LUND UNIVERSITY

Newton Fund

THE ROYAL SOCIETY

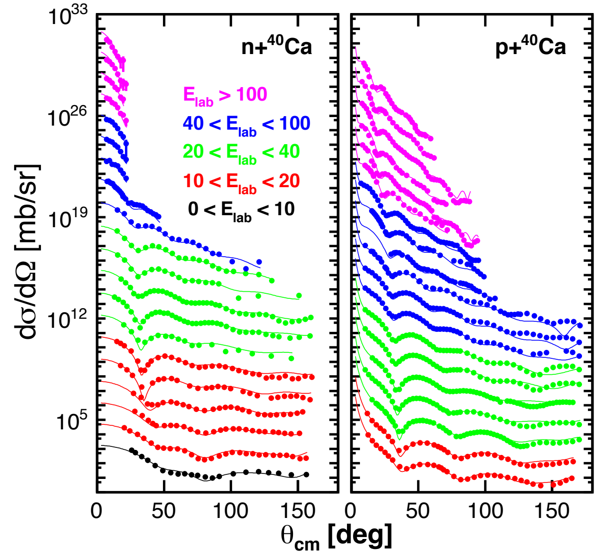
Optical potentials and knockout reactions from chiral interactions

Andrea Idini

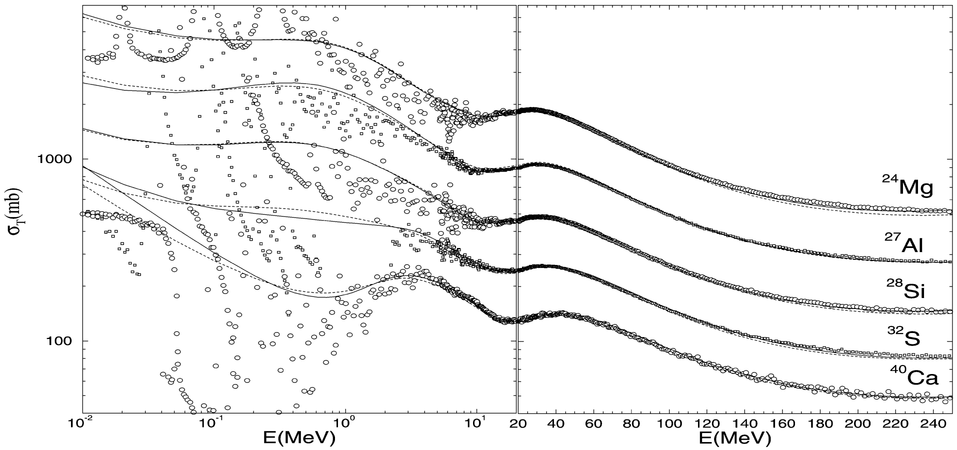
"Recent advances and challenges in the description of nuclear reactions at the limit of stability"

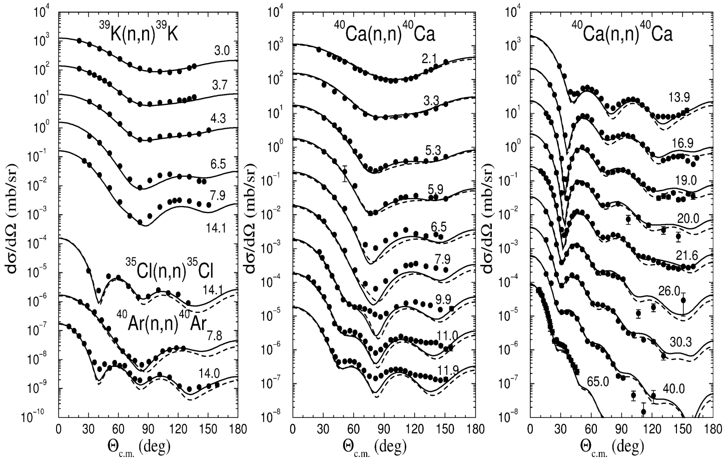
Why optical potentials?

- Optical potentials **reduce many-body complexity** decoupling structure contribution and reactions dynamics.
- Often fitted on elastic scattering data (locally or globally)
- A microscopic model is difficult but worth it



Dickhoff, Charity, Mahzoon, JPG44, 033001 (2017)





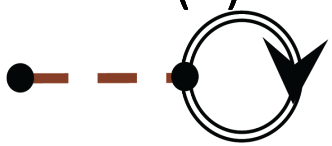
Koning, Delaroche, NPA713, 231 (2002)

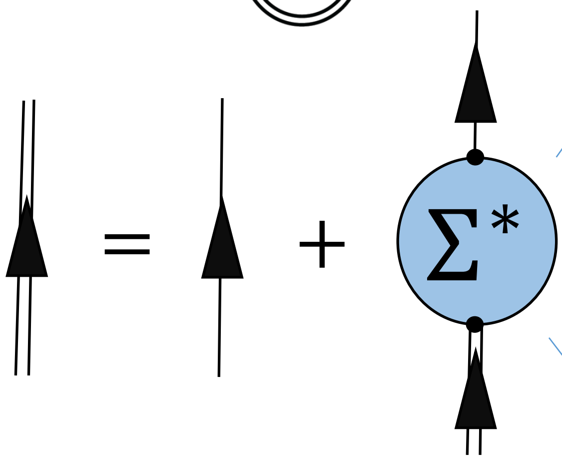
Dyson Equation

$$g_{\alpha\beta}(\omega) = g^0_{\alpha\beta}(\omega) + \sum_{\gamma\delta} g^0_{\alpha\gamma}(\omega)\Sigma^\star_{\gamma\delta}(\omega)g_{\delta\beta}(\omega)$$

HF

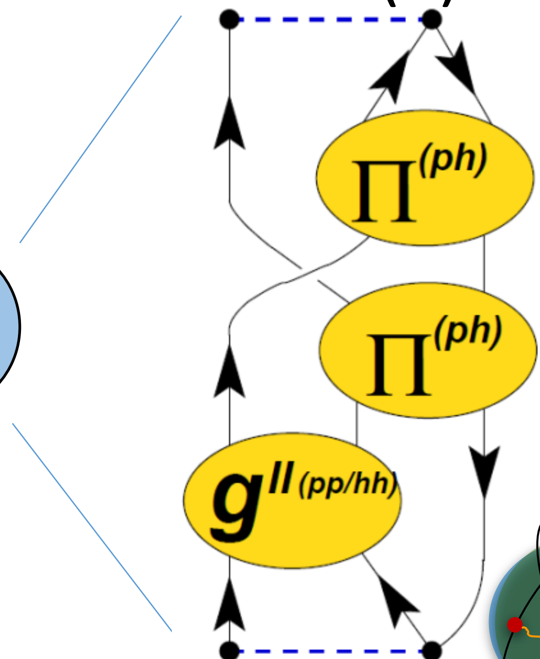
ADC(1)

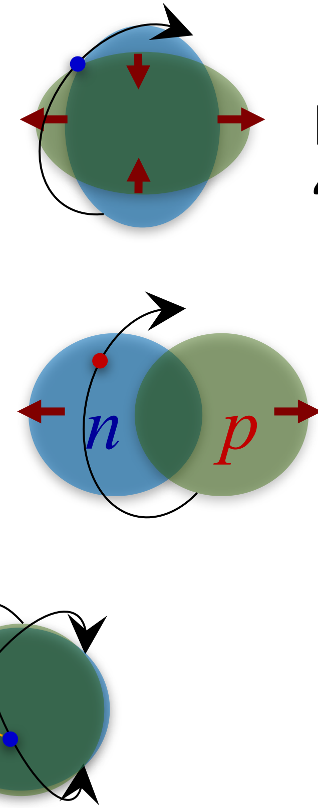




Faddeev RPA

ADC(3)



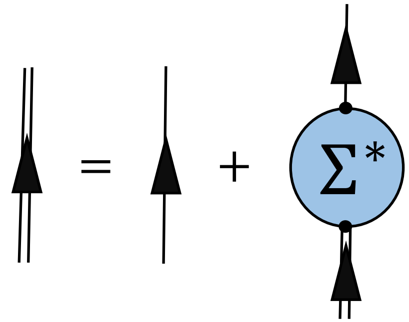


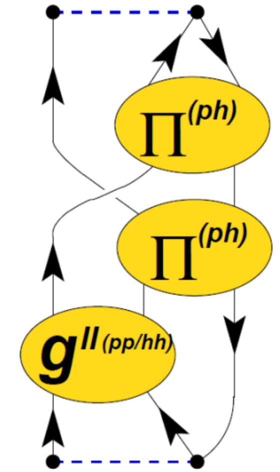
Particle hole 'polarization' propagator (ph-RPA)

Particle-particle (pp-RPA) two-body correlation 'ladder' propagator

Källén–Lehmann spectral representation

$$H(A) = T - T_{c.m.}(A+1) + V + W$$



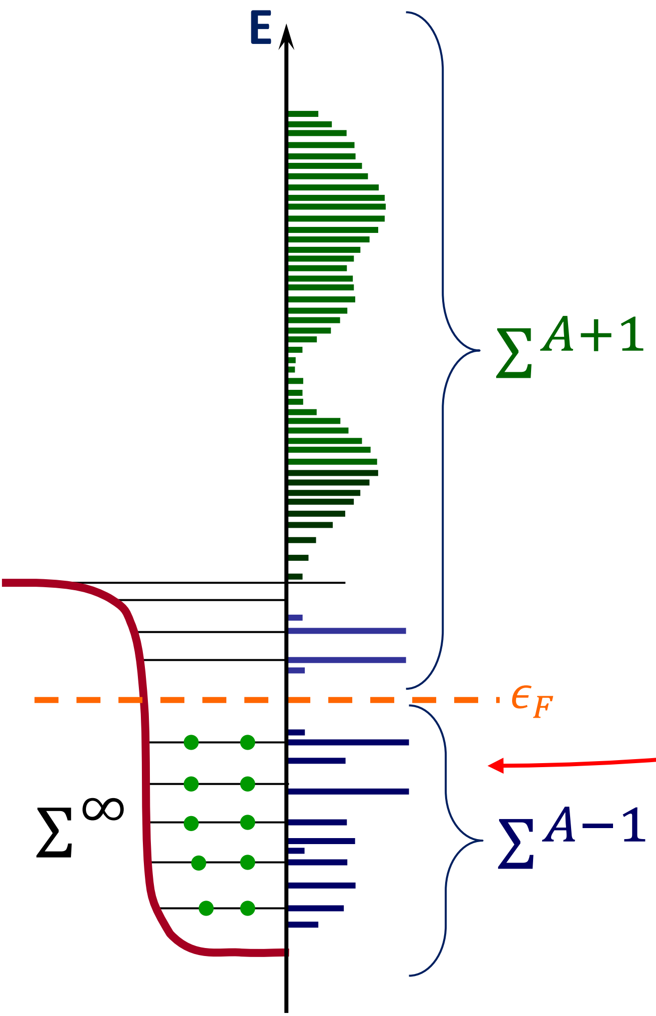


$$g_{\alpha,\beta}(E,\Gamma) = \sum_n \frac{\langle \Psi_0^A | c_\alpha | \Psi_n^{A+1} \rangle \langle \Psi_n^{A+1} | c_\beta^\dagger | \Psi_0^A \rangle}{E - E_n^{A+1} + E_0^A + i\Gamma} + \sum_i \frac{\langle \psi_0^A | c_\alpha^\dagger | \Psi_n^{A-1} \rangle \langle \Psi_n^{A-1} | c_\beta | \Psi_0^A \rangle}{E - E_0^A + E_i^{A-1} - i\Gamma},$$

Overlaps of A+1 and A-1 states

Excited states calculated from Dyson equation

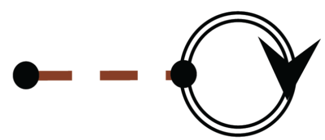
Nucleon elastic scattering



The irreducible self-energy is a nucleon-nucleus optical potential*

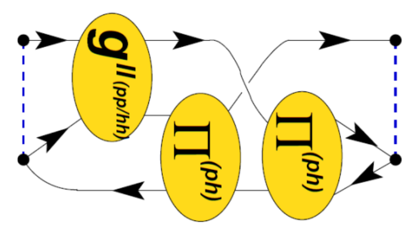
$$\Sigma^{*}_{\alpha\beta}(r, r'; \omega) = \Sigma^{\infty}_{\alpha\beta} + \sum_i \frac{m^i_\alpha \, m^{i*}_\beta}{\omega - \epsilon_i \pm i\eta}$$

correlated mean-field



resonances beyond mean-field

Correlations



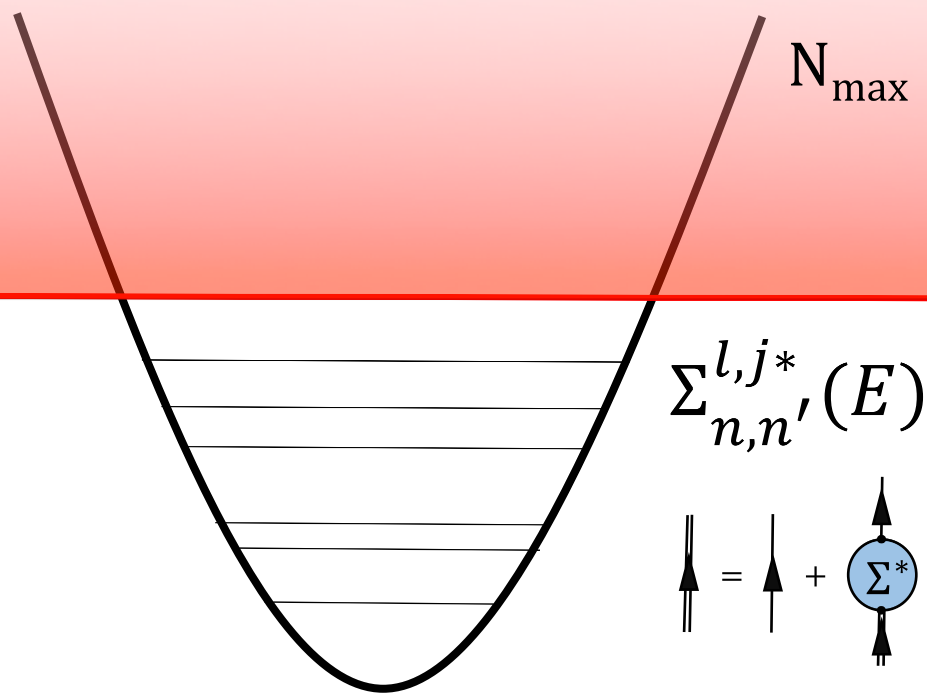
➔ This provides *consistent* many-body and scattering wave functions

*Mahaux & Sartor, Adv. Nucl. Phys. 20 (1991), Escher & Jennings PRC66:034313 (2002)

- Solve Dyson equation in HO Space, find $\Sigma^{l,j*}_{n,n'}(E)$

- diagonalize in full continuum momentum space $\Sigma^{l,j*}(k,k',E)$

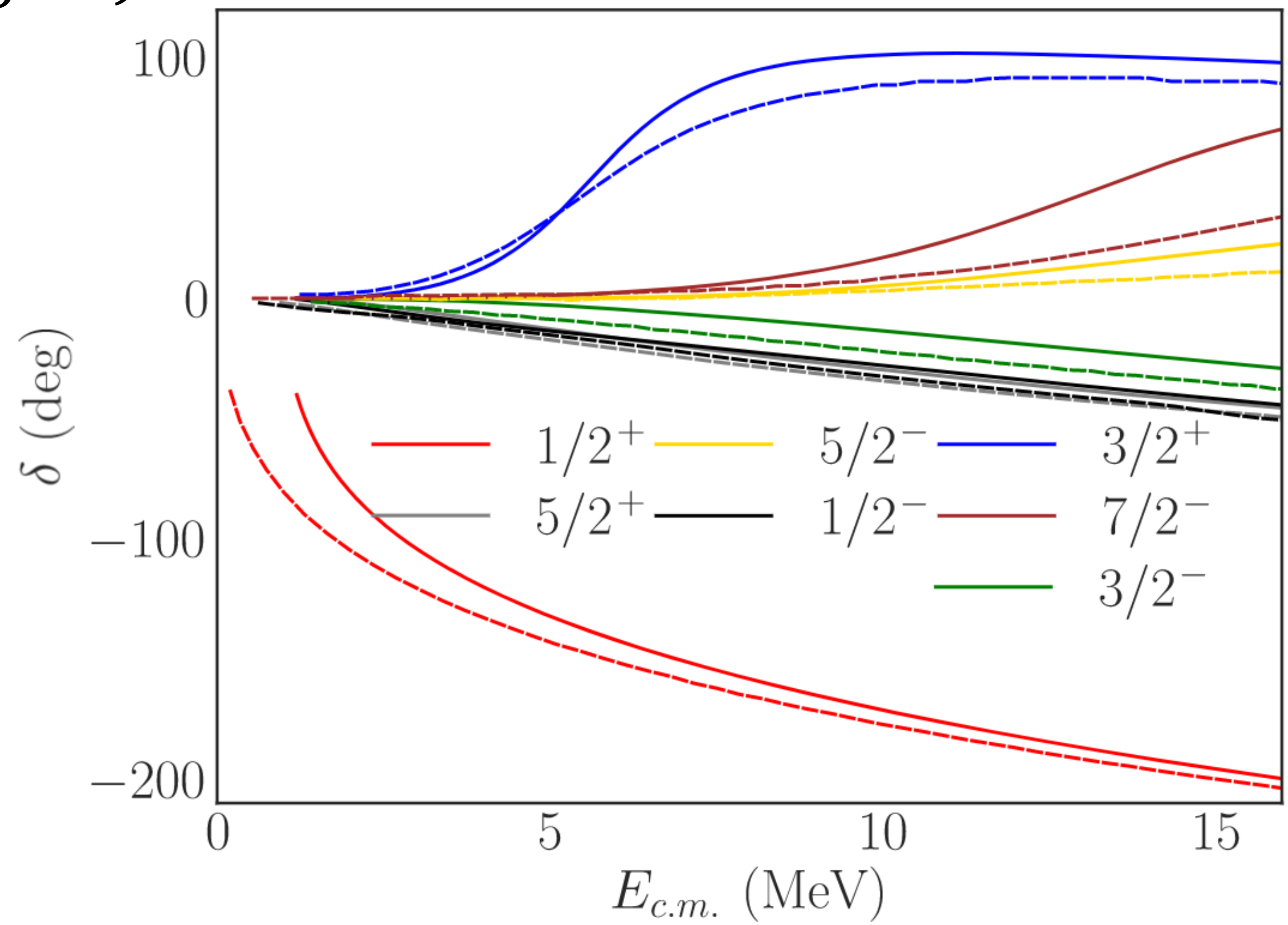
$$\frac{k^2}{2m}\psi_{l,j}(k) + \int dk'k'^2 \left(\Sigma^{l,j*}(k,k',E)\right)\psi_{l,j}(k') = \mathrm{E}\,\psi_{l,j}(k)$$



RESULTS

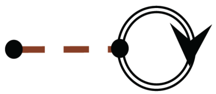
SRG-N^{3}LO, $\Lambda = 2.66$ fm^{-1}

$n + {}^{16}\mathrm{O}\,(g.s.)$



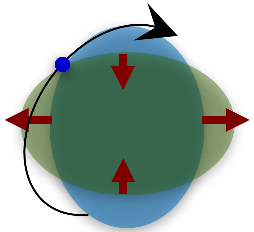
Navràtil, Roth, Quaglioni, PRC82, 034609 (2010)

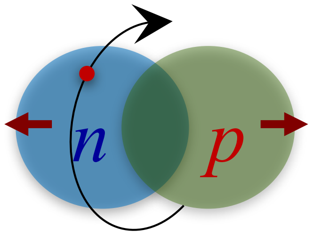
Σ^{∞}

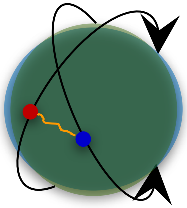


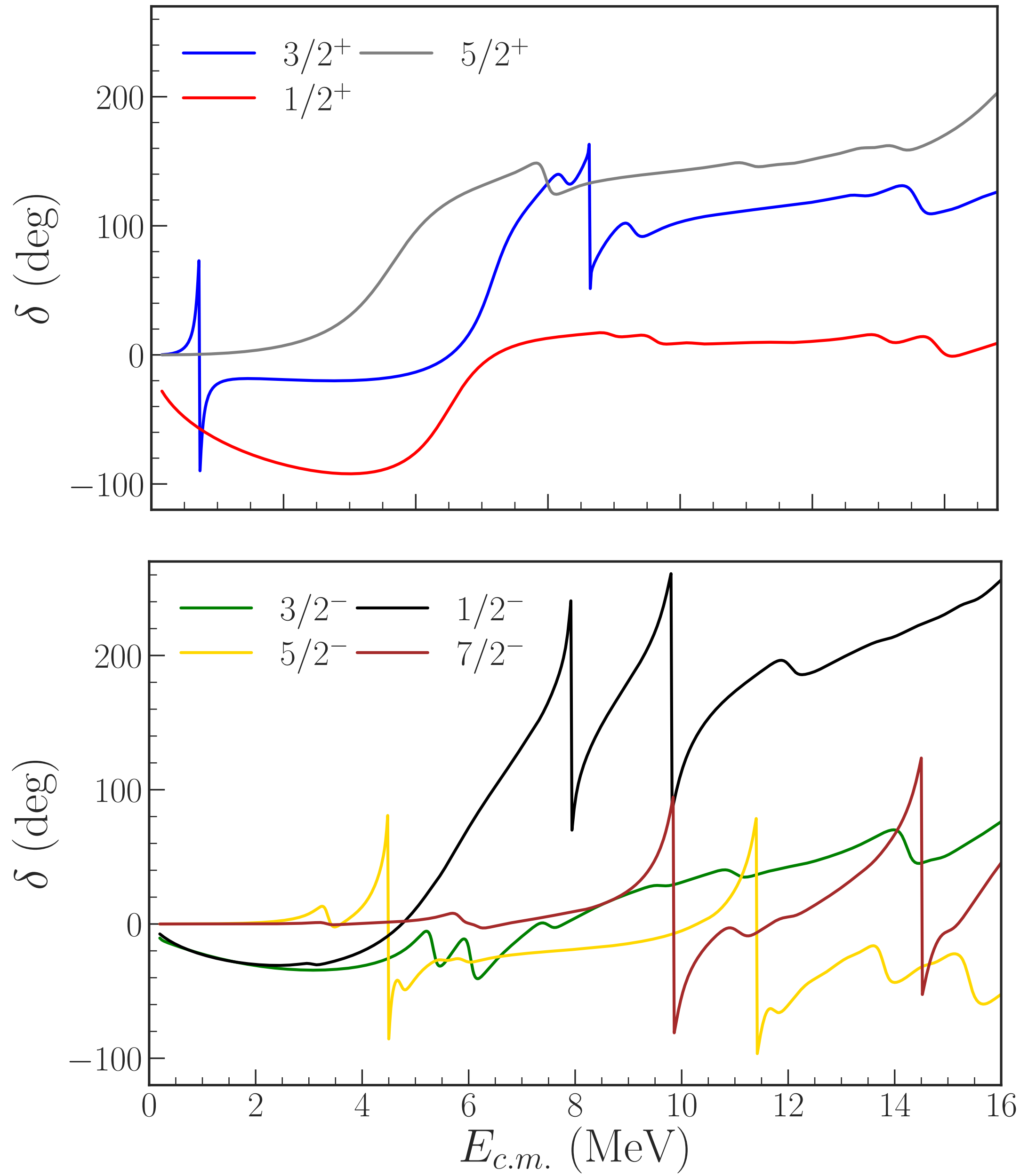
NNLO$_{sat}$

$n + {}^{16}\text{O}\ (g.s. + exc)$

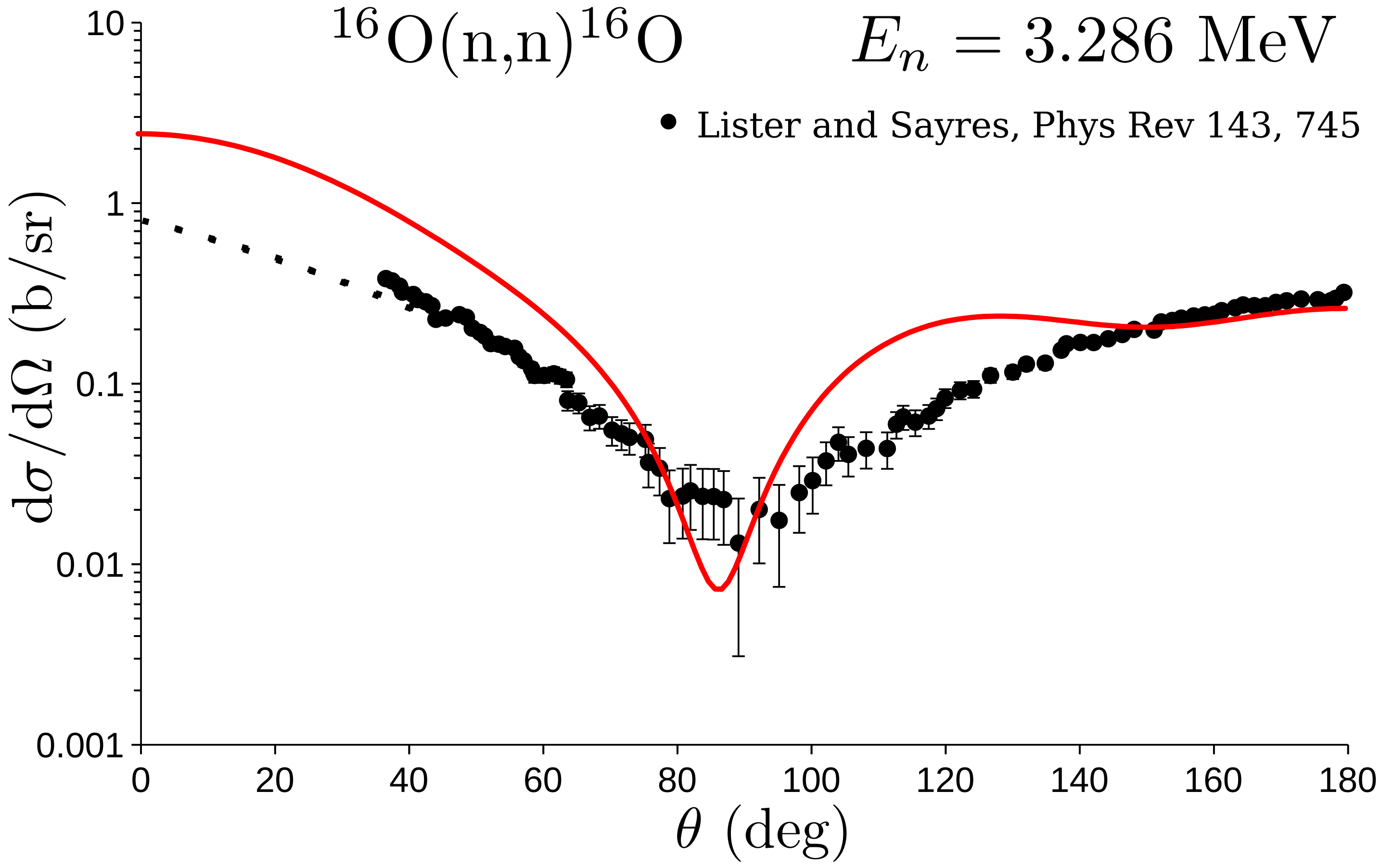


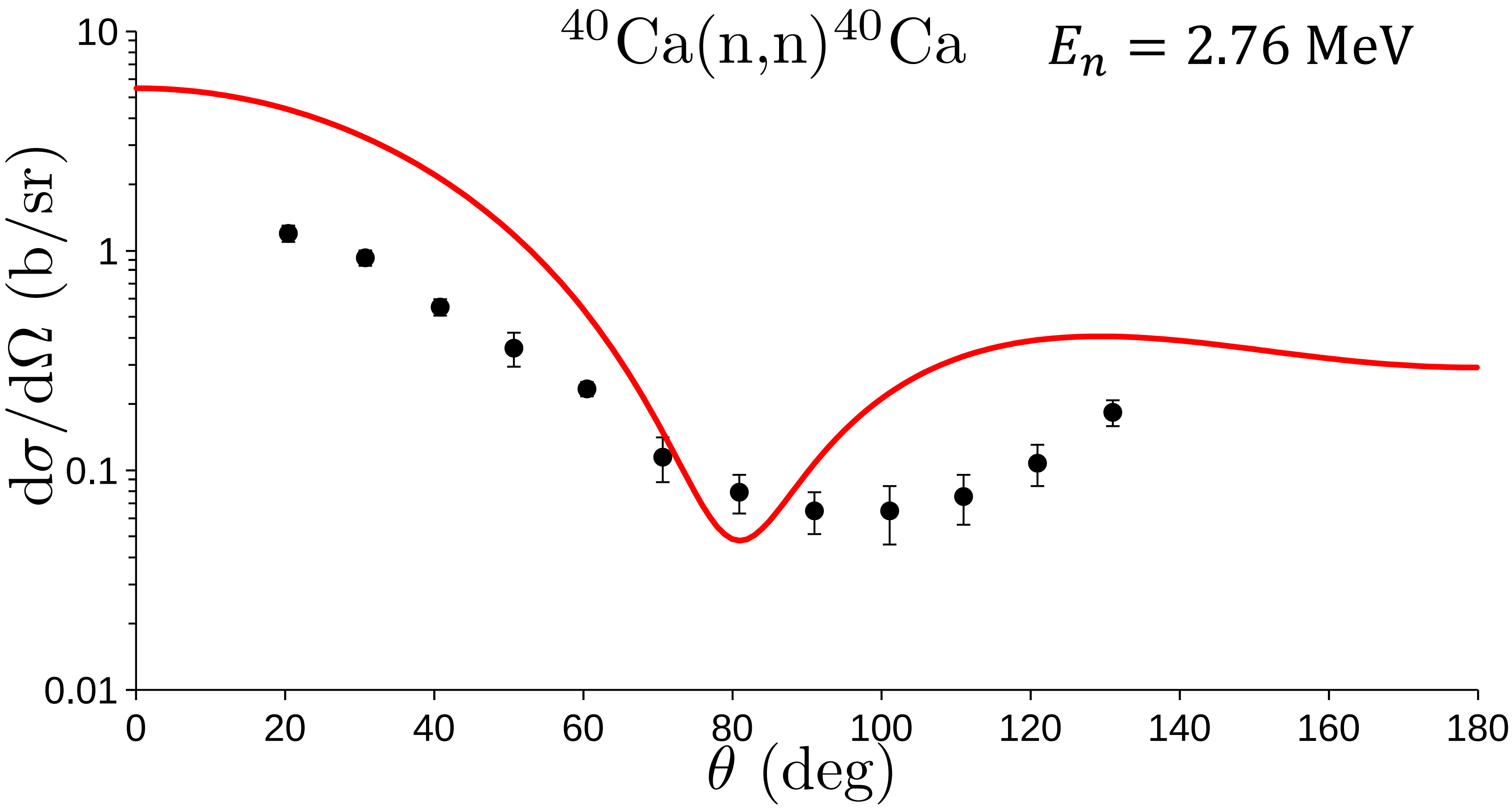






Using the ab initio optical potential for neutron elastic scattering on Oxygen

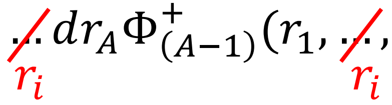


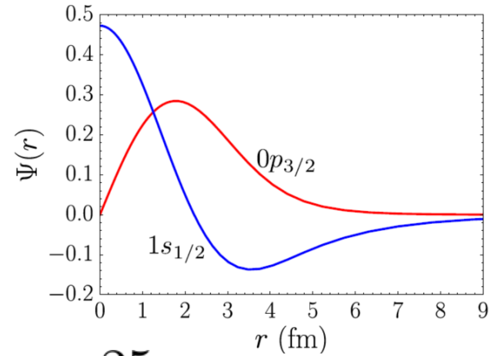


^{40}Ca(n,n)^{40}Ca
$E_n = 2.76$ MeV
dσ/dΩ (b/sr)
10
1
0.1
0.01
0
20
40
60
80
100
120
140
160
180
θ (deg)

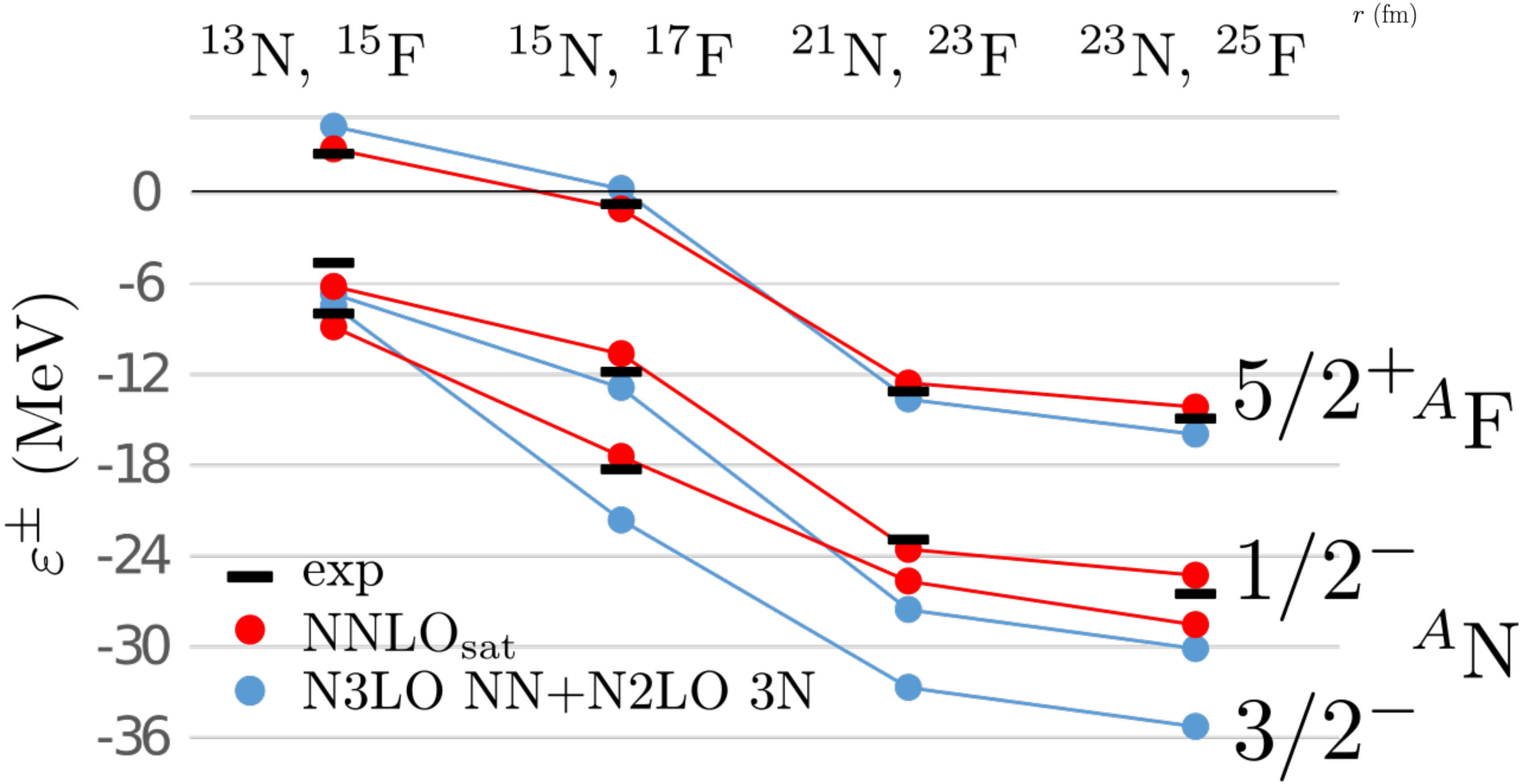
Overlap function

$$\Psi_i(r) = \sqrt{A}\int dr_1 \ldots dr_A \Phi^+_{(A-1)}(r_1, \ldots, r_{A-1})\Phi^+_{(A)}(r_1, \ldots, r_A)$$





Proton particle-hole gap

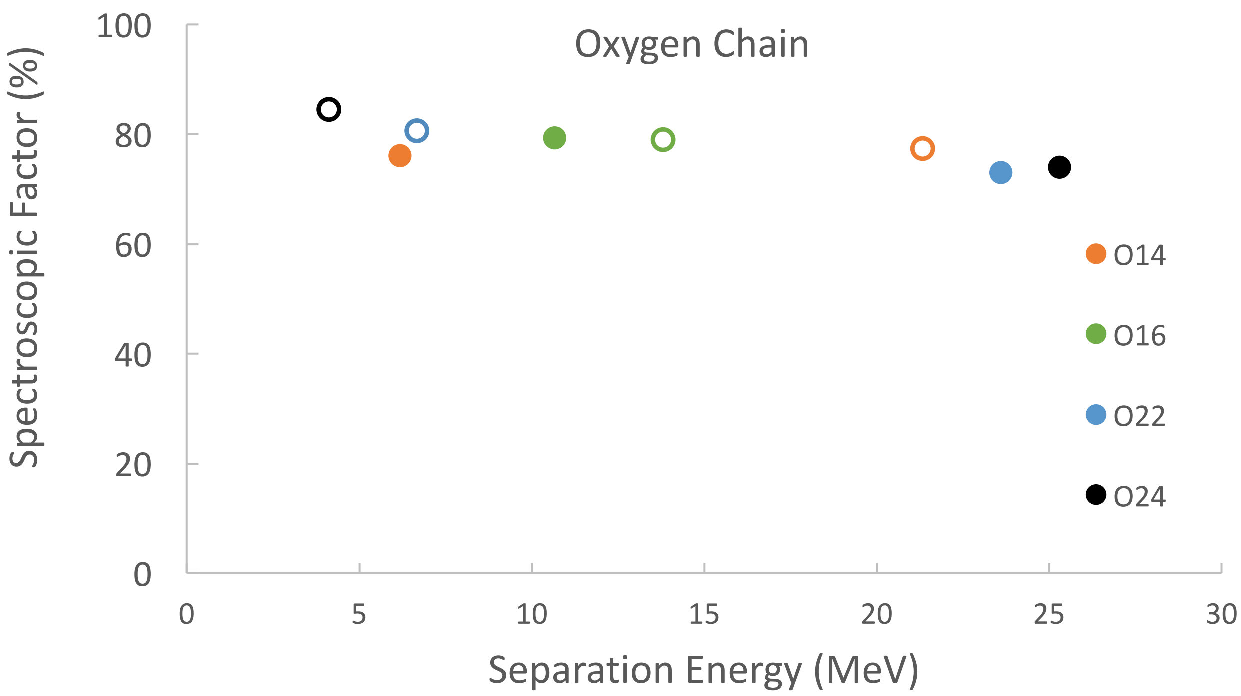


EM results from A. Cipollone PRC**92**, 014306 (2015)

Knockout Spectroscopic Factors

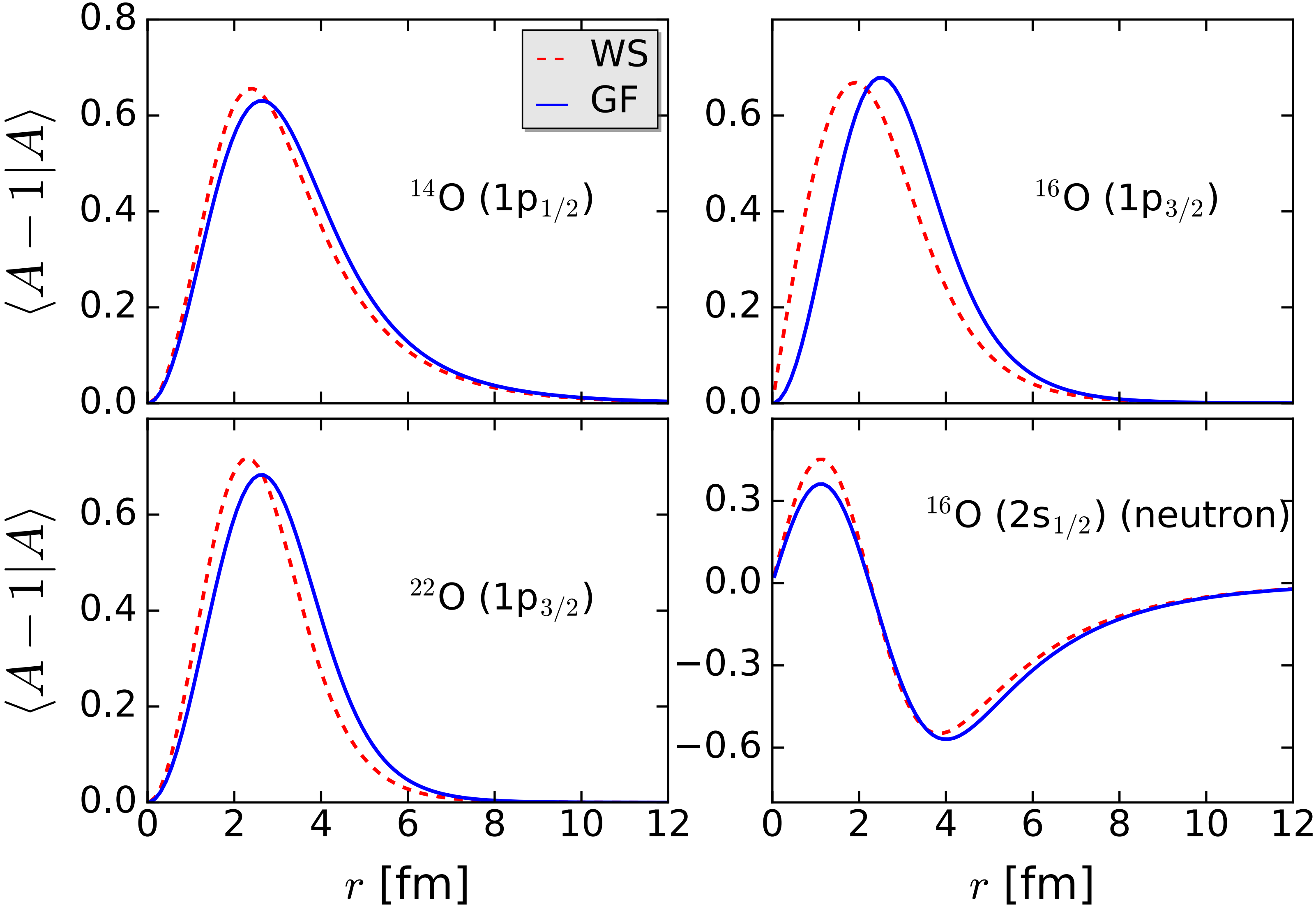
$$\frac{k^2}{2m}\psi_{l,j}(k) + \int dk' k'^2 \left(\Sigma^{l,j*}(k,k',E)\right)\psi_{l,j}(k') = \mathrm{E}\,\psi_{l,j}(k)$$

$$SF = \left|\left\langle \Phi_n^{(A-1)} \middle| \Phi_{g.s.}^{A} \right\rangle\right|^2$$ Calculated from overlap wavefunctions



open circles neutrons, closed protons

Overlap wavefunctions

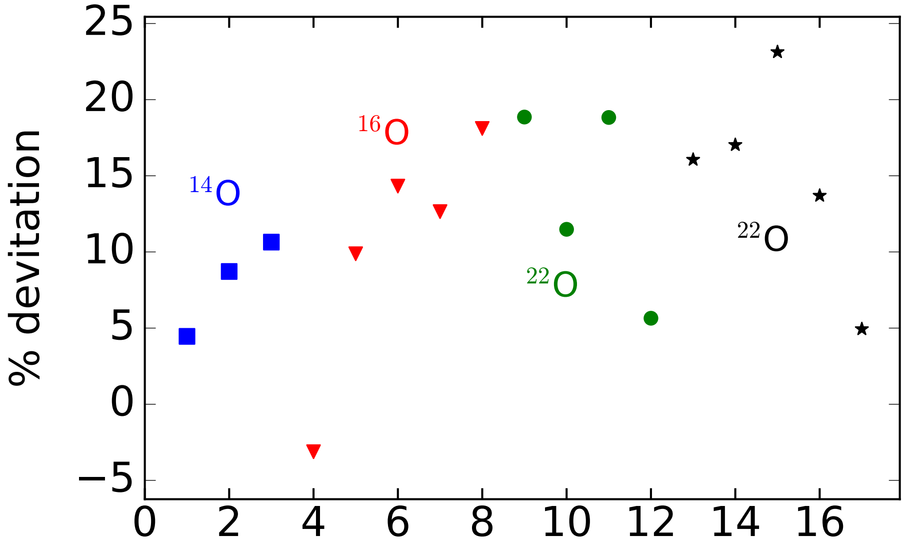


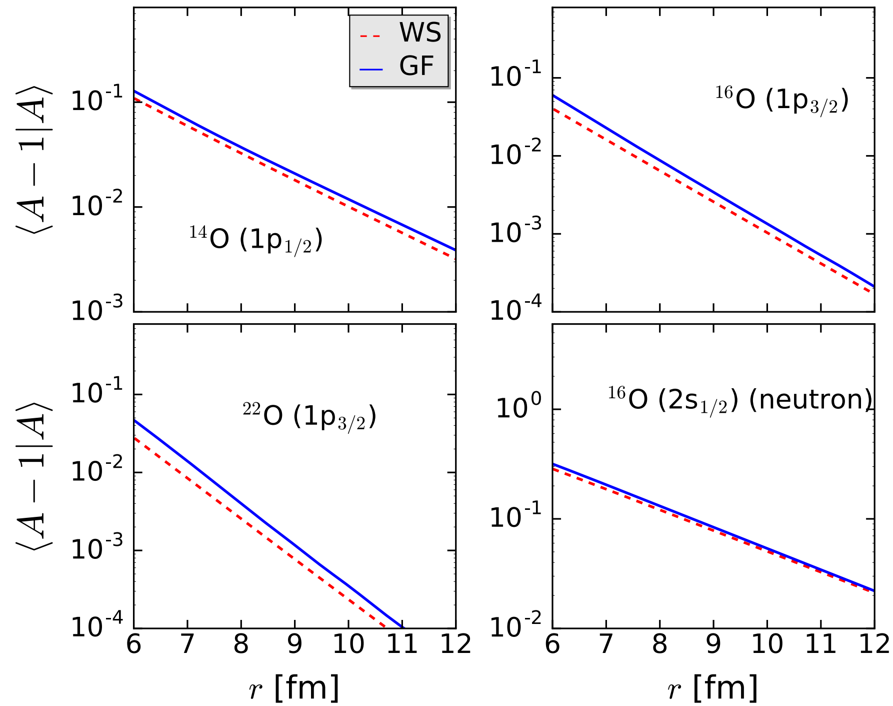
Collaboration with C. Bertulani

Nucleus (state)	E_B [MeV]	$\langle r^2 \rangle^{1/2}_{WS}$ [fm]	$\langle r^2 \rangle^{1/2}_{GF}$ [fm]	C_{WS} [$fm^{-1/2}$]	C_{GF} [$fm^{-1/2}$]	σ^{WS}_{qf} [mb]	σ^{GF}_{qf} [mb]	σ^{WS}_{kn} [mb]	σ^{GF}_{kn} [mb]	$C^2 S_{GF}$
^{14}O ($\pi 1p_{3/2}$)	8.877	2.856	2.961	6.785	7.172	27.38	28.60	27.19	27.42	0.548
						5%		<1%		

Deviation of quasifree (p, pn)
cross section calculation
for different wavefunctions

$$(\sigma_{GF} - \sigma_{WS})/\sigma_{WS}$$

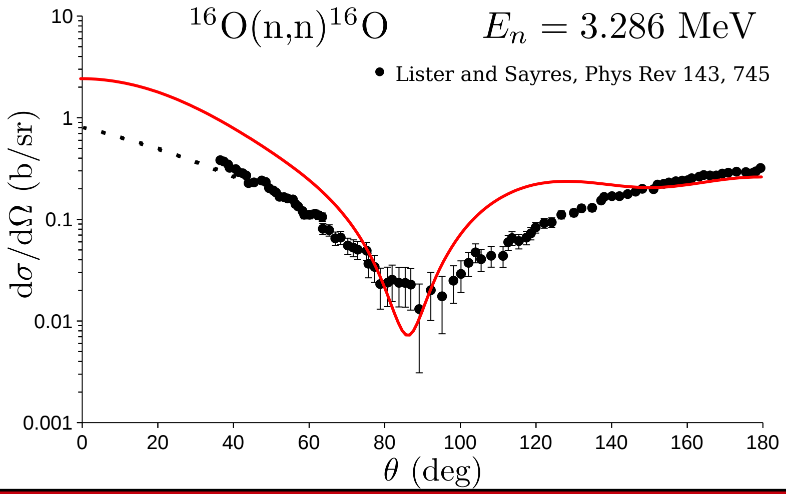


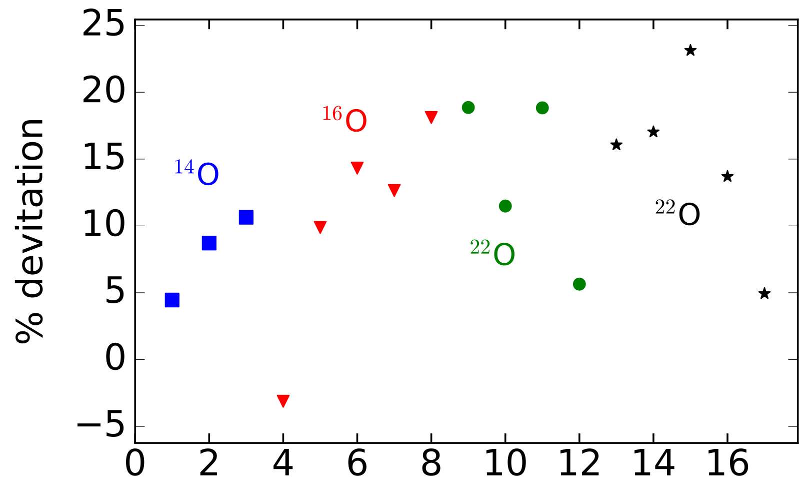


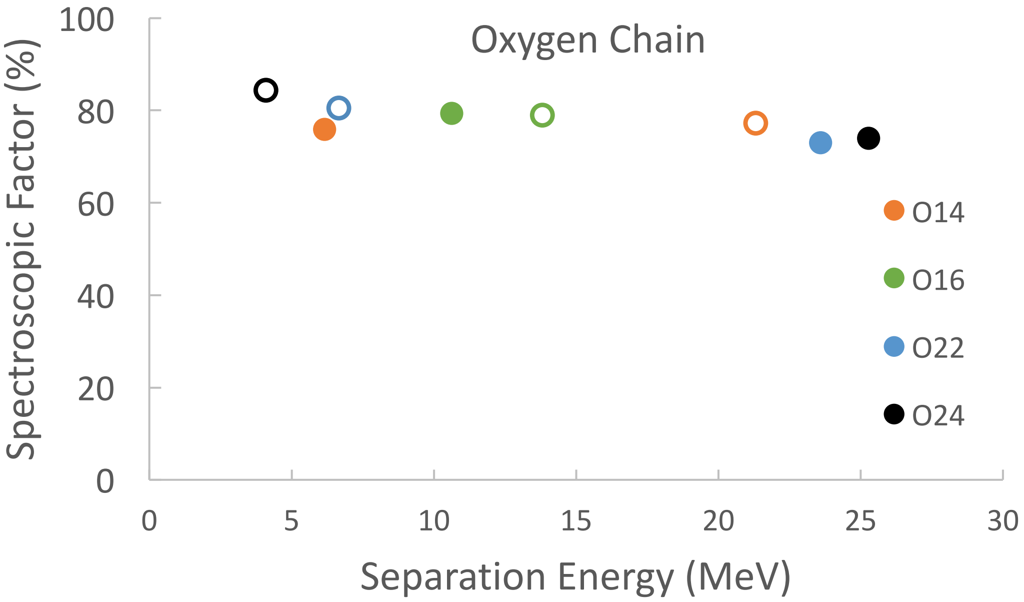
Collaboration with C. Bertulani

Conclusions and Perspectives

- We are developing an interesting tool to study nuclear reactions effectively.
  We have defined a non-local generalized optical potential corresponding to nuclear self energy.
- Spectroscopic Factors from ab-initio overlap wavefunctions differ from effective wood saxon. These do not seem to depend much on proton-neutron asymmetry



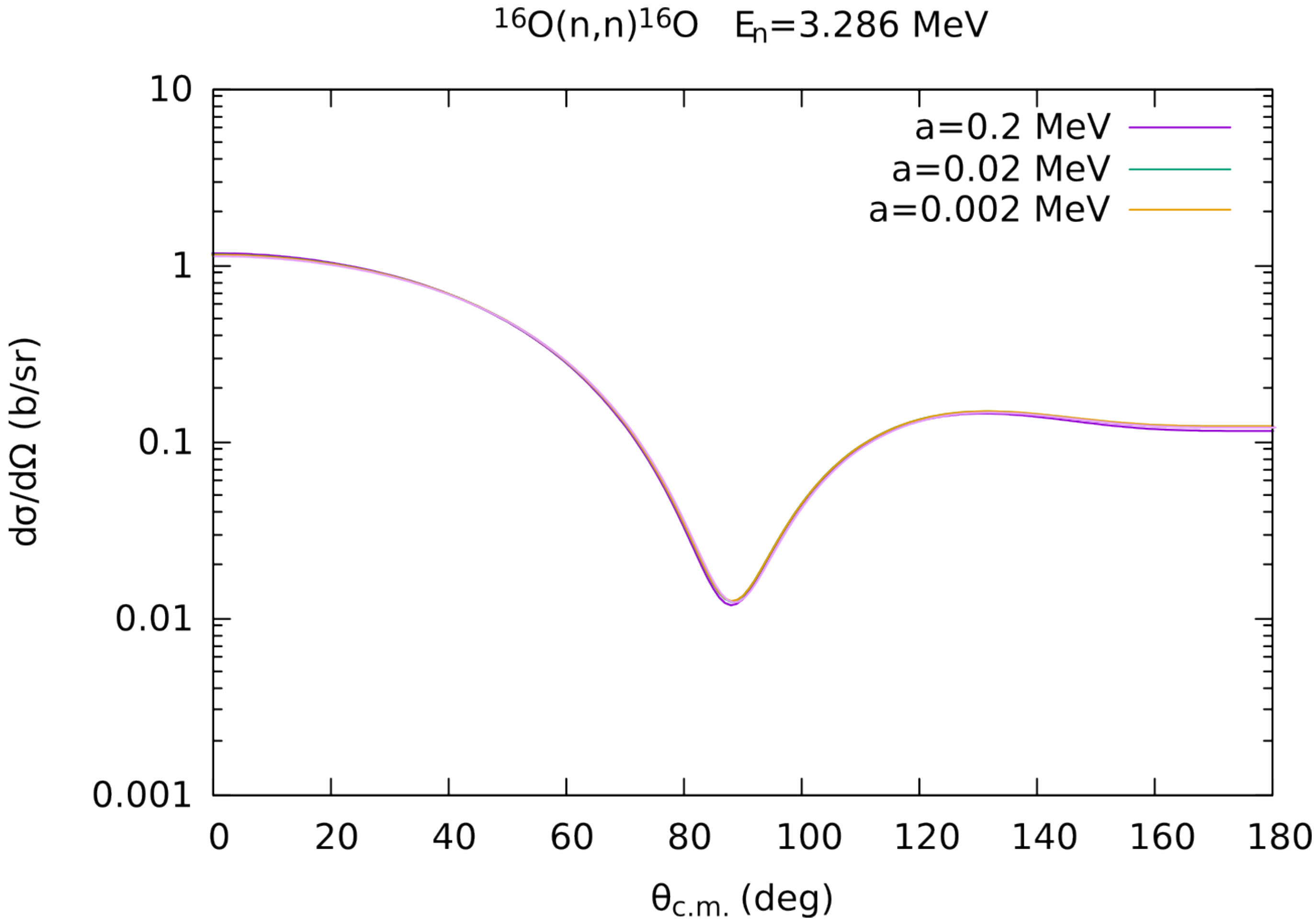



Oxygen Chain
Spectroscopic Factor (%)
100
80
60
40
20
0
0
5
10
15
20
25
30
Separation Energy (MeV)
O14
O16
O22
O24

«Imaginary» Parameter

$$\Gamma(E) = \frac{1}{\pi}\frac{a\,(E-E_F)^2}{(E-E_F)^2-b^2}$$

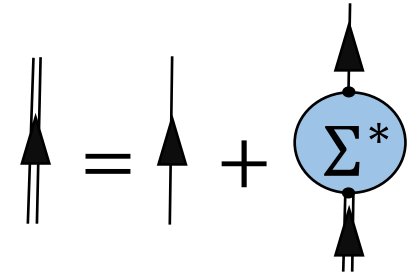
$b = 22.36$ MeV



Why Green's Functions?

Dyson Equation

$$g_{\alpha\beta}(\omega) = g^0_{\alpha\beta}(\omega) + \sum_{\gamma\delta} g^0_{\alpha\gamma}(\omega)\Sigma^\star_{\gamma\delta}(\omega) g_{\delta\beta}(\omega)$$



Equation of motion

$$\left(E + \frac{\hbar^2}{2m}\nabla^2_r\right) G(\mathbf{r},\mathbf{r}';E) - \int d\mathbf{r}''\Sigma(\mathbf{r},\mathbf{r}'';E) G(\mathbf{r}'',\mathbf{r}';E) = \delta(\mathbf{r}-\mathbf{r}')$$

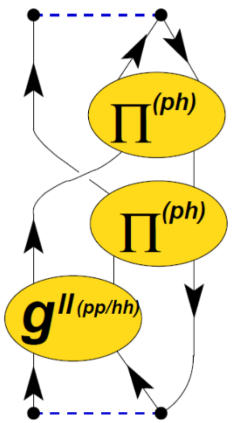
Corresponding Hamiltonian

$$\mathcal{H}_{\mathcal{M}}(\mathbf{r},\mathbf{r}') = -\frac{\hbar^2}{2m}\nabla^2_r \delta(\mathbf{r}-\mathbf{r}') + \Sigma(\mathbf{r},\mathbf{r}';E+i\epsilon)$$

Σ corresponds to the Feshbach's generalized optical potential

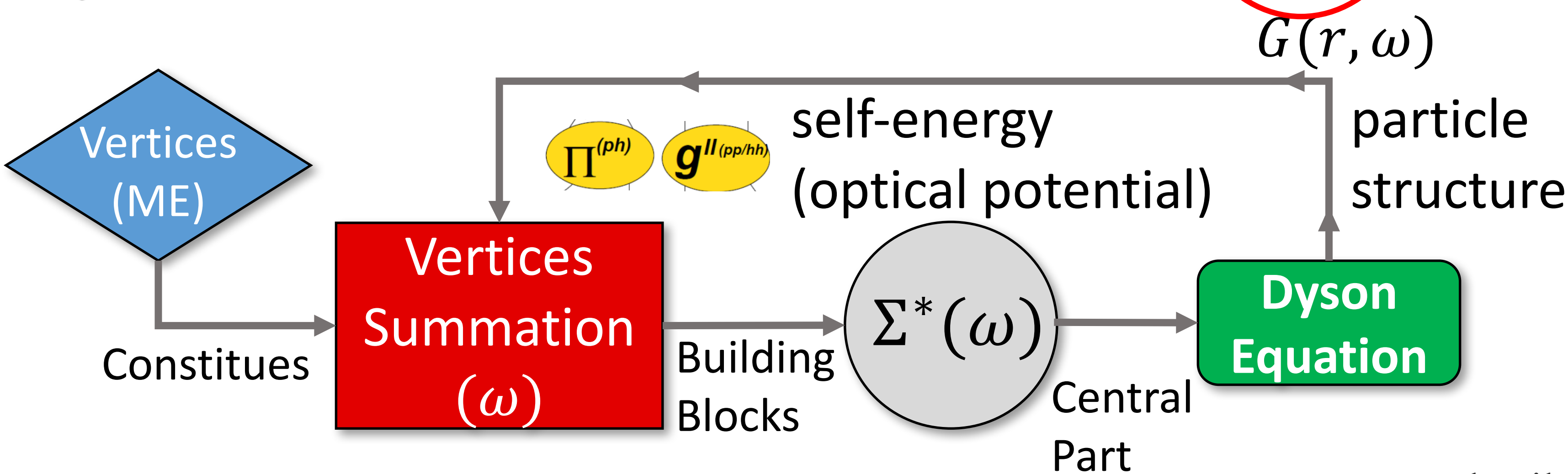
Escher & Jennings PRC66 034313 (2002)

$$\Sigma^\star_{\alpha\beta}(\omega) = \Sigma^{(\infty)}_{\alpha\beta} + \sum_{i,j} \mathbf{M}^\dagger_{\alpha,i}\left[\frac{1}{\omega - (\mathbf{K}^> + \mathbf{C}) + i\eta}\right]_{i,j}\mathbf{M}_{j,\beta} + \sum_{r,s}\mathbf{N}_{\alpha,r}\left[\frac{1}{\omega-(\mathbf{K}^<+\mathbf{D}) - i\eta}\right]_{r,s}\mathbf{N}^\dagger_{s,\beta}$$



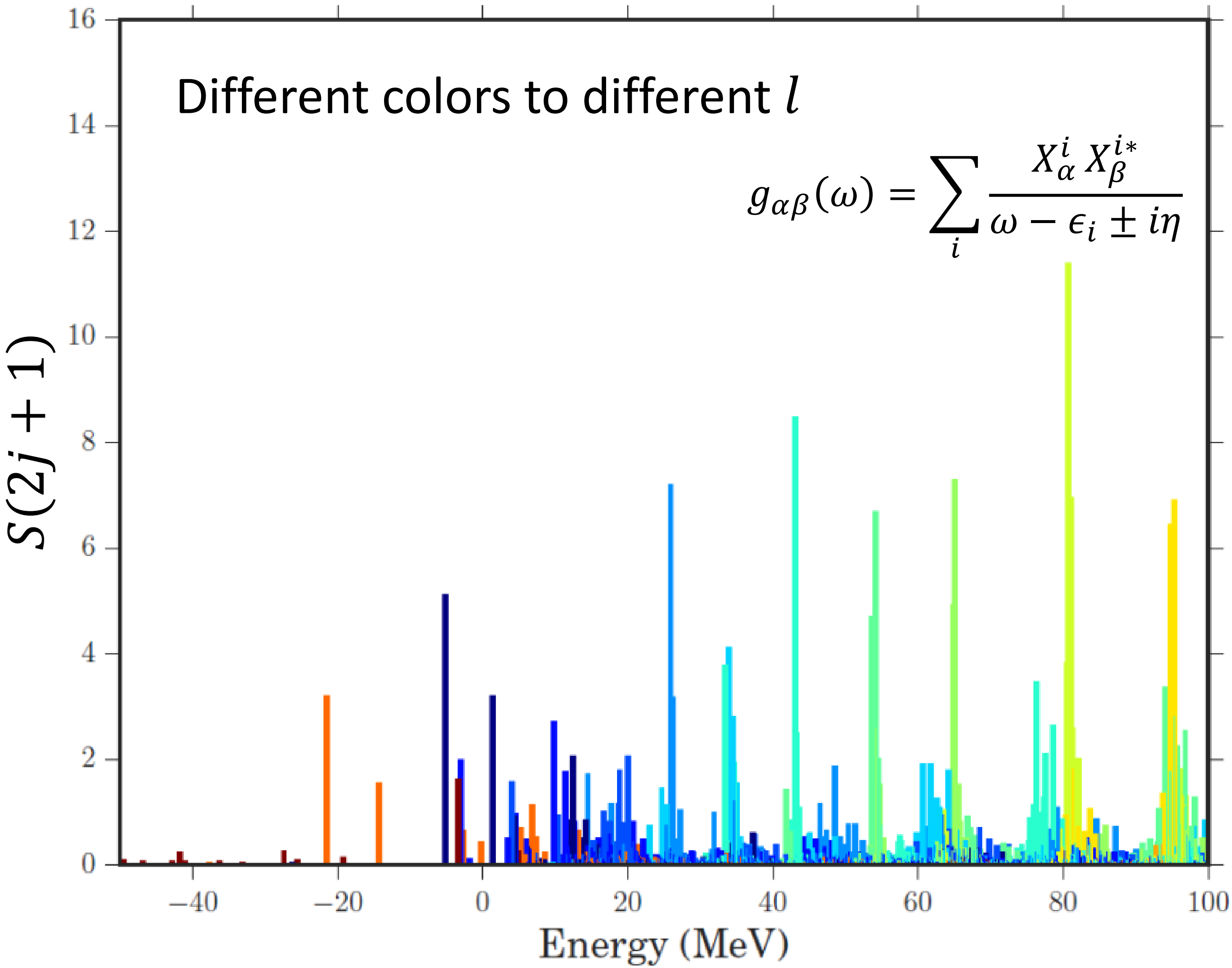
2p1h   2p2h   Unknown

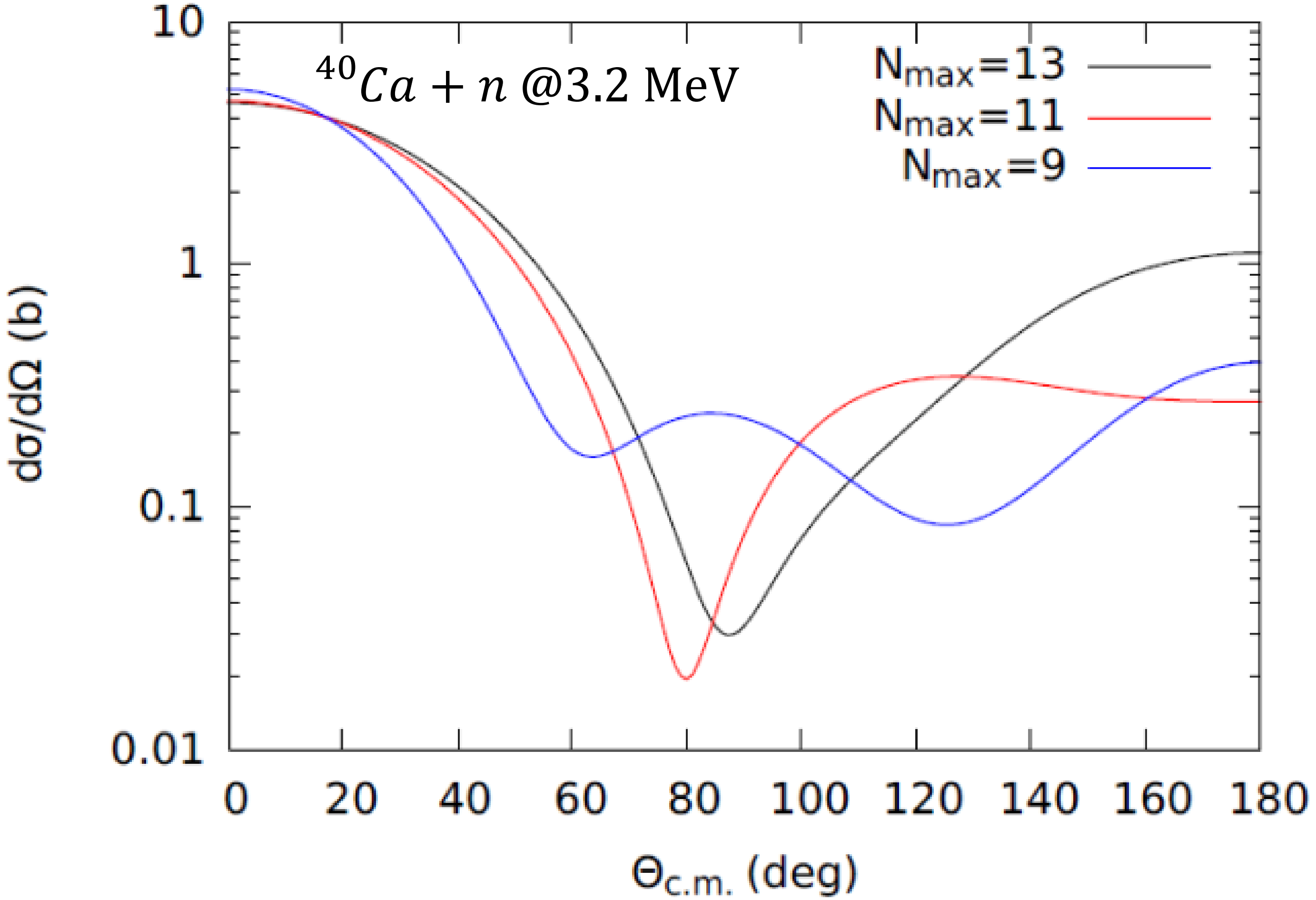
$$\begin{pmatrix} \widehat{T} + \Sigma^{(\infty)} & M^\dagger & N \\ M & E^> + C & \\ N^\dagger & & E^< + D \end{pmatrix}\begin{pmatrix}\mathcal{Z}^i\\ \mathcal{W}^i\\ \mathcal{V}^i\end{pmatrix} = \begin{pmatrix}\mathcal{Z}^i\\ \mathcal{W}^i\\ \mathcal{V}^i\end{pmatrix}\varepsilon_i$$



More details in C. Barbieri, A. Carbone, Lect. Notes Phys. arXiv:1611.03923 [nucl-th]

^{16}O neutron propagator




$^{40}Ca + n$ @3.2 MeV
N_{max}=13
N_{max}=11
N_{max}=9
10
1
0.1
0.01
dσ/dΩ (b)
0
20
40
60
80
100
120
140
160
180
$\Theta_{c.m.}$ (deg)

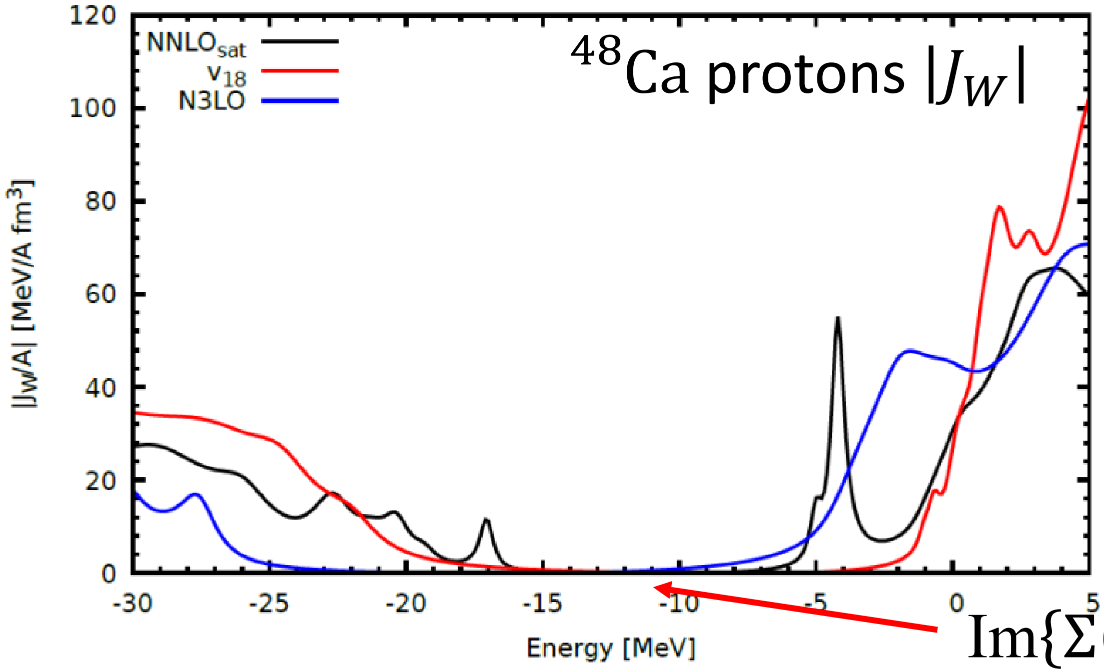
Volume integrals

$$J_W^{\ell}(E) = 4\pi \int drr^2 \int dr'r'^2 \text{Im } \Sigma_0^{\ell}(r, r', E)$$

Non local potential

$$J_V^{\ell}(E) = 4\pi \int drr^2 \int dr'r'^2 \text{Re } \Sigma_0^{\ell}(r, r'; E).$$

$$\tilde{\Sigma}_{n_a,n_b}^{\ell j}(E) = \sum_r \frac{m_{n_a}^r m_{n_b}^r}{E - \varepsilon_r \pm i\eta}$$



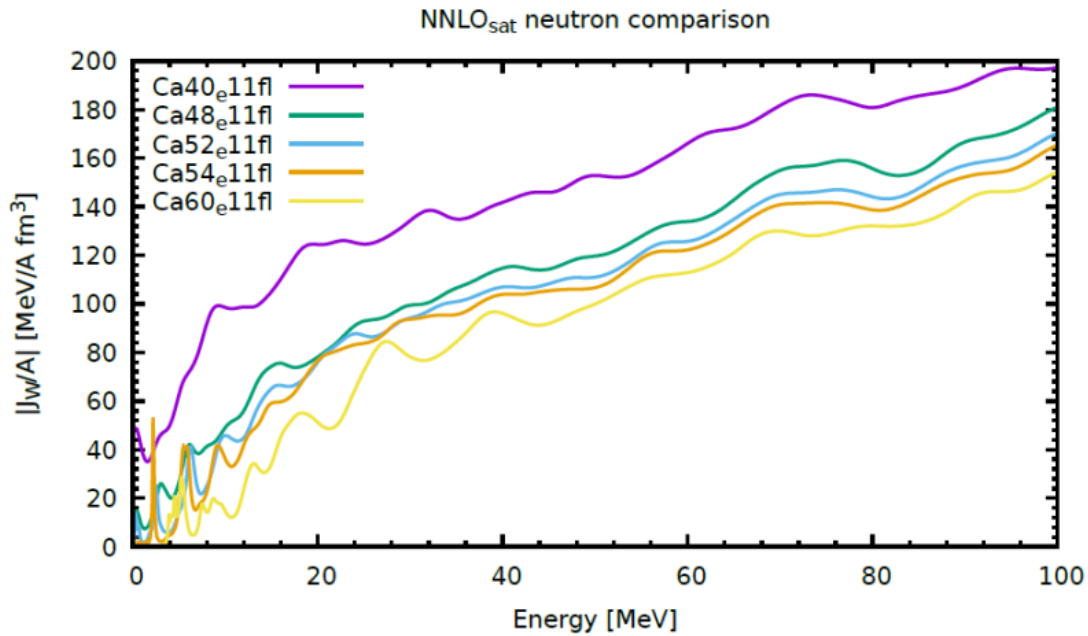
$\text{Im}\{\Sigma(\epsilon_F)\} = 0$

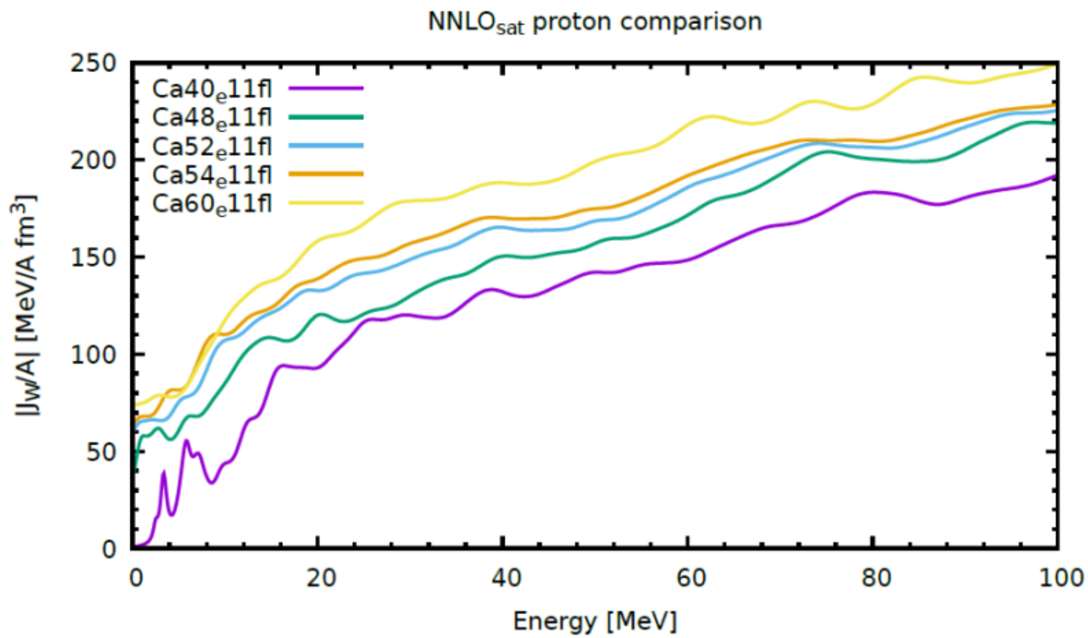
different Fermi energies and particle-hole gap for different interactions

S. Waldecker et al. PRC**84**, 034616(2011)

Ca isotopes

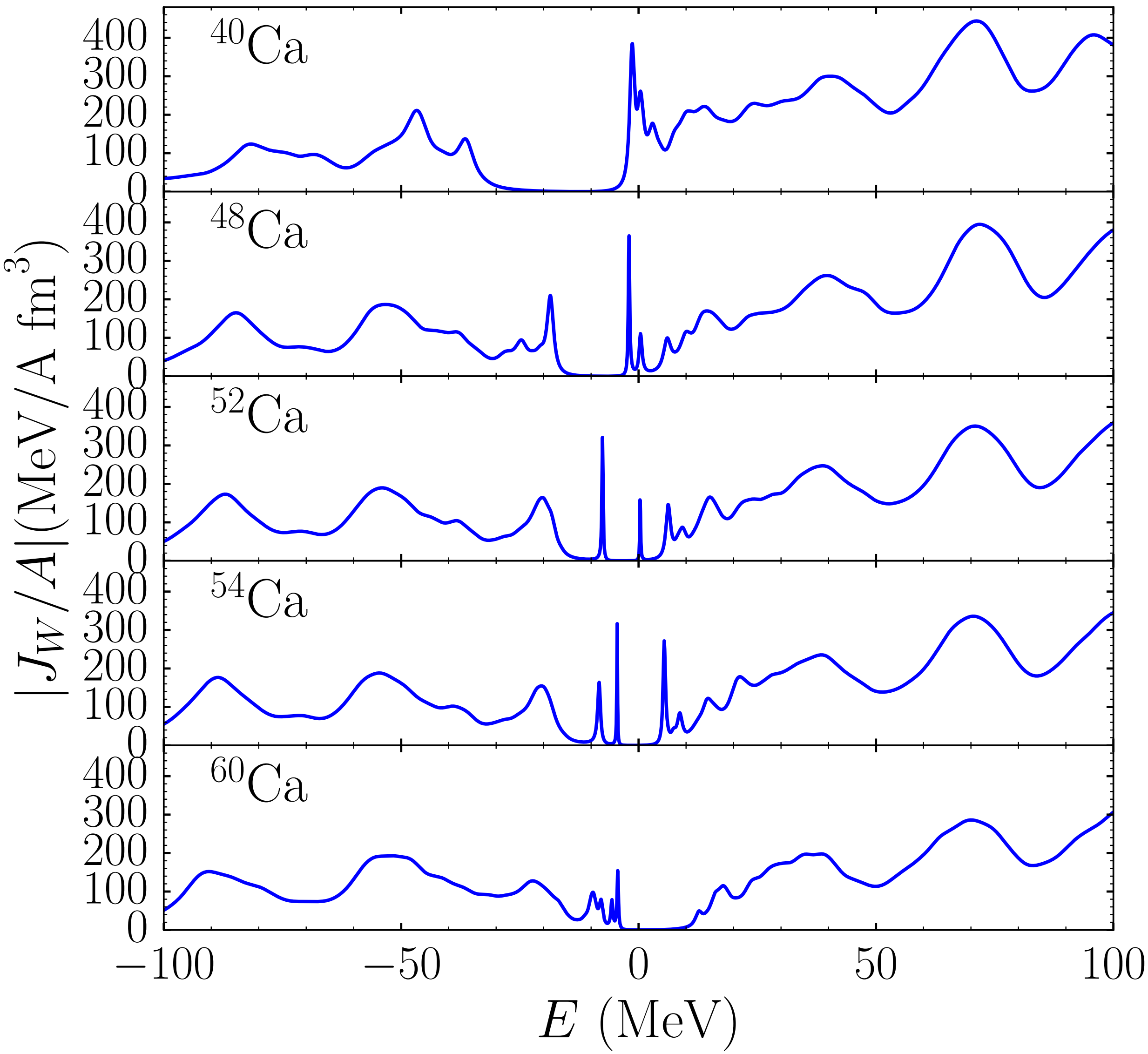
neutron and proton volume integrals of self energies.



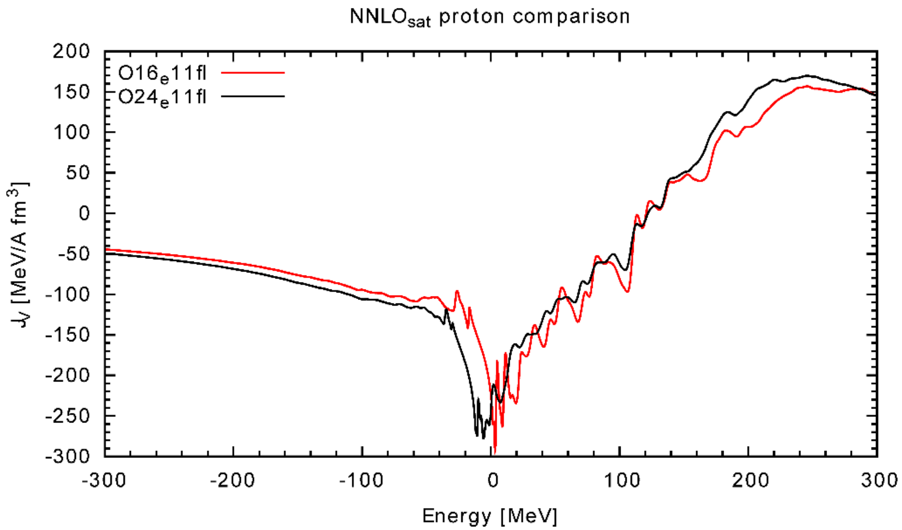


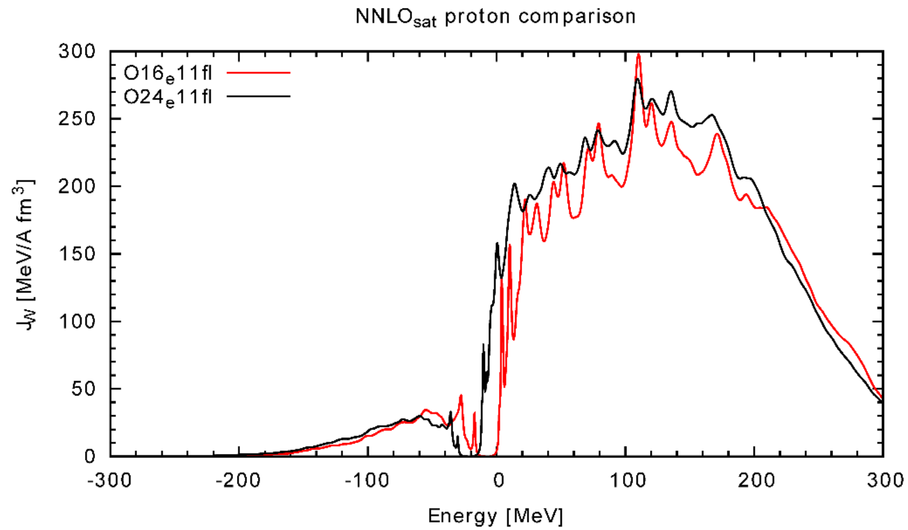
Ca isotopes

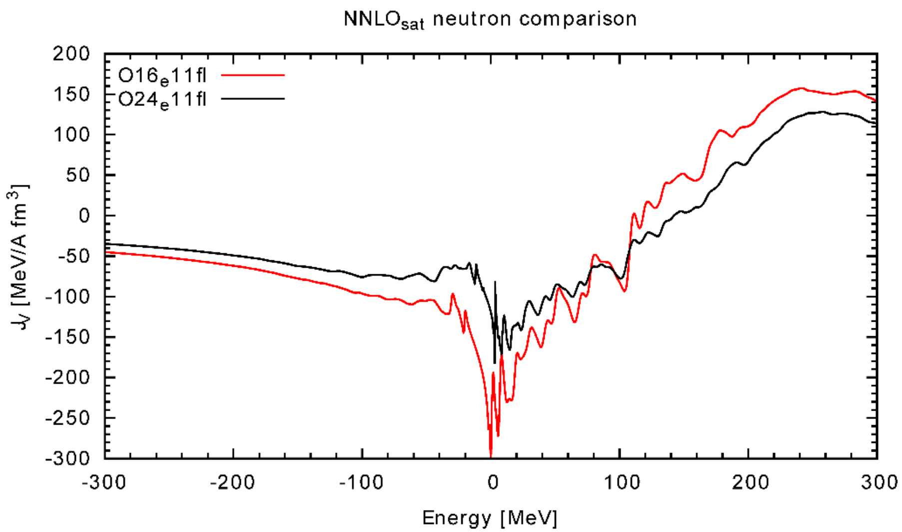
neutron volume integrals of self energies.

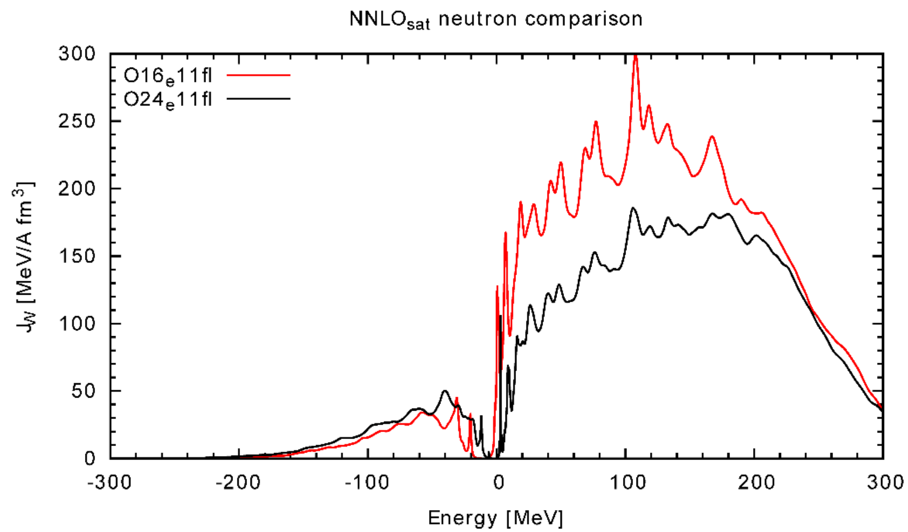


^{16}O and ^{24}O


NNLO$_{sat}$ proton comparison
O16$_e$11fl
O24$_e$11fl
J_V [MeV/A fm^3]
Energy [MeV]
200 150 100 50 0 -50 -100 -150 -200 -250 -300
-300 -200 -100 0 100 200 300


NNLO$_{sat}$ proton comparison
O16$_e$11fl
O24$_e$11fl
J_W [MeV/A fm^3]
Energy [MeV]
300 250 200 150 100 50 0
-300 -200 -100 0 100 200 300


NNLO$_{sat}$ neutron comparison
O16$_e$11fl
O24$_e$11fl
J_V [MeV/A fm^3]
Energy [MeV]
200 150 100 50 0 -50 -100 -150 -200 -250 -300
-300 -200 -100 0 100 200 300


NNLO$_{sat}$ neutron comparison
O16$_e$11fl
O24$_e$11fl
J_W [MeV/A fm^3]
Energy [MeV]
300 250 200 150 100 50 0
-300 -200 -100 0 100 200 300