R-matrix analysis of reactions in the ^{9}B compound system

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The ^{7}Li problem

Calculations of the abundance of ^{7}Li overestimate the value extracted from observations supposed to be sufficiently understood to isolate the primordial ^{7}Li component. The discrepancy with this observation by a factor of $2.2 \to 4.2$ corresponds to a deviation of $4.5\sigma \to 5.5\sigma$, a result that has only become more severe with time. It is essential to determine the nature of this discrepancy as big-bang nucleosynthesis (BBN) probes conditions of the very early universe and our understanding of physical laws relevant in an extreme environment.

Recent attention has focused on the role of reactions that destroy mass-7 nuclei at early times $\lesssim$ 1 s in the big-bang environment[1, 2]. The authors of Ref.[1], citing the TUNL-Nuclear Data Group (NDG) evaluation tables (below) conjecture that the putative $\frac{5}{2}^+$ resonance near 16.7 MeV may enhance the destruction of ^{7}Be through reactions like ^{7}Be(d,p)$\alpha\alpha$ and ^{7}Be(d,γ)^{9}B if the resonance parameters are within given ranges. These studies employ the Wigner limit to determine an upper bound on the contribution of resonances, particularly ^{9}B, to a resonant enhancement in reactions that destroy mass-7 nuclides, ^{7}Li in particular. Because there is a paucity of data in the region near the d+^{7}Be threshold where the assumed $\frac{5}{2}^+$ ^{9}B resonance inhabits, we wondered if the existing data may indicate the presence of such a resonance if a multichannel, unitary R-matrix evaluation is pursued.

Our motivation for the present study of the ^{9}B compound system is two-fold. The continuing light nuclear reaction program at Los Alamos National Laboratory, T-2 Theoretical Division provides light nuclear data for an array of end users, including the ENDF and ENSDF communities. Moreover, we are interested in updating the evaluation of the ^{9}B compound system to address the key question outlined above for BBN: does a resonance near the d+^{7}Be threshold cause an increase in the destruction of mass-7 nuclides in the early universe and possibly explain the ^{7}Li overprediciton problem?

TUNL NDG ^{9}B

E_x(MeV $\pm$ keV)	$J^\pi;T$	$\Gamma_{\rm cm}$(keV)
16.024 ± 25	$T = (\frac{1}{2})$	180 ± 16
16.710 ± 100	$(\frac{5}{2}^+);(\frac{1}{2})$	
17.076 ± 4	$\frac{1}{2}^-;\frac{3}{2}$	22 ± 5
17.190 ± 25		120 ± 40
17.540 ± 100	$(\frac{7}{2}^+);(\frac{1}{2})$	
17.637 ± 10		71 ± 8

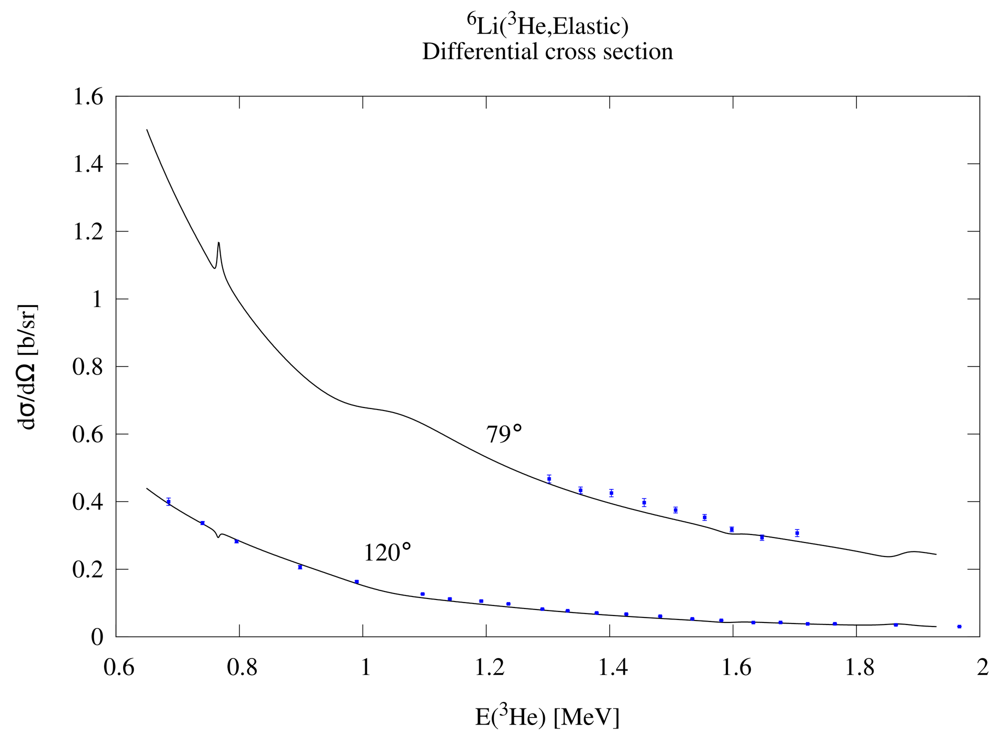
The R matrix formalism

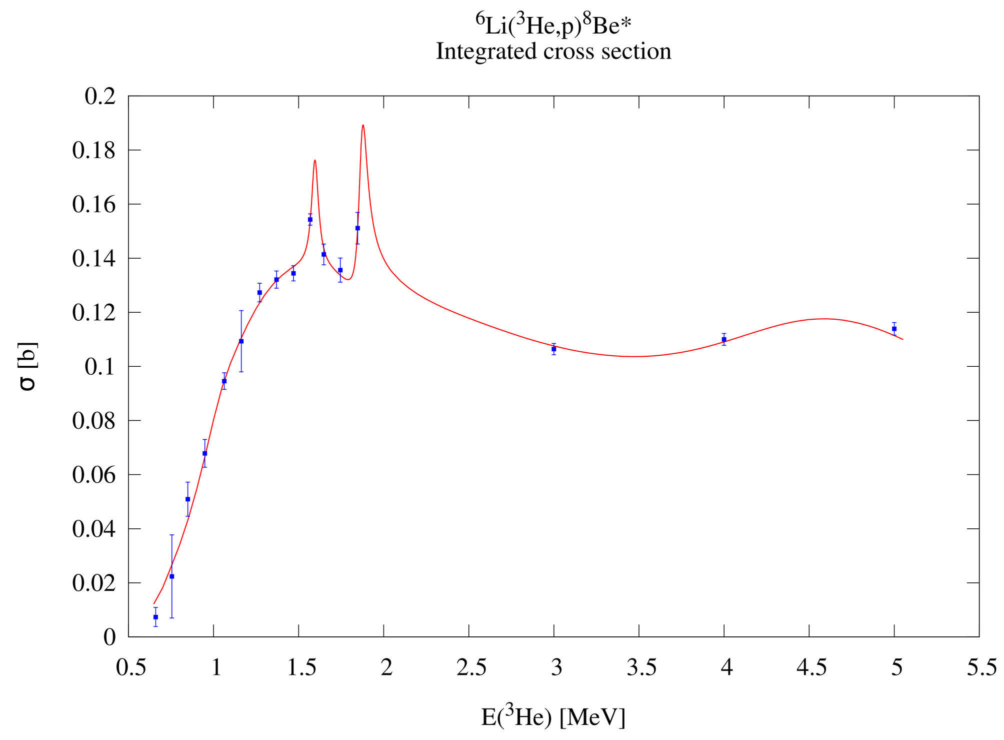
The R-matrix approach[3] is a unitary, multichannel parametrization that has proven useful for an array of nuclear reaction phenomenology, particularly for light nuclei[4].

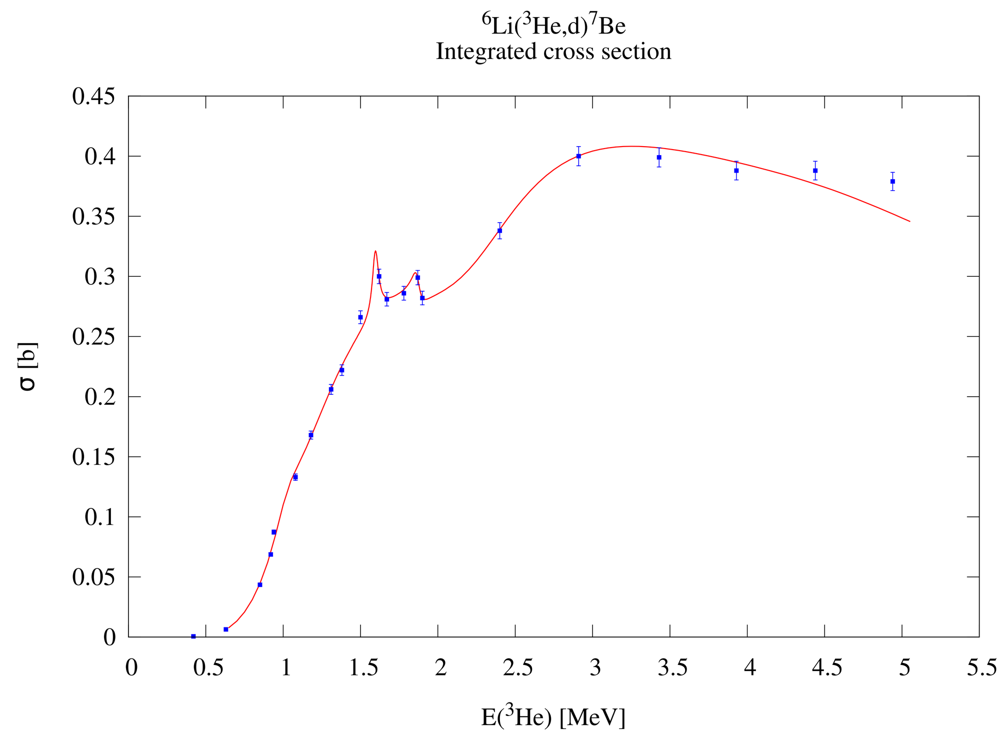
The R matrix is computed as the projection on channel surface functions, $|c)$ of the Green's function, $G_B = (H + \mathcal{L}_B - E)^{-1}$ where $\mathcal{L}_B$ is the Bloch operator, which accounts for the presence of a boundary condition, B on the channel surface.

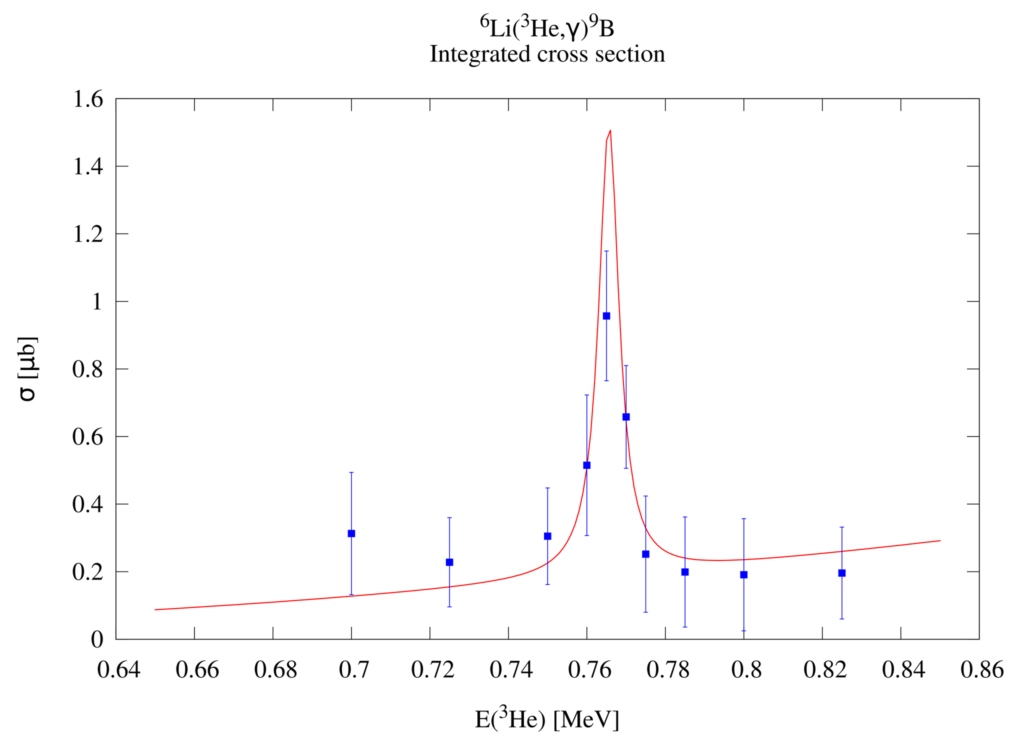
Analysis and results

We've included in the analysis the hadronic channels: d+^{7}Be partition with threshold of 16.5 MeV with up to D-waves, ^{3}He+^{6}Li at 16.6 MeV up to P-waves, and p+^{8}Be* at 16.7 MeV up to P-waves. The channel radii were constrained to lie in the range between 5.5 fm and 7.5 fm for these. The electromagnetic γ+^{9}B channels included were $E_1^{3/2}$, $M_1^{5/2}$, $M_1^{3/2}$, $M_1^{1/2}$, $E_1^{5/2}$, and $E_1^{1/2}$ with a channel radius of 50.0 fm.









References

[1] Cyburt and Pospelov. *Int.J.Mod.Phys.* E21 (2012), p. 1250004.

[2] Chakraborty, Fields, and Olive. *Phys.Rev.* D83 (2011), p. 063006.

[3] Wigner. *Phys.Rev.* 70 (1946), p. 15.

[4] Hale. *Nucl. Data Sh.* 109 (2008), p. 2812.

[5] Hale, Brown, and Jarmie. *Phys.Rev.Lett.* 59 (1987), p. 763.

[6] O'Malley et al. *Phys.Rev.* C84 (2011), p. 042801.

Resonance structure

The present R-matrix parametrization gives a resonance structure as presented in the table below. The resonance poles of the T matrix are determined by diagonalization of the complex "energy-level" matrix

$$\mathcal{E}_{\lambda'\lambda} = E_\lambda \delta_{\lambda'\lambda} - \sum_c \gamma_{c\lambda'}[L_c(E) - B_c]\gamma_{c\lambda},$$

where $L_c(E) = r_c(\partial\mathcal{O}/\partial r_c)\mathcal{O}^{-1}\big|_{r_c=a_c}$, $\mathcal{O}$ is the outgoing Coulomb wave function, and B_c is the boundary condition given at the channel radius, a_c. Details are given in Ref.[5].

The resonance structure shown in the table below differs significantly from that in the TUNL NDG table (at left). Possible reasons for the discrepancy include the fact that the current analysis is the first, to our knowledge, that includes much of the available data in the region below $E(^3\text{He})< 3.0$ MeV in a two-body unitary analysis. Several deductions about the resonance structure in the TUNL/ENSDF tables rely on associated production of ^{9}B experiments and single-level R-matrix parametrizations. While more data, particularly polarization observables, would constrain the current fit with greater confidence, the present analysis appears to be the most comprehensive available that accounts for the available data in a two-body unitary way.

Resonances from R matrix

E_x(MeV)	J^π	Γ(keV)	$E(^3\text{He})$	Strength
16.4754	$1/2^-$	768.46	-0.2054	weak
17.1132	$1/2^-$	0.14	0.7664	strong
17.2012	$5/2^-$	871.63	0.8984	weak
17.2809	$3/2^-$	147.78	1.0178	strong
17.6754	$5/2^+$	33.33	1.5947	strong
17.8462	$7/2^+$	2036.21	1.8509	weak
17.8577	$3/2^-$	42.52	1.8681	strong
18.0582	$3/2^+$	767.11	2.1689	weak
18.4229	$1/2^+$	5446.32	2.7309	weak
18.6872	$1/2^-$	10278.41	3.1124	weak
19.6192	$3/2^-$	1478.22	4.5104	weak

The ^{7}Li problem & ^{9}B

Returning the problem of the overprediction of ^{7}Li in current treatments of BBN, we see that the requirements for a near-threshold resonance of Refs.[1] and [2] are difficult to arrange given the resonance structure of table above. Both of these works require a narrow resonance, a few 10's of keV in width within 100 keV of the ^{3}He+^{6}Li (that is, 200 keV within the d+^{7}Be) threshold in order to explain the overproduction of ^{7}Li in BBN reaction network codes.

The current study does not conclusively eliminate the possibility of the mechanism of resonant enhancement of mass-7 destruction. The ^{9}B compound system was identified originally by Cyburt and Pospelov[1] as playing a potential role in the destruction of ^{7}Be precisely because there isn't much data in the region near the d+^{7}Bethreshold. Our analysis is performed on essentially the same data that the existent TUNL-NDG analyses a were performed, with the smallest energy probed about 400–500 keV above the ^{3}He+^{6}Li threshold. Recent data[6], not included in our analysis confirms our results.