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Search for resonant states in ^{10}C and ^{11}C and their impact on the primordial ^{7}Li abundance

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Abstract. The cosmological ^{7}Li problem arises from the significant discrepancy of about a factor 3 between the predicted primordial ^{7}Li abundance and the observed one. The main process for the production of ^{7}Li during Big-Bang nucleosynthesis is the decay of ^{7}Be. Many key nuclear reactions involved in the production and destruction of ^{7}Be were investigated in attempt to explain the ^{7}Li deficit but none of them led to successful conclusions. However, some authors suggested recently the possibility that the destruction of ^{7}Be by ^{3}He and ^{4}He may reconcile the predictions and observations if missing resonant states in the compound nuclei ^{10}C and ^{11}C exist. Hence, a search of these missing resonant states in ^{10}C and ^{11}C was investigated at the Orsay Tandem-Alto facility through ^{10}B(^{3}He,t)^{10}C and ^{11}B(^{3}He,t)^{11}C charge-exchange reactions respectively. After a short overview of the cosmological ^{7}Li problem from a nuclear physics point of view, a description of the Orsay experiment will be given as well as the obtained results and their impact on the ^{7}Li problem.

1. Introduction

The Big-Bang model of the Universe is mainly supported by three observational evidences: the expansion of the Universe, the Cosmic Microwave Background (CMB), and the primordial or Big-Bang Nucleosynthesis (BBN) of light nuclei like ^{2}H, ^{3,4}He, and ^{7}Li. The observed primordial abundances for D and ^{3,4}He agree well with the predictions of the BBN theory together with the precise WMAP cosmic baryon density while ^{7}Li observations lie below the BBN+WMAP expectations by a factor of ~ 3 [1, 2]. This observed deficit constitutes the so-called lithium

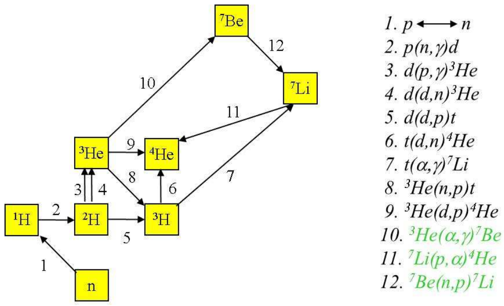

Figure 1. BBN nuclear reactions network.

problem. Many scenarios were proposed to try to explain this anomaly. The first one is related to the possibility of systematic errors in the extraction of Li abundances from the observed atomic spectra due to the used atmosphere models. But this is very unlikely since the various models give nearly the same results [3]. The second explanation is the possibility that the atmospheric ^{7}Li may have partially depleted from the atmosphere of the metal poor halo stars through rotationally induced mixing and/or diffusion [4]. But then a uniform destruction mechanism of ^{7}Li is needed all over this Spite plateau which exhibits a very little dispersion of the observed ^{7}Li abundance as a function of the metallicity of the stars. Some astrophysicists claim that the ^{7}Li problem point towards physics beyond standard model such as decay of super-symmetric particles, variation of the fundamental constants...[5, 6]. But before investigating these far going possibilities, one has to be sure about the nuclear data involved.

The main process for the production of the BBN ^{7}Li is the decay of ^{7}Be. Hence any reaction which produces or destroys ^{7}Be has an impact on ^{7}Li. Among the 12 BBN standard reaction network displayed in Fig. 1, the most important reaction which produces ^{7}Be is ^{3}He+^{4}He reaction and the main reaction which destroys it is ^{7}Be(n,p)^{7}Li followed by ^{7}Li(p,α)α. The cross section of ^{3}He(α,γ)^{7}Be reaction was measured by several groups using several methods and its knowledge is nowadays better than 8% according to the latest evaluation of solar fusion cross sections of Adelberger et al. [7]. Concerning ^{7}Be(n,p) reaction, its cross section is very well known according to the latest analysis of BBN rates performed by Descouvemont et al. [8] as well as the following reaction ^{7}Li(p,α)α.

Recently some authors [9, 10, 11, 12] investigated the possibility that missed resonances in some secondary destruction channels of ^{7}Li and ^{7}Be with p,n, d,t,^{3}He may be responsible of the ^{7}Li deficit. From their investigations, three promising candidates came out: ^{7}Be+d, ^{7}Be+^{3}He and ^{7}Be+^{4}He reactions. According to Cyburt et al. [12], the $5/2^+$ state close to 16.8 MeV excitation energy in the compound nucleus ^{9}B may enhance significantly the ^{7}Be+d reaction rate, thus leading to an appreciable depletion of ^{7}Li, if the deuteron width of the state is between 10-40 keV. For ^{7}Be+^{3}He channel, the presence of 1^- or 2^- state close to 15 MeV excitation energy in ^{10}C with a resonance energy between 50 to 100 keV and having a narrow width may reconcile the predicted primordial ^{7}Li with the observed one [9]. For ^{7}Be+^{4}He reaction, the solution may come from an existence of a hypothetical state close to 7.8 MeV in the compound nucleus ^{11}C and having a total width between 30-160 keV [11].

^{7}Be+d reaction was investigated by various works and was dismissed as possible solution to the ^{7}Li problem. Indeed, the ^{7}Be(d,p)2α cross section measurement [13] showed no enhancement of the cross section in the BBN region. The ^{7}Be(d,d) measurement [14] didn't observe any resonance in the region of interest and the extracted upper limit for the deuteron width of about 1 keV was found much less than the needed width to solve the ^{7}Li problem. And finally the recent study [15] of ^{7}Be(d,p)2α reaction rate using the spectroscopic properties of the state of interest at 16.8 MeV of ^{9}B (Ex=16.80 MeV±10 keV, Γ=81(5) keV, $J^\pi=5/2^+$) obtained from ^{9}Be(^{3}He,t)^{9}B measurement, showed that the state at 16.8 MeV can not enhance significantly ^{7}Be(d,p)2α reaction rate and its impact on ^{7}Li abundance is less than 4%.

So what about ^{7}Be+^{3}He and ^{7}Be+^{4}He? the case of ^{10}C is appealing because no states between 10 and 16.5 MeV are known and the state of interest lies close to 15 MeV. For ^{11}C, the excited states up to 9 MeV were studied through various indirect reactions and no state close to 7.8 MeV is reported. However, no dedicated measurements in this narrow energy region were carried out so one can not exclude that a weakly state in this energy region has been missed.

2. Experiment and results

A search for the missing levels has been performed at the ALTO facility [16]. ^{10}C and ^{11}C nuclei were populated with the (^{3}He,t) charge exchange reaction on ^{10}B and natural Boron targets. (^{3}He,t) measurements were also performed on C and Si_2O_4 targets because of the contamination of the boron targets by ^{12}C and ^{16}O nuclei. The emitted tritons were detected in the focal plane of Split-Pole spectrometer first by a position-sensitive gas detector and then by ΔE proportional gas counter. For ^{10}B(^{3}He,t) the tritons were detected at four different angles, 7°,10°,13° and 15° and for ^{11}B(^{3}He,t), they were detected at two angles, 7° and 10°. A good identification of the tritons and the deuterons was achieved by only using the position versus ΔE measured spectrum, see Fig. 2.

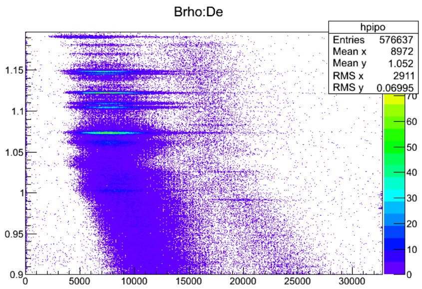

Figure 2. Bρ versus energy loss identification spectrum

The measured bρ position spectra for ^{11}C and ^{10}C at the angle of 10° are displayed in Fig. 3 and Fig. 4 respectively. The well populated peaks in ^{11}C spectrum are the already well known ^{11}C levels. No new peaks are observed at 10° in the energy region of interest between 7.79 and 7.9 MeV, neither at 7°. The very small "peaks" observed in this energy region are only statistical fluctuations. Thanks to the very large signal to background ratio measured in this spectrum, we can assert that it is very unlikely that a new state in ^{11}C exists in this energy region. Moreover, all the known states in the mirror nucleus ^{11}B below 9 MeV excitation energy have their counterpart in ^{11}C nucleus. For the ^{10}C case, no additionnal states in ^{10}C are observed around 15 MeV (see Fig. 4, blue histogram), the only states we observe are those coming from the ^{16}O contamination of the target as one can see in the spectrum (red histogram) obtained from the measurement on Si_2O_4 target. The same results were obtained at 7°, 13° and 15° measured angles. But since the background in this case is very important and the signal to background ratio is 10 times less than in the case of ^{11}C, we can not exclude that a state may be hidden in the background. However, from a chi2 study [16] of a simulated assumed state close to 15 MeV with various widths and various populated cross sections on the top of measured background, we could draw an exclusion zone in the plane of the charge-exchange cross section versus the width of the assumed state (see figure 4 in [16]) and conclude that any 1^- or 2^- state of ^{10}C in the excitation energy region around 15 MeV should have very likely, if present, a total width larger than 590 keV with a 95% CL to escape our detection.

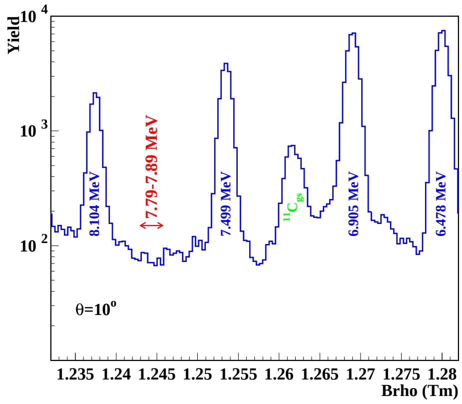

Figure 3. ^{11}C Bρ position spectrum measured at 10°.

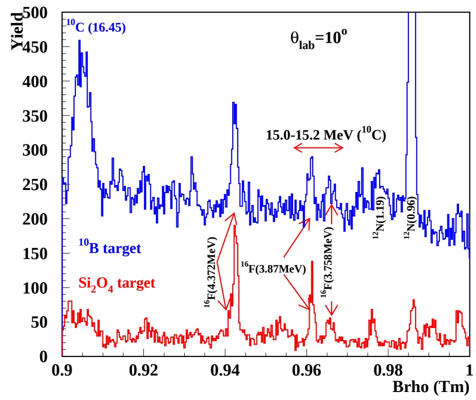

Figure 4. ^{10}C Bρ position spectrum measured at 10°.

Reaction rate calculations for the two only possible open channels, ^{7}Be(^{3}He,p)^{9}B and ^{7}Be(^{3}He,α)^{6}Be were performed assuming a 1^- state in the compound nucleus ^{10}C having a total width equal to our deduced lower limit, 590 keV, and even a three times lower value, 200 keV in case the differential charge-exchange cross section is three times smaller than the expected minimum one. The calculated ^{7}Be+^{3}He reaction rates [16] were included in a BBN nucleosynthesis calculation and were found to have no impact on the primordial ^{7}Li/H abundance. In conclusion, our results exclude ^{7}Be+^{3}He and ^{7}Be+^{4}He reactions as possible solution to ^{7}Li.

Finally With Orsay results [16] and those of previous works [13, 14, 15] concerning other possible resonant reaction channels, we may even say that the solution to the ^{7}Li problem has very likely to be found outside of nuclear physics.

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