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ScienceDirect

Nuclear Data Sheets 120 (2014) 184–187

Nuclear Data Sheets

www.elsevier.com/locate/nds

R-matrix Analysis of Reactions in the ^{9}B Compound System

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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→^{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,γ)^{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.

I. 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 astrophysics are supposed to be sufficiently understood to isolate the primordial ^{7}Li component. The ratio of the predicted ^{7}Li abundance to that observed [2, 3] is in the range $2.2-4.2$, which corresponds to a deviation of $4.5\sigma - 5.5\sigma$, 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 I.) 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 [10] 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 is located, 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?

II. THE R-MATRIX FORMALISM AND EDA CODE

The R-matrix approach [7–9] is a unitary, multichannel parametrization that has proven useful for an array of nuclear reaction phenomenology, particularly for light nuclei [11]. We give only a brief description here and refer to the literature for a more complete description [12, 13].

We consider only $2 \to 2$ body scattering and reaction processes for light nuclear systems. Configuration space is partitioned into an interior, strongly interacting region and an exterior, Coulomb or non-polarizing interaction region by giving a channel radius, a_c for each two-body channel. The boundary of separation of these regions is

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http://dx.doi.org/10.1016/j.nds.2014.07.041

TABLE I. 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.

E_x(MeV $\pm$ keV)	$J^\pi; T$	$\Gamma_{\rm cm}$(keV)	Decay
16.024 ± 25	$T = (\frac{1}{2})$	180 ± 16	
16.71 ± 100	$(\frac{5}{2}^+); (\frac{1}{2})$		
17.076 ± 4	$\frac{1}{2}^-; \frac{3}{2}$	22 ± 5	(γ,^{3}He)
17.190 ± 25		120 ± 40	p, d, ^{3}He
17.54 ± 100	$(\frac{7}{2}^+);(\frac{1}{2})$		
17.637 ± 10		71 ± 8	p, d, ^{3}He, α

the channel surface, $\mathcal{S} = \sum_c \mathcal{S}_c$.

The R matrix is computed as the projection on channel surface functions, $|c)$ of the Green's function, $G_B = (H + \mathcal{L}_B - E)^{-1}$

$$R_{c'c} = (c'|[H + \mathcal{L}_B - E]^{-1}|c) = \sum_\lambda \frac{(c'|\lambda)(\lambda|c)}{E_\lambda - E}, \tag{1}$$

where $\mathcal{L}_B$ is the Bloch operator, which accounts for the presence of a boundary condition, B on the channel surface. The Bloch operator ensures that the operator $H + \mathcal{L}_B$ is a compact, Hermitian operator having a real, discrete spectrum. The R-matrix parameters, E_λ and $\gamma_{\lambda c} = (c\,|\lambda)$ describe the spectrum and residues of the resolvent operator; they are treated as parameters adjusted to fit the observed data. Both hadronic and electromagnetic (*ie.* γ+^{9}B) channels can be handled in this approach. The transition matrix, $\mathbf{T}$ the square of which gives the observables (cross section, etc.) of the theory, is given as

$$\mathbf{T} = \rho^{1/2}\mathbf{O}^{-1}\mathbf{R}_L\mathbf{O}^{-1}\rho^{1/2} - \mathbf{F}\mathbf{O}^{-1}, \tag{2}$$

where $\mathbf{R}_L = (\mathbf{R}^{-1} - \mathbf{L} + \mathbf{B})^{-1}$, $\mathbf{L} = \rho\mathbf{O}'\mathbf{O}^{-1}$, and $\mathbf{F} = \mathrm{Im}\ \mathbf{O}$, where $\mathbf{O}$ is the diagonal matrix of outgoing (Coulomb) wave functions in the exterior region.

The R-matrix approach 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 χ^2 function with respect to variation of the R-matrix parameters E_λ and $\gamma_{\lambda c}$.

III. 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 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.

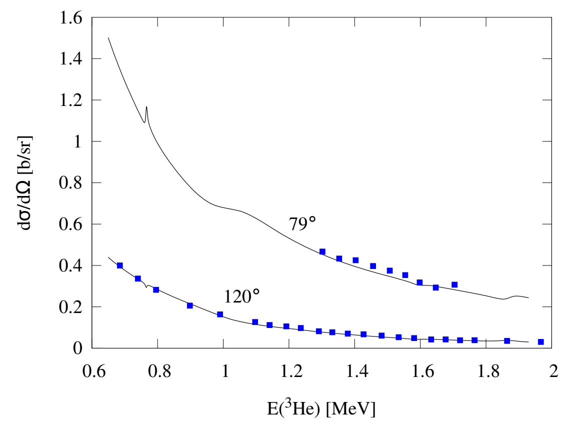

FIG. 1. Elastic differential cross section scattering data for ^{6}Li(^{3}He,^{3}He)^{6}Li at two lab angles from Ref.[15] plotted against the R-matrix fit (solid curve) for center-of-mass differential cross section vs. ^{3}He lab energy.

The ^{9}B analysis is based upon data gathered from the literature and stored in the EXFOR/CSISRS database [14]. We include 31 total elastic differential cross section data points at two lab angles (79° and 120°) for the ^{6}Li+^{3}He channel given in the range of ^{3}He lab energy, 1.30 MeV<E(^{3}He)<1.97 MeV [15]; 16 integrated cross section data points for ^{6}Li(^{3}He,p)^{8}Be* [16] where the final state channel is an average of the excited-states of the quasi-two-body final state of p+^{8}Be* given, in the range 0.66 MeV < E(^{3}He)< 5.00 MeV; 21 integrated cross section data points for the ^{6}Li(^{3}He,d)^{7}Be [17] in the range 0.42 MeV < E(^{3}He)< 4.94 MeV; and 10 capture data points from the ^{6}Li+^{3}He initial state in the energy range 0.7 MeV<E(^{3}He)< 0.825 MeV [18].

Using about 40 parameters, the results of the χ^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 χ^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. [18].

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

$$\mathcal{E}_{\lambda'\lambda} = E_\lambda\delta_{\lambda'\lambda} - \sum_c \gamma_{c\lambda'}[L_c(E) - B_c]\gamma_{c\lambda}, \tag{3}$$

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 condi-