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

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ND2013 Nuclear Data for Science and Technology

March 4-8, New York, NY

LA-UR-13-21473
Outline

- Motivation: ENDF/ENSDF evaluations, $^9\text{B}$ in BBN/$^7\text{Li}$ destruction
- R-matrix formalism: T-matrix/observables, EM channels, EDA code
- Summary of $^9\text{B}$ data: DCS, $\sigma$
- Analysis: $\chi^2/N_{\text{data}}$, resolution broadening
  - Used earlier 3-channel evaluation by G. Hale, added capture channel
- Resonance structure: implications for BBN
- Summary, findings & future work
Motivation

- Cross section evaluation & resonance structure
  
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<th>$E_x ,^a$ (MeV ± keV)</th>
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- Astrophysical applications
  - Big bang nucleosynthesis
    - Nuclear physics solution to $^7\text{Li}$ predicted overproduction problem? *(cf. Hoyle)*
    - Details next slide.

- Purpose within Los Alamos Nat. Lab programmatic
  - Continue the R-matrix program for various end-users
  - Ongoing/upcoming analysis releases: $^7\text{Be}$, $^{13}\text{C}$ *[G. Hale Tues. Session GA 2]*, $^{14}\text{C}$, $^{17}\text{O}$, ...
A nuclear physics solution to the BBN $^7$Li problem?

- **Primordial nucleosynthesis**
  - Probes early universe w/in standard model
  - Big-bang nucleosynthesis: $\text{D,}^4\text{He,}^7\text{Li}$ abundances
  - $\text{D,}^4\text{He}$ abundances agree with theo/expl uncertainties
  - At $\eta_{\text{wmap}}$ (CMB) $^7\text{Li}/H|_{\text{BBN}} \sim (2.2-4.2)^*^7\text{Li}/H|_{\text{halo}}$
  - Discrepancy $\sim 4.5-5.5\sigma$ → the “Li problem”

- **Resonant destruction $^7$Li (Hoyle-type solution)**
  - Prod. mass 7 “well understood”; destruction not
    - $^7\text{Be}(d,p)\alpha\alpha$ & $^7\text{Be}(d,\gamma)^9\text{B}$ resonant enhancement
    - Identify $^9\text{B}$ $E_{5/2^+}=16.7$ MeV $\approx E_{\text{thr}}(d+^7\text{Be})+200$ keV
      - *Near threshold*
    - $(E_r, \Gamma_d)=(170-220, 10-40)$ keV solve Li problem
  - Chakraborthy, Fields & Olive PRD83, 063006 (2011)
    - More general approach: A=8,9,10 & 11
    - Identify as possibly important: $^9\text{B,}^10\text{B,}^10\text{C}$
  - ‘Large’ widths
    - Both conclude “large channel radius” required

NB: both approaches assume validity of TUNL-NDG tables
R-matrix formalism

- R-matrix theory: unitary, multichannel parametrization of (not just resonance) data
- Interior/Exterior regions
  - Interior: strong interactions
  - Exterior: Coulomb/non-polarizing interactions
  - Channel surface
  \[ S_c : r_c = a_c \quad S = \sum_c S_c \]
- R-matrix elements
  - Projections on channel surface functions \( (r_c|c) \) of Green’s function
  \[ G_B = [H + \mathcal{L}_B - E]^{-1} \]
  - Boundary conditions
  \[ B_c = \frac{1}{u_c(a_c)} \frac{du_c}{dr_c} \bigg|_{r_c=a_c} \]
- E-M channels
  - Next slide
Electromagnetic channels

- **One-photon sector of Fock space**
  - Photon ‘wave function’
    \[ A_k(r) = \left( \frac{2}{\pi \hbar c} \right)^{1/2} \sum_{jm} i^j \sum_{\lambda',\lambda=e,m,0} Y_{jm}^{(\lambda')}(\hat{r}) u_j^{\lambda'}(r) Y_{jm}^{(\lambda)}(\hat{k}) \cdot \chi \]
  - Radial part
    \[ u_{ee} = -[f_j'(\rho) + t_{ee}^j h_j^+(\rho)] \quad u_{0e} = -\frac{\sqrt{j(j+1)}}{\rho} [f_j(\rho) + t_{e0}^j h_j^+(\rho)] \]
    \[ u_{mm}^j = [f_j(\rho) + t_{mm}^j h_j^+(\rho)] \quad u_{0m}^j = u_{me}^j = u_{em}^j = 0 \]
  - Photon channel surface functions
    \[ (r_c | c) = \left( \frac{\hbar c}{2\rho_\gamma} \right)^{1/2} \delta(r_\gamma - a_\gamma) \left[ \phi_{sv} \otimes Y_{jm}^{(e,m)}(\hat{r}_\gamma) \right]_{JM} \]
  - Photon ‘mass’: \( \hbar k_\gamma / c \)
  - R-matrix definition preserved
    \[ (c' | \psi) = \sum_c R_c^{B}_{c'} (c | \frac{\partial}{\partial r_c} r_c - B_c | \psi) \]

- **R-matrix**
  \[ T = \rho^{1/2} O^{-1} R_L O^{-1} \rho^{1/2} - FO^{-1} \]
  \[ R_L = [R_B^{-1} - L + B]^{-1} \]
  \[ L = \rho O'O^{-1} \]
  \[ F = \text{Im } O \]
Implementation in EDA

- **EDA = Energy Dependent Analysis**
  - Adjust $E_\lambda$ & $\gamma_{c\lambda}$

- **Any number of two-body channels**
  - Arbitrary spins, masses, charges (incl. mass zero)

- **Scattering observables**
  - Wolfenstein trace formalism

- **Data**
  - Normalization
  - Energy shifts
  - Energy resolution/spread

- **Fit solution**
  \[ \chi^2_{EDA} = \sum_i \left[ \frac{nX_i(p) - R_i}{\delta R_i} \right]^2 + \left[ \frac{nS - 1}{\delta S/S} \right]^2 \]

- **Covariance determined**
Summary of included $^9$B data

- $^6$Li+$^3$He elastic *Buzhinski et al., Izv. Rossiiskoi Akademii Nauk, Ser. Fiz., Vol. 43, p.158 (1979)*
  - Differential cross section
  - $1.30$ MeV < $E(^3$He) < $1.97$ MeV

- $^6$Li+$^3$He $\rightarrow$ p+$^8$Be* *Elwyn et al., Phys. Rev. C 22, 1406 (1980)*
  - Integrated cross section
  - Quasi-two-body, excited-state averaged final channel
  - $0.66$ MeV < $E(^3$He) < $5.00$ MeV

- $^6$Li+$^3$He $\rightarrow$ d+$^7$Be *D.W. Barr & J.S. Gilmore, unpublished (1965)*
  - Integrated cross section
  - $0.42$ MeV < $E(^3$He) < $4.94$ MeV

- $^6$Li+$^3$He $\rightarrow$ $\gamma$+$^9$B *Aleskic & Popic, Fizika 10, 273-278 (1978)*
  - Integrated cross section
  - $0.7$ MeV < $E(^3$He) < $0.825$ MeV
  - New to $^9$B analysis

Data for future evaluation
- Separate $^8$Be* states
  - $2^+$@200 keV [16.9 MeV], $1^+$@650 keV [17.6 MeV], $1^+$@1.1 MeV [18.2 MeV]
- n+$^8$B: $E_{\text{thresh}}(^3$He) = 3 MeV
- Simultaneous analysis with $^9$Be mirror system

All data from EXFOR/CSISRS database (in C4 format)
R-matrix configuration in EDA code

Hadronic channels (in blue, not included)

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<th>$p^8$Be$^{*+}(2)$</th>
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<td>0</td>
<td>$^{4}$S$_{3/2}$</td>
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<td>1</td>
<td>$^{4}$P$_{5/2,3/2,1/2}$</td>
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$E_{\text{thr}}$(CM, MeV) 16.6

Electromagnetic channel: $\gamma + ^9B \rightarrow E_1^{3/2}, M_1^{5/2}, M_1^{3/2}, M_1^{1/2}, E_1^{5/2}, E_1^{1/2}$

Full model space:
state number;
channel pair;
$LS; J; channel$
radius [fm]

1 1 4s 3/2 7.50000000f 20 1 4p 1/2 7.50000000f
2 1 4d 3/2 7.50000000f 21 1 2p 1/2 7.50000000f
3 1 2d 3/2 7.50000000f 22 2 4p 1/2 5.50000000f
4 2 4s 3/2 5.50000000f 23 3 2s 1/2 7.00000000f
5 3 6p 3/2 7.00000000f 24 4 M1 1/2 50.00000000f
6 3 4p 3/2 7.00000000f 25 1 4d 7/2 7.50000000f
7 3 2p 3/2 7.00000000f 26 3 6p 7/2 7.00000000f
8 4 E1 3/2 50.00000000f 27 1 4d 5/2 7.50000000f
9 1 4p 5/2 7.50000000f 28 1 2d 5/2 7.50000000f
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Analysis result: resonance structure

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S-matrix pole & residue  

Hale, Brown, Jarmie PRL 59 '87

\[
\mathcal{E}_{\lambda'\lambda} = E_\lambda \delta_{\lambda'\lambda} - \sum_c \gamma_{c\lambda'} [L_c(E) - B_c] \gamma_{c\lambda} \\
E_0 = E_r - i\Gamma/2 \quad \text{residue: } i\rho_0 \rho_0^T
\]

\[
\rho_{0c} = \left(\frac{2k_{0c}a_c}{N}\right)^{1/2} \mathcal{O}_c^{-1}(k_{0c}a_c) \sum_\lambda (\lambda|\mu_0)
\]

\[
N = \sum_{\lambda'\lambda}(\lambda|\mu_0)(\lambda'|\mu_0) \left[ \delta_{\lambda'\lambda} + \sum_c \gamma_{c\lambda'} \frac{\partial L_c}{\partial E} \bigg|_{E=E_0} \gamma_{c\lambda} \right]
\]

\[
L_c = r_c \frac{\partial \mathcal{O}_c}{\partial r_c} \mathcal{O}_c^{-1} \bigg|_{r_c=a_c}
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NB: no strong resonance seen

\(~100\text{ keV of } ^3\text{He}+^6\text{Li threshold}\)
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TUNL-NDG/ENSDF parameters

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NB: no strong resonance seen ~100 keV of $\text{^3He}+\text{^6Li}$ threshold

U N C L A S S I F I E D

Slide 11

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy’s NNSA
Observable fit: $^3$He+$^6$Li elastic DCS

$^6$Li($^3$He,Elastic)
Differential cross section

[$\chi^2/N_{data} = 1.91$]

$\frac{d\sigma}{d\Omega}$ [b/ster]

$E(^3$He) [MeV]

1/2$^-$ (.51 MeV, .14 keV)

3/2$^-$ (.68 MeV, 148 keV)

5/2$^+$ (1.1 MeV, 33 keV)

3/2$^-$ (1.2 MeV, 43 keV)

79°

120°

Room for improvement
Observable fit: $^6$Li($^3$He,p)$^8$Be* integrated x-sec

$^6$Li($^3$He,p)$^8$Be*
Integrated cross section

$\chi^2/N_{\text{data}} = 0.55$

$3/2^-$ (1.2 MeV, 43 keV)

$5/2^+$ (1.1 MeV, 33 keV)

$E(^3\text{He})$ [MeV]

$\sigma$ [b]
Observable fit: $^6\text{Li}(^3\text{He},d)^7\text{Be}$ integrated x-sec

$^6\text{Li}(^3\text{He},d)^7\text{Be}$
Integrated cross section

$\chi^2/N_{\text{data}} = 2.38$

$3/2^- (1.2 \text{ MeV}, 43 \text{ keV})$

$5/2^+ (1.1 \text{ MeV}, 33 \text{ keV})$
Observable fit: $^6$Li($^3$He,$\gamma$)$^9$B integrated x-sec

$^6$Li($^3$He,$\gamma$)$^9$B
Integrated cross section

$1/2^-(.51 \text{ MeV}, .14 \text{ keV})$ folded with Gaussian; width=5 keV

$\chi^2/N_{data} = 0.37$
Summary, findings & future work

- Nuclear physics/microphysics explanations for the “Li problem” have been entertained
  
- There are no resonances in $^9$B that reside within ~200 (~100) keV of the d+$^7$Be ($^3$He+$^6$Li) threshold with ‘large’ widths 10—40 keV
  
- This would appear to rule out scenarios considered by Cyburt & Pospelov (2009) and Chakraborty, Fields & Olive(2011) that low-lying, robust resonance in $^9$B could explain the “Li problem”
  
- It may be worth emphasizing that other nuclear physics explanations, such as insufficiently accurate and/or precise analyses of “known” nuclear reactions, may still be considered for the resolution of the “Li problem”
  
- While very useful, the TUNL-NDG/ENSDF tables may not be definitive; unitary analyses are req. and sometimes lacking; ***TO DO: submit new $^9$B analysis***

- **Need for dedicated, low-energy, high pol. facility**
  
- Improvements in the present analysis: more channels; incorporate p+$^8$Be* angular data; proper treatment three-body final states
Additional slides follow
 BBM reaction network (simplified)

1. $n \rightarrow p e n$
2. $n(p, \gamma)d$
3. $d(d, p)t$
4. $d(p, \gamma)^3He$
5. $d(d, n)^3He$
6. $^3He(n, p)t$
7. $t(d, n)^4He$
8. $d(d, \gamma)^4He$
9. $^3He(d, p)^4He$
10. $t(a, \gamma)^7Li$
11. $^4He(a, \gamma)^7Be$
12. $^7Be(n, p)^7Li$
13. $^7Be + d \rightarrow ^9B^*$
14. $^7Be + t \rightarrow ^{10}B^*$
15. $^7Be + ^3He \rightarrow ^{10}C^*$

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Figure 1
Simplified big bang nucleosynthesis nuclear network. Shown are 12 normally important reactions (blue) and 3 proposed test reactions (red).

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2.2. Light-Element Observations
Measuring the primordial abundance of any light element remains challenging. The BBN levels set at $z \sim 10^{10}$ are reliably accessible only in sites at $z \leq 3$ and often $z \sim 0$. Other nucleosynthesis processes have intervened, as evidenced by the nonzero metallicity of all known astrophysical systems. Thus, one seeks to measure light elements in the most metal-poor systems, then to obtain primordial abundances requires extrapolation to zero metallicity. The below discussion closely follows that of References 30–32.

2.2.1. Deuterium, $^3He$, and $^4He$.
Deuterium can be measured directly at high redshift. It is present in distant neutral hydrogen gas clouds, which are observed in absorption along sight lines to distant quasars. At present, there are seven systems with robust deuterium measurements (33–38). These lie around redshift $z \sim 3$ and have a metallicity that is $\sim 10^{-2}$ that of solar system material; thus, deuterium should be essentially primordial. For these systems, $D = (2.82 \pm 0.21) \times 10^{-5}$, where the error has been inflated by the reduced $\chi^2_{\nu} = 2.95$. www.annualreviews.org
Spite Plateau

- Measurement of primordial 7Li from low-metallicity halo dwarf stars

![Graph showing lithium abundances in selected metal-poor Galactic halo stars.](slide.png)

Figure 3

Lithium abundances in selected metal-poor Galactic halo stars. For each star, both lithium isotopes are plotted versus the star’s metallicity: \([\text{Fe/H}] = \log_{10} \left( \frac{\text{Fe/H}}{\text{Fe/H}_\odot} \right)\). Upper points show 7Li. The flatness of 7Li versus iron is known as the Spite plateau; it indicates that the bulk of the lithium is unrelated to Galactic nucleosynthesis processes and thus is primordial. The horizontal band gives the CMB + WMAP prediction; the gap between this prediction and the plateau illustrates the 7Li problem. Points below the Spite plateau show 6Li abundances; the apparent flatness of these points constitutes the 6Li problem. Curves show predictions of a Galactic cosmic-ray nucleosynthesis model. Points have been corrected for pre-main-sequence depletion. Abbreviation: CMB, cosmic microwave background. Reproduced from Reference 46 with permission.

Moreover, the Spite plateau level measures the primordial abundance. Thanks to the sustained effort of several groups (46, 48–56), a large sample of halo stars have measured lithium abundances. The dominant errors are systematic. A careful attempt to account for the full lithium error budget found \(\text{^{10}Li}/\text{H} = (1.23 \pm 0.68 - 0.32) \times 10^{-10}\), where the 95%-CL error budget is dominated by systematics (see also Section 3.1).

Finally, lithium has now been observed in stars in an accreted metal-poor dwarf galaxy. The Li/H abundances are consistent with the Spite plateau, indicating the plateau’s universality (58).

2.2.3. 6Li. Due to the isotope shift in atomic lines, 6Li and 7Li are in principle distinguishable spectroscopically. In practice, the isotopic splitting is several times smaller than the thermal broadening of stellar lithium lines. Nevertheless, the isotopic abundance remains encoded in the detailed shape of the lithium absorption profile. High–spectral resolution lithium measurements in halo stars attain the precision needed to observe isotope signatures. Some researchers have claimed to detect 6Li with isotopic ratios in the...