

FRIB

Most Wanted: Microscopic Nuclear Structure for Predictive Reaction Modeling

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ECT* workshop: Nuclear theory for astrophysics:
Bridging bound-state and continuum physics
21 May 2026



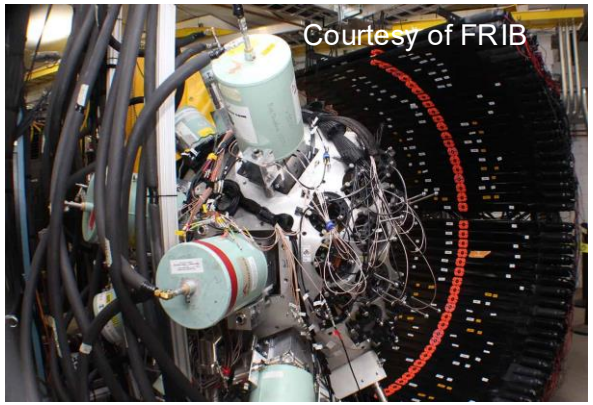
MICHIGAN STATE UNIVERSITY

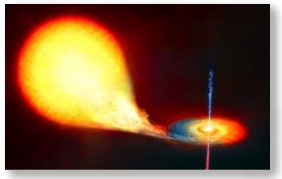


U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under the FRIB Theory Alliance award DE-SC0013617.

The era of rare isotope beams





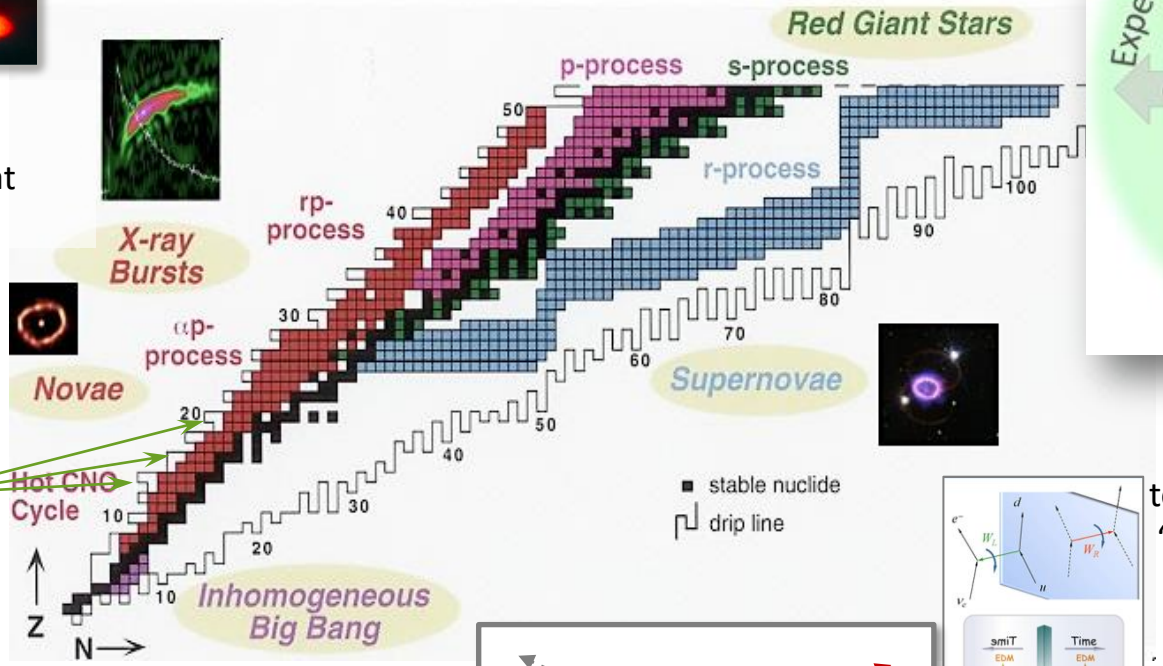
X-ray burst nucleosynthesis

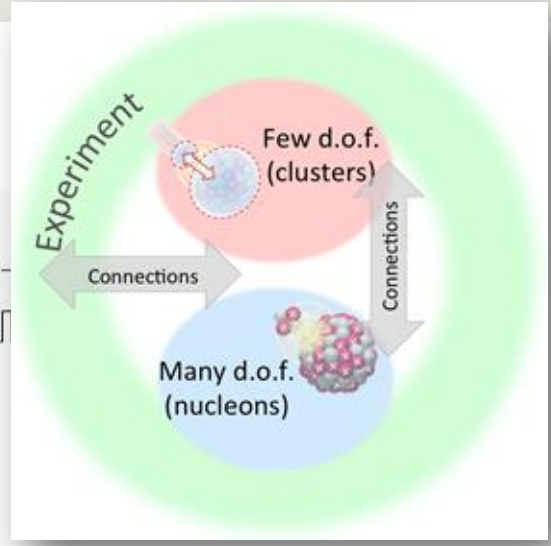
Alpha widths

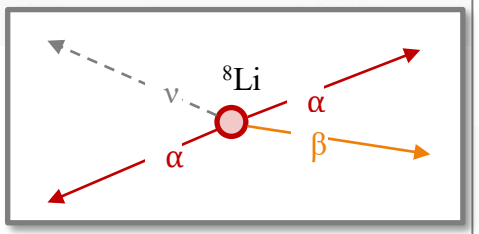
Reaction rates at low energies



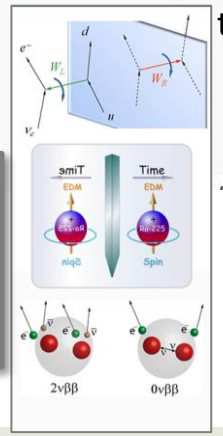
Close proximity of the drip lines





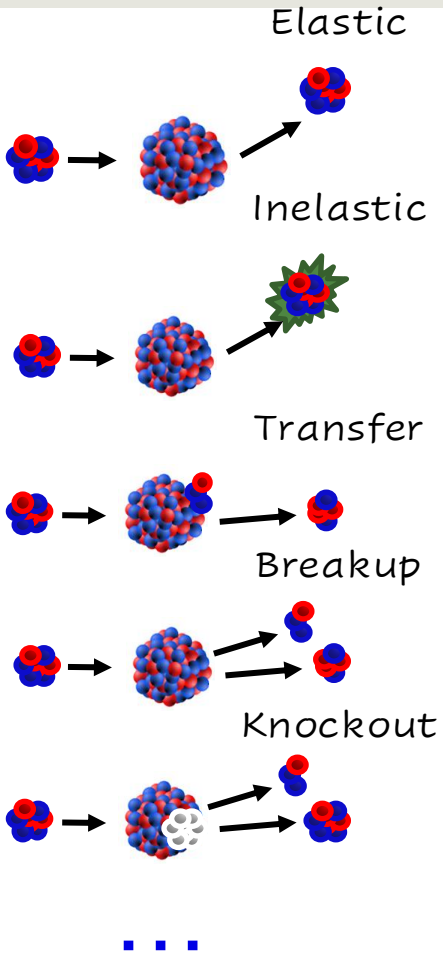


Fundamental symmetries



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

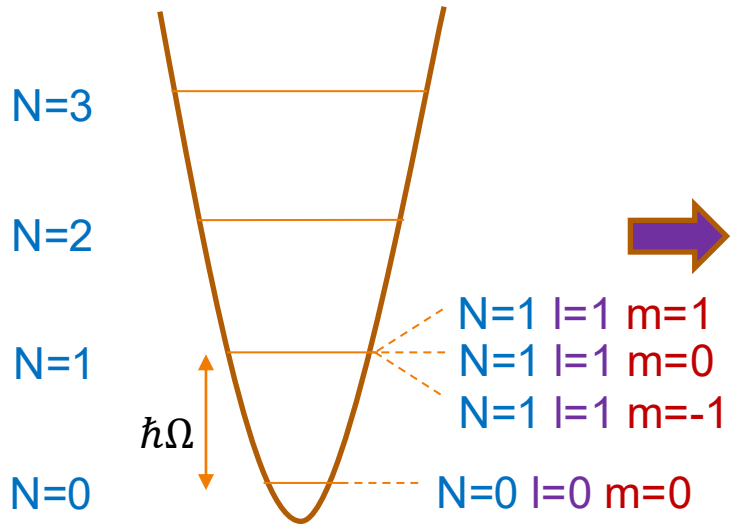
Reaction models need structure input



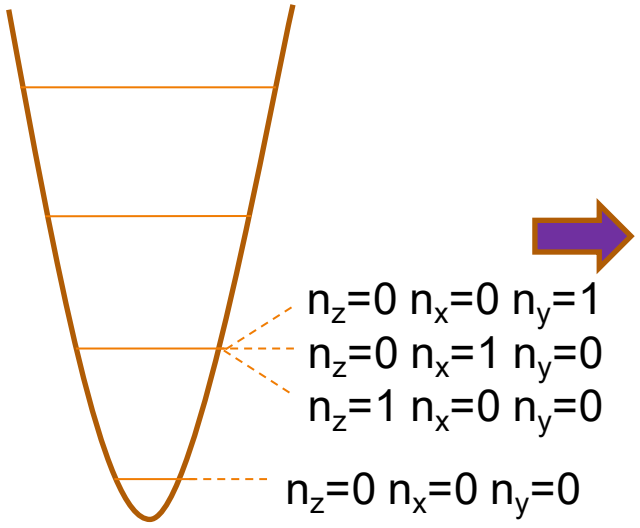
- Experiments need reaction models to interpret measured data
- Various reaction models require structure input (cluster wavefunctions, excitation spectrum, electromagnetic transitions, etc.)
- *Ab initio* structure methods can provide a reliable input especially for the tricky problems



Symmetry-adapted No-core Shell Model

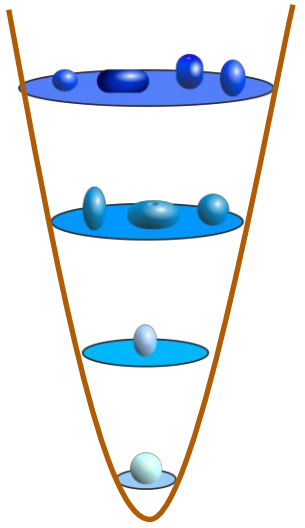


Spherical harmonic oscillator (HO): basis states given by {N l m}



$N = n_z + n_x + n_y$

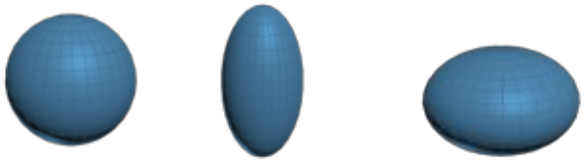
Basis states given by $\{n_x\ n_y\ n_z\}$



$\lambda = n_z - n_x$, $\mu = n_x - n_y$ (single particle)

Basis states given by (λ μ) quantum numbers

$$a^{+}_{Nlm} \equiv a^{+}_{(N\ 0)lm}$$

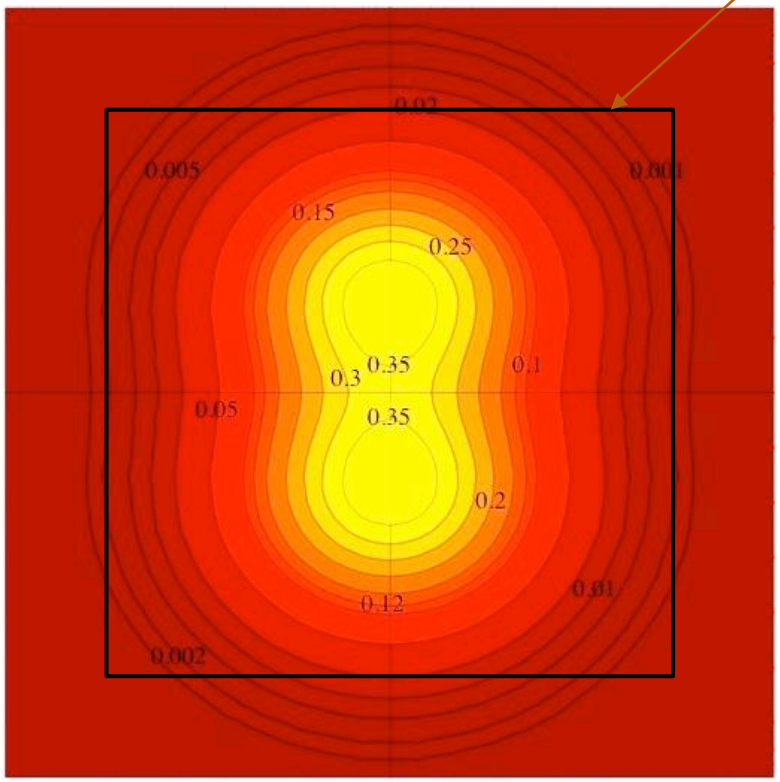


Sphere (0 0) Prolate (λ 0) Oblate (0 μ)

Symmetry-adapted basis helps reduce the models space size

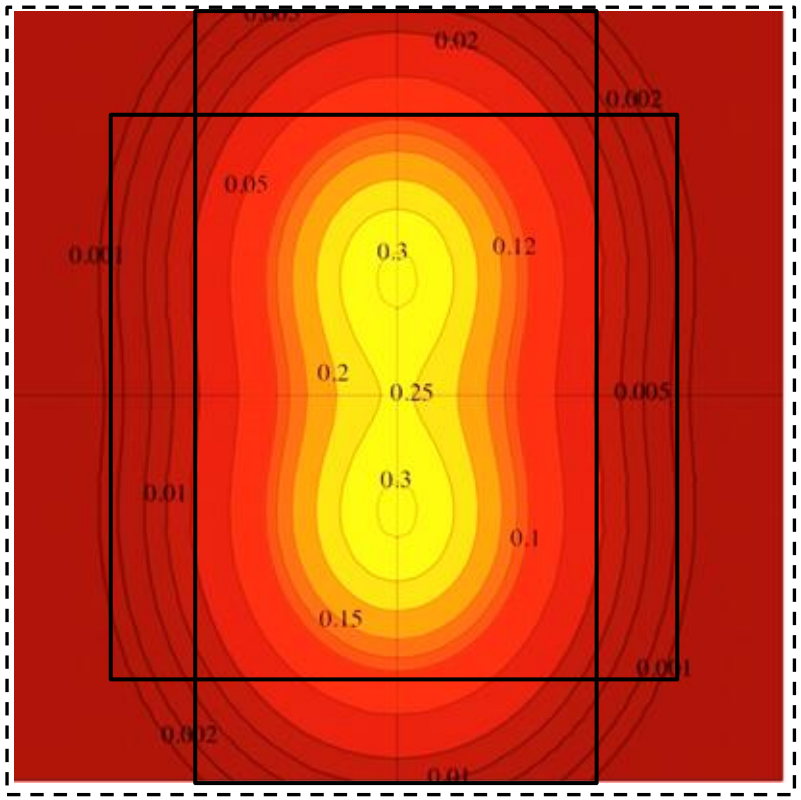
Conventional Shell Model

N_{max}



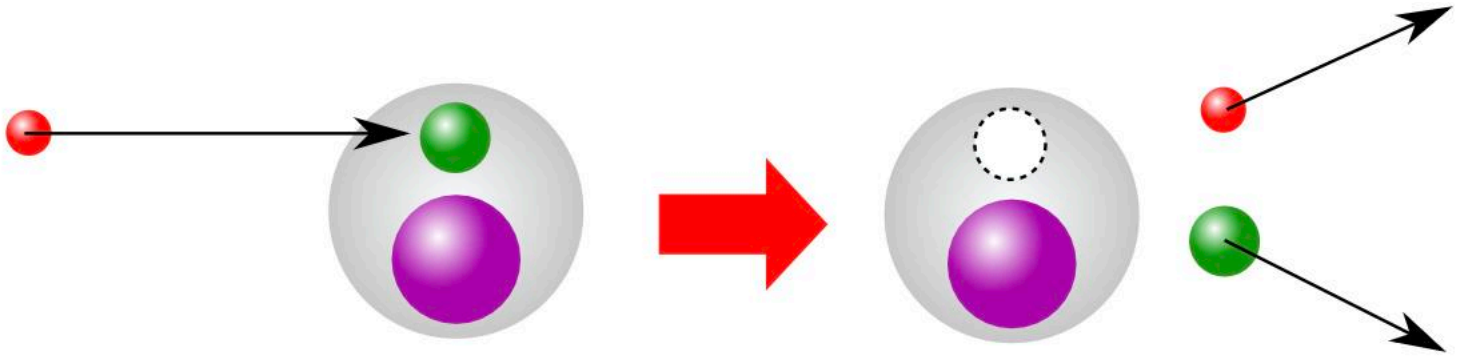
Nucleus in model space

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



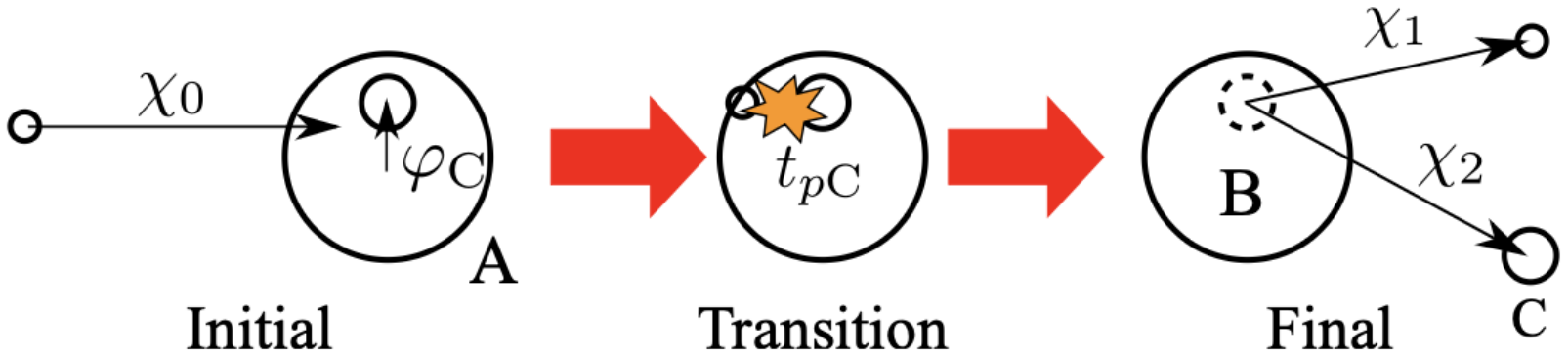
SU(3) and symplectic symmetry

Knockout reaction



- Typically >100 MeV/u incident energy
- Modeled as one-step direct reaction
- Probes mainly the ground state particle clustering in the target

Reaction model: Distorted Wave Impulse Approximation



Transition matrix

$$T = \langle \chi_1 \chi_2 \Phi_C \Phi_B \,|\, t_{pC} \,|\, \chi_0 \Phi_A \rangle = \langle \chi_1 \chi_2 \,|\, t_{pC} \,|\, \chi_0 \varphi_C \rangle$$

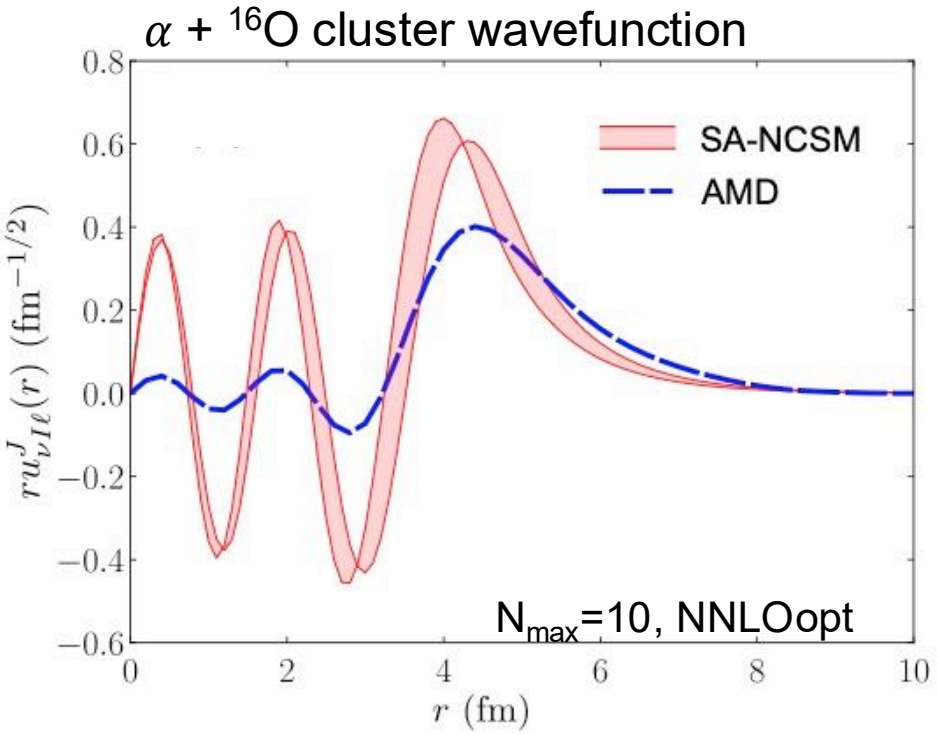
χ_i: Distorted waves under optical potentials

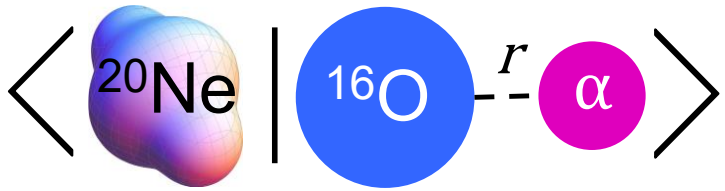
t_{pC}: p-C effective interaction in free space

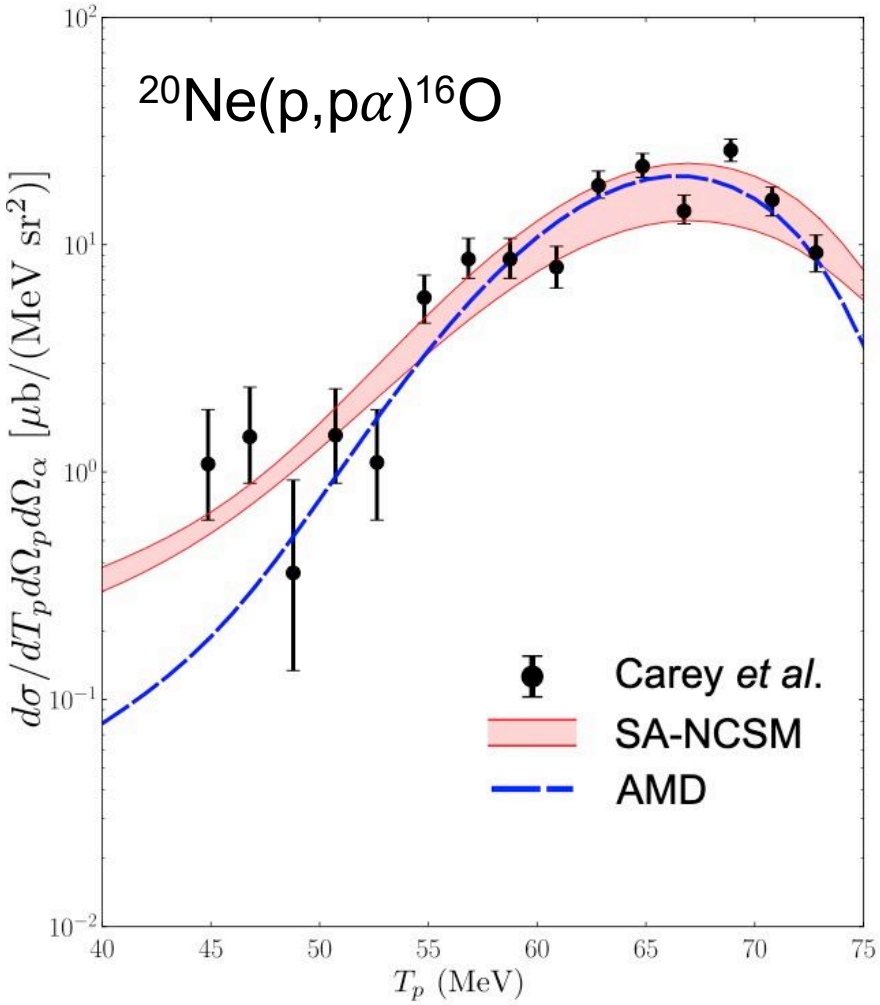
φ_C: Cluster wave function $\langle [\Phi_C \otimes \Phi_B] \,|\, \Phi_A \rangle$

Knockout cross section (Triple differential cross section) $\dfrac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} \propto |T|^2$

Ab initio informed knockout elucidates α clustering in ^{20}Ne





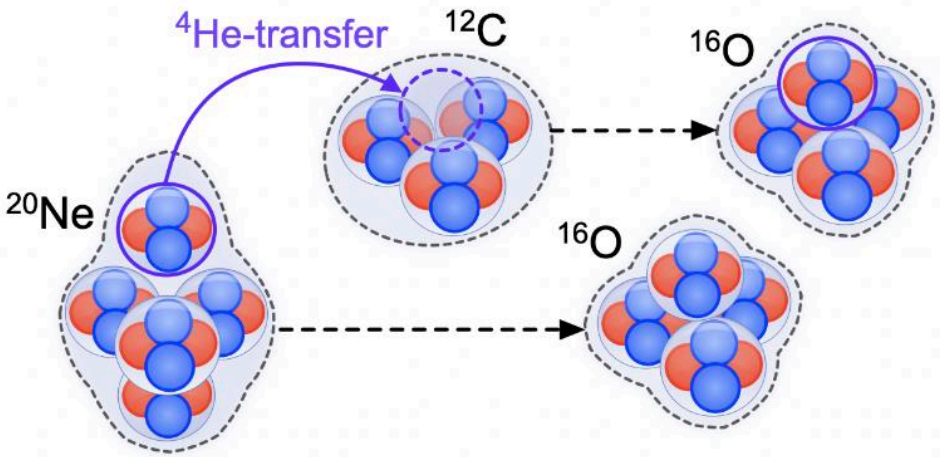


In collaboration with K. Yoshida (Osaka U.) and K. Ogata (Kyushu U.)

Sargsyan et al., PLB **866** 139563 (2025)

Quantifying α clustering in the ground states of ^{16}O and ^{20}Ne

^{12}C(^{20}Ne,^{16}O)^{16}O α-transfer reaction

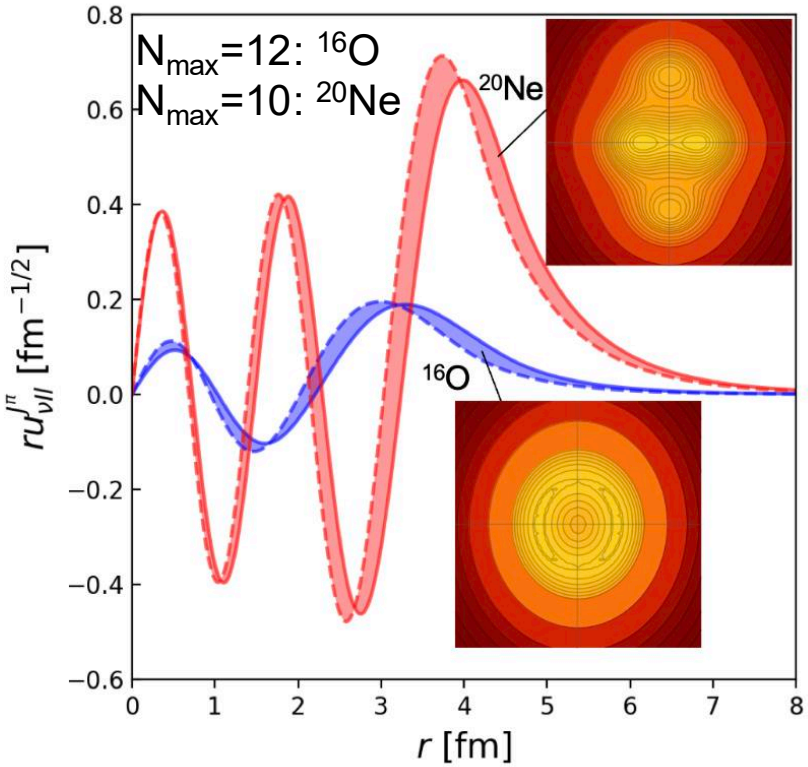


Experiment done
at Texas A&M
Cyclotron Institute

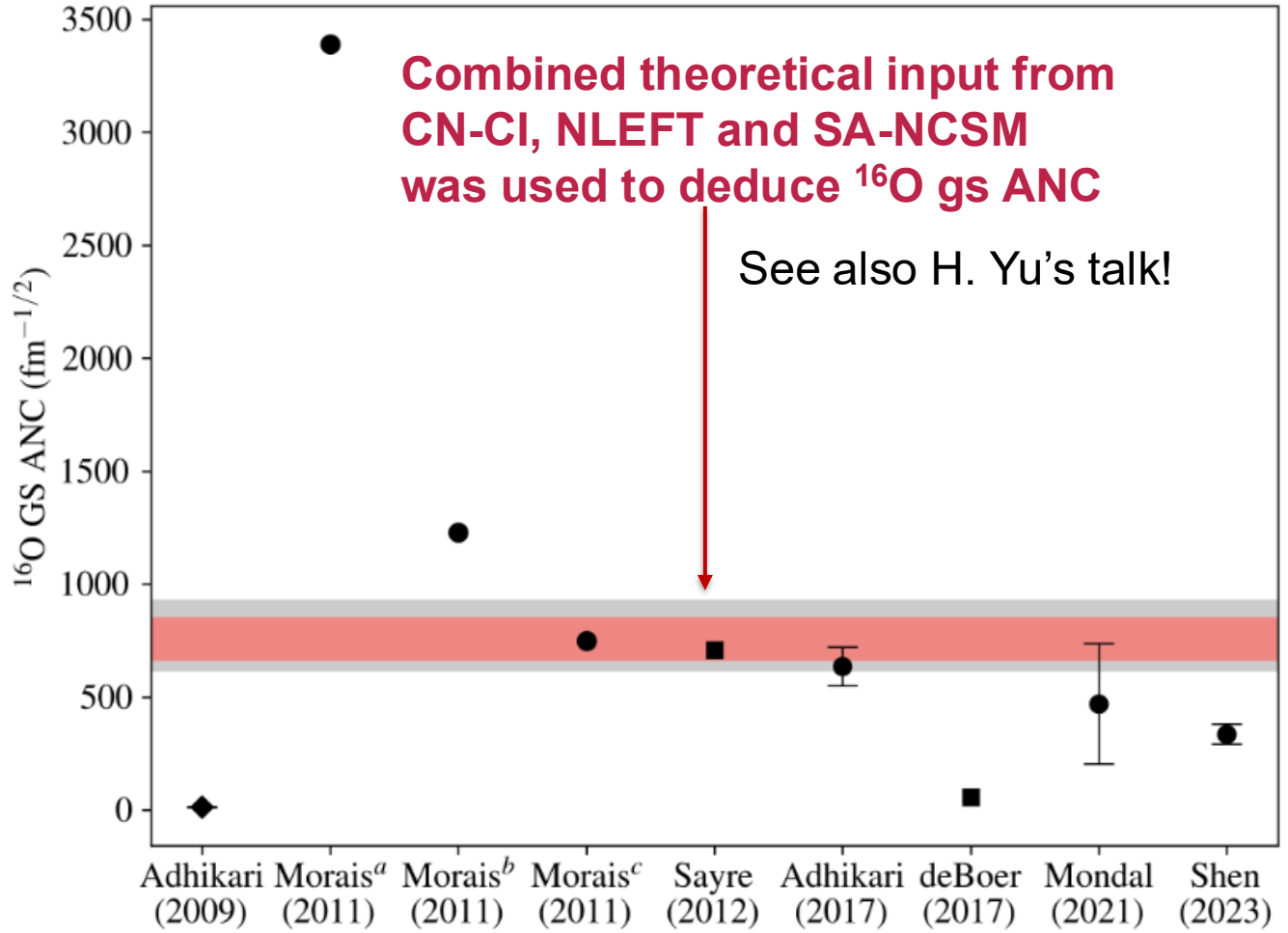
In collaboration with E. Harris
and G. Rogachev (TAMU)

- Reaction model: distorted wave Born approximation (DWBA)
- Extracted product of ANCs $C_{16O}C_{20Ne} \propto \left(\frac{d\sigma}{d\Omega}\right)_{transfer} / \left(\frac{d\sigma}{d\Omega}\right)_{elastic}$

α asymptotic normalization coefficient (ANC) for ^{16}O



α + ^{12}C and α + ^{16}O cluster wavefunctions from SA-NCSM using NNLO$_{opt}$



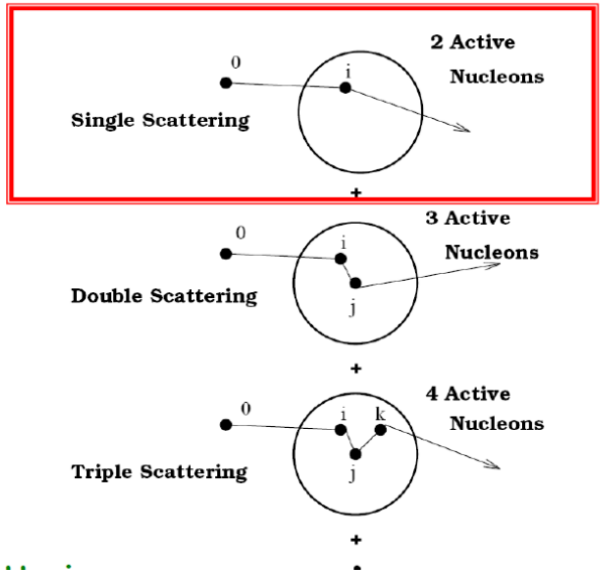
$$C_{16O} = (C_{16O}C_{20Ne})_{expt} \,/(C_{20Ne})_{theory}$$

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E. Harris et al., (incl. Sargsyan) arXiv:2507.17059

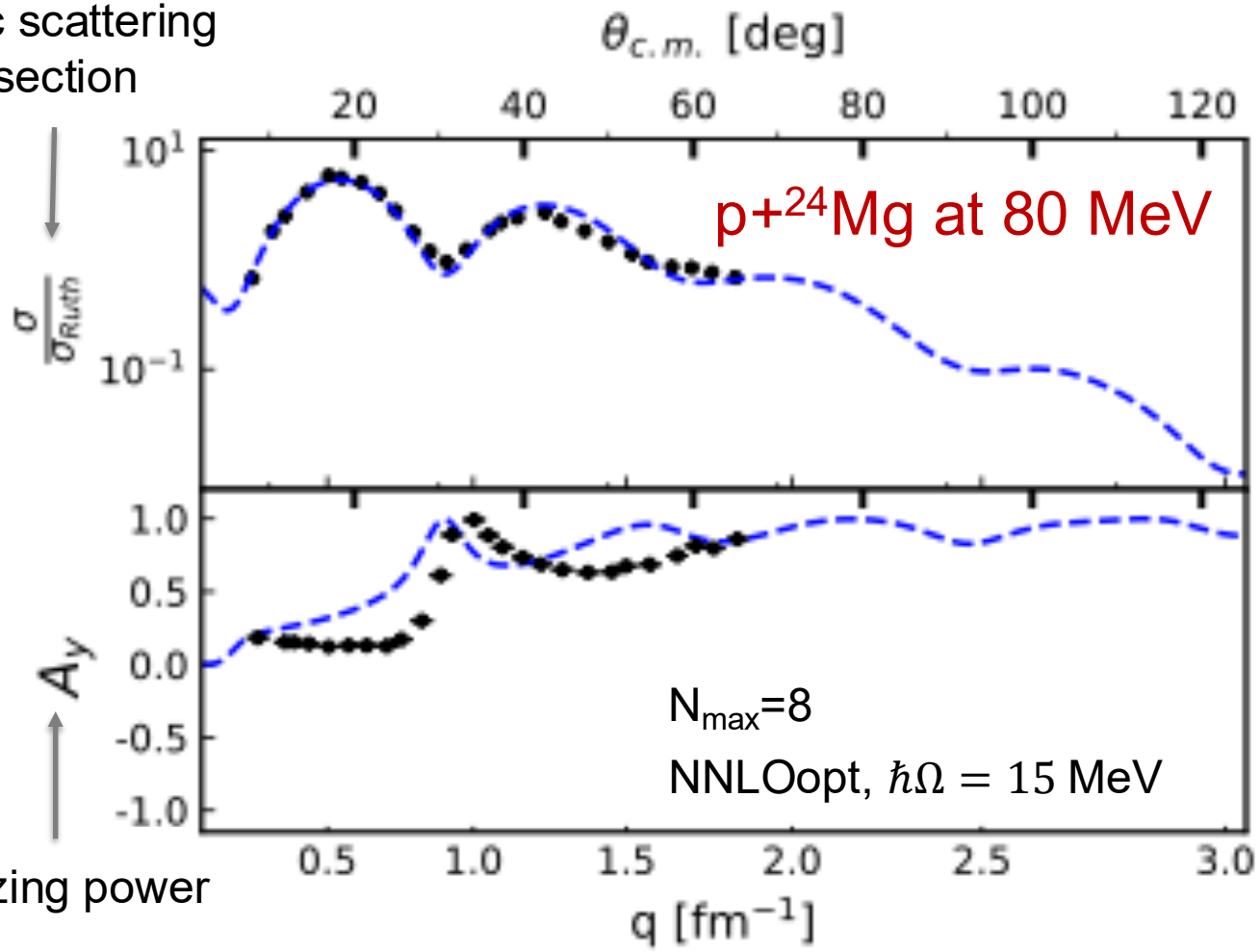
Ab initio optical potentials for E > 65 MeV

Multiple scattering expansion



In collaboration with C. Elster (OU)
(talk on Monday)

Elastic scattering cross section

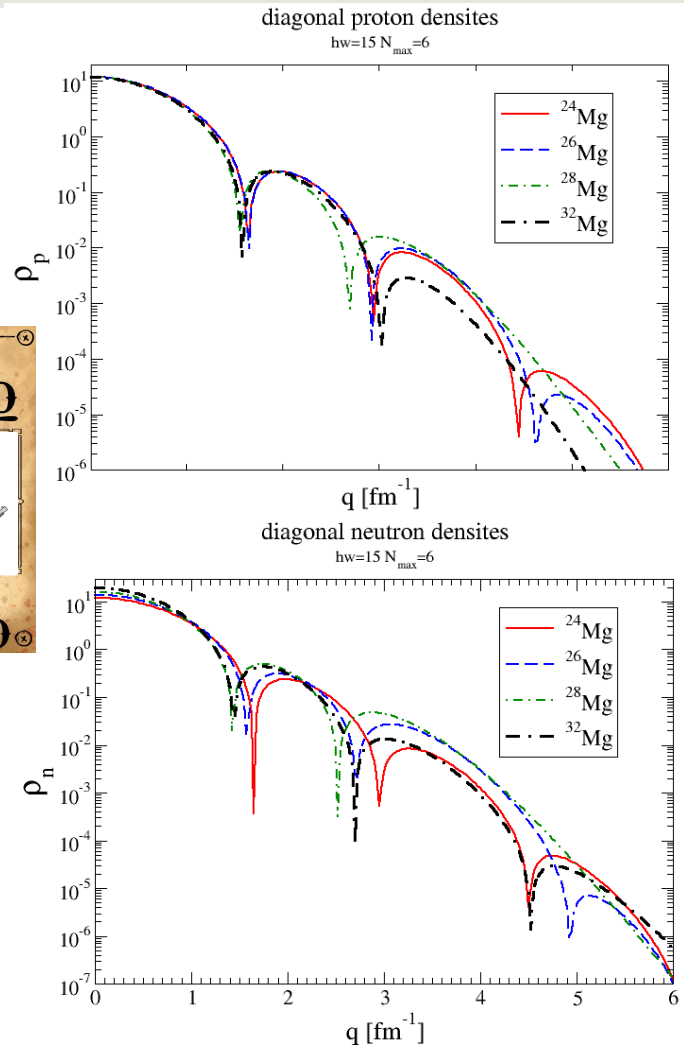


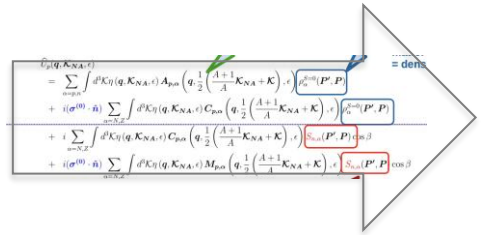
Analyzing power

Structure input from SA-NCSM

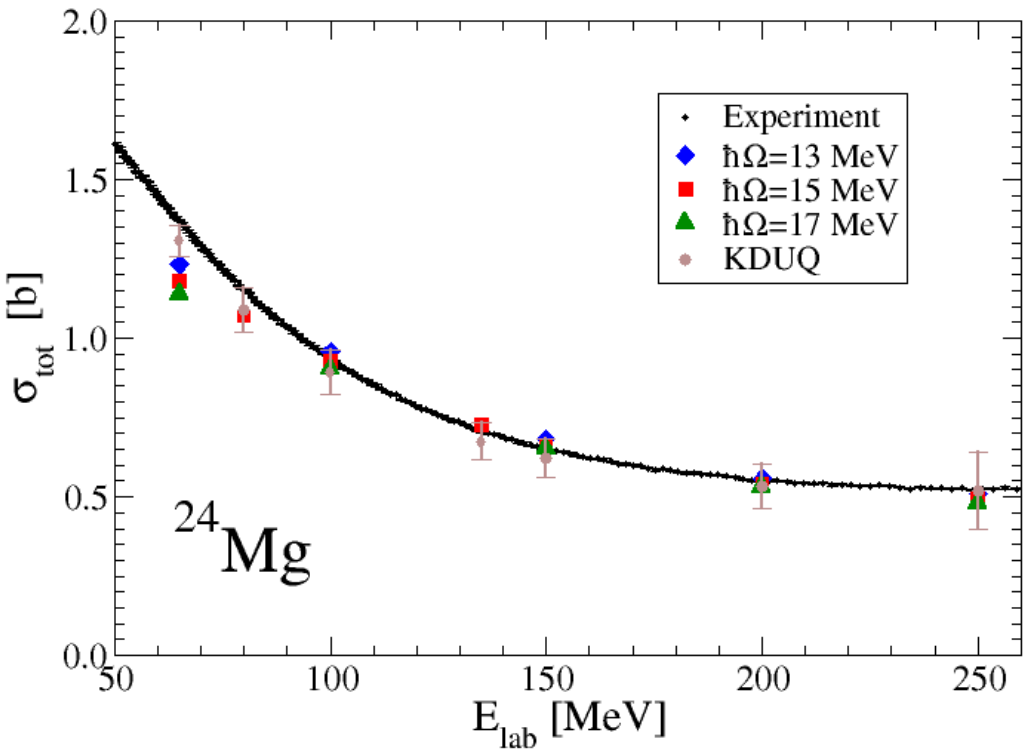
One-body densities of Mg isotopes from stable to N=20 lol







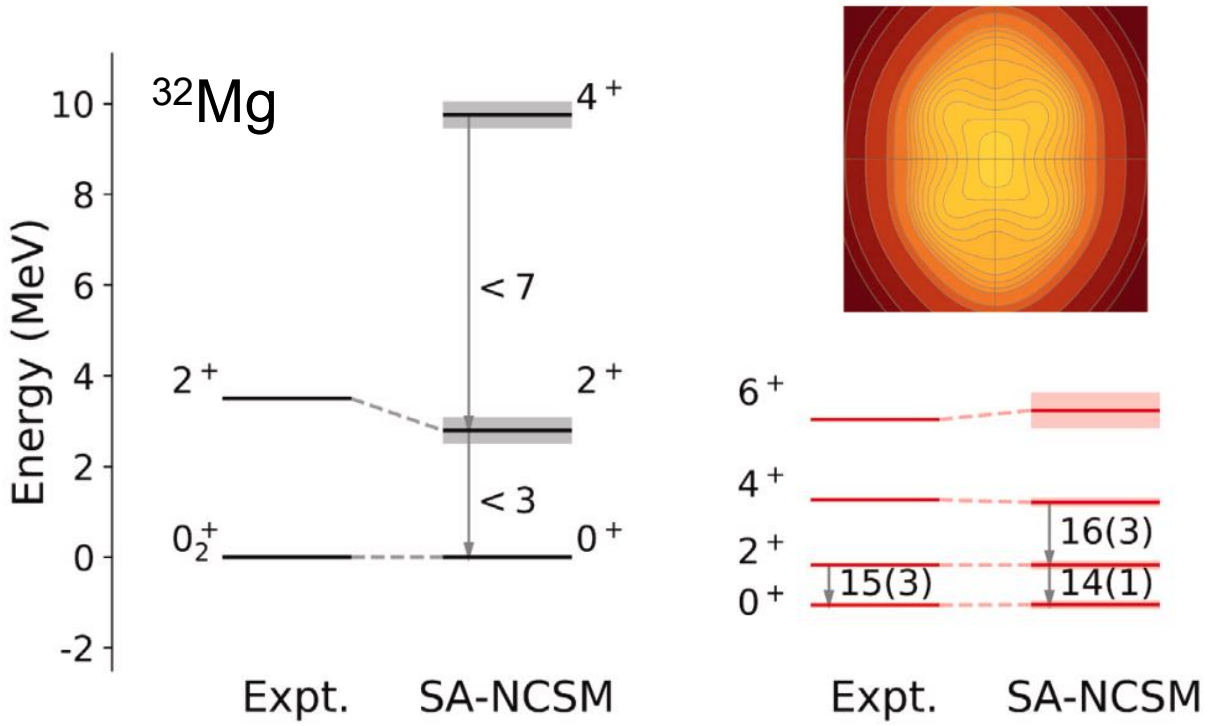
Neutron total cross sections

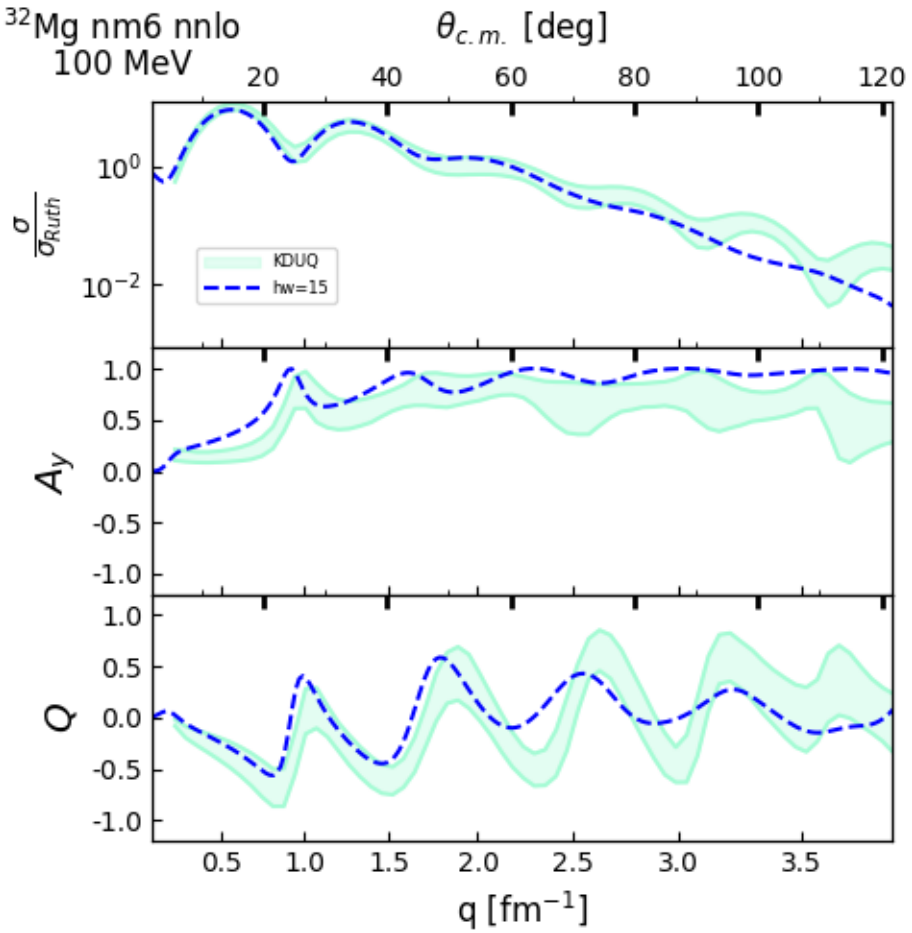


KDUQ: Pruitt et al., Phys. Rev. C **107**, 014602 (2023)

SA-NCSM structure input of ^{32}Mg for reactions calculations

7 PAC-approved FRIB experiments studying
N=20 island of inversion nuclei

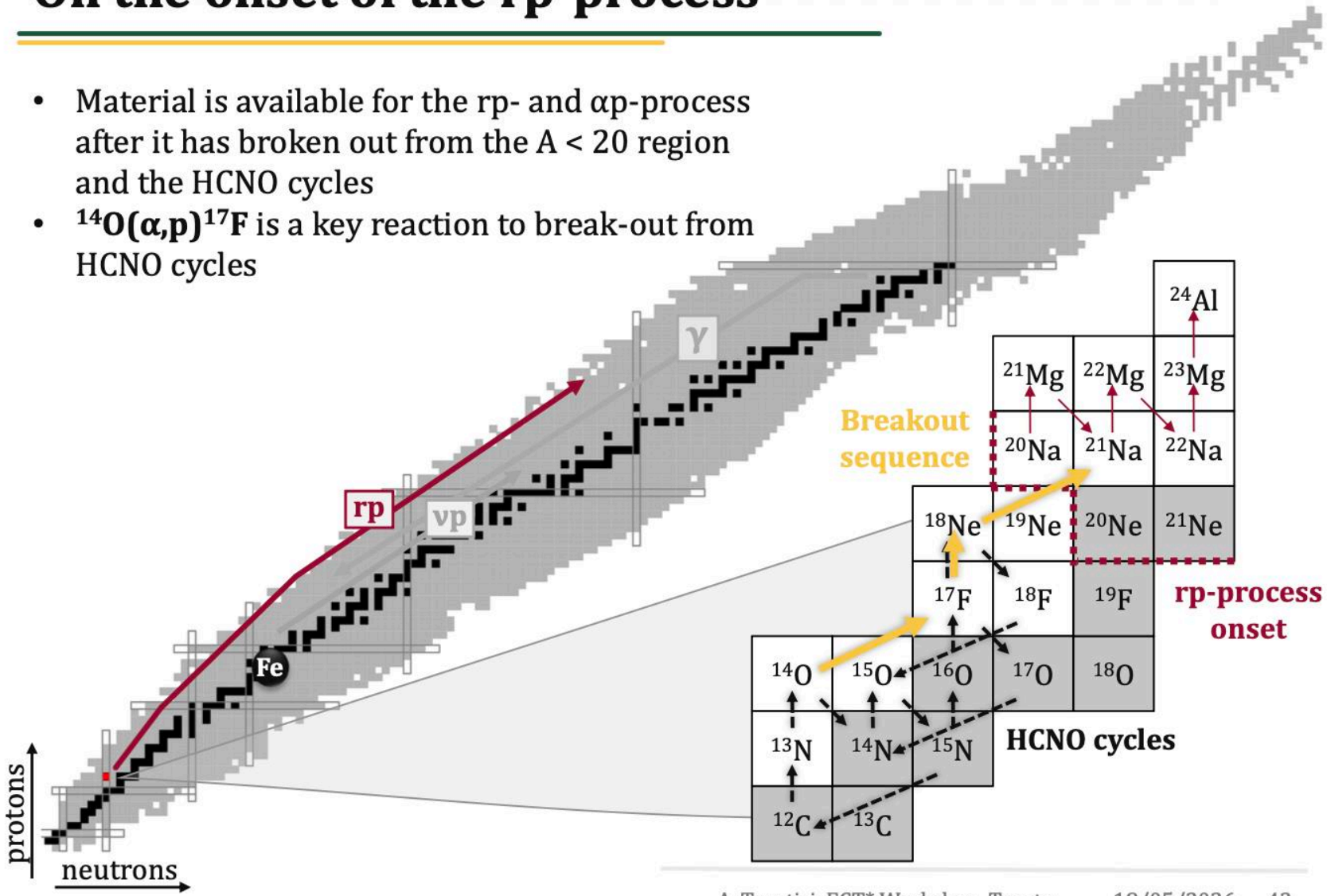




Launey, Sargsyan, et al., *Prog. Part. Nucl. Phys.* **148,** 104233 (2026)

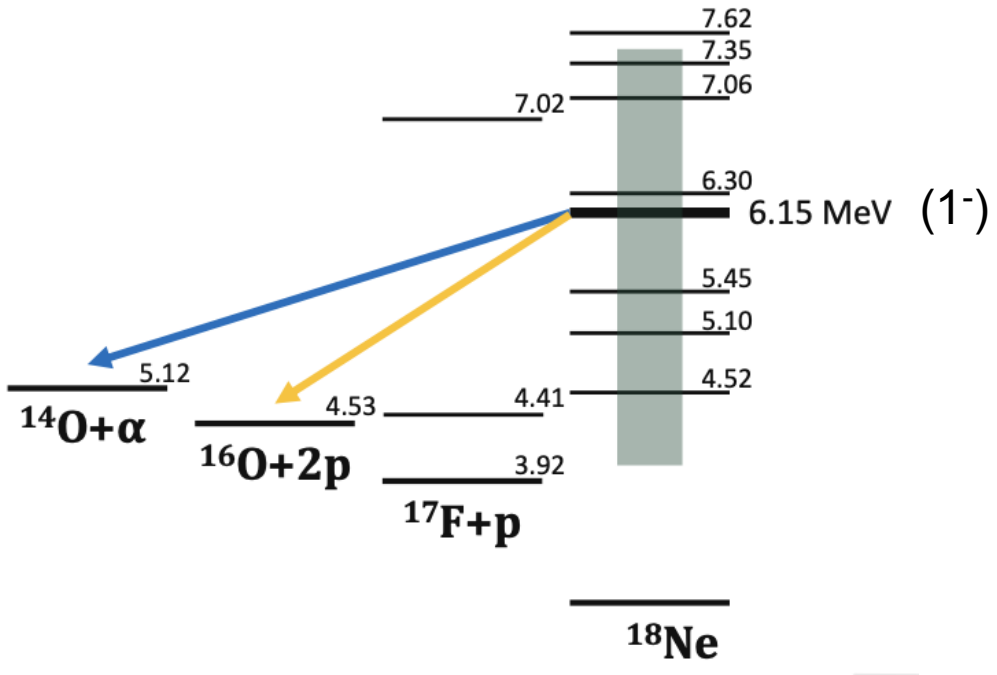
On the onset of the rp-process

- Material is available for the rp- and αp-process after it has broken out from the A < 20 region and the HCNO cycles
- **$^{14}O(\alpha,p)^{17}F$** is a key reaction to break-out from HCNO cycles



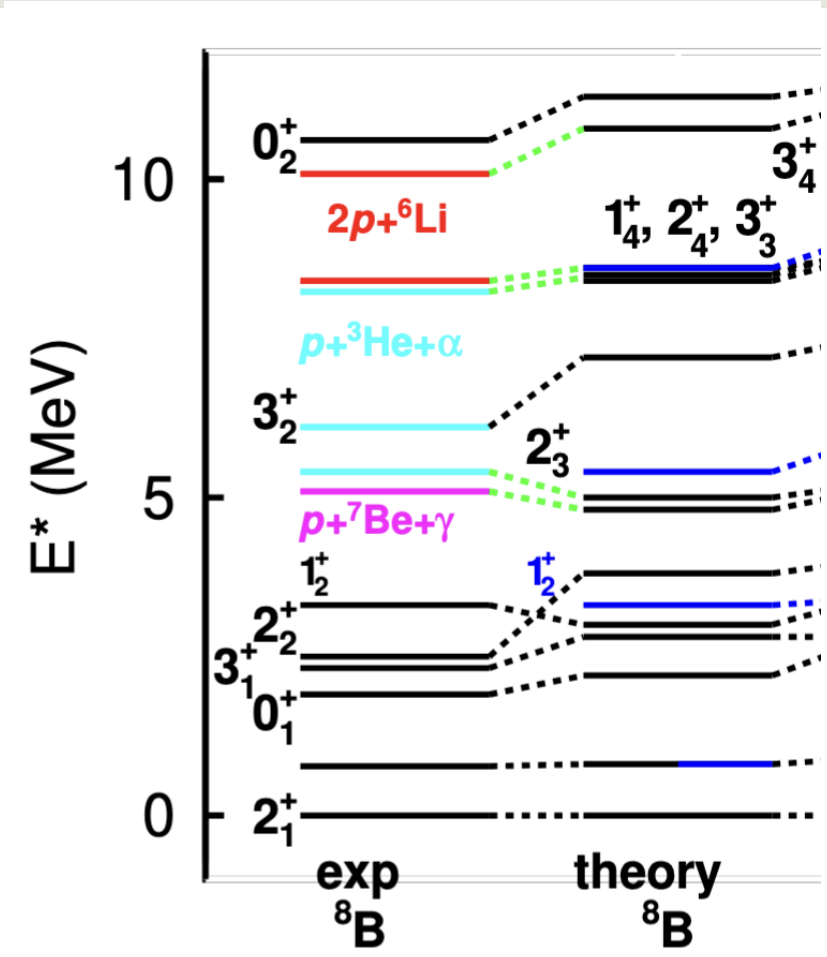
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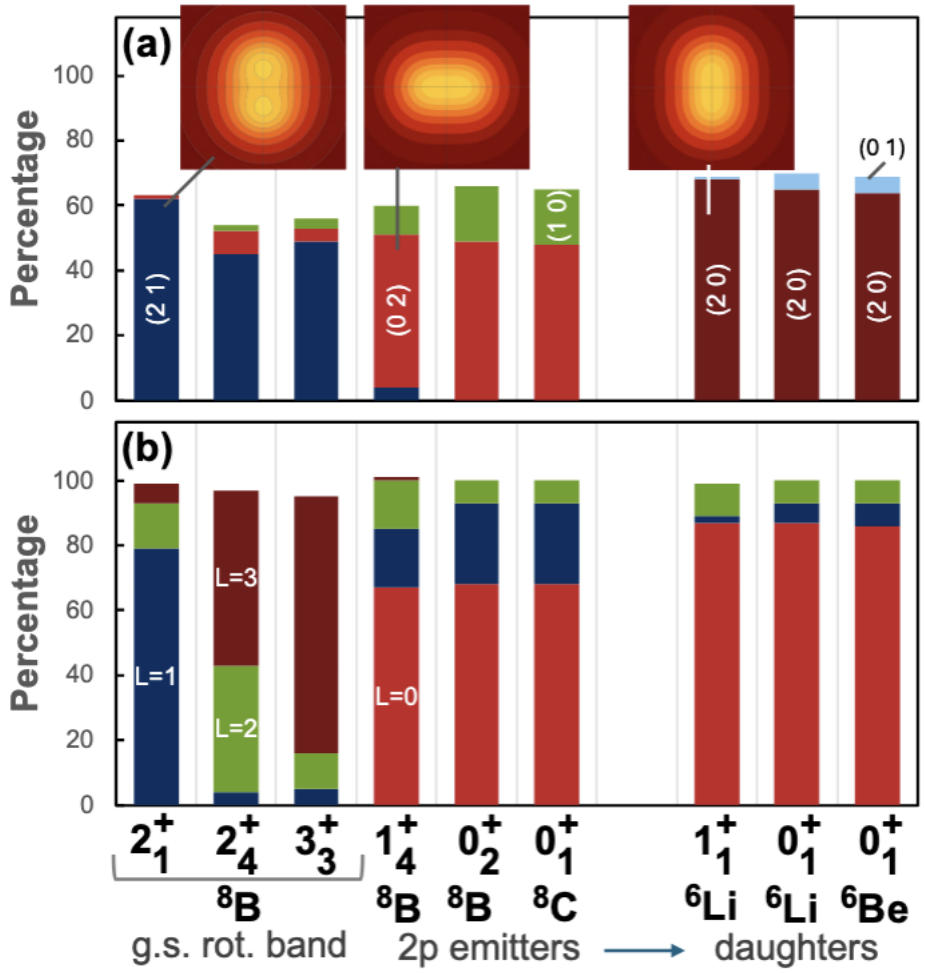
^{18}Ne (how structure methods can help)



Credit: Artemis Tsantiri

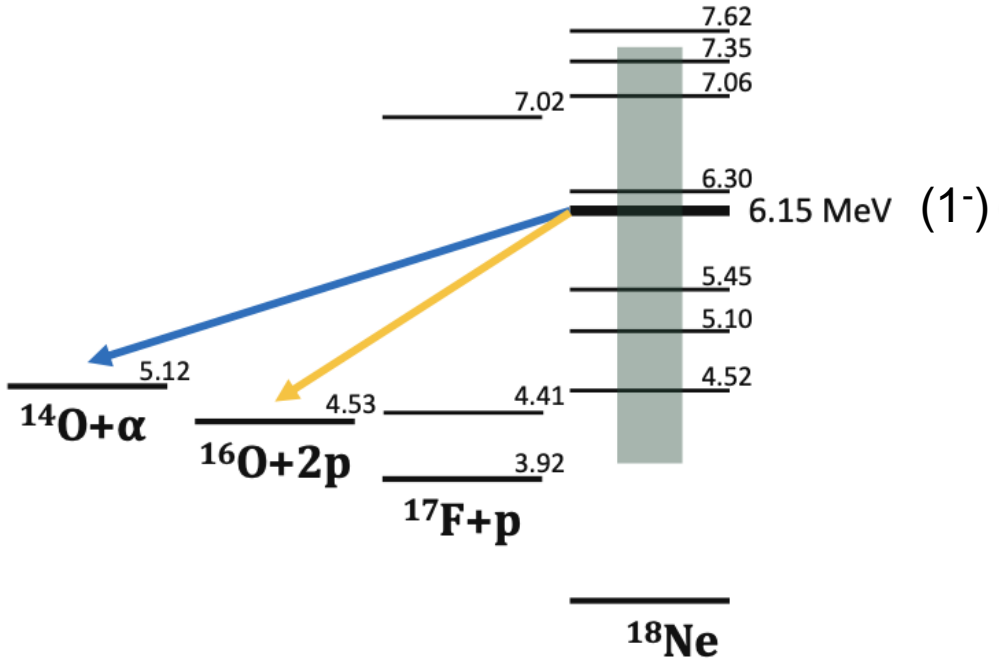
Structure calculations can be used to inform decay channels



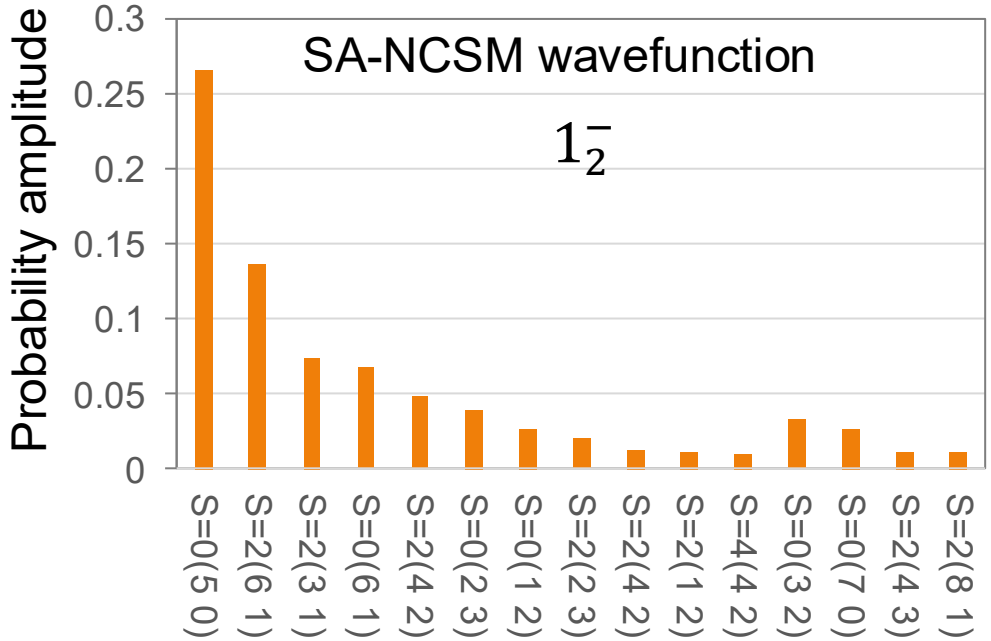


Charity, Sargsyan, *et al.* PRC 113, 024322 (2026)
& Charity, Sargsyan, *et al.* arXiv:2512.15598

^{18}Ne (how structure methods can help)

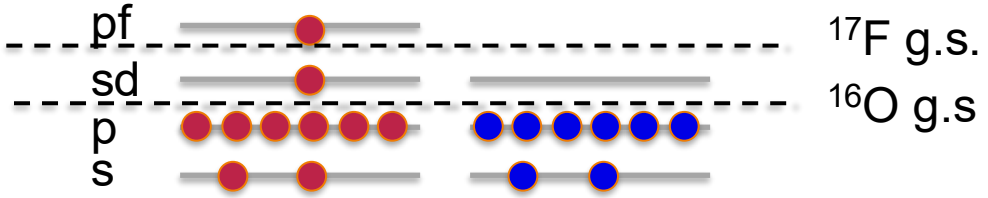


Credit: Artemis Tsantiri

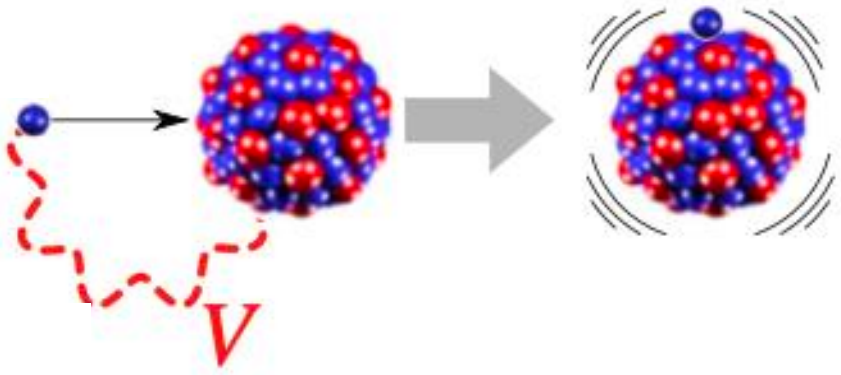


SU(3) quantum numbers

^{18}Ne 1$^-$
(5 0), (3 1), (1 2)



Embedding nuclear structure information within OP



Feshbach formalism

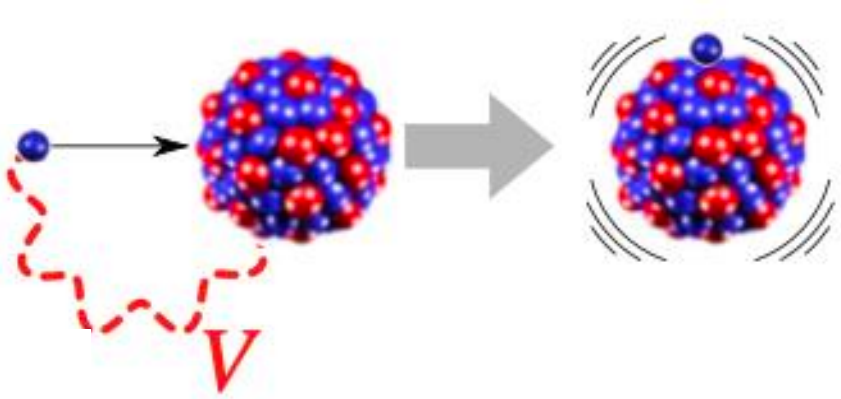
$$V(\boldsymbol{r},\boldsymbol{r}',E) = U_0(\boldsymbol{r}) + V_{PO}(\boldsymbol{r},\boldsymbol{r}',E-E_i)$$
$$= U_0(\boldsymbol{r}) + \sum_i U_{0i}(\boldsymbol{r})G_i(\boldsymbol{r},\boldsymbol{r}',E-E_i)U_{0i}(\boldsymbol{r}')$$

Static, energy-independent potential

Polarization potential: Requires input from nuclear structure

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

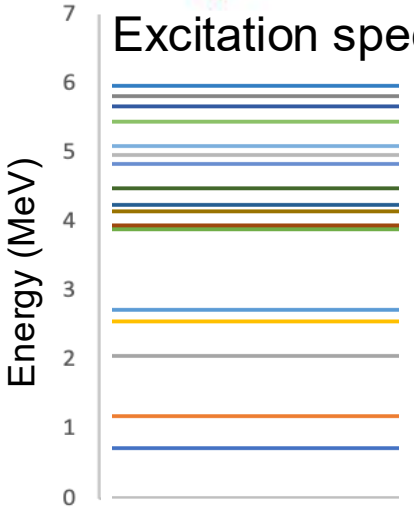
Embedding nuclear structure information within OP

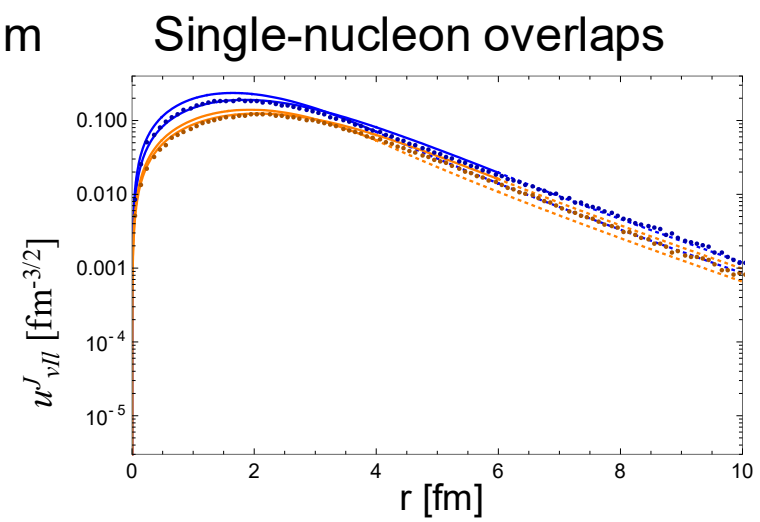


Feshbach formalism

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

Polarization potential: Requires input from nuclear structure

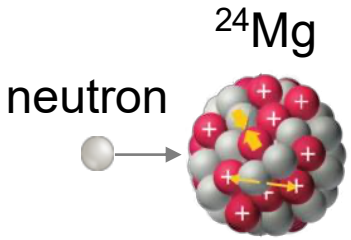


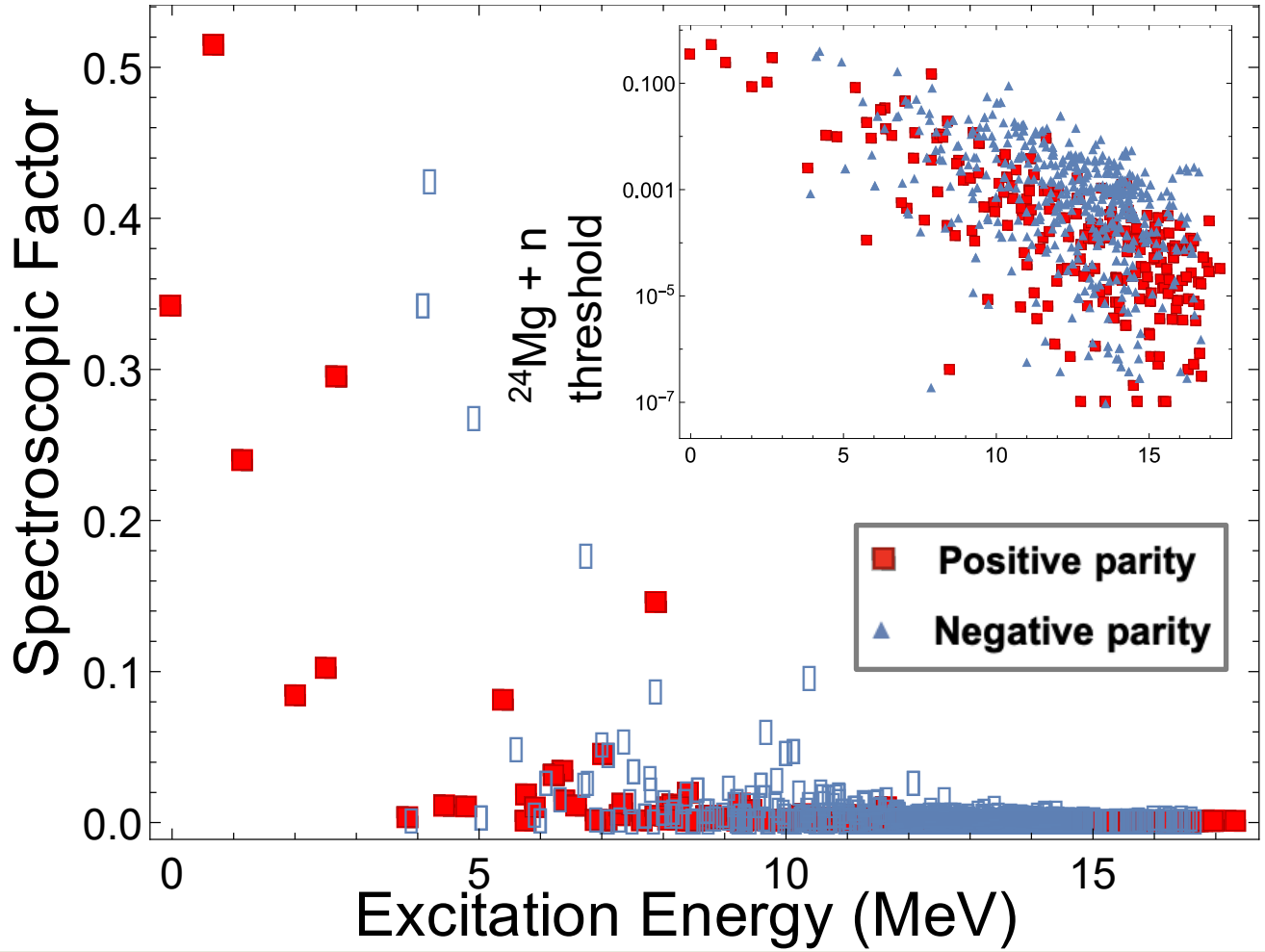


e.g., **shell model, RPA, ab initio models, ...**

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

1st ingredient for constructing OP: shell model input



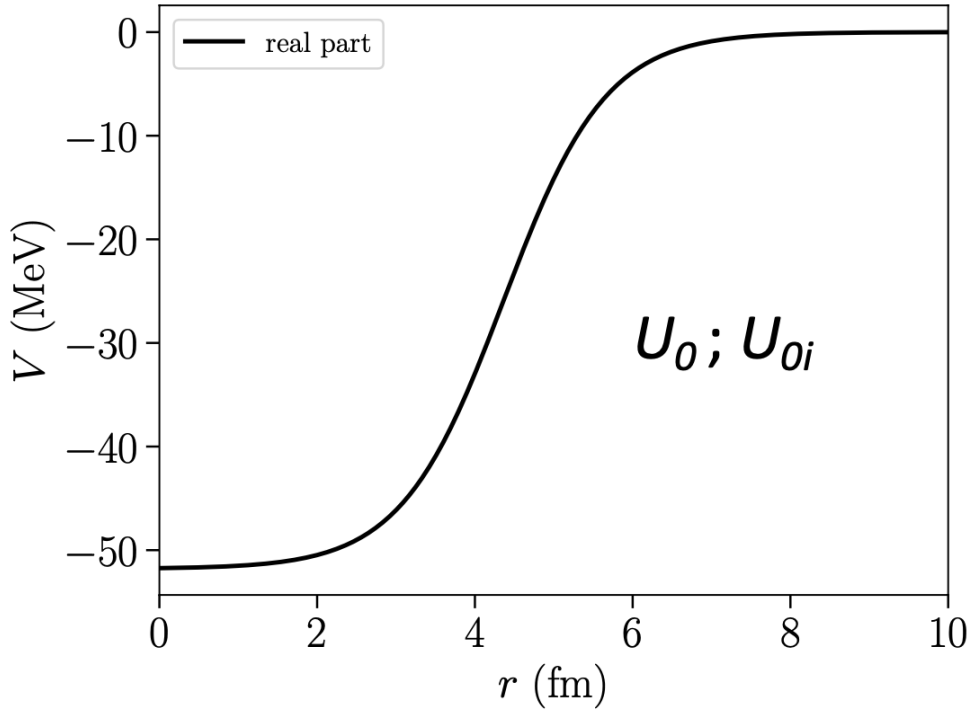


Around 600 intrinsic states

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

2nd 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



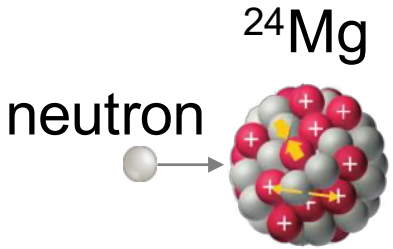
$$V(\boldsymbol{r},\boldsymbol{r}',E) = U_0(\boldsymbol{r}) + \sum_i U_{0i}(\boldsymbol{r})G_i(\boldsymbol{r},\boldsymbol{r}',E-E_i)U_{0i}(\boldsymbol{r}')$$

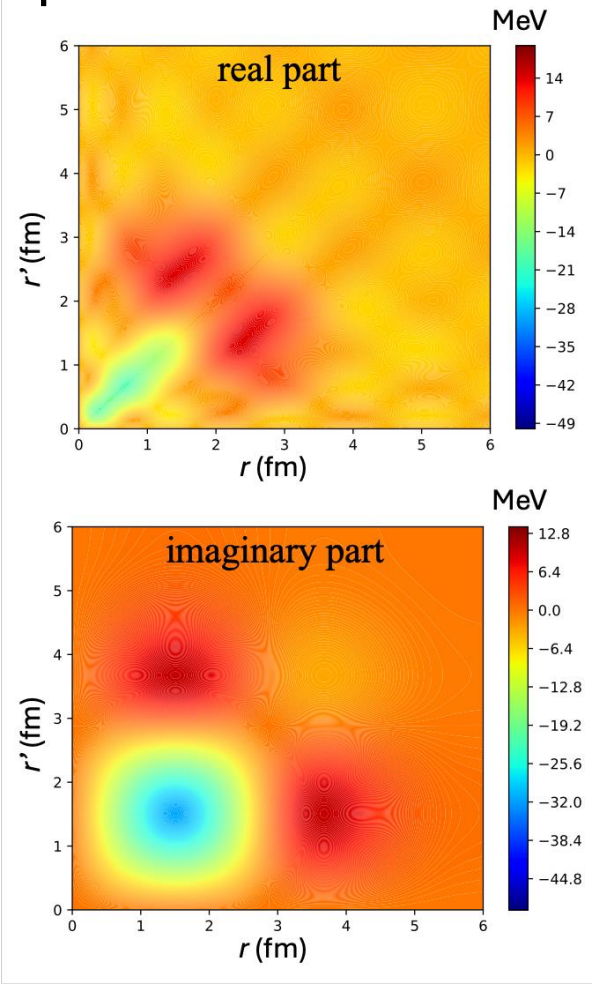
$$G(\boldsymbol{r},\boldsymbol{r}',E) = [E - T - V(r,r',E)]^{-1}$$

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

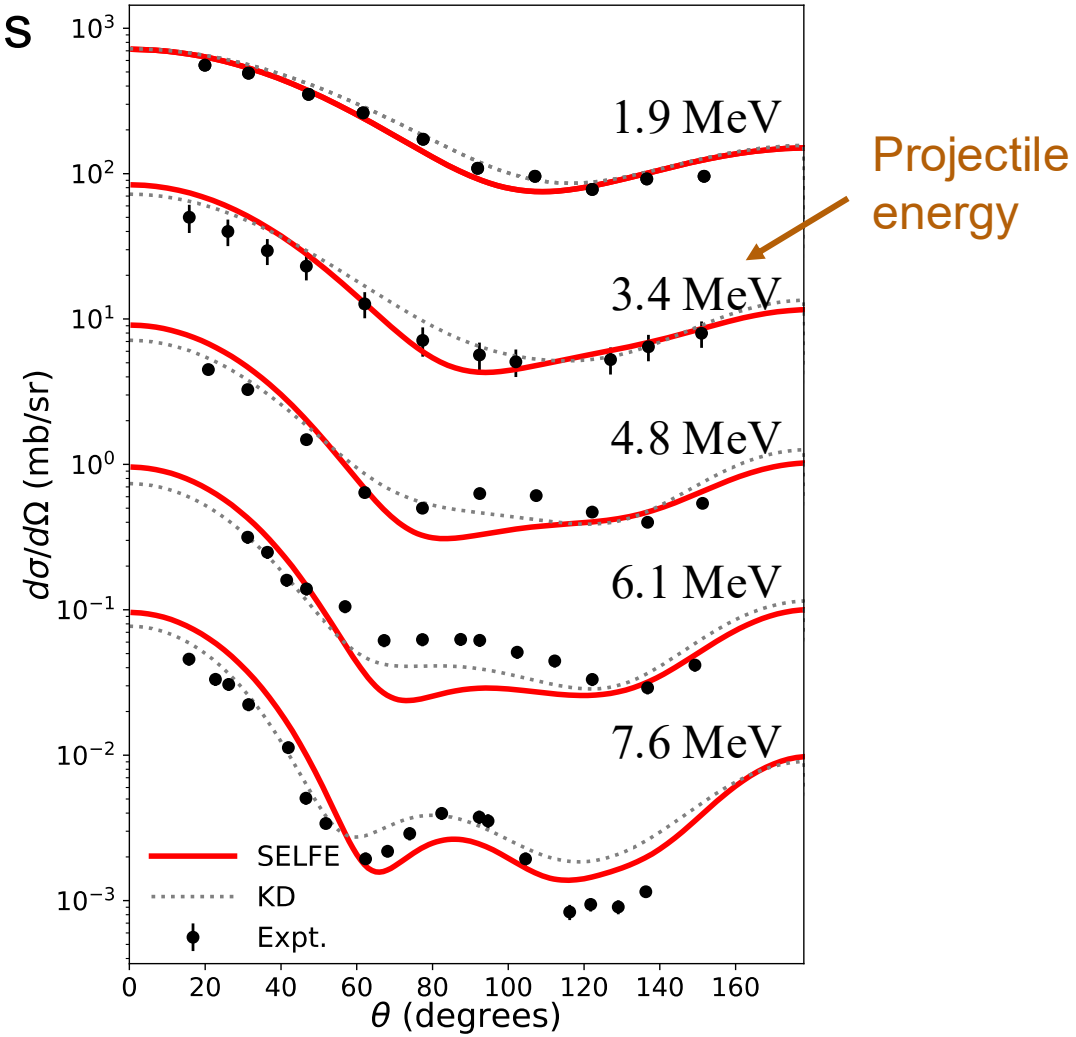
Accurate prediction without parameters fitted to experimental scattering data!

Optical potential for 3.4 MeV neutrons



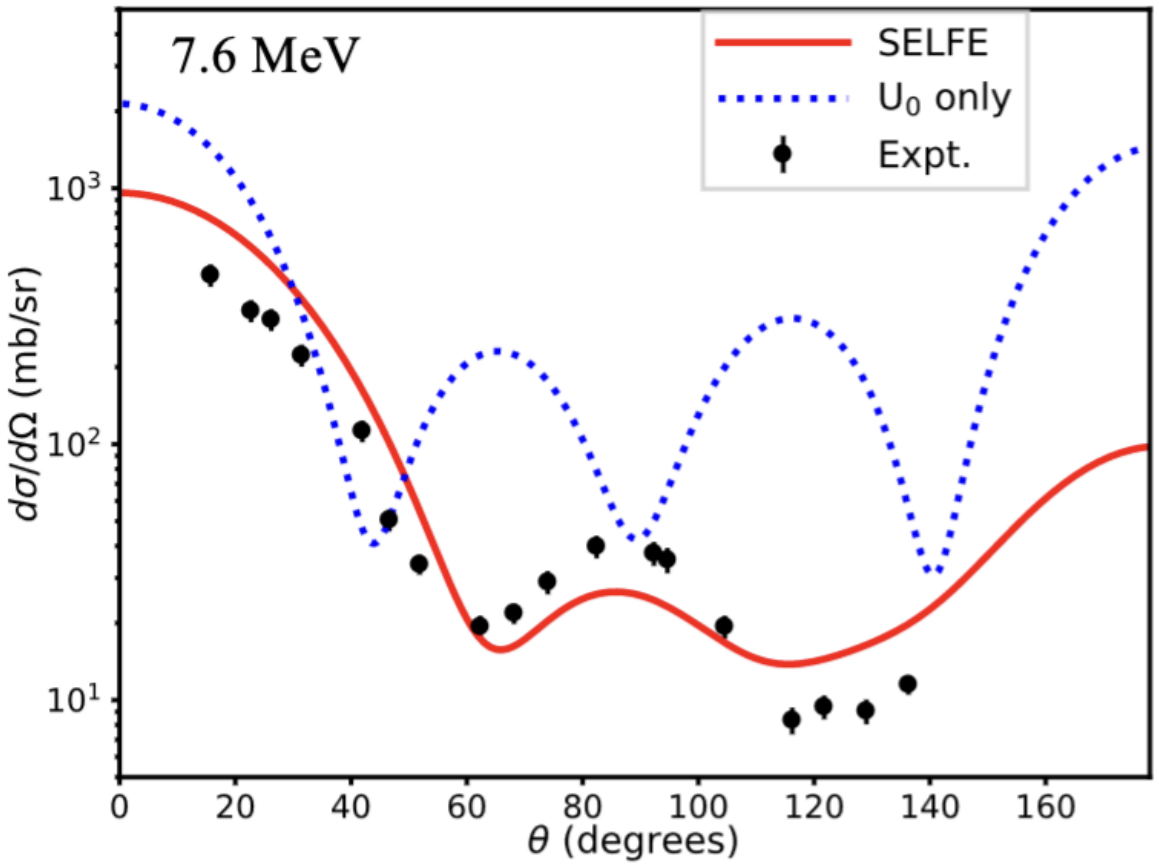


In collaboration with G. Potel (talk on Monday)



Sargsyan, Potel, Kravvaris, Escher, Phys. Rev. C 112, 054606 (2025) [Editors' suggestion]

No phenomenological imaginary terms



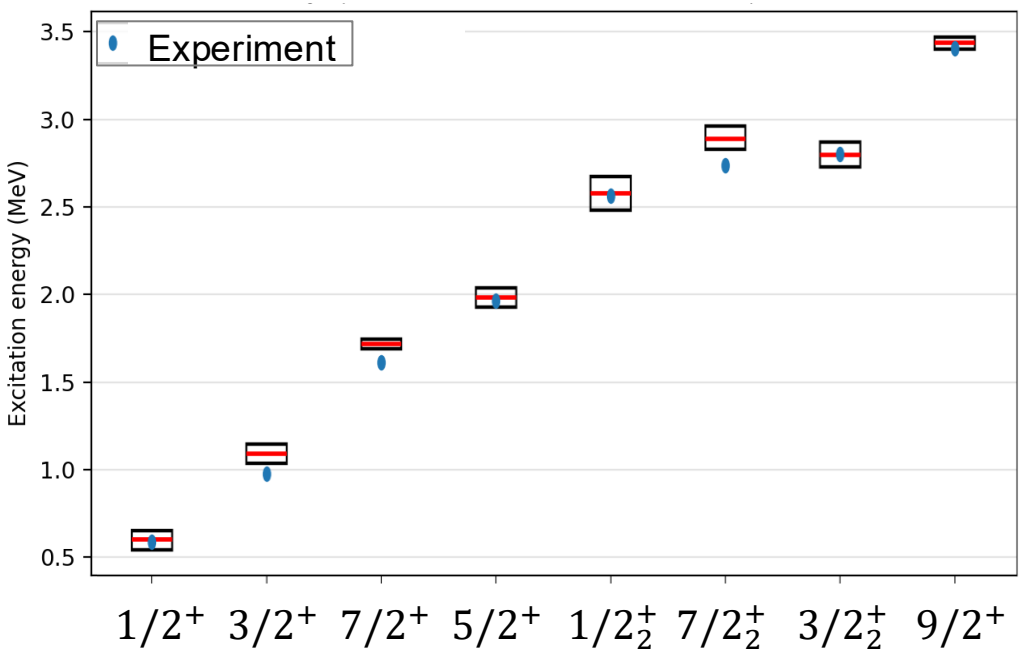
$$V(\boldsymbol{r},\boldsymbol{r}',E) = U_0(\boldsymbol{r},E) + V_{PO}(\boldsymbol{r},\boldsymbol{r}',E) = U_0(\boldsymbol{r},E) + \sum_i U_{0i}(\boldsymbol{r})G_i(\boldsymbol{r},\boldsymbol{r}',E)U_{0i}(\boldsymbol{r}')$$

Sargsyan, *et al.*, arXiv:2410.21714

Propagating structure uncertainties to reactions

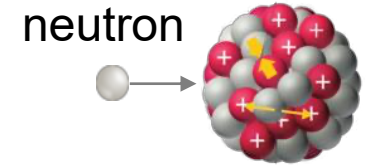
Uncertainty quantified shell model potential (USDBUQ)
O. Gorton, K. Kravvaris, Phys. Rev. C 112, 014302 (2025)

^{25}Mg spectrum

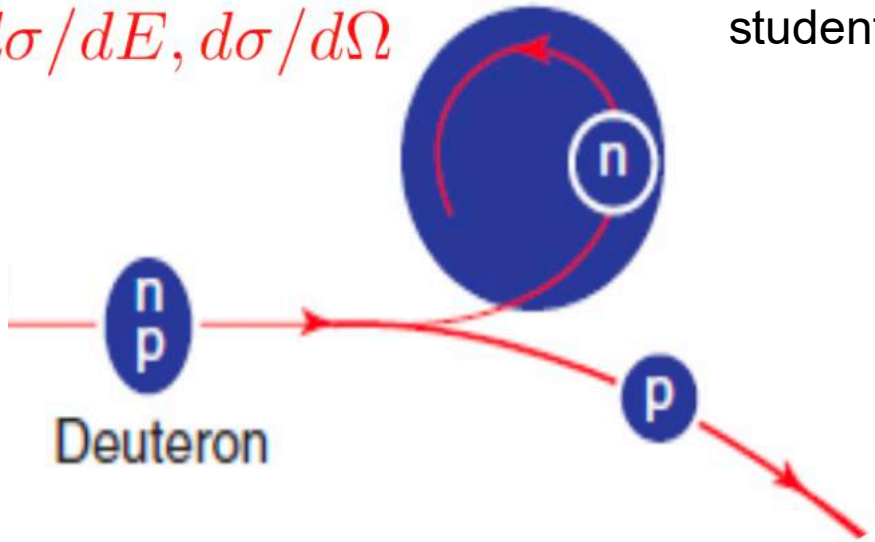


UQ

^{24}Mg
neutron



$d\sigma/dE, d\sigma/d\Omega$



Calculations by O. Fernandes

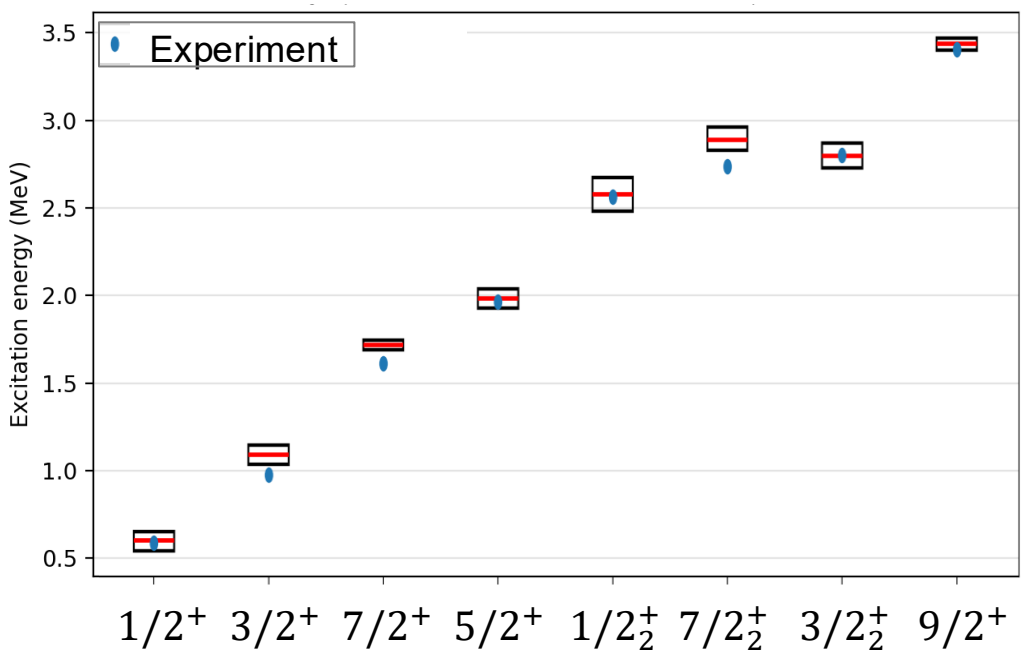


Ojas Fernandes, Undergraduate student @MSU

Propagating structure uncertainties to reactions

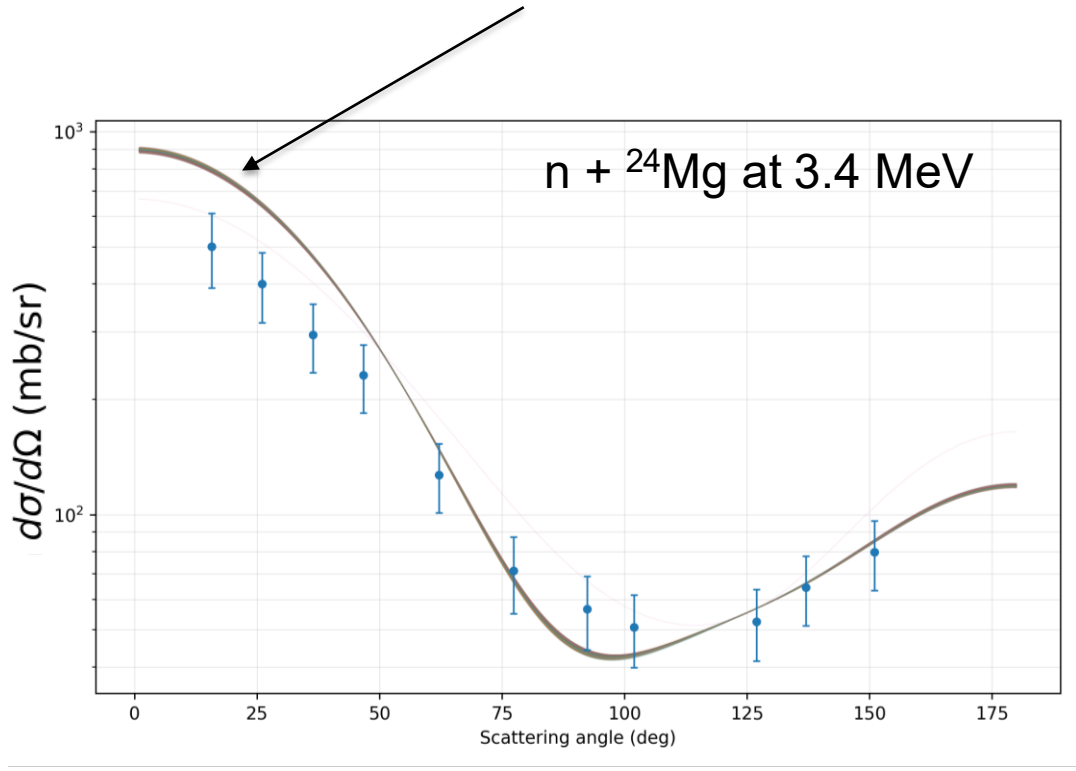
Uncertainty quantified shell model potential (USDBUQ)
O. Gorton, K. Kravvaris, Phys. Rev. C 112, 014302 (2025)

^{25}Mg spectrum



UQ

Uncertainty only from the positive parity states

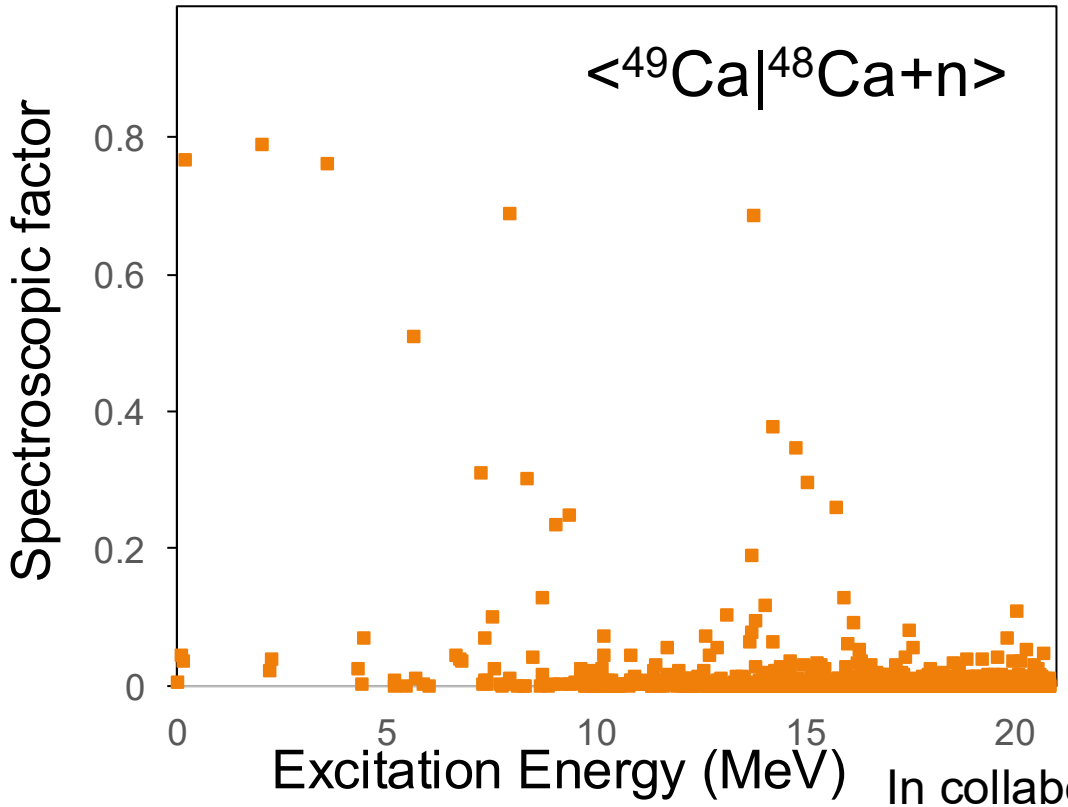


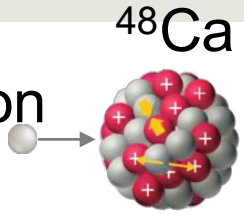
Calculations by O. Fernandes

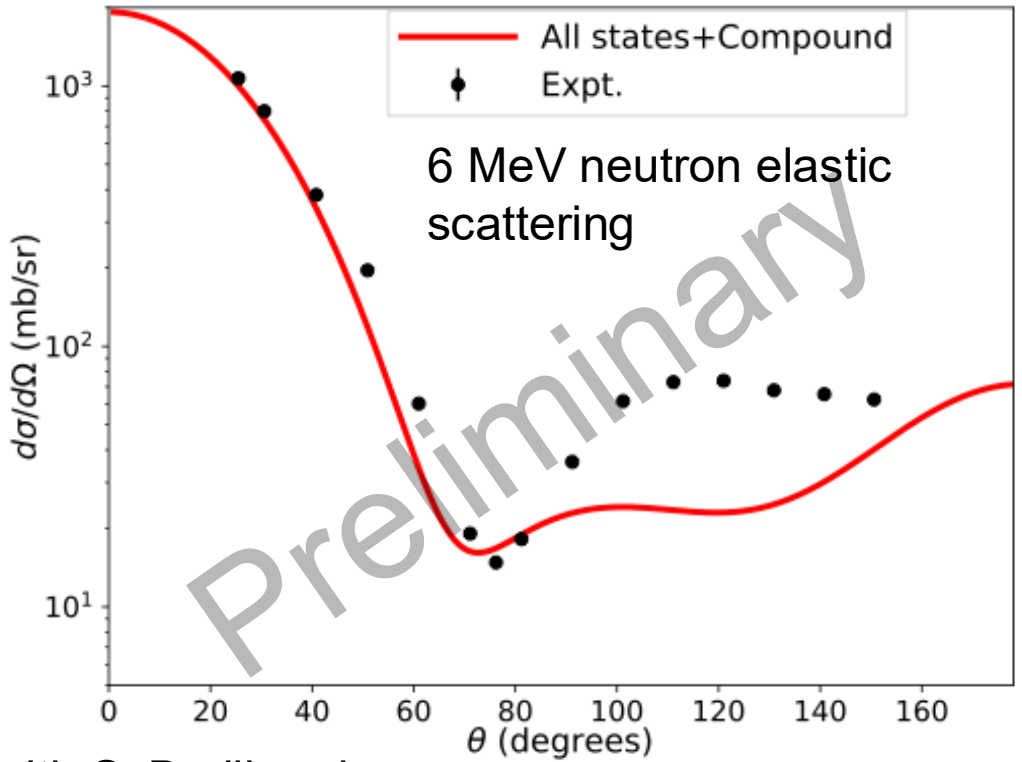
Versatile to any structure model

Structure input from *ab initio* SCGF

$\Delta NNLO_{GO}$ $\hbar\Omega$ =14 MeV







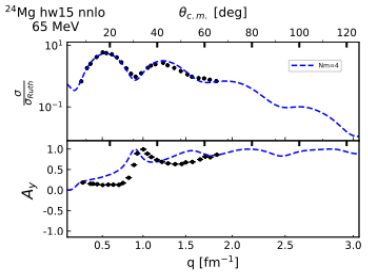
In collaboration with S. Brolli and C. Barbieri (talk on Tuesday)

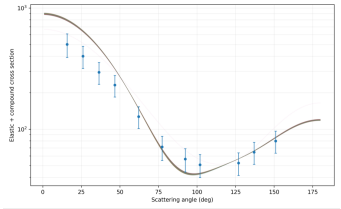
Summary

- Nuclear reaction models need input from structure
- Modern *ab initio* models can provide a reliable input with predictive capabilities
- We have used SA-NCSM to provide input to study alpha clustering in ^{16}O and ^{20}Ne via knockout and transfer reactions
- Multiple scattering approach with SA-NCSM densities provides a good description of Mg scattering data for >65 MeV and predictions where no data exists
- Our new approach for low-energy scattering uses spectroscopic factors and excitation energies to build an optical potential
- This approach can propagate structure uncertainties to reaction observables









Acknowledgements

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Kyle Beyer

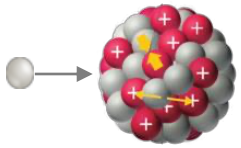
Oliver Gorton, Kostas Kravvaris

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Thank you!

Discussion questions, wishlist

- Constructing reaction models directly from the same microscopic Hamiltonians used in structure calculations
- Derive nonlocal, energy-dependent optical potentials with controlled uncertainties from many-body theory that work across target masses and energies
- Make these potentials accessible to experimentalists



Wishlist for microscopic optical potentials

- Structure input from more models (especially for heavy nuclei) – excitation spectrum/density of states, spectroscopic factors
- Uncertainty quantified structure input
- For systems at the dripline, precise measurements of thresholds