Resonance excitations in $^7\text{Be}(d,p)^8\text{Be}^*$ to address the cosmological lithium problem

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The cosmological lithium problem [1, 2] is a decades-old and yet unresolved problem in nuclear astrophysics. Recent revisits to the problem tried the avenue of resonance enhancement to account for higher excited states of $^7\text{Li}$ to address the cosmological lithium problem. The d + $^7\text{Be}$ rate used in BBN calculations [11] was based on [10]. Later work by Angulo [7] found even a smaller rate of d + $^7\text{Be}$. In addition to the ground state (gs) and first excited states of $^8\text{Be}$, the 11.4 MeV state in $^8\text{Be}$ was observed and cross sections were measured up to excitations of 13.8 MeV [9]. It was concluded [9] that higher energy states not observed in [8] contribute ~1/3 of the total S-factor instead of 2/3 estimated in [11].

Now, the destruction reaction might proceed through intermediate states; in $^8\text{Be}$ by $^7\text{Be}(d,p)^8\text{Be}^*$; in $^5\text{Li}$ by $^7\text{Be}(d,α)^5\text{Li}^*$ or in a democratic three-particle decay of the $^9\text{B}$ compound system [8]. Rijal stated in [8] that the (d,α) yield dominated over (d,p) yield. They claim to have found a new resonance inside the Gamow window ($T = 0.5 - 1$ GK, $E_{cm} = 0.11 - 0.56$ MeV), that reduces the predicted abundance of $^7\text{Li}$ but not sufficiently to solve it. However, Gai [12] pointed out that Rijal’s new d + $^7\text{Be}$ rate is nearly identical to [10] in the BBN region. Also the rates are uncertain by a factor of 10 due to uncertainty of the resonance energy around 16.8 MeV [12]. In this context, no data extracting contributions of the excited states around 16 MeV exist in the $^7\text{Be} + d$ channel.

The above mentioned 16.8 MeV state of $^9\text{B}$, may also decay by proton emission to a highly excited state in $^8\text{Be}$ at 16.262 MeV, subsequently breaking into two α-particles [13]. To determine fully the contribution of $^7\text{Be}(d,p)^8\text{Be}$ reaction to the $^7\text{Li}$ abundance, it needs to be measured for $^8\text{Be}$ excitations around 16 MeV. In order to measure that with good statistics, the experiment might be done at higher energies. The data are then used to normalize the excitation function calculated with

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short consecutive runs with measurements and normalization respectively, by taking impinging on a 15 µm Cd target. The intensity of the ion-source, the spread of the REX-EBIS charge breeder was fully stripped in the foil and removed. The total solid angle coverage of the detectors is ∼ 32% of 4π.

The detectors were calibrated with a 148Gd−235 Pu−241 Am−244Cm mixed α-source. For S3, due to higher dynamic range, we also used the elastic peaks from Rutherford scattering of 5 MeV/u 7Be and 5.15 MeV/u 12C beams on 208Pb. The light charged particles emitted from 7Be + d reaction, were identified by ΔE − E telescopes from the energy loss spectra (Fig. 2). Elastic 7Be scattered from Carbon of Cd2 was observed in S3.

Data from both W1 and BB7 were used to study excitations in 8Be. At BB7, we detected the gs and 3.03, 11.35, 16.63 MeV excited states of 8Be. After selecting the protons from ΔE − E spectra, the gs and 3.03 MeV states were completely stopped in ΔE of BB7 and were extracted from the excitation energy spectrum (Fig. 3 inset) after background subtraction. Since Fig. 3 shows only protons selected from ΔE − E spectrum, we do not observe kinematic bands corresponding to these two states at 130° − 170°. The higher excited states above 16 MeV were obtained from W1 using E vs θ plot (Fig. 3) of protons detected in coincidence with α-particles. To obtain data for forward scattered protons, the energy-energy correlation of two coincident α-particles at W1 with one hit at S3 were considered. The α-p coincidence efficiency at W1 drops sharply for excitation energy below 16 MeV. Hence the kinematic signatures corresponding to states below 16 MeV are absent at 40° − 80°. The energy resolution ∼ 660 keV due to beam, target straggling and detectors, limits the separation of narrowly spaced high lying resonances at 16.63 and 16.92 MeV, and resonances around 17 − 22 MeV. Earlier works [20, 21] suggest that the 16.63 MeV state is populated considerably more than 16.92 MeV. Hence, we refer to this doublet as 16.63 MeV. The inset of Fig. 5 shows excitation energy spectrum of 8Be from protons detected at W1 (blue) and BB7 (red). The corresponding fits are shown by dark-blue and brown dashed lines. The counts from BB7 are multiplied by two for

![FIG. 1: The detector setup for the 7Be + d experiment at 5 MeV/u.](image)

![FIG. 2: The ΔE − E spectrum of protons, deuterons, 3He and α, detected at W1 + MSX25 telescopes, from 5 MeV/u 7Be on Cd2 target.](image)
TABLE I: Excitations (E_x) of 8Be listed in Tilley et al. [22], and excitations (E^{fit}_x) and widths (Γ^{fit}) obtained from fitting the excitation energy spectrum in the inset of Fig. 3.

| E_x (MeV ± keV) | Γ (keV) | E^{fit}_x (MeV) | Γ^{fit} (MeV) |
|-----------------|--------|-----------------|---------------|
| 0.0             | ±0.25  | 0.02            | 0.71 ± 0.04   |
| 3.03 ± 10       | 1513 ± 15 | 3.51           | 2.00 ± 0.50   |
| 11.35 ± 150     | 3500   | 11.31           | 3.77 ± 0.27   |
| 16.62 ± 3       | 108.1 ± 0.5 | 16.50         | 1.18 ± 0.51   |
| 16.92 ± 3       | 74.0 ± 0.4  | 16.99           | 1.17 ± 0.51   |
| 17.64 ± 1.0     | 10.7 ± 0.5  | 17.50           | 0.71 ± 0.05   |
| 18.15 ± 4       | 135 ± 6   | 18.19           | 0.71 ± 0.05   |
| 18.91           | 122      | 18.80           | 0.67 ± 0.01   |
| 19.07 ± 30      | 270 ± 20  | 19.00           | 0.90 ± 0.25   |
| 19.235 ± 10     | 227 ± 16  | 19.28           | 0.71 ± 0.03   |
| 19.40           | 645      | 19.58           | 0.95 ± 0.27   |
| 19.86 ± 50      | 700 ± 100 | 19.79           | 0.95 ± 0.25   |
| 20.10           | 880 ± 20  | 20.00           | 1.10 ± 0.22   |
| 20.20           | 720 ± 20  | 20.29           | 1.41 ± 0.69   |
| 20.90           | 1600 ± 200 | 20.84          | 1.75 ± 0.15   |
| 21.50           | 1000     | 21.44           | 1.60 ± 0.60   |
| 22.05 ± 100     | 270 ± 70  | 22.10           | 0.94 ± 0.28   |

*The average uncertainty in the peak centroids is around 10%.

The 16–22 MeV excited states are populated for the first time from 7Be(d,p)8Be+. We did not find any evidence of (d,α) channel. The peaks are fitted simultaneously by Gaussian functions, with input of excitation energies and their widths [22]. The arrows show the excitation energies used in the fitting. The peak centroids and widths from the resultant fits are summarized in Table I. The fitted widths represent the quadratic sum of 660 keV experimental resolution and total decay width of the excited states.

FIG. 3: E vs θ for protons at W1 and BB7. The kinematic lines for different excited states of 8Be are shown for 7Be(d,p)8Be+ at 5 MeV/u. Inset shows the excitation energy spectrum of 8Be.

The angular distribution for 7Be + d elastic scattering from the present work is shown in Fig. 4(a). The scattering is quasi elastic as the 0.43 MeV state of 7Be could not be separated. However, the inelastic contribution is expected to be small [23]. The 7Be(d,p)8Be+ angular distributions for 16.63 MeV (×10−1 for clarity) and 3.03, 11.35 MeV (×10 for clarity) excited states are shown in Fig. 4(a)(b). At BB7, corresponding to excited states up to 16.63 MeV, the proton counts are obtained from background subtracted excitation energy histogram with an angular interval of two degrees. For excited states > 11.35 MeV detected at W1, we considered the coincidence efficiency to correct for proton counts detected in coincidence with α-particles using NPTool [24]. The errors in cross sections mainly arise from statistical uncertainties, systematic uncertainties in target thickness (∼10%) and beam intensity (∼10%).

FIG. 4: Angular distributions for 7Be(d,d) and 7Be(d,p) to 16.63 MeV (a); to 0.0, 3.03 and 11.35 MeV states (b). The corresponding FRESCO [25] calculations are shown by dashed and dotted lines in Fig. 4. The DWBA calculations require the OMP for the entrance channel d + 7Be, exit channel p + 8Be, and the core-core p + 7Be interactions. Woods-Saxon interaction potentials are used [26]. We started with OMP for d + 7Be [27], p + 7Be [28], and used SFRESCO [25] to arrive at the final OMP (Table II) by minimizing χ². Since p + 8Be elastic data are not available, we used OMP of p + 8Li [27] (Table II) for the exit channel. The n + 7Be binding potential [29] has a Wood-Saxon shape with r = 1.36 fm and a = 0.55 fm. Its depth is adjusted to reproduce effective neutron separation energy for each state of 8Be, while a spin-orbit potential with same geometry and fixed well depth of 9 MeV is included. A Gaussian interaction V_{np}(r) = -\frac{V_0}{\rho} \exp(-\rho^2/\rho_0^2) is used for the n–p system with V_0 = 72.15 MeV and \rho_0 = 1.484 fm.
TABLE II: Optical model parameters used in the present work. \( V \) and \( W \) are the real and imaginary depths in MeV, \( r \) and \( a \) are the radius and diffuseness in fm. \( R \approx r_s A^{1/3} \) fm \( (x = V, S, SO, C) \).

| Channel | \( V \) | \( r_V \) | \( a_V \) | \( W_S \) | \( r_S \) | \( a_S \) | \( V_{SO} \) | \( r_{SO} \) | \( a_{SO} \) | \( r_C \) |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| \( d + \ ^7\text{Be} \) | 80.98 | 1.35 | 0.83 | 36.91 | 2.21 | 0.10 | 2.08 | 0.49 | 0.42 | 1.30 |
| \( p + \ ^7\text{Be} \) | 92.07 | 0.87 | 0.89 | 1.23 | 0.10 | 0.10 | 16.82 | 1.34 | 0.12 | 1.14 |
| \( p + \ ^8\text{Be} \) | 82.60 | 1.10 | 0.41 | 1.97 | 1.10 | 1.30 | 5.54 | 1.14 | 0.57 | 1.14 |

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FIG. 5: (a) Excitation function for \( ^7\text{Be}(d,p)^8\text{Be}^* \). The solid triangle, diamond, square and circles correspond to total cross-sections due to gs, gs + 3.03, gs + 3.03 + 11.35 and gs + 3.03 + 11.35 + 16.63 MeV states respectively. The data in green, blue, red and magenta are the measurements of \( ^7\text{Be} \) and the present work. The violet (gs), cyan (gs + 3.03), yellow (gs + 3.03 + 11.35) and red (gs + 3.03 + 11.35 + 16.63) MeV bands are TALYS calculations normalized to the present data at 7.8 MeV (green vertical line). The bands do not include systematic uncertainty due to extrapolation. (b) The S-factor representation of the excitation function. The red dotted line is the estimate by Parker \( ^{14}\).

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The DWBA calculations are in good agreement with the data for gs, 3.03 and 11.35 MeV states in a limited angular range while for the 16.63 MeV state, only forward angles up to \( \sim 40^\circ \) could be reproduced. Consideration of compound nuclear contributions, coupled-channel calculations incorporating collective excitations of \( ^7\text{Be} \), inclusion of deuteron breakup and a \( d + ^7\text{Be} \) adiabatic potential might result in a better fit at large angles. The experimental spectroscopic factors \( C^2S \), are extracted by normalizing the calculated DWBA cross-sections to measured cross-sections. The average values of \( C^2S \) for the excited states of \( ^8\text{Be} \) are compared with the OXBASH \( ^{31}\) shell model calculations \( ^{32}\) in Table III. Assuming full isotropy for the gs, 3.03 and 11.35 MeV states, we obtain the total cross section \( \sigma \) for these states. For 16.63 MeV, \( \sigma \) is obtained by connecting the differential cross sections and integrating (Table III). To obtain the excitation functions of \( ^7\text{Be}(d,p)^8\text{Be}^* \), TALYS-1.95 \( ^{14}\) calculations are carried out and normalized to present experimental data. In Fig. (a), the normalized excitation functions from TALYS for gs, gs + 3.03, gs + 3.03 + 11.35 and gs + 3.03 + 11.35 + 16.63 MeV (colored bands to include error bars of the present data) have been compared to the data of \( ^{30}\). The calculations agree very well with \( ^{10}\) outside the Gamow window, for \( E_{cm} > 0.7 \) MeV. The data \( ^{8}\) for gs and 3.03 MeV are well below corresponding TALYS calculations (cyan). However, the data within and near Gamow window have relatively large errors. Inside Gamow window, TALYS calculations for higher excited states (cyan, yellow, red) overestimate \( ^{7}\) except at 0.22 MeV, within error bars. The systematic uncertainties due to extrapolation of the total S-factor from \( E_{cm} = 7.8 \) MeV to BBN energies is \( \sim 48\% \). This arises due to various phenomenological and microscopic models for level densities (\( \sim 46\% \)), choice of global deuteron (\( \sim 10\% \)) and proton (\( \sim 10\% \) OMP in TALYS. In Fig. (b), the corresponding astrophysical S-factor is shown. The S-factor band with contributions from gs + 3.03 + 11.35 MeV (yellow) converges to an average value of \( \sim 95.6 \) MeV b in the Gamow window.
which is close to Parker’s estimate of 100 MeV b. The S-factor band (red) with the contributions of all the states including 16.63 MeV gives a maximum of 167 MeV b inside the Gamow window, close to 162.0 MeV b for the claimed new resonance at 0.36 MeV [8]. If we assume a constant S-factor of 167 MeV b, then the ratio of reaction rate from the present work with [11] at the relevant BBN energies is less than 2 whereas for solving the Li problem this ratio needs to be around 100 [1]. Therefore, the BBN calculations of [8] seem to overestimate the importance of the 7Be + d reaction. Even the maximum S-factor inferred from this measurement would reduce the primordial Li abundance by less than 1% [33, 34] with respect to previous expectation [11] and thereby fail to alleviate the discrepancy between theory and observation.

In summary, the present experiment reports the first measurement of all resonances in the 7Be(d,p)8Be∗ channel up to 22 MeV. In particular, the 16.63 MeV state is analyzed in the context of the cosmological lithium problem. The measurement was carried out at a much higher center-of-mass energy of 7.8 MeV compared to the Gamow window. This facilitated populating the previously unsee higher excitations of 7Be with good statistics and their contributions to the total cross section are studied. The existing data within Gamow window has large error bars in energy as well as cross sections. The TALYS calculations normalized to the present data give an estimate of the contributions of resonance excitations in the (d,p) channel. It is apparent that inclusion of the 16.63 MeV state may lead to a maximum S-factor of 167 MeV b, higher than earlier used value of 100 MeV b [10]. But it does not fully account for the Lithium anomaly and our present understanding of nuclear physics may not solve this problem.

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