Ab initio calculations for low and intermediate energies nuclear reactions

Progress in *Ab Initio* Techniques in Nuclear Physics

Feb 27, 2019

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Carlotta Giusti (Pavia University)

Outline

1. Study of A=7 systems within the No-Core Shell Model with Continuum (NCSMC)

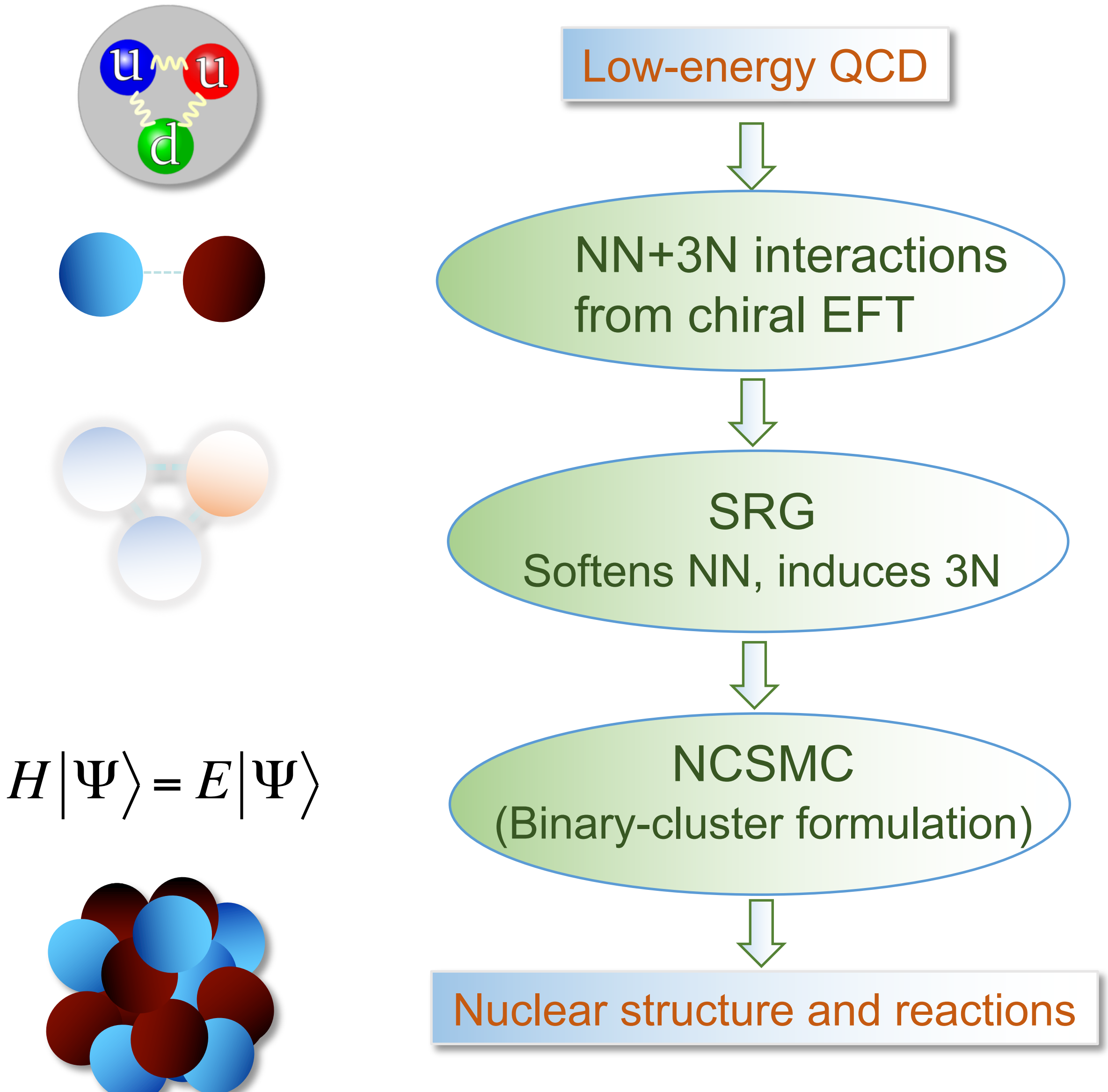
2. Microscopic optical potentials for intermediate energies with nonlocal *ab initio* densities

   - New chiral $\bar{\mathrm{N}}\mathrm{N}$ interaction at $\mathrm{N}^3\mathrm{LO}$
   - Application to antiproton elastic scattering

1.

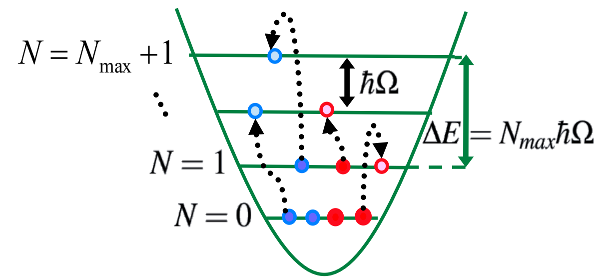
Study of A=7 systems

From QCD to nuclei

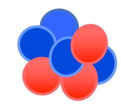


No-core shell model

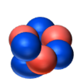
- No-core shell model (NCSM)
  - A-nucleon wave function expansion in the harmonic oscillator (HO) basis
  - Short- and medium-range correlations
  - Bound-states, narrow resonances



A



$$\Psi^{A} = \sum_{N=0}^{N_{\max}} \sum_{i} c_{Ni} \Phi_{Ni}^{A}$$

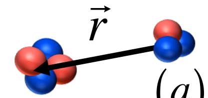
$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \big|^{(A)}$  $, \lambda \big\rangle$

Unknowns

No-core shell model with RGM

- NCSM with Resonating Group Method (NCSM/RGM)
  - Cluster expansion, clusters described by NCSM
  - Proper asymptotic behavior
  - Long-range correlations

$$\Psi^{(A)} = \sum_{\nu} \int d\vec{r}\; \gamma_{\nu}(\vec{r})\; \hat{A}_{\nu} \left| \underset{(A-a)}{} \overset{\vec{r}}{\longleftarrow} \underset{(a)}{}, \nu \right\rangle$$

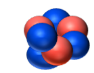


Unknowns

Unified approach to bound & continuum states; to nuclear structure and reactions

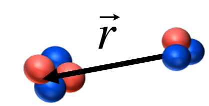
- No-core shell model (NCSM)
  - A-nucleon wave function expansion in the harmonic oscillator (HO) basis
  - Short- and medium-range correlations
  - Bound-states, narrow resonances

NCSM



- NCSM with Resonating Group Method (NCSM/RGM)
  - Cluster expansion, clusters described by NCSM
  - Proper asymptotic behavior
  - Long-range correlations

NCSM/RGM



- Most efficient: *ab initio* no-core shell model with continuum (NCSMC)

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

NCSMC

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left|^{(A)} \;, \lambda \right\rangle + \sum_{\nu} \int d\vec{r} \; \gamma_{\nu}(\vec{r}\,) \; \hat{A}_{\nu} \left|_{(A-a)} \overset{\vec{r}}{\longleftarrow} {}_{(a)} \;, \nu \right\rangle$$

Unknowns

Motivations

A=7 systems
(^{7}Be and ^{7}Li)

Motivations

Primordial ^{7}Li abundance in the early universe

PLB **757** (2016) 430

Fraction of pp-chain branches resulting in ^{7}Be versus ^{8}B neutrinos

Nuclear Astrophysics

$^{3}He(^{4}He,\gamma)^{7}Be$

$^{3}H(^{4}He,\gamma)^{7}Li$

A=7 systems (^{7}Be and ^{7}Li)

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Nuclear Astrophysics

^{3}He(^{4}He,γ)^{7}Be

^{3}H(^{4}He,γ)^{7}Li

A=7 systems (^{7}Be and ^{7}Li)

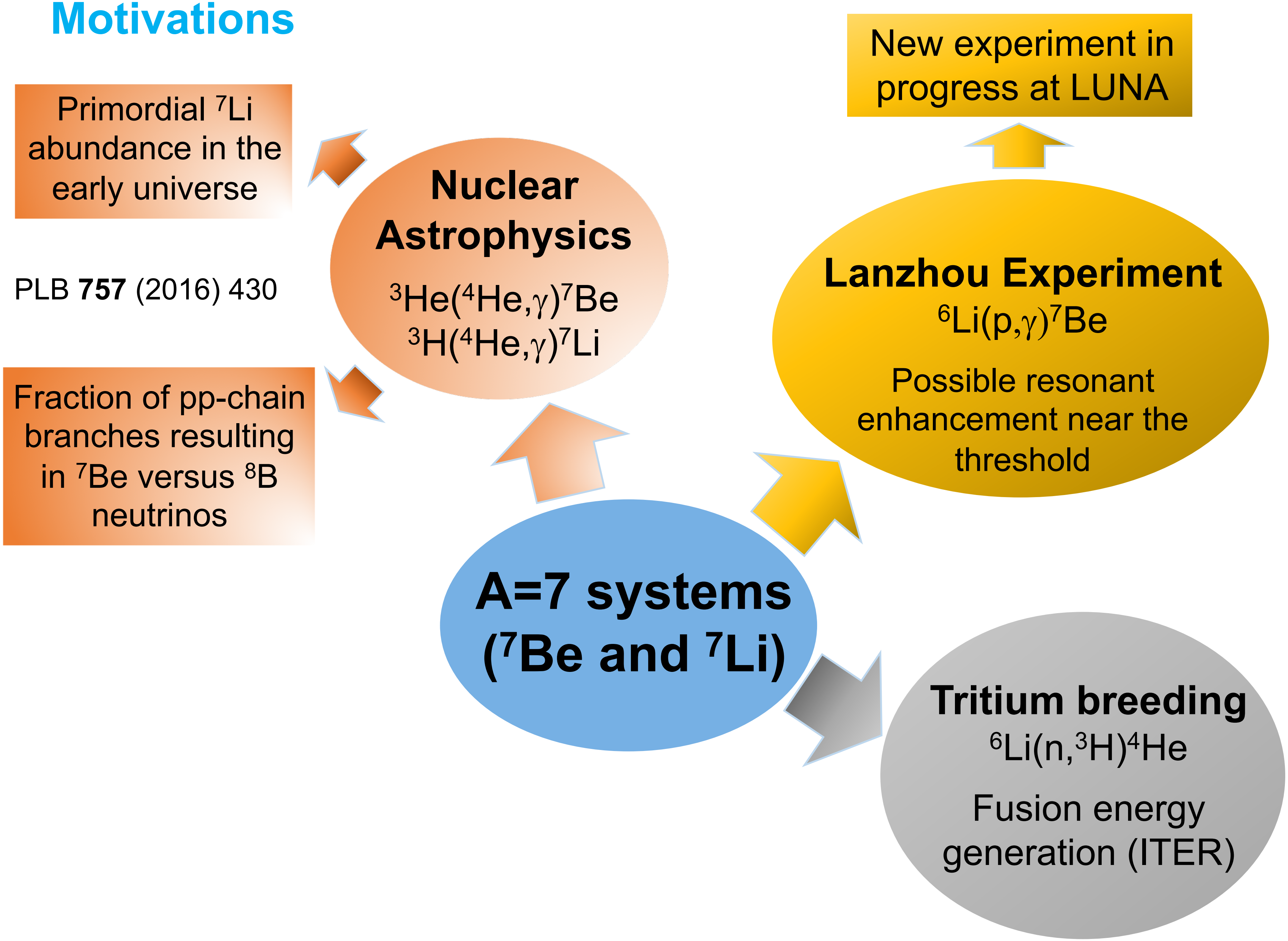
Lanzhou Experiment

^{6}Li(p,γ)^{7}Be

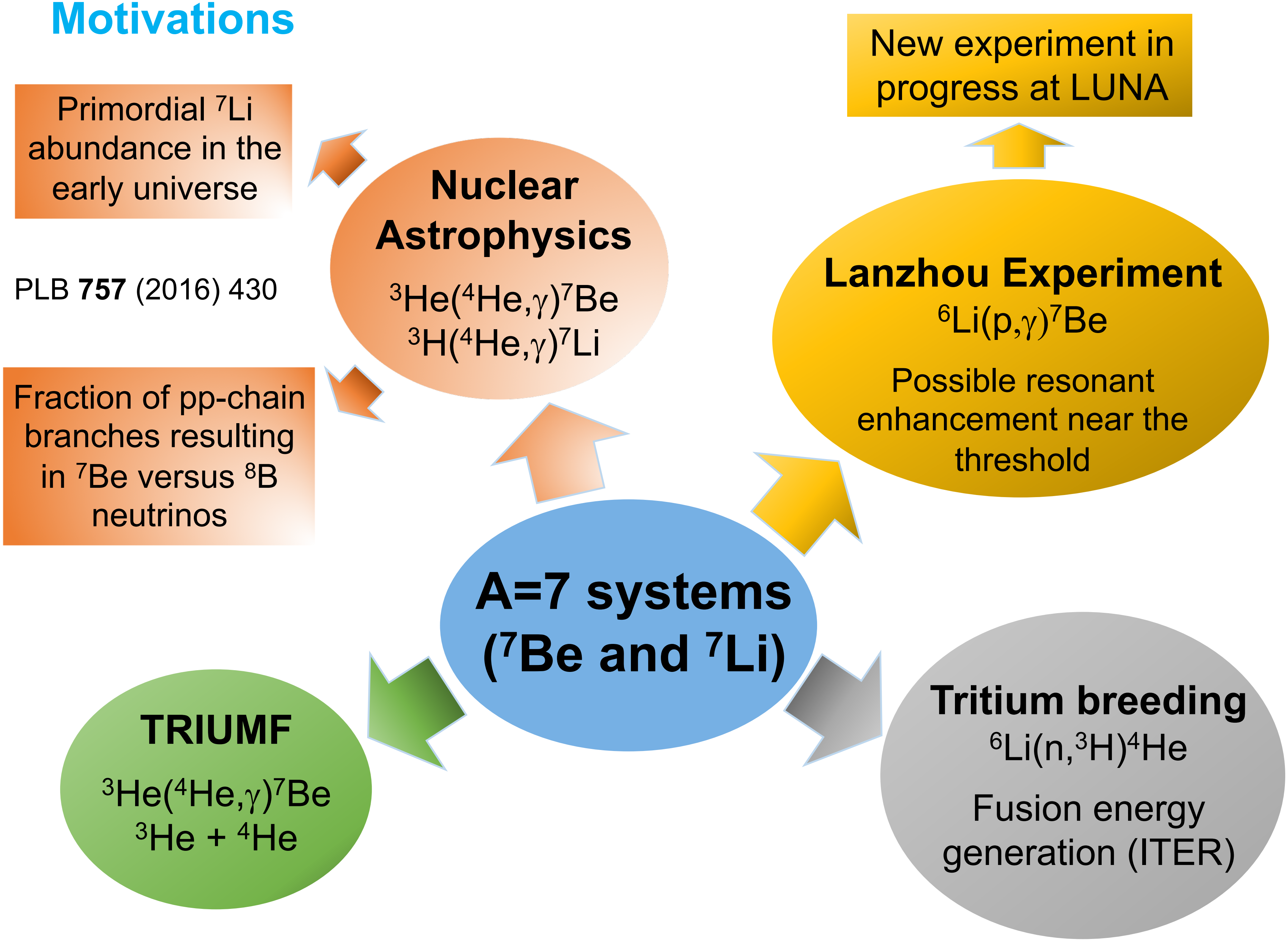
Possible resonant enhancement near the threshold

New experiment in progress at LUNA

Motivations



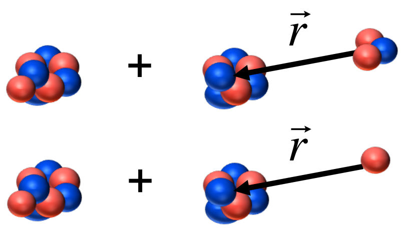
Motivations



NCSMC calculations of A=7 systems

- NN SRG-N^{3}LO [Entem, Machleidt, Phys. Rev. C, **68** 041001 (2003)]

- Calculations with NN SRG-N^{3}LO
  - ^{7}Be ~ $(^7\text{Be})_{\text{NCSM}}$ + $(^3\text{He} + {}^4\text{He})_{\text{NCSM/RGM}}$
    ~ $(^7\text{Be})_{\text{NCSM}}$ + $(p + {}^6\text{Li})_{\text{NCSM/RGM}}$
  - ^{7}Li ~ $(^7\text{Li})_{\text{NCSM}}$ + $(^3\text{H} + {}^4\text{He})_{\text{NCSM/RGM}}$
    ~ $(^7\text{Li})_{\text{NCSM}}$ + $(n + {}^6\text{Li})_{\text{NCSM/RGM}}$
    ~ $(^7\text{Li})_{\text{NCSM}}$ + $(p + {}^6\text{He})_{\text{NCSM/RGM}}$



- NCSM eigenstates
  - ^{3}He and ^{3}H : $(J^\pi, T) = (1/2^+, 1/2)$ eigenstate
  - ^{4}He: $(J^\pi, T) = (0^+, 0)$ eigenstate
  - ^{6}Li: $(J^\pi, T) = (1^+, 0), (3^+, 0), (0^+, 1), (2^+, 1)$ eigenstates
  - ^{6}He: $(J^\pi, T) = (0^+, 1), (2^+, 1)$ eigenstates
  - ^{7}Be and ^{7}Li: 8 negative- and 6 positive-parity eigenstates

^{7}Be system

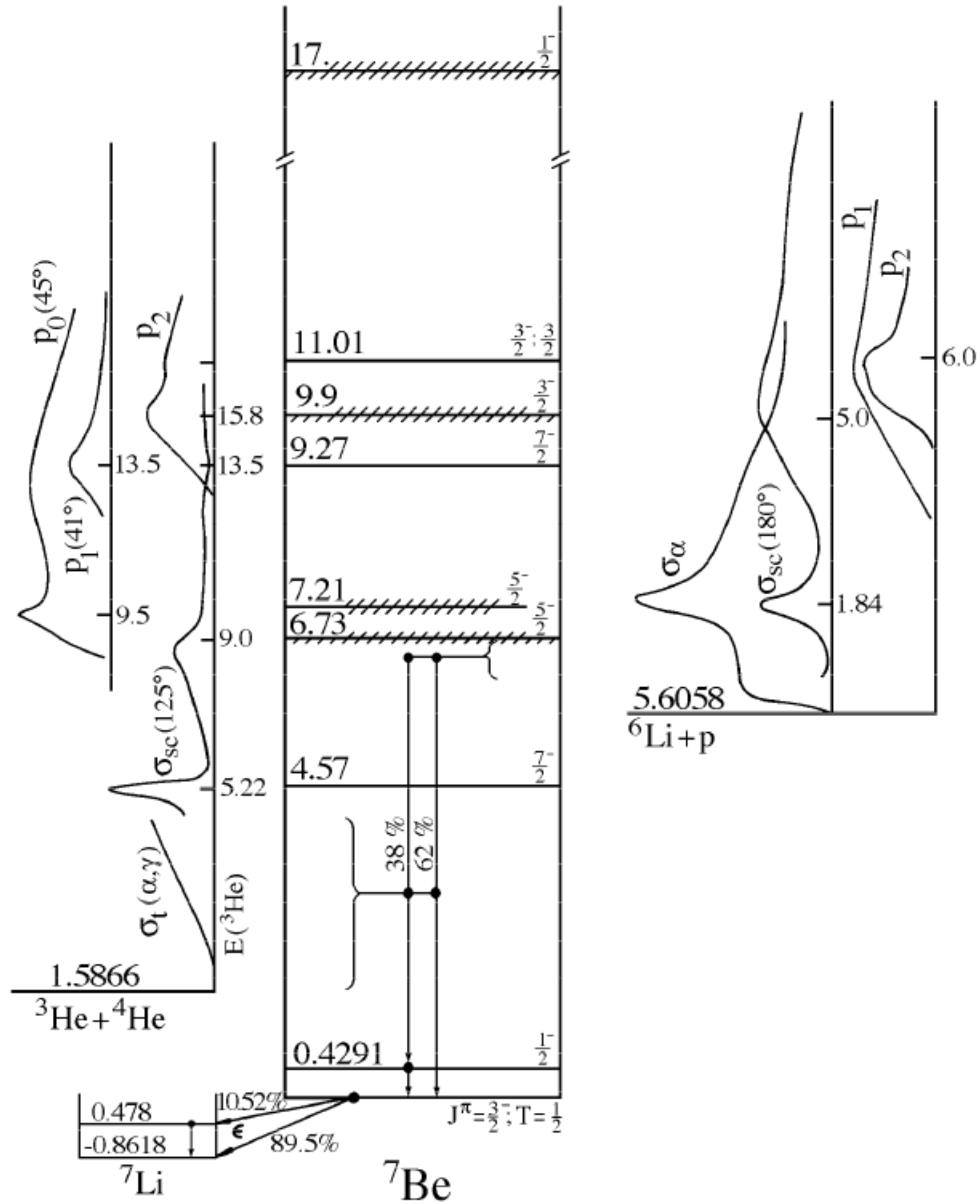
Analyzed mass partitions

- ^{3}He + ^{4}He
- p + ^{6}Li

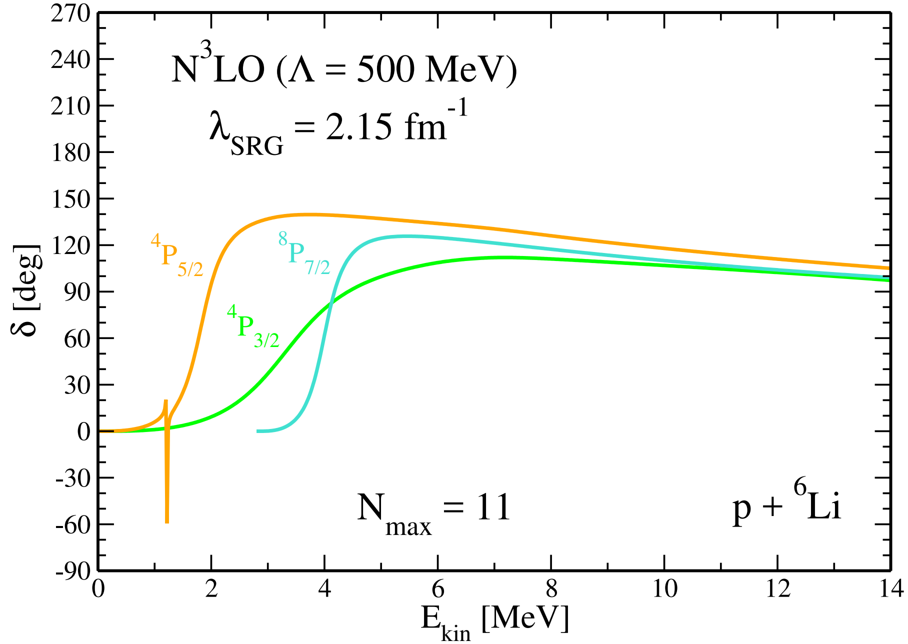
Exp.	$J^\pi = 3/2^-$
E [MeV]	-37.60

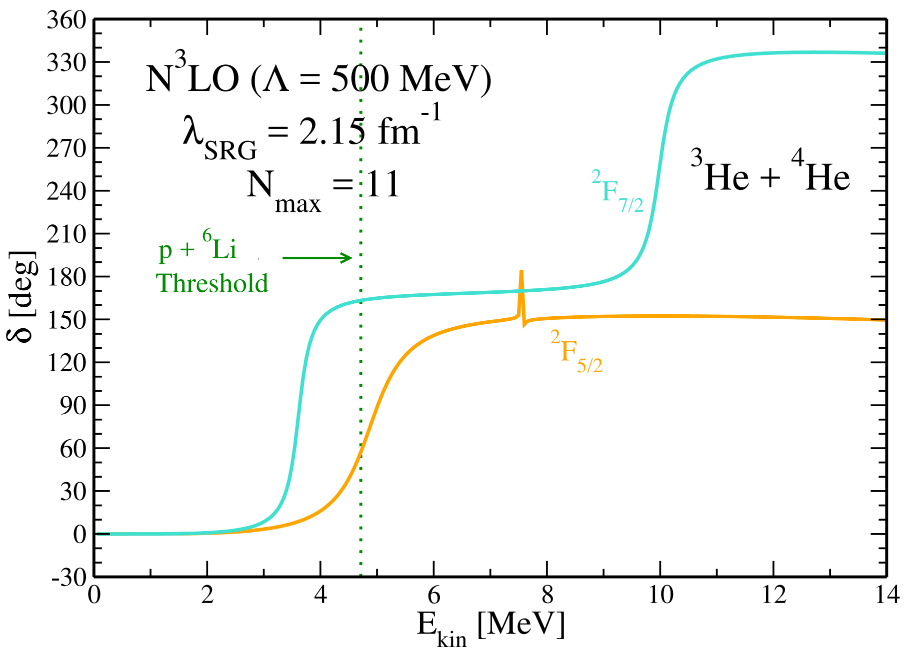
^{3}He + ^{4}He	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-1.519	-1.256
E [MeV]	-36.98	-36.71

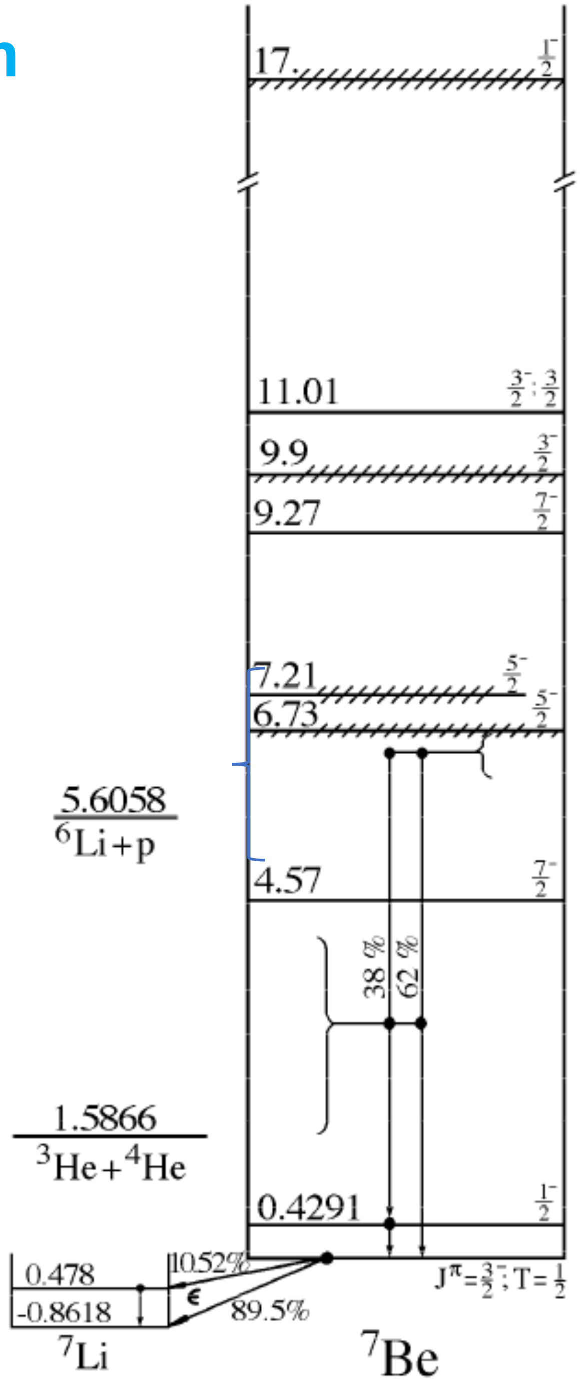
p + ^{6}Li	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-5.729	-5.389
E [MeV]	-36.47	-36.13



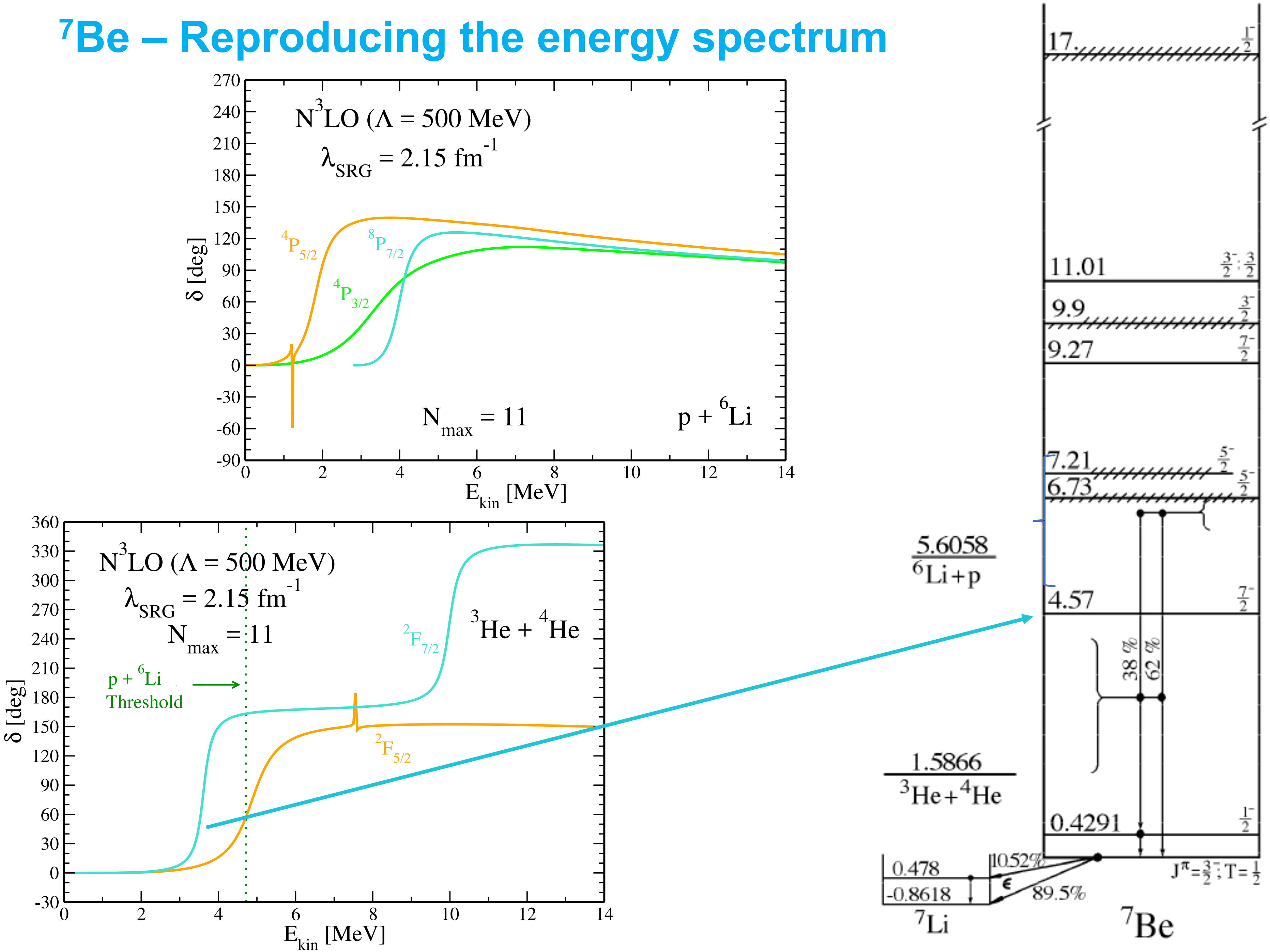
^{7}Be – Reproducing the energy spectrum



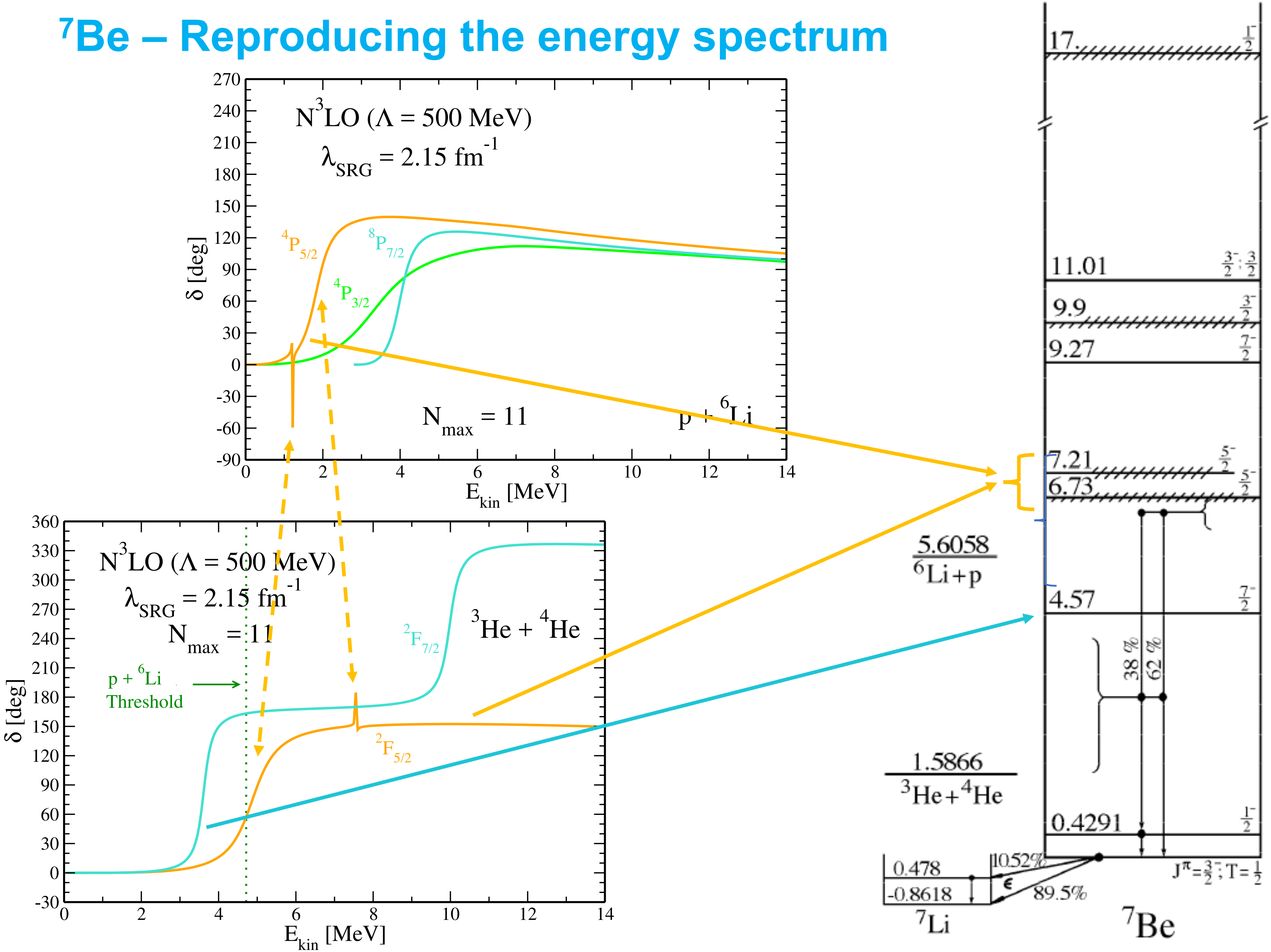




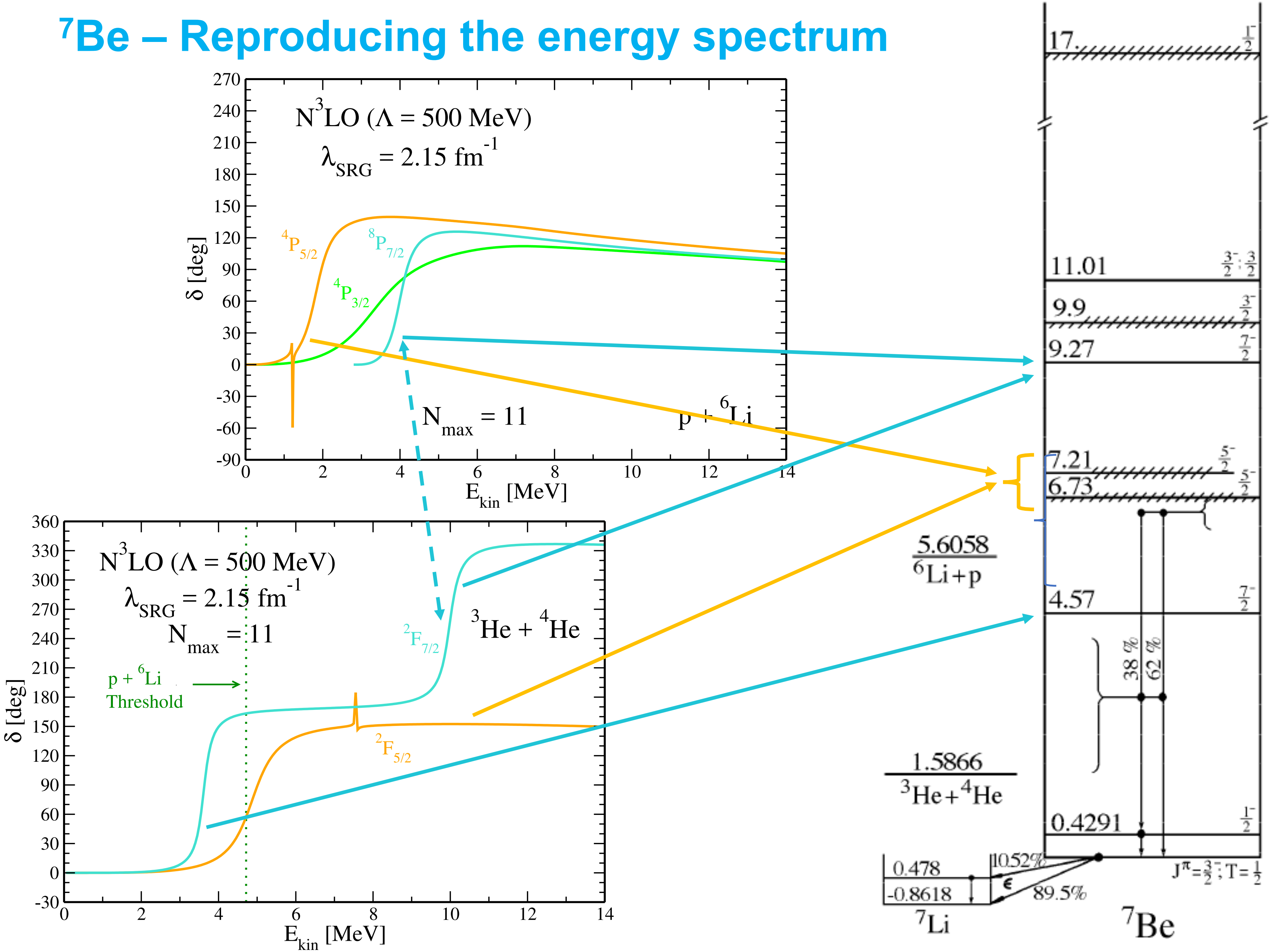
⁷Be – Reproducing the energy spectrum



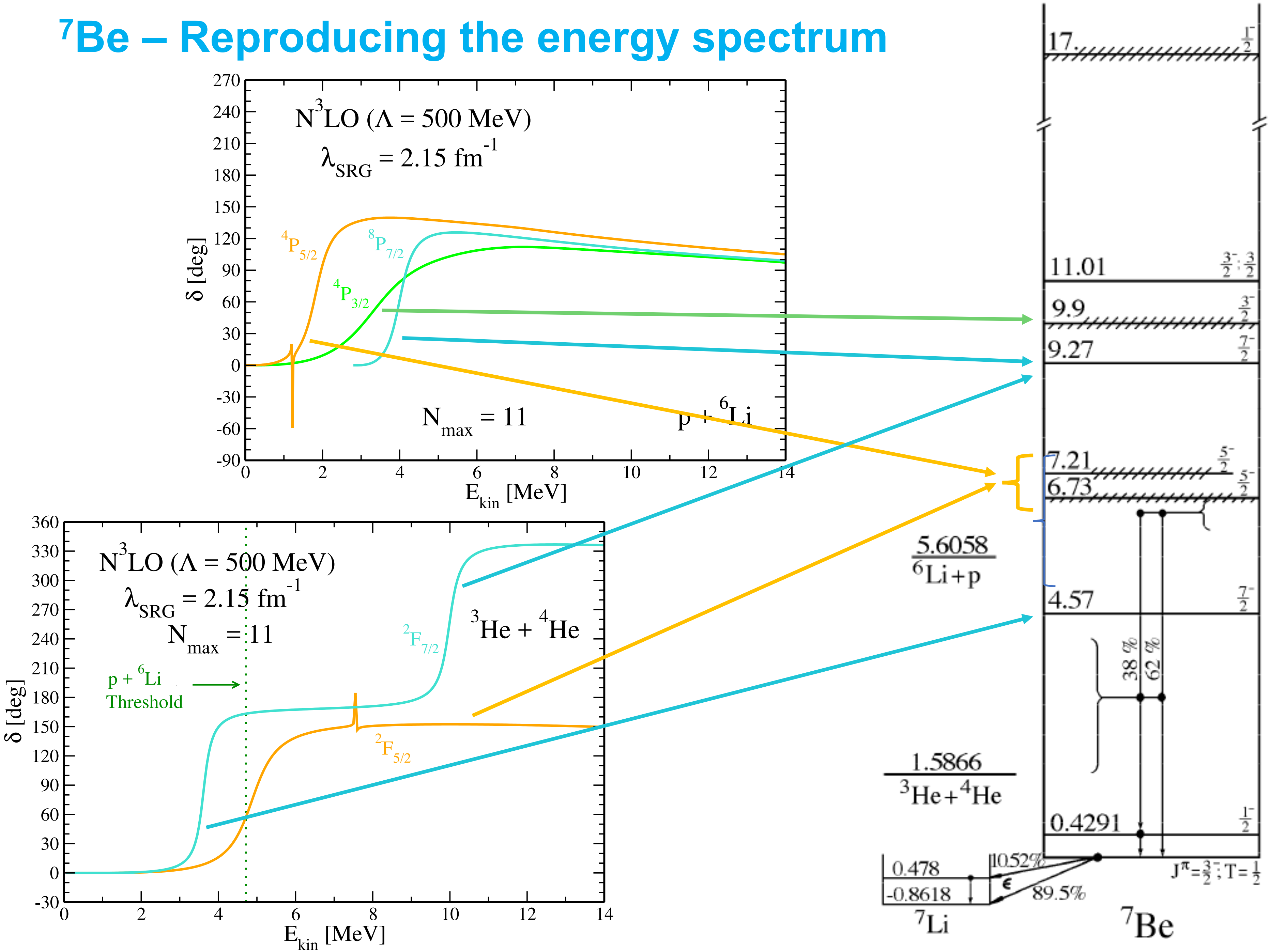
^{7}Be – Reproducing the energy spectrum



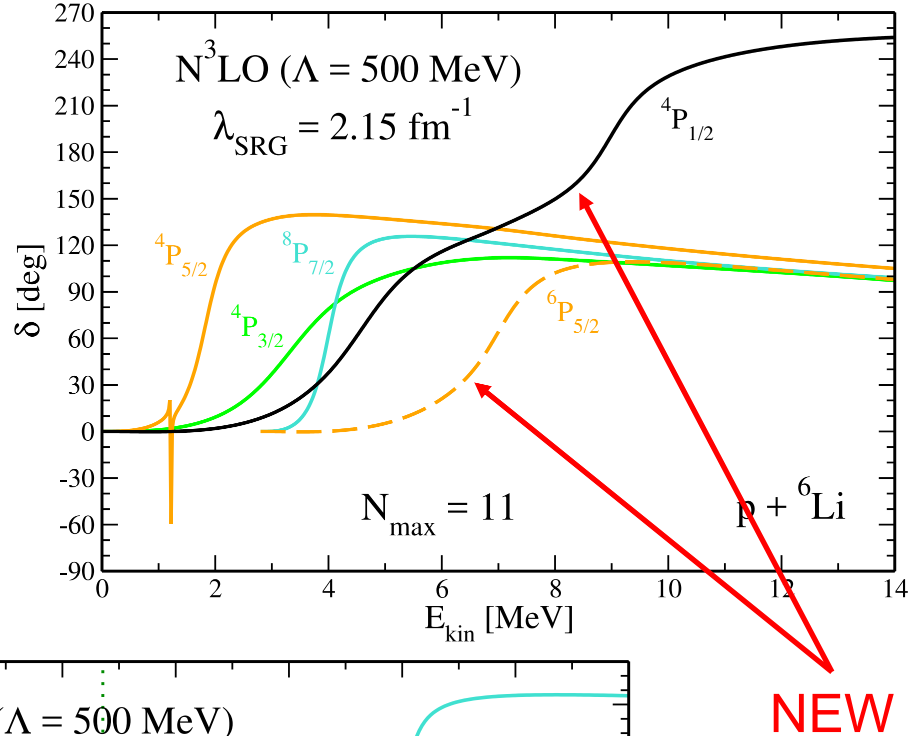
^{7}Be – Reproducing the energy spectrum

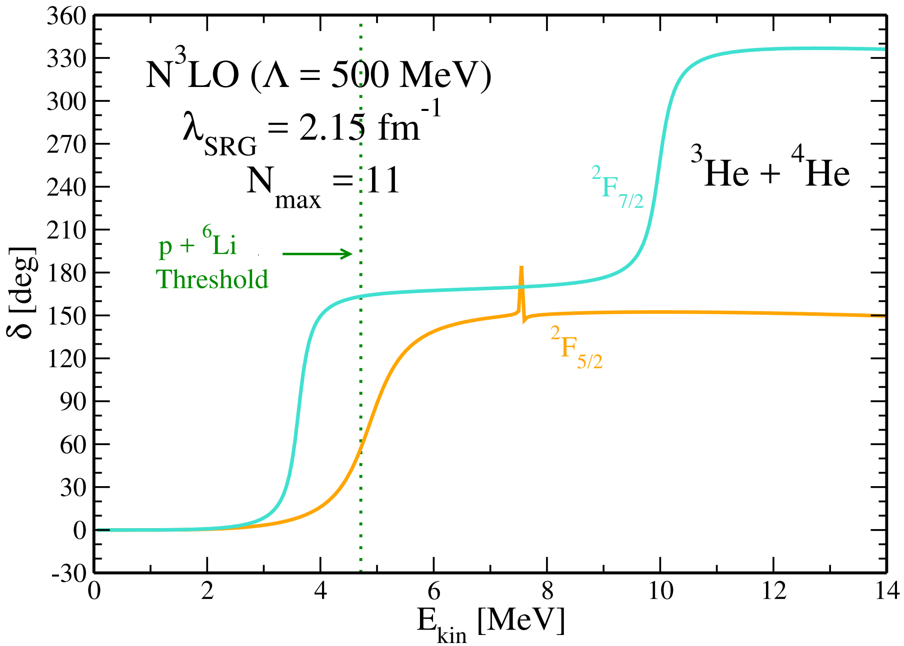


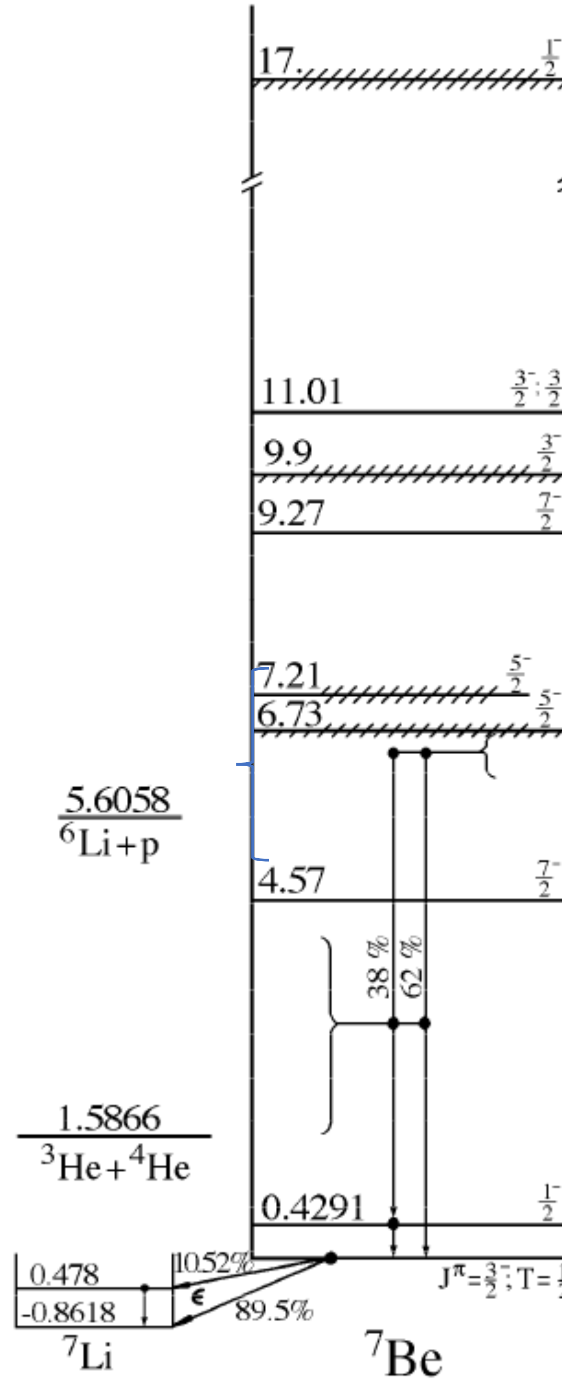
^{7}Be – Reproducing the energy spectrum



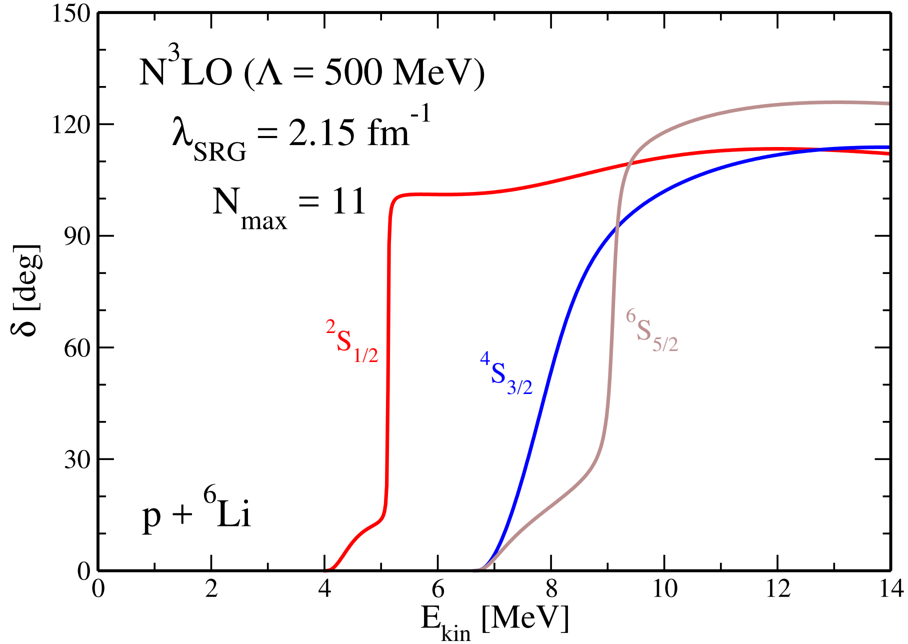
^{7}Be – New negative-parity states

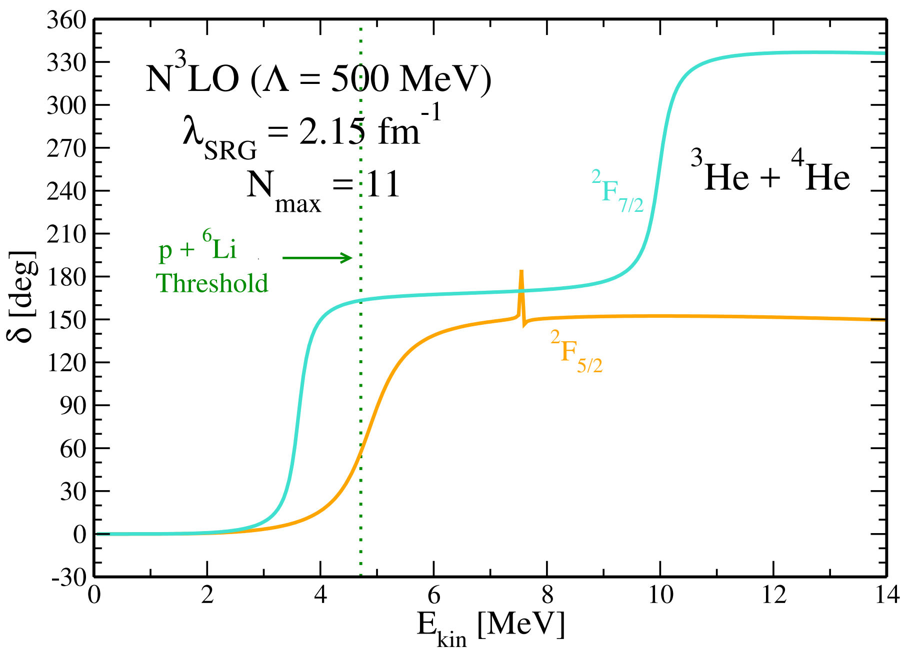


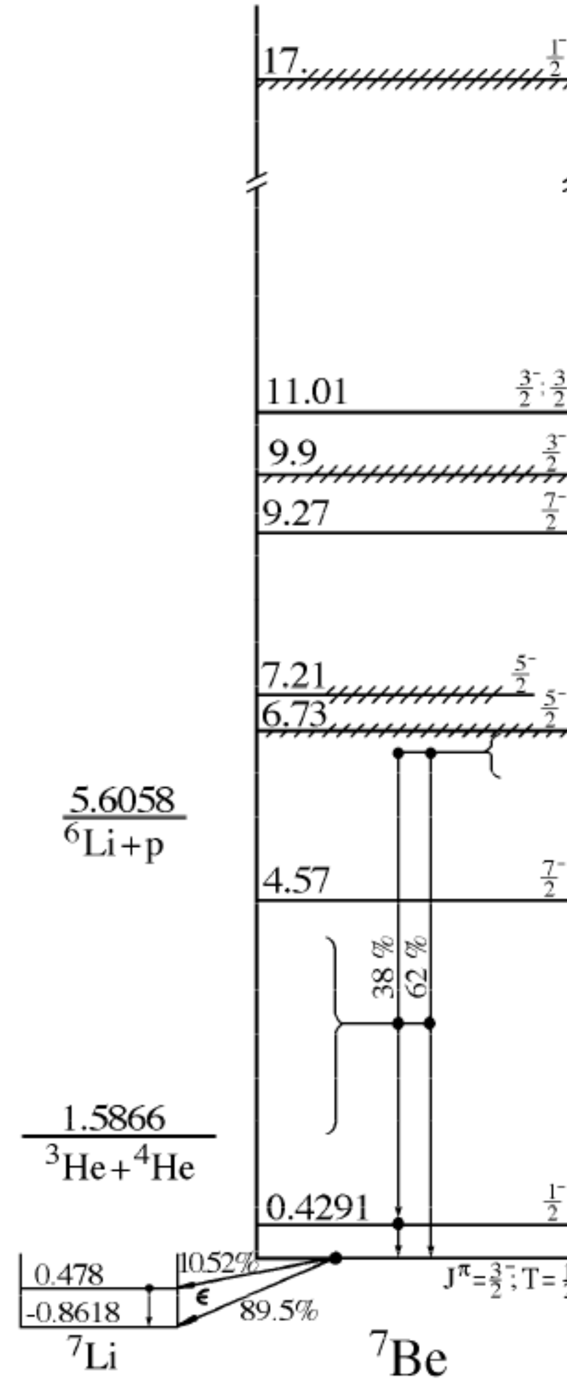




^{7}Be – New positive-parity states







^{7}Li system

Analyzed mass partitions

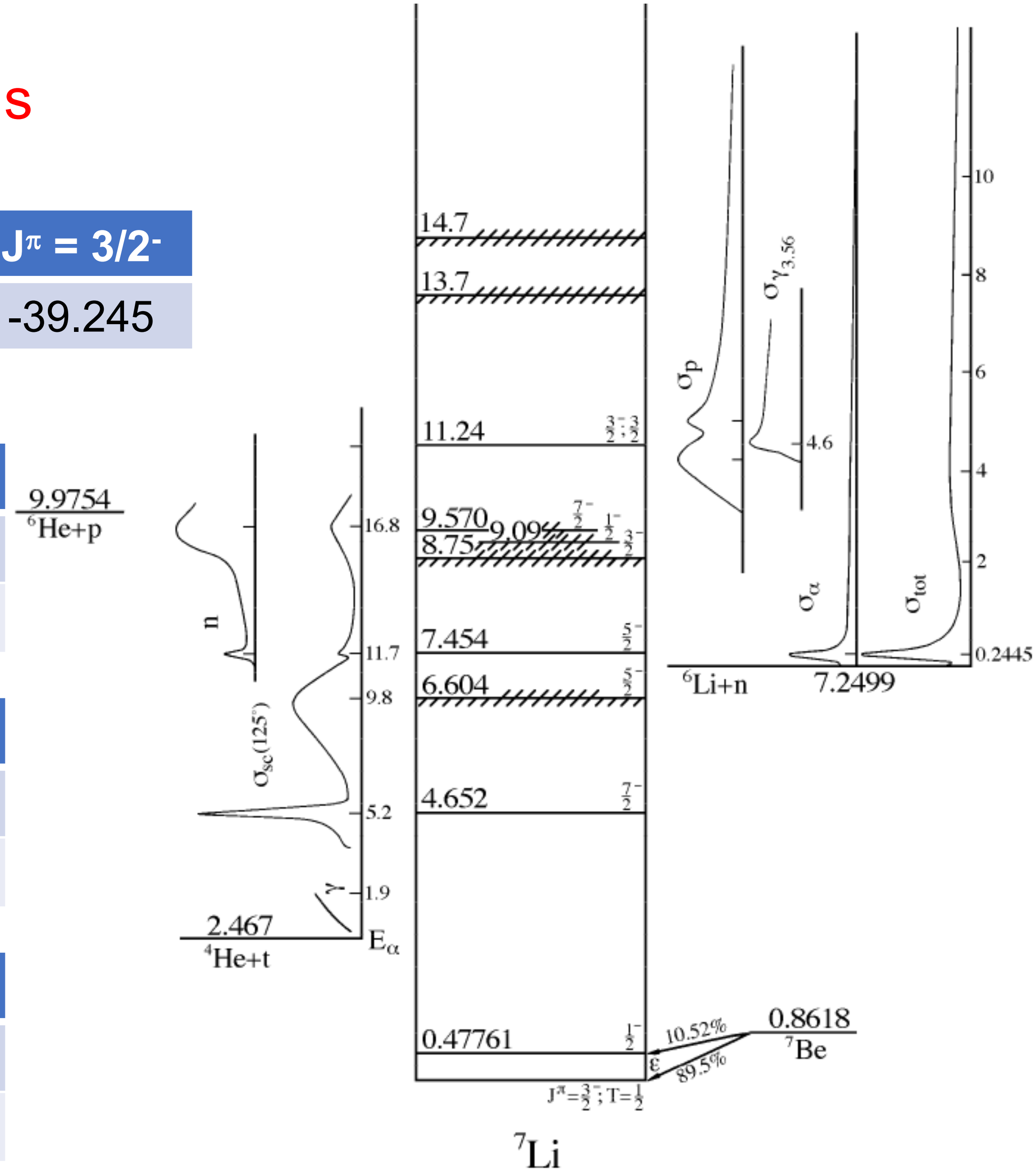
- ^{3}H + ^{4}He
- n + ^{6}Li
- p + ^{6}He

Exp.	$J^\pi = 3/2^-$
E [MeV]	-39.245

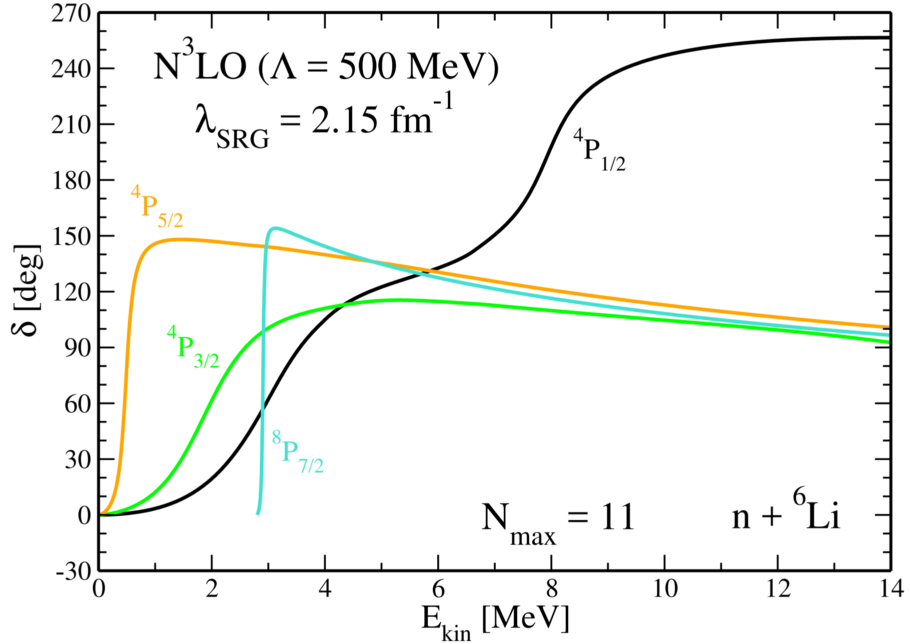
^{3}H + ^{4}He	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-2.432	-2.153
E [MeV]	-38.65	-38.37

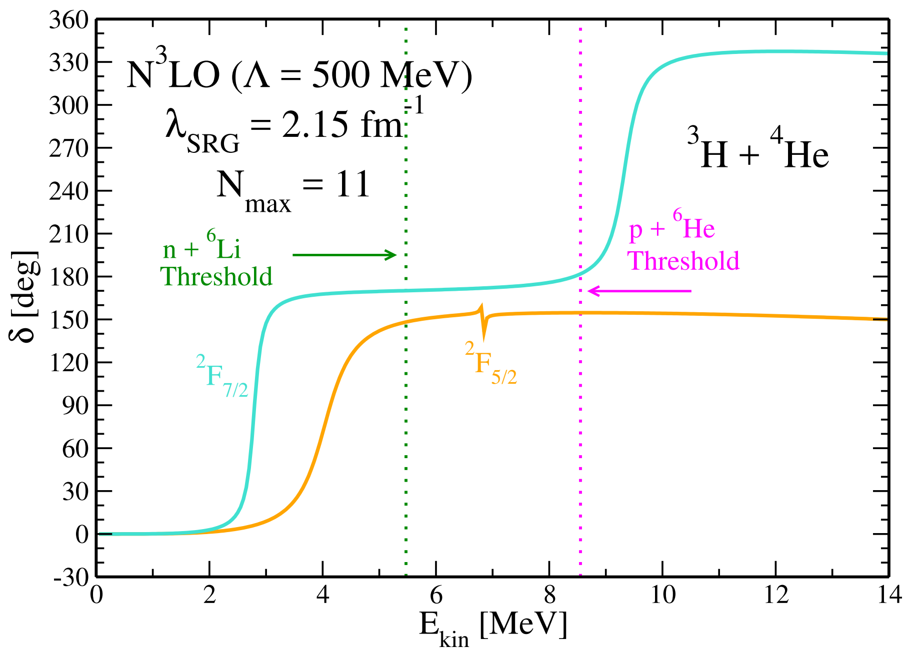
n + ^{6}Li	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-7.381	-7.048
E [MeV]	-38.13	-37.79

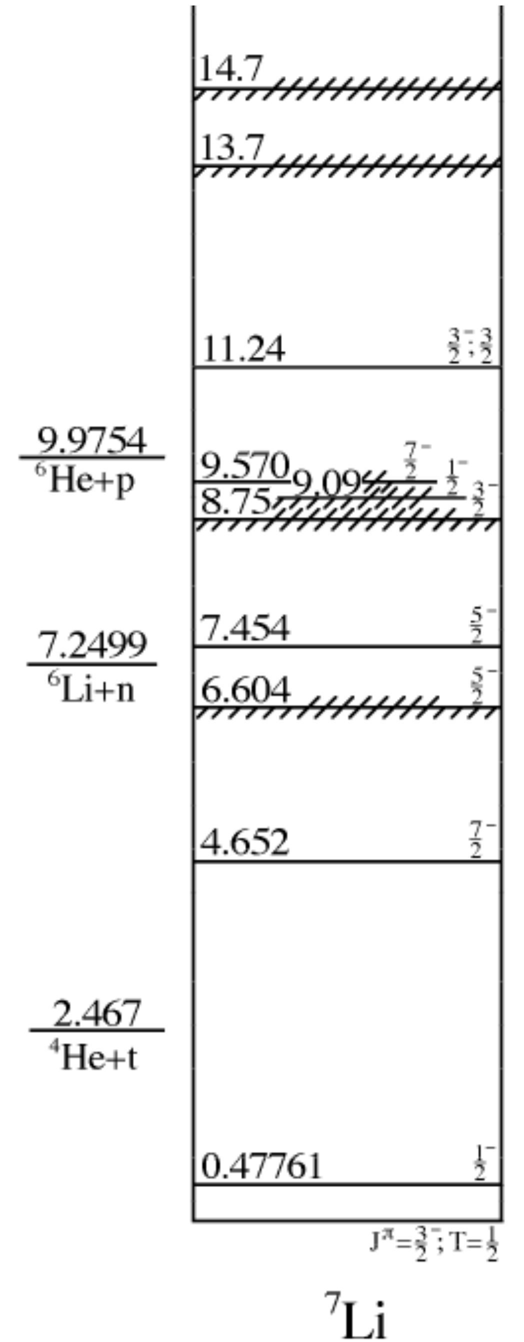
p + ^{6}He	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-10.40	-10.06
E [MeV]	-38.06	-37.73



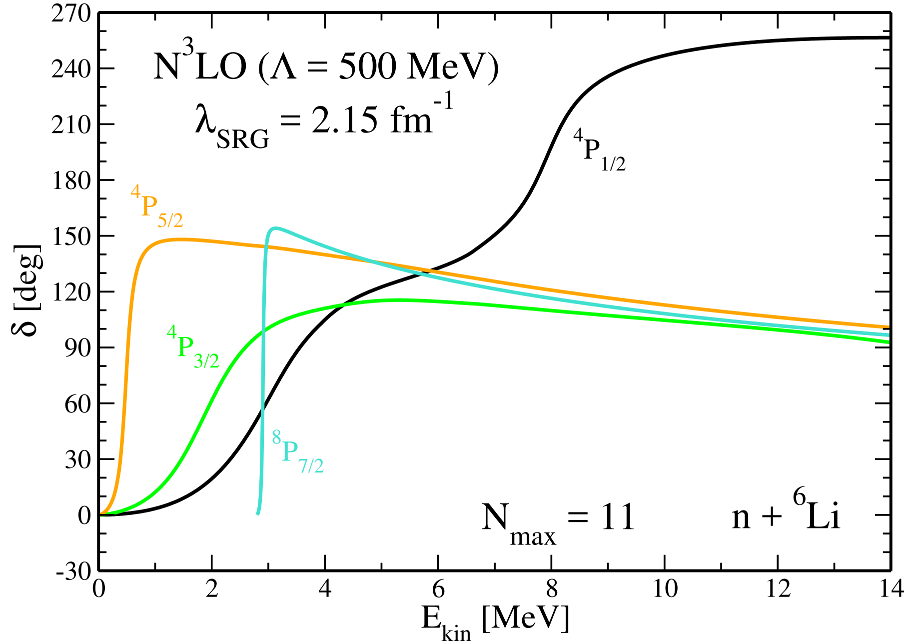
^{7}Li – Reproducing the energy spectrum

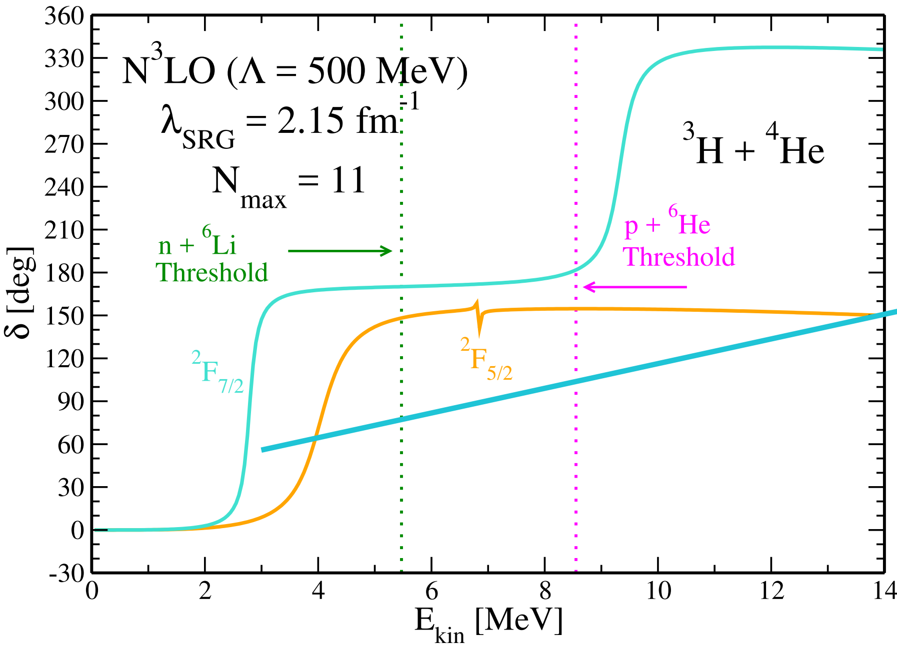


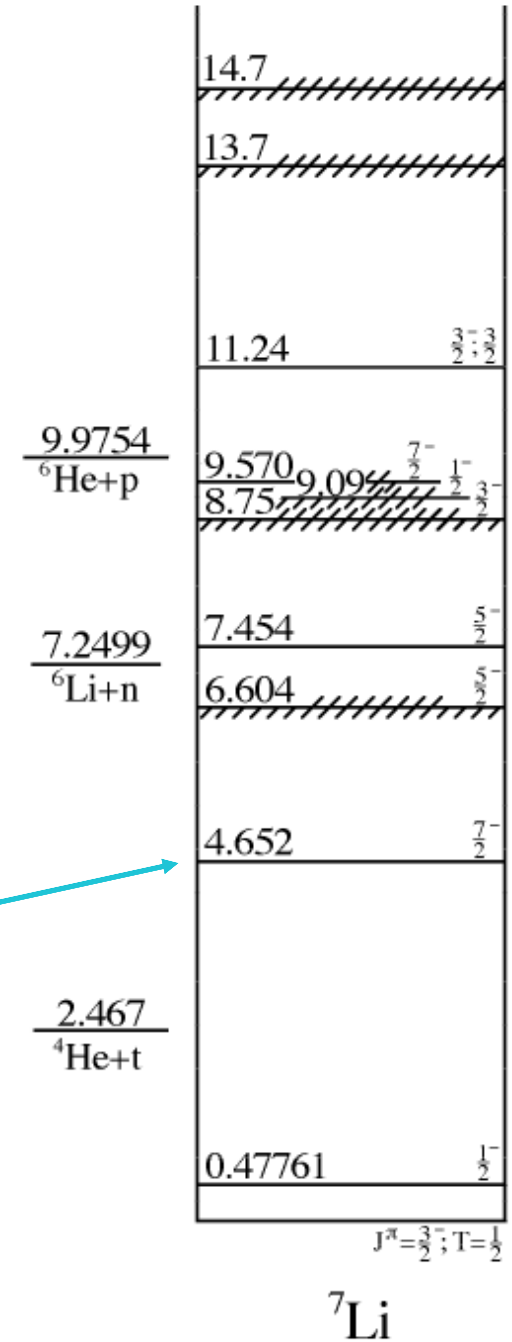




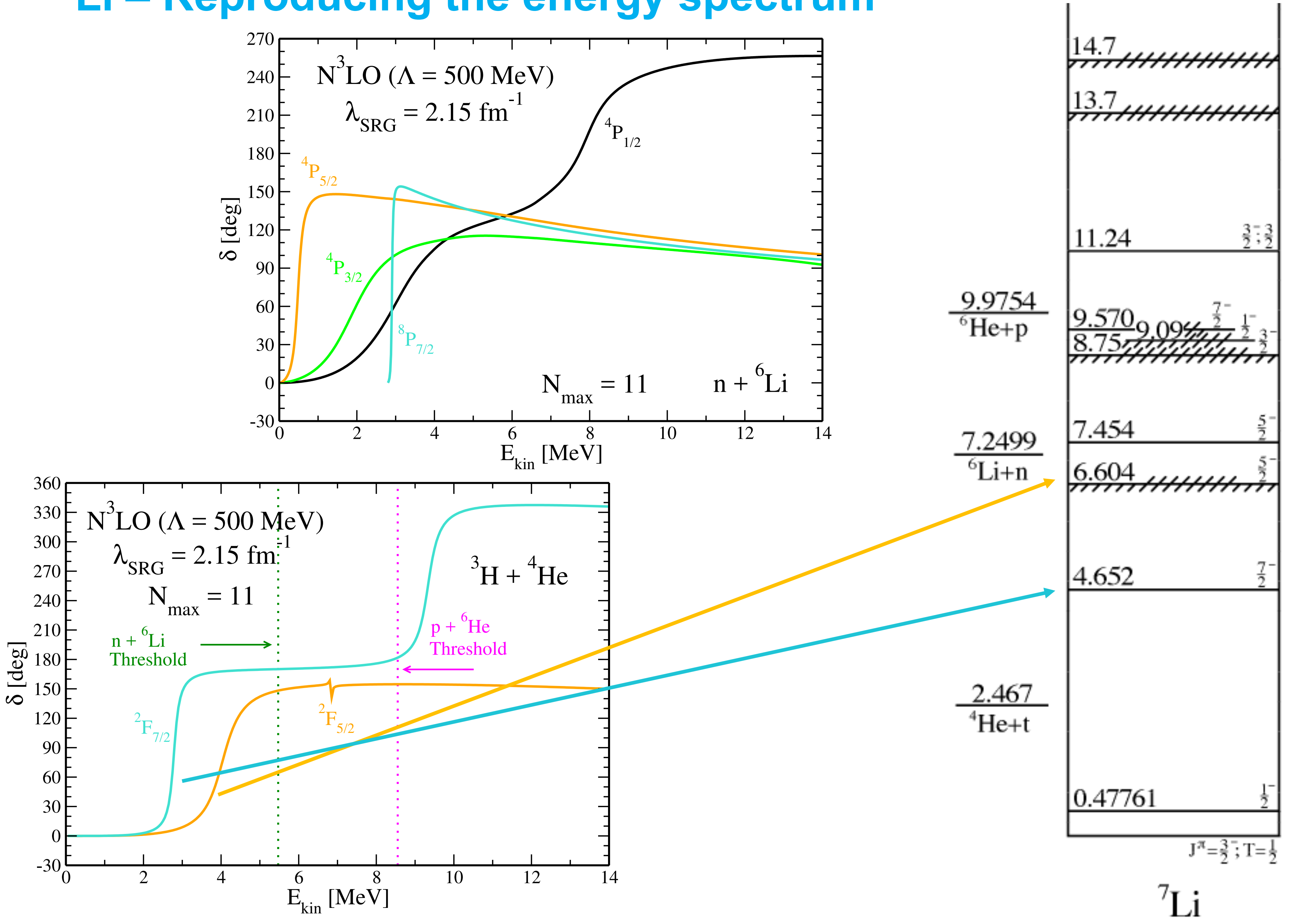
^{7}Li – Reproducing the energy spectrum







^{7}Li – Reproducing the energy spectrum



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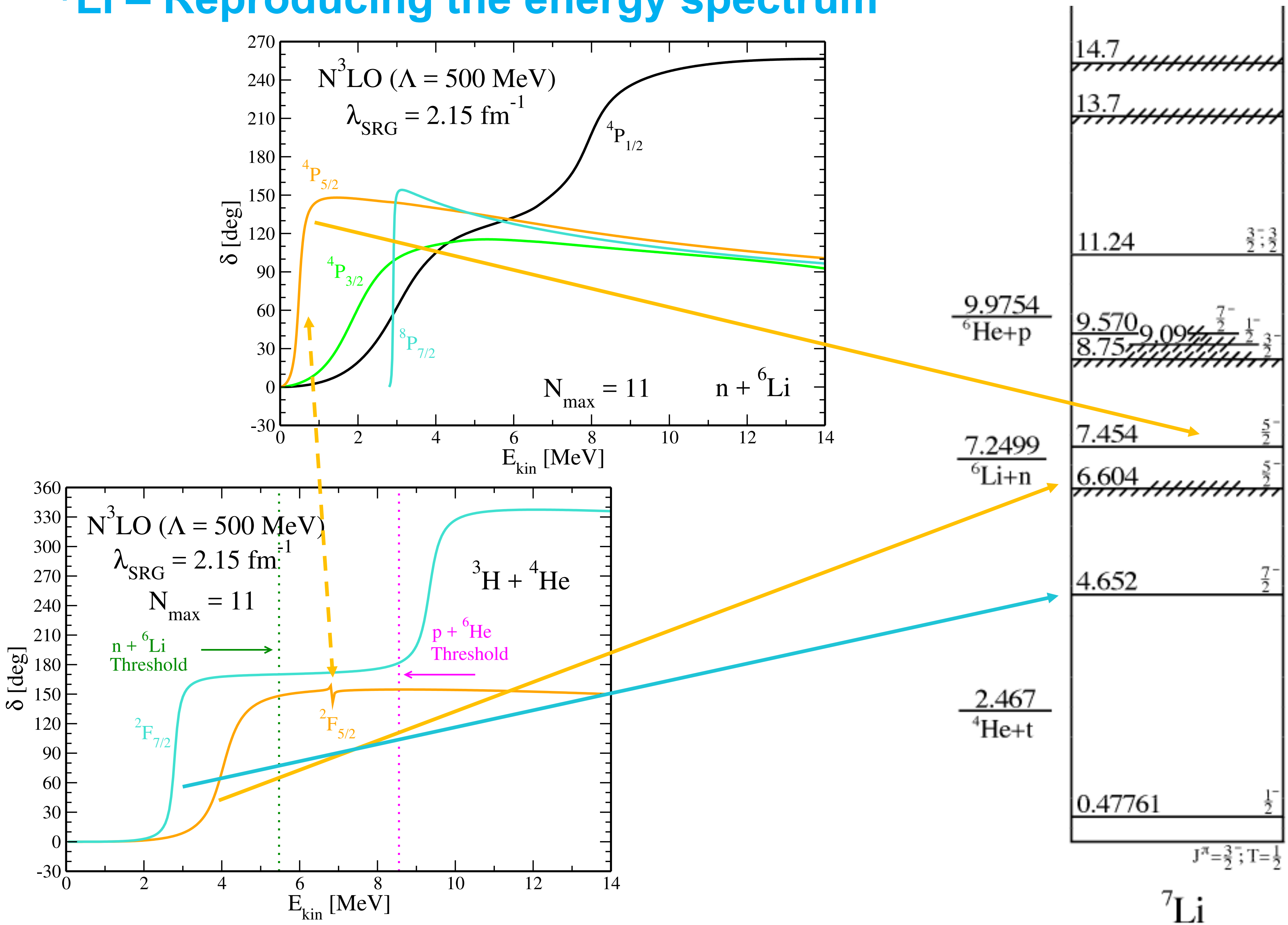

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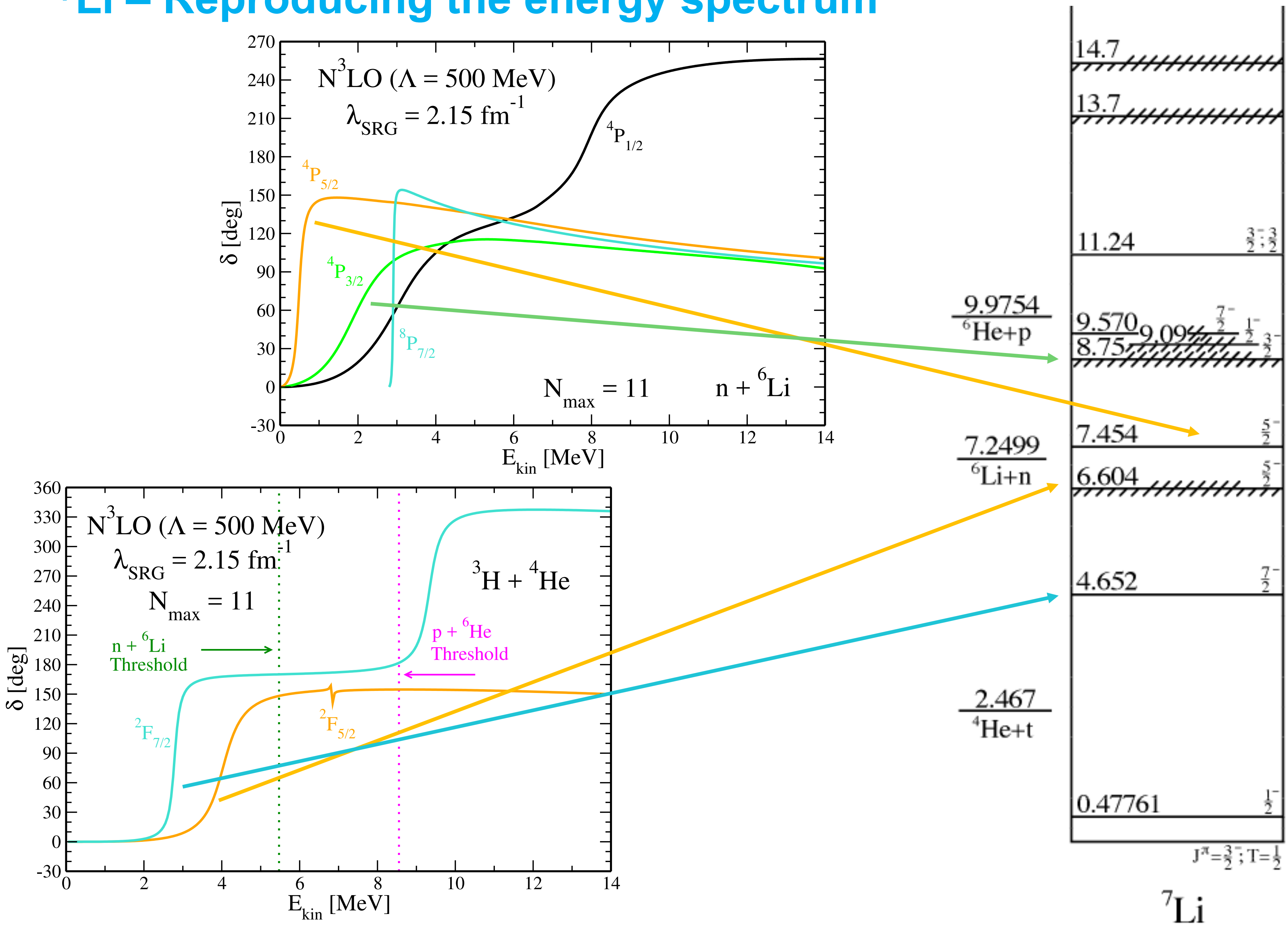

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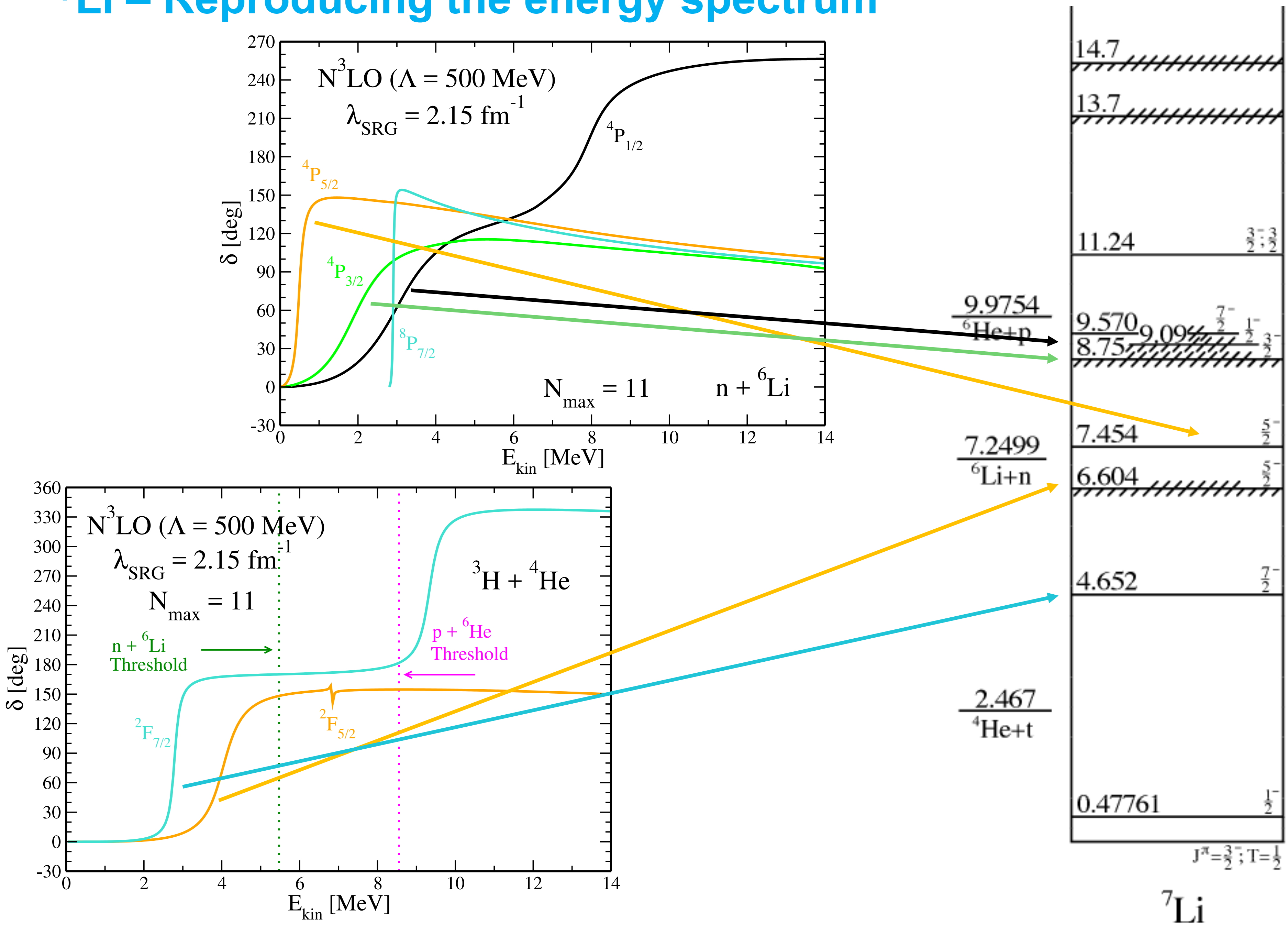

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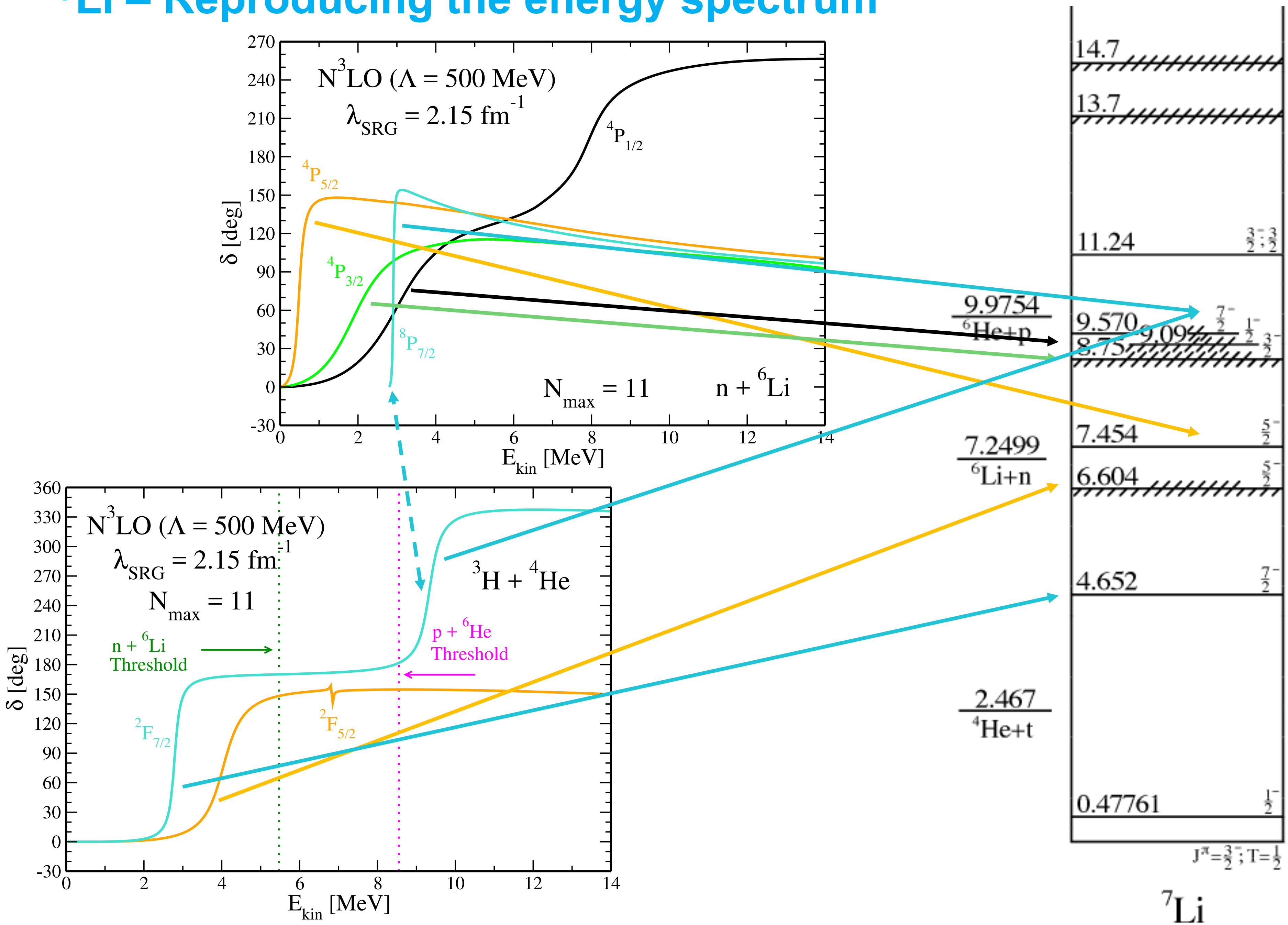
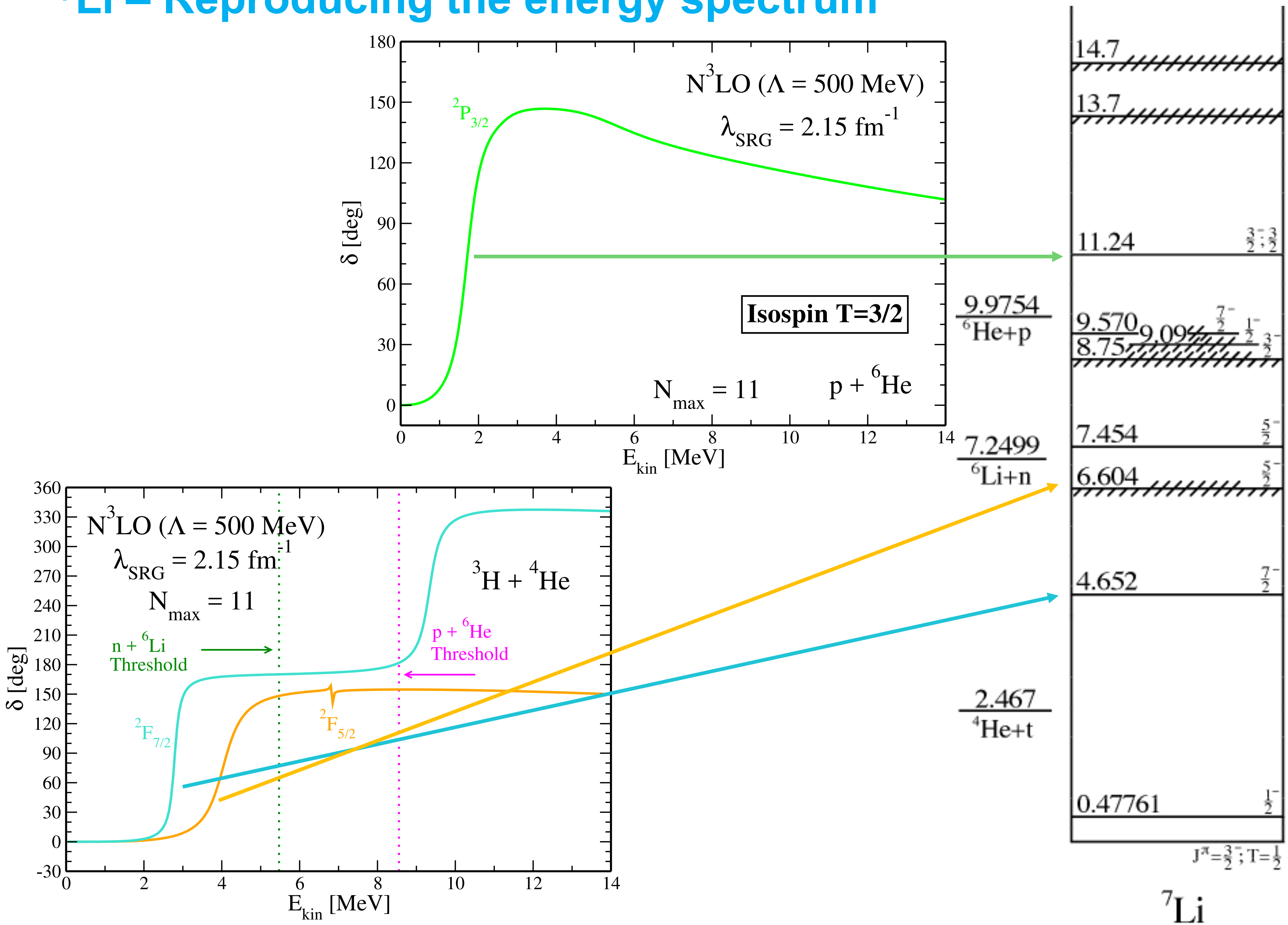
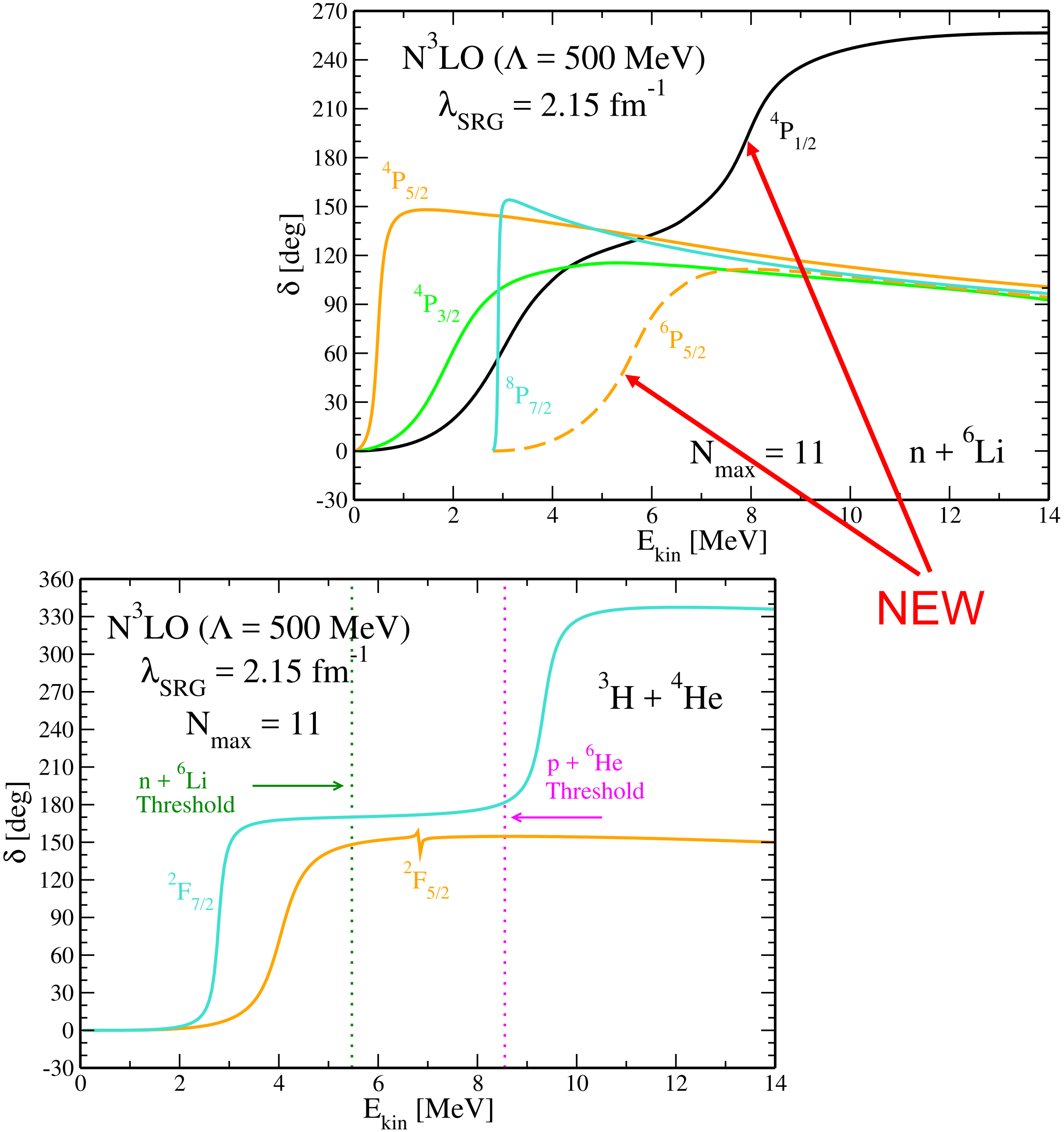
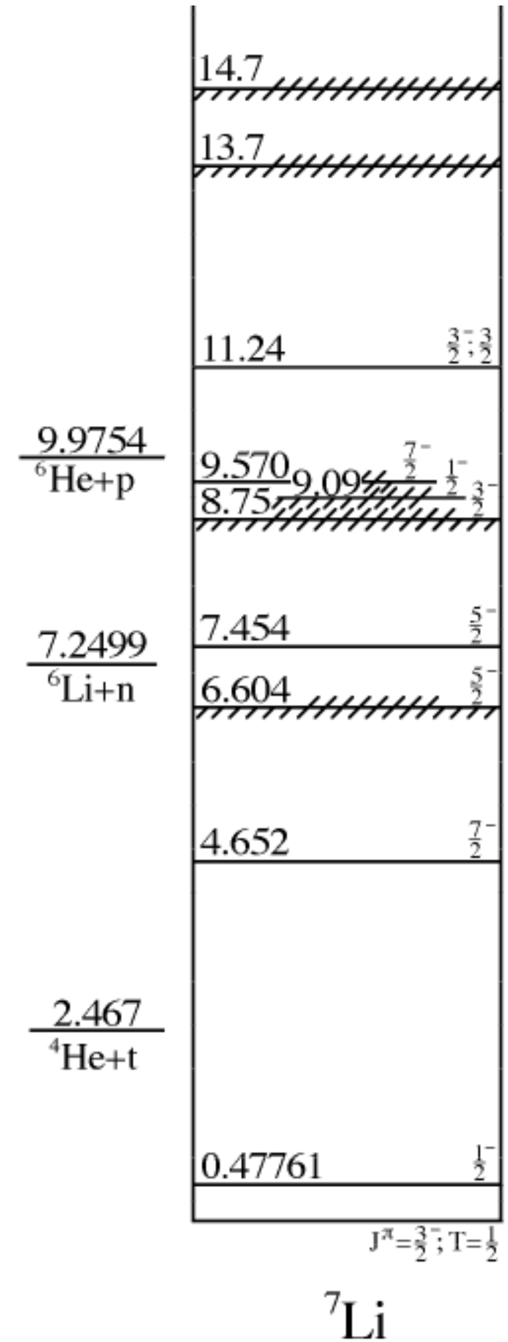


^{7}Li – Reproducing the energy spectrum



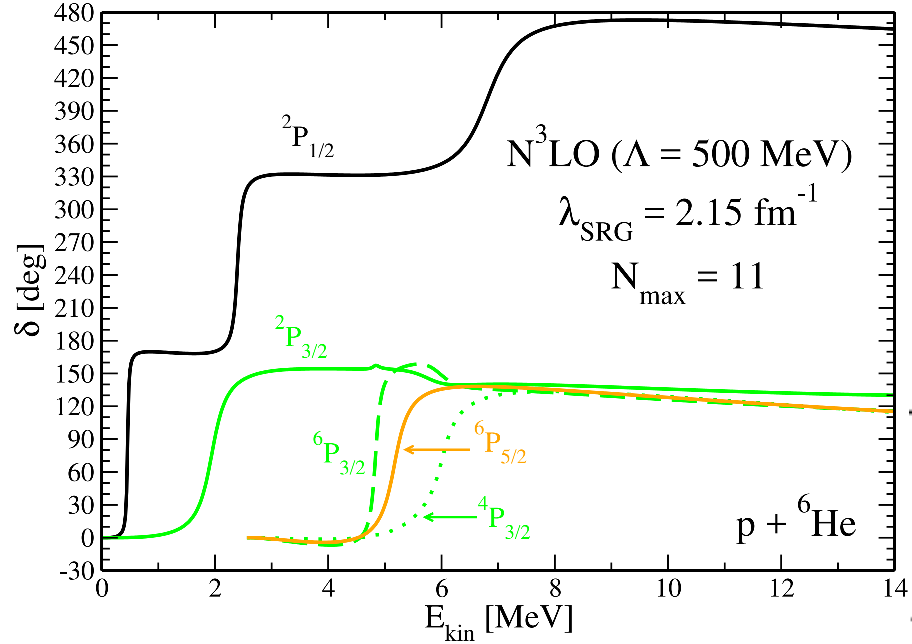
^{7}Li – New negative-parity states

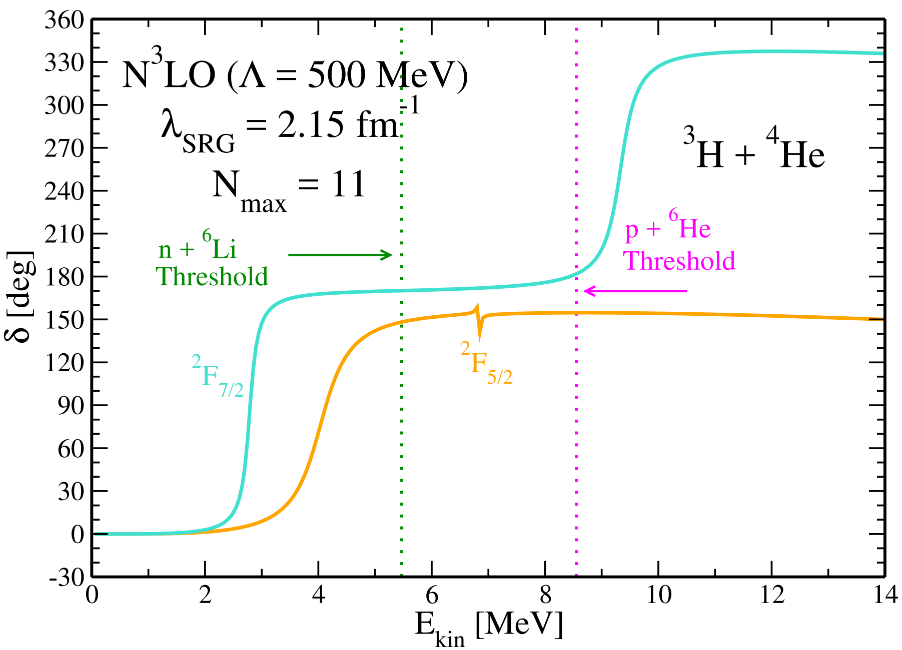


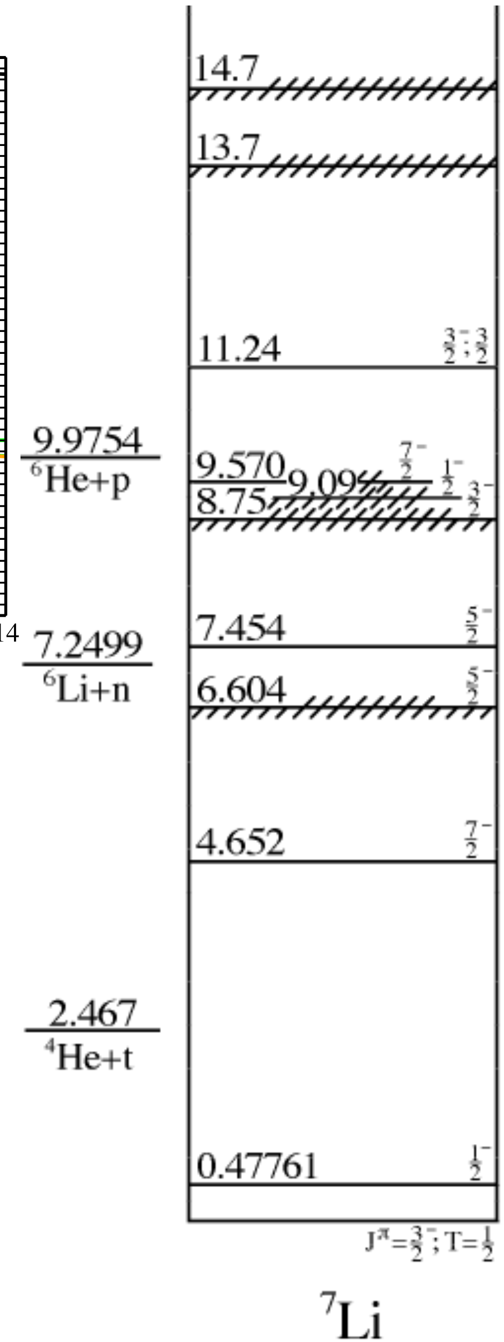


^{7}Li – New negative-parity states

7 new T=1/2 resonances

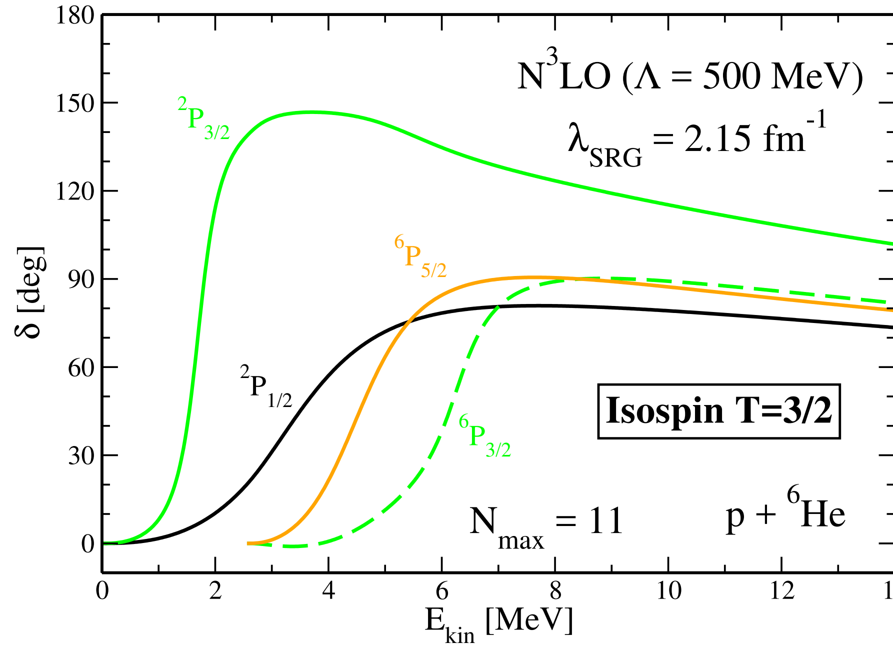


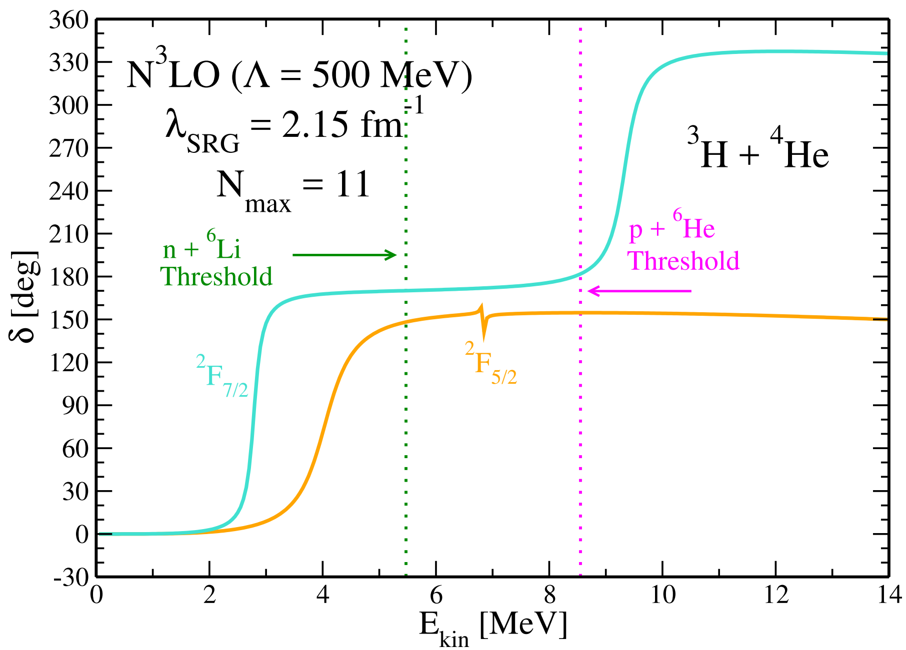


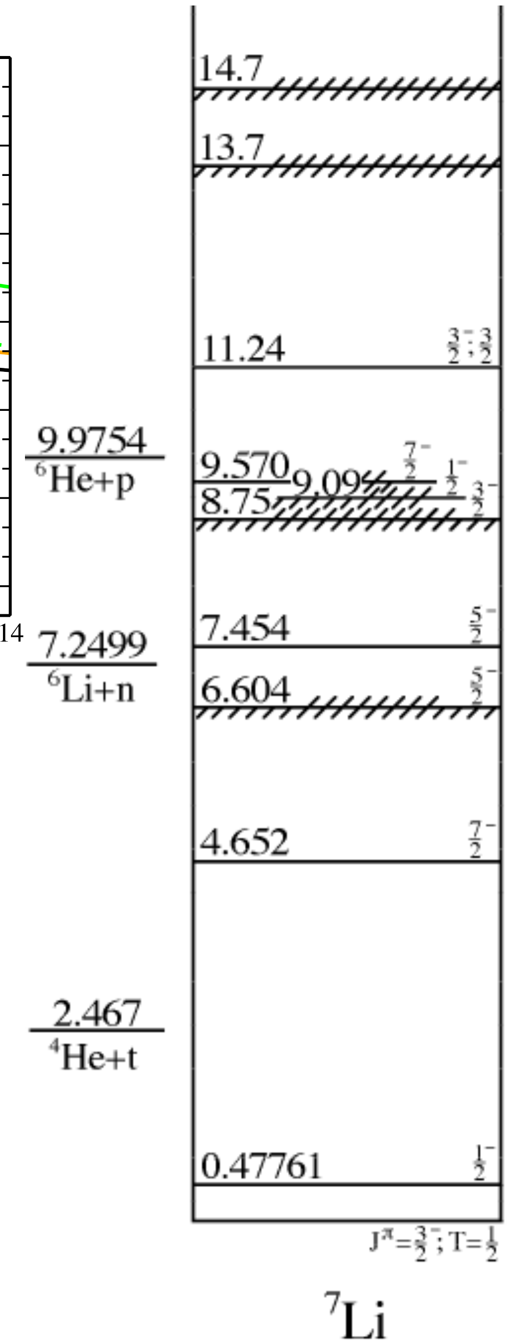


^{7}Li – New negative-parity states

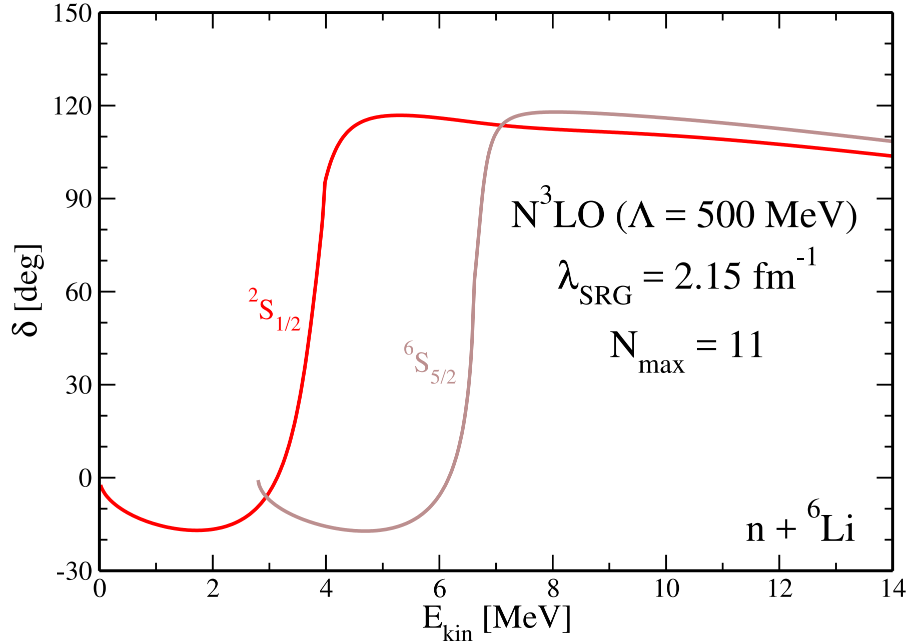
3 new T=3/2 resonances

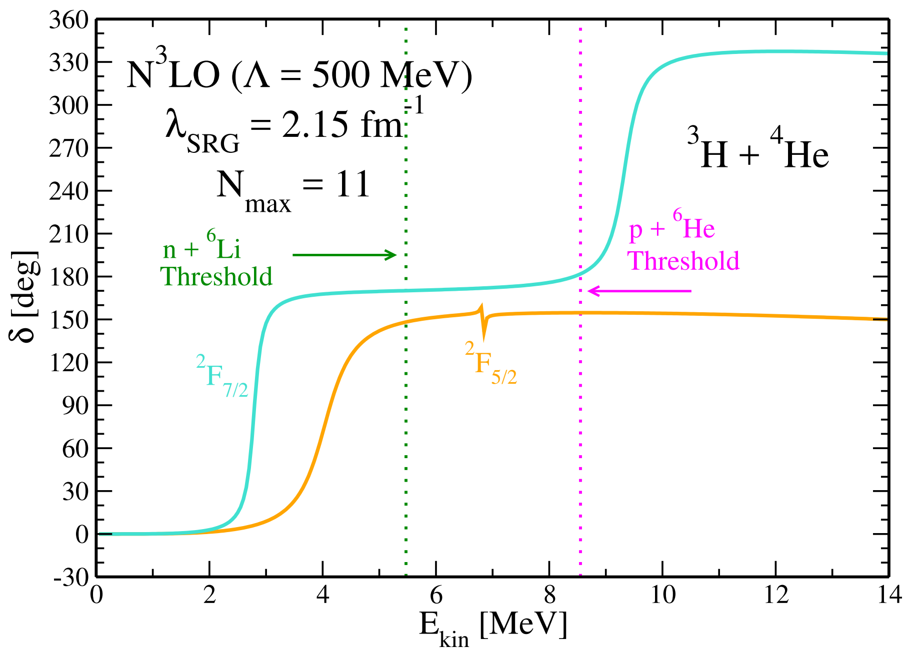


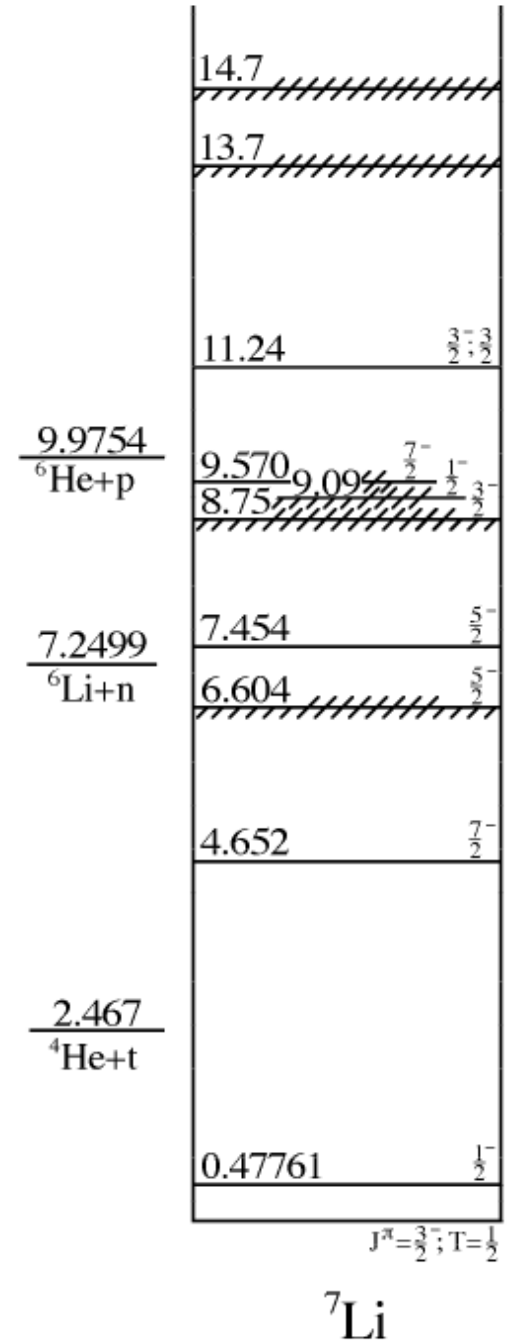




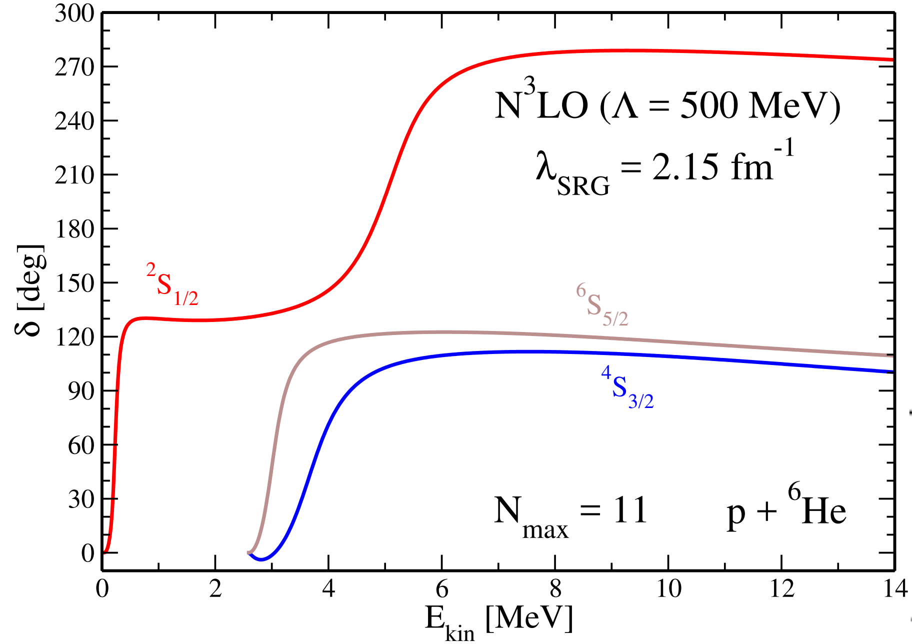
^{7}Li – New positive-parity states

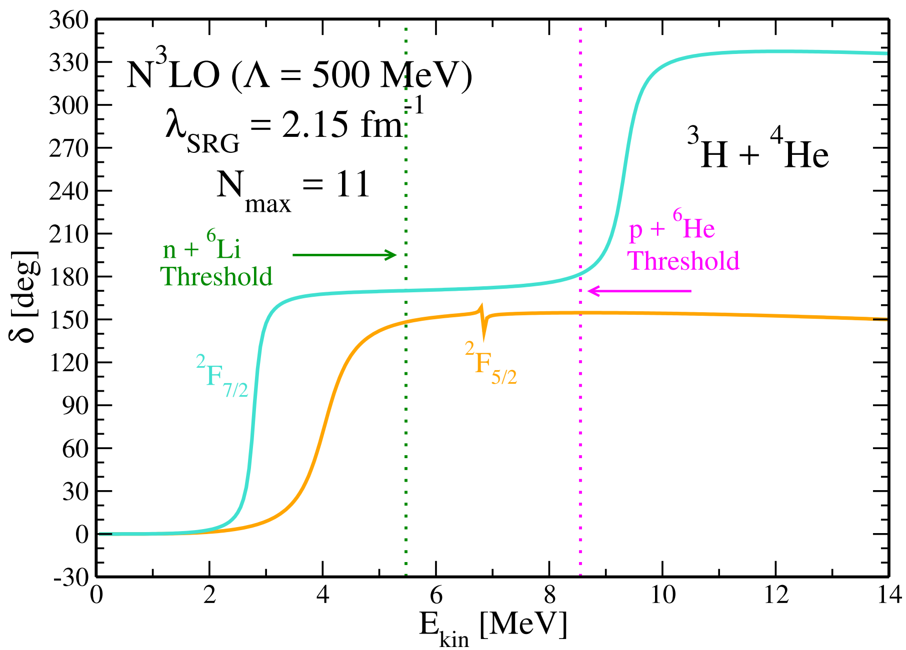


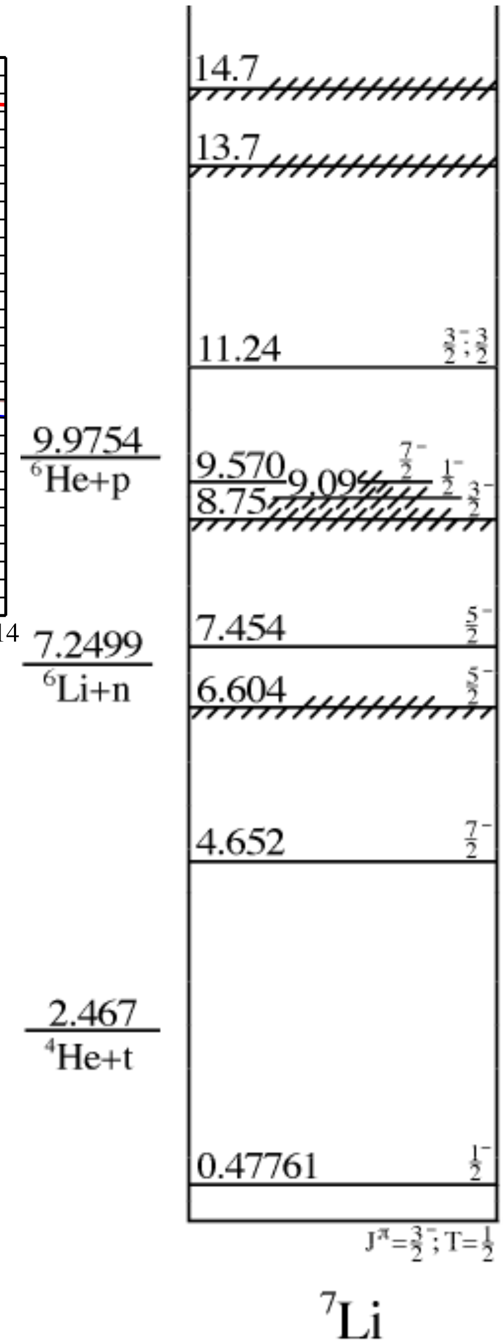




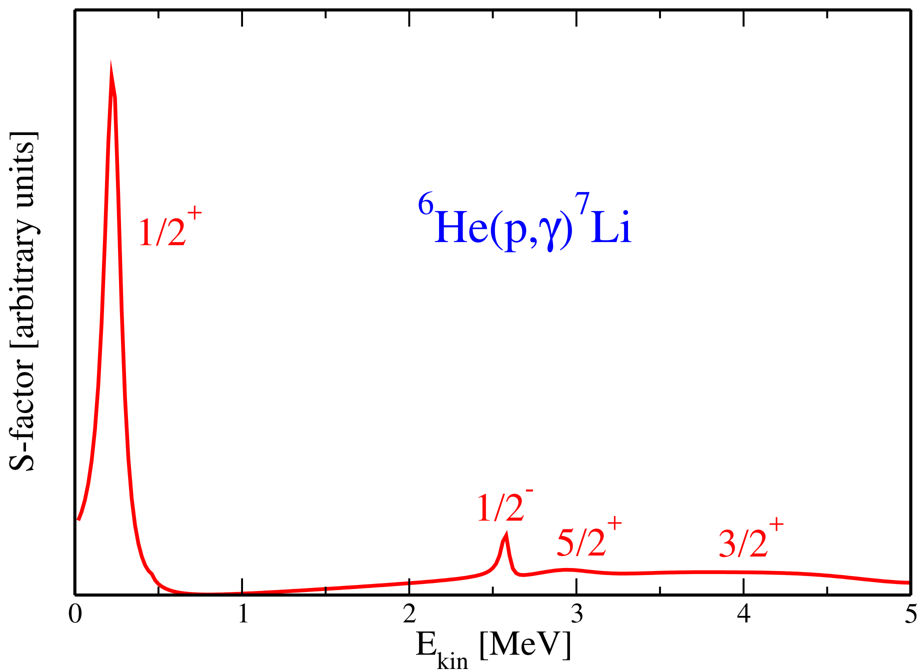
^{7}Li – New positive-parity states







S-factors

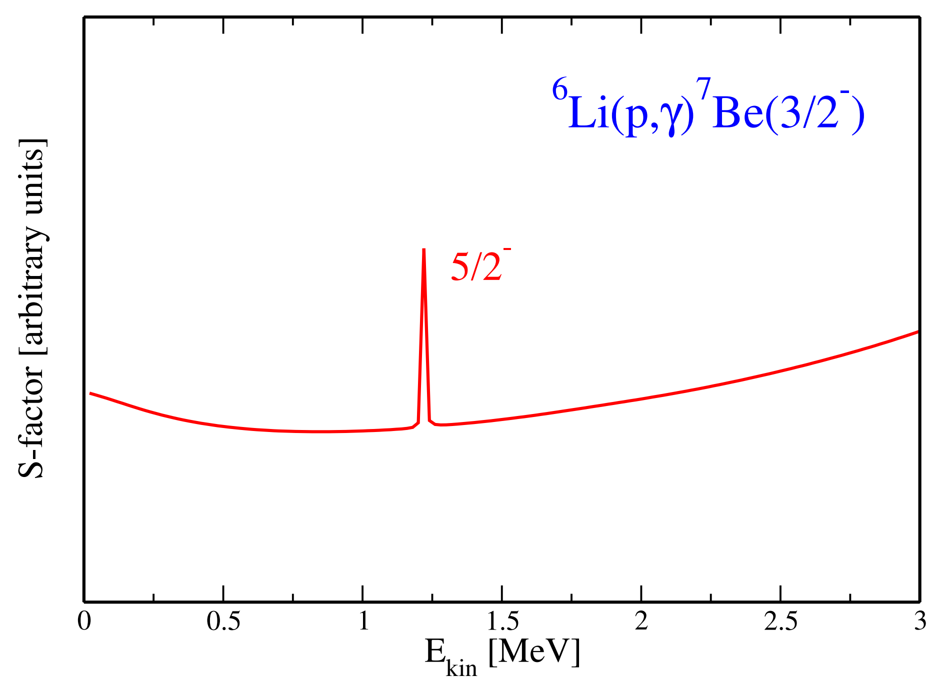


Cross section and S-factor

$$\sigma(E) = S(E)E^{-1}\exp[-2\pi\eta(E)]$$

Sommerfeld parameter

$$\eta(E) = \frac{Z_1 Z_2 e^2}{\hbar v}$$



2.

Microscopic optical potentials for intermediate energies

Motivation

1. Facility for Antiprotons and Ion Research (FAIR) is currently under construction and experiments on antiproton scattering off nuclear targets will probably experience a renaissance

2. A new $\bar{\mathrm{N}}\mathrm{N}$ chiral interaction has been recently derived up to N^3LO in the chiral expansion scheme
   ➡ Dai, Haidenbauer, Meißner, JHEP **2017**, 78 (2017)

Purpose: Construction of a microscopic Optical Potential (OP) for antiproton elastic scattering off nuclei

➡ No fitting to $\mathrm{N}(\bar{\mathrm{N}})$ - nucleus elastic scattering data

➡ More predictive power where experimental data do not exist

Method: Extension of the Watson multiple scattering theory to antiproton-nucleus scattering

Statement of the problem

Lippmann-Schwinger (LS) equation for the projectile-nucleus transition amplitude

$$T = V + VG_0(E)T$$

All two particle interactions

$$V = \sum_{i=1}^{A} v_{0i}$$

Green function propagator

$$G_0(E) = (E - H_0 + i\epsilon)^{-1}$$

where

$$H_0 = h_0 + H_A$$

h_0 kinetic term of the projectile

$$H_A |\Phi_A\rangle = E_A |\Phi_A\rangle$$

target Hamiltonian

Statement of the problem

Lippmann-Schwinger (LS) equation for the projectile-nucleus transition amplitude

$$T = V + VG_0(E)T$$

Let's introduce the optical potential U

$$T = U + UG_0(E)PT$$

$$U = V + VG_0(E)QU$$

Projection operators

$$P + Q = 1$$

$$[G_0, P] = 0$$

In the case of elastic scattering,

P projects onto the elastic channel

$$P = \frac{|\Phi_A\rangle\langle\Phi_A|}{\langle\Phi_A|\Phi_A\rangle}$$

Statement of the problem

Lippmann-Schwinger (LS) equation for the projectile-nucleus transition amplitude

$$T = V + VG_0(E)T$$

Transition amplitude *T* for elastic scattering

$$T_{\rm el} \equiv PTP = PUP + PUPG_0(E)T_{\rm el}$$

we need to calculate *PUP*

Statement of the problem

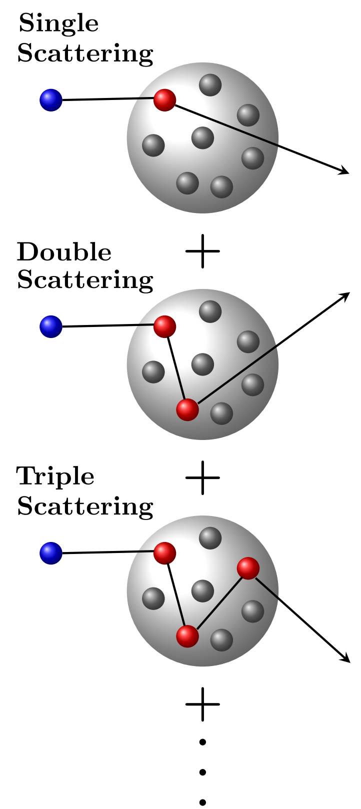
Lippmann-Schwinger (LS) equation for the projectile-nucleus elastic transition amplitude

$$T_{\rm el} = PUP + PUPG_0(E)T_{\rm el}$$

Spectator expansion for U

Chinn, Elster, Thaler, Weppner, PRC **52,** 1992 (1995)

$$U = \sum_{i=1}^{A} \tau_i + \sum_{i,j\neq i}^{A} \tau_{ij} + \sum_{i,j\neq i,k\neq i,j}^{A} \tau_{ijk} + \cdots$$



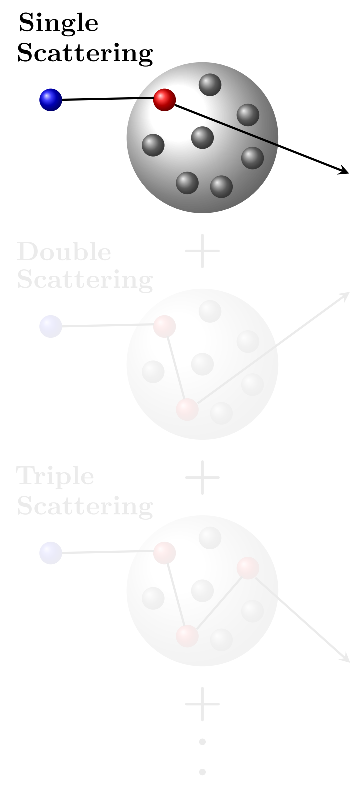
Single scattering approximation

Lippmann-Schwinger (LS) equation for the projectile-nucleus elastic transition amplitude

$$T_{\rm el} = PUP + PUPG_0(E)T_{\rm el}$$

Spectator expansion for U

Chinn, Elster, Thaler, Weppner, PRC **52,** 1992 (1995)



Single scattering approximation

$$U = \sum_{i=1}^{A} \tau_i + \sum_{i,j\neq i}^{A} \tau_{ij} + \sum_{i,j\neq i,k\neq i,j}^{A} \tau_{ijk} + \cdots$$

Impulse approximation

Lippmann-Schwinger (LS) equation for the projectile-nucleus elastic transition amplitude

$$T_{\rm el} = PUP + PUPG_0(E)T_{\rm el}$$

Spectator expansion for U

Chinn, Elster, Thaler, Weppner, PRC **52,** 1992 (1995)

$$\tau_i \approx t_{0i}$$

Impulse approximation

$$U = \sum_{i=1}^{A} t_{0i} \quad \begin{cases} t_{0i} = v_{0i} + v_{0i} g_i t_{0i} \\ g_i = \dfrac{1}{E - h_0 - h_i + i\epsilon} \end{cases}$$

The interaction between the projectile and the target nucleon is considered as free

The first-order optical potential

$$U(\alpha, \boldsymbol{q}, \boldsymbol{K}; E) = \sum_{N=n,p} \int d^3\boldsymbol{P}\, \eta(\boldsymbol{P}, \boldsymbol{q}, \boldsymbol{K})\, t_{\alpha N}\left[\boldsymbol{q}, \frac{1}{2}\left(\frac{A+1}{A}\boldsymbol{K} - \boldsymbol{P}\right); E\right]$$
$$\times \rho_N\left(\boldsymbol{P} - \frac{A-1}{2A}\boldsymbol{q}, \boldsymbol{P} + \frac{A-1}{2A}\boldsymbol{q}\right)$$

$$\boldsymbol{q} = \boldsymbol{k}' - \boldsymbol{k}$$
$$\boldsymbol{K} = \frac{1}{2}(\boldsymbol{k}' + \boldsymbol{k})$$

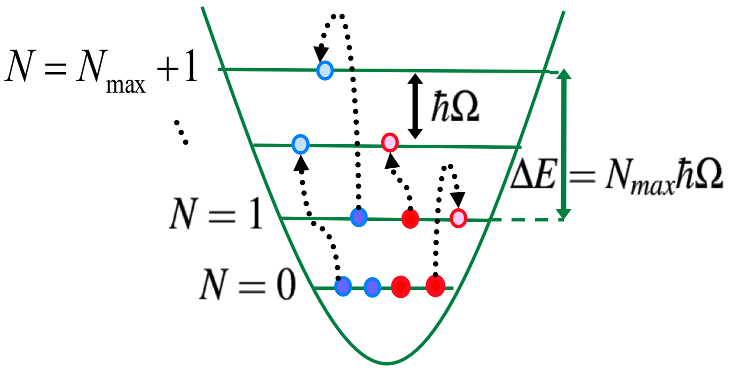
Basic ingredients

- (Anti)nucleon-nucleon scattering matrix $t_{\alpha N}$
- Non-local nuclear densities

Projectiles
$$\alpha = (p, n, \bar{p})$$

$$\rho_{\text{op}} = \sum_{i=1}^{A} \delta(\boldsymbol{r} - \boldsymbol{r}_i)\delta(\boldsymbol{r}' - \boldsymbol{r}'_i)$$

The matrix elements between a general initial and final state are obtained from the NCSM
PRC **97**, 034619 (2018)



Chiral interaction

- Target density

  NN - N^{4}LO500   Entem, Machleidt, Nosyk, PRC **96** 024004 (2017)

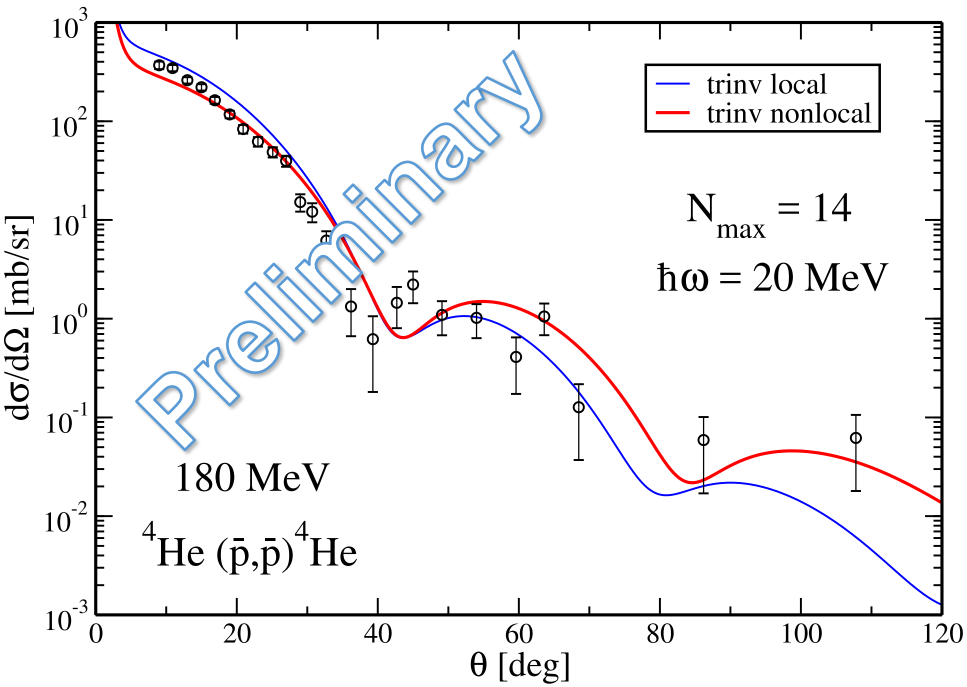
  \+ 3N - N^{2}LO   Navratil, Few-Body Syst. **41** 117 (2007)

- Scattering matrix

  $\bar{\mathrm{N}}\mathrm{N}$ – N^{3}LO   Dai, Haidenbauer, Meißner, JHEP **2017**, 78 (2017)

  - Local regulator for the long range part: $R = 0.9$ fm
  - Non-local regulator for the contact terms: $\Lambda = 2\,R^{-1}$
  - The $\bar{\mathrm{N}}\mathrm{N}$ interaction is connected to the NN one through the G-parity in an unambiguous way

Scattering observables



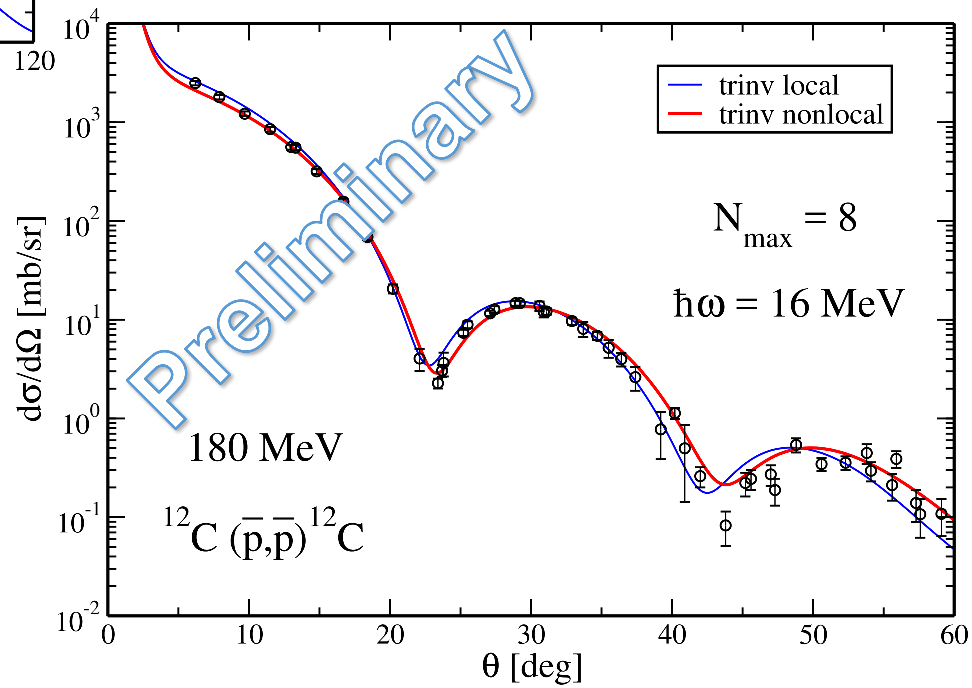
Experimental data are from the LEAR collaboration at CERN

Factorized optical potential

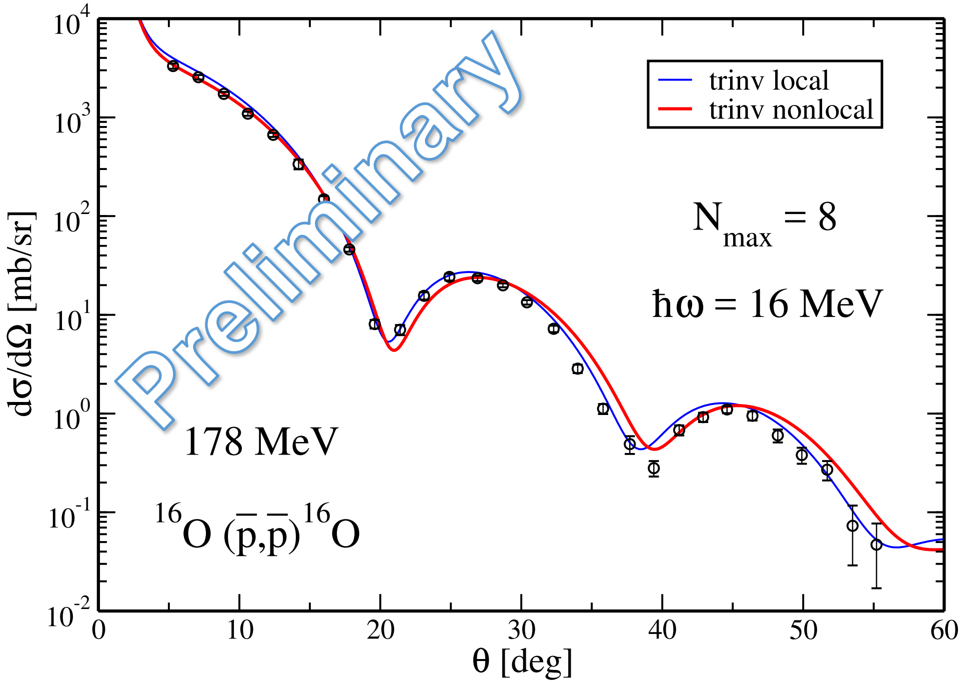
$$U(\boldsymbol{q},\boldsymbol{K};E) \sim \sum_{\alpha=n,p} t_{p\alpha}\left[\boldsymbol{q},\frac{A+1}{2A}\boldsymbol{K};E\right]\rho_\alpha(q)$$

FF from local density

$$\rho_\alpha(q) = 4\pi\int_0^\infty drr^2 j_0(qr)\rho_\alpha(r)$$



Scattering observables



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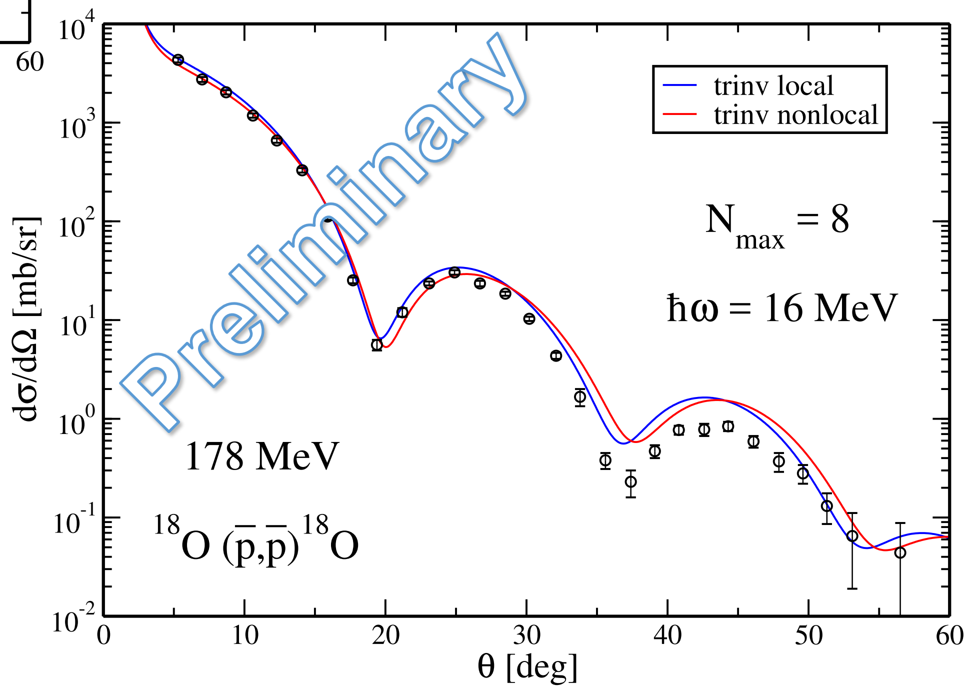
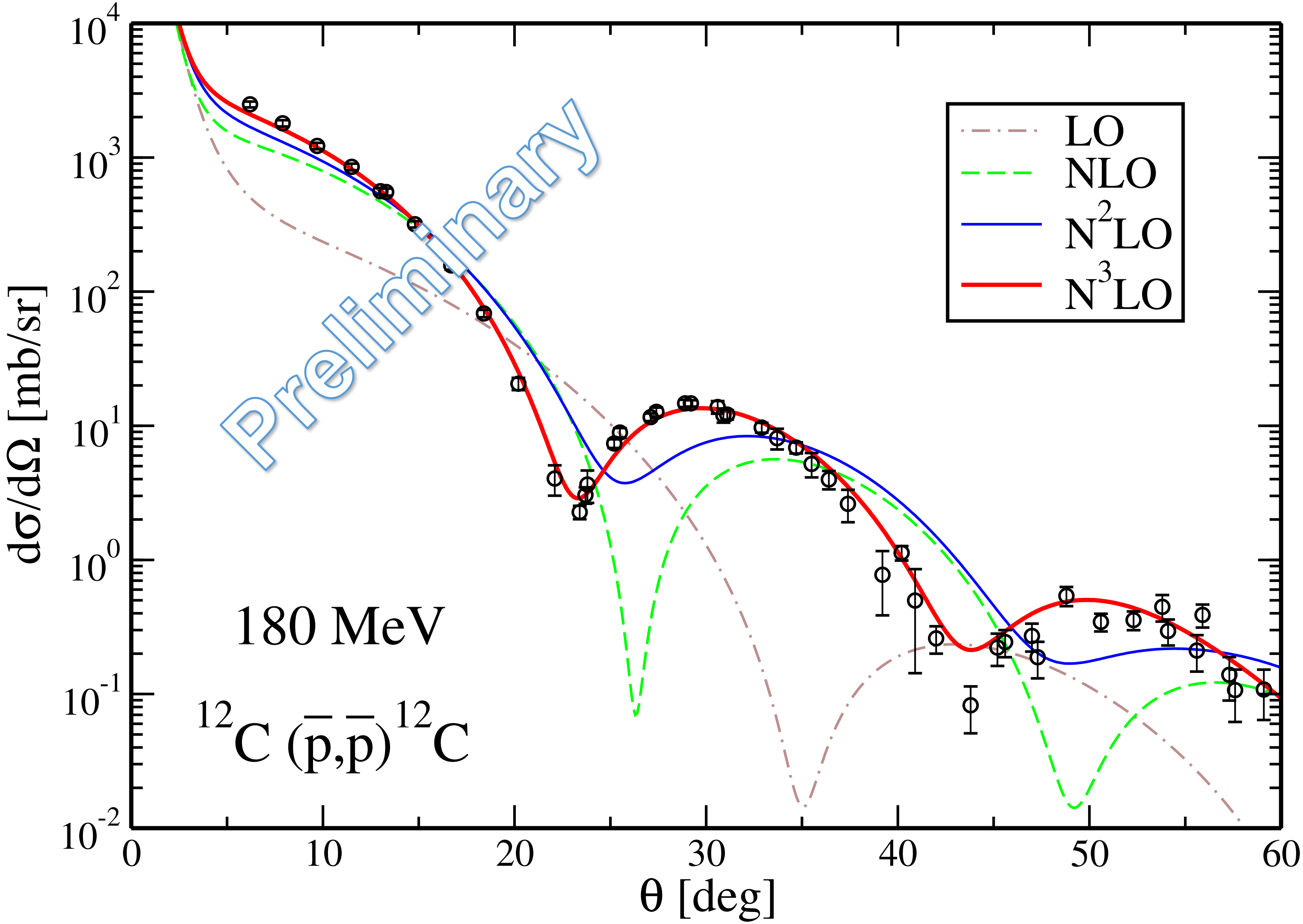


Scattering observables



Summary & Outlook

- Reproduction of the experimental spectrum of ^{7}Be and ^{7}Li
- Predictions for possible new resonant states (π=+,–)

  ➡ Coupling between different mass partitions

  ➡ Inclusion of the 3N force

- Good description of the data with the microscopic OP

  ➡ Inclusion of the 3N force in NA scattering

  ➡ Inclusion of medium effects

- Importance of $\bar{\mathrm{N}}\mathrm{NN}$ force