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The interaction of deuterons and neutrons with ^{7}Be and the "primordial ^{7}Li problem"

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Abstract. We discuss the implication for Big Bang Nucleosynthesis (BBN) of two new measurements on the interaction of deuterons with ^{7}Be and neutrons with ^{7}Be. We review the recent (strong) statements of the Florida State University (FSU) group by Rijal et al., on the relevance of the d + ^{7}Be interactions for BBN. We show that this reaction does not play any significant role in BBN, as has been established by Caughlan and Fowler in 1988 (and by others before). We review the recently published measurement at the SARAF in Israel on the interaction of neutrons with ^{7}Be together with concurrent measurements of the n_TOF at CERN and of the Kyoto group. Only the SARAF measurement is in the BBN window, and we test the earlier extrapolation (by the n_TOF and Kyoto groups) into the BBN window. In contrast we conclude s-wave, and not p-wave, dominance, in the BBN window, of the interaction of neutrons with ^{7}Be. Both the FSU and SARAF results indicate lack of standard nuclear physics solution to the "Primordial ^{7}Li Problem"

Key words. Big Bang Nucleosynthesis, Primordial ^{7}Li problem

1. Introduction

Standard cosmology predicts the original (primordial) chemical composition of the Universe very precisely, as the result of a brief period of Big Bang nucleosynthesis (BBN) (Schramm et al. 1998; Burles et al. 2001; Cyburt et al. 2016). In a minimal model (only standard model particles, no large lepton/antilepton asymmetry), the only astrophysical input to the BBN calculation is the baryon density of the Universe, which is now known precisely (Dunkley et al. 2009). Within plausible errors, the observed abundances of helium and especially deuterium are in good agreement with the BBN predictions at the known baryon density. The only other sources of significant uncertainty in the standard model of BBN are the cross sections of the twelve "canonical" BBN nuclear reactions (Smith et al. 1993). With total errors of the order of a few percent or less, the BBN predictions are a very specific consequence of modern cosmology and in that sense, BBN is one of the most remarkable achievements of modern cosmology and nuclear astrophysics. However, early on it was already noticed that BBN theory fails to predict correctly the observed abundance of ^{7}Li. It over predicts the abundance of ^{7}Li by approximately a factor of three and up to five sigma deviation from observation (Fields 2011). This disagreement is very dificult to understand in terms of cosmology and it has been dubbed the "Primordial ^{7}Li Problem". Approximately 95% of the pri-

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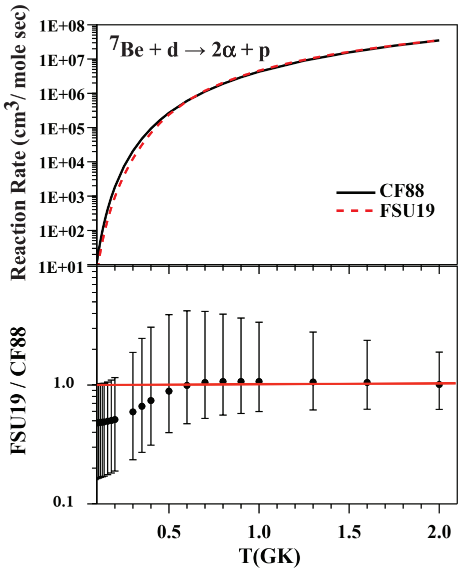

Fig. 1. (Color Online) A comparison of the FSU19 reaction rate published in Rijal et al. (2019) and the CF88 rate Caughlan & Fowler (1988), and the ratio of the two rates. Over the BBN region of interest of 0.5 - 0.9 GK, the two rates are identical.

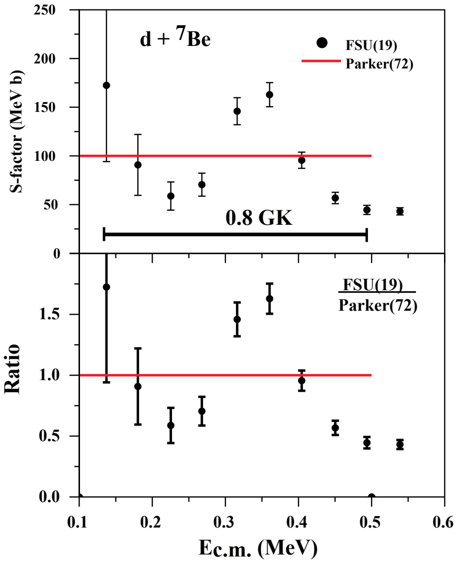

Fig. 2. (Color Online) A comparison of the s-factor measured in the Gamow window of BBN indicated in Rijal et al. (2019) and Parker 1972(educated guess) of constant s-factor ~100 MeV b Parker (1972), and the ratio of the two s-factors.

mordial ^{7}Li is the by-product of the electron capture beta-decay of the primordial ^{7}Be that occurred approximately a hundred years after its formation, when the plasma cooled down enough for the ^{7}Be to capture an electron. Hence, in a search for standard nuclear physics solution to the ^{7}Li problem a lot of effort has been invested in measuring the direct destruction of ^{7}Be which must compete with the standard indirect destruction of ^{7}Be in the reaction chain ^{7}Be(n,p)^{7}Li(p,α) that is included in BBN. In this paper we consider one provocative statement on the destruction of ^{7}Be by deuterons, and we also discuss *the last possible avenue* for the destruction of ^{7}Be by neutrons.

2. The FSU measurement, Rijal et al.: the interaction of d + ^{7}Be

Rijal et al. (2019) measured the cross section of the d + ^{7}Be → 2α + p reaction at energies relevant for Big Bang Nucleosynthesis (BBN) from which they deduced the new “rates derived from our excitation function” (Rijal et al. 2019), shown in Fig. 5 of Rijal et al. (2019), hereafter the new “FSU19 rate”. Based on their new rate they claim that “the resonance reduces the predicted abundance of primordial ^{7}Li”, and they derive: “our reaction rates predict (^{7}Li/H)$_p$ = 4.24 - 4.61× 10^{-10}”, as shown in Fig. 6 of Rijal et al. (2019).

In this comment we demonstrate that the FSU19 rate of the d + ^{7}Be reaction, is the same rate that has been used in BBN for over fourty years. And the ^{7}Li abundance deduced in Rijal et al. (2019) was published more than twenty years ago. Furthermore, the impression that the FSU19 rate is larger (which leads to smaller primordial ^{7}Li abundance) is based on a selective “straw man” comparison with other rates that have not been used in BBN. Specifically, their statement that ”the resonance reduces the predicted abundance of primordial ^{7}Li”, is incorrect. No reduction of the abundance of ^{7}Li beyond that which was already calculated by the practitioner of BBN, can be deduced from the FSU19 rate. Rijal et al. chose to compare in Fig. 5 (Rijal et al. 2019), their d + ^{7}Be rate to a rate based on s-factor data that was obtained at higher energies by Kavanagh in 1960 (Kavanagh 1960) and the more recent rate published by Angulo et al. (2005). These comparisons give the impression that a new higher d +^{7}Be rate was measured in the FSU experiment. As such they conclude that their new rate including a resonance "reduces the predicted abundance of primordial ^{7}Li". But the so-labeled "Kavanagh rate", was never used by the practitioner of BBN (over the last sixty years) and it is not relevant for the discussion of BBN. The rate of Angulo et al., was also not used in BBN, since it is even smaller than the d + ^{7}Be rate that was used in BBN. Simply put, the "straw man" comparison of the FSU19 rate with the rates of Kavanagh and Angulo et al. shown in Fig. 5 of Rijal et al. (2019), is irrelevant for BBN. Instead, in Fig. 1 we show the d + ^{7}Be rate that was used by the practitioner in the field of BBN over the last thirty years as already published in 1988 by Caughlan and Fowler, hereafter the "CF88 rate" (Caughlan & Fowler 1988). Prior to CF88 the FCZ75 compilation of 1975 Fowler et al. (1975) listed the same rate as in CF88. Rijal et al. did not consider CF88 (or FCZ75 rate) and in their Fig. 5 they chose not to compare the CF88 rate to their rate. In Fig. 1 we compare the FSU19 rate to the CF88 rate. The ratio of the two rates is also shown in Fig. 1. Clearly, over the region of interest for BBN indicated in Fig. 5 of Rijal et al. (2019), of T= 0.8 GK (neglecting their incorrect statement, the BBN region should read 0.5 - 0.9 GK), the central values of the FSU19 rate is identical to the CF88 rate. Rijal et al. did not measure a new rate for the d + ^{7}Be interaction during BBN.

Furthermore, considering the very large uncertainties of the FSU19 rate Rijal et al. (2019) shown in Fig. 1, which is due to the ill determined resonance energy (of 16.85 ±0.045 MeV), rates which differ by up to a factor of 10 are consistent with their data. As such the CF88 and FSU19 rates are hardly different if not identical over the entire reported temperature range of Fig. 5 of Rijal et al. (2019). Since no state is known in ^{9}B at the proposed "new resonance" energy of 16.85 MeV, resolving such a major systematical uncertainty would have been essential for making the FSU19 rate of some relevance for BBN, beyond merely confirming the CF88 rate. Such an uncertainty can be resolved by measuring the excitation function of the ^{6}Li(^{3}He,d)^{7}Be reaction at the appropriate low energies. Instead of resolving this systematic uncertainty Rijal et al. resort to speculations that their resonance may have been observed in another measurement of the (^{3}He,t) reaction at 16.80 MeV.

The seminal compilation of stellar nuclear rates by Caughlan and Fowler includes the interaction of d + ^{7}Be that has been used in BBN over the last 32 years. Using the CF88 rate it was concluded long ago that the d + ^{7}Be reaction does not play a significant role in BBN. As such it is not included in the twelve canonical reactions that are relevant for BBN (Smith et al. 1993). We note that the more recent REACLIB compilation (Cyburt et al. 2010), referenced by Rijal et al., contains no new information on the interaction of d + ^{7}Be beyond the CF88 compilation. In fact, quite to the contrary, in REACLIB we find the list of the well known twelve canonical reactions of BBN (listed as "popular reactions of BBN") that does not include the d +^{7}Be reaction. This reaction was recognized as irrelevant for BBN long before the compilation of the REACLIB. The d + ^{7}Be rate listed in the CF88 compilation, was based on the work of Parker (1972), which Rijal et al. dismiss as arbitrary for multiplying the "cross-section data from Kavanagh (1960) by an arbitrary factor of 3". But Parker stated very clearly that he "multiplied by a factor of ~3 [Kavanagh's s-factor] to take into account contributions from higher excited states in ^{8}Be". Parker's educated guess of the s-factor was not "arbitrary" and should not be labeled as such, even if one claims that it is based on incorrect assumption(s). In Fig. 2, we compare the s-factor of the d + ^{7}Be reaction deduced by Parker (of ∼ 100 MeV b) (Parker 1972) with the FSU19 s-factor (Rijal et al. 2019) measured at their indicated region of interest (0.8 GK). In this region of interest, Parker's simple assumption of a constant s-factor is on average a reasonable approximation of the s-factor measured by the FSU group. It is than little wonder that Rijal et al. also observed that the $(^7\mathrm{Be/H})_p \approx 4.51 \times 10^{-10}$, predicted using

Parker's rate, agrees with their result, and indeed with their entire stellar burning rate.

We conclude that Parker's rate for the d + ^{7}Be reaction (which is based on the most elementary assumption of a constant s-factor), and the CF88 and FCZ75 rates (which are based on Parker's rate), and the FSU19 rate deduced from their measurement, are all the same over the region of interest, and no new information relevant for BBN has been gained since Parker's paper of 1972. The conclusion that the interaction of d + ^{7}Be plays no significant role in BBN, was not altered by Rijal et al. As such, the d + ^{7}Be interaction must still be ignored and not included in the twelve canonical reactions of BBN (Smith et al. 1993). Perhaps a more disturbing observation is the discrepancy between the FSU findings and our well established understanding of BBN. For example, Coc and Davids recently demonstrated that using publicly available codes such as PRIMAT (Coc & Davids 2019), the d + ^{7}Be rate would have to be ∼30 times larger than the CF88 rate to play a significant role in BBN. Similarly, not including the Parker rate (or the FSU19 rate) the practitioner of BBN (Nollett 2019) concluded long ago a change in the ^{7}Li/H abundance by no more than 1%. It is not clear why Rijal et al. claim a Li/H change by ∼15%. We can only suspect a mistake in their unspecified code for BBN calculation. Indeed in their erratum (Rijal et al. 2019), Rijal et al. indicate an error in their code, but still they claim a significant decrease of the ^{7}Li abundance, larger than their quoted error, when comparing the abundance calculated without including their rate, to the abundance calculated including their rate. But the error quoted by Rijal et al. of ±0.3% (Rijal et al. 2019), is a factor of 10 smaller than the realistic error quoted by most practitioners in the field. Simply put, Rijal et al. (2019), contradict the very understanding of BBN that has been established over many years of research by the practitioners in the field. Indeed, the $(^7\mathrm{Li/H})_p$ quoted by Rijal et al. of 4.24 - 4.61 $\times^{-10}$ can already be deduced, when using the now known baryon density, from the BBN calculations of more than twenty years ago (Smith et al. 1993).

In conclusion, the long standing observation that the interaction of d + ^{7}Be plays very little role if any, in BBN, has not been altered using the so-called FSU19 new rate (Rijal et al. 2019). And in any case, the FSU19 rate published in Rijal et al. (2019), should not be considered anew, since the same rate was already published thirty years ago by Caughlan & Fowler (1988).

3. The SARAF measurement, Gai et al.: the interaction of n + ^{7}Be

We used the neutron beams produced at the Soreq Applied Research Accelerator Facility (SARAF) (Mardor et al. 2018), by bombarding a liquid lithium target (LiLiT) (Feinberg et al. 2009) with 1-2 mA proton beam with energy Ep = 1.935 MeV, and energy spread of ±15 keV. These neutrons (E_n = 10 - 170 keV) covering the BBN window (T = 0.5 - 0.9 GK, kT = 43 - 81 keV), are confined to the forward angles ($\theta \leq 60°$) with a quasi-Maxwellian energy distribution and an "effective temperature" kT = 49.5 keV. The neutron beam flux (∼ 10^{10} n/s/cm^2) was measured on-line, with a fission fragment detector and off-line, by placing a gold foil right behind the detector setup and measuring the accumulated activity of the 412 keV line from the ^{197}Au(n,γ) reaction with a well-known energy dependent cross section. The experimental procedures and calibrations of our CR39 nuclear track detectors (NTD), are discussed in detail in Kading et al. (2020) and the measurements of the interaction of n + ^{7}Be were discussed in Gai (2017); Gai et al. (2020) and are not repeated here.

As discussed in Kading et al. (2020) the interaction of neutrons with the NTD CR39 plates yield a background due to the ^{17}O(n,α) reaction inside the CR39 plate. Since the tracks are formed inside the NTD, this background extends up to ∼2.1 MeV (Kading et al. 2020). This background on one hand limits the sensitivity for measuring small cross sections of alpha-particles up to ∼2.1 MeV, but on the other hand it provides an "internal calibration line" for measuring large cross section of alpha-particles with energies up to ∼2.1 MeV. We use this ^{17}O(n,α) background to place

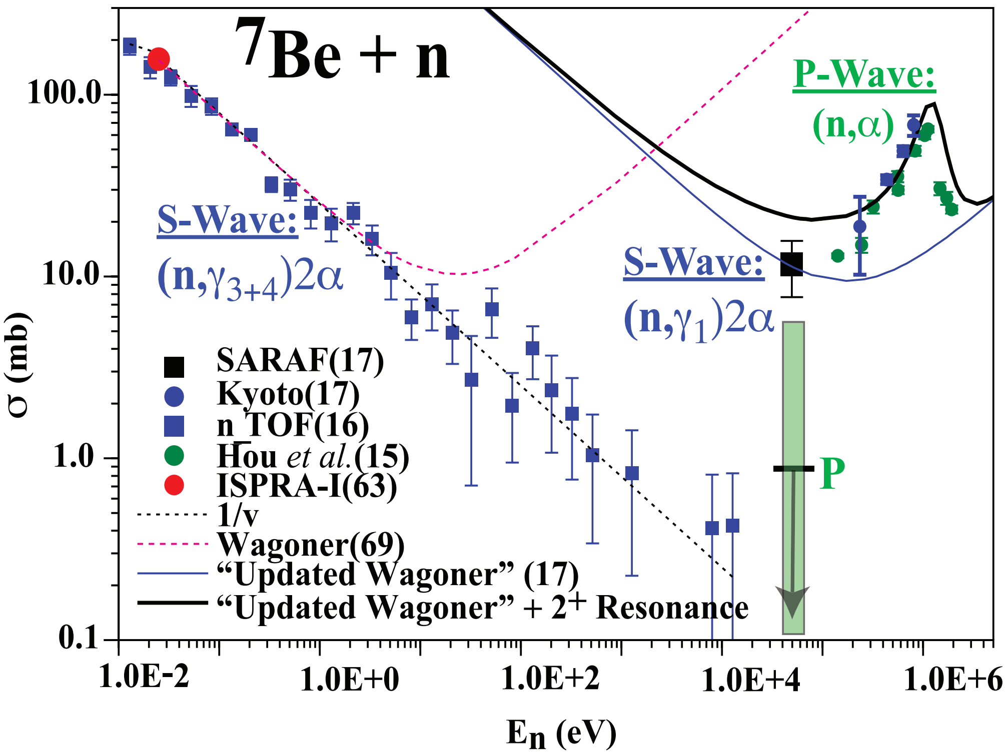

Fig. 3. Current world data (Gai 2017; Gai et al. 2020; Barbagallo et al. 2016; Hou et al. 2015; Kawabata et al. 2017; Bassi et al. 1963) on alpha-particles from the interaction of neutrons with ^{7}Be. The Big Bang window for the formation of ^{7}Be is indicated by a bright green vertical full rectangle.

an upper limit on the low cross section for high energy, 9.5 and ~8.4 MeV, alpha-particles from the ^{7}B(n,α) and ^{7}Be(n,$\gamma_{3,4}$)^{8}Be*(~16.8 MeV) reactions, respectively (Gai et al. 2020). These high energy alpha-particles were degraded in our setup with a 25 micron aluminum foil (Kading et al. 2020), to E_α = 1-3 MeV, which includes the energy range of up to ~2.1 MeV, of the observed background "calibration line". In a separate experiment we measured the cross section of the ^{7}Be(n,γ_1)*Be(3.03 MeV) using a comparison of measurements with "foil in and out". We note that the large width of the 2$^+$ at 3.03 MeV in ^{8}Be, leads to alpha-particles with energies up to ~2.2 MeV, again quite similar to our "internal calibration line" from the ^{17}O(n,α) reaction inside the CR39 plate (Kading et al. 2020). In Fig. 3 we show the world data (Barbagallo et al. 2016; Hou et al. 2015; Kawabata et al. 2017; Bassi et al. 1963) together with our results from the SARAF measurement (Gai 2017; Gai et al. 2020) on alpha-particles from the interaction of neutrons with ^{7}Be. We also show in the same figure Wagoner (1969) compilation of these cross sections that was labeled as "^{7}Be(n,α)" (Wagoner 1969, and is used today in BBN calculations), together with our "updated Wagoner rate" that includes the 2$^+$ state at 20.1 MeV in ^{8}Be. Our new rate is based on measured "direct" data only (Gai 2017; Gai et al. 2020; Barbagallo et al. 2016; Kawabata et al. 2017). In the BBN window the undated rate is considerably smaller than Wagoner (1969) rate, indicating that the destruction of ^{7}Be by neutrons during BBN does not lead to a viable solution of the "Primordial lithium problem". However, we conclude s-wave dominance of the interaction of neutrons with ^{7}Be in the BBN window, as expected due to the low lying 2^- state at E_n = 10 keV in ^{8}Be. Our conclusion contradicts the earlier extrapolations (Barbagallo et al. 2016; Kawabata et al. 2017) that suggested p-wave dominance in the interaction of neutrons with ^{7}Be.

4. Conclusions

The "Primordial ^{7}Li Problem", that was observed in BBN calculations early on, remains unsolved using standard nuclear physics considerations.

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