Towards Microscopic Optical potential from Coupled Cluster

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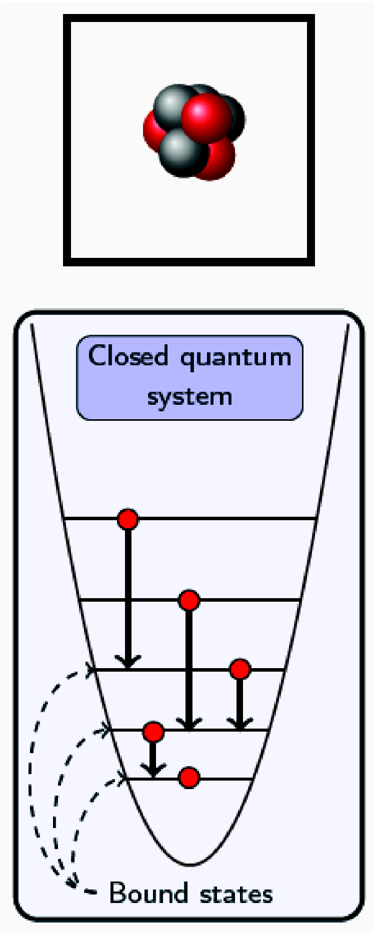
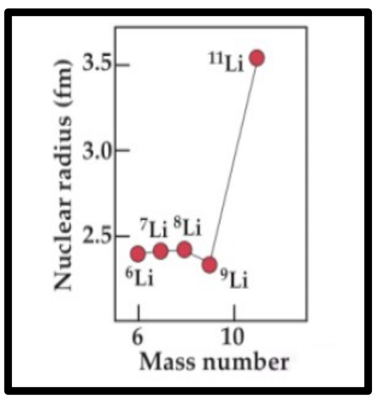
Nuclei far from stability

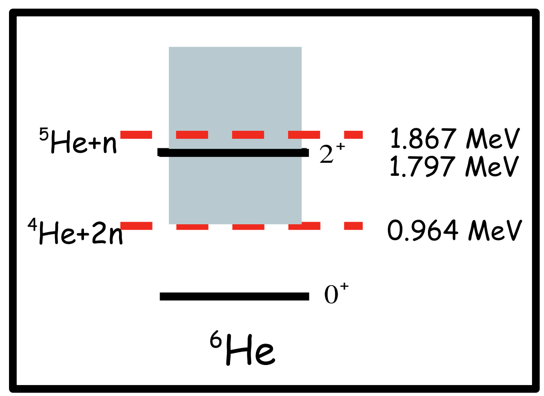


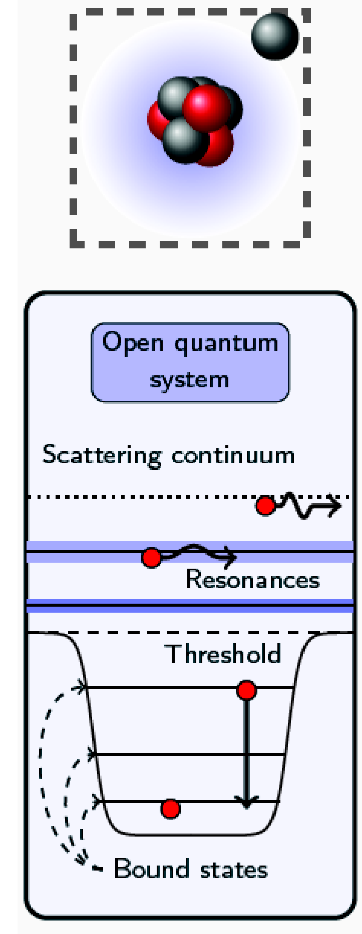
- structure and reaction channels influence each other

Unification of nuclear structure and reactions

- Near-threshold effects
- Exotic decay modes



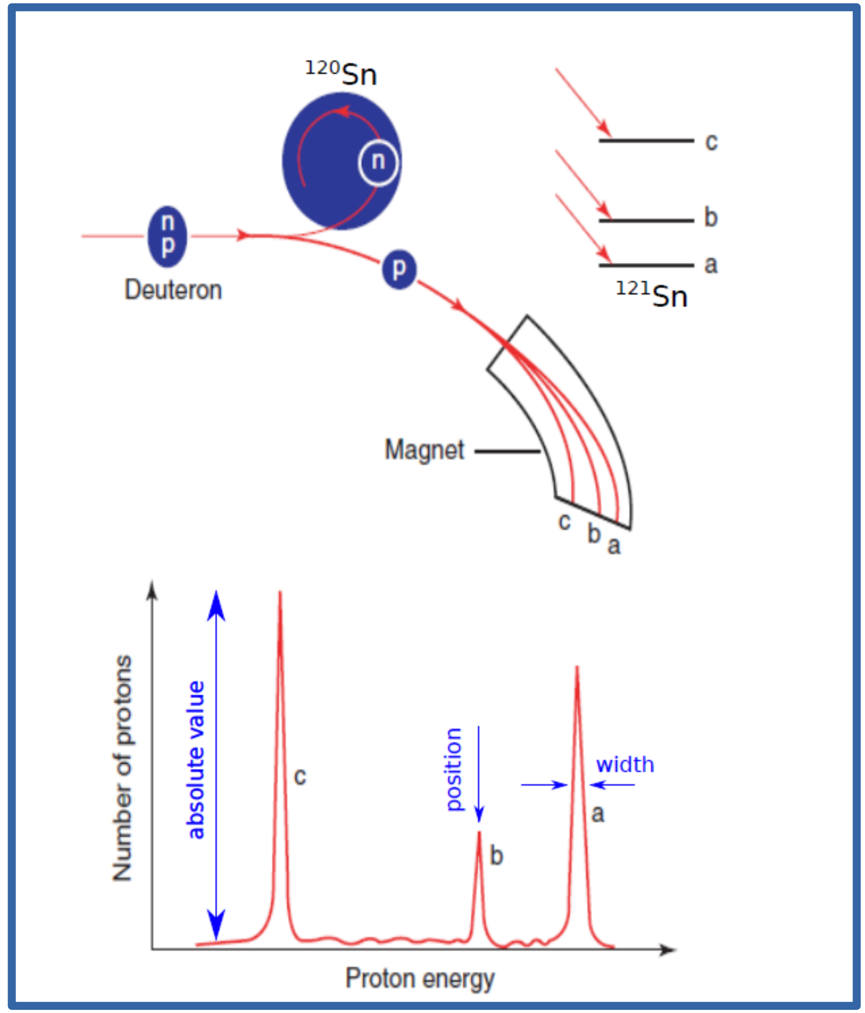




Taking into account the coupling to the continuum states is essential for the description of drip-lines nuclei.

Nuclear structure with transfer reactions

- transfer reactions probe nuclear response to the addition of nucleon
- information about nuclear structure from:
    - *angular differential cross section*
    - *absolute value*
    - *position*
    - *width (in the continuum)*



A standard approach to reactions:

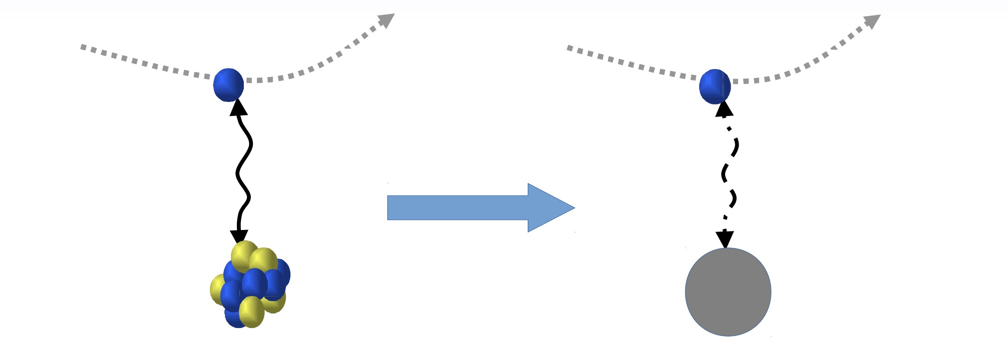
$$\sigma = S_i^2 \tilde{\sigma}$$

spectroscopic factor from structure model

cross section from few-body/reaction models

can suffer from inconsistency between the two schemes !

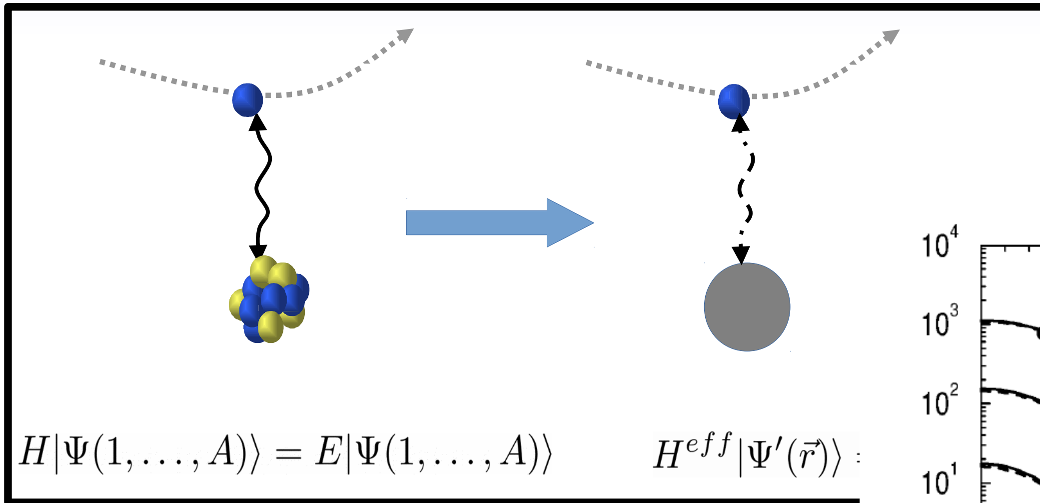
Nucleon-Nucleus Optical Potential



$$H|\Psi(1,\ldots,A)\rangle = E|\Psi(1,\ldots,A)\rangle$$

$$H^{eff}|\Psi'(\vec{r})\rangle = E|\Psi'(\vec{r})\rangle$$

Nucleon-Nucleus Optical Potential



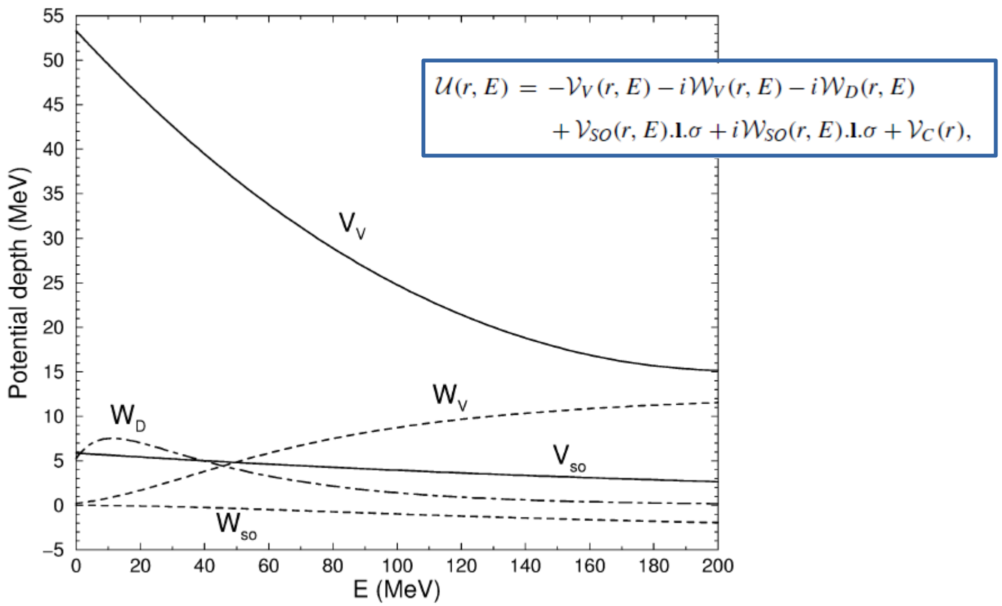
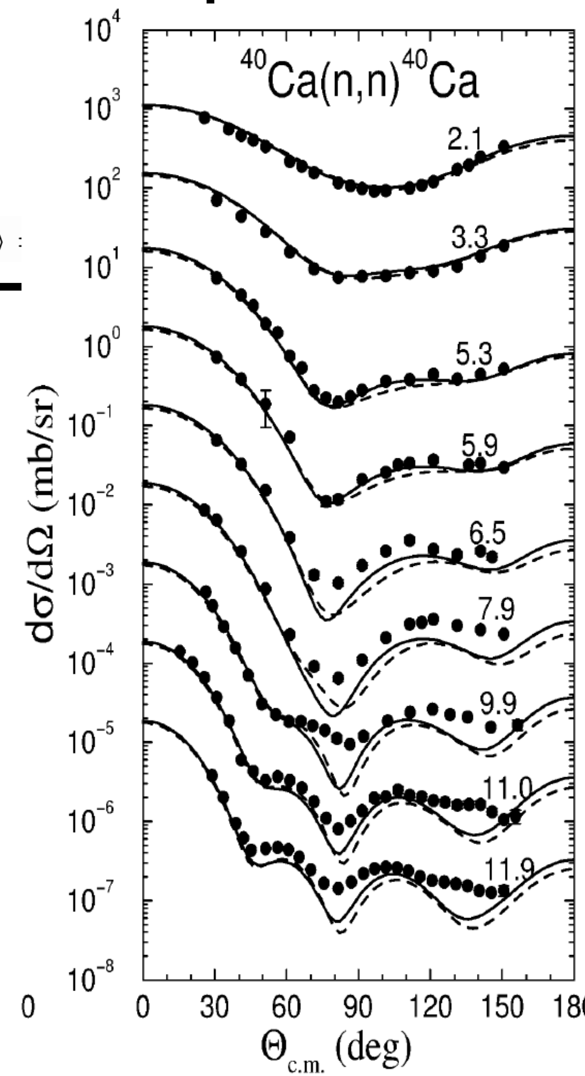
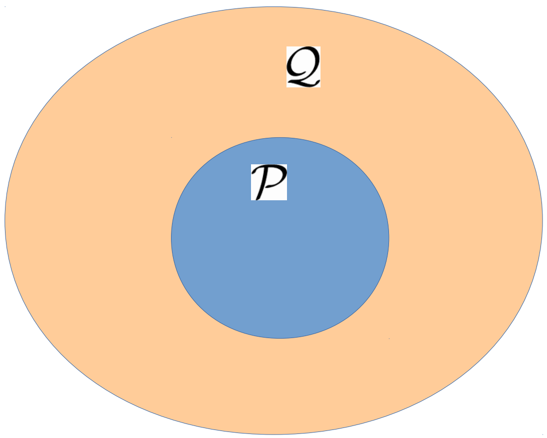


Fig. 1. The various potential well depths as a function of incident (laboratory) energy, see Eq. (7). As an example, the values for neutrons incident on ^{56}Fe are plotted.



Phenomenological *local* potential (A.J Koning, J. P. Delaroche, NPA 2003)

Feshbach (1958)



$$\left[E - H_{PP} - H_{PQ}\frac{1}{E - H_{QQ}}H_{QP}\right]|\Psi_P\rangle = 0$$

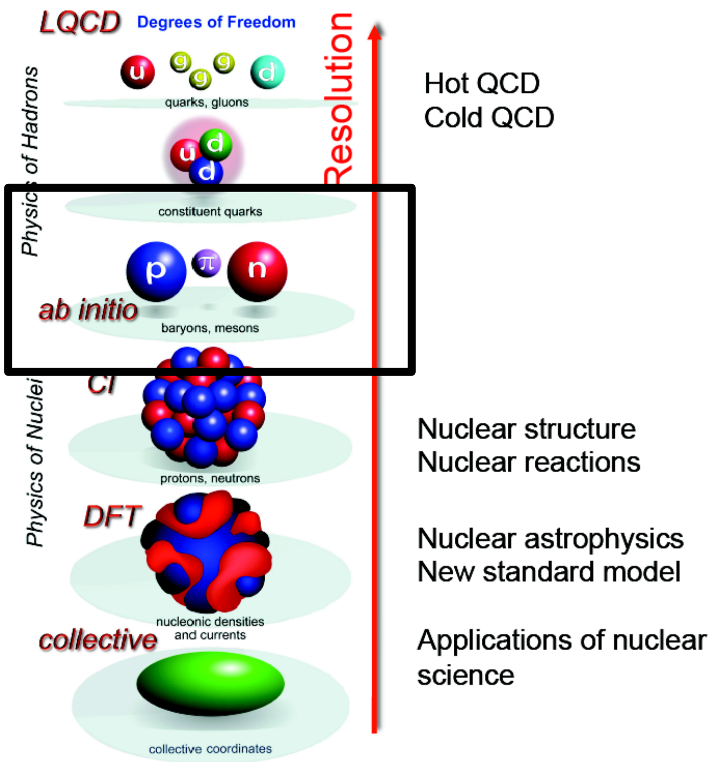
optical potential in P

energy-dependent/non-local/complex

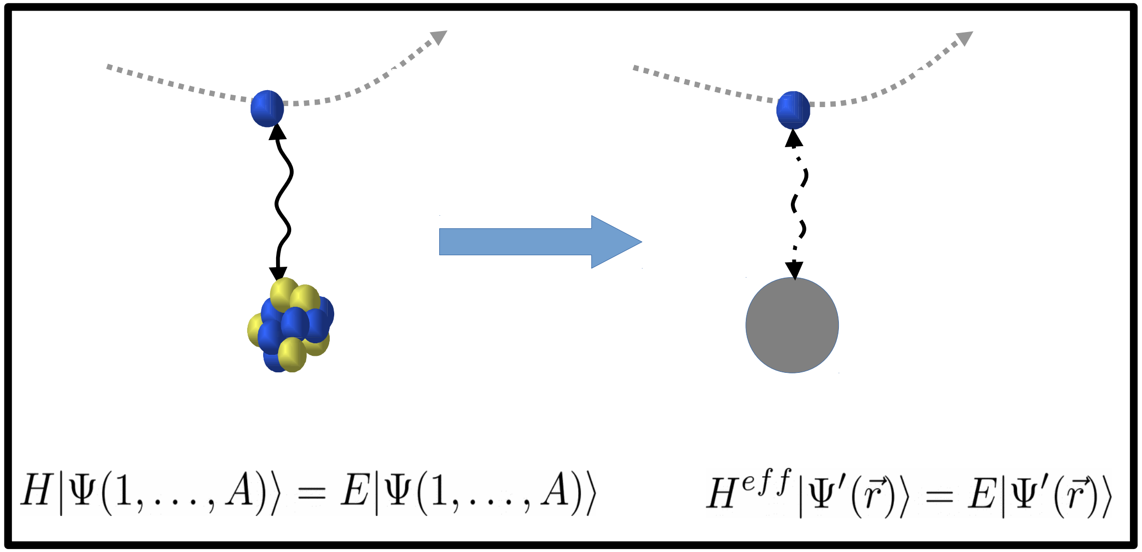
$$\begin{cases} |P\rangle \equiv |\text{elastic scattering}\rangle \\ |Q\rangle \equiv |\text{inelastic processes, breakup}\ldots\rangle \end{cases}$$

Microscopic Optical Potential

* all nucleons are active, chiral-EFT n-n, 3n interactions



(taken from W. Nazarewicz, JPG 2016)



* Goals: predictive theory for nuclear reactions, reliable/accurate extrapolations for systems far from stability.

Single-particle Green's function

$$G(\alpha, \beta, E) = \langle \Psi_0^A | a_\alpha \frac{1}{E - (H - E_0^A) + i\eta} a_\beta^\dagger | \Psi_0^A \rangle$$
$$+ \langle \Psi_0^A | a_\beta^\dagger \frac{1}{E + (E_0^A - H) - i\eta} a_\alpha | \Psi_0^A \rangle$$

$$\eta \to 0$$

Single-particle Green's function

$$G(\alpha,\beta,E) = \langle\Psi_0^A|a_\alpha \frac{1}{E-(H-E_0^A)+i\eta} a_\beta^\dagger|\Psi_0^A\rangle$$

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$\eta \to 0$

Single-particle Green's function

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$\eta \to 0$

Dyson equation

$$G(\alpha,\beta;E) = G^{(0)}(\alpha,\beta;E) + \sum_{\gamma,\delta} G^{(0)}(\alpha,\gamma;E)\Sigma(\gamma,\delta;E)G(\delta,\beta;E)$$

nucleon-nucleus potential

Coupled Cluster Theory

(G. Hagen, T. Papenbrock, M. Hjorth-Jensen, D. J. Dean, RPP 2014)

Exponential ansatz

$$|\Psi\rangle = e^{T}|\Phi\rangle$$

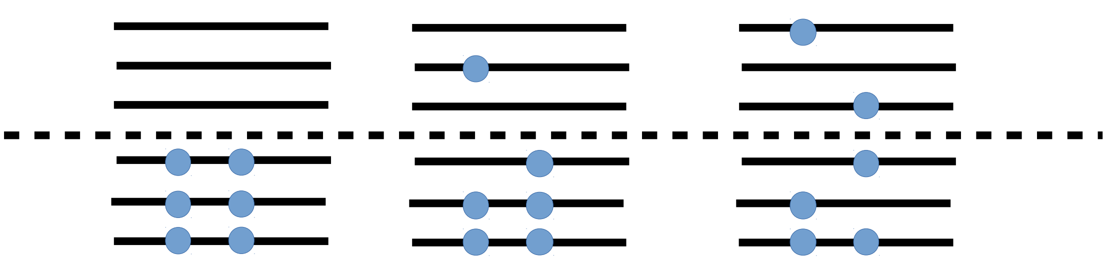
Similarity-transformed Hamiltonian

$$\bar{H} \quad = \quad e^{-T} H e^{T}$$

1p-1h operator

$$T = T_1 + T_2 + \ldots$$

2p-2h operator

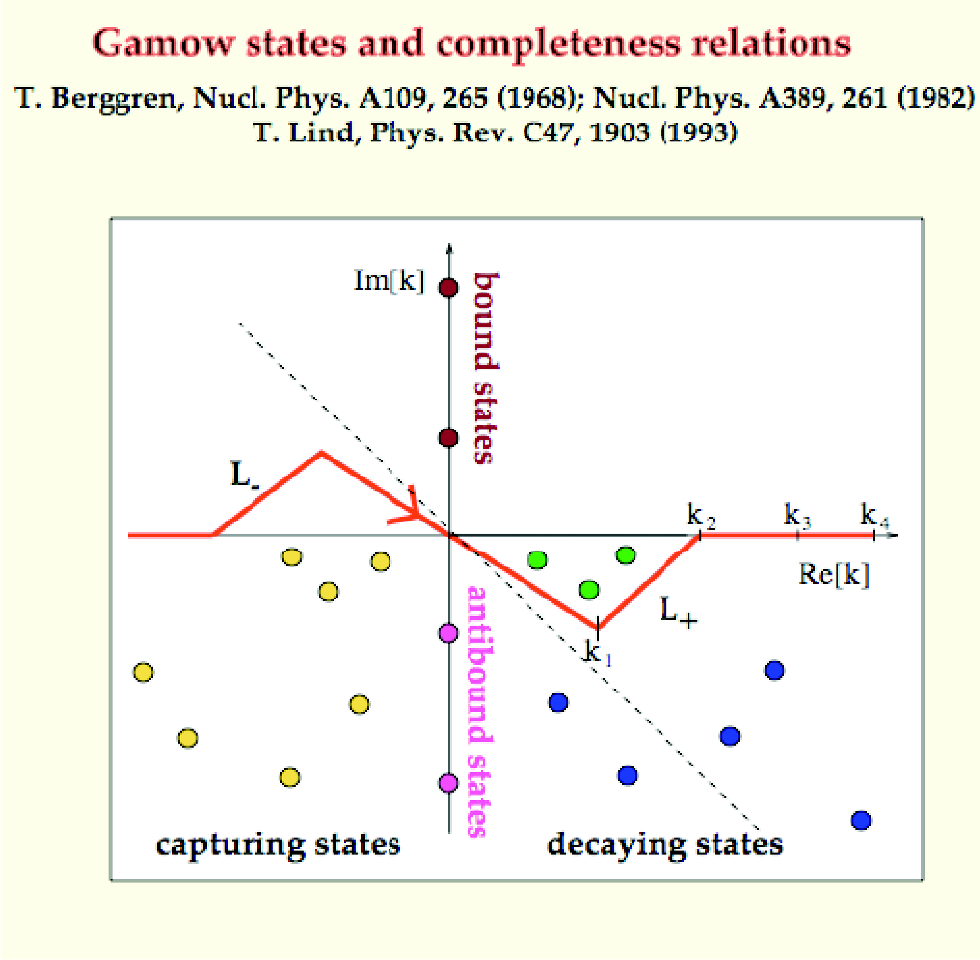


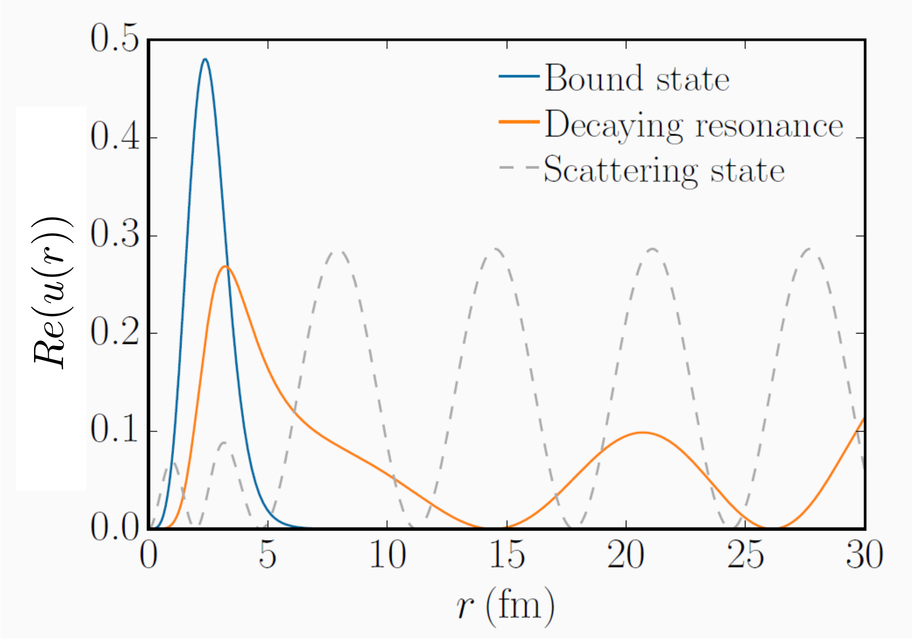
$|\Phi\rangle$ 1p-1h 2p-2h

Coupled cluster equations

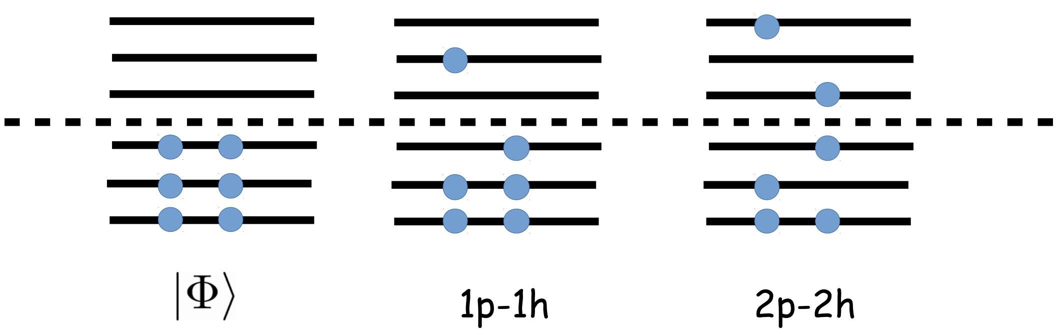
$$\begin{aligned} E &= \langle\Phi|\bar{H}|\Phi\rangle \\ 0 &= \langle\Phi_i^a|\bar{H}|\Phi\rangle \\ 0 &= \langle\Phi_{ij}^{ab}|\bar{H}|\Phi\rangle \\ &\ldots \end{aligned}$$

Coupled Cluster with the Berggren basis





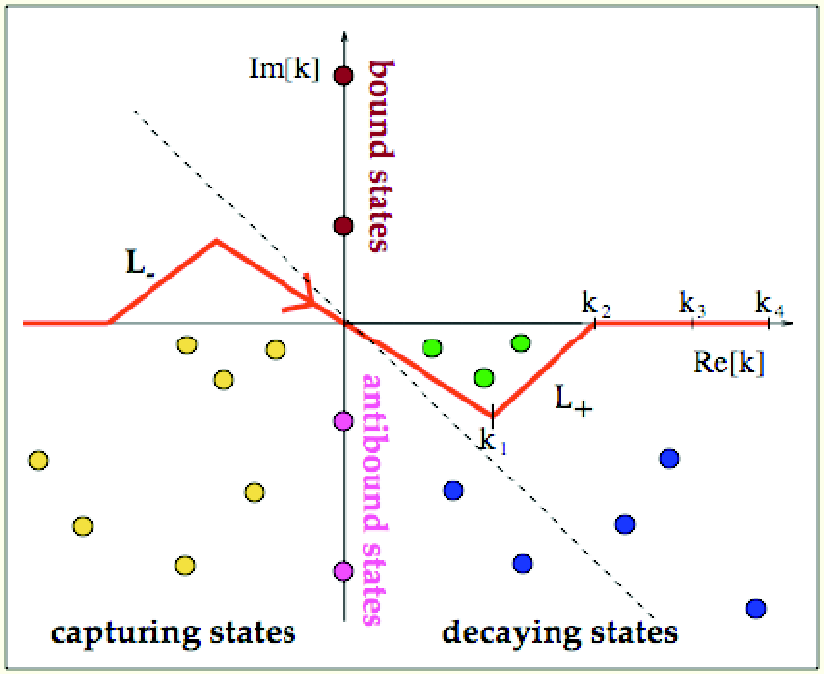
- Discretization: $\sum_i |u_\ell(k_i)\rangle \langle \tilde{u}_\ell(k_i)| \approx \hat{1}_{\ell,j}$.
- Many-body: $\sum_i |SD_i\rangle \langle SD_i| \approx \hat{1}$.

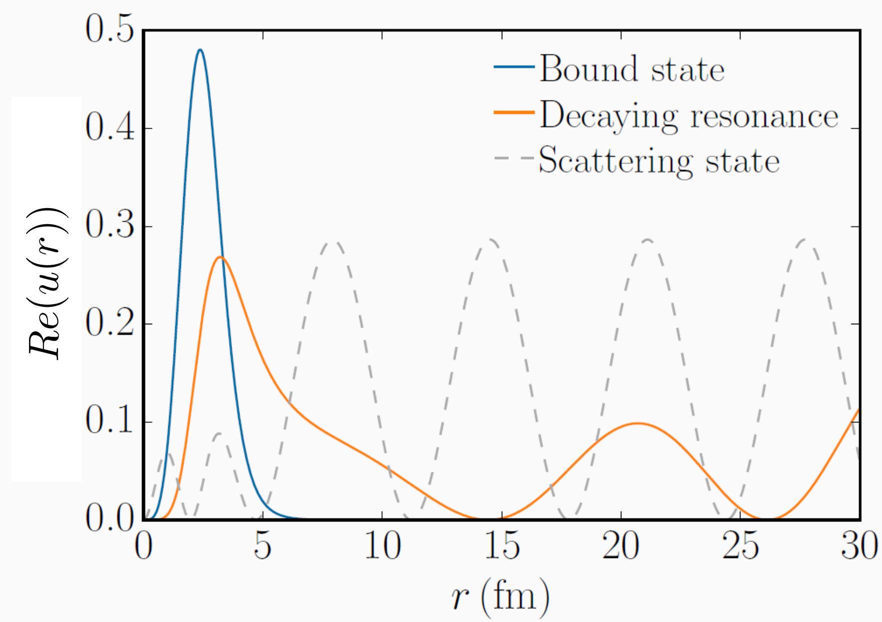


Coupled Cluster with the Berggren basis

Gamow states and completeness relations

T. Berggren, Nucl. Phys. A109, 265 (1968); Nucl. Phys. A389, 261 (1982)
T. Lind, Phys. Rev. C47, 1903 (1993)





- Discretization: $\sum_i |u_\ell(k_i)\rangle \langle \tilde{u}_\ell(k_i)| \approx \hat{1}_{\ell,j}$.
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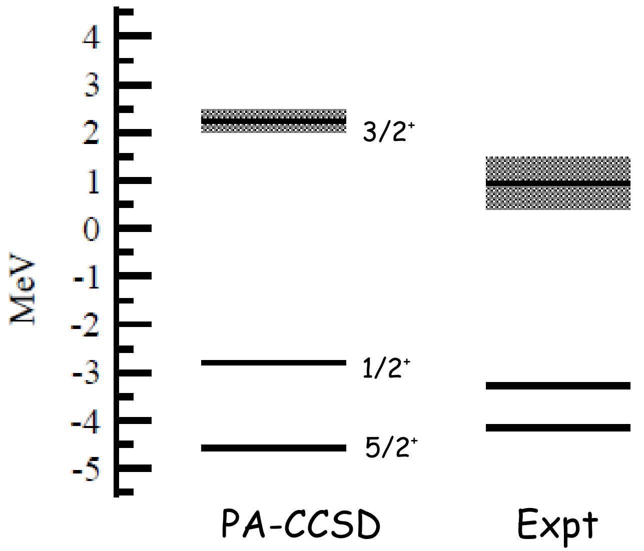
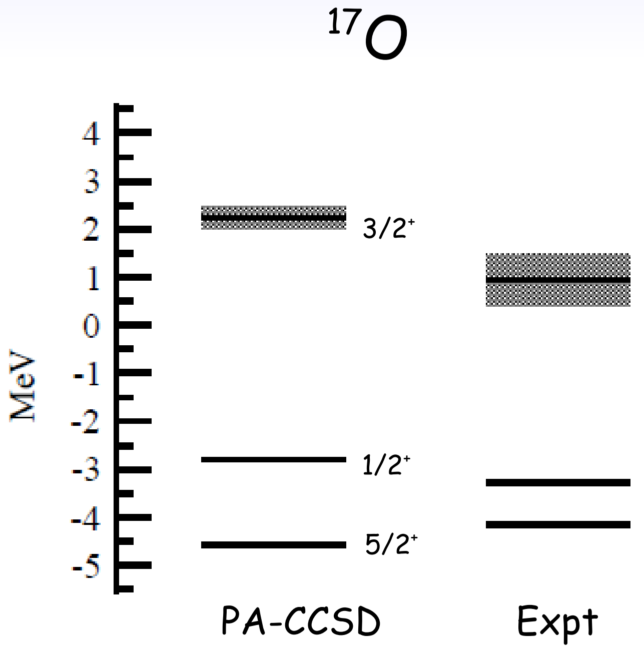
$$G(\alpha, \beta, E) = \langle \Psi_0^A | a_\alpha \frac{1}{E - (H - E_0^A) + i\eta} a_\beta^\dagger | \Psi_0^A \rangle + \ldots$$

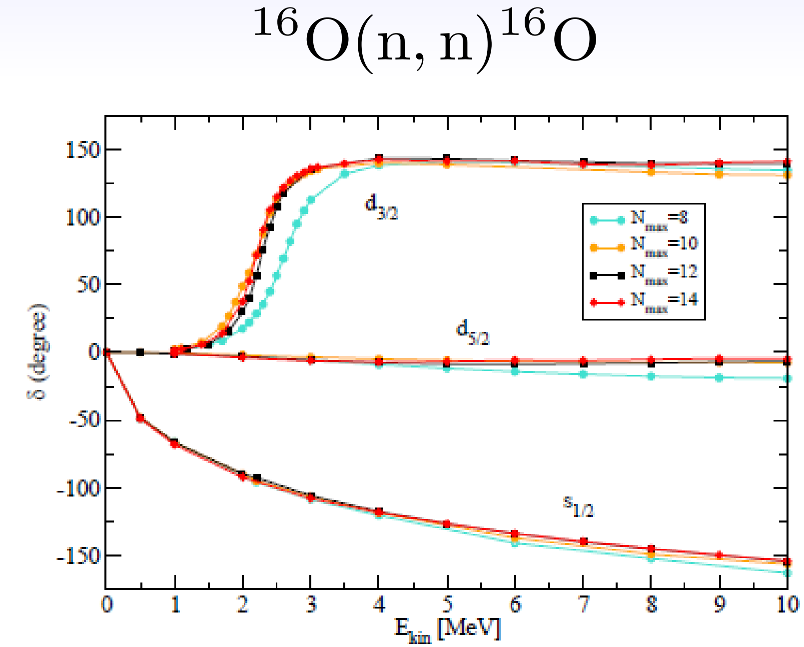
CC(SD) with N^2LO_{opt} : ^{16}O and ^{17}O

^{17}O



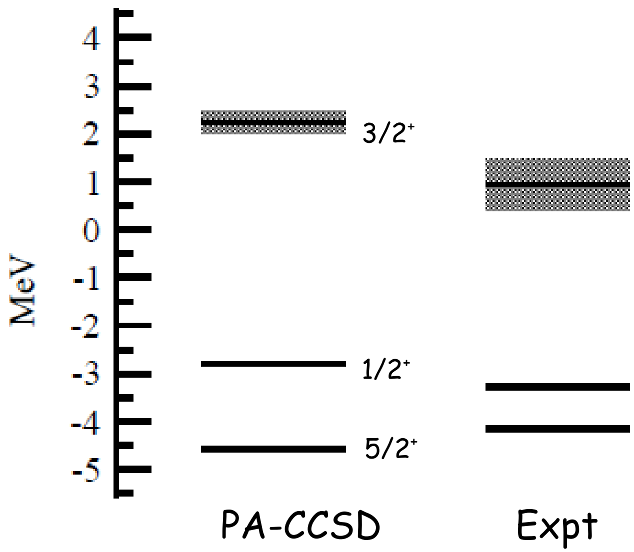
CC(SD) with N^2LO_{opt} : ^{16}O and ^{17}O



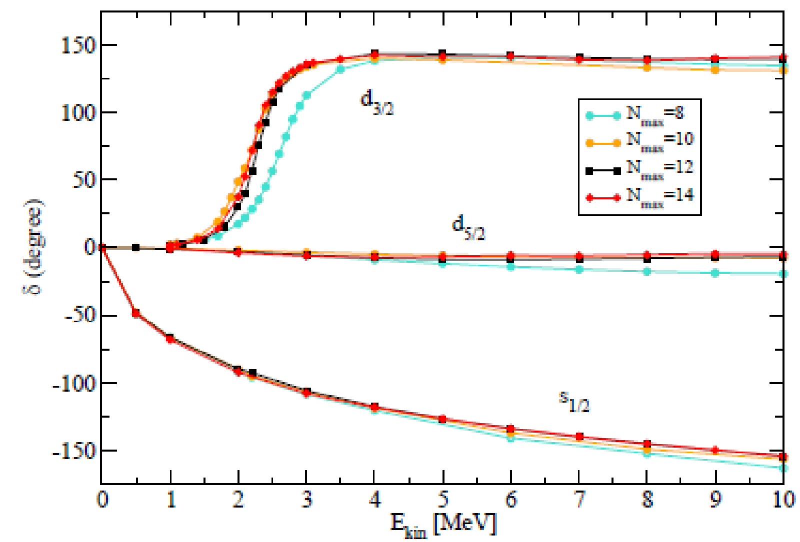


CC(SD) with N^2LO_{opt} : ^{16}O and ^{17}O

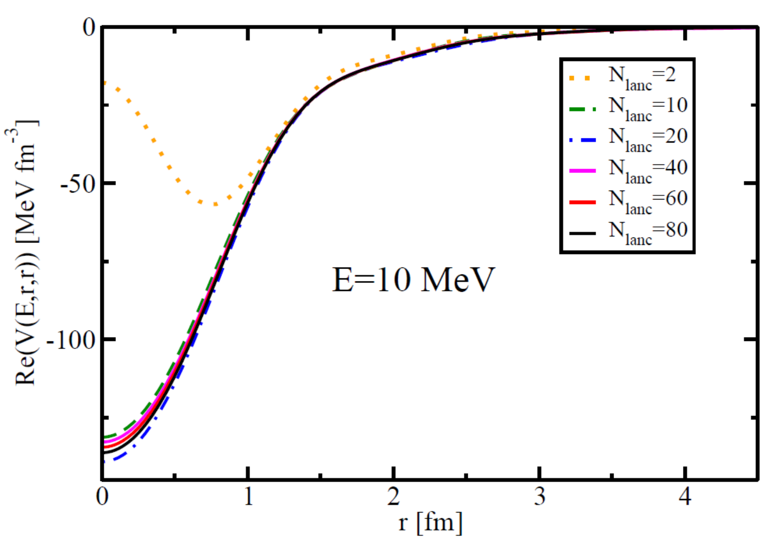
^{17}O



$^{16}O(n,n)^{16}O$

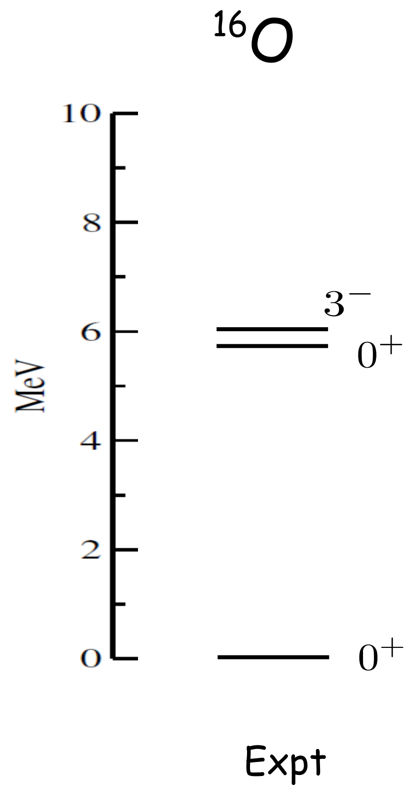


Real part of the (diagonal) neutron S-wave potential @ 10 MeV as a function of the number of Lanczos iterations.

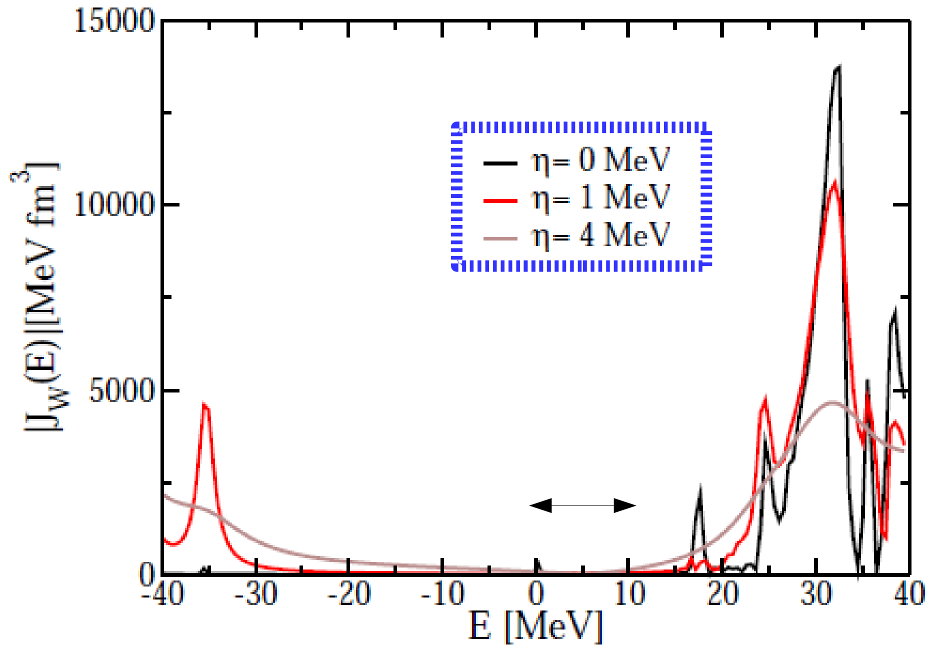


(**J. R**, P. Danielewicz, G. Hagen, F. Nunes, T. Papenbrock, PRC 2017)

CC(SD) with N^2LO_{opt} : too small absorption



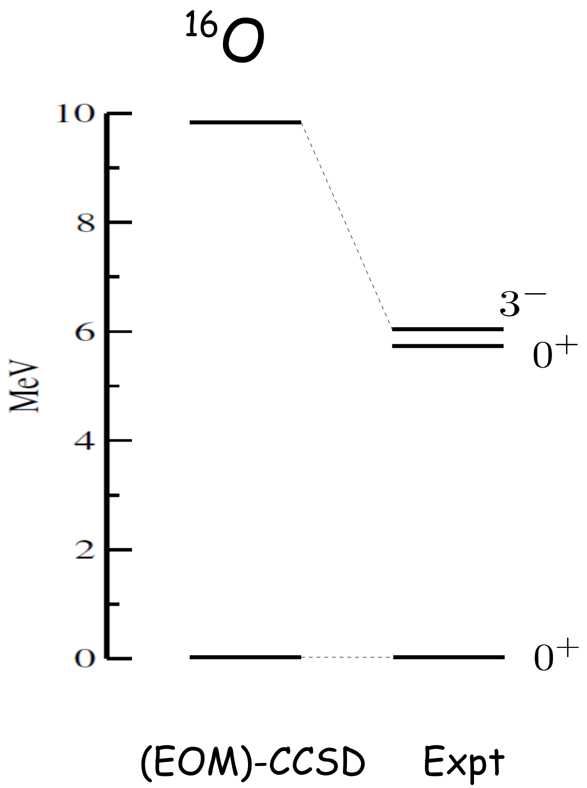
Volume integral of the imaginary part of the neutron s-wave optical potential



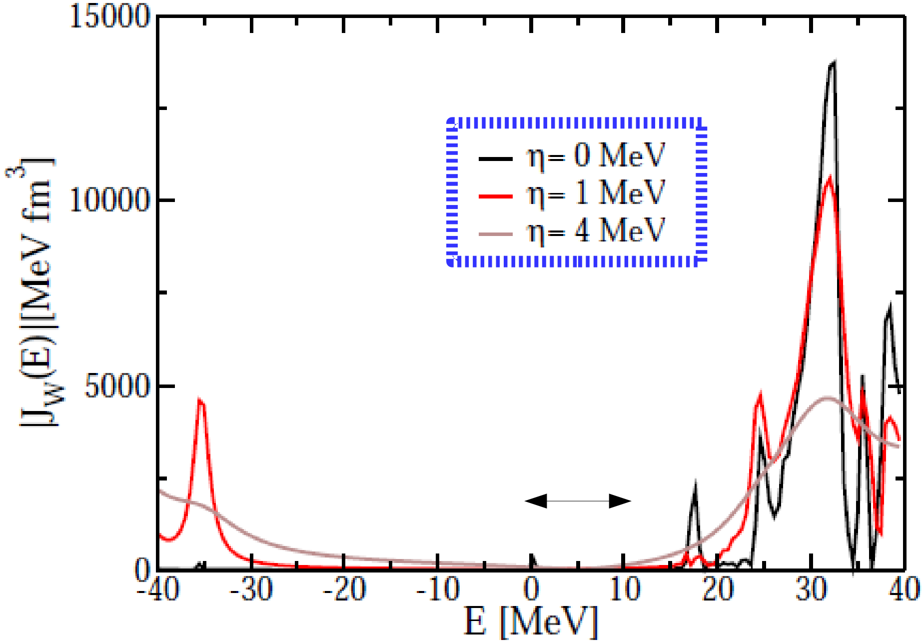
$$G(\alpha,\beta,E) = \langle \Psi_0^A | a_\alpha \frac{1}{E-(H-E_0^A)+i\eta} a_\beta^\dagger | \Psi_0^A \rangle + \ldots$$

* calculated optical potential has no absorption below 10 MeV

CC(SD) with N^2LO_{opt} : too small absorption



Volume integral of the imaginary part of the neutron s-wave optical potential

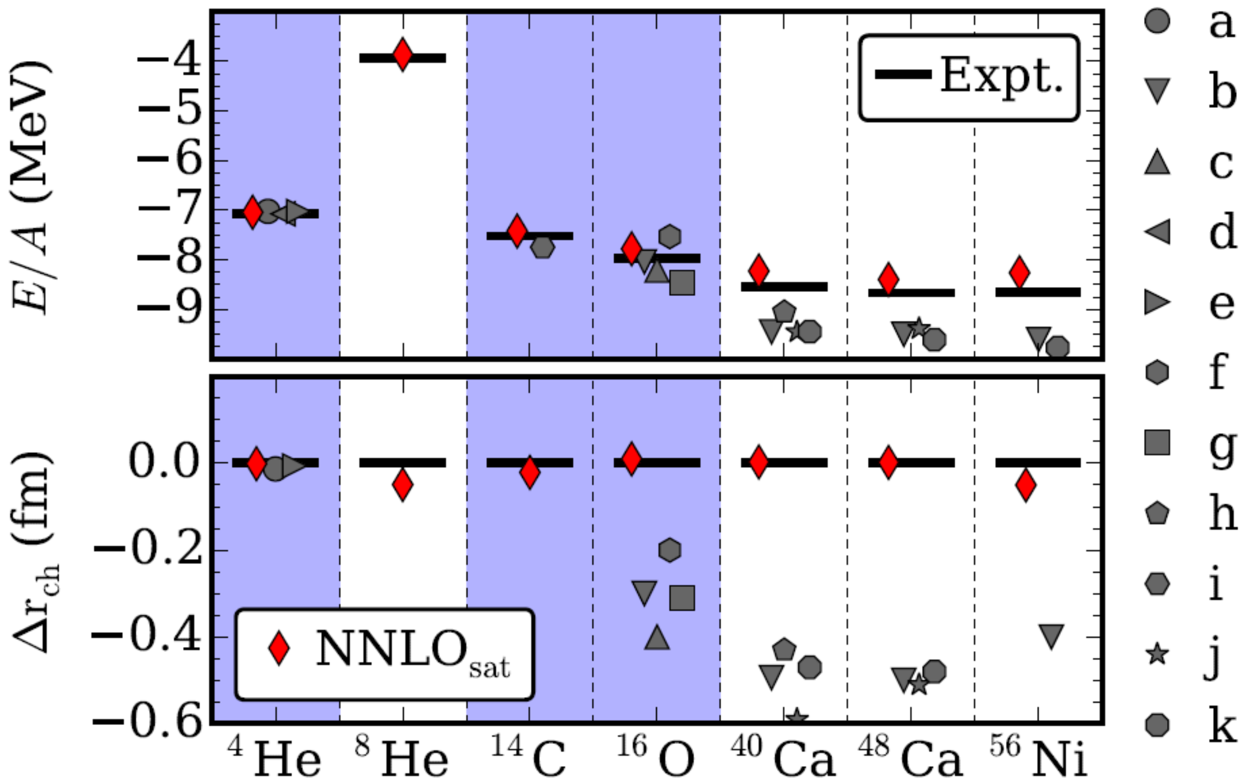


$$G(\alpha,\beta,E) = \langle\Psi_0^A|a_\alpha \frac{1}{E-(H-E_0^A)+i\eta} a_\beta^\dagger|\Psi_0^A\rangle + \ldots$$

* calculated optical potential has no absorption below 10 MeV
* absorption can be artificially increased by using finite value for η

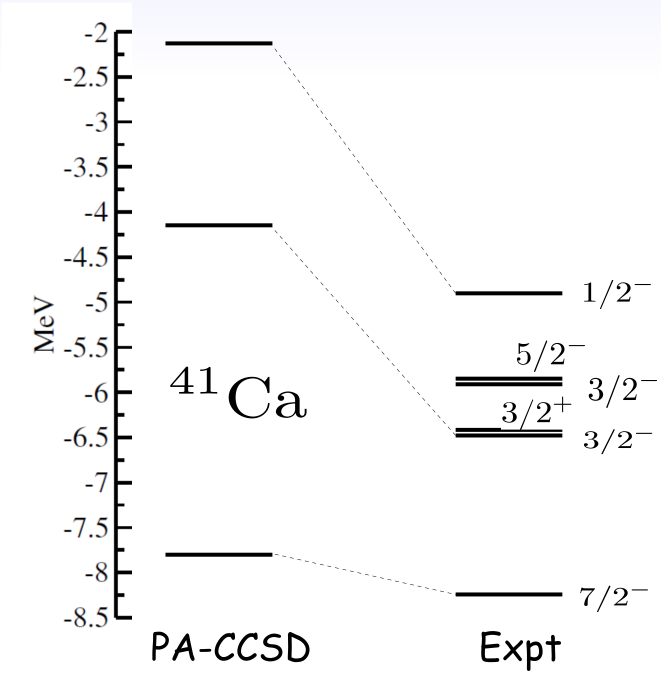
$^{40}Ca/^{48}Ca$

- N2LOsat interaction (A. Ekström *et al*, 2015) : 2 and 3-body terms
- reproduction of binding energies and nuclear radii

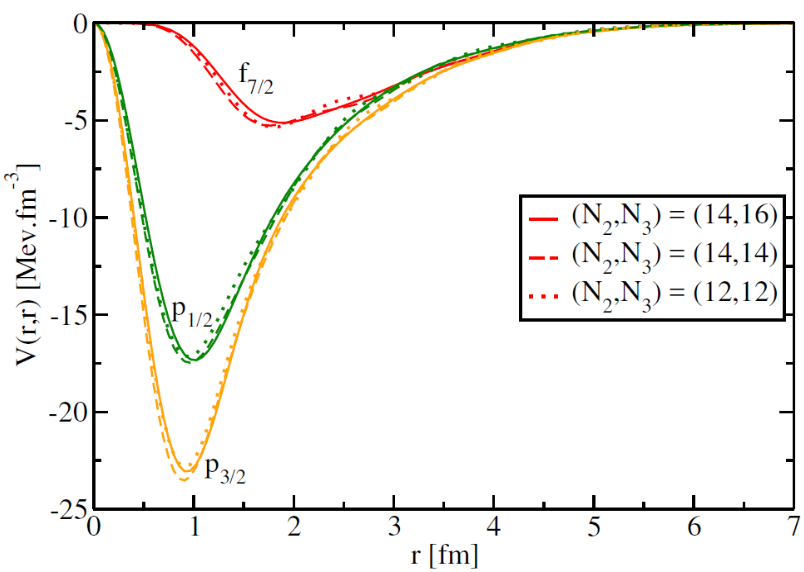


(taken from G. Hagen et *al*, 2016)

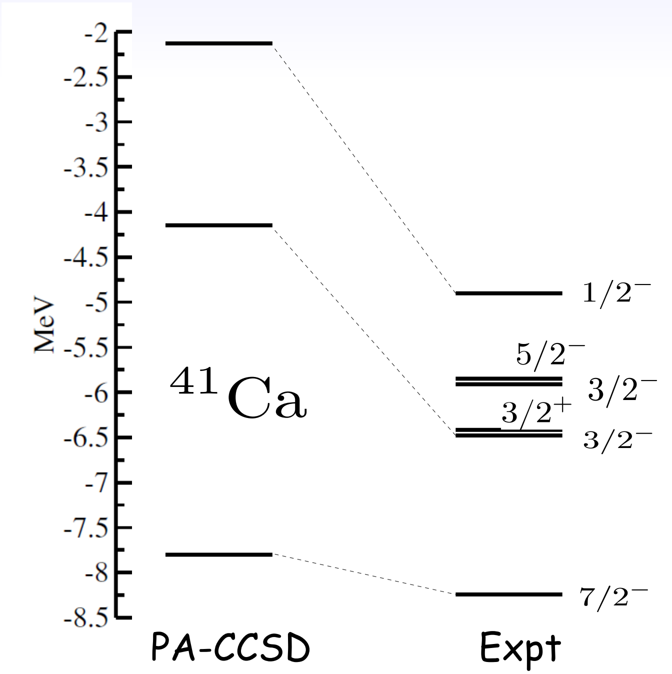
$^{40}Ca(n,n)^{40}Ca$

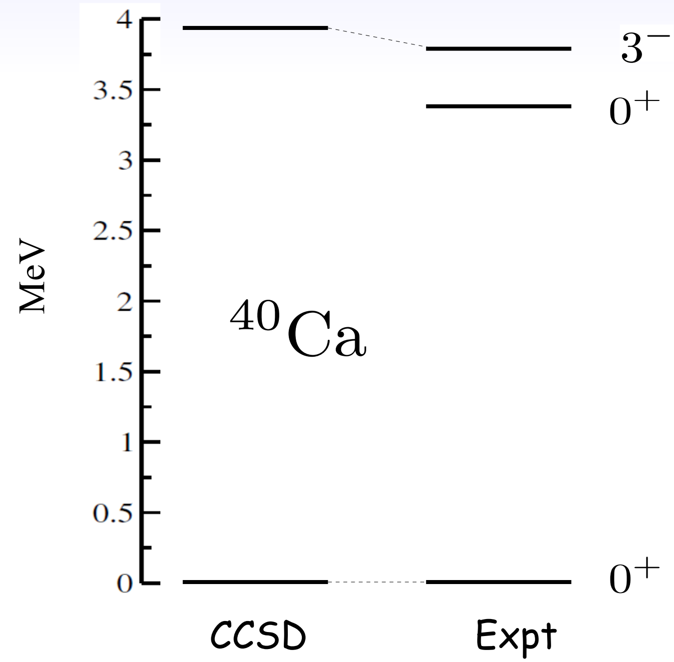


Real part of V(r,r) for the bound states in ^{41}Ca



$^{40}Ca(n,n)^{40}Ca$





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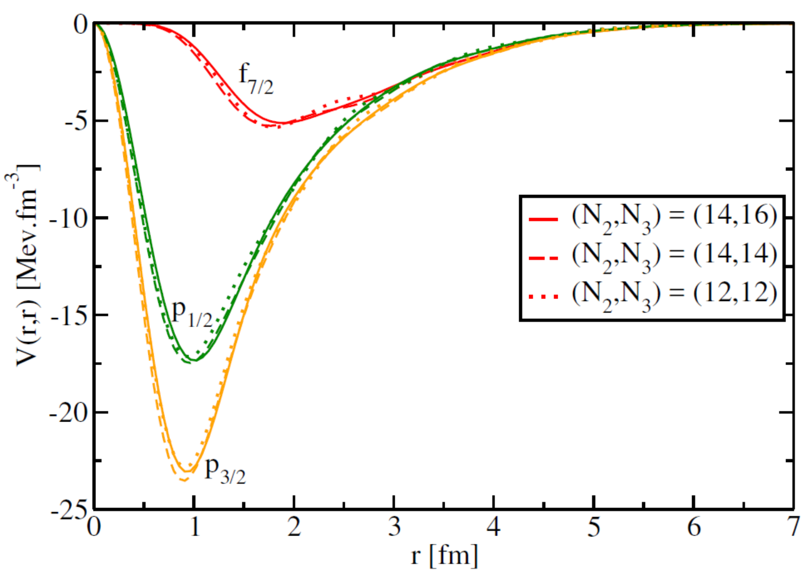
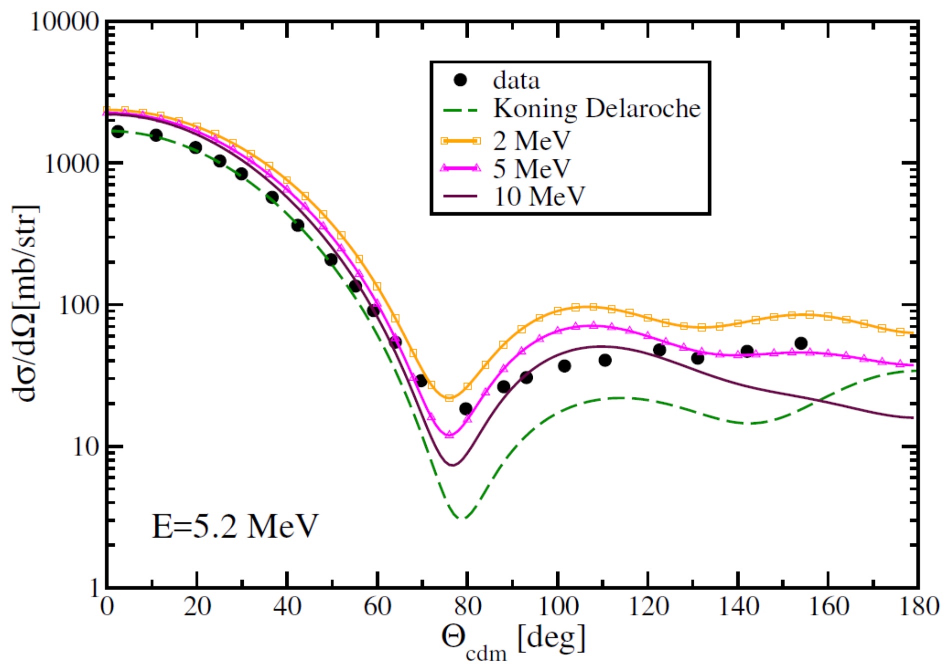
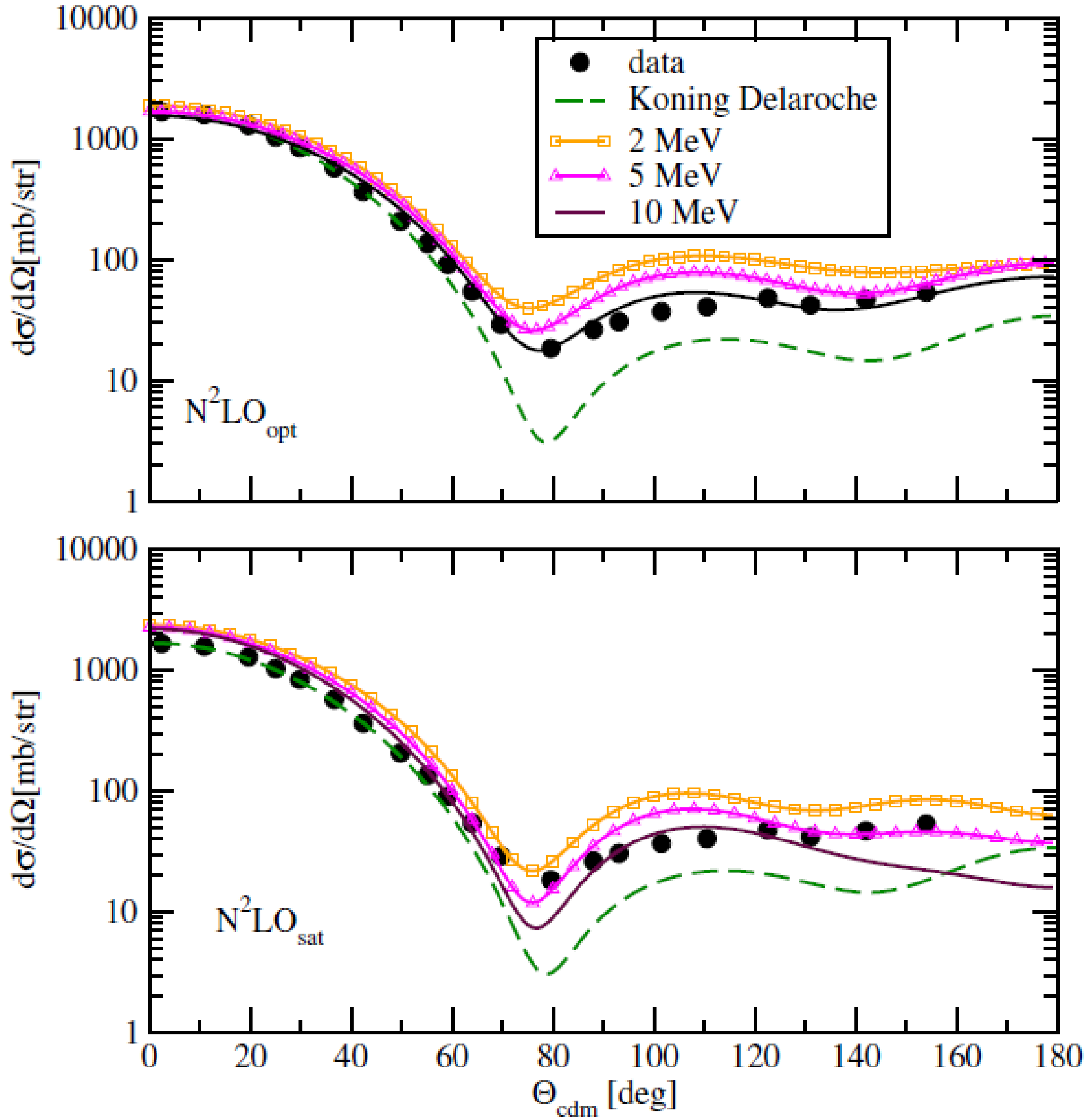
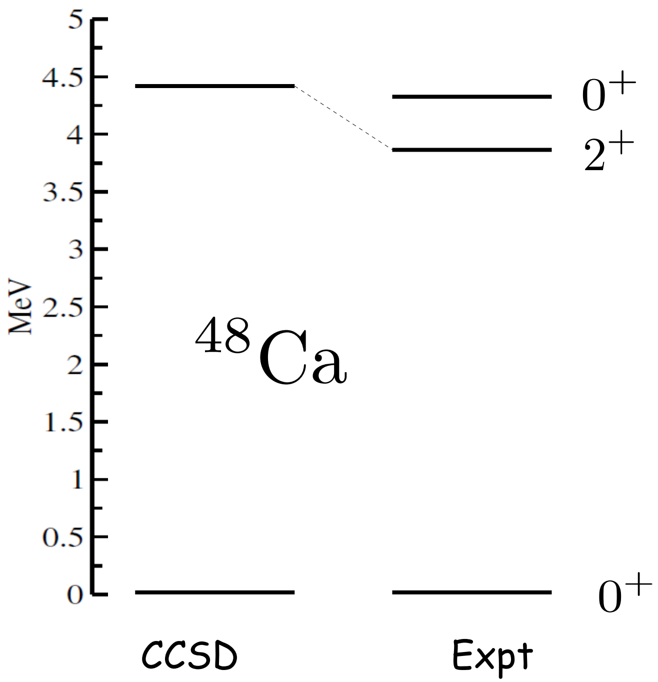




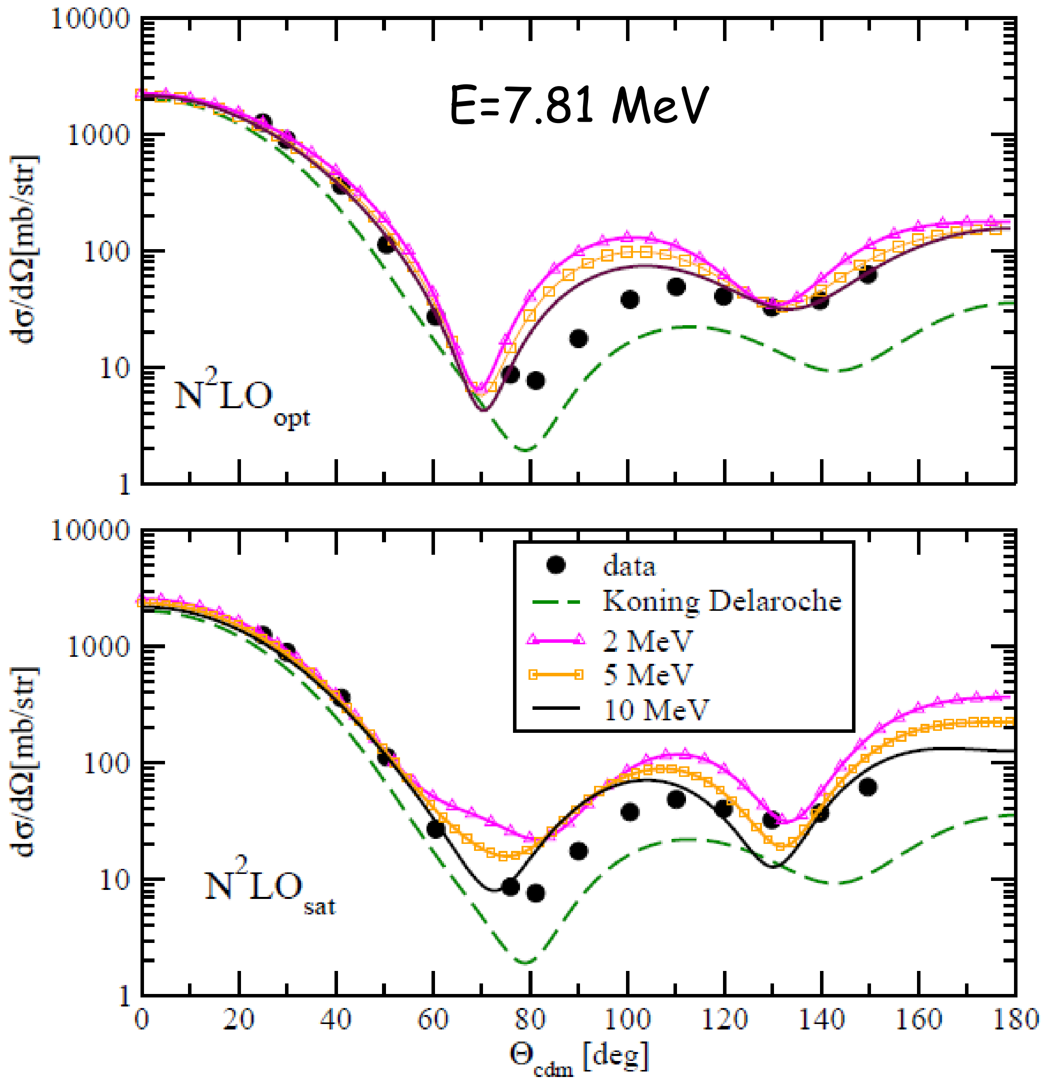
$^{40}Ca(n,n)^{40}Ca$ @ 5.2 MeV



$^{48}Ca(n,n)^{48}Ca$



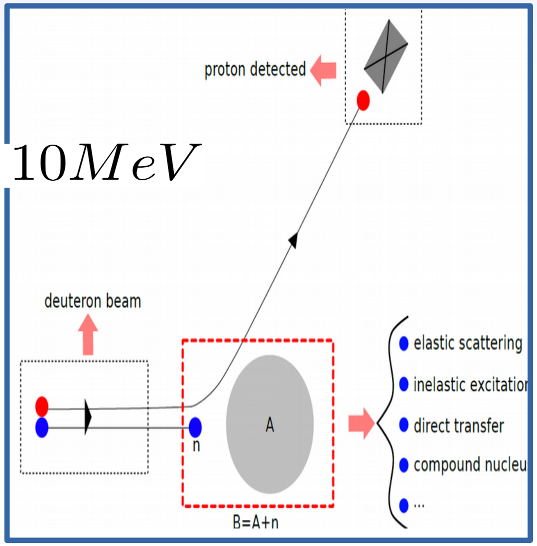
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
MeV
48Ca
0+
2+
0+
CCSD
Expt



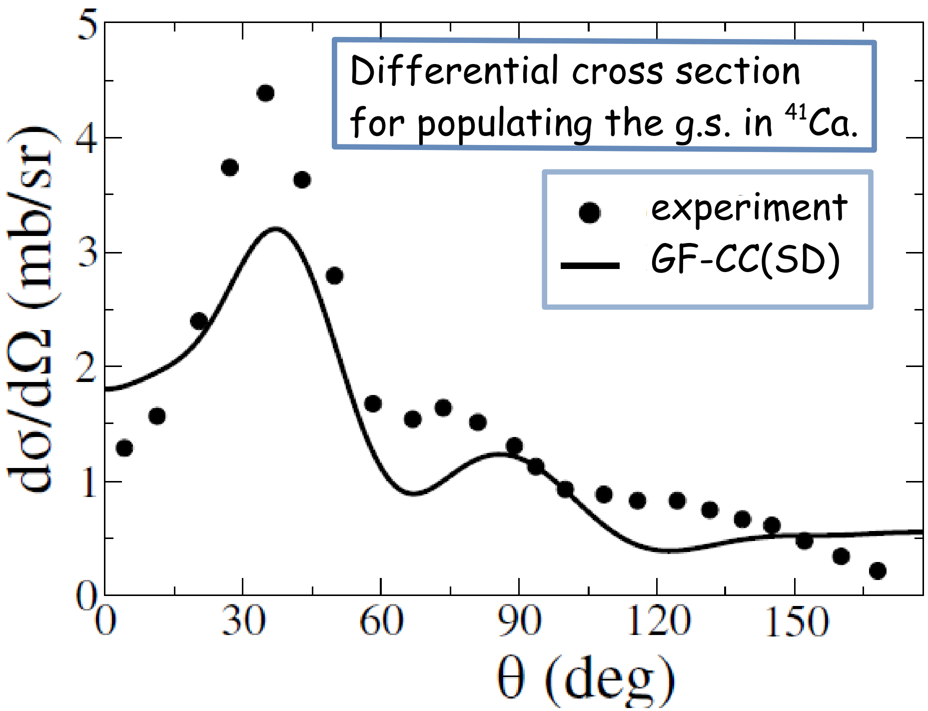
E=7.81 MeV
N2LOopt
N2LOsat
dσ/dΩ[mb/str]
10000
1000
100
10
1
data
Koning Delaroche
2 MeV
5 MeV
10 MeV
0
20
40
60
80
100
120
140
160
180
Θcdm [deg]

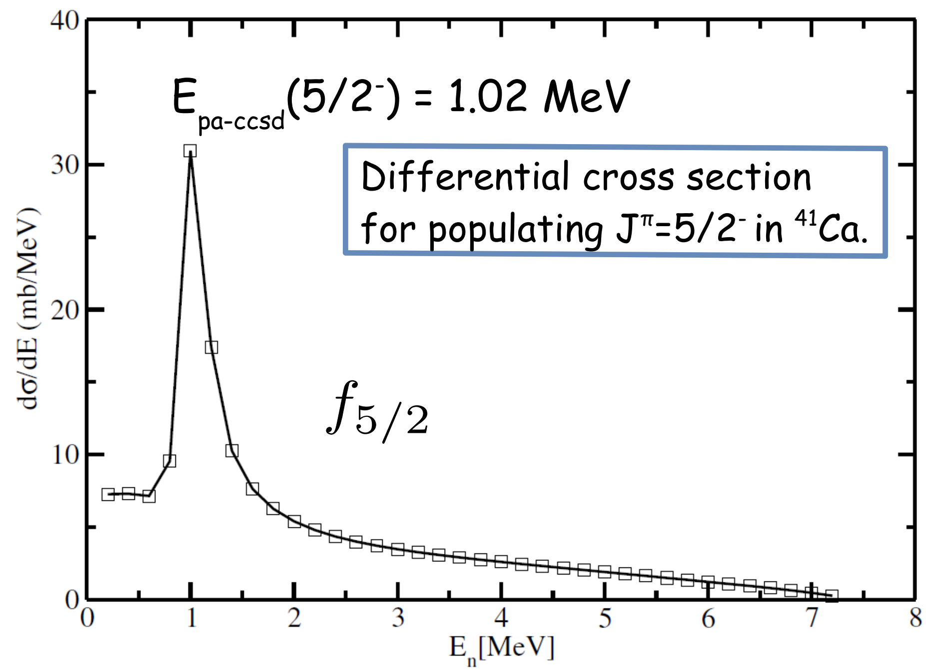
$^{40}Ca(d,p)$

$E_d = 10MeV$



reaction formalism
by G. Potel, F. Nunes, I. Thompson (2015)





$E_{exp}(7/2^-)$= -8.36 MeV
$E_{pa-ccsd}(7/2^-)$= -7.84 MeV

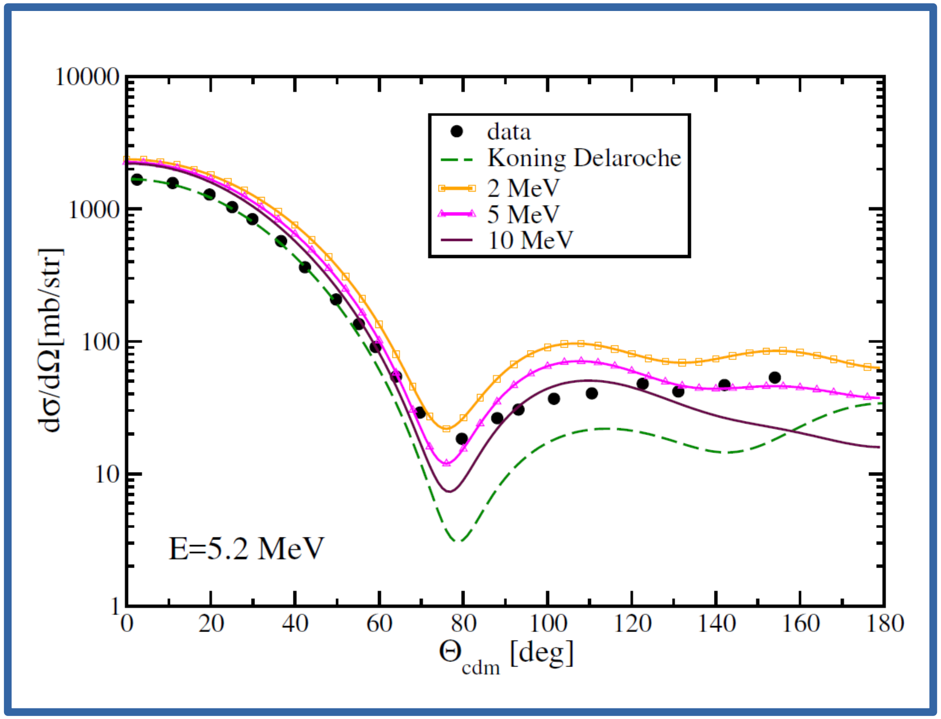
$E_{exp}(5/2^-)$= -5.78 MeV

Microscopic nucleon-nucleus optical potential

- Coupled Cluster Green's function with chiral-EFT nn,3n potentials
- Continuum (Berggren) basis

→ qualitative agreement with data, but overall lack of absorption

→ preliminary results for (d,p) reactions



Outlook:

→ CCSD(T)

→ Use of the dispersion relation starting with the CCGF potential + perturbation...

→ other chiral-EFT interaction...