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

[arXiv:1602.04404]

FUSTIPEN

French-U.S. Theory Institute for Physics with Exotic Nuclei

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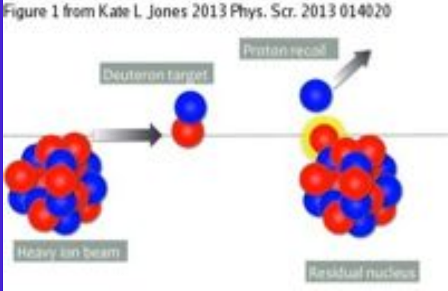
TRIUMF

Figure 1 from Kate L Jones 2013 Phys. Scr. 2013 014020

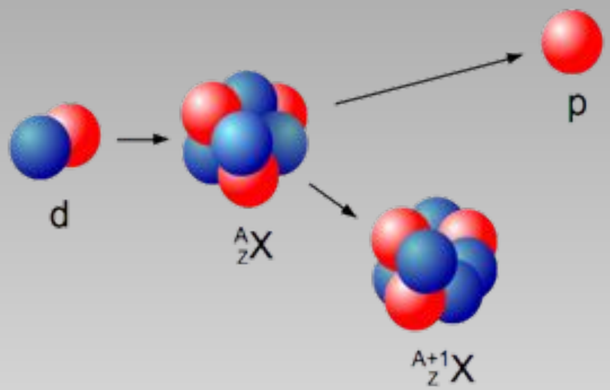


Outline

- 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 and ^{7}Li(d,d)^{7}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):



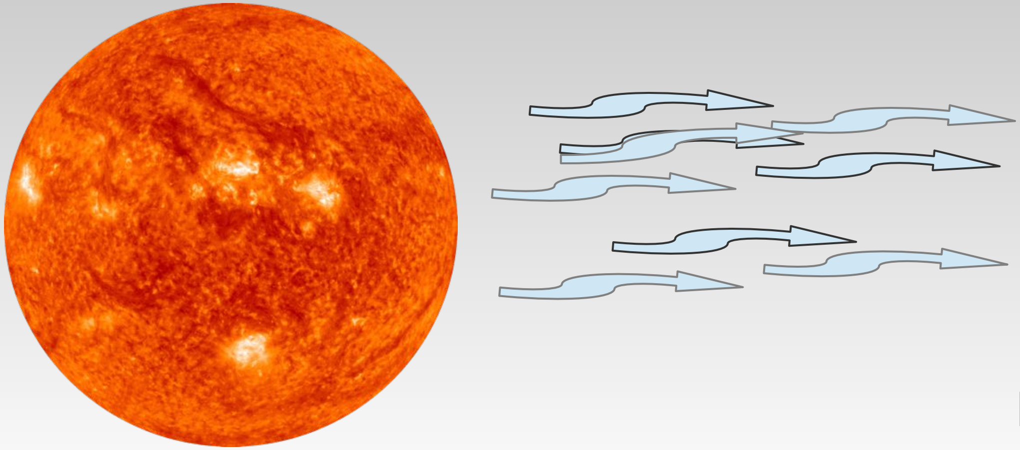
(*d*,p) reaction in direct kinematics

- 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

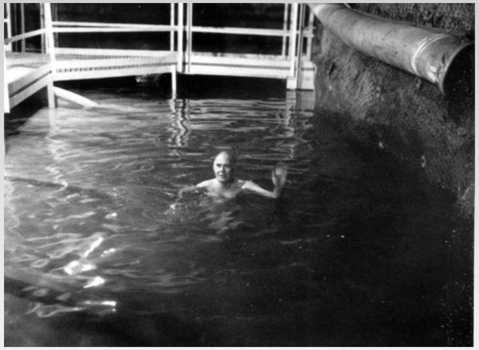
^{7}Li(d,p)^{8}Li transfer reaction

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

Solar neutrino problem:



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

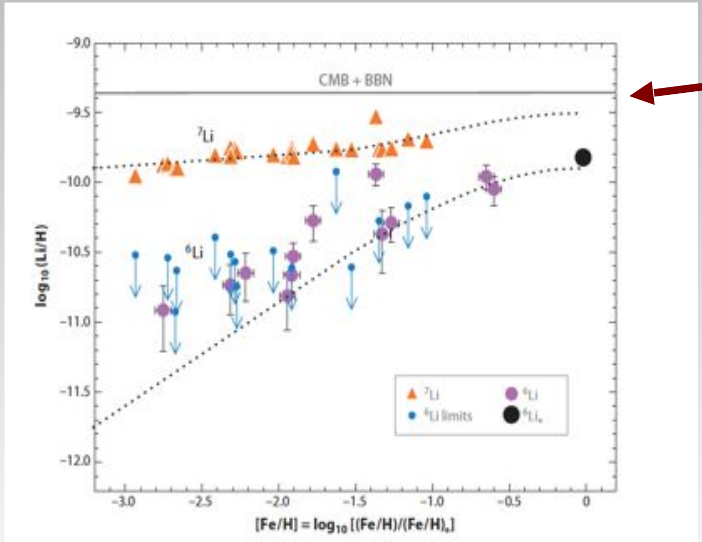


R. Davis Jr takes a dip
At Homestake Mine (1971)

^{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

- Possible mechanism of destruction of ^{7}Li in the context of baryon-inhomogeneus models of the primordial nucleosynthesis



Primordial Lithium problem:

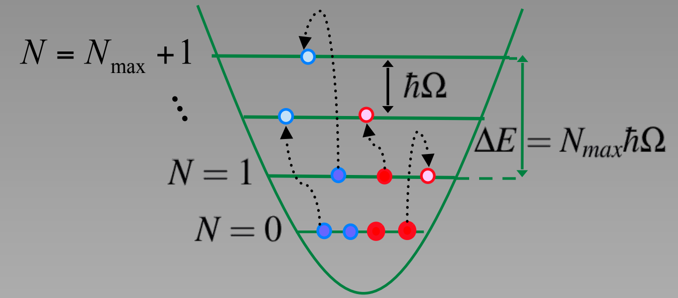
- 4-5σ discrepancy between observed and calculated (CMB+BBN) abundance of ^{7}Li
- Nuclear solution to the problem: *d*-^{7}Li destruction mechanism is ruled out (but only in a standard BBN scenario PRC 47, 2369 1993)

Ann. Rev. Nucl. Part. Sci. 2011 61:47-68

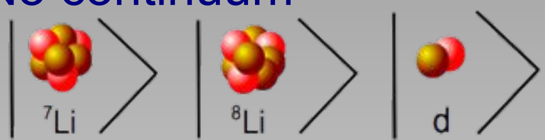
No-core shell model combined with the resonating group method (NCSM-RGM) and NCSM with continuum (NCSMC)

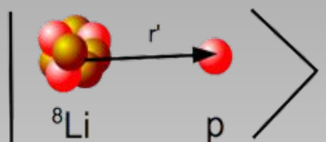
No-core shell model (NCSM):

- 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)

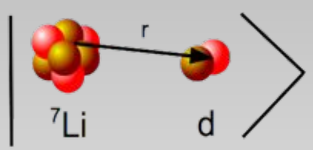




NCSM+Resonating group method (NCSM-RGM):

- 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)

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

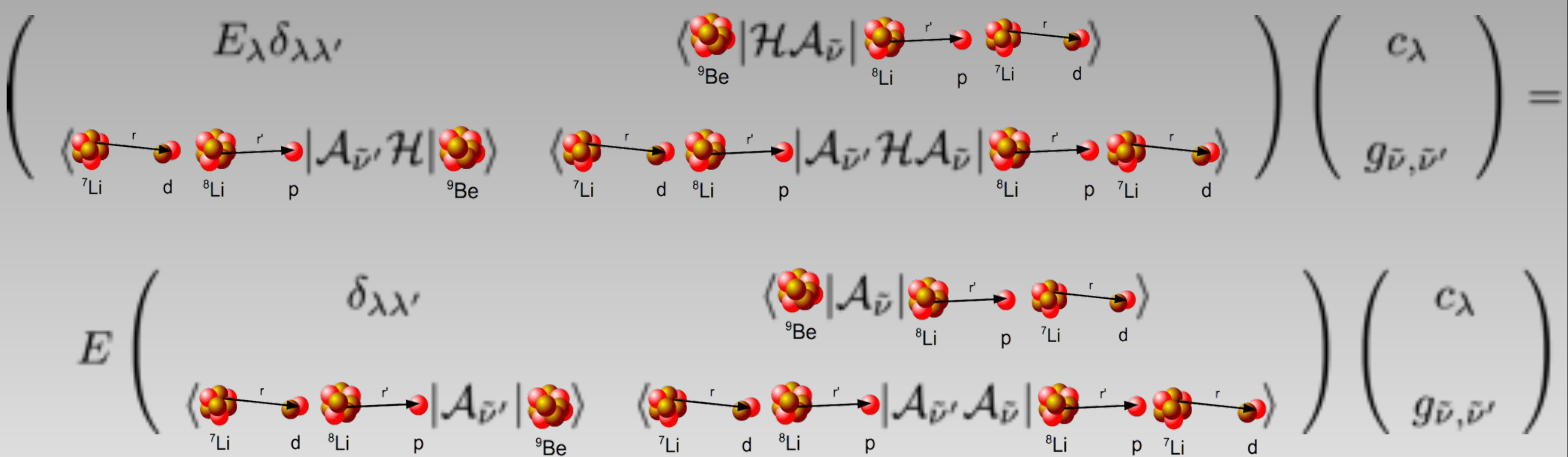
Variational amplitudes
(unknowns of the many-body problem)

NCSM-RGM and NCSMC equations

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

Internal A-nucleon microscopic Hamiltonian

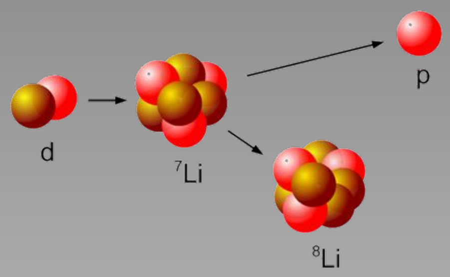
Coupled-channel equations solved for the amplitude c_λ and g_ν



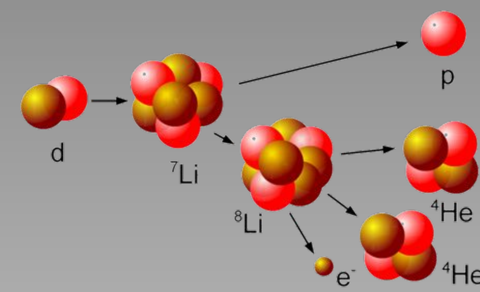
Coupled-channel microscopic *R*-matrix method on Lagrange mesh provides Scattering matrix and Asymptotic Normalization Coefficients by matching internal solution to known asymptotic

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

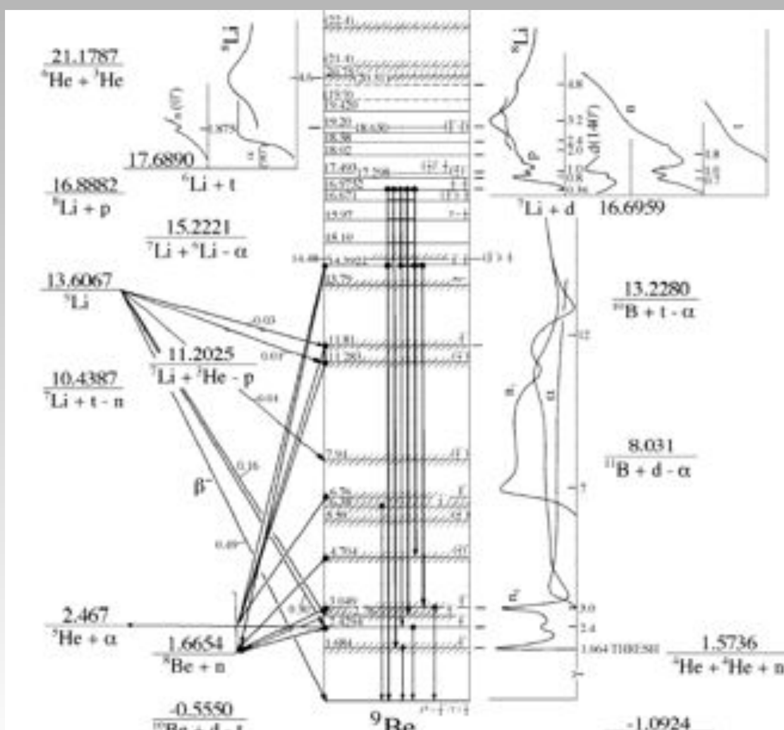
^{7}Li(d,p)^{8}Li reaction and structure of ^{9}Be



“Model space” reaction

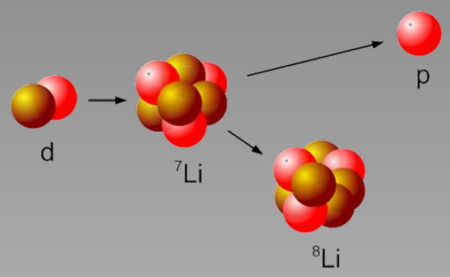


“Real world” reaction

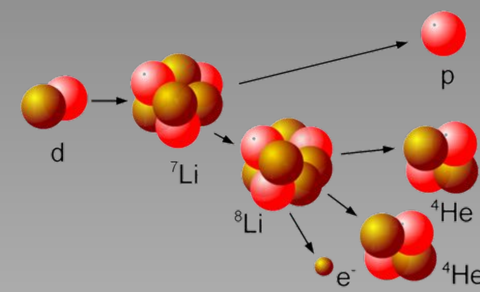


^{9}Be ground state is stable
All excited states are unbound

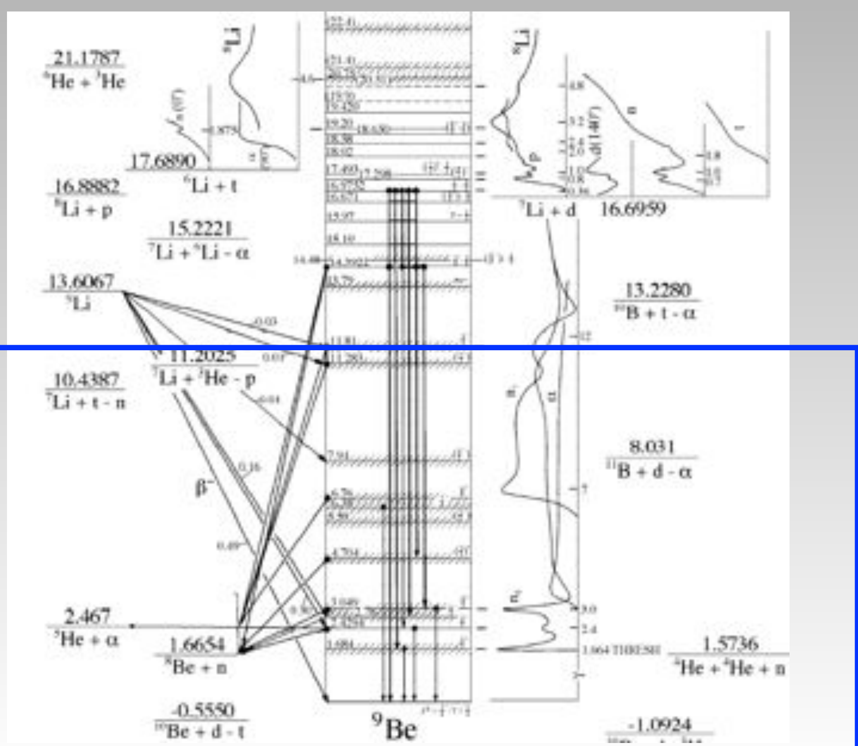
^{7}Li(d,p)^{8}Li reaction and structure of ^{9}Be



“Model space” reaction



“Real world” reaction



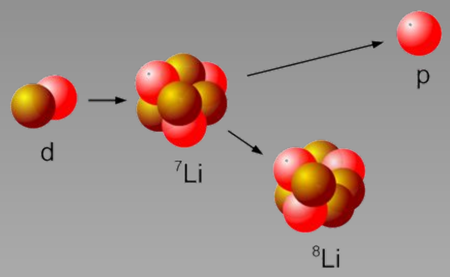
^{9}Be ground state is stable
All excited states are unbound

Inclusion of the continuum:

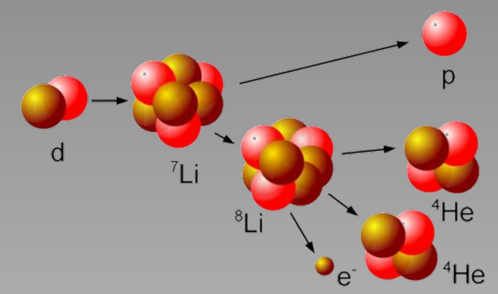
- Low-energy spectrum: n-^{8}Be (n-α-α)

[J. Langhammer, P. Navrátil, S. Quaglioni, G. Hupin, A. Calci, and R. Roth, PRC(R) 91, 021301 (2015)]

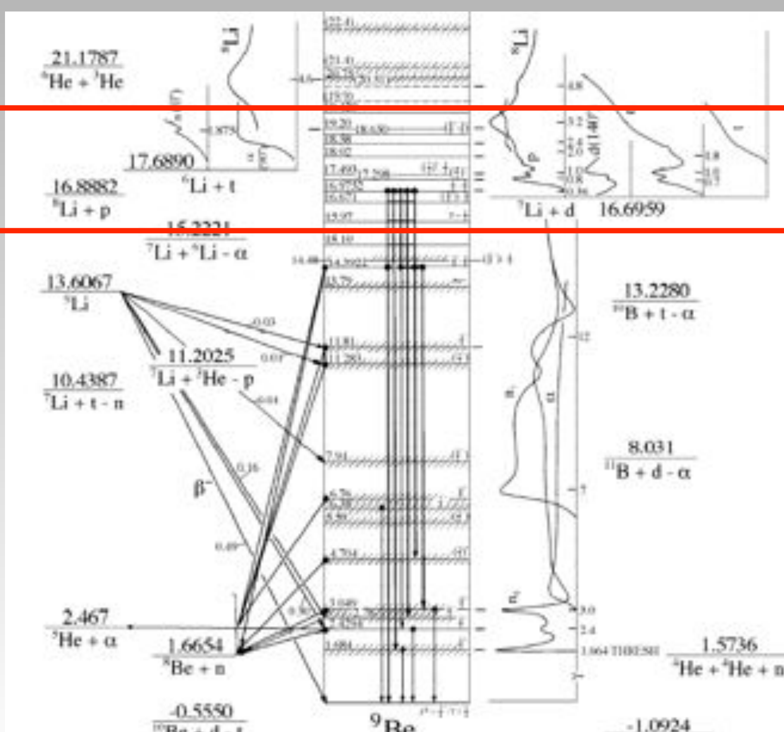
^{7}Li(d,p)^{8}Li reaction and structure of ^{9}Be



“Model space” reaction



“Real world” reaction

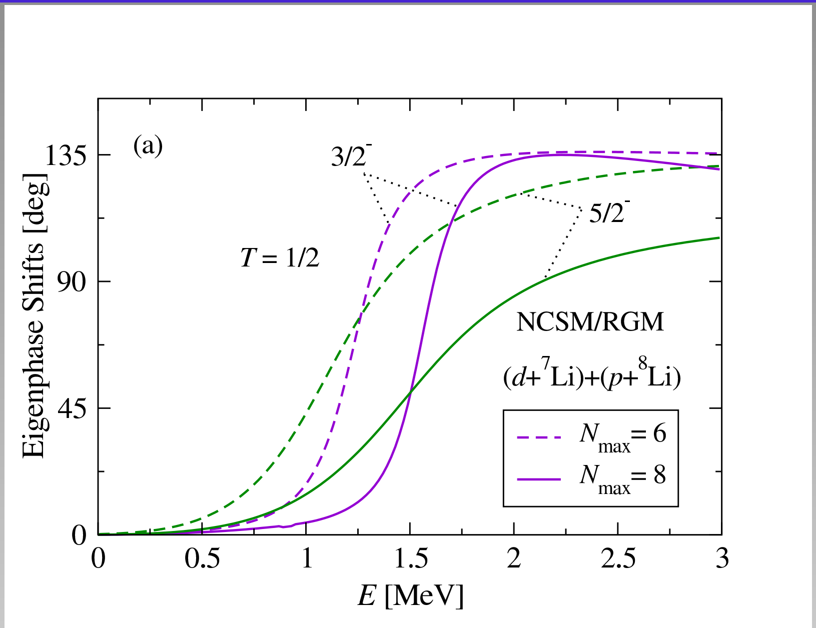


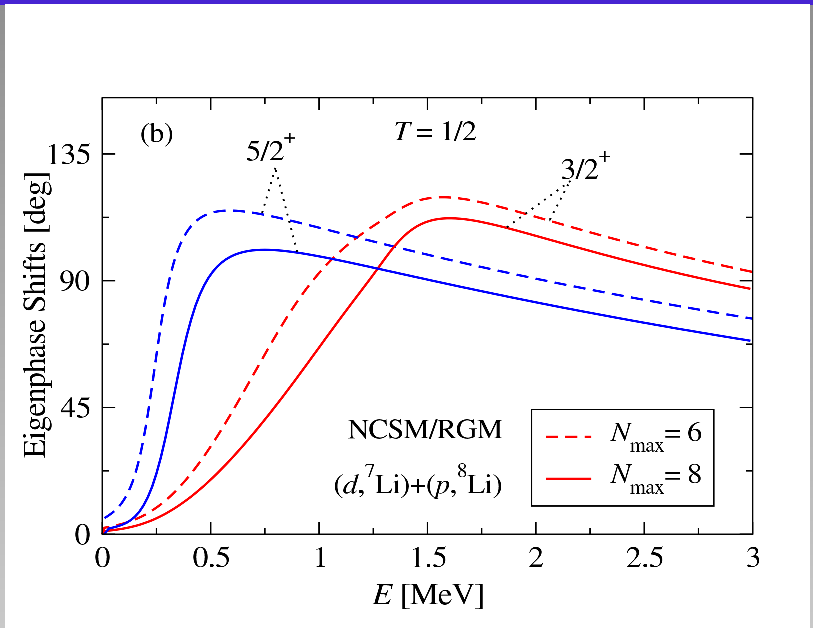
^{9}Be ground state is stable
All excited states are unbound

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 ħΩ=20 MeV):

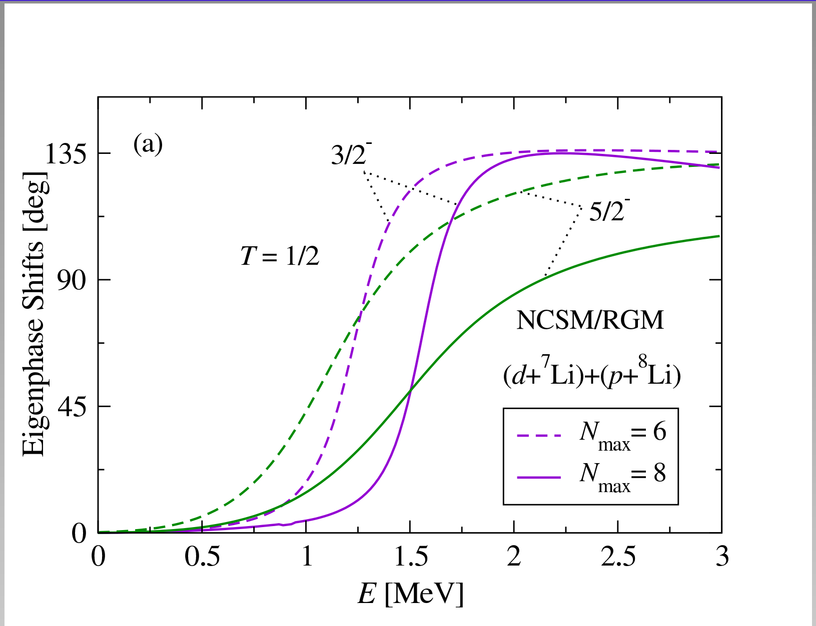
$|d(d^*)+{}^7Li_{gs}\rangle + |d(d^*)+{}^7Li_{1ex}\rangle + |p+{}^8Li_{gs}\rangle + |p+{}^8Li_{1ex}\rangle + |p+{}^8Li_{2ex}\rangle + |p+{}^8Li_{3ex}\rangle$

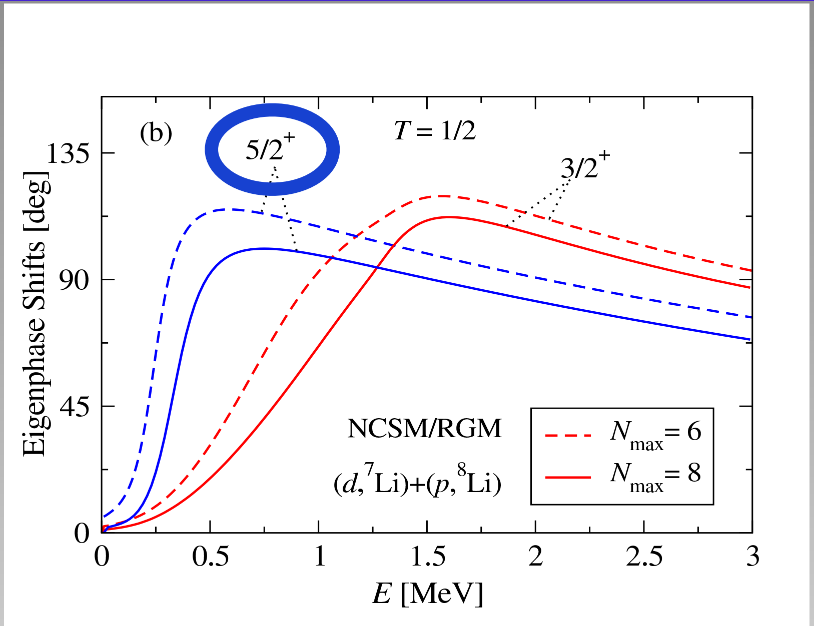
Virtual breakup of the deuteron: 4 pseudostates

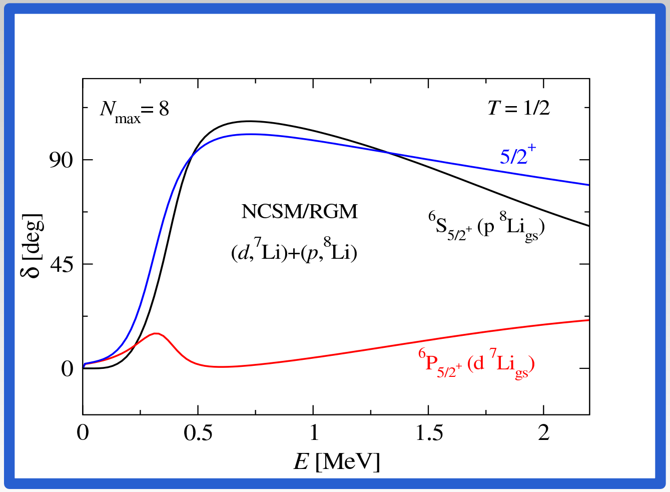
Chiral nuclear interaction:

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





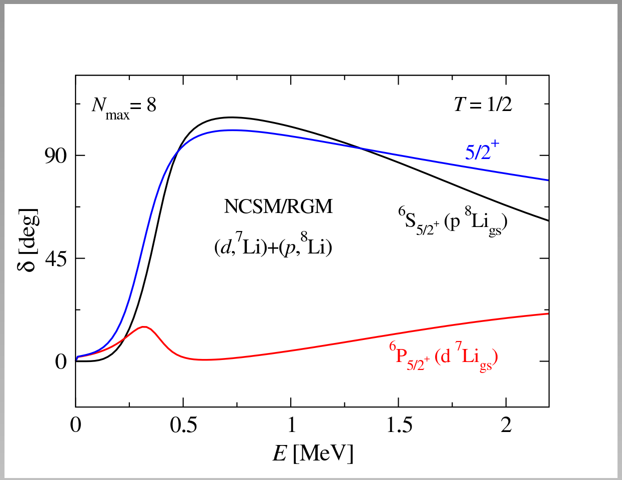


Dominant partial waves above p + ^{8}Li threshold: $3/2^{-,+}$, $5/2^{-,+}$

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

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

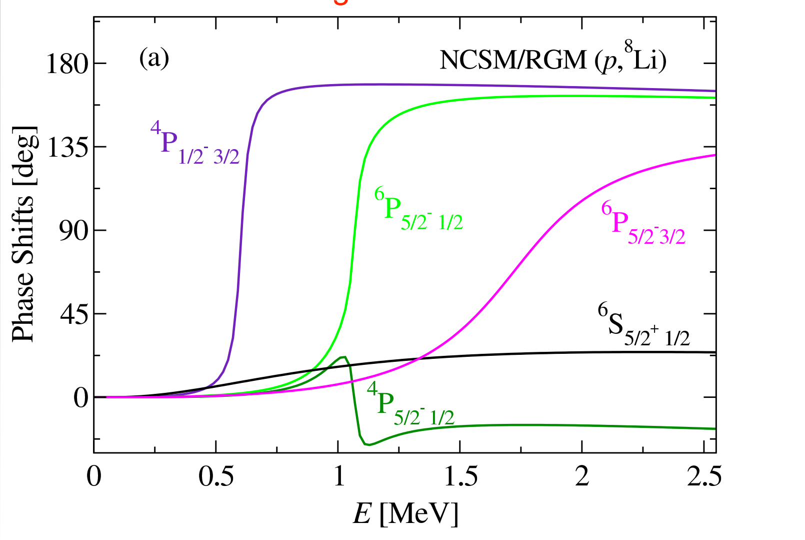
(p, ^{8}Li) UNcoupled NCSM-RGM calculation Phase shifts



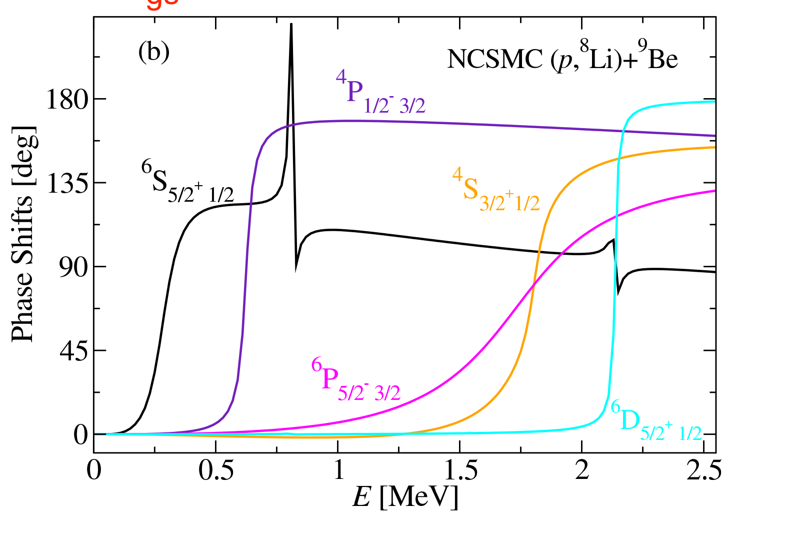
- T=3/2 resonances ($1/2^-$, $5/2^-$) reproduced.
- S-wave phase shift in $5/2^+$ strongly suppressed in NCSM-RGM calculation.
- Effects of the short-range correlations in NCSMC calculation: 1) Resonant S-wave in $5/2^+$ enhanced; 2) P-wave in $J=5/2^-$ e $T=1/2$ becomes bound.

Model space (N_{max}=8 ħΩ=20 MeV):

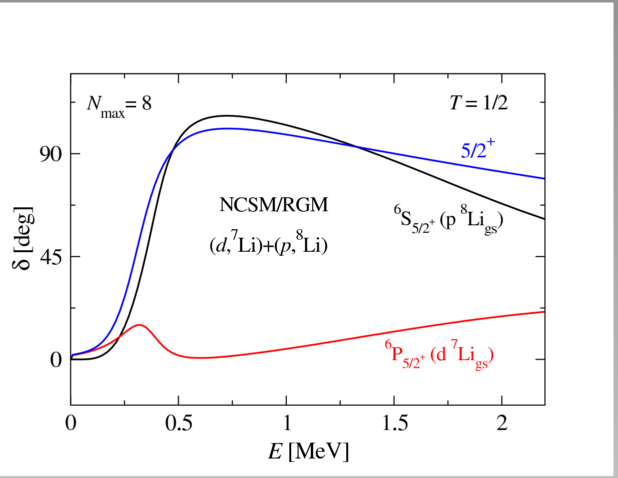
|p+^{8}Li$_{gs}$> + |p+^{8}Li*>



|p+^{8}Li$_{gs}$> + |p+^{8}Li*> + |^{9}Be$_{gs}$>+ |^{9}Be*>



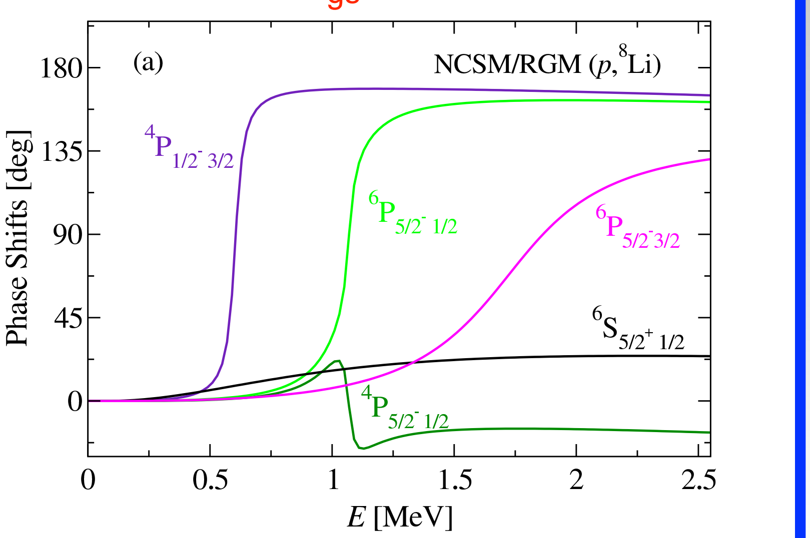
(p, ^{8}Li) UNcoupled NCSM-RGM calculation Phase shifts



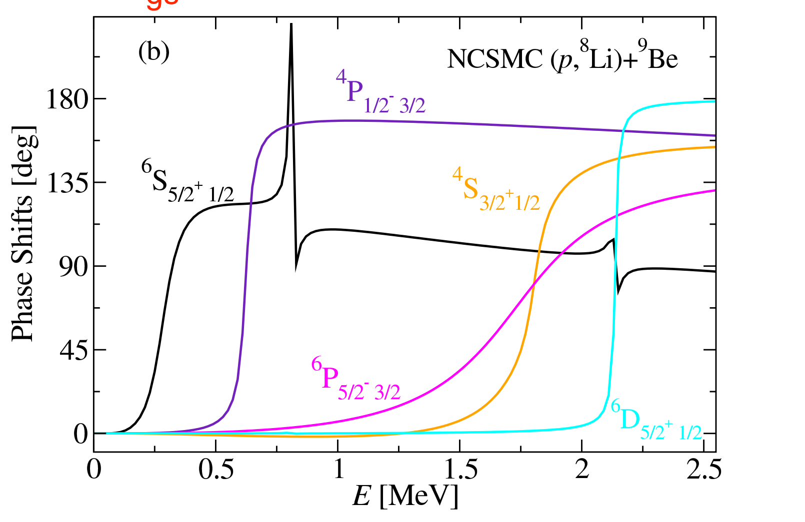
- T=3/2 resonances (1/2$^-$, 5/2$^-$) reproduced.
- S-wave phase shift in 5/2$^+$ strongly suppressed in NCSM-RGM calculation.
- Effects of the short-range correlations in NCSMC calculation: 1) Resonant S-wave in 5/2$^+$ enhanced; 2) P-wave in J=5/2$^-$ e T=1/2 becomes bound.

Model space (N_{max}=8 ħΩ=20 MeV):

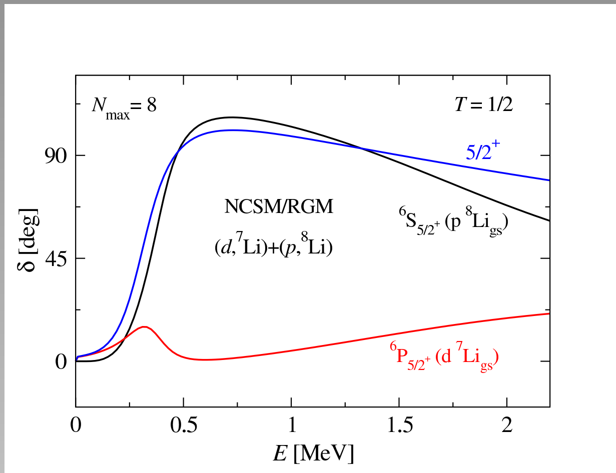
|p+^{8}Li$_{gs}$> + |p+^{8}Li*>



|p+^{8}Li$_{gs}$> + |p+^{8}Li*> + |^{9}Be$_{gs}$>+ |^{9}Be*>



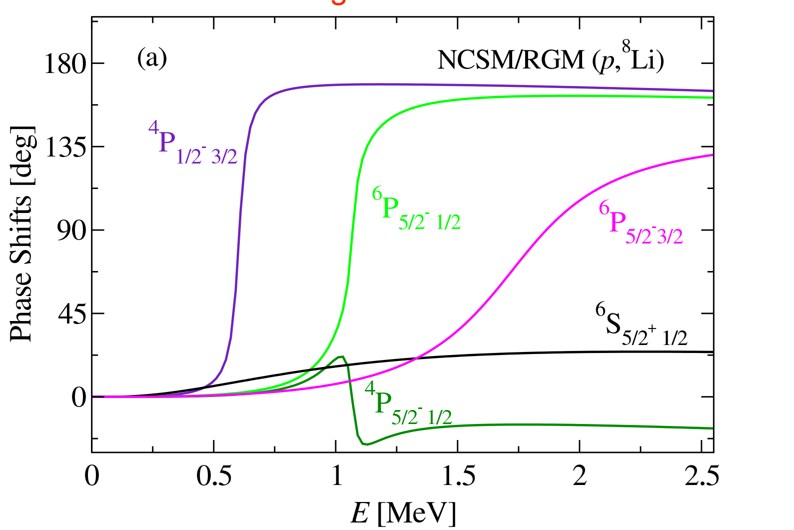
(p, ^{8}Li) UNcoupled NCSM-RGM calculation Phase shifts



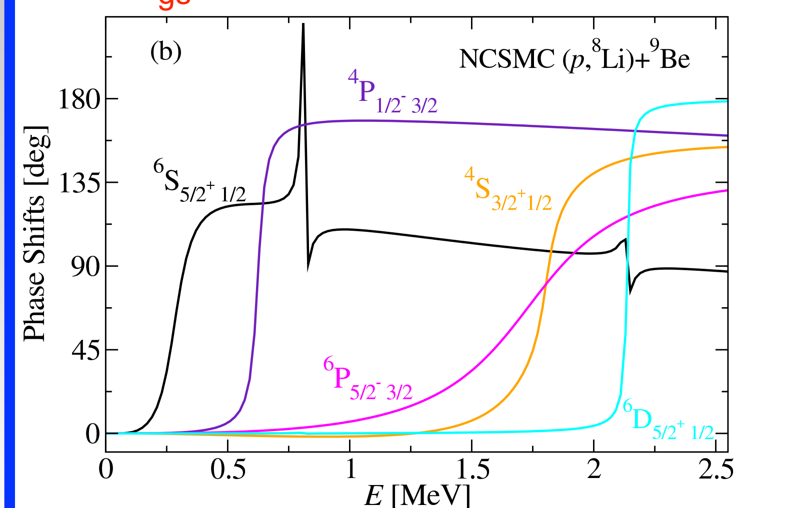
- T=3/2 resonances (1/2$^-$, 5/2$^-$) reproduced.
- S-wave phase shift in 5/2$^+$ strongly suppressed in NCSM-RGM calculation.
- Effects of the short-range correlations in NCSMC calculation: 1) Resonant S-wave in 5/2$^+$ enhanced; 2) P-wave in J=5/2$^-$ e T=1/2 becomes bound.

Model space (N_{max}=8 ħΩ=20 MeV):

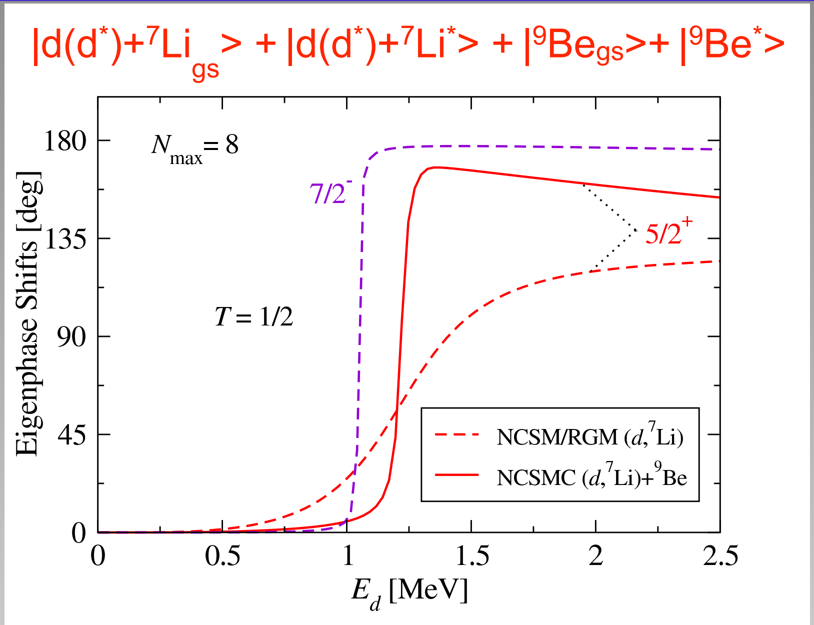
|p+^{8}Li$_{gs}$> + |p+^{8}Li*>

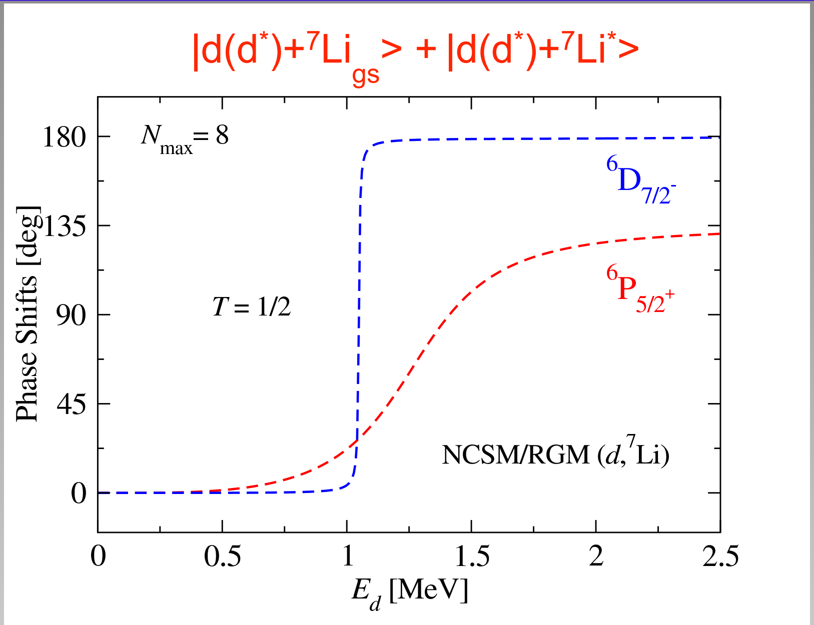


|p+^{8}Li$_{gs}$> + |p+^{8}Li*> + |^{9}Be$_{gs}$>+ |^{9}Be*>



(d, ^{7}Li) UNcoupled NCSM-RGM and NCSMC calculation



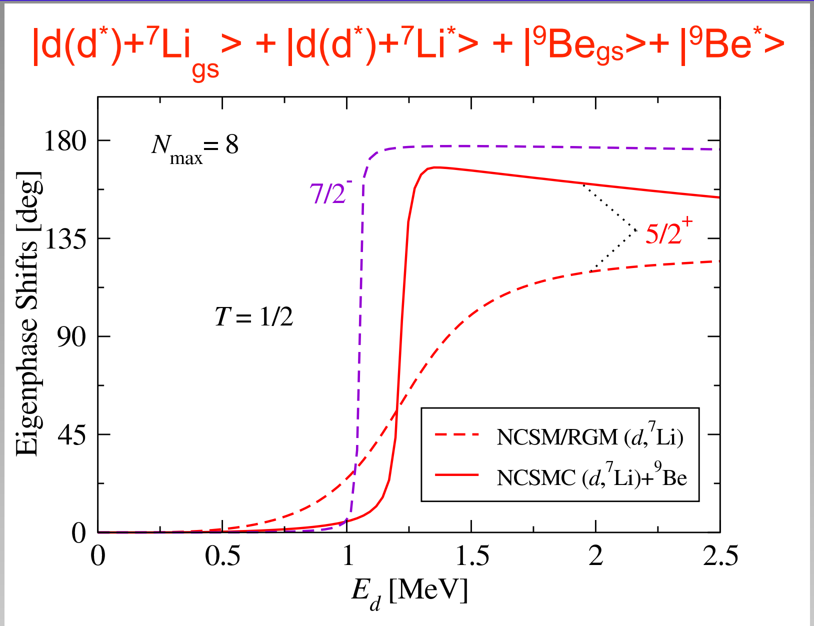


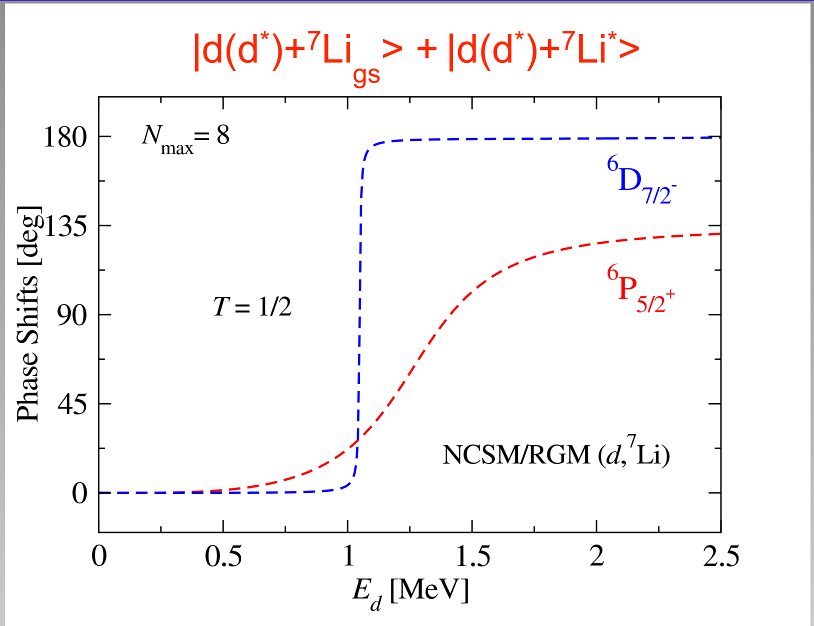
- Dominant resonances:
  J=7/2$^-$ in D-wave and 5/2$^+$ in P-wave.

- Effect of the short-range correlations on J=5/2$^+$ in NCSMC calculation:
  Decreased width of the resonance.

- Coupling effect:
  Quenching of $^6P_{5/2+}$ resonance

(d, ^{7}Li) UNcoupled NCSM-RGM and NCSMC calculation





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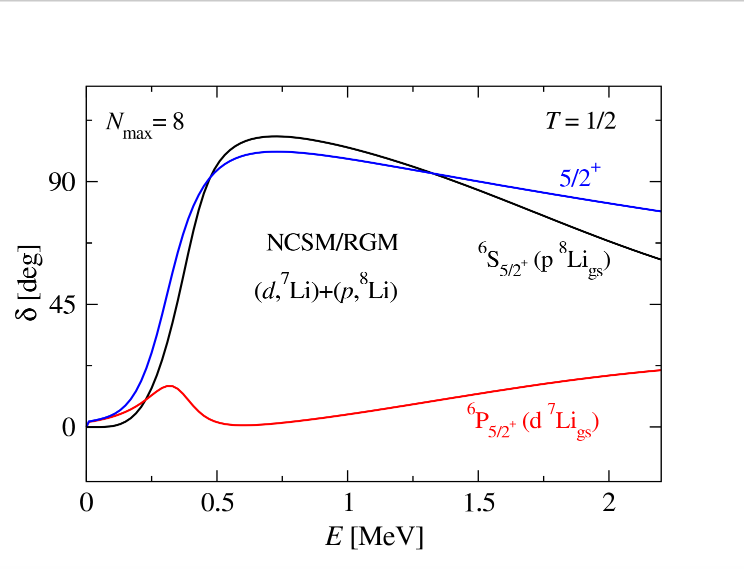
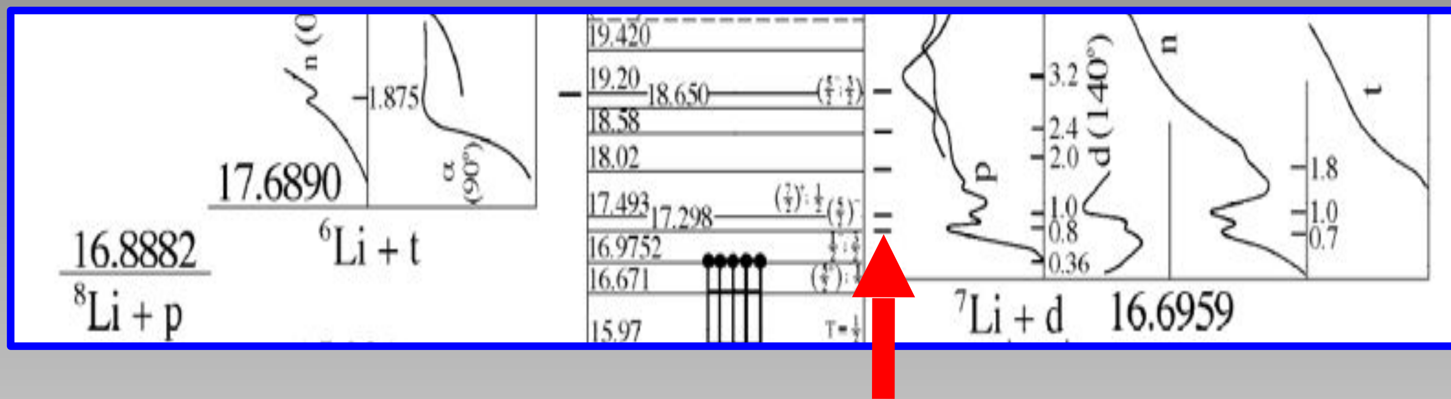


Spin-parity assignment of 0.78 MeV resonance of ^{9}Be

^{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)

LE JOURNAL DE PHYSIQUE TOME 33, MAI-JUIN 1972, PAGE 485

Classification
Physics Abstracts
12.13 — 12.37

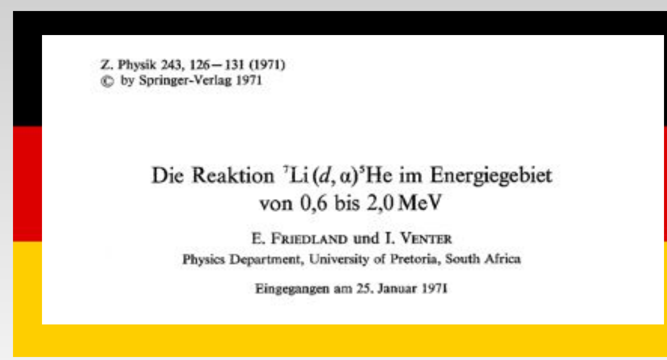
CONTRIBUTION A L'ÉTUDE EXPÉRIMENTALE DE LA RÉACTION ^{7}Li(dα)^{5}He A BASSE ÉNERGIE

J. DECHARGE
CEA, Centre d'Etudes de Limeil, BP n° 27, 94-Villeneuve-Saint-Georges, France

et G. SURGET (*), G. BRUNO, M. Y. DECHARGE
CEA, Centre de Bruyères-le-Châtel, BP n° 61, 92-Montrouge, France

(*Reçu le 17 août 1971, révisé le 24 novembre 1971 et le 21 janvier 1972*)

E(~17.3 MeV) --> 3/2$^-$, 5/2$^-$



Z. Physik 243, 126—131 (1971)
© by Springer-Verlag 1971

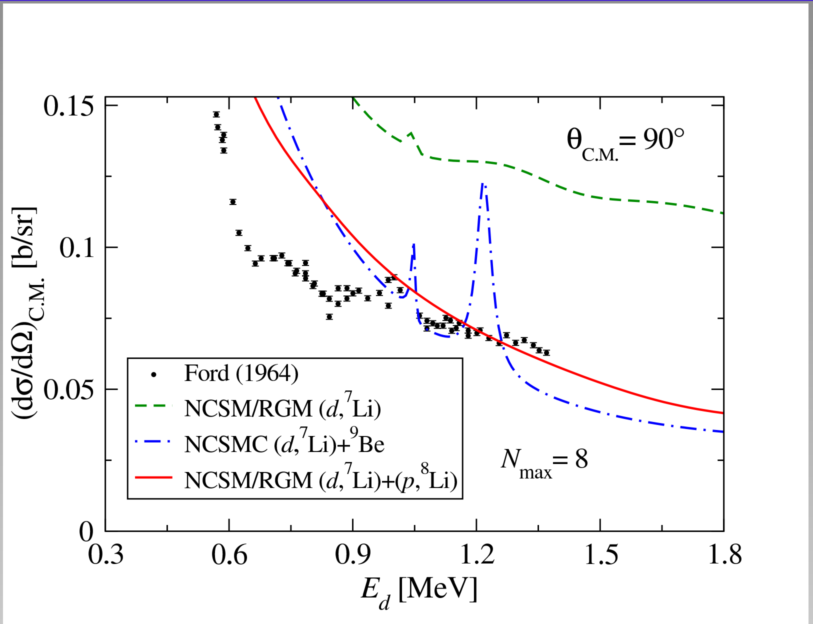
Die Reaktion ^{7}Li$(d, \alpha)^5$He im Energiegebiet von 0,6 bis 2,0 MeV

E. FRIEDLAND und I. VENTER
Physics Department, University of Pretoria, South Africa

Eingegangen am 25. Januar 1971

E(~17.3 MeV) --> 3/2$^+$,5/2$^+$,7/2$^+$

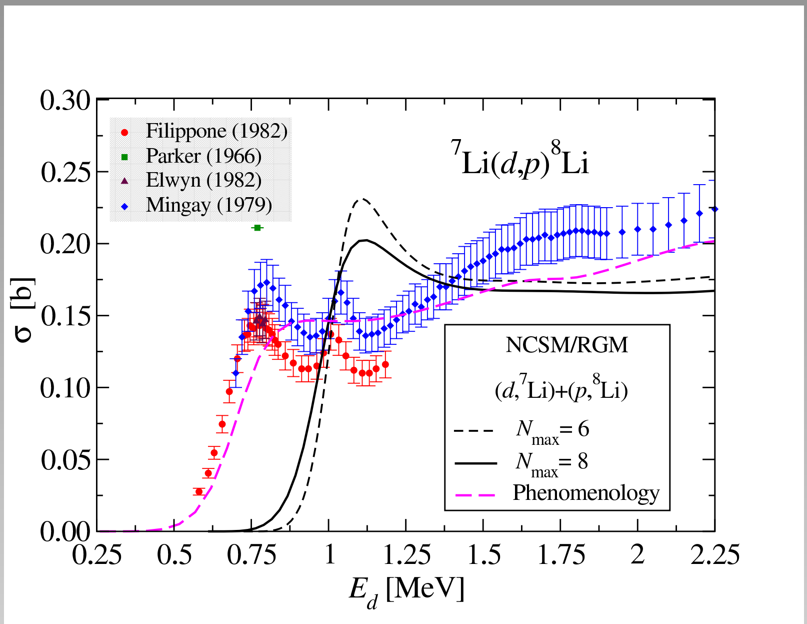
^{7}Li(d,d)^{7}Li cross section

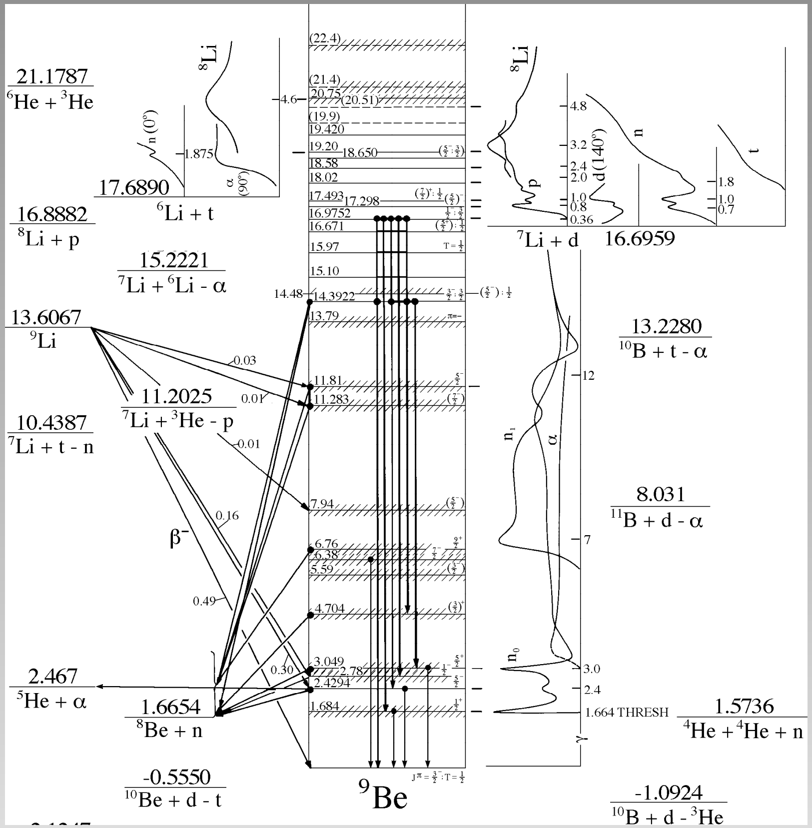


Experimental resonant peaks at 0.8 MeV (S-wave) and 1.0 MeV (P-wave)
('elastic' process not ideal probe for the ^{9}Be resonant states)

- 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

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



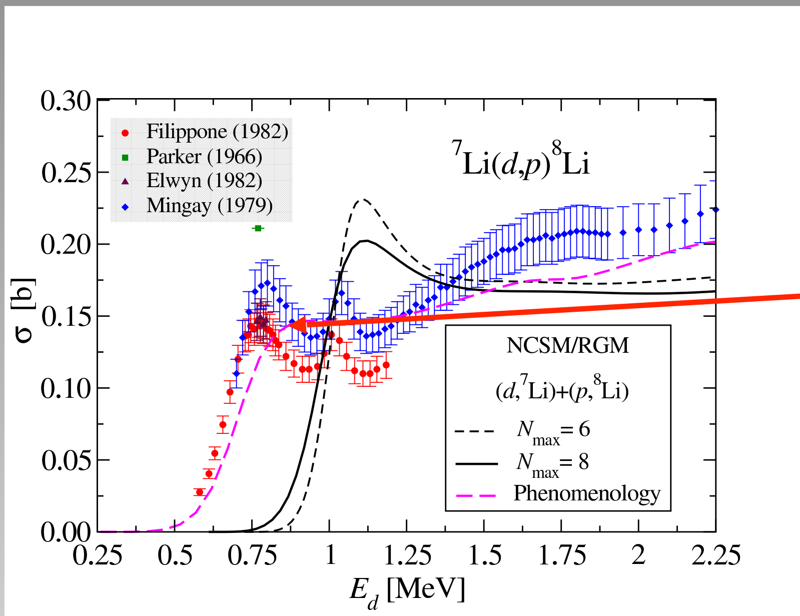


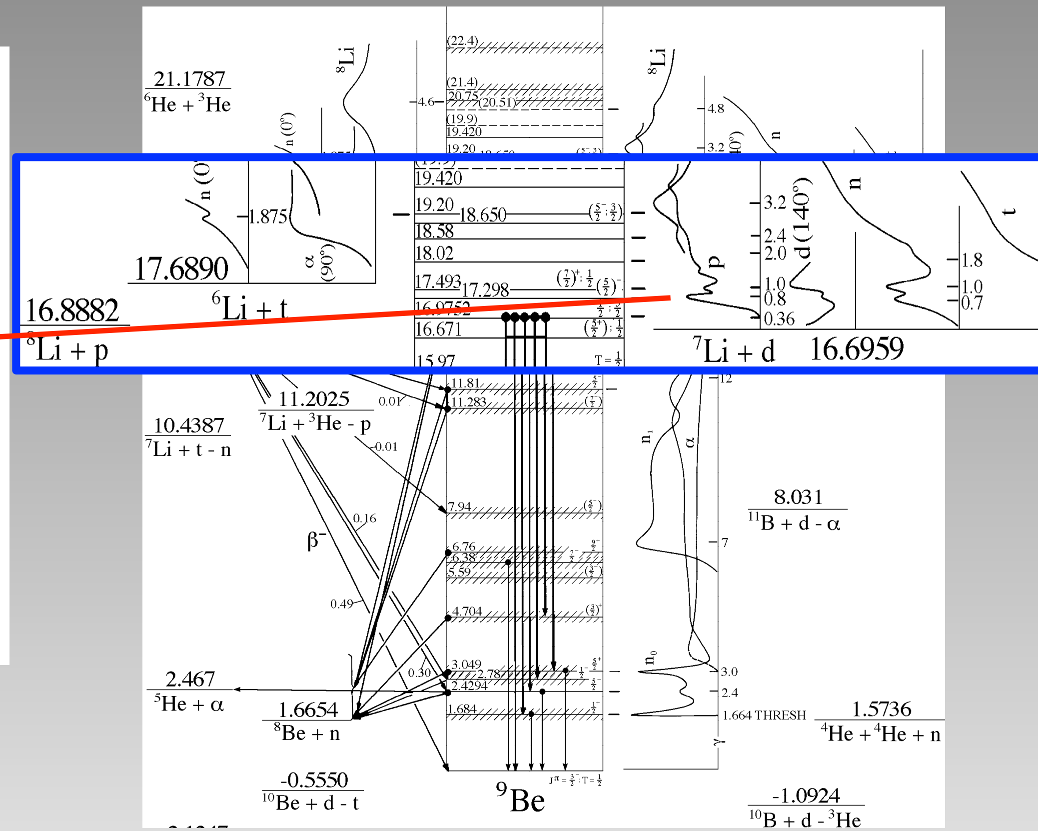
Included channels:
(1) p, ^{8}Li (2) d, ^{7}Li (3) coupling (d,p)
(4) virtual breakup of d

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





Included channels:
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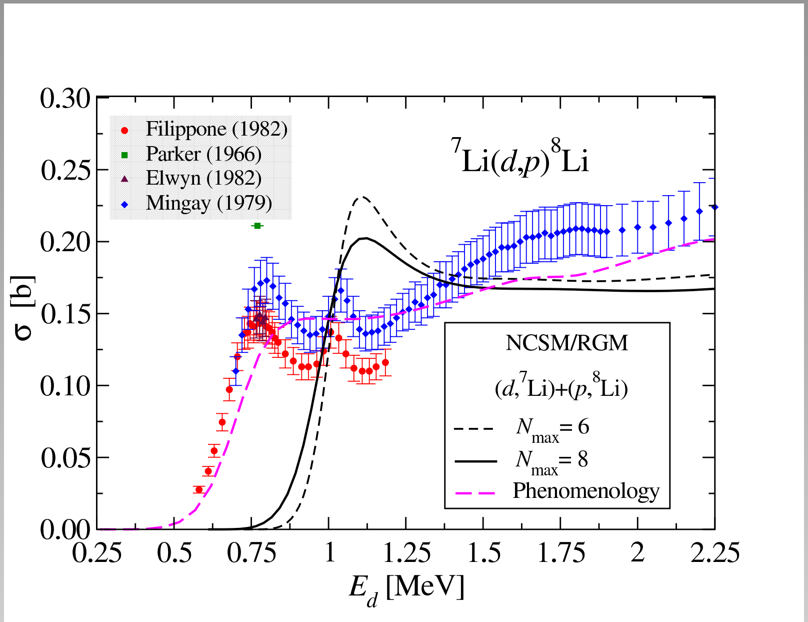
(4) virtual breakup of d

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

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

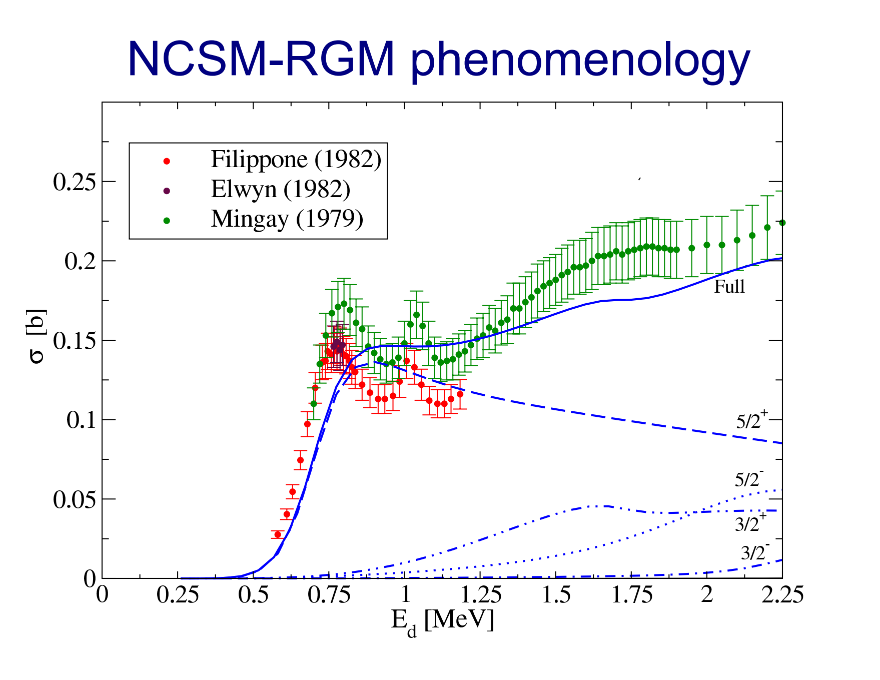
Included channels:
(1) p, ^{8}Li (2) *d*, ^{7}Li (3) coupling (*d*,p)
(4) virtual breakup of *d*

Not-included channels:
(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

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)

Conclusions & Perspectives

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

- Inclusion of the "elastic" and coupling channel in the description of transfer reactions

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