# NON-LOCAL OPTICAL POTENTIALS

## Why we should care…

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INT, 16 Mar 2017

Supported by: NNSA, NSF, DOE

# Reaction theory for heavy exotic nuclei

$^{6}Li(d,p)^{7}Li$

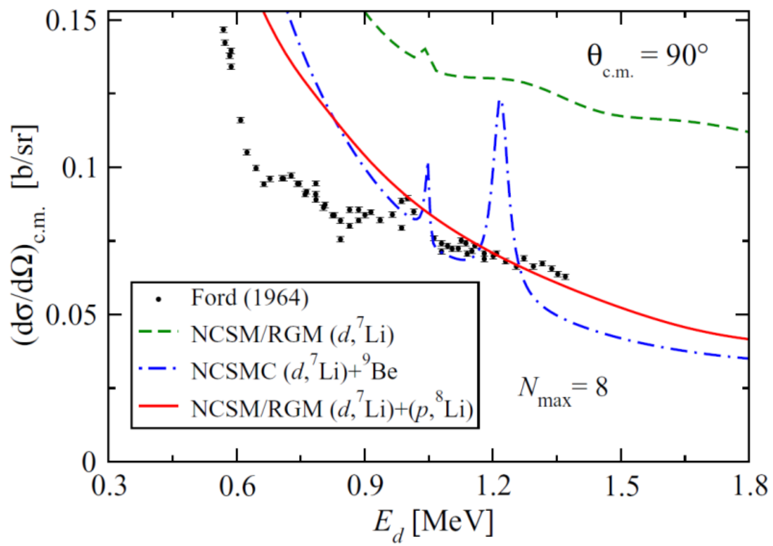



FIG. 7. Computed $^{7}Li(d,d)^{7}Li$ differential cross sections in the c.m. frame at the deuteron scattering angle of 90° as function of the kinetic energy of deuterons in the laboratory system, compared to the experimental data of Ref. [39]. The three sets of theoretical curves correspond to calculations within the $(d,{}^{7}Li)$ NCSM-RGM (green dashed line), $(d,{}^{7}Li) + {}^{9}Be$ NCSMC (blue dash-dotted line), and $(d,{}^{7}Li) + (p,{}^{8}Li)$ NCSM-RGM (red solid line) model spaces.

PRC93, 054606 (2016)

$^{132}Sn(d,p)^{133}Sn$

$^{59}Cu(d,n\gamma)^{60}Zn^{*}$

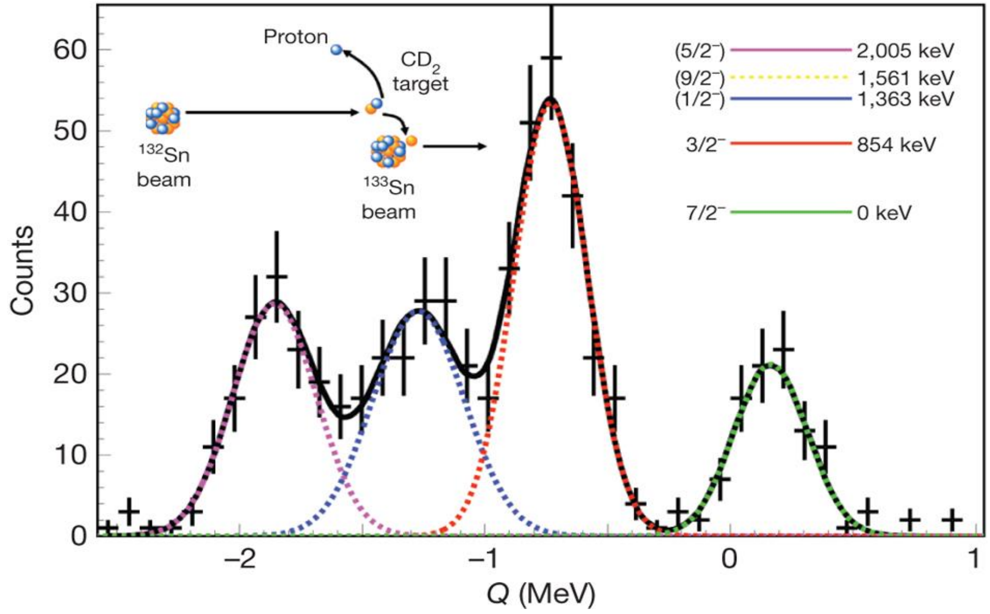
$^{95}Mo(d,p\gamma)\ ^{96}Mo^{*}$

…?

# Our starting point

- A complex many-body problem
- Scattering boundary conditions
- Importance of thresholds
- Large Coulomb interactions
- Specific clustering

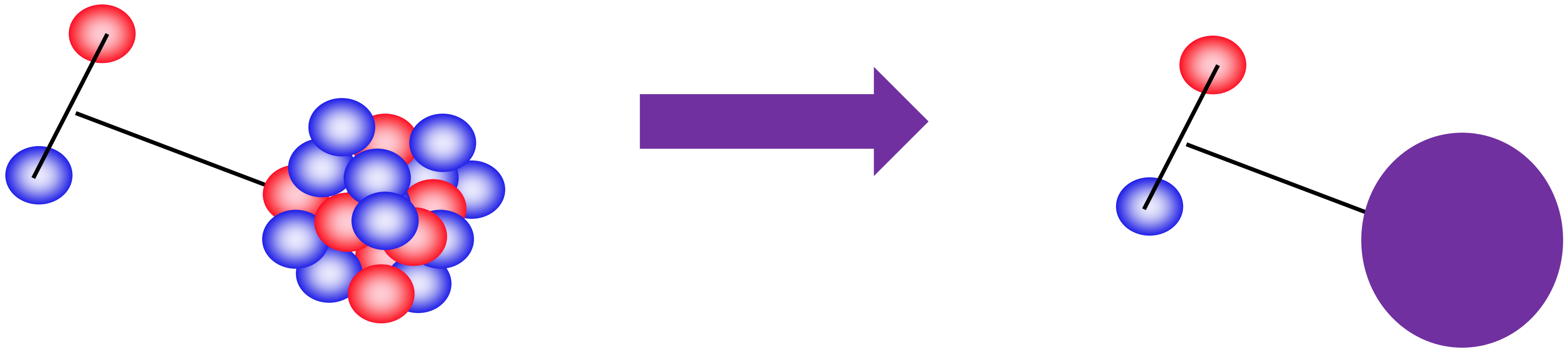
d($^{132}$Sn,$^{133}$Sn)p@5 MeV/u



# 1. reduction to few-body

- Reducing the many-body problem to a few-body problem introduces effective interactions.
- How does the original many-body Hamiltonian relate to the few-body Hamiltonian?

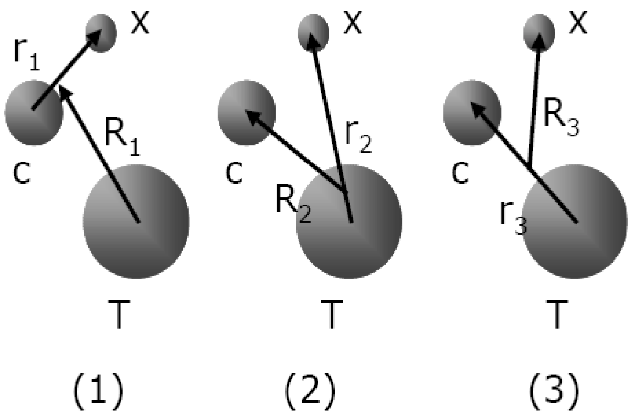
$$\mathcal{H}_{3B} = T_{\mathbf{r}} + T_{\mathbf{R}} + U_{nA} + U_{pA} + V_{np}$$



# 2. solving the few-body

**Faddeev Formalism**

$$\begin{aligned}
(E - T_1 - V_{xc})\Psi^{(1)} &= V_{xc}(\Psi^{(2)} + \Psi^{(3)}) \\
(E - T_2 - V_{ct})\Psi^{(2)} &= V_{ct}(\Psi^{(3)} + \Psi^{(1)}) \\
(E - T_3 - V_{tx})\Psi^{(3)} &= V_{tx}(\Psi^{(1)} + \Psi^{(2)})
\end{aligned}$$




**CDCC, ADWA, etc, etc…**

(this is another talk…)

# 3. determining $V_{eff}$

Currently our bipolar thinking:

- $V_{eff}$ is effective interaction between N-A and should describe elastic scattering (global optical potential)

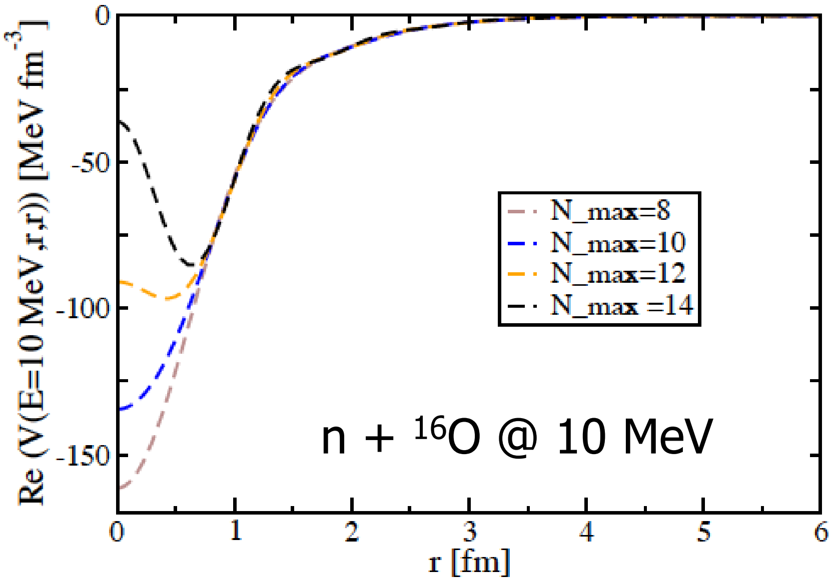
- $V_{eff}$ is self energy of N+A system and can be extracted from many-body theories (microscopic optical potential)

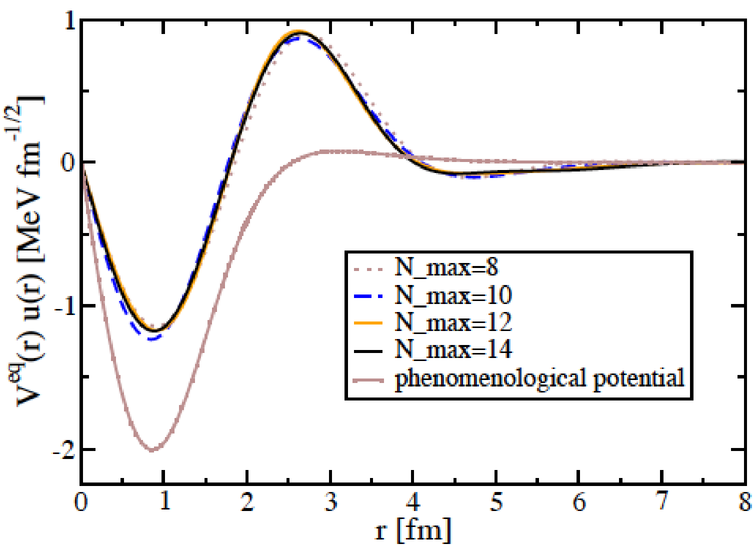
# 3. microscopic $V_{eff}$

- $V_{eff}$ is self energy extracted from coupled-cluster CCSD

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

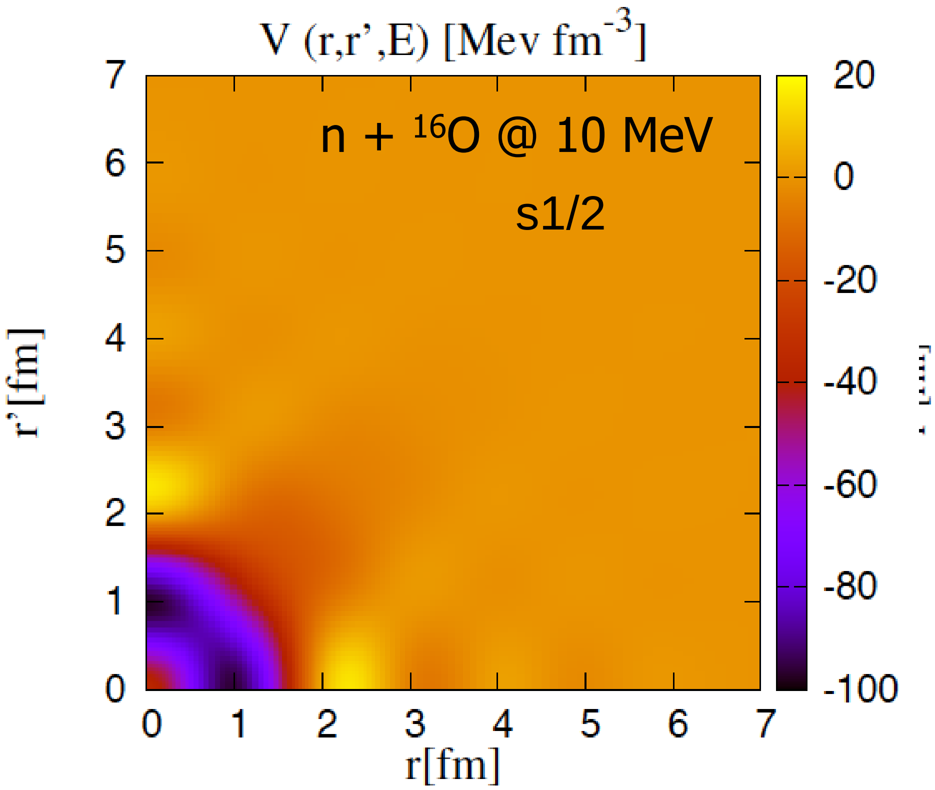
Ab-initio Hamiltonian: $NN_{opt}$
Basis: HO and Breggren
Extend for convergence of potential.

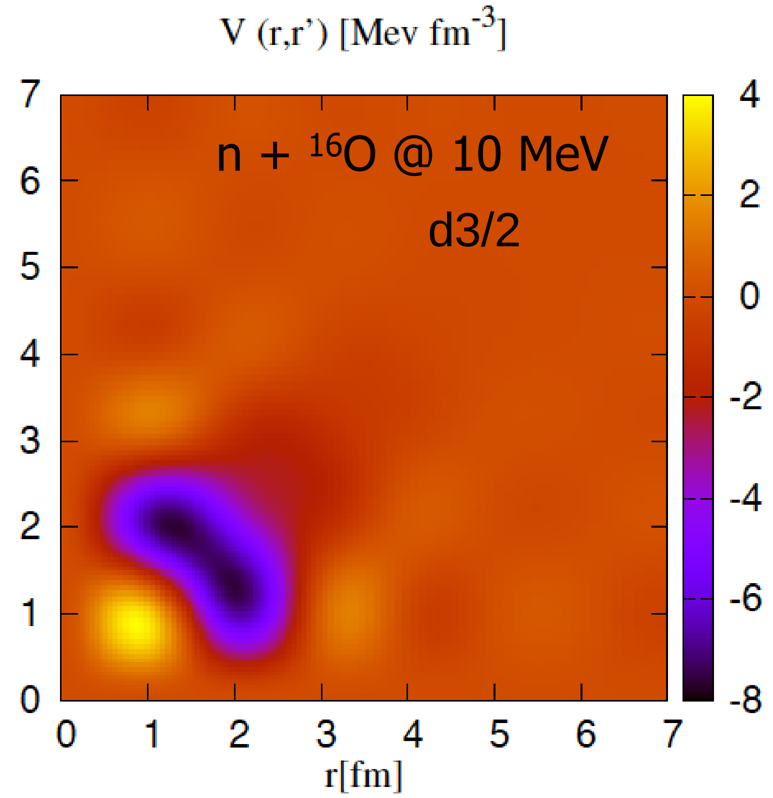



Rotureau et al., PRC95, 024315 (2017)

# 3. microscopic $V_{eff}$




The effective interaction is non-local!

Rotureau et al., PRC95, 024315 (2017)

# 3. microscopic $V_{eff}$

- Non-locality is large, varying with R and E and non-Gaussian!

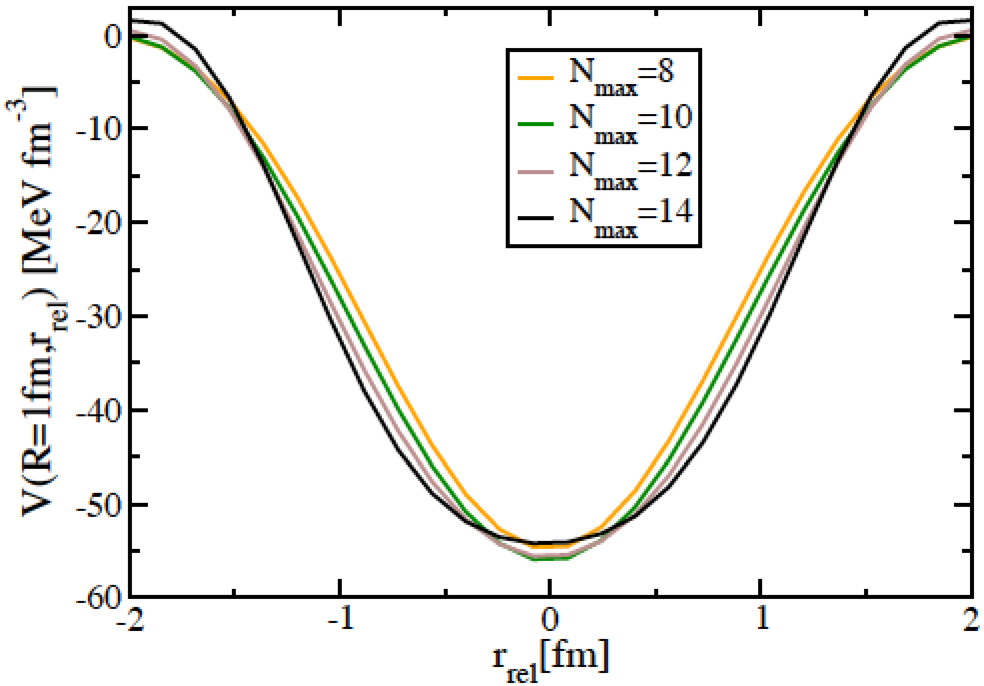



FIG. 8. Neutron $s$-wave optical potential at E=10 MeV plotted as $V(R + r_{\mathrm{rel}}/2, R - r_{\mathrm{rel}}/2)$ at fixed $R = 1/2$ fm. Here $N_{max} = 14$ and 50 discretized $s$-wave shells are included in the single-particle basis.

Rotureau et al., PRC95, 024315 (2017)

# 3. microscopic $V_{eff}$

- There remains an energy dependence!
- Absorption is small from E=0-10 MeV.

n + $^{16}$O

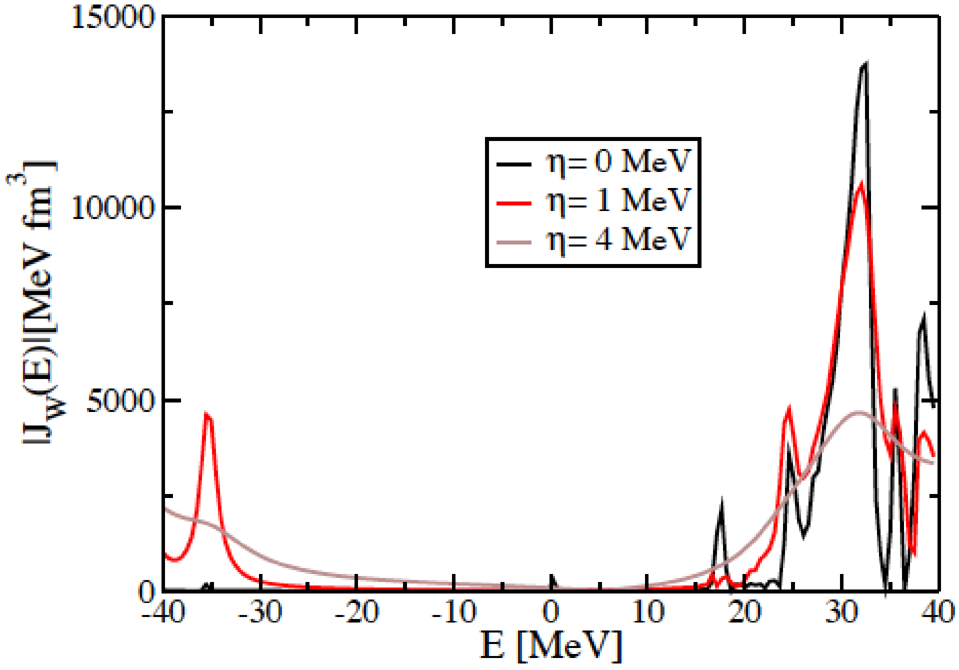



FIG. 11. Neutron $s$-wave imaginary volume integral $J_W(E)$ for several values of $\eta$. Calculations were performed at $N_{\max} = 14$ with 50 discretized $s_{1/2}$ shells.

Rotureau et al., PRC95, 024315 (2017)

# 3. non-local phenomenological $V_{eff}$

$$U^{NL}(\mathbf{R},\mathbf{R}') = \sum_L \frac{2L+1}{4\pi}\frac{g_L(R,R')}{RR'}P_L(\cos\theta)$$

$$\begin{aligned} g_L(R,R') &= h_L(R,R')\,U_{WS}\left(\frac{1}{2}(R+R')\right) \\ h_L(R,R') &= \frac{2i^L z}{\pi^{\frac{1}{2}}\beta} j_L(-iz)\exp\left(-\frac{R^2+R'^2}{\beta^2}\right) \\ &\approx \frac{1}{\pi^{\frac{1}{2}}\beta} e^{-\left(\frac{R-R'}{\beta}\right)^2} \quad \text{for } |z| \gg 1. \end{aligned}$$

Perey and Buck (1962): only surface imaginary

| $V_V$ (MeV) | $a_V$ (fm) | $W_S$ (MeV) | $a_S$ (fm) |
|---|---|---|---|
| 71.00 | 0.65 | 15.00 | 0.47 |
| $U_{SO}$ (MeV) | $a_{SO}$ (fm) | $\beta$ (fm) | $r_0$ (fm) |
| 7.18 | 0.65 | 0.85 | 1.22 |

Tian, Pang and Ma (2015): only surface imaginary

| $V_V$ (MeV) | $a_V$ (fm) | $r_V$ (fm) | $W_S$ (MeV) | $a_S$ (fm) | $r_S$ (fm) | $\beta$ (fm) |
|---|---|---|---|---|---|---|
| 70.00 | 0.61 | 1.25 | 21.11 | 0.46 | 1.15 | 0.90 |
| $W_V$ (MeV) | $a'_V$ (fm) | $r'_V$ (fm) | $U_{SO}$ (MeV) | $a_{SO}$ (fm) | $r_{SO}$ (fm) | / |
| 1.39 | 0.55 | 1.17 | 9.00 | 0.59 | 1.10 | / |

# 3. non-local phenomenological $V_{eff}$

- Perey and Buck: best for E<20 MeV
- Tian, Pang, Ma: best for E>20 MeV
    - (volume absorption important)
- Joint analysis of low energy and high energy data indicates, for both PB and TPM, residual energy dependence is needed!

Lovell, Bacq et al., in preparation (2017)

# 3. non-local phenomenological $V_{eff}$

- Strong energy dependence of local phenomenological potentials!
- Example Becchetti and Greenlees (1969)

$$
\begin{aligned}
Vv &= 54 - 0.32E - 24(N-Z)/A \\
Wv &= 0.22E - 1.6 \\
Ws &= 13 - 0.25E - 12(N-Z)/A
\end{aligned}
$$

We took 27 sets of data for elastic angular distributions:
targets $^{48}Ca$, $^{90}Zr$ and $^{208}Pb$
energies 6-40MeV

Assume same Gaussian non-locality of either PB or TPM

Minimization results show no energy dependence is required for the real part

Lovell, Bacq et al., in preparation (2017)

# 3. non-local phenomenological $V_{eff}$

- Both volume and surface absorption was considered:

$$W_v = dE + e \qquad W_s = aE + b\frac{N-Z}{A} + c$$

- 5 parameter minimization of 27 elastic scattering data sets

( error from covariant matrix – 1$\sigma$ error bar)

Energy dependence in imaginary part of optical potential is required!!!

Lovell, Bacq et al., in preparation (2017)

# 4. non-locality in reactions

- Effect of non-locality?
- How to deal with non-locality?
- How to pin down non-locality?
- Is this a relevant question?

# non-locality effect in transfer reactions

- Systematic study of effect of nonlocality in (d,p)
  - Titus et al., PRC89, 034609 (2014)
- Similar study with DOM interaction
  - Ross et al., PRC92, 044607 (2015)
- Inclusion of non-locality in adiabatic theories implemented
  - Titus et al. PRC 93, 014604 (2016)
- New reaction code NLAT
  - Titus et al., CPC 207, 499 (2016)
- Systematic study of effect of nonlocality in (d,n)
  - Ross et al., PRC 94, 014607 (2016)

# non-locality effect on wavefunctions

<u>BOUND STATES</u>

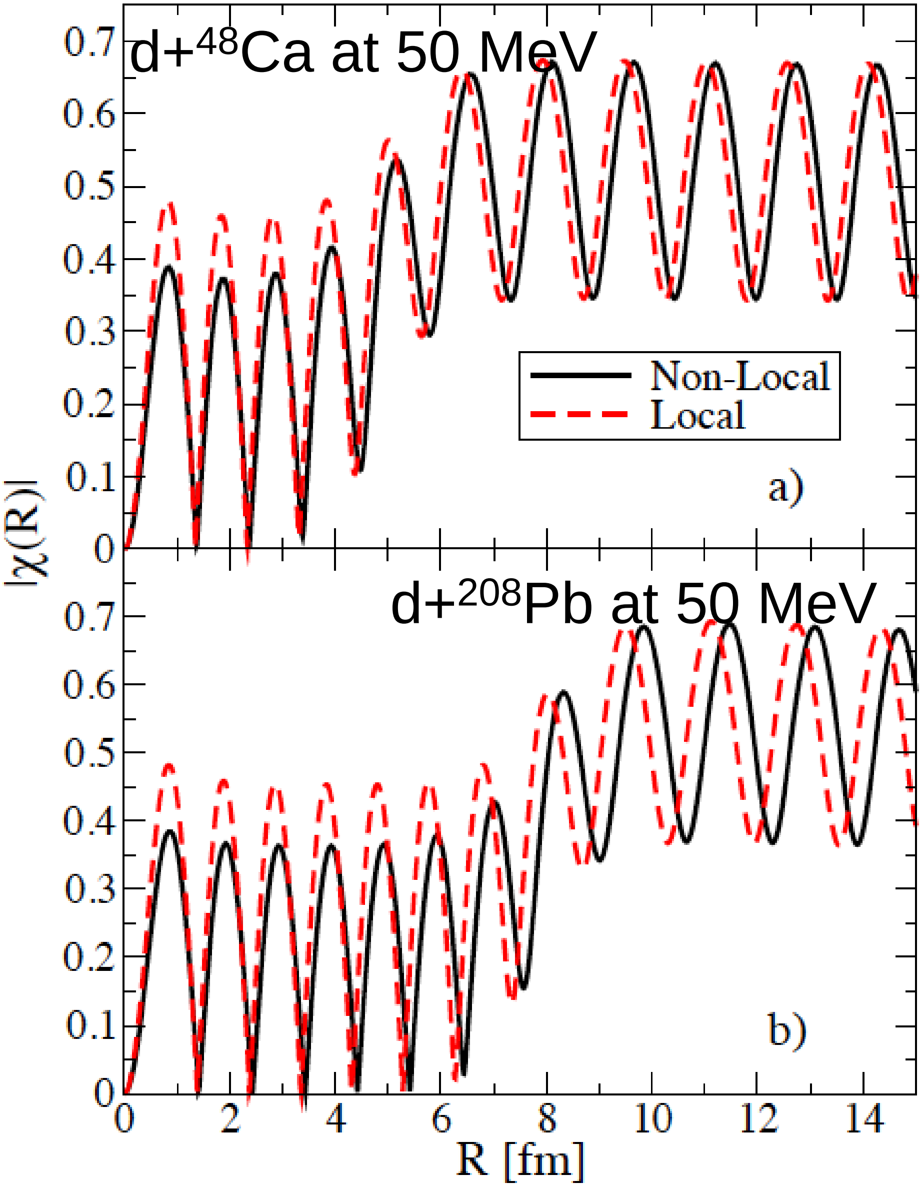
- Fitted separation energy
- Reduction of strength in interior
- Increase of magnitude in asymptotics

<u>SCATTERING STATES</u>

- Fitted nucleon elastic scattering
- Reduction of strength in interior

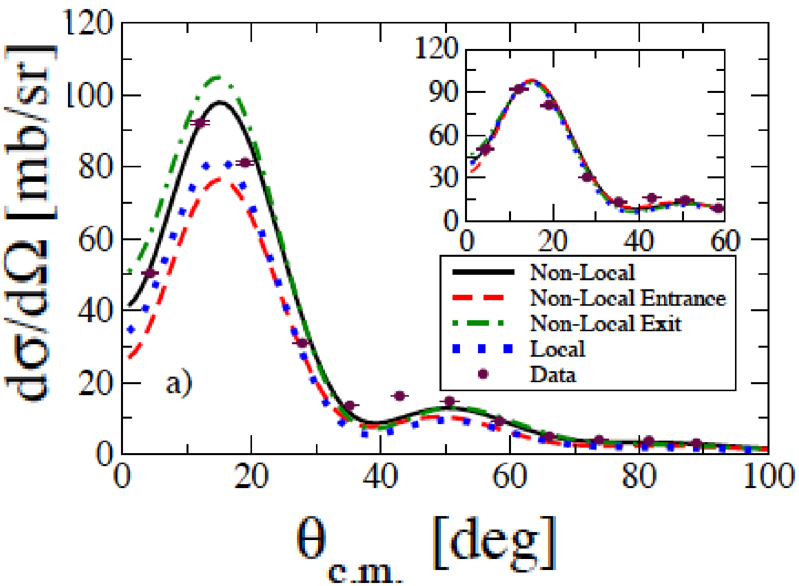
<u>THREE-BODY DEUTERON SCATTERING STATES</u>

- Fitted nucleon elastic scattering
- Reduction of strength in interior
- Deuteron elastic no longer reproduced

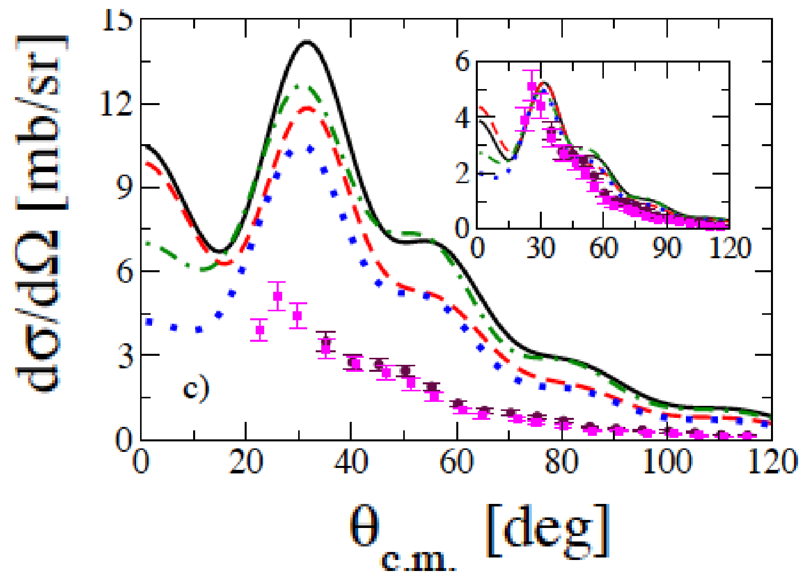


# non-locality effect in (d,p) with ADWA

$^{48}$Ca(d,p) at 10 MeV

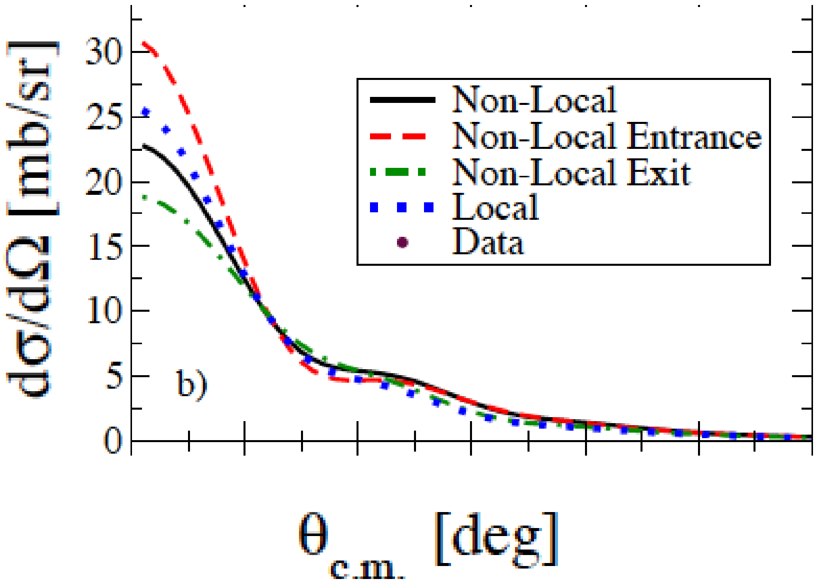



$^{208}$Pb(d,p) at 20 MeV

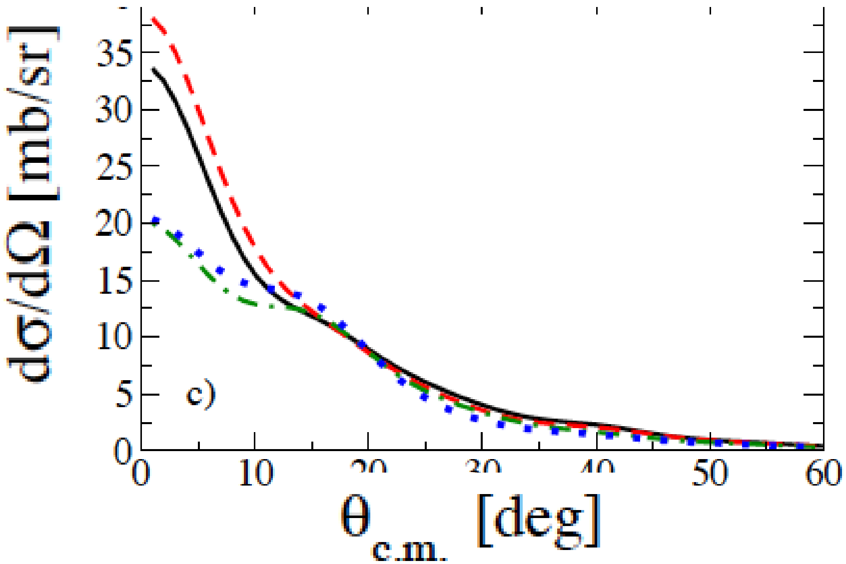


# non-locality effect in (d,p) with ADWA

$^{132}$Sn(d,p) at 50 MeV




$^{208}$Pb(d,p) at 50 MeV



# non-locality effect in (d,p) with ADWA

## Transfer cross sections: Nonlocal relative to local at first peak

| | $E_{lab} = 10$ MeV | $E_{lab} = 20$ MeV | $E_{lab} = 50$ MeV |
|---|---|---|---|
| $^{16}\mathrm{O}(1d_{5/2})(d,p)$ | 27.2% | 24.9% | 22.3% |
| $^{16}\mathrm{O}(2s_{1/2})(d,p)$ | 15.5% | 7.1% | 20.7% |
| $^{40}\mathrm{Ca}(d,p)$ | 48.5% | 43.3% | 4.8% |
| $^{48}\mathrm{Ca}(d,p)$ | 19.4% | 14.9% | 41.9% |
| $^{126}\mathrm{Sn}(d,p)$ | 36.9% | 33.6% | 6.9% |
| $^{132}\mathrm{Sn}(d,p)$ | 25.7% | 3.2% | −10.9% |
| $^{208}\mathrm{Pb}(d,p)$ | 52.5% | 35.0% | 64.8% |

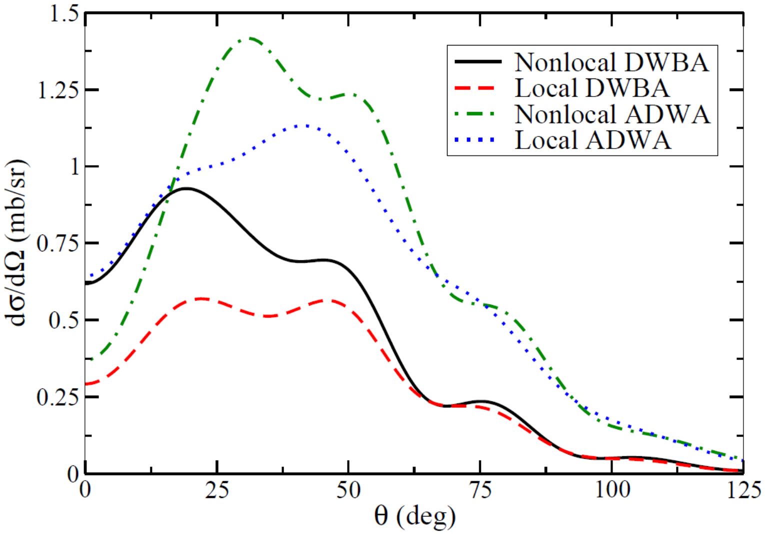
Low Energy

- General enhancement of cross section
- Proton channel most important
- Deuteron channel had a modest impact

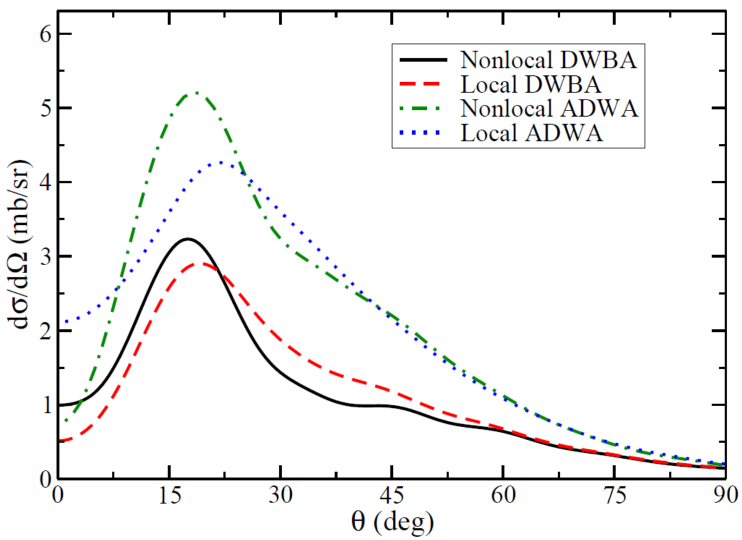
High Energy

- Deuteron channel more important, specially for heavy targets
- Competition between effects of bound and scattering effects in proton channel.

# non-locality effect in transfer reactions




$^{208}Pb(d,n)^{209}Bi$ @ 20 MeV




$^{208}Pb(d,n)^{209}Bi$ @ 50 MeV

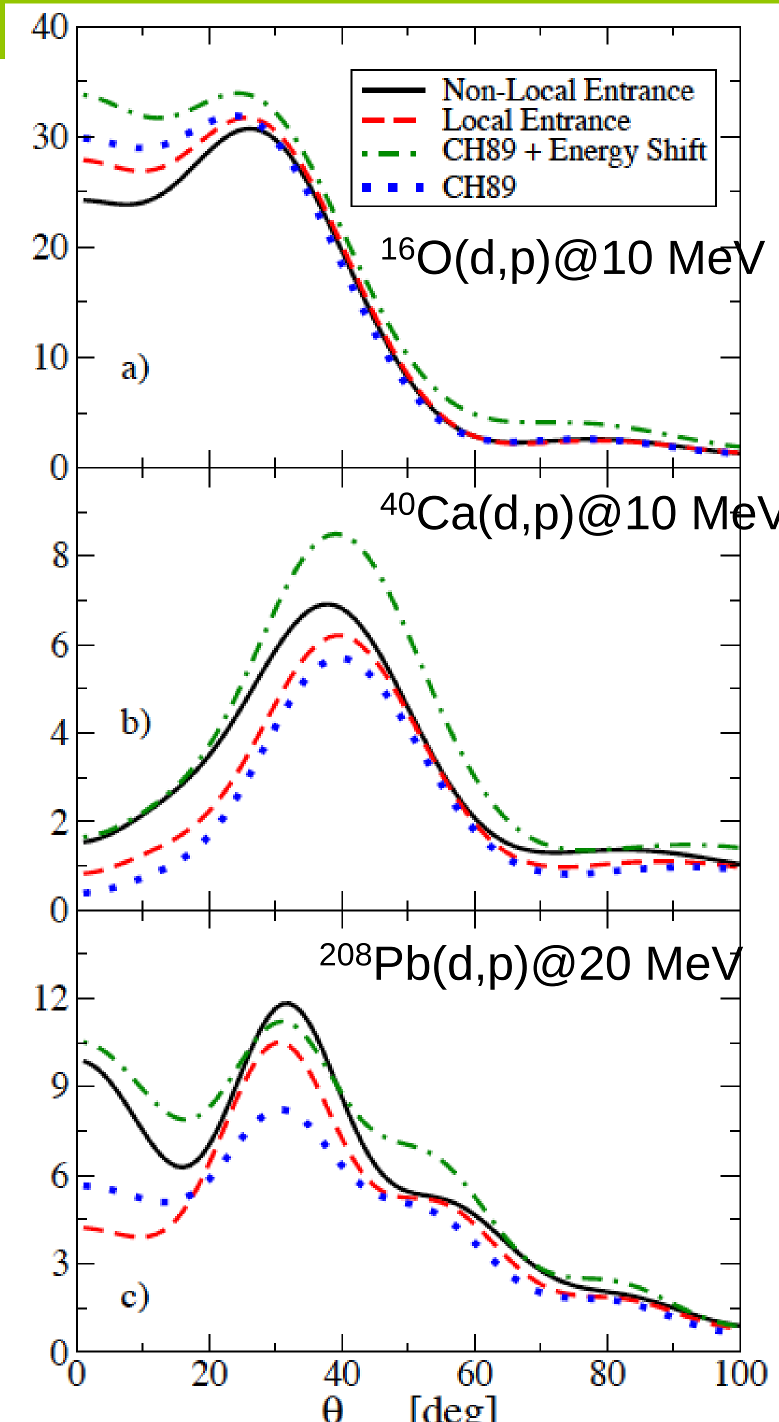
- In general there are very few examples of (d,n) data out there
- Non-locality in optical potential can produce large differences in the angular distribution
- Neutron angular distributions can provide constrains
- Important to get the most forward angles!!!

Ross, Titus and Nunes, PRC 94, 014607 (2016)

# non-locality effect: energy shift

N. K. Timofeyuk and R. C. Johnson, Phys. Rev. Lett. **110**, 112501 (2013).
N. K. Timofeyuk and R. C. Johnson, Phys. Rev. C **87**, 064610 (2013).

Energy shift does not provide a quantitative description of the effect of nonlocality:
neither shape nor magnitude



# Concluding remarks

Solving the few-body problem

A lot of progress has been made and more developments are ongoing for (d,p) on heavy targets (another talk...)

Determining the effective interactions

Revival of microscopic interactions from ab-initio calculations

Without artificial factors, all fall short in describing accurately elastic scattering

From data, need both non-locality and energy dependence

Including non-locality

We understand non-locality affects transfer observables and know how to include it. How do we constrain it? Need guidance from microscopic theory

# Thank you for your attention


MSU few-body group : **Luke Titus*, Alaina Ross, Amy Lovell,** Terri Poxon-Pearson, **Jimmy Rotureau** and Gregory Potel

Collaboration with **Pierre-Loic Bacq** and Pierre Capel (ULB)

Supported by: NNSA, NSF, DOE