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## SHORT COMMUNICATIONS

# Effect of the Neutron Lifetime on Processes in the Early Universe

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**Abstract**—The influence of the neutron lifetime on the abundance of light elements produced during the primordial nucleosynthesis early in the birth of the Universe is considered. Among light elements, namely, D, $^3$He, $^4$He, and $^7$Li, $^4$He proves to be most sensitive to neutron lifetime $\tau_n$. Astronomic data on the light element abundance also provide the best accuracy for $^4$He. The solution of a number of problems discussed in this paper requires improving the accuracy of observations for the $^4$He abundance and refining the value of $\tau_n$.

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## NEUTRON LIFETIME

A neutron is a particle that, along with a proton, enters into the composition of an atomic nucleus. It has a half-integer spin; its charge equals zero; and its mass is higher than that of a proton (in energy units) by $Q \equiv \Delta mc^2 = 1.29$ MeV, where $\Delta m = m_n - m_p$ is the difference between the proton and neutron rest masses (this value exceeds the electron mass roughly by 2.5 times). In the free state, a neutron is unstable and decomposes into a proton, electron, and electron antineutrino ($\beta^-$-decay). According to recent measurements, the neutron lifetime is equal to $\tau_n = 880.3 \pm 1.1$ s [1]. The neutron lifetime is measured by different techniques, among which the following three can be distinguished:

(i). Measurements in a neutron beam with decay product detection (see, e.g., [2]).

(ii). The use of traps with material walls (bottles), from which ultracold neutrons with velocities below several meters per second (which corresponds to a classical gas temperature of $10^{-3}$ K and de Broglie wavelength $\lambda \sim 100$ nm) reflect without losses (see, e.g., [3]).

(iii) The use of magnetic traps, which exploit the interaction of the neutron magnetic moment with an external magnetic field (see, e.g., [4]).

At present, the values of $\tau_n$ obtained by these approaches differ considerably [5, 6]. This discrepancy becomes especially clear, in particular when the results obtained by the first and second techniques mentioned above are compared. In the former case (neutron beams), $\tau_{\text{beam}} = 887.7 \pm 1.2$ s [8]; in the latter case (material traps), $\tau_{\text{bottle}} = 879.9 \pm 0.9$ s [7]. This differs by 3.9σ from the worldwide average value. The reasons for this discrepancy have not been elucidated so far [9], since different experiments exhibit different systematic errors, but no compelling arguments in favor of a given technique have been suggested.

Researchers at Petersburg Nuclear Physics Institute (PNPI) have been carrying out regular measurements of the neutron lifetime for a long time. A great step forward in this field of knowledge is an experiment with a large material trap that allows lifetime measurements of a free neutron with an accuracy of 0.5 s. This experiment was prepared in the PNPI and was conducted in France (2014–2015) on a reactor at the Institut Laue–Langevin.

## SIGNIFICANCE OF THE NEUTRON LIFETIME IN ASTROPHYSICS

The exact determination of the neutron lifetime is of great importance as an independent problem of nuclear physics and weak interaction physics. This question is also of great significance for different astrophysical problems and cosmology. For example, when massive stars experience gravitational collapse, their central areas are rapidly (within several seconds or several fractions of a second) compressed up to nuclear densities simultaneously with the neutronization process (electrons are embedded in protons). This collapse results in the explosion of a supernova and produces a neutron star [10]. This explosion generates intense neutron beams, which provide rapid *s* and *r* processes of nucleosynthesis; they produce elements

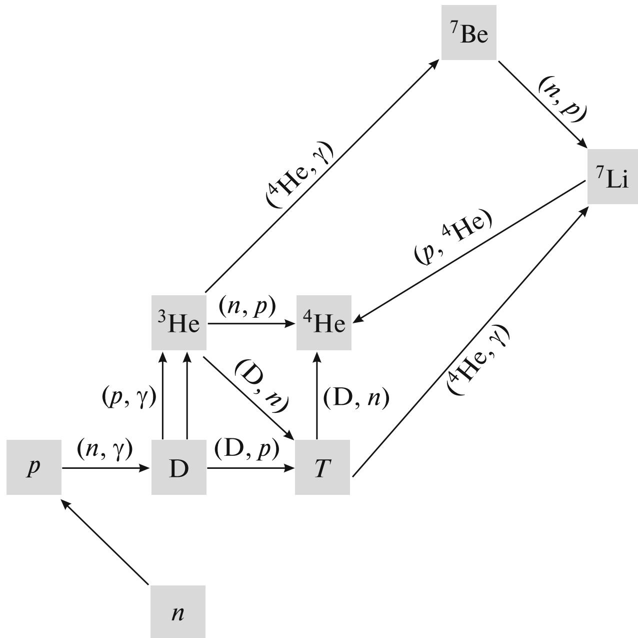


**Fig. 1.** Twelve main reactions used in the numerical codes for the primordial nucleosynthesis.

heavier than iron in the galaxies [11]. Obviously, neutron lifetime is one of the parameters that govern the relative abundance of heavy elements produced during the stellar evolution in galaxies.

Neutron lifetime also plays a key role in cosmology. According to recent observations [12], the Universe we live in consists of 95% dark energy (68.3%) and dark matter (26.8%), while ordinary (baryonic) matter accounts for as little as 5%. In turn, a major part of baryonic matter (by weight) includes hydrogen (75%) and helium (24%), the relative densities of which were established in the course of the primordial nucleosynthesis in the early Universe (within several minutes of the Big Bang). Heavier elements with nucleus charge $Z > 3$ account for 1% [13]. Using the primordial nucleosynthesis theory, one can determine the concentrations of light elements (hydrogen, deuterium, helium, and lithium) by numerical simulation and then compare them with the observations. Using different neutron lifetimes in a numerical simulation, we obtain different relative concentrations of the above elements. The reason for this is as follows. It is assumed that, directly after the birth of the Universe, it was too hot for atomic nuclei to exist. At temperature $T \gtrsim 1$ MeV, forming nuclei that were heavier than hydrogen were instantly destroyed by photons, the relative concentration of which is several billions times higher than the baryon concentration in the Universe $\eta \equiv n_b/n_\gamma \simeq 6.1 \times 10^{-10}$ [1]. The relative concentration of protons and neutrons as a function of decreasing temperature is estimated by the following relationship: $n_n/n_p \propto \exp(-Q/kT)$. However, thermodynamic equilibrium maintaining this relationship through weak interaction reactions is disturbed, since the Universe expands at temperatures less than 0.8 MeV and ratio $n_n/n_p$ freezes at 1/5. Subsequently, the concentrations change due to the β-decay alone and their ratio decreases down to 1/7 by the onset of nuclear reactions [14]. If the lifetime of neutrons is shorter, their fraction decreases further. The mass fraction of $^4$He ($Y_p$) versus relative proton and neutron concentration $n/p$ can be estimated from the simple relationship [1, 15]

$$Y_p = \frac{2n}{n+p} = \frac{2(n/p)}{n/p+1} \approx 0.25. \quad (1)$$

It can be seen that the shorter the length of $\tau_n$, the smaller the content of helium produced in the primordial nucleosynthesis.

To measure the abundance of helium and other elements in the Universe, spectroscopic experiments are applied. However, the Universe originated more than 13 billion years ago and the primary concentrations of elements have changed since then and continue to change during a star's evolution. As is known, heavier nuclei are produced from light nuclei during thermonuclear synthesis in stars. In small stars, this cycle terminates with carbon and oxygen and, in massive stars, it terminates with iron; even heavier

Present-day observations on the primordial abundance of light elements. Values predicted from the numerical simulation [21] of the primordial nucleosynthesis with parameter $\eta = 6.1 \times 10^{-10}$, which was determined by analyzing data for the relic radiation anisotropy analysis [12] are given for comparison

| Element | Predictable value | Observed value | Reference |
|---|---|---|---|
| $^4$He | $0.2471 \pm 0.0003$ (0.1%) | $0.2551 \pm 0.0022$ (0.9%) | [18] |
| | | $0.2449 \pm 0.0040$ (1.6%) | [19] |
| | | $0.251 \pm 0.014$ (5.6%) | [12] |
| D | $(2.58 \pm 0.13) \times 10^{-5}$ (5.0%) | $(2.53 \pm 0.04) \times 10^{-5}$ (1.6%) | [22] |
| | | $(2.48 \pm 0.13) \times 10^{-5}$ (5.2%) | [23] |
| | | $(3.26 \pm 0.29) \times 10^{-5}$ (8.9%) | [20] |
| $^7$Li | $(4.68 \pm 0.67) \times 10^{-10}$ (14%) | $(1.58^{+0.34}_{-0.28}) \times 10^{-10}$ (22%) | [24] |

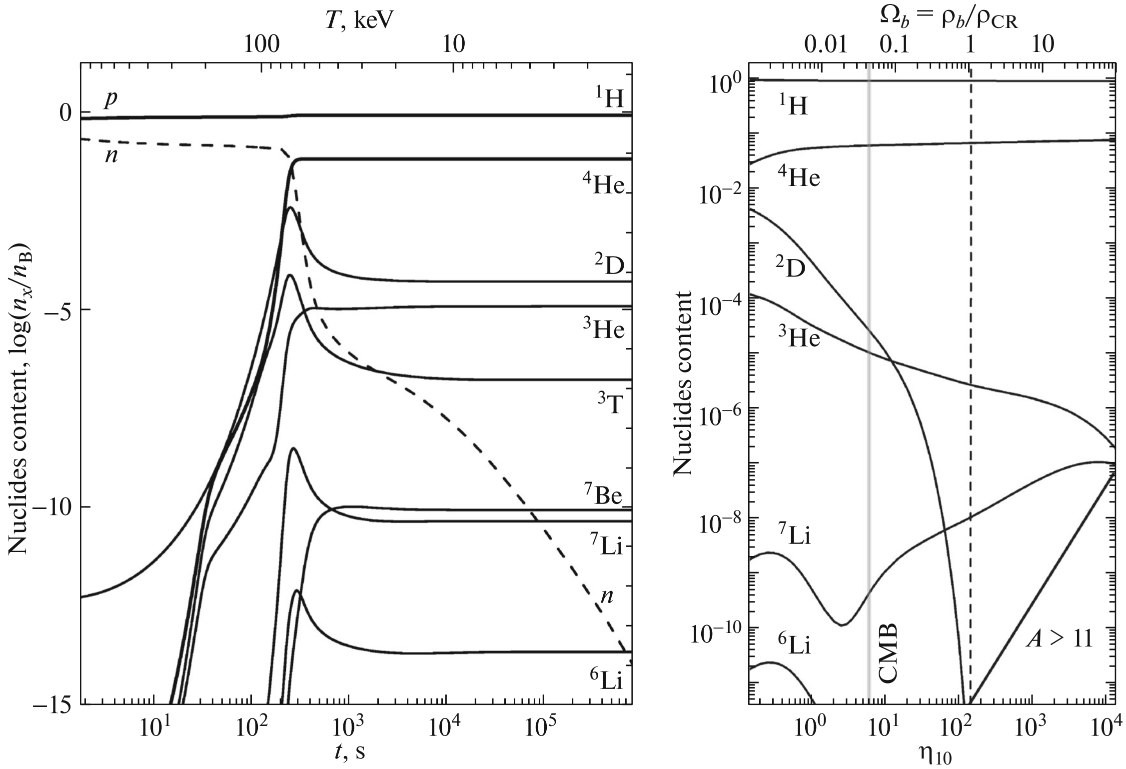


**Fig. 2.** Relative content of light nuclides vs. cosmological time elapsed from the Big Bang (left panel) and nuclide yields vs. key cosmological parameter (baryon-to-photon ratio $\eta_{10} = 10^{10}\eta$, right panel). Calculations were carried out using the original numerical code for the primordial nucleosynthesis [20].

nuclides result from supernova explosions. Thus, after the emergence of stars, the concentration of heavy nuclei in the interstellar medium grows over time. As for, deuterium, the element second in mass after hydrogen, it is assumed to be burnt up during stellar evolution, although there may be some processes that produce deuterium in small amounts [16].

In astrophysics, elements heavier than helium ($Z > 2$) are referred to as *metals* and their relative concentration is usually called *metallicity*. This parameter can relate the composition of the primordial substance to the composition of clouds enriched with the products of the evolution of stars of the first and next generations. Thus, it becomes possible to make necessary corrections to experimental data. Modern techniques for determining the concentrations of primordial elements measure the abundances of light elements, namely, helium-4 ($Y_p$), deuterium, and lithium. To this end, the observations of clouds of a partially ionized substance and the extrapolation of data to zero metallicity are used. The metallicity is usually estimated as a ratio of iron-to-hydrogen atom concentration; however, other elements, e.g., silicon or oxygen can also be used.

The currently available models of the primordial nucleosynthesis include 12 main reactions (Fig. 1), and the extended versions can comprise up to 424 reactions [17]. The absence of a stable element with mass number $A = 5$ signifies a bottleneck in the chain of nuclear reactions. This implies that neutrons burn up mainly in $^4$He.

Figure 2 plots the relative content of light nuclides versus the cosmological time that elapsed from the Big Bang (left panel), as well as the nuclide yield versus the key cosmological parameter, the baryon-to-photon ratio $\eta \equiv n_b/n_\gamma$ (right panel). Calculations were carried out using the corresponding numerical code for primordial nucleosynthesis [18].

The $^4$He concentration in the interstellar medium can only increase over time because hydrogen transforms into helium during the stellar evolution. The $^4$He primordial composition is estimated by extrapolating the dependence of the observed helium abundance on the metallicity to zero metallicity. However, it is still difficult to determine the fraction of helium in the interstellar matter. At present, there are two results that intersect at a level of 1.6σ, which were obtained by different teams of researchers [19, 20] (see table).

The D : H isotope ratio that arises by the end of the primordial nucleosynthesis could only decrease during the subsequent evolution of the Universe; when the interstellar matter penetrates stars, deuterium rapidly burns out. This means that any estimate of D : H

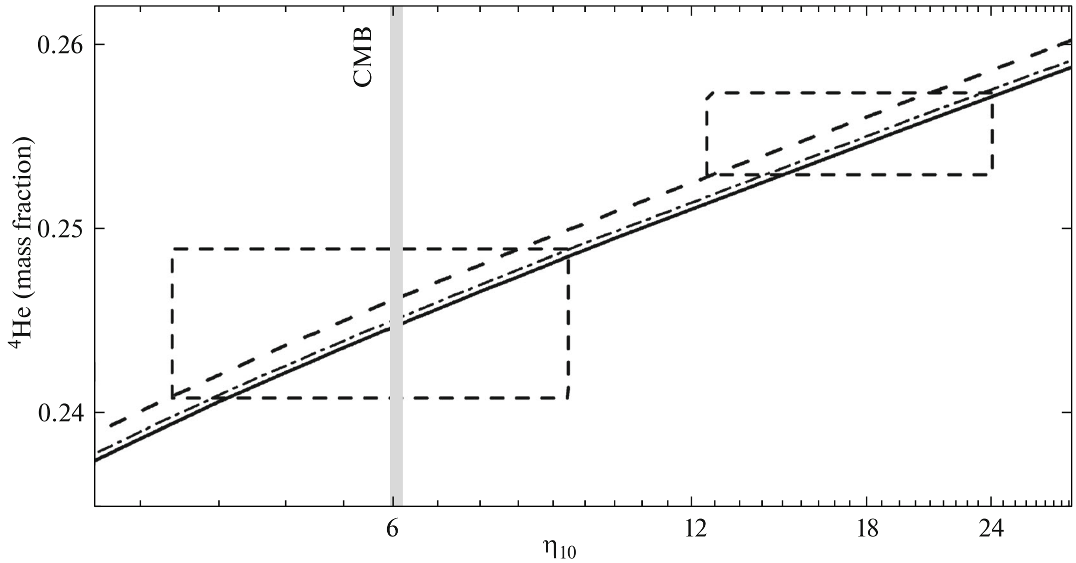


**Fig. 3.** $^4$He weight fraction calculated for different neutron lifetimes ($\tau_n$ = 885.7, 880.3, 878.5 s) vs. baryon-to-photon ratio $\eta_{10}$. Solid curve corresponds to the smallest value of $\tau_n$. Vertical band shows the allowable value of $\eta_{10}$ obtained from the data for the relic radiation anisotropy [12]. Dashed rectangles outline observation data for the $^4$He fraction obtained in [19] (upper rectangle) and [20] (lower rectangle).

is the lower limit of its primary value. Therefore, to determine the primordial value of D : H, the isotopic composition of the interstellar matter at early stages of the cosmological evolution should be measured. For these purposes, the absorption spectra of quasars with high red shifts are used. Deuterium measurement techniques, as well as their advantages and disadvantages, are described in detail in [25].

Lithium-7 is the heaviest among stable light element. It is of interest from the viewpoint of the primordial nucleosynthesis, since the fraction of even heavier elements that appeared at the time was extremely small [1, 26]. However, simulation data for primordial nucleosynthesis differ by three times from observation data, which is nowadays known as the Primordial Lithium Problem [27].

On the other hand, in the primordial nucleosynthesis model, the sensitivities of different nuclides to a change in the neutron lifetime vary. The sensitivity coefficients, which show variations in the abundance of the element over the lifetime of the neutron, can be found in, e.g., [28]. When the relative change in the values of interest, $\Delta X_i/X_i$, is not higher than 10%, their variations are well described by a linear approximation. For example, it was shown [15] that the use of the lifetime found in [3], $\tau_n = 878.5 \pm 0.7$ s, instead of the mean world value, $\tau_n = 885.7 \pm 0.8$ s (used that time), leads to better agreement between the results, namely, between the baryon asymmetry measured by the Wilkinson Microwave Anisotropy Probe and the value $Y_p = 0.2452 \pm 0.0015$ borrowed from [29]

Calculations of the primordial nucleosynthesis show that $^4$He is most sensitive to a change in the neutron lifetime. In Fig. 3, data on primary $^4$He calculated for $\tau_n$ = 885.7, 880.3, and 878.5 s are shown. It can be seen that, although the variations in the weight of helium with $\tau_n$ is less than the observation inaccuracy outlined by rectangles, it is comparable to the inaccuracy. Hence, further improvement in the observation accuracy will require knowledge of the correct neutron lifetime. The discrepancy between the $^4$He data obtained in [18] (Fig. 3, upper rectangle) and analytical data for the relic radiation anisotropy [12, 22] can be interpreted as the presence of additional relativistic degrees of freedom, for example, a sterile neutrino. The shorter the length of $\tau_n$, the more realistic this supposition is.

In conclusion, it should be emphasized that, for the problem to be considered solved, it is first necessary to raise the accuracy of the observation data on the $^4$He abundance and refine the value of $\tau_n$.


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