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Review

The ^{7}Be destruction reactions and the cosmological lithium problem

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Abstract In this review, we survey a number of experiments over the last few decades, that specifically study the destruction of the ^{7}Be nucleus, in search for a solution to the long standing cosmological lithium problem. The destruction of ^{7}Be by both neutrons and charged particles are discussed. However, the reduction in the abundance of the primordial ^{7}Li is found to be negligible and thus the lithium anomaly remains. The second lithium problem involving ^{6}Li is still controversial. Overall, it appears that the solution to the lithium problems may not reside in nuclear physics.

1 Introduction

The cosmological lithium problem [1–4] is at present a very important and thought-provoking topic in nuclear astrophysics. The problem depicts a serious anomaly in the abundance of ^{7}Li between observation and prediction of the big-bang nucleosynthesis (BBN) theory. With a baryon-to-photon ratio $\eta = (6.104 \pm 0.058) \times 10^{-10}$ [5], the BBN theory predicts a ^{7}Li abundance about three times higher than that observed in metal-poor stars. There is, however, a very good agreement between observation and prediction for lighter nuclei like ^{2}H and ^{4}He. In search for a solution, the problem has been approached from several directions like nuclear physics, astrophysics and exotic physics beyond the standard model [3]. The present review explores some of the nuclear physics experiments that were carried out to find a solution to the lithium problem.

The BBN models depend on the nuclear reaction rates obtained from experimental data. Thus, scrutiny of the relevant nuclear reaction cross-sections and thereby nuclear physics inputs to BBN theory are needed [3, 4]. In BBN, the abundance of ^{7}Li is the result of directly synthesized ^{7}Li, as well as those from the electron capture (EC) β-decay of ^{7}Be and the charge-exchange reaction ^{7}Be(n, p)^{7}Li. However, 95% of the primordial ^{7}Li is the by-product of EC of primordial ^{7}Be ($T_{1/2} = 53.22$d [6]) after the stopping of nucleosynthesis. This is due to the reason that most of the directly synthesized ^{7}Li is immediately destroyed through the ^{7}Li(p, α)^{4}He reaction. Since the net ^{7}Be is the resultant of the production and destruction reactions of ^{7}Be, it is important to accurately determine the thermonuclear reaction rates of ^{7}Be. The key ^{7}Be production channel is ^{3}He(α, γ)^{7}Be. It has been extensively studied [7, 8] and the cross-section is known to a few percent accuracy [9]. However, theoretical and experimental investigations indicate that this reaction may not solve the lithium problem [10, 11]. The relevant ^{7}Be destruction channels are ^{7}Be(n, α), (n, p), (d, p), (d, α), (d, ^{3}He) and (α,γ). A higher rate of neutron or charged-particle-induced reactions on ^{7}Be leads to a lower remaining ^{7}Be and thereby a lower ^{7}Li abundance, affecting the lithium anomaly. It may be noted that the ^{7}Be abundance is much lower than that of lighter nuclei, implying that a very small fraction of these nuclei can result in a significant depletion of ^{7}Be [10].

While addressing the ^{7}Li anomaly, it appears that there may be a second anomaly involving the ^{6}Li nucleus [12]. In some metal-poor stars, the abundance of ^{6}Li display a plateau like structure with respect to metallicity [13, 14] similar to ^{7}Li, suggesting a BBN origin. The observed values of ^{6}Li/^{7}Li ratio is $0.01 - 0.10$ [15] as compared to BBN calculations of $\sim 10^{-5}$ [12]. The BBN predictions in case of ^{6}Li, however, underestimate the observed abundance by a factor of $\sim 10^3$ [2, 14]. It is to be noted that more recent studies [15] have contradicted the ^{6}Li detections in Spite plateau stars. The disagreement in case of the lithium isotopes is indeed perplexing, since one finds remarkable agreement between BBN predictions and primordial abundances of ^{2}H and ^{4}He [3]. It is also

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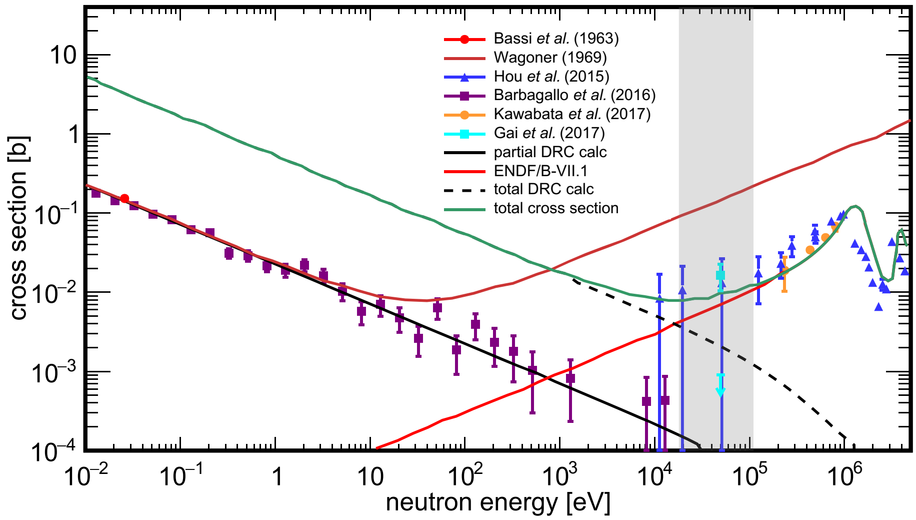

Fig. 1 The current world data on the ^{7}Be(n, α)^{4}He reaction. The shaded area corresponds to the neutron energy region of interest for BBN

interesting to study nuclear reactions that may impact both the lithium anomalies simultaneously. In this review, we study the ^{7}Be destruction reaction ^{7}Be(d, ^{3}He)^{6}Li, that produces ^{6}Li on the one hand, and destroys ^{7}Be on the other, thus decreasing ^{7}Li abundance indirectly.

In Sect. 2, we review some of the relevant ^{7}Be destruction reaction experiments, carried out till date to address the lithium problems. In Sect. 3, we discuss briefly recent efforts in inhomogeneous big-bang nucleosynthesis, to look for a solution to the lithium problem. The review ends with an outlook in Sect. 4.

2 Nuclear reactions that destroy ^{7}Be

2.1 ^{7}Be(n, α)^{4}He

The ^{7}Be(n, α)^{4}He reaction rate was first estimated theoretically by Wagoner in 1969 [16], and used in BBN calculations. Only a direct reaction contribution was included without considering any resonant component. Hou et al. [17] revised this rate based on indirect cross-section data available for the ^{4}He(α, n)^{7}Be and ^{4}He(α, p)^{7}Li reactions by applying charge symmetry and the principle of detailed balance. The result shows that the earlier rate [16] was overestimated by about a factor of ten. The BBN calculations with the new rate [17] even led to a 1.2% increase in the ^{7}Li abundance, thereby worsening the ^{7}Li problem further. The energy-dependent cross-section of this reaction was first measured by Barbagallo et al. [18], from 10 meV to 10 keV neutron energy at n_TOF of CERN as shown in Fig. 1. Two Si–^{7}Be–Si arrays were placed directly in the neutron beam, and coincidences between the two alpha-particles were recorded. The results are compatible at thermal neutron energy, with an earlier measurement at a nuclear reactor in 1963 [19], indicated by the red dot in Fig. 1. The reported energy dependence reflected the need for improvement of cross-section estimates used in BBN calculations. Kawabata et al. [20] measured the cross-section of the ^{4}He(α, n)^{7}Be time-reversed reaction at low energies at RCNP. By using the detailed balance principle, they obtained the ^{7}Be(n, α)^{4}He reaction cross-sections at $E_{\mathrm{cm}} = 0.20{-}0.81$ MeV, slightly above the BBN energy window as shown by the shaded area in Fig. 1. The obtained cross-sections are much larger than the cross-sections for s-wave neutrons inferred from [18], but significantly smaller than the BBN calculations. The details of the theoretical calculations included in Fig. 1 are given in [18]. Gai et al. [21] reported the first measurement of ^{7}Be(n, α) and (n, $\gamma\alpha$) reactions at BBN temperatures (kT = 49.5 keV, T = 0.57 GK) at SARAF. The cross-section is considerably smaller than that used in BBN calculations [16], denoted by the brown line in Fig. 1. The measured upper limit of 0.9 mb (shown by an arrow) matches with [18] at 12.7 keV, but is a factor of about 7 lower than those of [17, 20]. The α particles were measured also from the ^{7}Be(n, γ)^{8}Be*(3.03 MeV) reaction, and the cross-section was an order of magnitude higher than that of [18]. Gai's work also rules out any unknown resonance in ^{8}Be at the BBN window. The experiments discussed above lead to the conclusion that the (n, α) reaction plays an insignificant role in the context of the Li problem.

2.2 ^{7}Be(n, p)^{7}Li

The ^{7}Be(n, p)^{7}Li reaction cross-section was measured by Damone et al. [22] from thermal to approximately 325 keV neutron energy (Fig. 2) at n_TOF of CERN. The two previous time-of-flight measurements at Dubna and Los

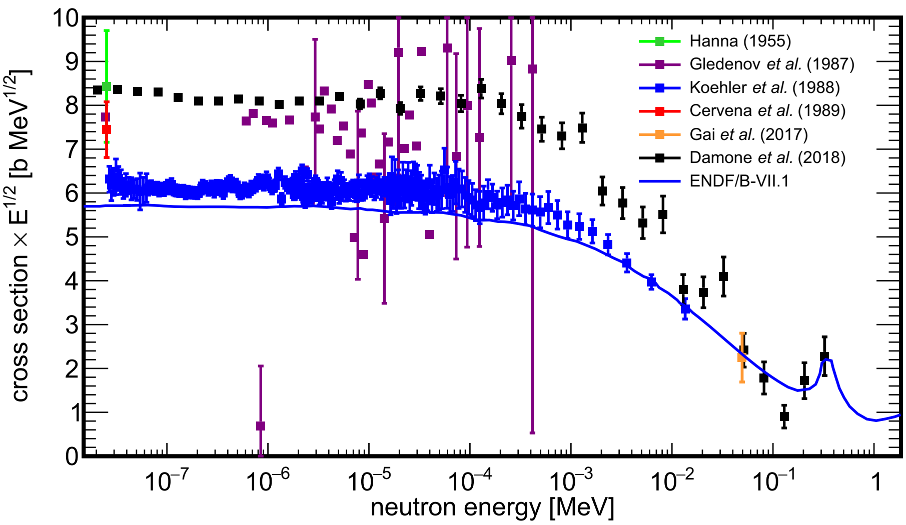

Fig. 2 The current world data on the ^{7}Be(n, p)^{7}Li reaction

Alamos, respectively [23, 24], did not cover the BBN energy window, and showed sizeable discrepancies. Later, Gai et al. [21] reported the measurement of the ^{7}Be(n, p) reaction in addition to the (n, α) as discussed above. The measurement at 49.5 keV agrees very well with that of [22] as well as the extrapolated cross-sections from [24]. It was concluded, that the (n, p) reaction has a minor influence on the cosmological lithium problem.

2.3 ^{7}Be(d, p)^{8}Be(2α)

The reaction ^{7}Be(d, p)^{8}Be(2α) has a high Q value of 16.67 MeV. The relevant Gamow window is T = 0.5–1 GK and center of mass energy E_{cm} = 0.11–0.56 MeV. In 1960, the earliest cross-section measurement of this reaction was reported by Kavanagh at Caltech [25], although the cosmological lithium problem appeared much later. A deuteron beam ranging in energy from 0.7 to 1.7 MeV was bombarded on a ^{7}Be target, resulting in excitations of up to 11 MeV in ^{8}Be. The relevant E_{cm} = 0.6–1.3 MeV and the protons detected by a NaI(Tl) detector, correspond to the ^{8}Be ground state (0^{+}), 3.03 MeV (2^{+}) excited state and a continuum extending up to 11 MeV. The data lacked complete angular distributions and in 1972, Parker [26] converted it to total cross-section by assuming isotropy and multiplying the differential cross-sections by 4π. He further multiplied it by a factor of 3 to take in to account the contributions from higher excited states in ^{8}Be not observed in [25]. A constant S factor of $\sim$ 100 MeV b was thus adopted by Parker. The d + ^{7}Be rate used in BBN calculations [27] for the past 3 decades was based on this estimate [26].

In 2005, an experiment at lower E_{cm} of 0.38 and 1.23 MeV was carried out by Angulo et al. [28] at the CYCLONE radioactive beam facility at Louvain-la-Neuve, Belgium. They found a significantly reduced cross-section in the BBN Gamow window compared to Parker's estimate. A ^{7}Be beam with an average intensity of 2×10^{6} pps was used to bombard a 200 μg/cm^{2} CD$_{2}$ target at incident energies of 5.55 and 1.17 MeV. The charged particles emitted from the reaction were detected at laboratory angles of 7.6°–17.4°. In addition to the ground state and first excited state of ^{8}Be, the broad 11.4 MeV (4^{+}) state of ^{8}Be was observed. The cross-sections were measured up to excitations of 13.8 MeV and a smaller rate of d + ^{7}Be was obtained [28]. The conclusion of this work was that the higher energy states, not observed in [25] contribute about 1/3 of the total S factor instead of the 2/3 as estimated by Parker [26]. Therefore, in reality, the S factor at BBN energies was not underestimated by Parker but it was overestimated. The reaction rate is smaller by a factor of $\sim$ 2 at 1.0$-$1.23 MeV and by $\sim$ 10 at energies relevant to BBN.

In 2019, this reaction was measured by Rijal et al. [29] at the relevant BBN energies, using the RESOLUT radioactive beam facility at Florida State University. A ^{7}Be beam of energy 19.7 MeV and intensity $\sim 5 \times 10^{4}$ pps was incident on a pure deuterium gas target. The coincident detection of all three particles in the exit channel, namely p, α and α were carried out. These might arise through intermediate states in ^{8}Be by ^{7}Be(d, p)^{8}Be*; in ^{5}Li by ^{7}Be(d, α)^{5}Li* or in a democratic three-particle decay of the ^{9}B compound system [29]. The ^{7}Be(d, p)^{8}Be(2α) and ^{7}Be(d,α)^{5}Li(p)α reactions were distinguished by the distribution of events on a Dalitz plot (Fig. 3). It was found that the (d, α) dominated the (d, p) channel at all energies [29] as shown in Fig. 4.

In 2022, Ali et al. [30], reported the measurement of the (d, p) reaction at HIE-ISOLDE, CERN. In the experiment, a 5 MeV/u ^{7}Be beam of intensity $\sim 5 \times 10^{5}$ pps was incident on a 15μm thick CD$_{2}$ target. An array of double sided Silicon strip detectors covering 8–165° (Micron S3, W1, BB7) [31] was used to detect the emitted particles. The earlier experiments [25, 28, 29] on the ^{7}Be(d, p)^{8}Be* reaction could not evaluate the effects of the

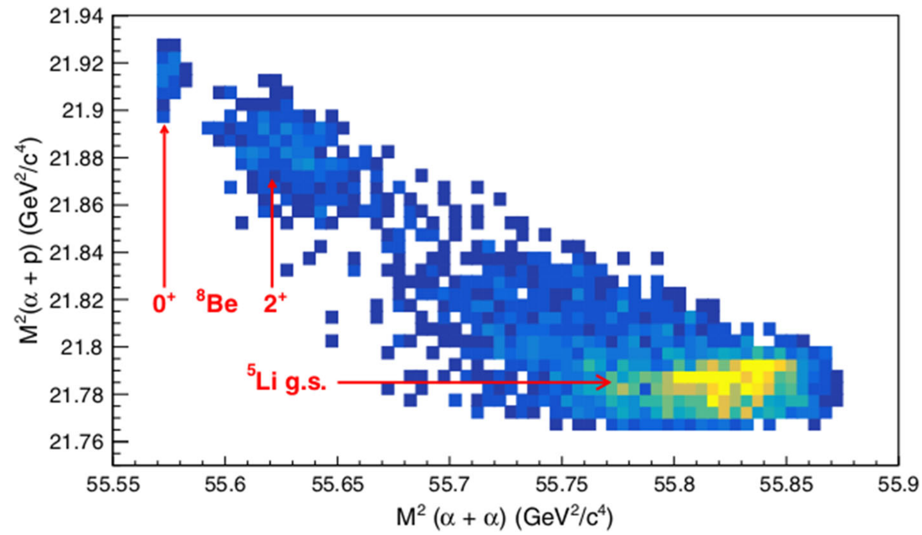

Fig. 3 Dalitz plot analysis of $p + 2\alpha$ events at $E_{\mathrm{cm}} = 1.15 \pm 0.20$ MeV [29]

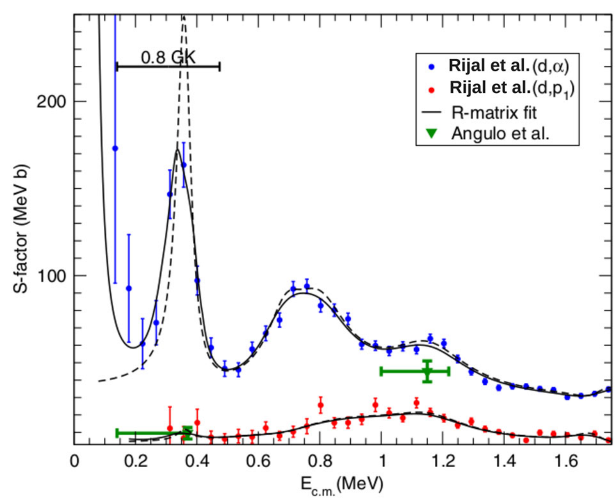

Fig. 4 S factor representation of the experimental data for the (d,α) and the (d,p_1) channels from [29]

higher excited states of ^{8}Be (close to the Q-value of 16.67 MeV) on the reaction rate. The measurements in [30] populated the higher excited states of ^{8}Be up to 22 MeV for the first time in this channel. In Fig. 5, the excitation energy spectrum of ^{8}Be from protons detected at W1 (blue) and BB7 (red) detectors [30] are shown, as well as the corresponding Gaussian fits. The (d, p) S factor (Fig. 6) was obtained by normalizing the TALYS calculations to the data at $E_{\mathrm{cm}} = 7.8$ MeV [32]. The contributions of the higher excited states in the total cross-section at the relevant big-bang energies are obtained by extrapolation to the Gamow window. Including the 16.63 MeV state, the S factor comes out to be 167 MeV b, about 70% higher than the estimate of 100 MeV b from earlier work [26]. However, the reduction in the primordial ^{7}Li abundance comes out to be less than 1% and thereby fails to alleviate the anomaly.

2.4 ^{7}Be(d,α)^{5}Li(p)α

As discussed above, Rijal et al. [29] identified the events from this reaction for the first time as is apparent from the Dalitz plot (Fig. 3). A new resonance at $E_{\mathrm{cm}} = 0.36(5)$ MeV was observed inside the relevant Gamow window (Fig. 4). They claimed that the ^{7}Li/H abundance is reduced by 1.4–8.1% from their measured reaction rate, although not sufficient to alleviate the lithium anomaly. However, in contrast to the claims, it was later shown by Gai [21] that the new ^{7}Be + d rate is nearly the same as the CF88 rate [27] over the BBN region of interest. Also, the rates are uncertain by a factor of 10 due to uncertainty of the resonance energy around 16.8 MeV [21].

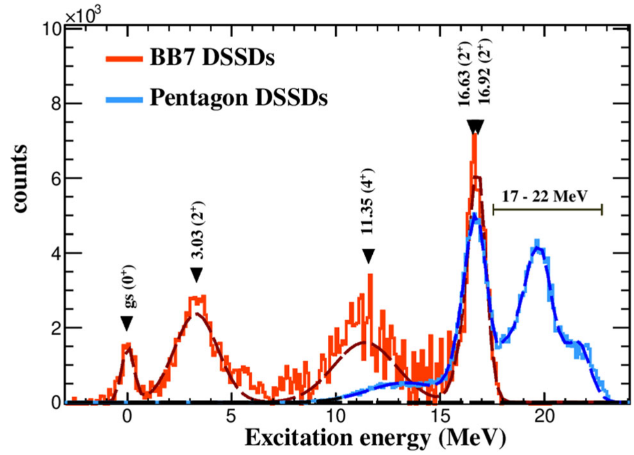

Fig. 5 The excitation energy spectrum showing the ^{8}Be states from the ^{7}Be(d,p)^{8}Be*(2α) measurement at 5 MeV/u [30]

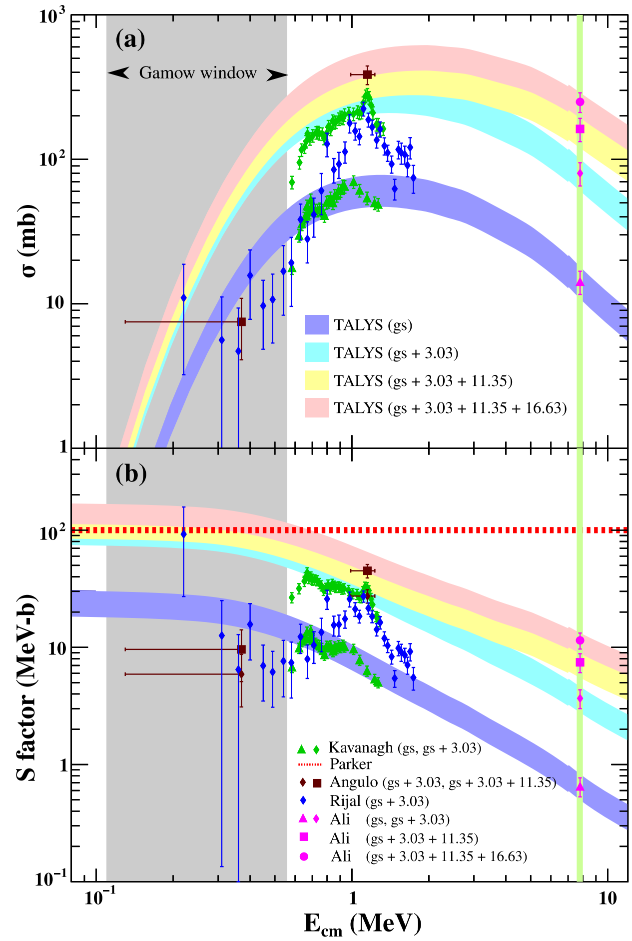

Fig. 6 **a** Excitation function for ^{7}Be(d, p)^{8}Be*. The solid triangle, diamond, square and circles correspond to total cross-sections due to gs (ground state), gs + 3.03, gs + 3.03 + 11.35 and gs + 3.03 + 11.35 + 16.63 MeV states, respectively. The experimental data from [25, 28–30] are shown in green, brown, blue and magenta. 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 data of Ali et al. [30] 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 [26]

2.5 ^{7}Be(d,^{3}He)^{6}Li

The first measurement of the ^{7}Be(d, ^{3}He)^{6}Li angular distribution was carried out by Li et al. [33], at $E_{\mathrm{cm}} = 4.0$ and 6.7 MeV with secondary ^{7}Be beams. The excitation function of the ^{7}Be(d, ^{3}He)^{6}Li reaction was calculated with TALYS [32], by normalization to the experimental data. A BBN network calculation was done to investigate the influence on the ^{6}Li and ^{7}Li abundances. Initially, the authors considered the (d, ^{3}He) reaction rate to be the same as (d, p) rate. When they multiplied this rate by a factor of 100, their BBN calculations resulted in a 45% decrease in abundance of ^{7}Li and 47% increase in abundance of ^{6}Li [33]. The work of Li et al. [33] involved low ^{7}Be beam intensities of 5000 pps. The emitted ^{3}He and ^{6}Li were selected from ΔE–E spectrum using gates from

Monte Carlo simulations of the ^{7}Be(d, ^{3}He)^{6}Li reaction. Although background subtraction was carried out using a carbon target, no kinematical signatures were shown to confirm that the selected ^{3}He and ^{6}Li are from the above reaction [33].

Later, the work of Ali et al. [34] involved the measurement of the ^{7}Be(d, ^{3}He)^{6}Li* reaction cross-sections at 5 MeV/u. The effect of the ^{7}Be(d, ^{3}He)^{6}Li reaction on both the ^{6}Li and ^{7}Li abundances were investigated at the relevant BBN energies. The excitation function was calculated by TALYS and normalized to the experimental data. The S factor of the (d, ^{3}He) channel obtained from [34] is about 50% lower than the data at nearby energies [33]. The (d, ^{3}He) reaction rate is found to have ≤ 0.1 % effect on the ^{6,7}Li abundances.

2.6 ^{7}Be(α, γ)^{11}C

The impact of the radiative capture reaction ^{7}Be(α, γ)^{11}C on the primordial ^{7}Li abundance is also discussed in [10]. The authors state that a narrow resonance in the low energy region in ^{11}C could appreciably reduce the ^{7}Li abundance. However, the experiment by Hammache et al. [35] reported that no new resonance exist in the excitation energy region of interest. Further studies on the reaction was carried out by Hartos et al. [36] using a two-body potential model. The calculations show that the appearance of very low energy resonances in ^{11}C, relevant to BBN is improbable. Increasing the reaction rate of ^{7}Be(α, γ)^{11}C by a factor of about 10^4 does not yield any notable change in the ^{7}Li abundance [36]. Thus, it may be concluded that the influence of this reaction on the cosmological lithium problem is negligible.

3 Inhomogeneous nucleosynthesis and the lithium problem

During the early 1990s, the homogeneous standard BBN (SBBN) was generally accepted with $\eta \sim 3 \times 10^{-10}$ [37]. In 1992, the Cosmic Microwave Background (CMB) anisotropies were discovered by COBE [38], and later by the CMB-WMAP satellites [39]. These observations resulted in an η value almost twice as large, being $(6.104 \pm 0.058) \times 10^{-10}$ at present [5]. It can be seen that, with increasing η, the theoretical calculations of the lithium abundance increases consistently, leading to the lithium overproduction problem in SBBN. Now, the standard BBN ends after the production of ^{7}Li. However, for an early universe that is inhomogeneous, nucleosynthesis in neutron-rich regions might produce an observable amount of $A > 12$ isotopes. In the 1980's, when an inhomogeneous BBN (IBBN) model [37, 40, 41] was put forward to explain the missing dark matter problem, there was no lithium overproduction problem in SBBN. However in IBBN [40], there was overabundance of ^{7}Li by a factor ~ 3 with respect to SBBN. Therefore, it was considered as a hypothetical model to explain a larger baryon density, and playing an important role in the big-bang nucleosynthesis of ^{7}Li. Recently, there has been revisions in the IBBN model [42, 43]. The aim is to solve the lithium anomaly by considering the fluctuations/inhomogeneities of the primordial magnetic field (PMF), satisfying the cosmological constraints on observed CMB anisotropies. In this context, there are several important reactions destroying ^{7}Li by ^{7}Li(n, γ)^{8}Li(n, γ)^{9}Li and ^{7}Li(n, γ)^{8}Li(^{4}He,n)^{11}B. This would also build up abundances of Be, B and intermediate-mass nuclei in IBBN. Further theoretical studies are also going on [43, 44] to combine both PMF-CMB inhomogeneities and baryon-inhomogeneities as in the original IBBN model [40]. Thus, some of the above reactions may be studied in greater details in pursuit of a solution to the cosmological lithium problem.

4 Outlook

The attractive proposition of finding a nuclear physics solution to the cosmological lithium problem, led to several experiments in the last few decades. We reviewed in this article a set of experiments till date, that involved the ^{7}Be destruction channels. However, the studies conclude that the reduction in the primordial ^{7}Li abundance is negligible and thereby fails to alleviate the lithium anomaly. It appears that nuclear physics solutions are inadequate to solve this problem. Several other avenues like inhomogeneous nucleosynthesis [40], presence of exotic particles during big-bang as well as non-extensive statistics [45] are also being pursued to address this intriguing anomaly. It would be indeed interesting to find out if the lithium problem truly points toward exotic new physics.

Data availability No data associated in the manuscript.

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