R-matrix analysis of reactions in the $^9$B compound system applied to the $^7$Li problem in BBN

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Abstract. Recent activity in solving the ‘lithium problem’ in big bang nucleosynthesis has focused on the role that putative resonances may play in resonance-enhanced destruction of $^7$Li. Particular attention has been paid to the reactions involving the $^9$B compound nuclear system, $^d + ^7$Be $\rightarrow ^9$B. These reactions are analyzed via the multichannel, two-body unitary R-matrix method using the code EDA developed by Hale and collaborators. We employ much of the known elastic and reaction data, in a four-channel treatment. The data include elastic $^3$He $+ ^6$Li differential cross sections from 0.7 to 2.0 MeV, integrated reaction cross sections for energies from 0.7 to 5.0 MeV for $^6$Li($^3$He,p)$^8$Be$^*$ and from 0.4 to 5.0 MeV for the $^6$Li($^3$He,d)$^7$Be reaction. Capture data have been added to an earlier analysis with integrated cross section measurements from 0.7 to 0.825 MeV for $^6$Li($^3$He,$\gamma$)$^9$B. The resulting resonance parameters are compared with tabulated values, and previously unidentified resonances are noted. Our results show that there are no near $d + ^7$Be threshold resonances with widths that are 10's of keV and reduce the likelihood that a resonance-enhanced mass-7 destruction mechanism, as suggested in recently published work, can explain the $^7$Li problem.

1. Introduction

Calculations of the abundance of $^7$Li [1] overestimate the value extracted from observations of low-metallicity halo dwarf stars [2], where the stellar dynamics are supposed to be sufficiently understood to isolate the primordial $^7$Li component. The discrepancy with this (and others, including [3]) observation by a factor of 2.2 $\rightarrow$ 4.2 corresponds to a deviation of 4.5$\sigma$ $\rightarrow$ 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 $A = 7$ nuclei at early times $\lesssim 1$ s in the big-bang environment [4, 5]. The authors of Ref. [4], citing the TUNL-Nuclear Data Group (NDG) evaluation tables [6], (See Table 1) conjecture that the putative $^{5/2} +$ resonance near 16.7 MeV may enhance the destruction of $^7$Be through reactions like $^7$Be ($d$,$p$)$^{\alpha}$ and $^7$Be ($d$,$\gamma$)$^9$B if the resonance parameters are within given ranges. These studies employ approximations 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 $^{5/2} +$ $^9$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.
Table 1. The TUNL-NDG/ENSDF resonances in the $^9$B compound nuclear system [6] for resonances that are low-lying with respect to the d-$^7$Be threshold, which occurs at 16.4901 MeV.

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 overprediction problem?

2. The $R$-matrix formalism and EDA code
The $R$-matrix approach [7, 8, 9] is a unitary, multichannel parametrization that has proven useful for an array of nuclear reaction phenomenology, particularly for light nuclei. The reader is referred to the literature for details [10]. It is implemented in the EDA (Energy Dependent Analysis) code developed by Hale and collaborators [11]. The available two-body scattering and reaction data is described by minimization of the $\chi^2$ function with respect to variation of the $R$-matrix parameters $E_\lambda$ and $\gamma_{\lambda c}$.

3. Analysis and results
The $R$-matrix configuration, constructed for input into the EDA code, is given in terms of the included channel partitions (pairs), the $LS$ terms for each partition, and the channel radii and boundary conditions, $B_c$ for each channel.

We have 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 $\gamma$+$^9$B channels included were $E_{3/2}$, $M_{5/2}$, $M_{3/2}$, $E_{1/2}$, and $E_{5/2}$ with a channel radius of 50.0 fm.

The $^9$B analysis is based upon data gathered from the literature. (See Ref. [12] for details.)

Using about 40 parameters, the results of the $\chi^2$ minimization result in a $T$ matrix which gives the solid curves appearing in Figs[1][4], plotted along with the data obtained from references cited in the paragraphs above. The fit quality is fair with $\chi^2$/datum of 1.91, 0.55, 2.38, and 0.37 for Figs[1][4] respectively. The fit to the capture data, Fig[4] has been folded with a Gaussian acceptance function whose width is 5 keV to match the quoted energy resolution in Ref. [16].

The present $R$-matrix parametrization gives a resonance structure as presented in Table 2.

The resonance poles of the $T$ matrix are determined by diagonalization of the complex “energy-level” matrix

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

where $L_c(E) = r_c(\partial O/\partial r_c)O^{-1}|_{r_c=a_c}$, $O$ 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. [17].
threshold in the center-of-mass. The column labeled $E$ restates the real part of the resonance pole position relative the ground state of $^7$He. The spin-parity is given in the second column. The width $\Gamma$ is the center-of-mass width in keV. The 'Strength' function is the ratio of the sum of the channel widths (defined in Ref. [17]) divided by the total width, $\Gamma^{-1}\sum_i\Gamma_i$. Resonances labeled ‘strong’ are clearly seen in at least one of the figures. The resonance structure shown in Table 2 differs significantly from that in Table 1.

The first column of Table 2 gives the real part of the pole position, $E_0 = E_r - i\Gamma/2$, where $E_0$ is one of the eigenvalues of the energy-level matrix, Eq.(1) relative the ground state of $^9$B. The spin-parity is given in the second column. The width $\Gamma$ is the center-of-mass width in keV. The following column restates the real part of the resonance pole position relative the $^3$He + $^6$Li threshold in the center-of-mass. The column labeled $E(3\text{He})$ is the corresponding lab energy. The ‘Strength’ function is the ratio of the sum of the channel widths (defined in Ref. [17]) divided by the total width, $\Gamma^{-1}\sum_i\Gamma_i$. Resonances labeled ‘strong’ are clearly seen in at least one of the figures. The resonance structure shown in Table 2 differs significantly from that in Table 1.

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. [4] and [5] are difficult to arrange given the resonance structure of Table 2. Both of these works require a narrow resonance, a few 10’s of keV in width with a 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 [1].

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**Figure 1.** (a) Elastic scattering data from [13] plotted against the $R$-matrix fit (solid curve) for center-of-mass differential cross section vs. $^3$He lab energy.

**Figure 2.** Reaction data from [14], integrated cross section vs. $^3$He lab energy.

| $E_x$(MeV) | $J^\pi$ | $\Gamma$(keV) | $\text{Re}E_0$(MeV) | $\text{Im}E_0$(keV) | $E(3\text{He})$(MeV) | Strength |
|-----------|--------|---------------|----------------------|---------------------|-----------------------|----------|
| 16.4754   | $1/2^-$| 768.46        | -0.1369              | -384.2              | -0.2054               | 0.06 weak |
| 17.1132   | $1/2^-$| 0.14          | 0.5109               | -0.07               | 0.7664                | 1.00 strong |
| 17.2012   | $5/2^-$| 871.63        | 0.5989               | -435.8              | 0.8984                | 0.40 weak |
| 17.2809   | $3/2^-$| 147.78        | 0.6785               | -73.9               | 1.0178                | 0.77 strong |
| 17.6754   | $5/2^+$| 33.33         | 1.0631               | -16.7               | 1.5947                | 0.98 strong |
| 17.8462   | $7/2^+$| 2036.21       | 1.2339               | -1018.1             | 1.8509                | 0.15 weak |
| 17.8577   | $3/2^-$| 42.52         | 1.2454               | -21.3               | 1.8681                | 0.97 strong |
| 18.0582   | $3/2^+$| 767.11        | 1.4459               | -383.6              | 2.1689                | 0.54 weak |
| 18.4229   | $1/2^+$| 5446.32       | 1.8206               | -2723.2             | 2.7309                | 0.03 weak |
| 18.6872   | $1/2^-$| 10278.41      | 2.0749               | -5139.2             | 3.1124                | 0.15 weak |
| 19.6192   | $3/2^-$| 1478.22       | 3.0069               | -739.1              | 4.5104                | 0.52 weak |
4. Summary and findings

We’ve studied a possible resonant enhancement of the destruction of mass-7 ($^7$Be, in particular) in BBN scenarios. The near threshold, narrow state anticipated in Refs. [4] and [5] appear not to be supported by our multichannel, two-body unitary $R$-matrix analysis.

Our analysis determines a resonance structure significantly different from that published in the TUNL-NDG/ENSDF compilation [6], as can be seen by comparing the results from the present analysis in Table 2 with the table, Table 1 for the TUNL-NDG/ENSDF analysis.

Our findings for the role of a putative resonance in $^9$B near the d+$^7$Be threshold as envisioned in Refs. [4] and [5] is that their particular mechanism of resonant enhancement of mass-7 destruction is an unlikely explanation to the $^7$Li problem in BBN, though low-energy data would allow a more conclusive statement of this finding or its converse.

This work was carried out under the auspices of the National Nuclear Security Administration.

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