3N force contribution to the distorted-wave theory of (d,p) reactions

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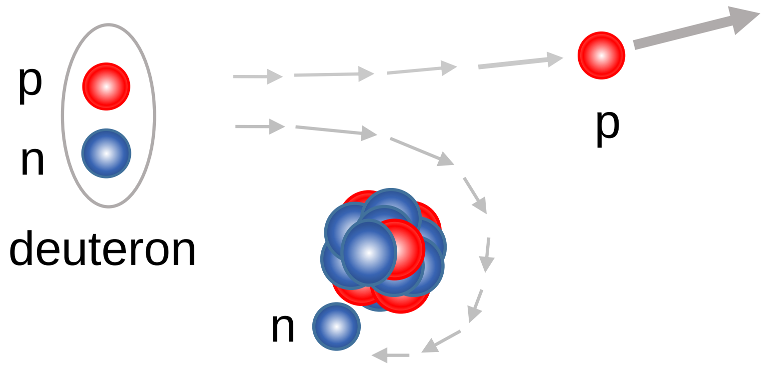
Deuteron stripping reactions



Motivation for (d,p) experiments:

(d,p) reactions can

1) help to discover unknown states
2) determine their spin and parity
3) measure occupancies of nuclear shells in these states through spectroscopic factors studies.

How do we achieve this?

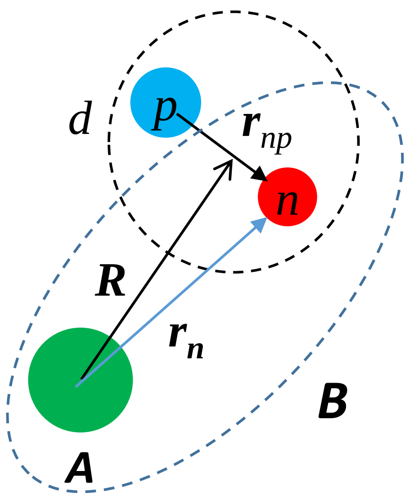
By comparing measured and theoretical cross sections.

$$\frac{\sigma_{\text{exp}}(\theta)}{\sigma_{\text{theor}}(\theta)}$$

Distorted wave amplitude of $A(d,p)B$ reactions

$$T_{(d,p)} = \langle \Psi^{J_B}_{M_B} \psi^{J_p}_{M_p} \chi_{\boldsymbol{k}_p}(\boldsymbol{R}_p) | V_{np}(\boldsymbol{r}) | \Psi^{J_A}_{M_A} \psi^{J_d}_{M_d} \chi_{\boldsymbol{k}_d}(\boldsymbol{R}_d) \rangle$$

distorted waves



wave functions
of B and A

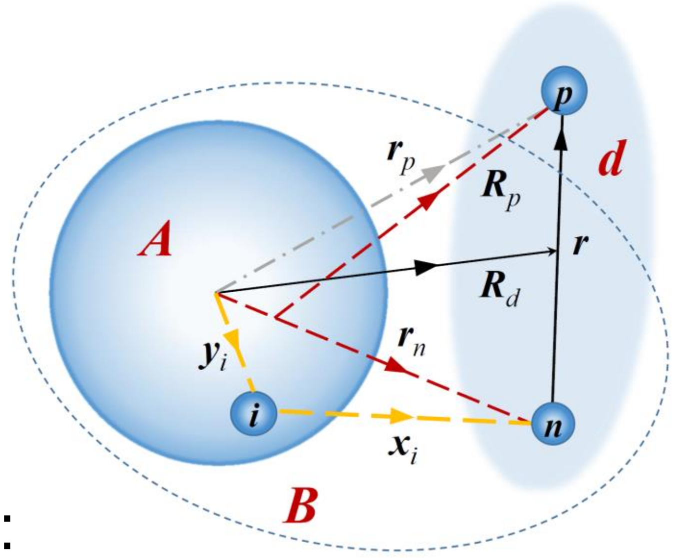
Overlap integral

$$\langle \psi_B | \psi_A \rangle = I(\boldsymbol{r}_n)$$

What changes does 3N force bring?

Distorted wave theories:

DWBA and ADWA



$$T_{(d,p)} = T^{2N}_{(d,p)} + T^{3N}_{(d,p)}$$

Hamiltonian with 2N contribution only:

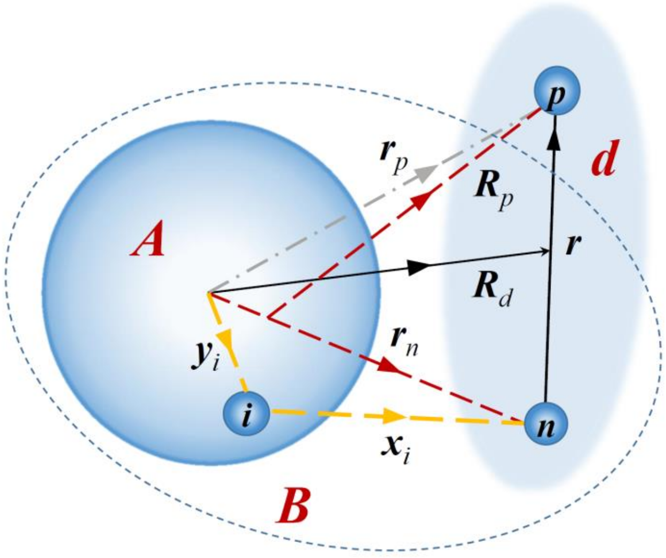
$$T^{2N}_{(d,p)} = \langle \Psi^{J_B}_{M_B} \psi^{J_p}_{M_p} \chi_{\boldsymbol{k}_p}(\boldsymbol{R}_p) | V_{np}(\boldsymbol{r}) | \Psi^{J_A}_{M_A} \psi^{J_d}_{M_d} \chi_{\boldsymbol{k}_d}(\boldsymbol{R}_d) \rangle$$

phenomenological, 3N should be there

Hamiltonian with 3N contribution includes new term:

$$T^{3N}_{(d,p)} = \langle \Psi^{J_B}_{M_B} \psi^{J_p}_{M_p} \chi_{\boldsymbol{k}_p}(\boldsymbol{R}_p) | \sum_{i \in A} W_{ipn} | \Psi^{J_A}_{M_A} \psi^{J_d}_{M_d} \chi_{\boldsymbol{k}_d}(\boldsymbol{R}_d) \rangle$$

Difference between 2N and 3N contributions:



2N contains overlap integral

$$\langle \psi_B | \psi_A \rangle = I(\boldsymbol{r}_n)$$

3N contains different matrix element:

$$\left\langle \psi_B \left| \sum_{i \in A} W_{inp} \right| \psi_A \right\rangle = F(\boldsymbol{r}_n, \boldsymbol{R}_p)$$

It is not proportional to the overlap integral and the corresponding cross section cannot be factorized via spectroscopic factors!

Assumptions are needed to proceed with evaluating 3N contributions:

- 3N force is contact

$$W_{ijk} = I_3[(\tau_i \cdot \tau_j)\delta(r_{ik})\delta(r_{jk}) + (\tau_i \cdot \tau_k)\delta(r_{ij})\delta(r_{jk}) + (\tau_k \cdot \tau_j)\delta(r_{ik})\delta(r_{ji})]$$

- Nucleus A is a double-closed shell
- A and B are described by Hartree-Fock model
- Single-particle wave functions in A and B are the same
- The difference in centre-of-mass positions in A and B is neglected

With these assumptions, available DW codes can be used in which overlap function should be modified:

3N force strength

Deuteron w.f. at $r_{np} = 0$

$$I_{lj}^{\mathrm{mod}}(r) = I_{lj}(r)\left[1 + \frac{I_3 \psi_d(0)}{D_0}\left(\rho_A(r) - \tfrac{1}{2}\rho_A^{(\mathrm{n})}(r)\right)\right]$$

Overlap function (HF s.p.w.f.)

Density of nucleus A

Neutron density of nucleus A

$$D_0 = \int d\boldsymbol{r}\, V_{np}(\boldsymbol{r})\varphi_d(\boldsymbol{r})$$

D_0 is independent of NN model

$\psi_d(0)$ is model-dependent:

NN Model	Ref	$\psi_d(0)/Y_{00}(\hat{\boldsymbol{r}})$
Reid soft core	[17]	0
Argonne V18	[18]	0.079
CD-Bonn	[19]	0.30
χEFT N4LO: 0.8 fm	[20]	-0.22
χEFT N4LO: 0.9 fm	[20]	-0.11
χEFT N4LO: 1.0 fm	[20]	-0.026
χEFT N4LO: 1.1 fm	[20]	0.062
χEFT N4LO: 1.2 fm	[20]	0.14
χEFT N2LO: 1.0 fm	[21]	0.282

Choice of I_3

$$I_3 = -\frac{9}{2}\frac{c_E}{F_\pi^4 \Lambda_\chi}$$

Low-energy constant

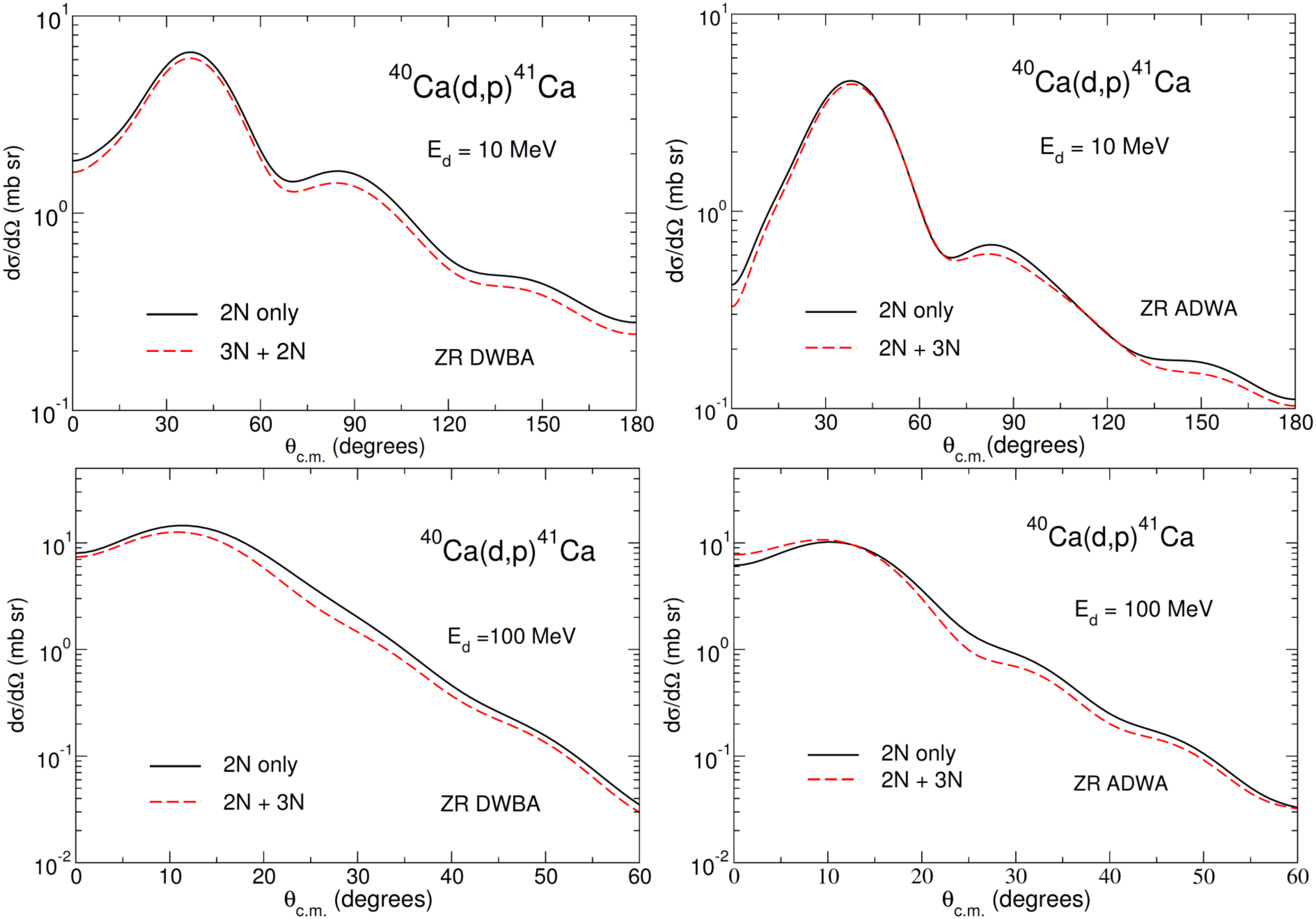
Chiral symmetry breaking scale, ~ 700 MeV

Weak pion decay constant = 92.4 MeV

J.E. Lynn et al: *Chiral Three-Nucleon Interactions in Light nuclei, Neutron-Alpha Scattering and Neutron Matter*

Phys. Rev. Lett. 116, 062501 (2016)

V_{3N}	R_0 (fm)	c_E	c_D
$\mathrm{N^2LO}$ $(D1, E\tau)$	1.0	−0.63	0.0
	1.2		
$\mathrm{N^2LO}$ $(D2, E\tau)$	1.0	−0.63	0.0
	1.2	0.09	3.5
$\mathrm{N^2LO}$ $(D2, E\mathbb{1})$	1.0	0.62	0.5
$\mathrm{N^2LO}$ $(D2, E\mathcal{P})$	1.0	0.59	0.0



$^{40}Ca(d,p)^{41}Ca$
E_d = 10 MeV
2N only
3N + 2N
ZR DWBA
$d\sigma/d\Omega$ (mb sr)
$\theta_{c.m.}$ (degrees)
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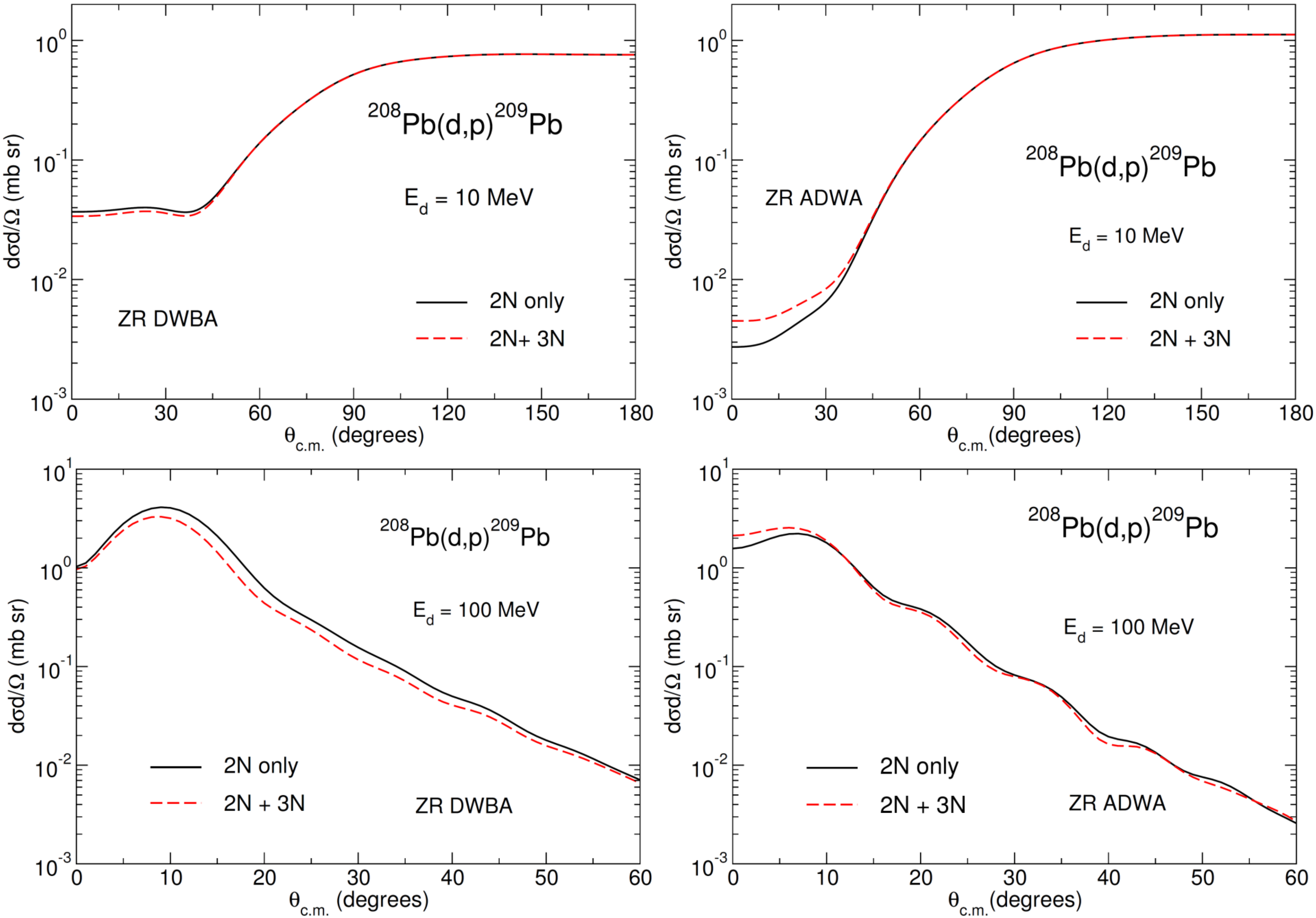

^{208}Pb(d,p)^{209}Pb
E_d = 10 MeV
ZR DWBA
2N only
2N+ 3N
$d\sigma/d\Omega$ (mb sr)
$\theta_{c.m.}$ (degrees)
^{208}Pb(d,p)^{209}Pb
ZR ADWA
E_d = 10 MeV
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2N + 3N
$d\sigma/d\Omega$ (mb sr)
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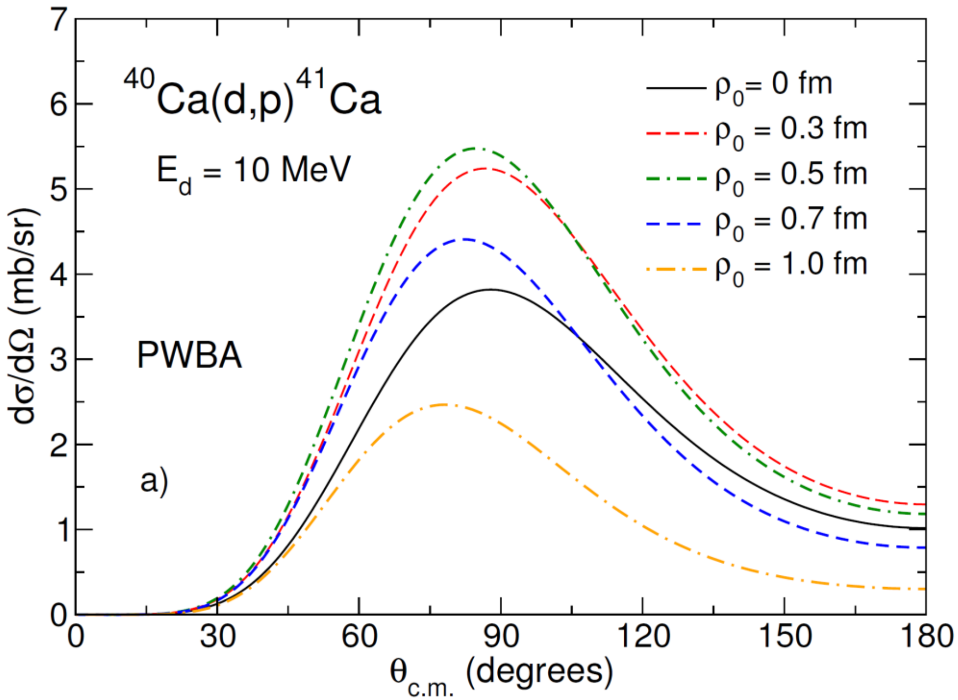
2N only
2N + 3N
ZR ADWA
$d\sigma/d\Omega$ (mb sr)
$\theta_{c.m.}$(degrees)

Finite-range effects in Plane-Wave Born Approximation

$$T^{3N}_{(d,p)} = \langle \Psi^{J_B}_{M_B} \psi^{J_p}_{M_p} \chi_{\boldsymbol{k}_p}(\boldsymbol{R}_p) | \sum_{i \in A} W_{ipn} | \Psi^{J_A}_{M_A} \psi^{J_d}_{M_d} \chi_{\boldsymbol{k}_d}(\boldsymbol{R}_d) \rangle$$

using plane waves

$$W_{ijk} = W_0 e^{-\frac{1}{3}\frac{r_{ij}^2 + r_{jk}^2 + r_{ki}^2}{\rho_0^2}}$$

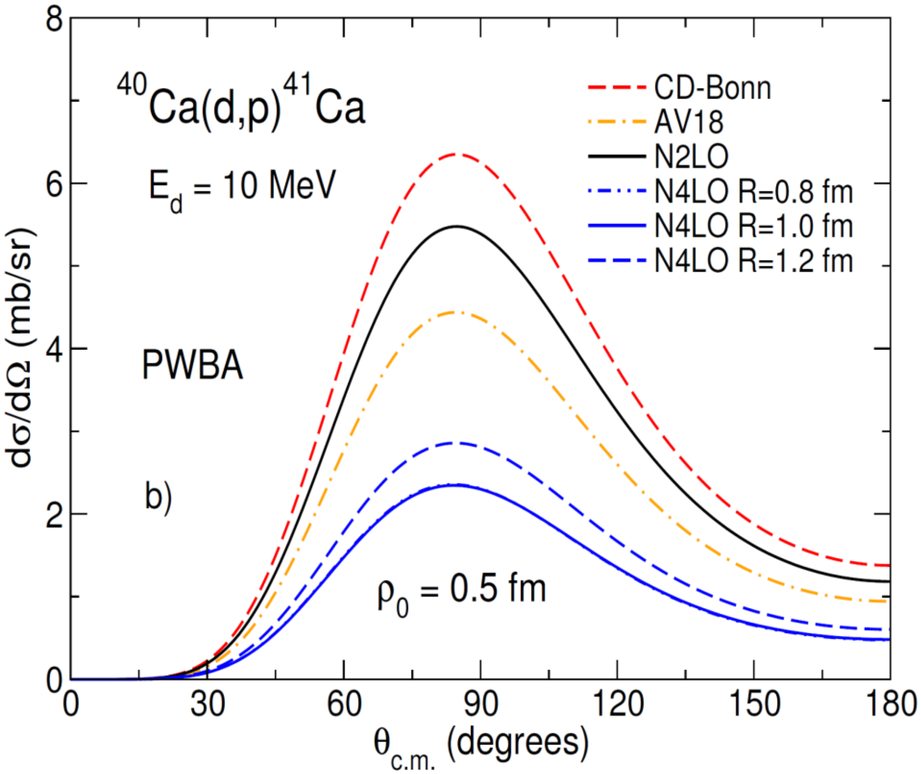


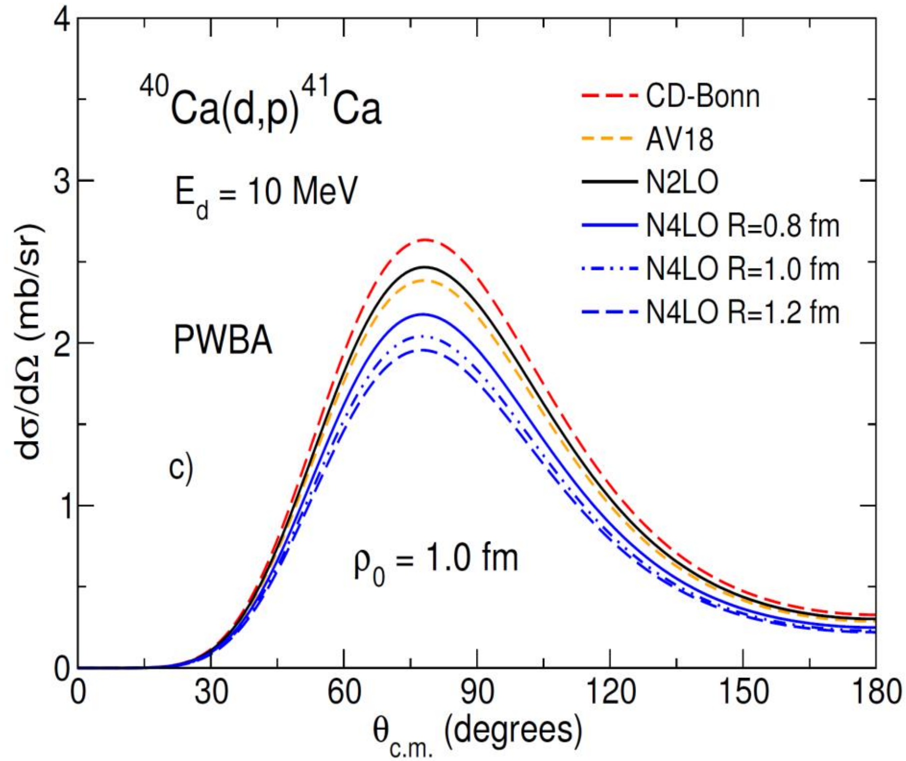
Fixed volume integral

$$I_3 = \int d\boldsymbol{r}_{12} d\boldsymbol{r}_{13} W(\rho_{ijk})$$

Deuteron wave function:
χEFT at N2LO

Sensitivity to the deuteron wave function for a fixed 3N force





Conclusions

Contribution to the (d,p) cross sections from 3N force cannot be factorized via spectroscopic factors.

With the chosen parametrization of the ***zero-range*** 3N force the contribution from 3N vertex can be noticeable at energies above the Coulomb barrier.

PWBA cross sections are very sensitive to the range of the 3N force and to the choice of the 2N force.

What should be done to clarify the 3N contribution in (d,p) reactions?