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The Interaction of Neutrons with ^{7}Be at BBN Temperatures: Lack of Standard Nuclear Solution to the "Primordial ^{7}Li Problem"

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Abstract. We report the first measurement of alpha-particles from the interaction of neutrons with ^{7}Be at "temperatures" of Big Bang Nucleosynthesis (BBN). We measured the Maxwellian averaged cross sections (MACS), with neutron beams produced by the LiLiT at the SARAF in Israel (with kT = 49.5 keV hence 0.57 GK). In addition, we measured the cross section of the ^{7}Be(n,p) reaction, which is in excellent agreement with the recent measurement of the n_TOF collaboration, further substantiating our method as a demonstration of *"proof of principle"*. The cross section for the ^{7}Be(n,$\gamma\alpha$) and the ^{7}Be(n,α) reaction measured in the "BBN window" is considerably smaller than compiled by Wagoner in 1969 and used today in Big Bang Nucleosynthesis (BBN). We also rule out a hitherto unknown resonance in ^{8}Be at the BBN window, that was conjectured as a possible standard nuclear physics solution to the "Primordial ^{7}Li Problem". Together with previous results, we deduce a new Wagoner-like Rate for the destruction of ^{7}Be by neutrons which is based on all current measured data. We conclude the lack of a standard nuclear solution to the "Primordial ^{7}Li Problem". Our upper limit on the cross sections for the high energy alpha-particles is in agreement with recent measurement of the n_TOF collaboration, but it is considerably smaller than the p-wave extrapolation of the Kyoto collaboration. We measured the alpha-particles from the ^{7}Be(n,γ_1)^{8}Be*(3.03 MeV) reaction, which is considerably larger than a previous s-wave estimate. Hence, in contrast, we conclude s-wave dominance at BBN energies, as would be expected due to the broad (122 keV) low lying 2^- state at En = 10 keV.

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) [1–3]. 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 [4]. 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[5].

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With total errors of the order 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 [6]. This disagreement is very difficult to understand in terms of cosmology and it has been dubbed the "Primordial ^{7}Li Problem". Approximately 95% of the primordial ^{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. 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 "the last possible avenue" for the destruction of ^{7}Be by neutrons.

We report here on a new investigation of the possible direct destruction of ^{7}Be by neutrons that is generically labelled in BBN as ^{7}Be(n,α) reactions. We measured, for the first time, the MACS of the interaction of neutrons with ^{7}Be in the BBN window. This allowed us to examine extrapolations into the BBN window of the cross sections measured at lower energies [7] and at higher energies [8,9]. We conclude an s-wave dominance of the cross section at the BBN window, in contrast to a previous claim of p-wave dominance [9]. We do not find evidence for a substantial increase in the cross section of the direct destruction of ^{7}Be beyond the indirect rate for the destruction of ^{7}Be already included in BBN and we conclude that there is still no standard solution for the "Primordial ^{7}Li Problem".

2 The SARAF Measurement

We used the neutron beams produced at the Soreq Applied Research Accelerator Facility (SARAF) [10] by bombarding a liquid lithium target (LiLiT) [11] with 1-2 mA proton beam with energy Ep = 1.935 MeV, and energy spread of ±15 keV. These neutrons (10 - 170 keV) covering the BBN window (T = 0.5 - 0.9 GK, kT = 43 - 81 keV), as shown in Fig.1, are confined to the forward angles ($\theta < 60^{\circ}$) with a quasi-Maxwellian energy distribution and an "effective temperature" kT = 49.5 keV. The neutron beam intensity (~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 are discussed in detail in [12,13] and not repeated here.

The procedures for preparing the ^{7}Be and the ^{9}Be targets were discussed in [14] and are not repeated here. The ^{7}Be and ^{9}Be targets were prepared using the same electro-deposition cell and were placed in the same experimental setup and bombarded by the same neutron beams produced by the liquid lithium target (LiLiT) [11]. The ^{9}Be target was used to measure the background in our experimental setup. The ^{7}Be target activity at the time of irradiation (3.95 GBq) was measured using a HPGe detector placed at 5 meters from the target leading to ^{7}Be areal density of 5.19 x 10^{16} ^{7}Be/cm^{2}.

Due to the large background from the intense neutron beam we used nuclear track detectors (NTD, CR39 plates) to measure the alpha-particles and protons, produced in the interaction of neutrons with ^{7}Be. As discussed in [12], the NTD were calibrated with alpha-particles from a standard ^{148}Gd (3.18

MeV) source, and 1.5 MeV protons and 1.5 MeV alpha-particles extracted from the Weizmann 3 MV single ended van de Graaff accelerator, using Rutherford back scattering (RBS) off a thin (100/ cm^2) gold foil, as discussed in [12]. The CR39 plates were etched in a standard 6.25 N NaOH solution for 30 minutes at 90°C to produce micron size circular pits that were viewed with a microscope as discussed in [12]. The etching procedure, microscopy, digital image processing and data analyses, are discussed in great details in [12] and are not repeated here.

As discussed in [12], our short etch time at high temperatures, yields a small efficiency for detecting 1.5 MeV protons of only 8.7% ±3%. We used Monte Carlo simulation to calculate the solid angle $\Omega/4\pi = 0.0038$ for a CR39 scanned area of 3.66 mm^2 at 7 mm from the 8 mm diameter target.

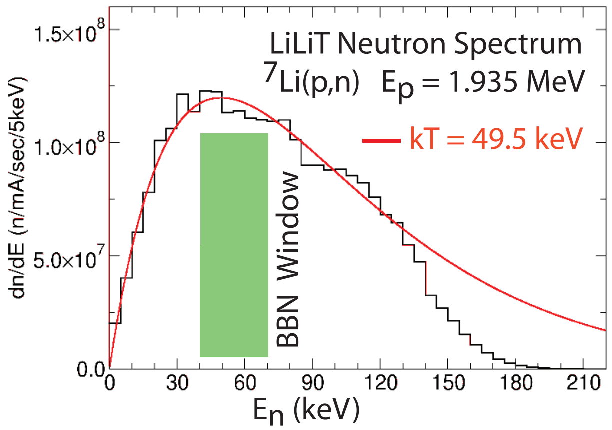

Fig. 1: The Quasi-Maxwellian neutron spectrum produced at the SARAF [10] by the LiLiT [11]. The BBN window is indicated, and the spectrum is compared to a Maxwellian with kT= 49.5 keV.

3 Results

As discussed in [12] the interaction of neutrons with the NTD CR39 plates yield a background due to the $^{17}O(n,\alpha)$ reaction inside the CR39 plate. 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. Hence, we use this $^{17}O(n,\alpha)$ background to place an upper limit on the low cross section for high energy, 9.5 and ~8.4 MeV, alpha-particles from the $^7B(n,\alpha)$ and $^7Be(n,\gamma_{3,4})^8Be^*$ reactions, respectively. These high energy alpha-particles were degraded in our setup with a 25 micron aluminum foil [12], to E_α = 1-3 MeV, including the energy range of the observed background. In a separate experiment we measured the cross section of the $^7Be(n,\gamma_1)^*Be(3.03\ MeV)$ using a comparison of measurements with “foil in” and “foil out”. We note that the large width of the 2^+ at 3.03 MeV in ^8Be, leads to alpha-particles with energies up to ~2.2 MeV, again quite similar to our “internal calibration line” from the $^{17}O(n,\alpha)$ reaction inside the CR39 plate [12].

3.1 High Energy Alpha Particles from the $^7B(n,\alpha)$ and $^7Be(n,\gamma_{3,4})^8Be^*$ reactions.

In Fig. 2 we show a comparison of the spectra of radii of pits measured with ^7Be and ^9Be targets with a 25 microns aluminum foil placed in front of the CR39 plate to stop the large flux of 1.5 MeV protons from the $^7Be(n,p)$ reaction, which however also stop the low energy alpha-particles from the

^{7}Be(n,γ_1)Be*(3.03 MeV) reaction. Due to the large angle acceptance the degrader foil would have degraded the 9.5 and ~8.4 MeV alpha-particles from the ^{7}B(n,α) and ^{7}Be(n,$\gamma_{3,4}$)^{8}Be* reactions, respectively, to E_α = 1-3 MeV. The spectra measured with ^{9}Be and ^{7}Be targets are normalized to the ^{9}Be "background spectrum", using the integrated beam intensity and the area of the CR39 plate scanned by our microscope. The region of interest for alpha particles with energies up to ~2.1 MeV of 1.5 – 3.4 microns, deduced from our calibration [12], is indicated in yellow. Over this region of interest, no significant deviation of the yield measured with the ^{7}Be target is observed over the yield measured with the ^{9}Be target. The measured spectra arise solely from the interaction of neutrons with the CR39 itself as observed in [12]. This allow us to extract an upper limit of 0.9 mb, on the combined cross sections for the emission of 9.5 MeV and ~8.4 MeV alpha-particles from the ^{7}B(n,α) and ^{7}Be(n,$\gamma_{3,4}$)^{8}Be* reactions, respectively. This upper limit is in excellent agreement with the measurement of the n_TOF collaboration at energies up to 12.7 keV [7], but it is approximately a factor 10 lower that the cross section extrapolated into the BBN window from measurements at higher energies, measured down to 210 keV by the Kyoto group [9].

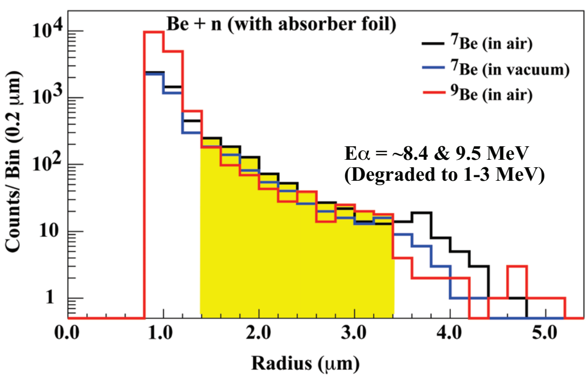

Fig. 2: The measured pit radii for alpha-particles from the interaction of neutrons with ^{7}Be after traversing the 25 micron aluminum stopper foil in air or vacuum (Black and Blue), compared to the same measurement with ^{9}Be target in air (Red). The alpha-particle radii region of interest (RRI) defined in our calibration measurement [12] is indicated in yellow. The spectra are normalized to the measured beam intensity, and the scanned area of the ^{9}Be background measurement.

3.2 Protons from the ^{7}Be(n,p) Reaction

In Fig. 3 we show a comparison of the spectra of radii of pits measured with ^{7}Be target without a foil (Black) and with a 25 microns aluminum foil placed in front of the CR39 plate (Red). We note that these two regions where measured simultaneously, with the foil only covering half of the 6 mm diameter open area of the collimator in front of the CR39 plate described in [12]. These two regions of foil in and foil out, are in the same CR39, placed above each other as depicted in Fig. 3, and are separated by less than 0.5 mm. They are exposed to the same background. The calibration measured with 1.5 MeV protons discussed in [12] and shown in blue at the bottom of Fig. 3, indicate the 1.5 MeV protons from the ^{7}Be(n,p) reaction are expected at radii 0.8 – 1.4 microns. Over this region we observe 1344 ±134 counts above background, corresponding to a cross section of 10.1 ±1.0 (stat), ±1.5 (syst) b. Our MACS cross section measured at 49.5 keV is in excellent agreement with the cross section measured by the n_TOF collaboration [15], but it was announced in the NPA8 meeting [13], one year before the publication of the n_TOF measurement [15], and it serves as a *"proof of principle" of the method.*

3.3 Alpha-Particles from the ^{7}Be(n,γ_1)8Be*(3.03 MeV) Reaction

Using the foil in/out method discussed above and the results shown in Fig. 3, we measured in the region corresponding to alpha-particles with energies up to ~2.1 MeV, an excess = 121 - 82 = 39 ±14 counts above the very low background, also shown in Fig. 3 in red. Again, this region is defined by the interaction of cold neutrons (black) or the interaction of epithermal neutrons (dashed red) with CR39 as discussed in [12]. Note that the "1.5 MeV" alpha particles from the 2^+ of ^{8}Be*(3.03 MeV), extends to approximately 2.2 MeV due to the large width (1.5 MeV) of this state. Hence the "internal calibration line" from the interaction of neutrons with CR39 can be used to define the region of interest of the "1.5 MeV" alpha-particles. In sharp contrast to the difference between the scanned region corresponding to the foil in (up) and foil out (down), a comparison of beam left and beam right regions on the CR39 plate, that contains both foil in and foil out regions plus the 0.5 mm separation, showed no statistically significant deviation with 115 ±11 counts on beam left and 102 ±10 counts on beam right.

Using the excess of 39 ±14 counts, with the efficiency for detecting 1.5 MeV alpha particle of 75% (smaller than 100% due to the cut below 1.5 microns), the beam-target luminosity and the solid angle discussed above (with two alpha-particles emitted from ^{8}Be), we deduce the cross section of 16.4 ±6 mb, of the ^{7}Be(n,γ_1)*Be(3.03 MeV) reaction. This cross section is approximately a factor 10 larger than the theoretical estimate of the n_TOF group [7]. It yield a large B(E1:$2^- \rightarrow 2^+_1$) = 0.040(14) W.u. which interestingly equals the other two known B(E1)s of the 2^- state at 18.91 MeV to the third and fourth 2^+ states 16.626 and 16.922 MeV.

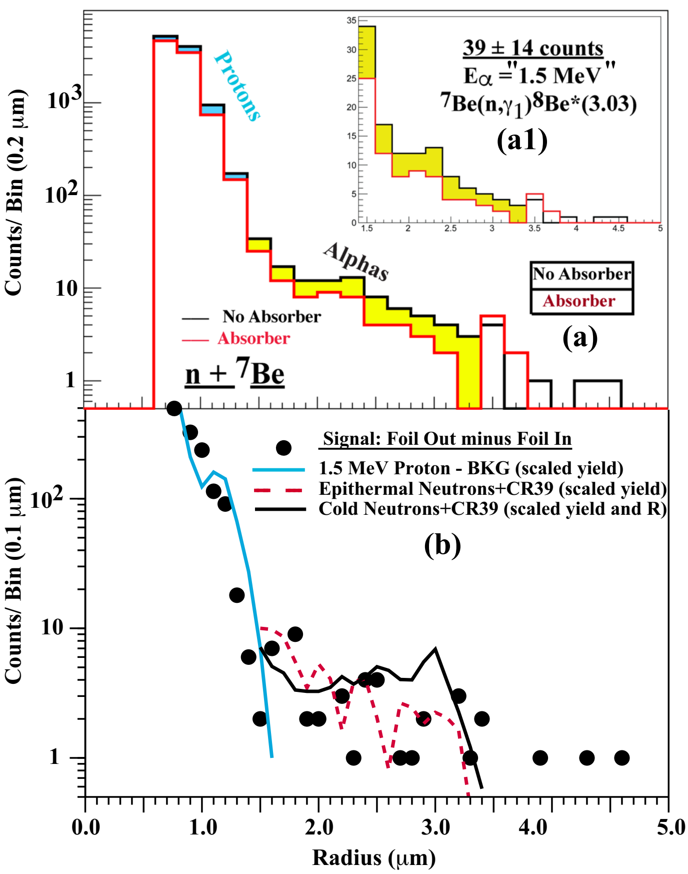

Fig. 3: (a) Comparison of pit radii from n + ^{7}Be interactions measured in vacuum with (red) and without (black) 25 microns aluminum stopper foil, as discussed in the text. The alpha-particle (proton) radii region of interest (RRI) defined in our calibration measurement [12] is indicated in yellow (blue). (b) The measured yield (foil out) above background (foil in) is compared to our measured calibration for 1.5 MeV protons (blue) and the "internal calibration line" from the interaction of cold neutrons (black) and epithermal neutron (hashed red) with the CR39 plate itself, revealed in [12], and discussed in the text.

4 Conclusions

In Fig. 4 we show the world data [7-9,13,16] on alpha-particles from the interaction of neutrons with ^{7}Be. We also show in the same figure Wagoner 1969 compilation of this cross section that was generically labeled as ^{7}Be(n,α) [17] (used today by the practitioners of BBN), and our "update Wagoner rate" that includes the 2^+ state at 20.1 MeV in ^{8}Be. Our new rate is based on measured data only [7,9,13]. In the BBN window it is considerably smaller than Wagoner '69 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 En = 10 keV in ^{8}Be. The large measured B(E1:$2^- \rightarrow 2^+_1$), is also of great interest, since the 2^+_1 at 3.03 MeV in ^{8}Be is known to be α+α clustering state, which may lead to interesting conclusions on the structure of the 2^- state at 18.91 MeV.

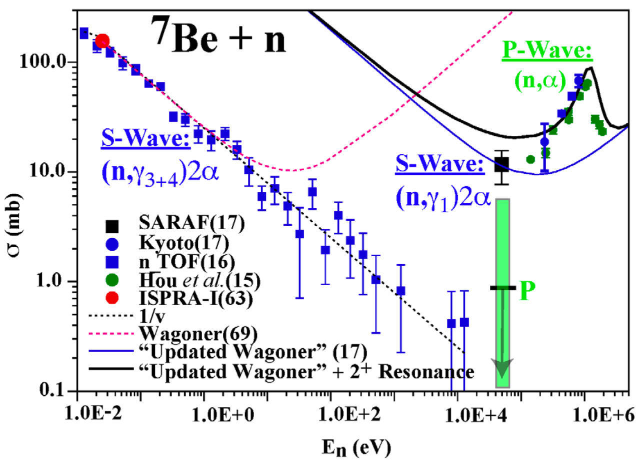

Fig. 4: Current world data [7-9,13,16] on alpha-particles from the interaction of neutrons with ^{7}Be. The Big Bang window for the formation of ^{7}Be is indicated by a (bright green) vertical full rectangle.

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