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A method for investigation of the D(^{4}He, γ)^{6}Li reaction in the Ultralow energy region under a high background

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ABSTRACT

The cosmological lithium problem, that is, a noticeable discrepancy between the predicted and observed abundances of lithium, is in conflict with the Standard Big Bang Nucleosynthesis model. For example, the abundance of ^{7}Li is 2–4 times smaller than predicted by the Standard Big Bang Nucleosynthesis. As to the abundance of ^{6}Li, recent more accurate optical investigations have yielded only the upper limit on the ^{6}Li/^{7}Li ratio, which makes the problem of ^{6}Li abundance and accordingly of disagreement with the Standard Big Bang Nucleosynthesis predictions less acute. However, experimental study of the D(^{4}He, γ)^{6}Li reaction cross section is still of current importance because there is a theoretical approach predicting its anomalously large value in the region of energies below the Standard Big Bang Nucleosynthesis energy. The work is dedicated to the measurement of the cross section for the D(^{4}He, γ)^{6}Li reaction proceeding in zirconium deuteride at the incident ^{4}He$^+$ion energy of 36 keV. The experiment is performed at a pulsed Hall plasma accelerator with an energy spread of 20% FWHM. A method for direct measurement of the background from the reaction chain D(^{4}He, ^{4}He)D → D(D, n)^{3}He → (n, γ) and/or (n, n' γ) ending with activation of the surrounding material by neutrons is proposed and implemented in the work. An upper limit on the D(^{4}He, γ)^{6}Li reaction cross section $\sigma \le 7 \cdot 10^{-36}$ cm^2 at the 90% confidence level is obtained.

1. Introduction

The experimental basis of the Standard Cosmological Big Bang Model comprises the expansion of the Universe observed through the red shift, cosmic microwave radiation, and primordial synthesis of light elements [1–4]. It is believed that cosmological nuclear synthesis of light elements began approximately 5 s after the Big Bang and proceeded successively in the energy interval most effective for astrophysical reactions (400–30 keV) with the formation of the nuclei ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, and ^{7}Be (Fig. 1 from [5]). A small amount of the ^{7}Li and ^{6}Li nuclei (because of a still insufficient concentration of the ^{4}He and ^{3}He nuclei and a rather high Coulomb barrier of ~1 MeV for the reactions) are produced in the reactions ^{4}He(^{3}H, γ)^{7}Li, ^{4}He(^{3}He, γ)^{7}Be → ^{7}Li, and ^{2}H(^{4}He, γ)^{6}Li. But the ^{7}Li and ^{6}Li nuclei are loosely bound and fast destroyed, and the absence of stable nuclei with the atomic numbers $A=5$ and $A=8$ leads to freeze-out of nucleosynthesis, Fig. 1.

Within the standard cosmological model abundances of light elements are calculated by numerically solving a system of evolution equations for the main characteristics of the nuclear synthesis. These are the cosmic scale factor, the total baryon density with the dark matter and dark energy added, the chemical potential of the electron gas, the Universe temperature T, and abundances of all particles participating in mutual transformations. These calculations yield the following mass abundances of light elements relative to the hydrogen abundance [3,4]:

^{4}He – $Y_p \approx 0.24709 \pm 0.00025$; D/H$=(2.58 \pm 0.19) \cdot 10^{-5}$; ^{3}He/H $=(1.039 \pm 0.090) \cdot 10^{-5}$; ^{7}Li/H$=(4.68 \pm 0.67) \cdot 10^{-10}$; $\log_{10}$(^{6}Li/H)$= -(13.89 \pm 0.02)$; ^{6}Li/^{7}Li$=2.75 \cdot 10^{-5}$.

The mass abundances of light nuclei obtained using the means of observational astronomy are $Yp = 0.2465 \pm 0.0097$ [6], D/H$=(2.59 \pm 0.15) \cdot 10^{-5}$ [7], ^{7}Li/H$=(1.58 \pm 0.31) \cdot 10^{-10}$ [8], and ^{6}Li/^{7}Li$=0.13 \pm 0.05$ [9].

Thus, the amount of the ^{7}Li nuclei is 2–4 times smaller than the Standard Big Bang Nucleosynthesis predicts. This is the cosmological lithium problem existing for more than 20 years. Two hypotheses are investigated to explain the contradiction. The first

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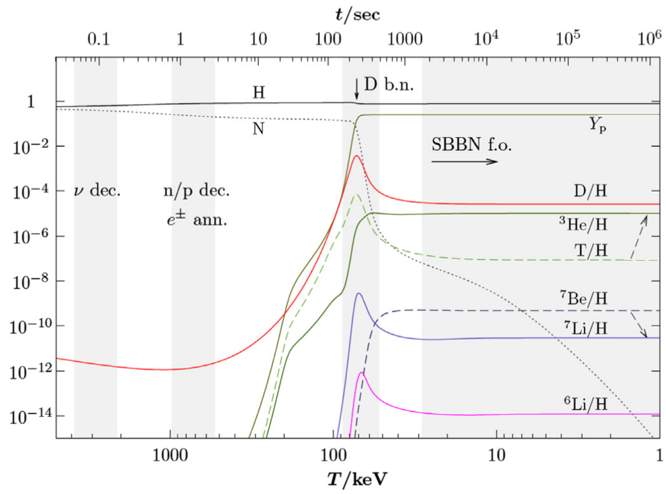

Fig. 1. (Reproduced from [5]): Time and temperature evolution of all Standard Big Bang Nucleosynthesis – relevant nuclear abundances. The vertical arrow indicates the moment at $T_9 \approx 0.85$ at which most of the helium nuclei are synthesized. The gray vertical bands indicate main Big Bang Nucleosynthesis stages. From left to right: neutrino decoupling, electron-positron annihilation and n/p freeze-out, D bottleneck, and freeze-out of all nuclear reactions.

hypothesis questions the standard Big Bang Nucleosynthesis model and includes several models aimed at modifying the Big Bang Nucleosynthesis model so as to eliminate the cosmological lithium problem using nonstandard physics [3,5]. The second hypothesis assumes that the cross sections for the nuclear reactions that may result in lithium isotopes can by modified by involving unknown narrow resonances, or other nuclear reactions [4,10].

As to the ^{6}Li abundance, recent more accurate optical investigations [11] have yielded only the upper ratio limit on the ^{6}Li/^{7}Li ratio, $^6\mathrm{Li}/^7\mathrm{Li} \leq 0.01$, which made the problem of ^{6}Li abundance and accordingly of disagreement with the Standard Big Bang Nucleosynthesis predictions less acute.

Until recently, the cross section for the main ^{6}Li production reaction D(^{4}He, γ)^{6}Li has not been experimentally measured in the region of Big Bang Nucleosynthesis energies. The point is that the cross section for this reaction of radiative capture of α particles by deuterons is unusually small because, according to the isotopic spin selection rules, E_1–M_1 transitions are strongly suppressed when $\Delta T = 0$ (isospins of all participating particles are zero), and the decisive role is played by the $E2$ multipole, the small value of which is in turn determined by the kinematic suppression factor that enters into the electromagnetic transition operator. To compare, the cross section for the reaction of the radiative capture of α particles by a heavier hydrogen isotope tritium ^{3}H(^{4}He, γ)^{7}Li is more than three orders of magnitude larger [12]. In the latter reaction, the E_1 multipole dominates.

In connection with the small cross section for the D(^{4}He, γ)^{6}Li reaction, two attempts were made to obtain experimental data on this reaction in the Big Bang Nucleosynthesis energy region using Coulomb dissociation of the ^{6}Li nucleus into the в αD channel in the field of a heavy nucleus ^{208}Pb(^{6}Li, αD)^{208}Pb [13,14], which resulted in establishing upper limits. The same was achieved in the attempt to measure directly the D(^{4}He, γ)^{6}Li reaction yield at the ^{4}He$^+$ion energy $E_\alpha = 160$ keV (E_α is the helium ion energy in the laboratory coordinate system) using a highly pure germanium (HPGe) detector [15]. Finally, in 2014 the LUNA collaboration directly measured the yield from the D(^{4}He, γ)^{6}Li reaction at the ^{4}He$^+$ion energies $E_\alpha = 280$ and 400 keV ($E = 94$ and 134 keV in the c.m.s.) [16]. The result of the experiment was determination of the ^{6}Li mass abundance $^6\mathrm{Li/H} = (0.74 \pm 0.16) \cdot 10^{-14}$ and the ratio $^6\mathrm{Li}/^7\mathrm{Li} = (1.5 \pm 0.3) \cdot 10^{-5}$, which thus confirmed the status of the cosmological lithium problem. In addition, the experimental results agreed well with one of the recent theoretical calculations [17] where contributions from the E_1 and E_2 multipoles were considered. It is noteworthy that in [16] they did not perform the direct measurement of the background with subsequent subtraction of the background event from the experimental data.

In [18] an attempt was made to solve the cosmological lithium-6 problem using two approaches. In one it is assumed that during Big Bang Nucleosynthesis there were charged massive (1–100 GeV) supersymmetric scalar leptons (stau) which could be bound with light nuclei and affect cross sections of fusion reactions. In the other approach the ^{4}He+^{2}H interaction potential is modified within the optical model by including the long-range part in it. The modification of the potential considerably increases the cross section in the energy region below the Big Bang Nucleosynthesis energy.

The authors show that good agreement between the calculated D(^{4}He, γ)^{6}Li reaction cross section and the experimental results [19] can be obtained by fitting the parameters of the long-range part of the potential. It was decided to verify the results of the calculations [18] and measure the reaction cross section in the region of energies below the Big Bang Nucleosynthesis energy.

2. Investigation of background conditions

In view of the small cross section for the reaction реакции D(^{4}He, γ)^{6}Li ($E_\gamma = 1.481$–1.490 MeV), its accompanying background processes and their minimization methods play an important part in the investigation of this reaction. The background processes are the environmental radioactive radiation, cosmic radiation, and radiation accompanying the reaction under investigation. Pulsed operation of the Hall plasma accelerator allows continuous measurement of the cosmic radiation and natural radioactive backgrounds during the experiment. To this end, in the intervals between the 10 μs long operating pulses within which the accelerated ^{4}He$^+$ion beam hits the target, background events are recorded for the identical period of time but without applying high voltage. Thus, background events are accumulated in parallel with the accumulation of the events from the detectors during the acceleration; i.e., in addition to a factor of 10^5 suppression of the background from cosmic radiation and natural radioactivity, it is measured without spending extra time for this procedure. By the radiation accompanying the reaction under investigation is meant γ radiation resulting from a chain of background reactions D(^{4}He, ^{4}He)D→D(D, n)^{3}He→(n, γ) and/or (n, n'γ) ending with activation of the surrounding material by neutrons ($E_n = 2.5$ MeV) and occurrence of γ rays with the energy close to $E_\gamma = 1.48$–1.52 MeV. To study the problem, we first used the LUNA information from the investigations of the same reaction at higher ^{4}He$^+$ion energies and approximately the same neutron energy [20]. The LUNA setup comprised a brass collimator, a copper calorimeter, and lead shielding (mass 3390 kg). Due to the neutron activation of the materials in the setup, the γ energy spectrum recorded by the HPGe detector features intense γ lines of ^{52}Cr ($E_\gamma = 1434$ keV), ^{65}Cu ($E_\gamma = 1482$ keV), ^{63}Cu ($E_\gamma = 1547$ keV), ^{65}Cu ($E_\gamma = 1623$ keV), ^{63}Cu ($E_\gamma = 1861$ keV), ^{56}Fe ($E_\gamma = 1811$ keV), ^{63}Cu ($E_\gamma = 2012$ keV), and ^{63}Cu ($E_\gamma = 2081$ keV). It is seen that neutron activation increased the Compton background relative to natural background by a factor of more 50. It follows that such materials as copper, stainless steel, brass, and lead should be avoided in the setup.

The γ detection system of our setup designed for investigating radiative capture reactions consists of eight $10 \times 10 \times 40$ cm^3 NaI (Tl) detectors [21–23]. The detectors weigh ~117 kg, of which 98.7 kg is the iodine mass, 17.8 kg is the sodium mass, and 0.5 kg is