Ab initio many-body calculations of single-nucleon transfer reactions with deuteron projectile

[arXiv:1602.04404, accepted on PRC]

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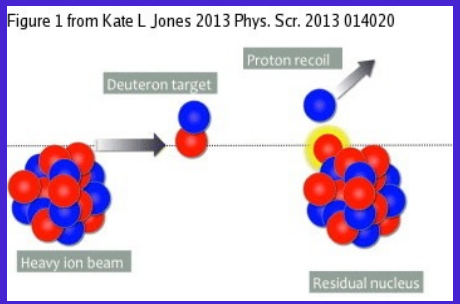
In collaboration with:
G. Hupin (CEA, DAM),
P. Navrátil (TRIUMF),
S. Quaglioni (LLNL).

TRIUMF

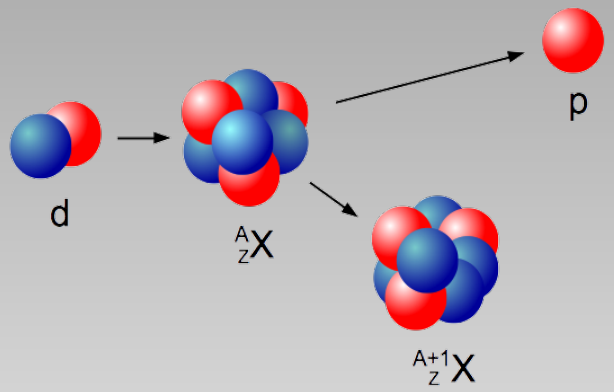


Outline

- Motivations for the study of transfer reactions and interest in ^{7}Li(*d*,p)^{8}Li reaction
- The No-Core Shell Model with Resonating Group Method (NCSM/RGM) and with continuum (NCSMC)
- Results on ^{7}Li(*d*,p)^{8}Li reactions and resonances of ^{9}Be above *d*-^{7}Li threshold:
  - (Eigen)phase shifts
  - Cross sections
- Conclusions & perspectives

Deuteron-nucleus reaction: experimental motivations

Intense experimental activity (direct and inverse kinematics):



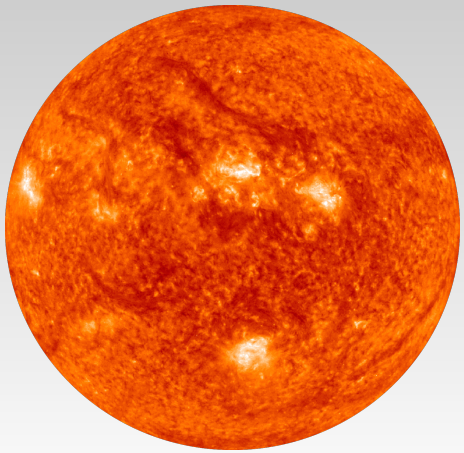
(*d*,p) reaction in direct kinematics

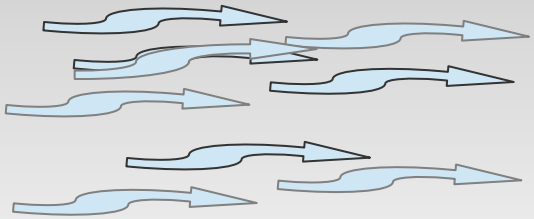
- Structure and spectroscopy of nuclei
- Nucleosynthesis and nuclear fusion applications ($^{3}H(d,n)^{4}He$ reaction)
- Surrogate for (p/n) capture reactions
- Calibration reaction for measurement of processes of interest

^{7}Li(*d*,p)^{8}Li transfer reaction

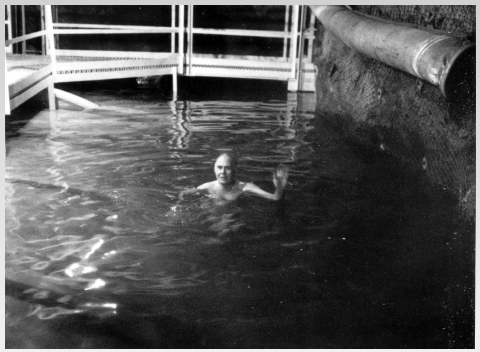
- Calibration reaction for astrophysical process: ^{7}Li(*d*,p)^{8}Li as target calibration for ^{7}Be(p,γ)^{8}B

Solar neutrino problem:





$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

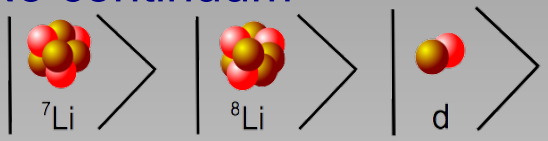


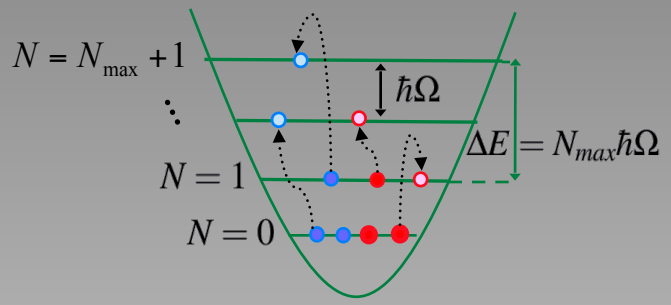
R. Davis Jr takes a dip
At Homestake Mine (1971)

No-core shell model combined with the resonating group method (NCSM-RGM) and NCSM with continuum (NCSMC)

No-core shell model (NCSM):

- A-nucleon wave function expansion in the harmonic-oscillator (HO) basis
- Short- and medium-range correlations
- No continuum



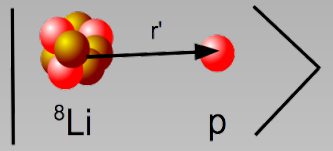


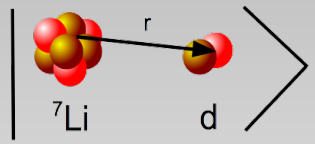
P. Navrátil at al. PRL **84**, 5728 (2000)

NCSM+Resonating group method (NCSM-RGM):

- Microscopic approach to describe the scattering of clusters
- Long range correlations (relative motion of clusters)

K. Wildermuth, Y.C. Tang A unified theory of the nucleus 1977





NCSM with continuum (NCSMC):

S. Baroni, P. Navrátil, and S. Quaglioni, PRL 110, 022505 (2013); PRC 87, 034326 (2013)

$$|\Psi_A^{J^\pi T}\rangle = \sum_\lambda c_\lambda |\ ^9\mathrm{Be}\ \rangle + \sum_{\tilde{\nu}} \int dr\, r^2 \frac{g_{\tilde{\nu}}^{J^\pi T}(r)}{r} \hat{\mathcal{A}}_{\tilde{\nu}} |\ ^7\mathrm{Li}\ \text{---}\ \mathrm{d}\ \rangle + \sum_{\tilde{\nu}'} \int dr'\, r'^2 \frac{g_{\tilde{\nu}'}^{J^\pi T}(r')}{r'} \hat{\mathcal{A}}_{\tilde{\nu}'} |\ ^8\mathrm{Li}\ \text{---}\ \mathrm{p}\ \rangle$$

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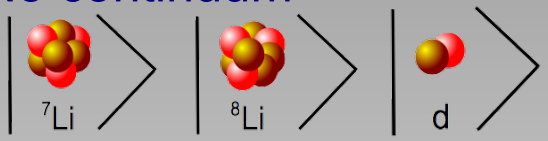

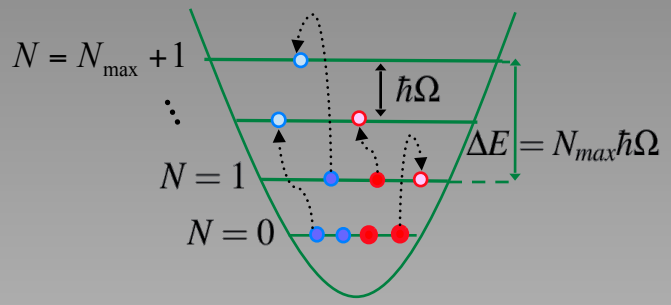

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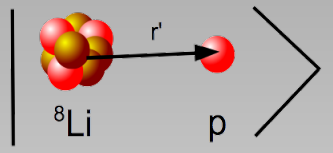

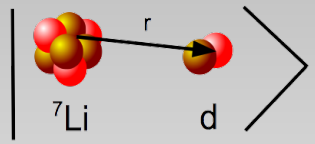

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Variational amplitudes
(unknowns of the many-body problem)

NCSM-RGM and NCSMC equations

$$\mathcal{H} = T_{\rm rel}(r) + \mathcal{V}_{\rm rel} + \bar{V}_{\rm C}(r) + H_{(A-a)} + H_{(a)}$$

Internal A-nucleon microscopic Hamiltonian

Coupled-channel equations solved for the amplitude c_λ and g_ν

$$\begin{pmatrix} E_\lambda \delta_{\lambda\lambda'} & \langle {}^9\mathrm{Be} | \mathcal{H}\mathcal{A}_{\tilde{\nu}} | {}^8\mathrm{Li}\ r'\ \mathrm{p}\ r\ {}^7\mathrm{Li}\ \mathrm{d} \rangle \\ \langle {}^7\mathrm{Li}\ r\ \mathrm{d}\ {}^8\mathrm{Li}\ r'\ \mathrm{p} | \mathcal{A}_{\tilde{\nu}'}\mathcal{H} | {}^9\mathrm{Be} \rangle & \langle {}^7\mathrm{Li}\ r\ \mathrm{d}\ {}^8\mathrm{Li}\ r'\ \mathrm{p} | \mathcal{A}_{\tilde{\nu}'}\mathcal{H}\mathcal{A}_{\tilde{\nu}} | {}^8\mathrm{Li}\ r'\ \mathrm{p}\ r\ {}^7\mathrm{Li}\ \mathrm{d} \rangle \end{pmatrix} \begin{pmatrix} c_\lambda \\ g_{\tilde{\nu},\tilde{\nu}'} \end{pmatrix} =$$

$$E \begin{pmatrix} \delta_{\lambda\lambda'} & \langle {}^9\mathrm{Be} | \mathcal{A}_{\tilde{\nu}} | {}^8\mathrm{Li}\ r'\ \mathrm{p}\ r\ {}^7\mathrm{Li}\ \mathrm{d} \rangle \\ \langle {}^7\mathrm{Li}\ r\ \mathrm{d}\ {}^8\mathrm{Li}\ r'\ \mathrm{p} | \mathcal{A}_{\tilde{\nu}'} | {}^9\mathrm{Be} \rangle & \langle {}^7\mathrm{Li}\ r\ \mathrm{d}\ {}^8\mathrm{Li}\ r'\ \mathrm{p} | \mathcal{A}_{\tilde{\nu}'}\mathcal{A}_{\tilde{\nu}} | {}^8\mathrm{Li}\ r'\ \mathrm{p}\ r\ {}^7\mathrm{Li}\ \mathrm{d} \rangle \end{pmatrix} \begin{pmatrix} c_\lambda \\ g_{\tilde{\nu},\tilde{\nu}'} \end{pmatrix}$$

Coupled-channel microscopic *R*-matrix method on Lagrange mesh provides Scattering matrix and Asymptotic Normalization Coefficients by matching internal solution to known asymptotic

M. Hesse, J.M. Sparenberg, F. Van Raemdonck, and D. Baye, Nucl Phys. A 640, 37 (1988)

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$$\begin{pmatrix} E\delta_{\lambda\lambda'} - \langle {}^{7}\mathrm{Li}\,{}^{8}\mathrm{Li}\,{}^{9}\mathrm{Be}|\mathcal{A}_{\tilde{\nu}'}\mathcal{H}|\rangle & \langle {}^{9}\mathrm{Be}|\mathcal{H}\mathcal{A}_{\tilde{\nu}}|{}^{8}\mathrm{Li}\,p\,{}^{7}\mathrm{Li}\,d\rangle \\ \langle {}^{7}\mathrm{Li}\,d\,{}^{8}\mathrm{Li}\,p|\mathcal{A}_{\tilde{\nu}'}\mathcal{H}\mathcal{A}_{\tilde{\nu}}|{}^{8}\mathrm{Li}\,p\,{}^{7}\mathrm{Li}\,d\rangle & E\delta_{\nu\nu'} - \langle {}^{7}\mathrm{Li}\,d\,{}^{8}\mathrm{Li}\,p|\mathcal{A}_{\tilde{\nu}'}|\rangle \end{pmatrix} \begin{pmatrix} c_\lambda \\ g_{\tilde{\nu},\tilde{\nu}'} \end{pmatrix} = E \begin{pmatrix} c_\lambda \\ g_{\tilde{\nu},\tilde{\nu}'} \end{pmatrix}$$

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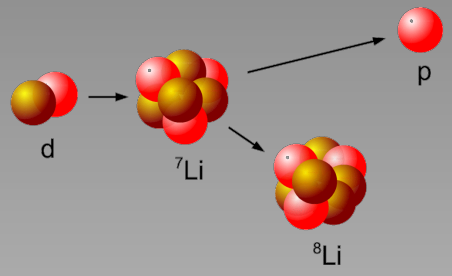
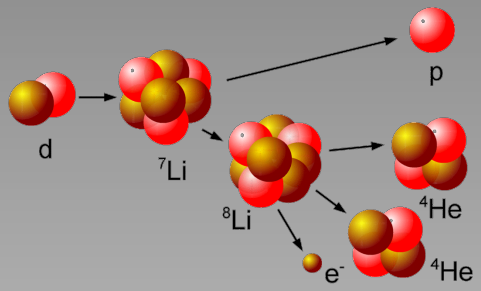
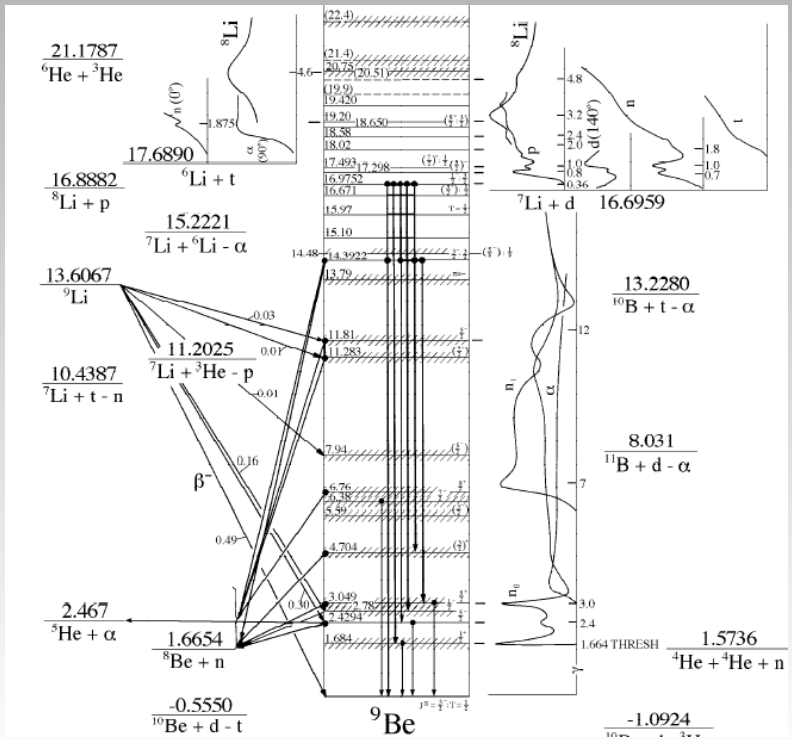
^{7}Li(*d*,p)^{8}Li reaction and structure of ^{9}Be



"Model space" reaction



"Real world" reaction



^{9}Be ground state is stable
All excited states are unbound

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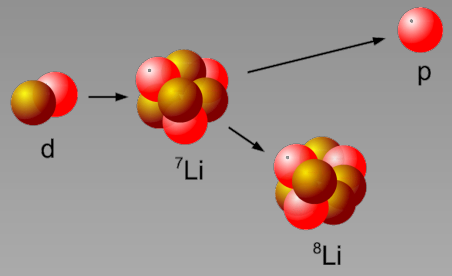

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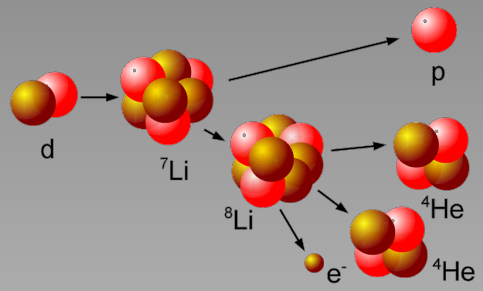

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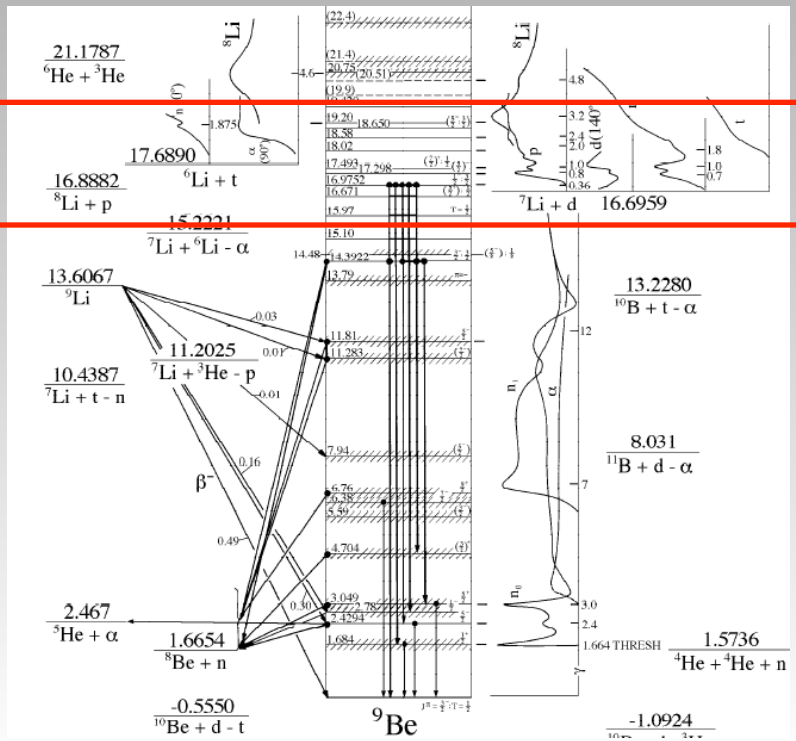
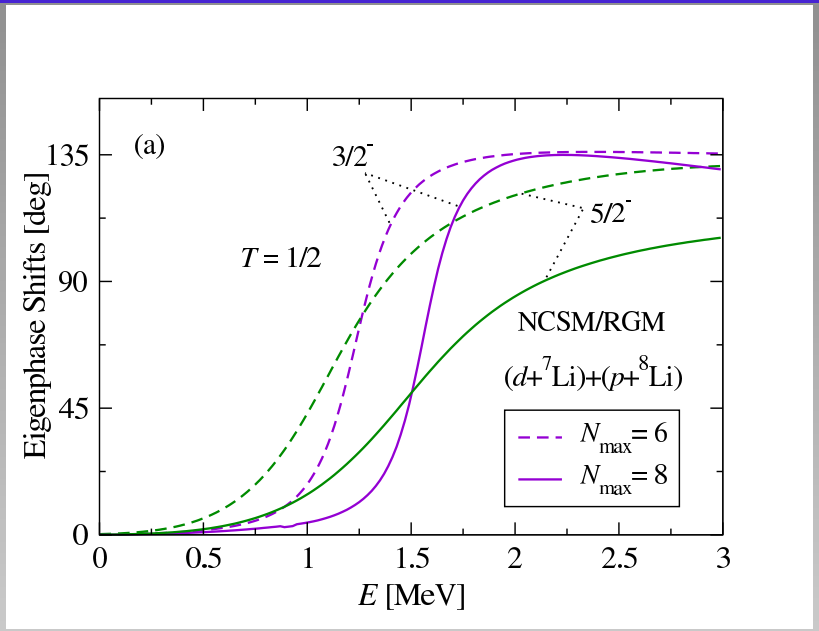


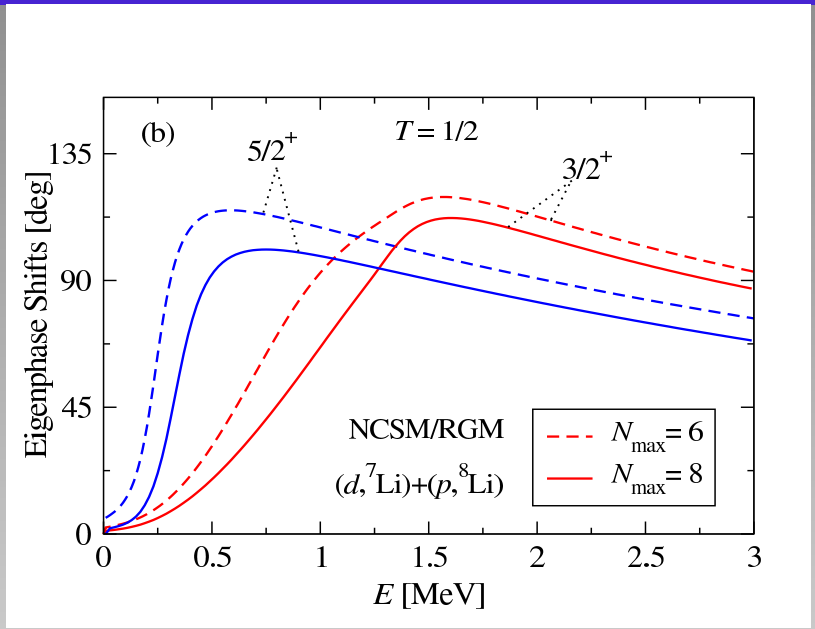
^{9}Be ground state is stable
All excited states are unbound

Inclusion of the continuum:

- Low-energy spectrum: n-^{8}Be (n-α-α)
- High-energy spectrum: *d*-^{7}Li , p-^{8}Li

(d, ^{7}Li) + (p, ^{8}Li) coupled NCSM-RGM calculation
Eigenphase shifts





Model space (N_{max}=6,8 $\hbar\Omega$=20 MeV):

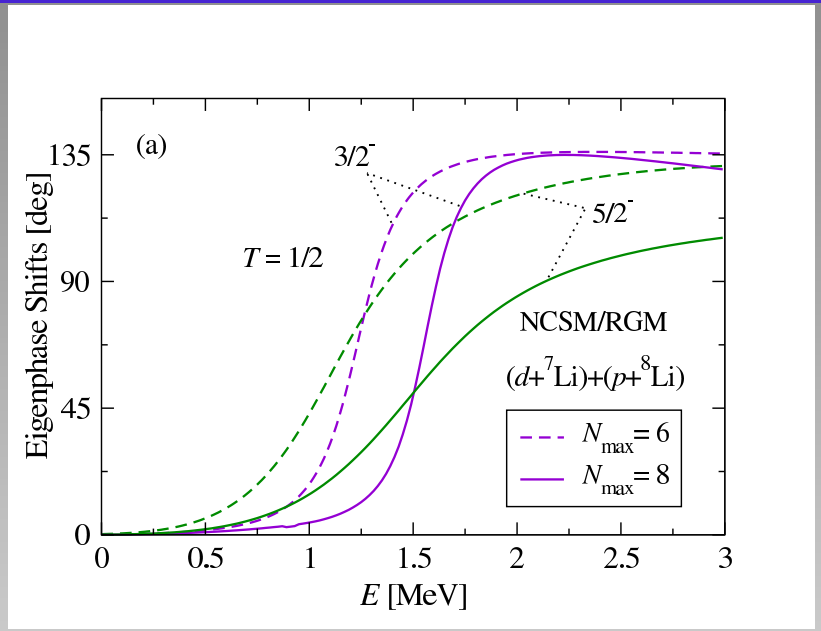
$|d(d^*)+^7Li_{gs}> + |d(d^*)+^7Li_{1ex}> + |p+^8Li_{gs}> + |p+^8Li_{1ex}> + |p+^8Li_{2ex}> + |p+^8Li_{3ex}>$

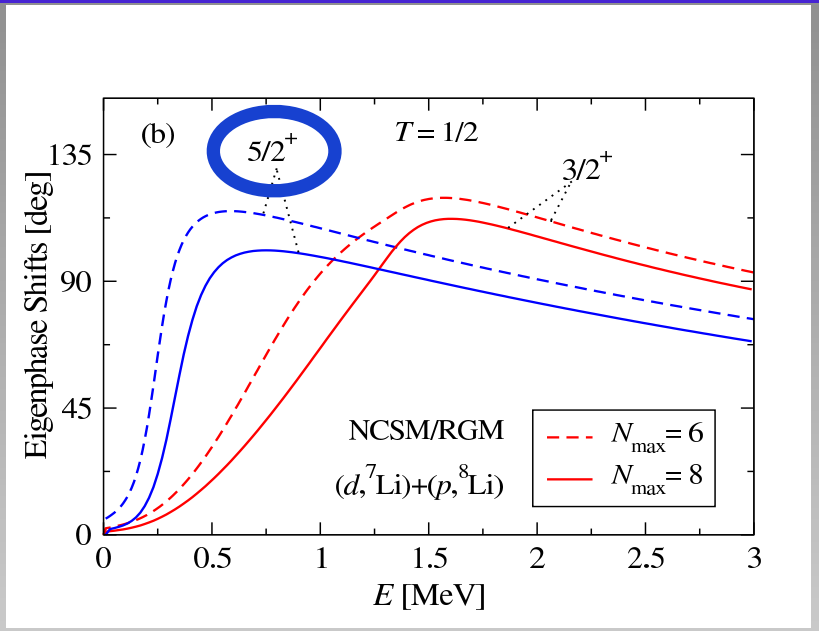
Virtual breakup of the deuteron: 4 pseudostates

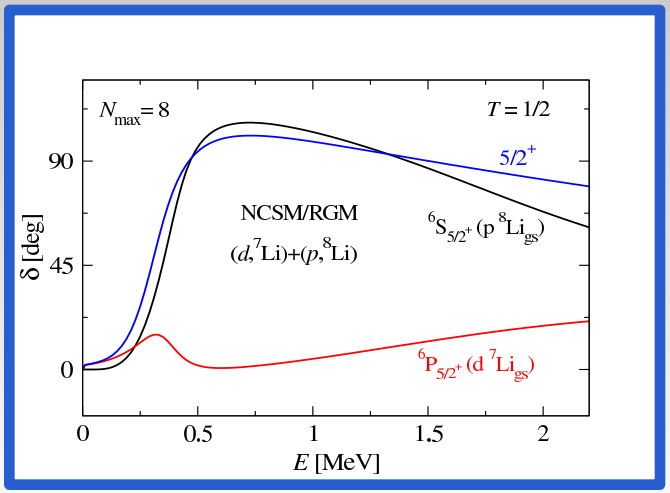
Chiral nuclear interaction:

Entem-Machleidt SRG-evolved (Λ=2.02 fm^{-1}) NN force at N^{3}LO (cutoff 500 MeV)

(d, ^{7}Li) + (p, ^{8}Li) coupled NCSM-RGM calculation
Eigenphase shifts







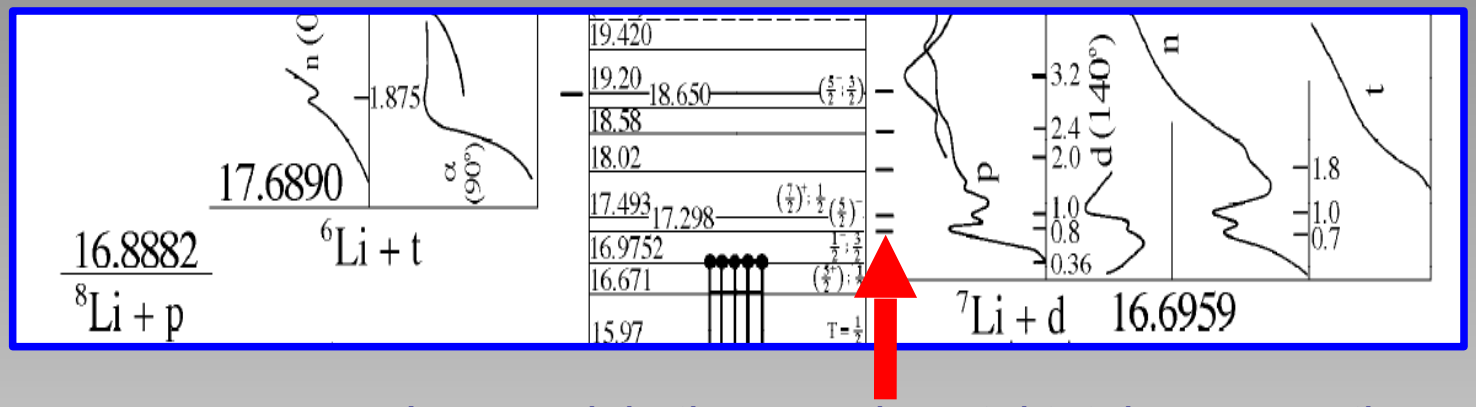
Dominant partial waves above p + ^{8}Li threshold: $3/2^{-,+}$, $5/2^{-,+}$

Main phase shifts for $5/2^+$:

- P-wave in (d, ^{7}Li)
- Resonant S-wave in (p, ^{8}Li)

Spin-parity assignment of 0.78 MeV resonance of ^{9}Be

^{9}Be spectrum above *d*-^{7}Li threshold



Low peak in the experimental total cross section:
E(5/2^{-})~0.78 MeV above the threshold
(Uncertain spin-parity assignment)

Spin-parity assignment of 0.78 MeV resonance of ^{9}Be

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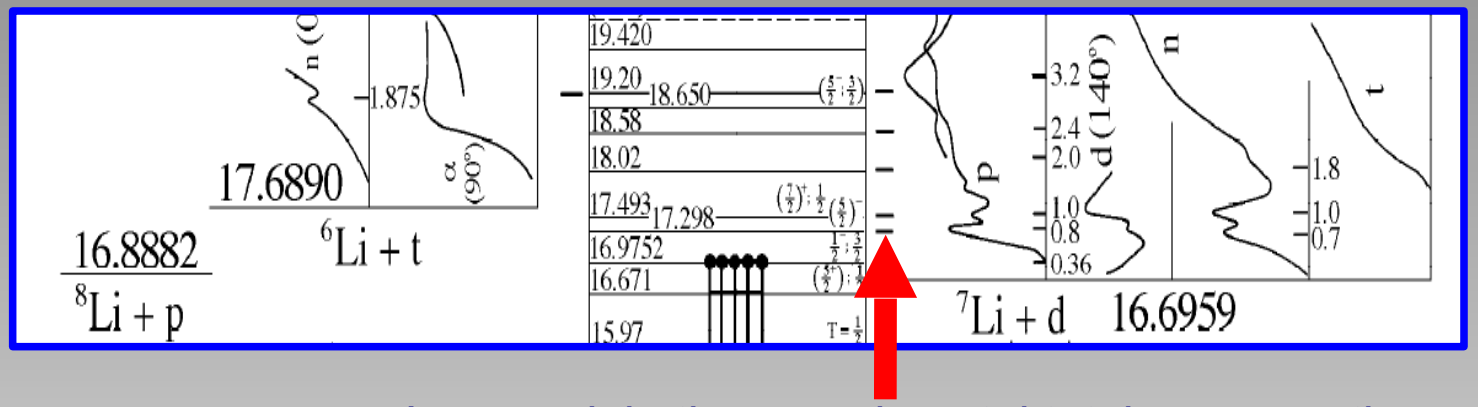

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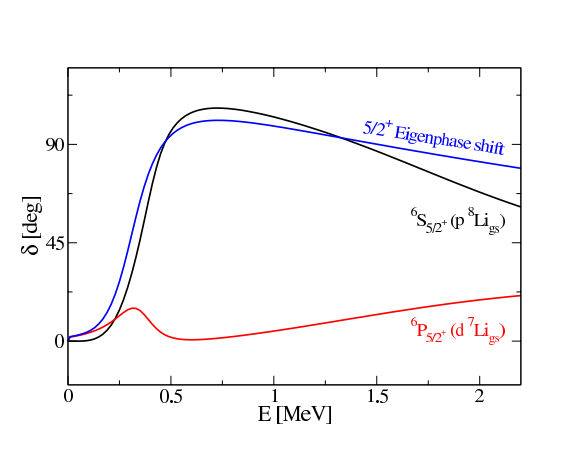
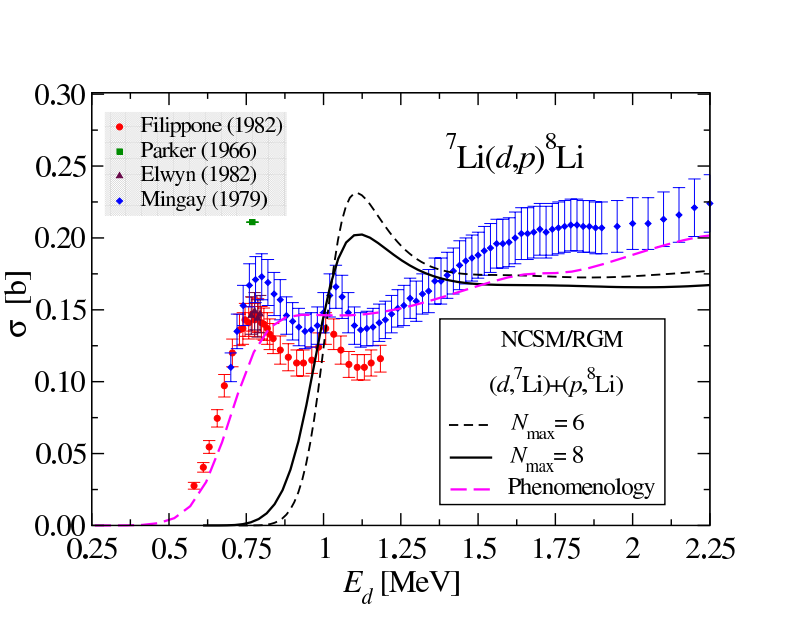
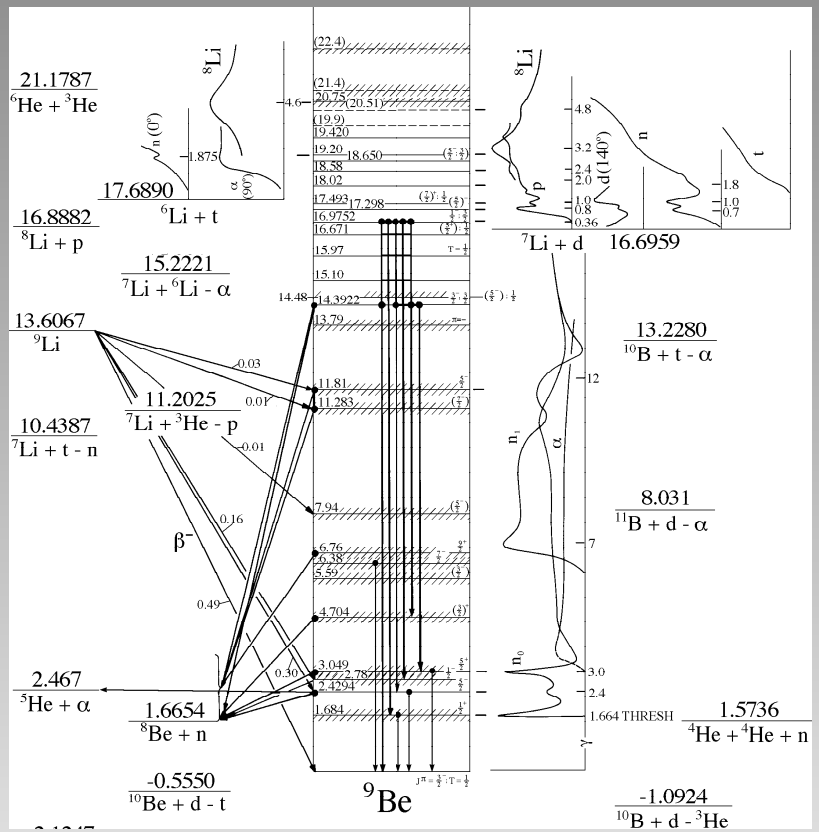


d-^{7}Li (p wave) → ^{9}Be (5/2^{+}) → p-^{8}Li (s wave)

^{7}Li(d,p)^{8}Li total cross section



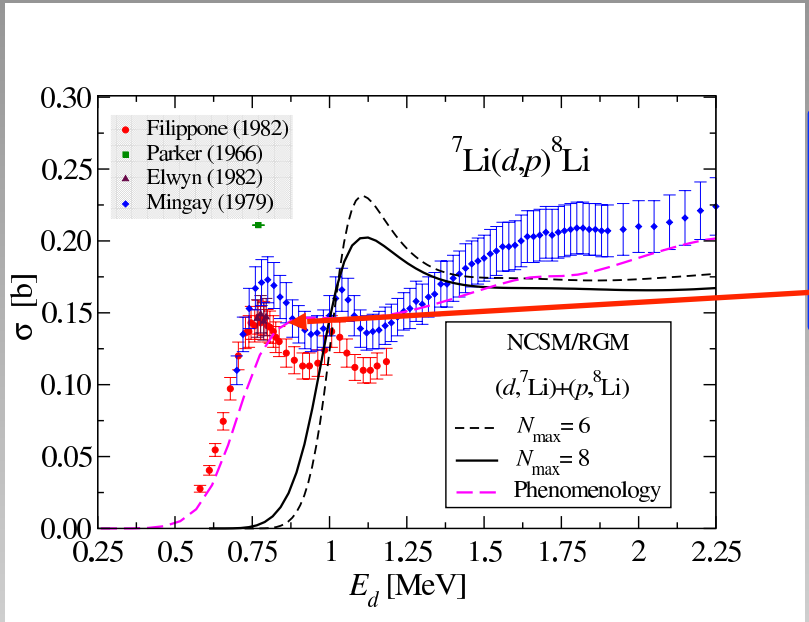


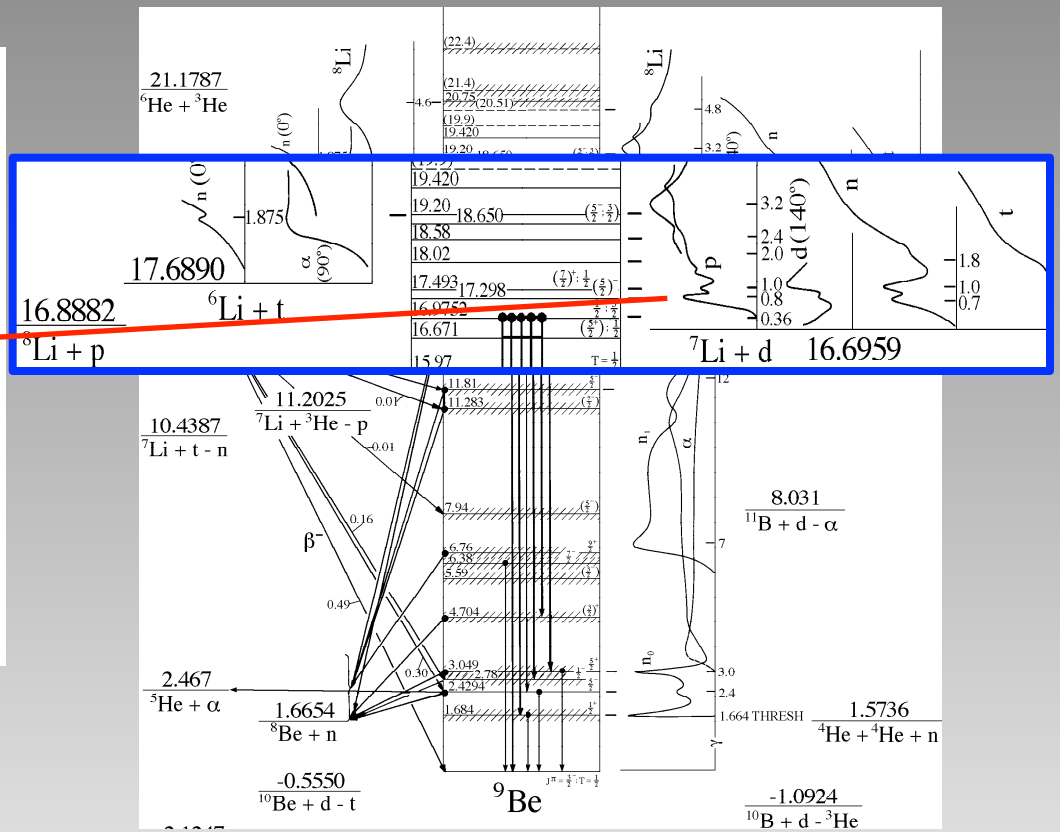
Included channels:
(1) p, ^{8}Li (2) d, ^{7}Li (3) coupling (d,p)
(4) virtual breakup of d

Not-included channels:
(1)^{8}Be, n (2) ^{6}Li, t

Channel	Exp. thresh. [MeV]	Theo.thresh. [MeV]
d, ^{7}Li	-41.470	-40.124
p, ^{8}Li	-41.278	-39.659
Q-value	-0.193	-0.465

^{7}Li(d,p)^{8}Li total cross section





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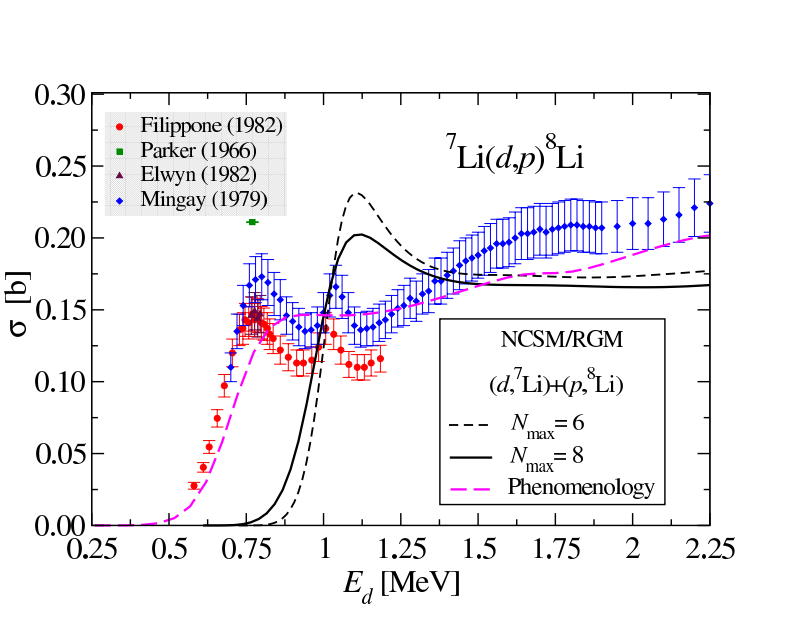
Experimental recommended value
0.147±0.011 b (Γ≈0.2 MeV) at 0.78 MeV
of deuteron kinetic energy

Calibration peak for
^{7}Be(p,γ)^{8}B radiative capture reaction

^{7}Li(d,p)^{8}Li total cross section



- Position of the first resonant peak overestimated by ~ 0.33 MeV (see Q-value)
- Peak at 17.493 MeV (^{9}Be spectrum) not reproduced (missing ^{8}Be(α-α)-n? 3N forces?)

d, ^{7}Li, ^{8}Li NCSM energies adjusted to reproduce the experimental Q-value of the reaction

position of first peak slightly overestimated

Included channels:
(1) p, ^{8}Li (2) *d*, ^{7}Li (3) coupling (*d*,p)
(4) virtual breakup of *d*

Not-included channels:
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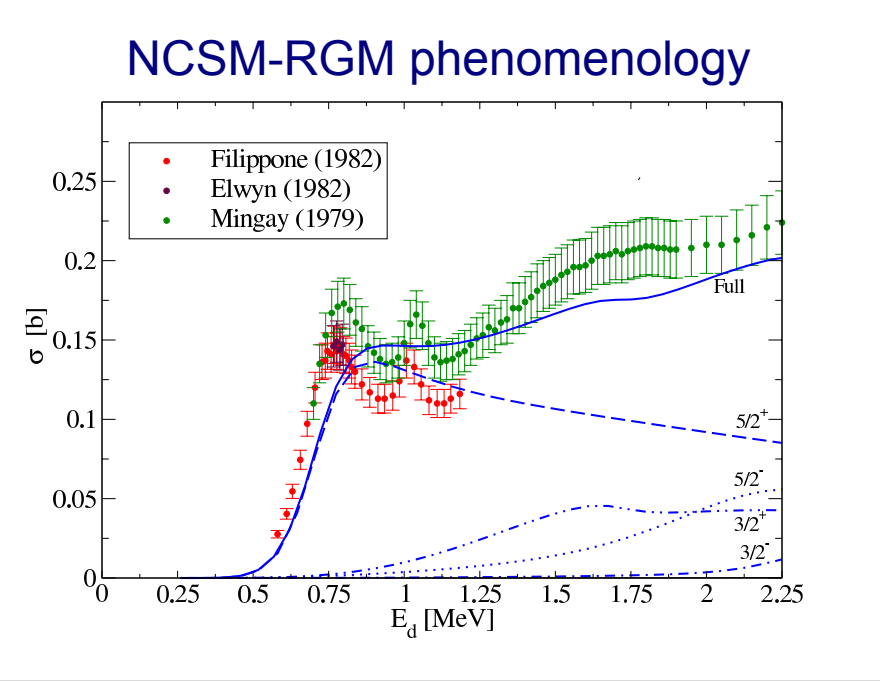
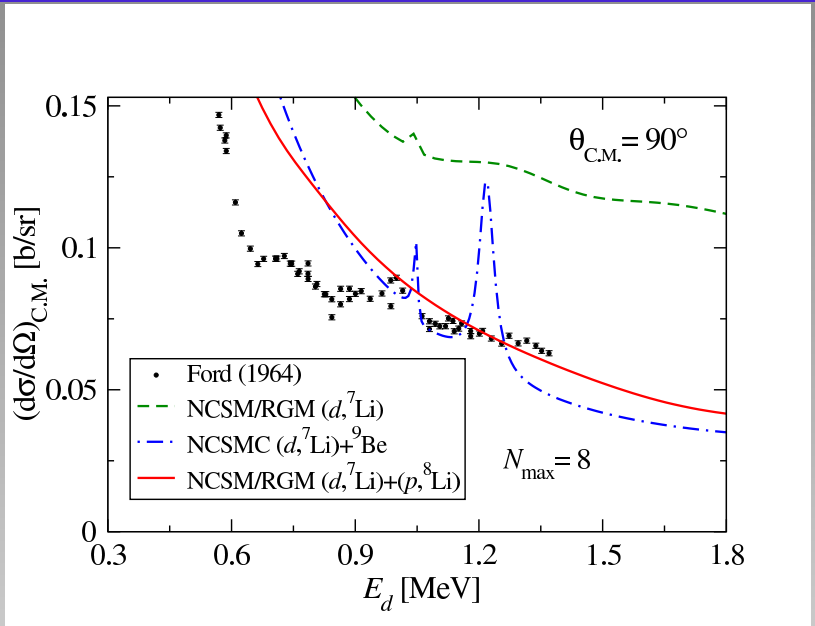
Impact of different partial waves on NCSM-RGM total cross section

^{7}Li(d,p)^{8}Li cross section



- Confirmed dominant role played by $5/2^{+}$ partial wave
- Below ~2 MeV the cross section is dominated by positive-parity partial waves
- Increasing trend up to deuteron break-up fairly well reproduced (contribution from $5/2^{-}$ and $3/2^{+}$ partial wave)

^{7}Li(d,d)^{7}Li cross section (NCSMC)



Experimental resonant peaks at 0.8 MeV (S-wave) and 1.0 MeV (P-wave)
('elastic' process not ideal probe for the ^{9}Be resonant states)

- Peak structure (1 MeV and 1.2 MeV) in uncoupled calculations (J=7/2^{-} in D-wave and 5/2^{+} in P-wave). …shifted at higher energy (missing bare 3N? SRG parameter dependence?)
- Effect of the short-range correlations in NCSMC calculation: Increased lifetime of the resonance too narrow peaks (lack of p-^{8}Li decay channel. other mass partition?)
- Qualitative trend of the data reproduced by NCSMC and coupled NCSM-RGM calculations …still not-converged calculation at N_{max}=8

Conclusions & Perspectives

First application of the NCSM-RGM for deuteron-projectile and p-shell nucleus as target

Study of the ^{7}Li(*d*,p)^{8}Li transfer reaction and of the ^{9}Be resonances above *d*-^{7}Li threshold:

- Discussion of the spin-parity assignment of E_d=0.78 MeV resonance

To be done:

- Complete the calculation of the ^{7}Li(*d*,p)^{8}Li transfer reaction in the NCSMC framework
- Include 3N force also for p-shell nuclei