{0i}(\boldsymbol{r}')$$



- static potential U_0 : real, local Woods-Saxon adjusted to reproduce binding energy of ^{25}Mg
- couplings U_{0i}: same real Woods-Saxon, but adjusted to each E_i and multiplied by spectroscopic factor Si from shell model

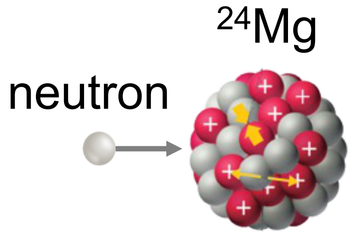
3rd ingredient: iterative scheme for self consistent OP

$$V(\mathbf{r},\mathbf{r}',E) = U_0(\mathbf{r}) + \sum_i U_{0i}(\mathbf{r})G_i(\mathbf{r},\mathbf{r}',E-E_i)U_{0i}(\mathbf{r}')$$

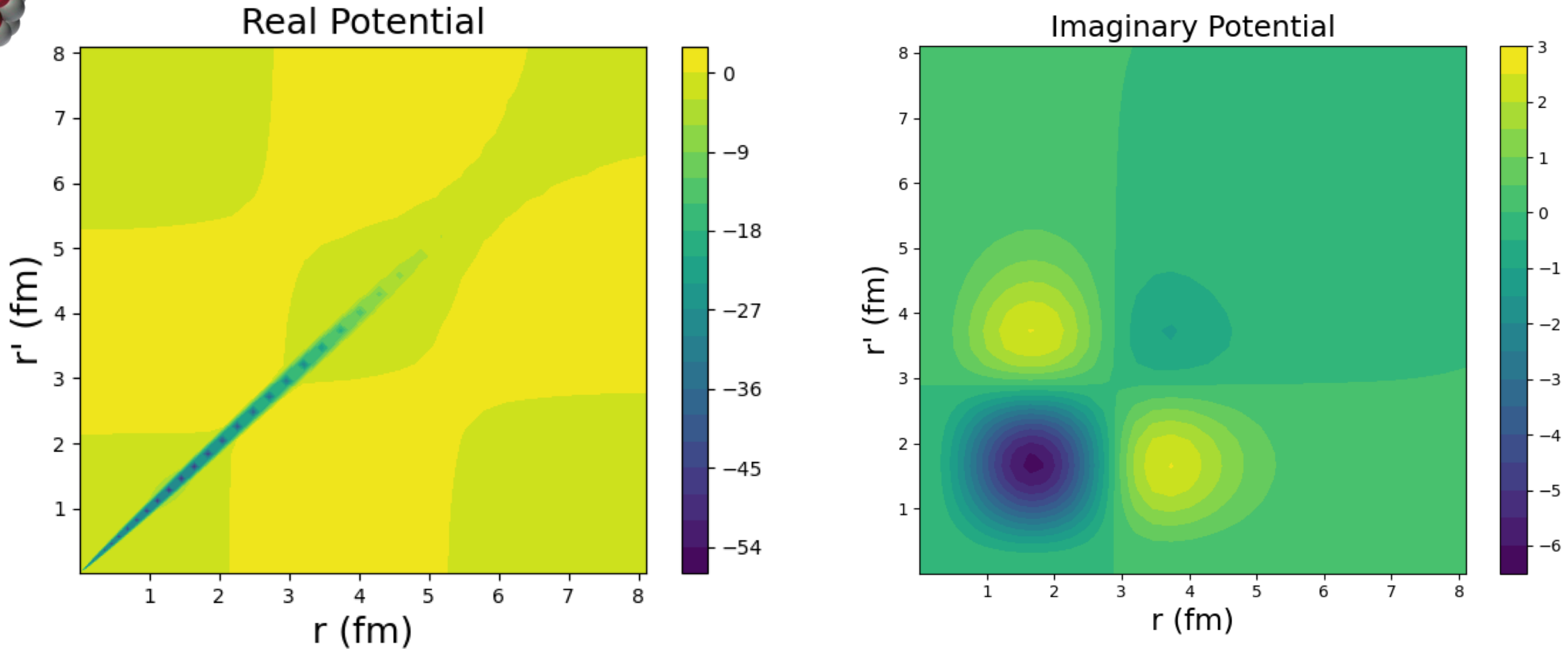
$$G(\mathbf{r},\mathbf{r}',E) = [E - T - V(r,r',E)]^{-1}$$

- Start with U_0 and obtain $V^{(1)}$
- Plug back in $V^{(1)}$ and obtain $V^{(2)}$
- Repeat until the volume integral converges $J^{(n)} = \int \mathcal{V}^{(n)}(\mathbf{r},\mathbf{r}')\,d\mathbf{r}\,d\mathbf{r}'$,

OP is complex, energy-dependent, dispersive, and non-local



3.4 MeV projectile energy



Facility for Rare Isotope Beams
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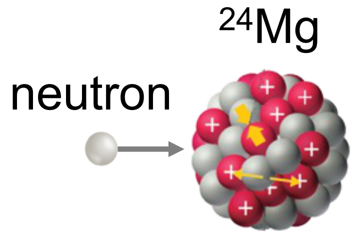
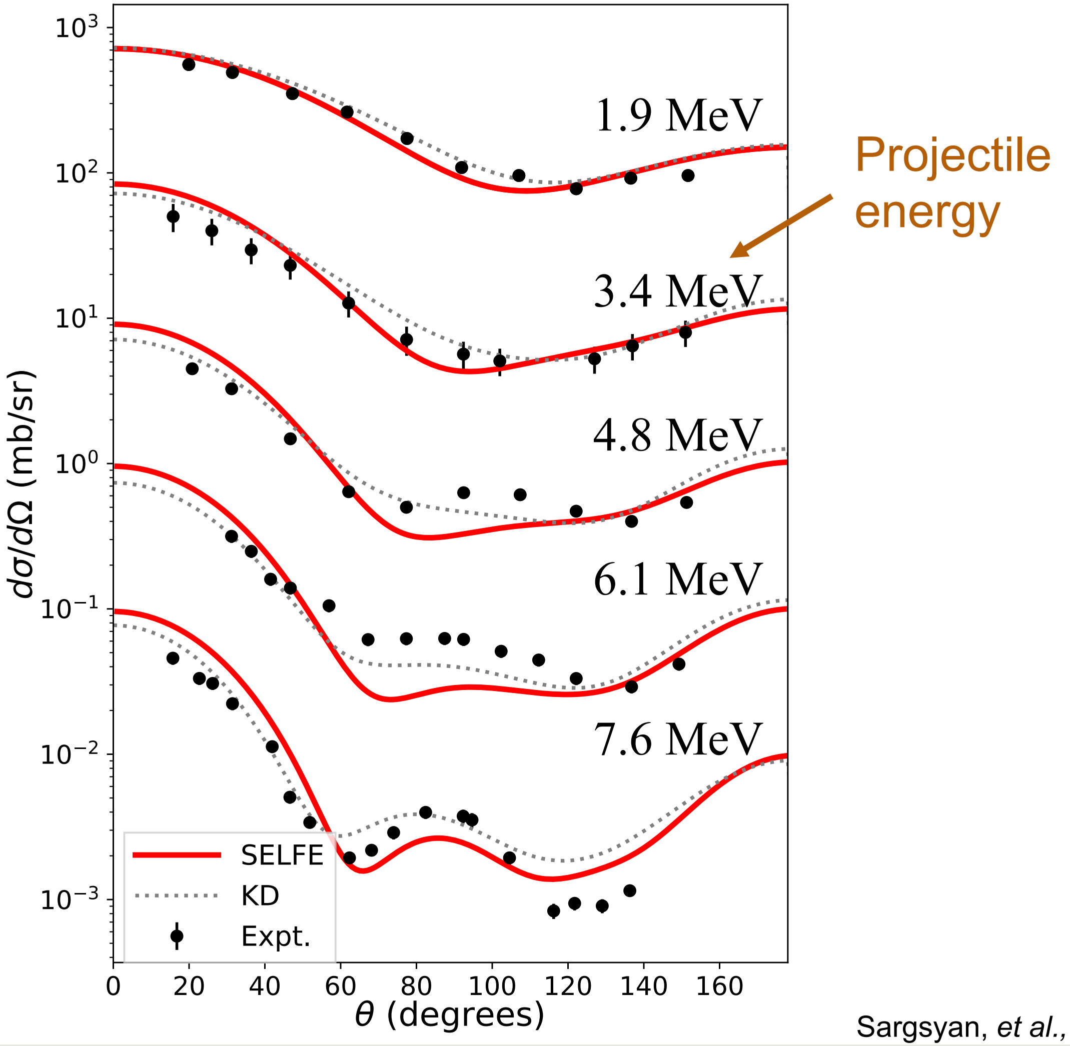
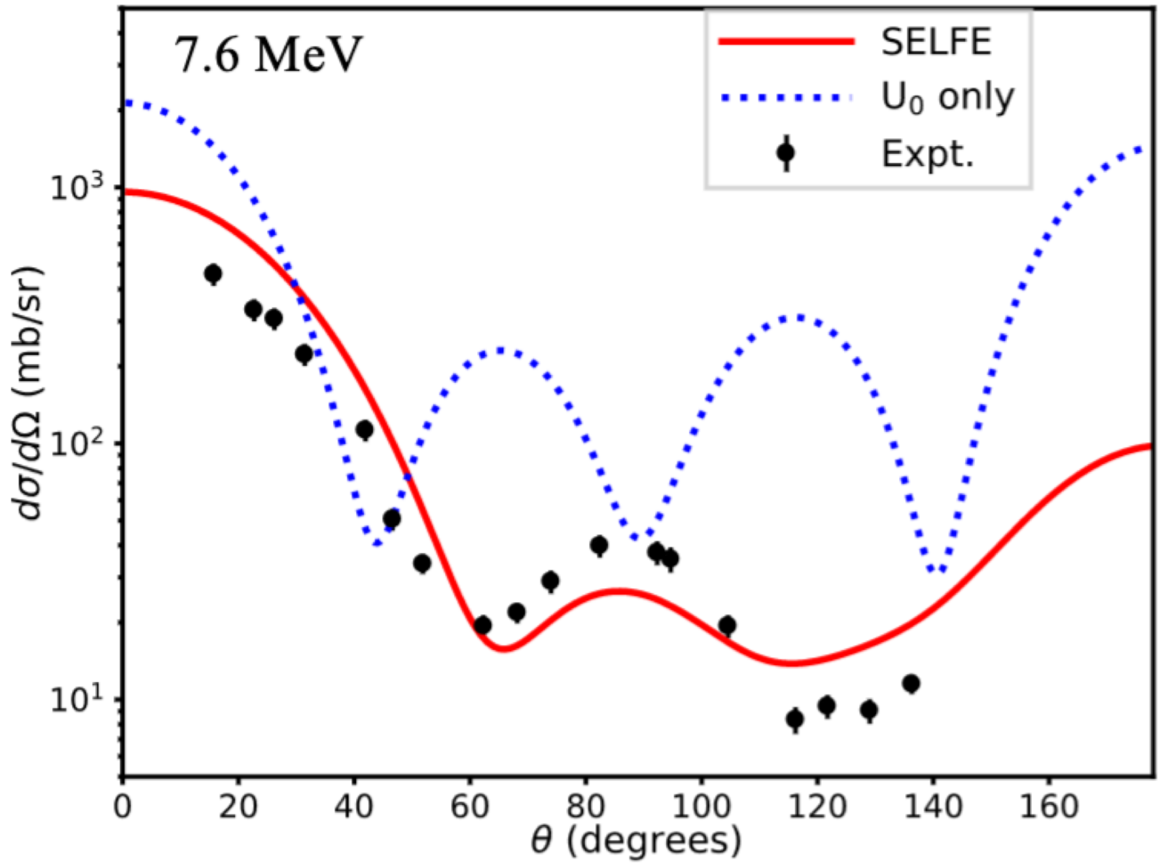
Accurate prediction without parameters fitted to experimental scattering data!





Sargsyan, *et al.*, in preparation

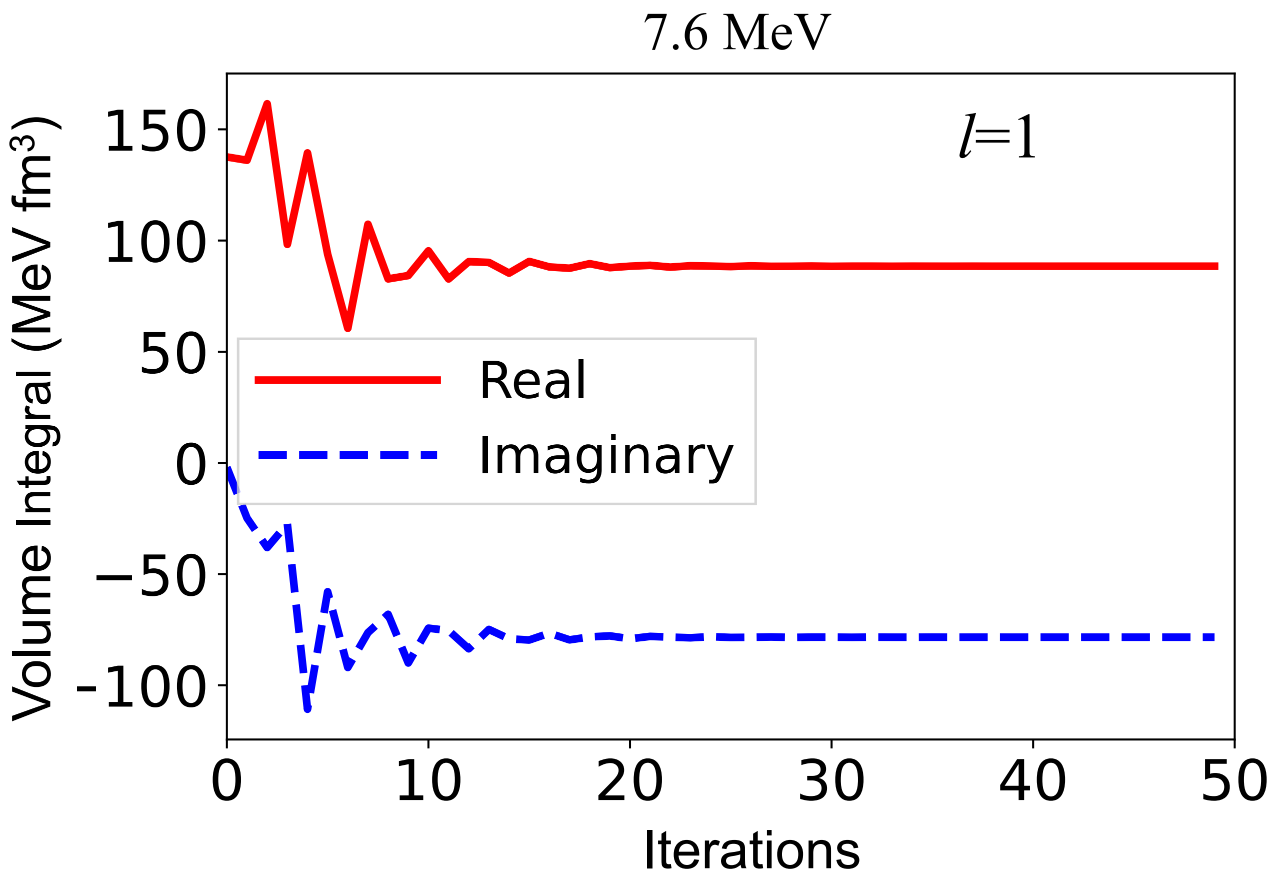
No phenomenological imaginary terms



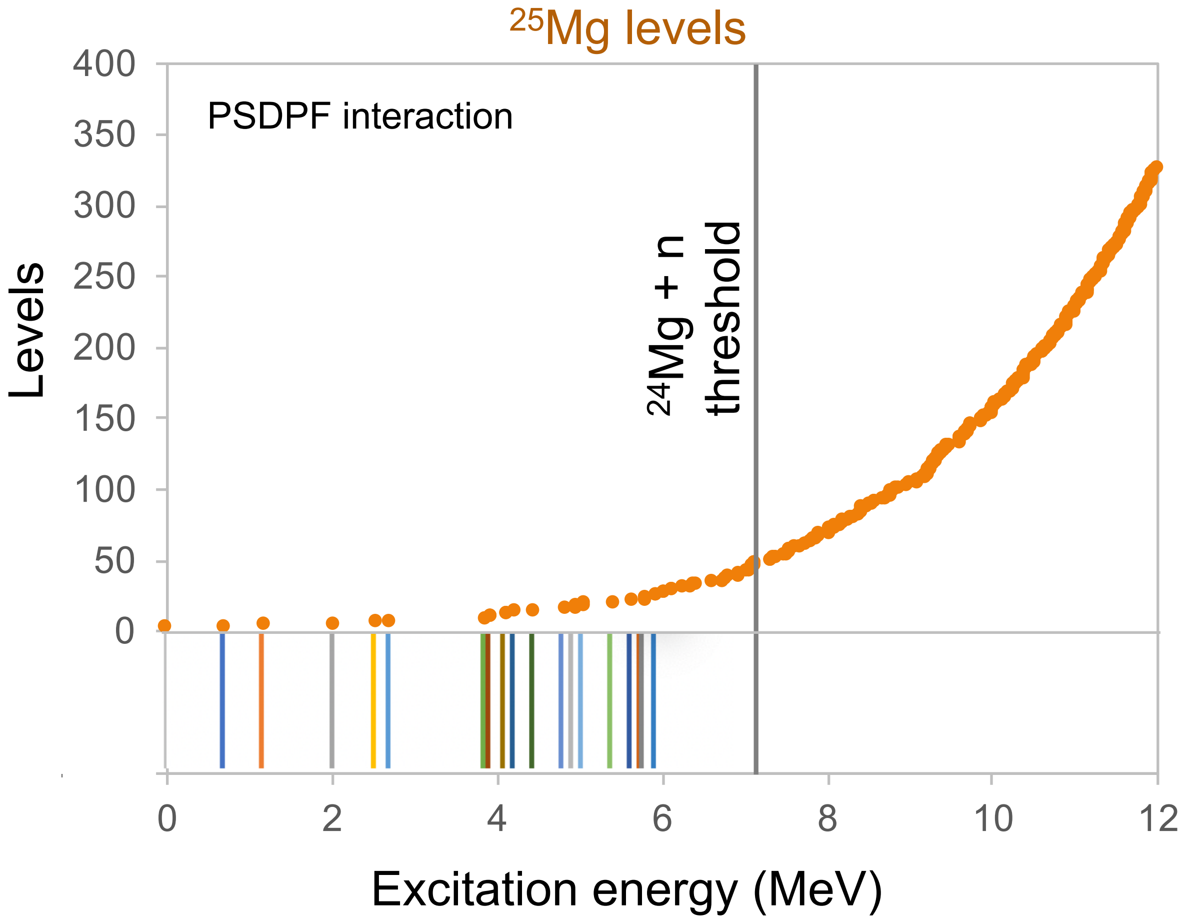
$$V(\mathbf{r},\mathbf{r}',E) = U_0(\mathbf{r},E) + V_{PO}(\mathbf{r},\mathbf{r}',E) = U_0(\mathbf{r},E) + \sum_i U_{0i}(\mathbf{r})G_i(\mathbf{r},\mathbf{r}',E)U_{0i}(\mathbf{r}')$$

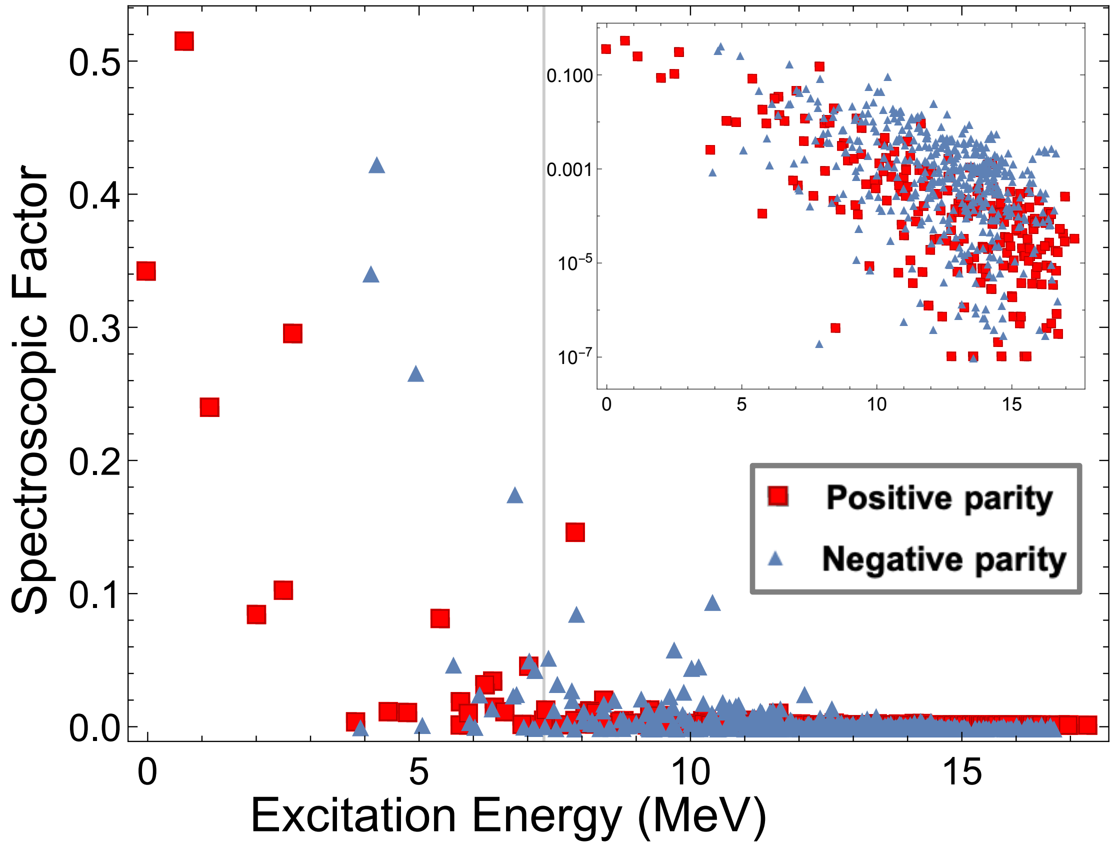
Potential volume integral convergence

$$J^{(n)} = \int \mathcal{V}^{(n)}(\mathbf{r}, \mathbf{r}')\, d\mathbf{r}\, d\mathbf{r}',$$

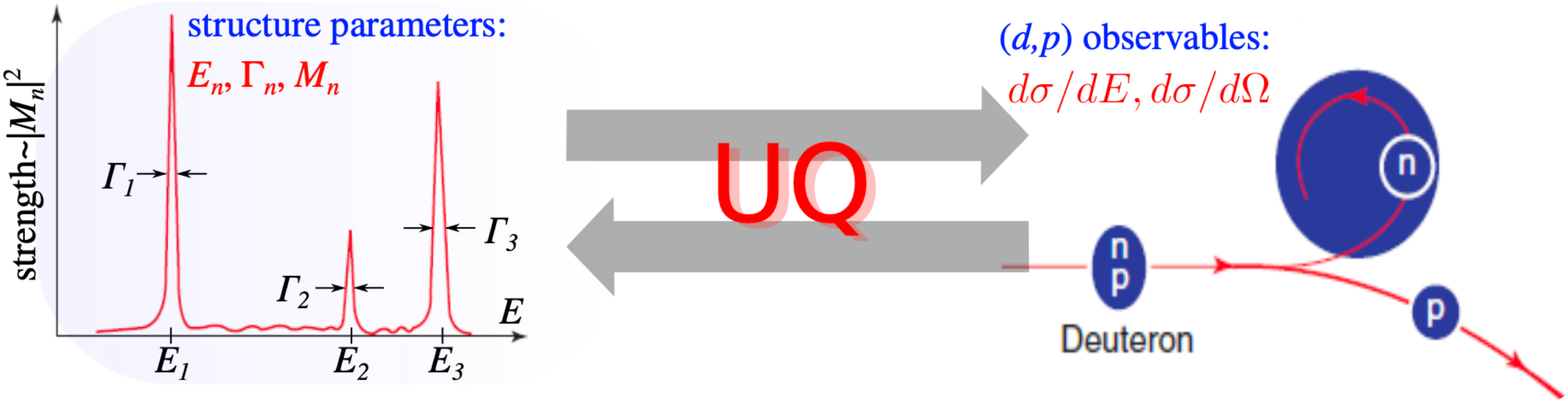


Ingredients for constructing neutron+^{24}Mg OP





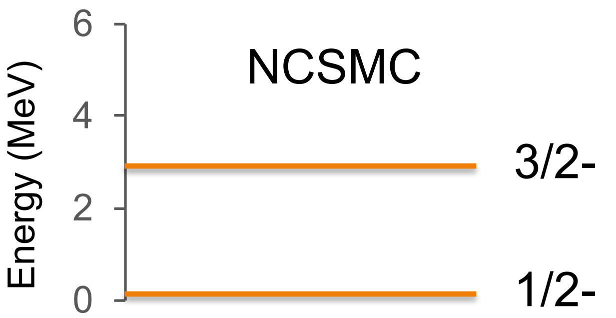
Quantify uncertainties in the structure parameters that define OP



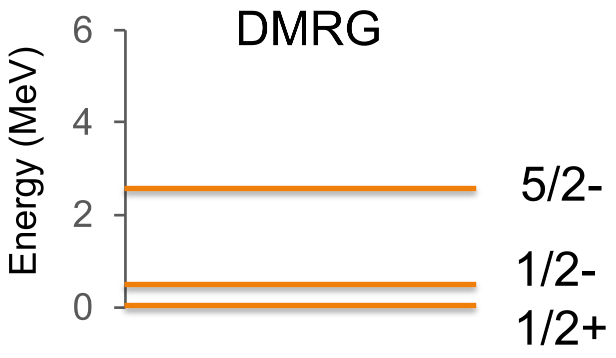
Can also be used to constrain the underlying chiral forces if we use ab initio inputs

Elusive ground state of ^{9}He

^{9}He -- Nucleus with the highest neutron to proton ratio!

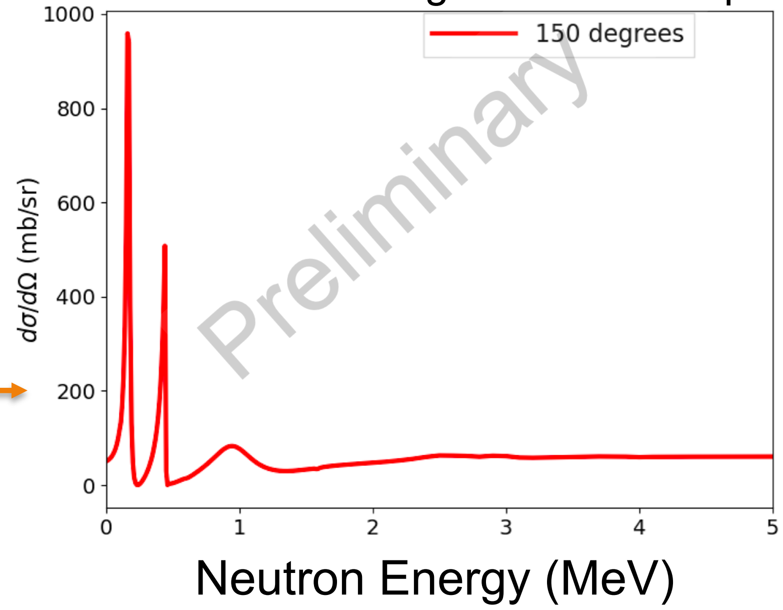


Vorabbi *et al*., PRC **97**, 034314 (2018)

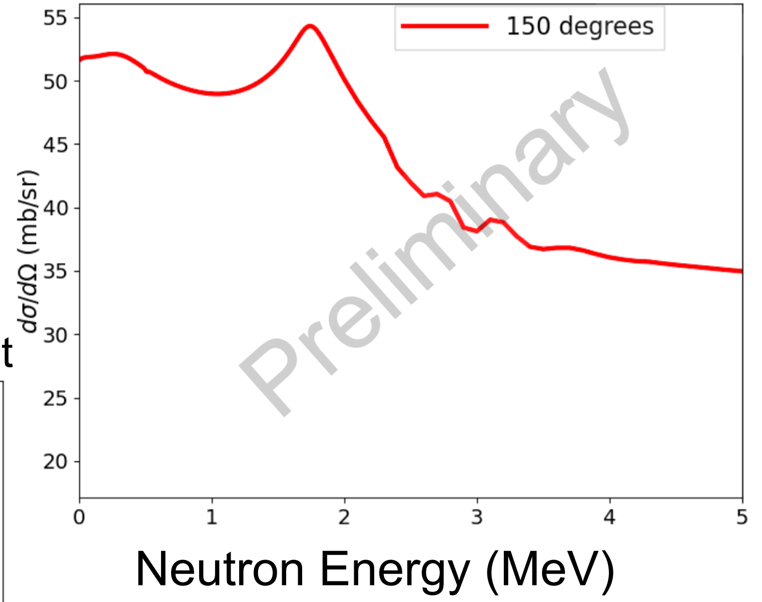


Fossez, *et al*, PRC 98, 061302(R) (2018)

n+^{8}He elastic scattering with DMRG input



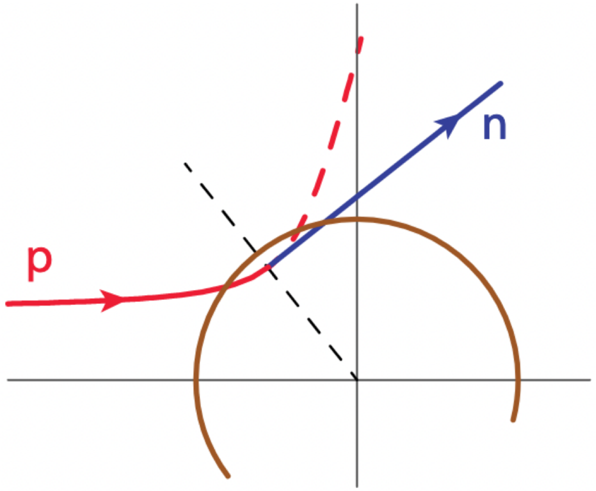
n+^{8}He elastic scattering with NCSMC input



Calculate (d,p) observables with and without ½+ state and propose an experiment at FRIB to measure $^{8}He(d,p)$

See Gregory's talk tomorrow for GF transfer!

Reactions for the studies of charge-exchange processes



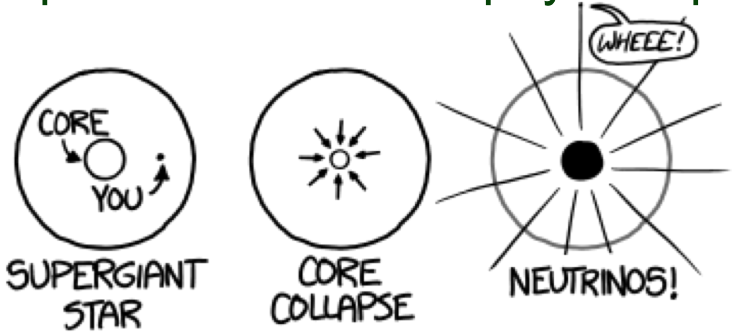
Danielewicz *et al.,* Nuc. Phys. A, 2017

- Charge-exchange reactions have been used to constrain (double) β-decay rates and neutrino-induced reactions

$$\frac{d\sigma}{d\Omega}(q \approx 0) \sim B(GT)$$

Taddeucci et al., Nucl. Phys. A469 (1987) 125-172

- Electron capture rates in astrophysical processes



- FRIB PAC experiment

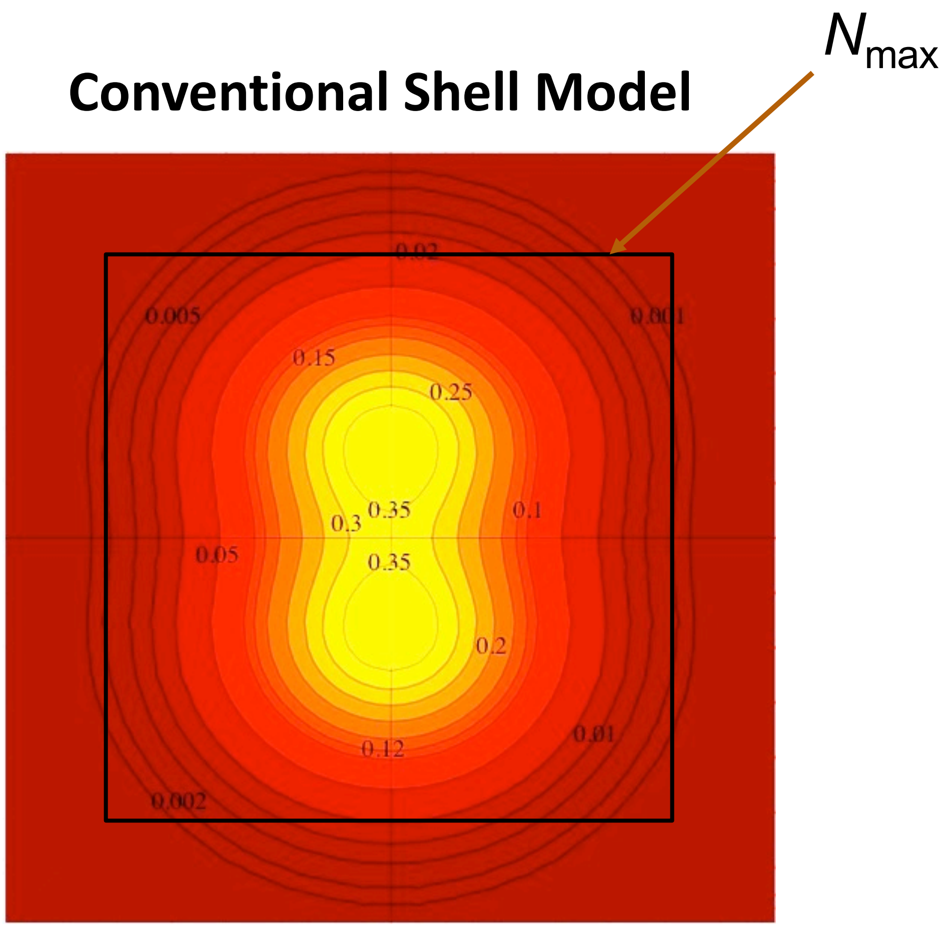
"Constraining electron-capture rates in and near the N=20 island of inversion"

- Need isospin dependent optical potentials
- Use ab initio symmetry-adapted no-core shell model to provide input

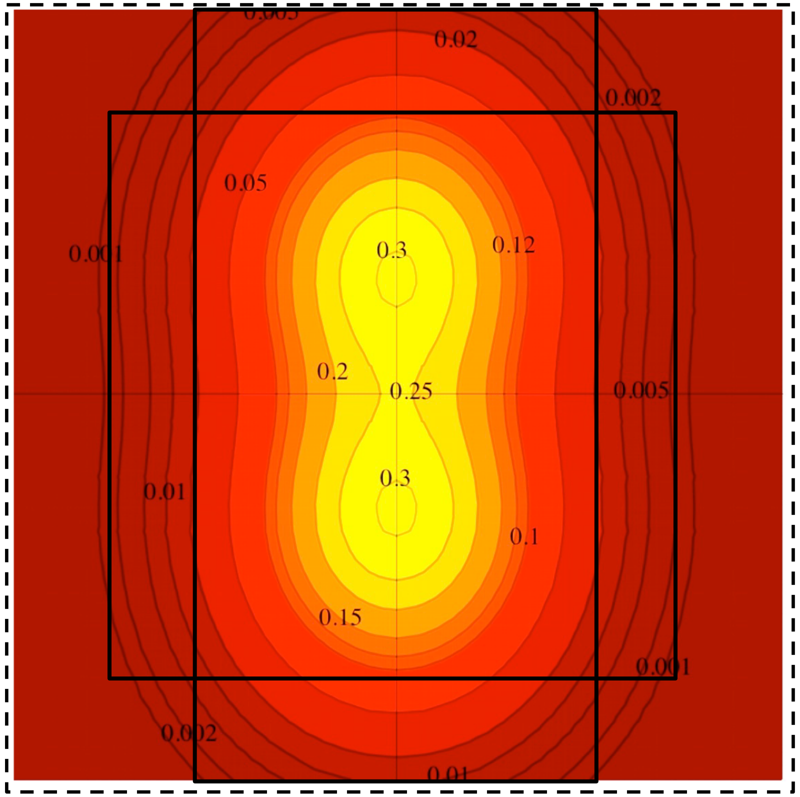
Symmetry-adapted no-core shell model (SA-NCSM)

Nucleus in model space

Conventional Shell Model

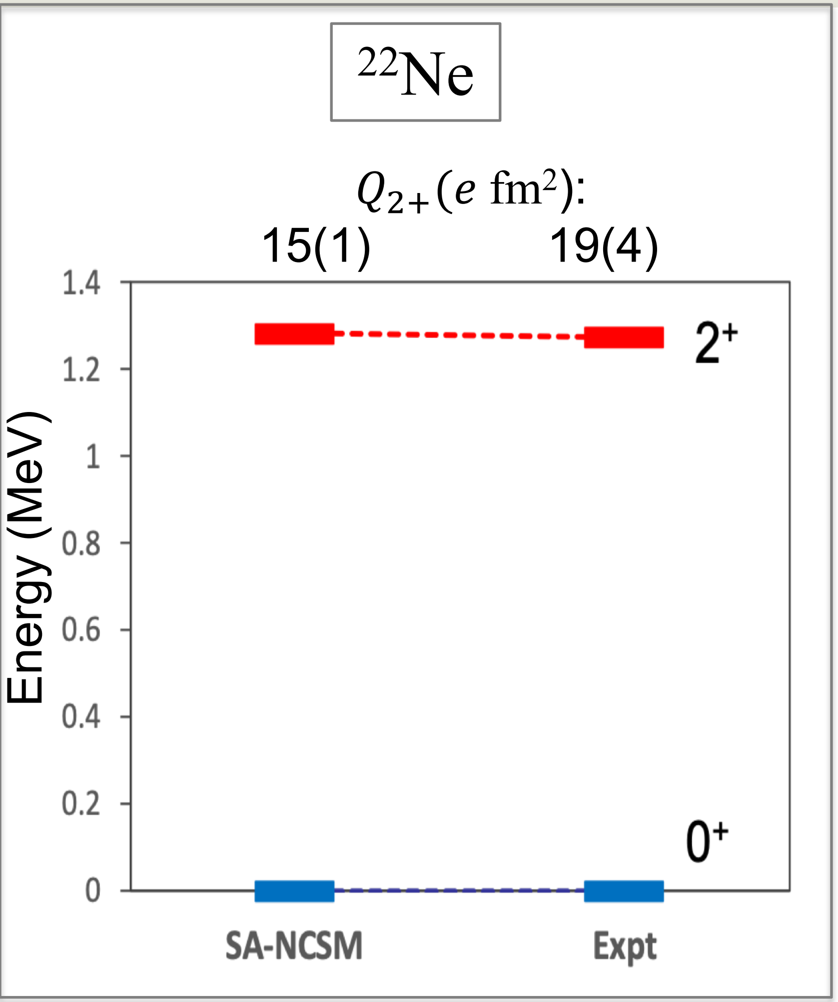


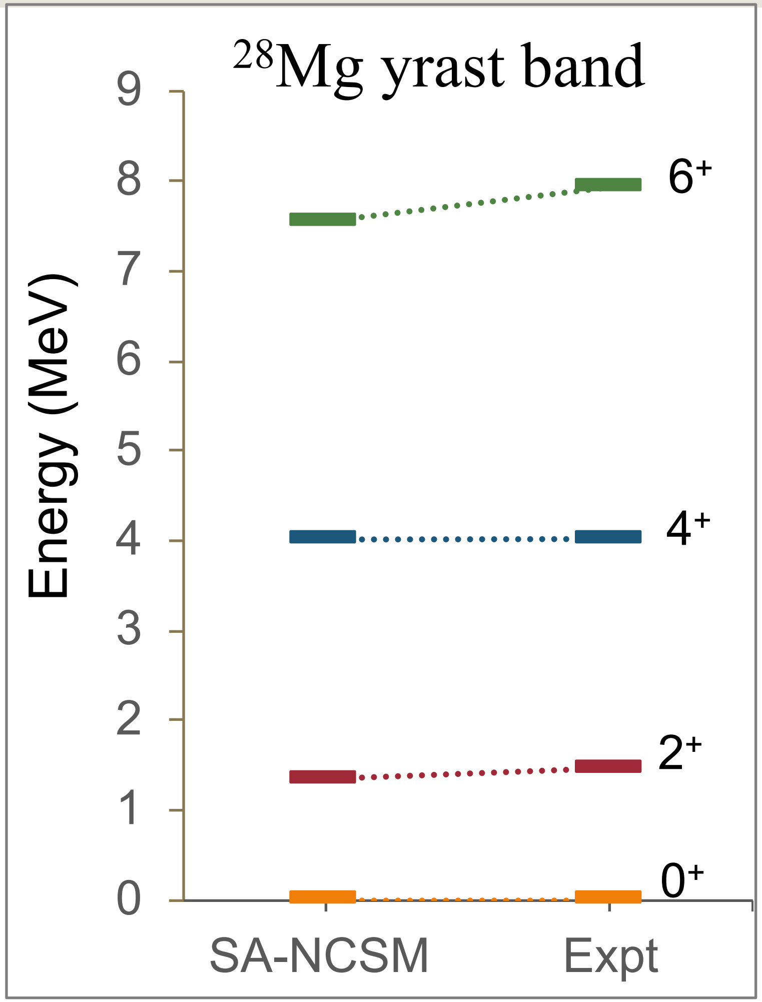
Ab initio **Symmetry-adapted No-core Shell Model (SA-NCSM)**

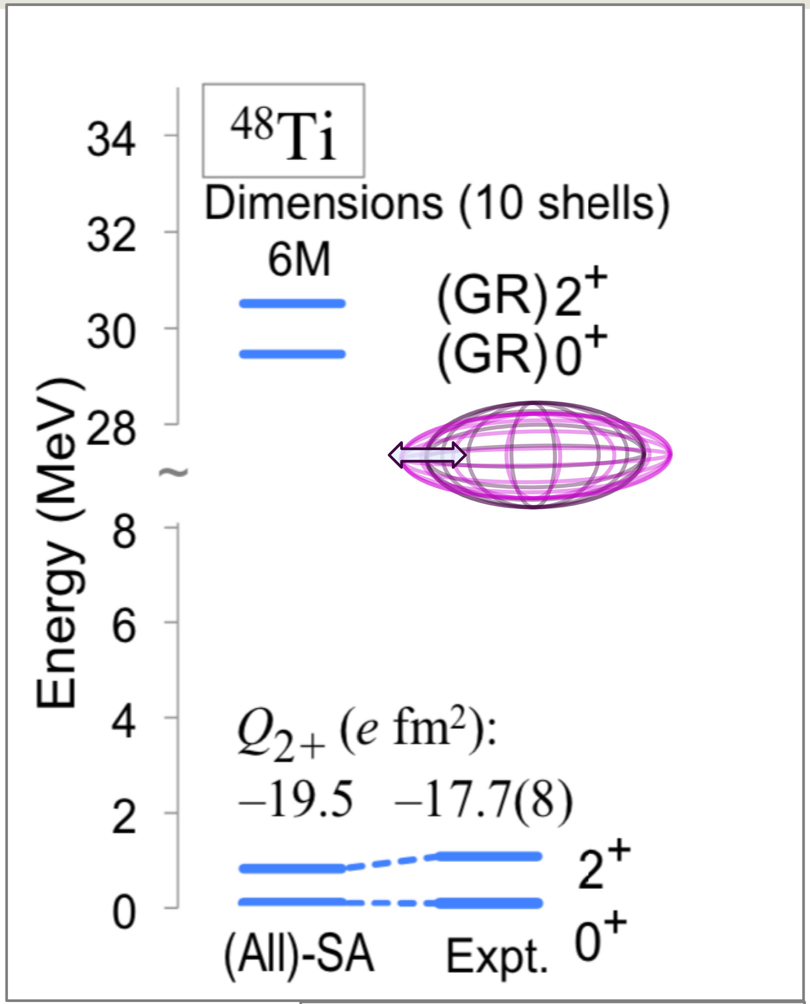


SU(3) and symplectic symmetry

SA-NCSM can reach intermediate mass nuclei

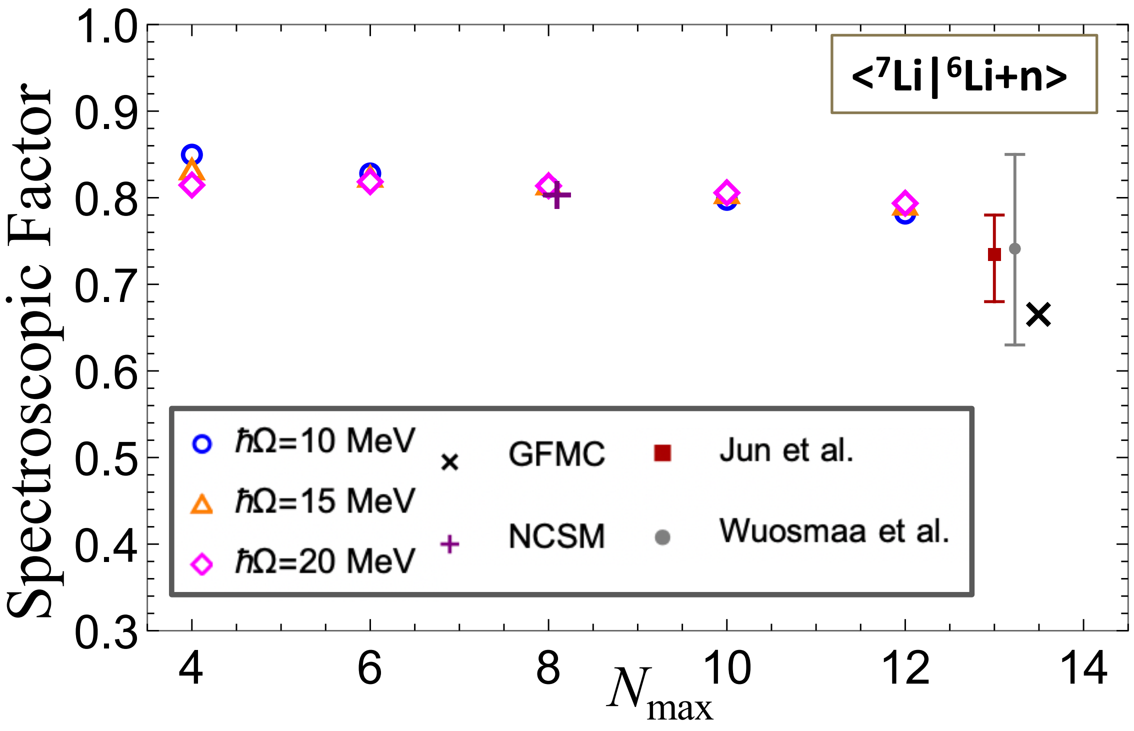


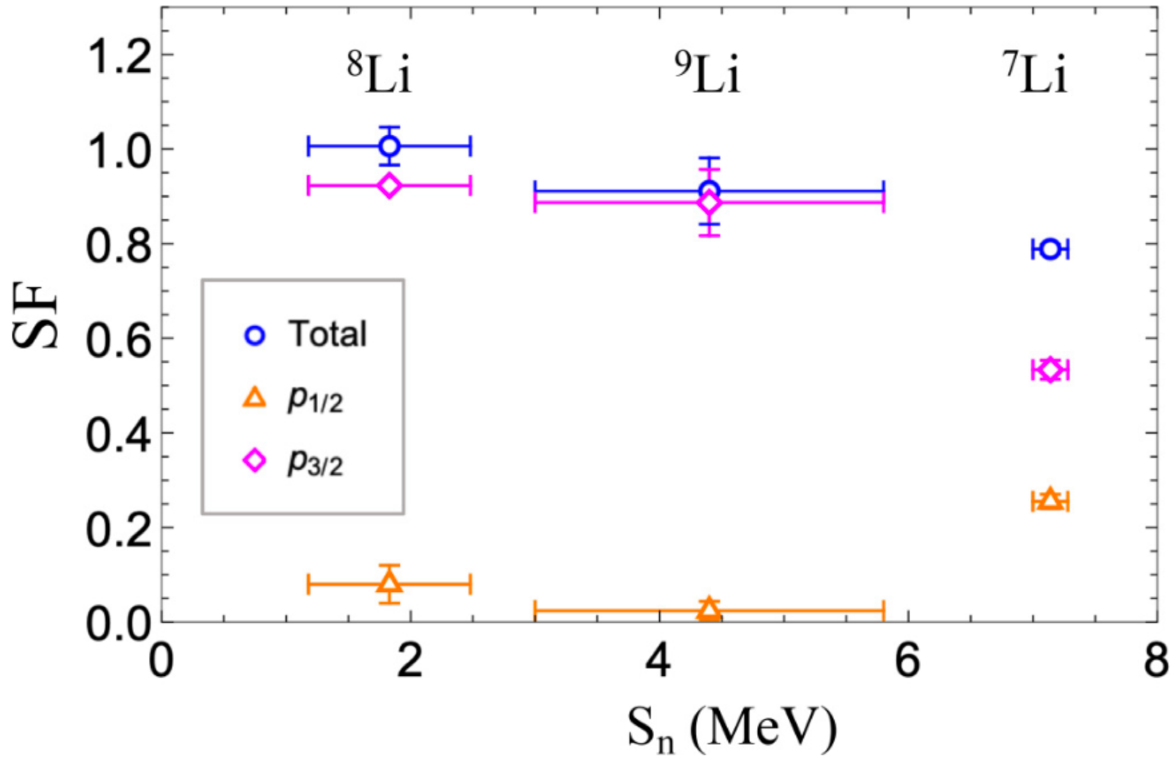




NNLO$_{\mathrm{opt}}$ $\hbar\Omega = 15$ MeV

Ab initio SA-NCSM can provide input for OP

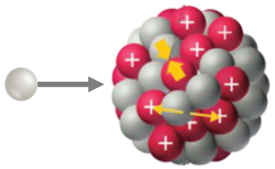




Sargsyan, *et al.* PRC **108**, 054303 (2023)

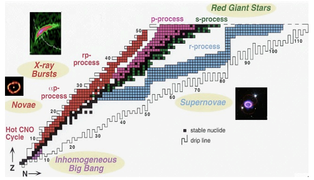
Summary

- We develop a new code to build nucleon-nucleus optical potentials (OPs) for reliable calculations of nuclear reactions

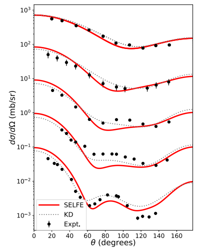


- The method can be applied to any mass range as long as structure calculations are available

- First scattering results for ^{24}Mg based on shell model structure input are in good agreement with measurements
- We can use ab initio structure input to propagate nucleon-nucleon interaction uncertainties to scattering observables



- Calculations of n+^{8}He scattering with different structure inputs can shed light on the possible parity inversion in ^{9}He ground state



- We aim to extend the framework for charge-exchange reaction studies

Acknowledgements

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FRIB

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Kristina Launey
LSU

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U.S. Department of Energy

Thank you!

Back up slide zone

Iterative scheme for self consistent V_{PO}

$$\mathcal{V}^{(0)} = V_{00},$$

$$\mathcal{V}^{(1)} = V_{00} + \lim_{\eta\to 0} \sum_i V_{0i}(r_n)\left(E - T - \mathcal{V}^{(0)}(E_i; \mathbf{r}_n, \mathbf{r}'_n) + i\eta\right)^{-1} V_{i0}(r'_n),$$

$$\cdots$$

$$\mathcal{V}^{(n+1)} = V_{00} + \lim_{\eta\to 0} \sum_i V_{0i}(r_n)\left(E - T - \mathcal{V}^{(n)}(E_i; \mathbf{r}_n, \mathbf{r}'_n) + i\eta\right)^{-1} V_{i0}(r'_n),$$

$$J^{(n)} = \int \mathcal{V}^{(n)}(\mathbf{r}_n, \mathbf{r}'_n)\, d\mathbf{r}\, d\mathbf{r}',$$

$$\varepsilon = \left| \frac{J^{(n+1)} - J^{(n)}}{J^{(n+1)} + J^{(n)}} \right| \ll 1.$$

Volume integral convergence condition

Elastic and absorption cross sections can be calculated from the OP

$$V(\boldsymbol{r},\boldsymbol{r}',E) = U_0(\boldsymbol{r}) + V_{PO}(r,r',E-E_i)$$

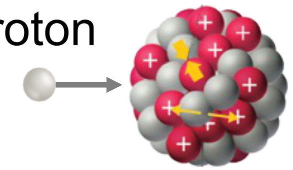
$$\big(E - T - V(\boldsymbol{r},\boldsymbol{r}',E)\big)\phi = 0$$

→ elastic scattering cross sections from phase shifts

$$\sigma_{abs} \sim \langle \phi | Im(V_{PO}) | \phi \rangle = 0$$

→ Absorption cross section from imaginary part of the polarization potential

^{40}Ca + p elastic scattering with 10 states



Parameters for levels in ^{40}Ca

λ_n^{π}	1^-	2^+	2^+	2^+	3^-	3^-	4^+	4^+	5^-	5^-
E_n (MeV)	18.0	3.9	8.0	16.0	3.73	15.73	8.0	20.0	4.48	16.48
$\beta_\lambda(n)$	0.087	0.143	0.309	0.250	0.354	0.380	0.254	0.457	0.192	0.653

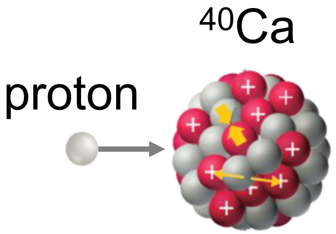
Rao, et al., Nuclear Physics A207 (1973) 182-208.

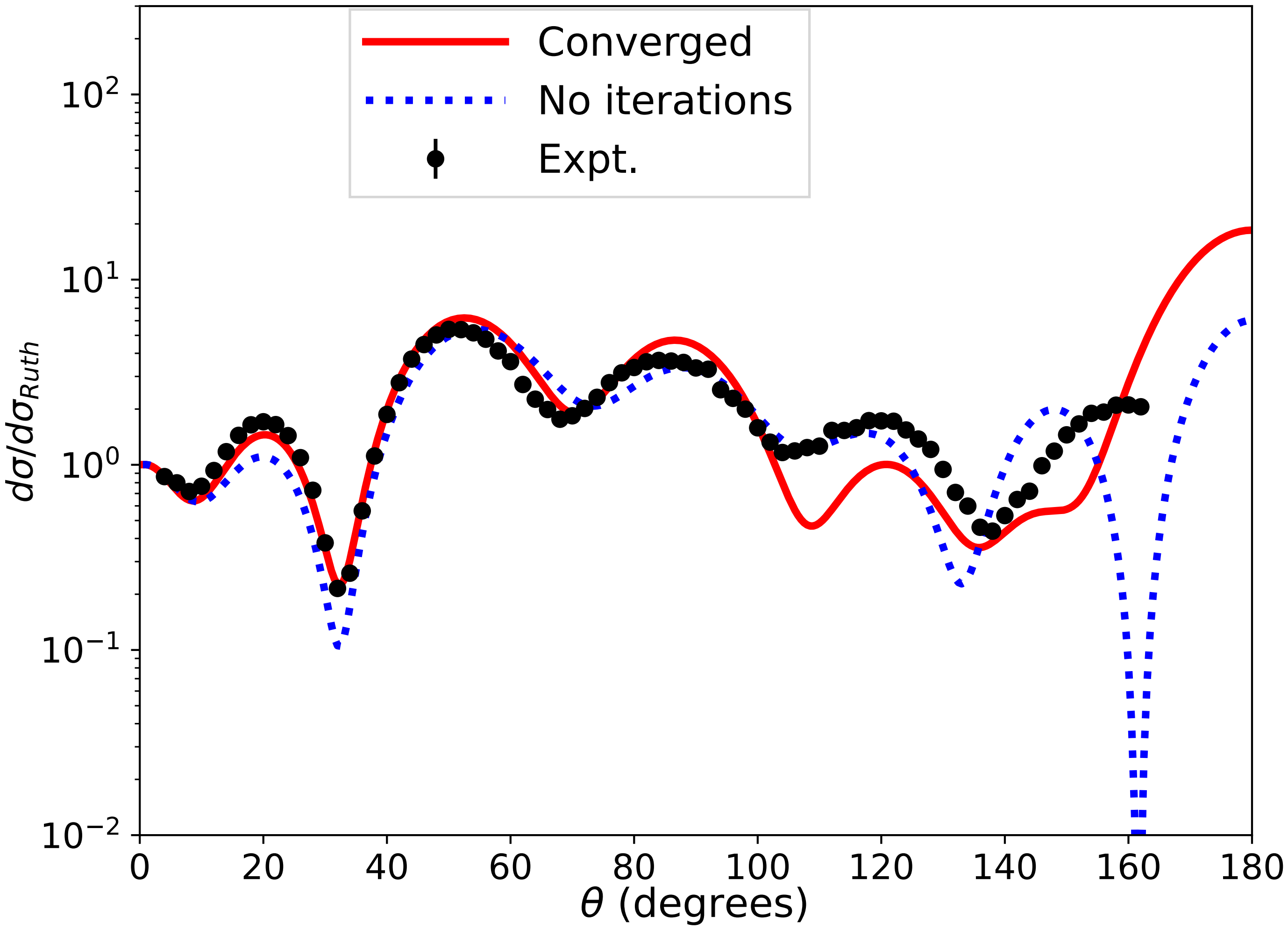
$$V(\boldsymbol{r},\boldsymbol{r}',E) = V_{00}(\boldsymbol{r},E) + V_{PO}(\boldsymbol{r},\boldsymbol{r}',E)$$

Woods-Saxon:
V_0 = -50 MeV
R_0 = 1.2$A^{1/3}$
a = 0.65

10 intrinsic states

^{40}Ca + p elastic scattering at 30 MeV

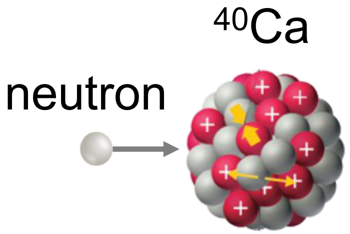


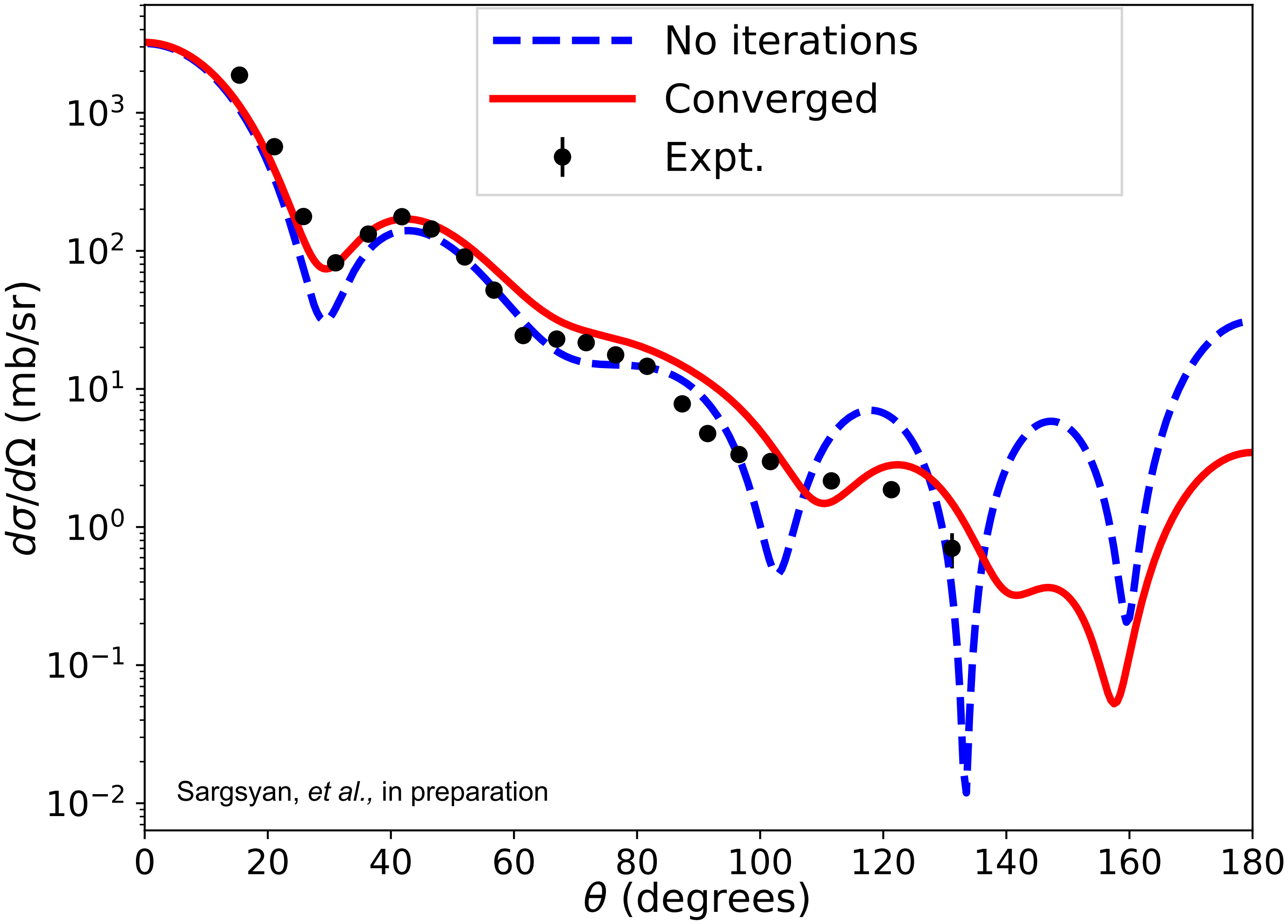


10 intrinsic states

Grigor Sargsyan

Neutron elastic scattering over ^{40}Ca at 30 MeV





10 intrinsic states

Grigor Sargsyan