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Isotopes: How did they all begin? Primordial nucleosynthesis: experimental study of the roles of neutrons

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Abstract
Light nuclei with mass number of below 8 are considered to be produced by the so-called the Big-bang nucleosynthesis (BBN) occurring in the early universe. Since BBN depends on various assumptions related to the origin of the universe and the laws of fundamental interactions and elementary particles, those assumptions can be verified by comparing the abundances of light isotopes calculated with BBN and the astronomically observed ones. Since the neutrons are the starting materials of BBN together with protons, and also they are electrically neutral, they play a unique and critical roles in BBN. In this paper status of the BBN analysis and experimental studies of the properties of neutrons relevant to BBN will be reviewed.

Keywords Big-bang · Nucleosynthesis · Origin of elements · Neutron life-time · Large-extra dimensions

Introduction

When did the Universe begin? How did the Universe begin? Why was the Universe born? What is the fate of the Universe?—Those are the questions not only from cosmologists but from rather general people, since they are closely related to origins of the solar-system, the Earth, and lives. A hint to those questions was obtained from the systematic observation of the red shift z of the distant galaxies as a function of the distance R from the Earth. and the distance R of galaxies. It was found that z shows a clear proportionality to R [1], which is called the Hubble-Lemaître law. It is the direct evidence of the fact that our universe is expanding as suggested from the solution of the Einstein's equation for the universe. Alpher [2] considered that the temperature and the density of the early universe should be much higher than those of the present, and light nuclei could be produced via the nuclear reaction network shown by Fig. 1. Since the half-lives of the isotopes with the mass number 8 are too short to maintain nuclear reactions, it is not possible to produce heavier elements in significant amounts. This process is called the big-bang nucleosynthesis (BBN), and is considered to be responsible for the origin of light elements up to lithium.

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Theory

The standard model of BBN assumes the following conditions;

(1) isotropic and homogeneous matter distribution,
(2) general relativity,
(3) standard theory of electromagnetic and weak interactions,
(4) neutrinos are light and stable, and
(5) number of species of light neutrinos is three.

These assumptions can be verified through the comparison of the abundances of light isotopes obtained from the BBN calculations and the ones from astronomical observations.

Figure 2 shows the comparison of the abundances of light isotopes from the observations and the ones calculated with the standard BBN model as a function of the baryon-to-photon ratio η_{10} in units of 10^{10}, which is equivalent to the baryon density at the epoch of BBN.

As can be found in Fig. 2, the observed abundances of ^{4}He and D are well reproduced by the standard BBN calculation with η_{10} determined by the observation of the fluctuation of the cosmic-microwave background [3], which is one of the pieces of evidence for the big-bang theory. On the other hand, the observed abundance of ^{7}Li is more than a factor of two smaller than the BBN calculation with the

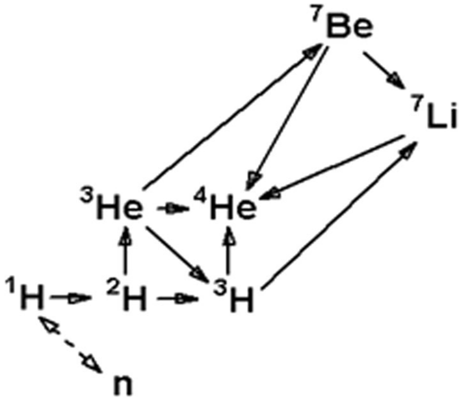

Fig. 1 Nuclear reaction network of the standard big-bang nucleosynthesis

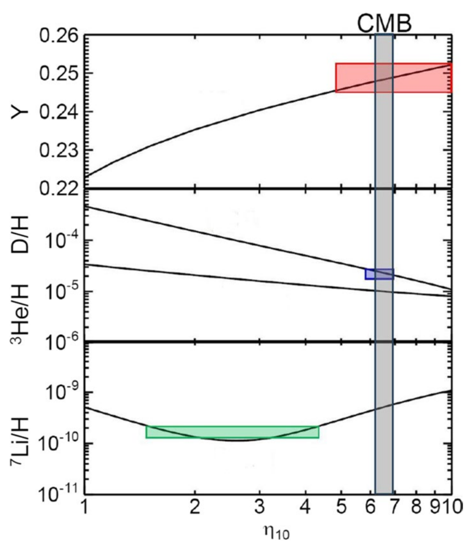

Fig. 2 Comparison of observed (colored boxes) and calculated (solid curves) abundances of light isotopes. *Y* denotes the mass fraction of ^{4}He. A gray band shows the region of the baryon-to-photon ratio η_{10} determined from the WMAP observation of the fluctuation of cosmic-microwave background [3]

same value of η_{10}, which is called the "lithium problem", suggesting that there should be some problem in either the assumptions for the standard BBN, the data of the relevant nuclear reaction rates, or the astronomical observations.

Experiment

To calculate the production yields of light isotopes in BBN, reliable data of the thermal reaction rates of the relevant nuclear reactions are required. The reaction rate dependence of the production yields of the isotopes are studied in Ref. [4], and it was found that the reaction rates of neutron β-decay, ^{1}H(n,γ)^{2}H, ^{2}H(p,γ)^{3}He, ^{2}H(d,n)^{3}He, ^{3}He(n,p)^{3}H, ^{3}He(d,p)^{4}He, ^{3}He(α,γ)^{7}Be, ^{7}Be(n,p)^{7}Li are influential for the ^{7}Li yield in the BBN calculation. The rates of those reactions have recently been revisited experimentally. The new data of the ^{3}He(α,γ)^{7}Be [5] and ^{3}He(d,p)^{4}He [6] reactions were found to agree with the previously adopted values within the uncertainty of the evaluation. New measurement of the ^{7}Be(n,p)^{7}Li reaction rate by the n_TOF collaboration reported a 20–40% enhancement of the cross section near the reaction threshold energy, but the ^{7}Li yield of the BBN calculation is reduced by only 13%, which is not enough to suppress the over production of ^{7}Li in the BBN calculation [7]. For the ^{7}Li(p,α)^{4}He reaction, there has been a large discrepancy between existing cross section data, but the most recent result confirmed the evaluated nuclear data. In addition, since the BBN yield of ^{7}Li is not sensitive to the ^{7}Li(p,α)^{4}He reaction rate, 10% change in the reaction rate results in only 0.5% change in ^{7}Li yield, according to the study of Ref. [4], the reaction is not relevant to the lithium problem. The reaction rates of ^{7}Be(d,p)^{7}Li and ^{7}Be(d,$p\alpha$)^{4}He were remeasured with the uncertainty of 30%, which gives the lower limit of the ratio of ^{7}Li production yield in BBN to the observed ^{7}Li abundance of 2.18 [8], suggesting the lithium problem cannot be solved with the updated data. Finally, the ^{7}Be(n,α)^{4}He reaction rate was determined from the measurements of the cross sections of the forward reaction, i.e. the ^{7}Be(n,α)^{4}He reaction [9] as well as the time-reversed ^{4}He(α,n)^{7}Be reaction [10], and the reaction rate was found to be not sufficiently large to reduce the ^{7}Li yield in the BBN calculation to the level of the observed abundance.

Another important nuclear parameter is the life-time of neutrons τ_n, because it affects the production yields of light isotopes by determining the initial ratio between the numbers of protons and neutrons and by changing neutron density during the BBN process [11]. So far, there has been a discrepancy as large as 5σ between the experimental data of τ_n measured with the storage method [12] and the beam method [12] as shown in Fig. 4. Namely, in the storage method, a known number $n(t=0)$ of ultra-cold neutrons (UCNs) are injected into a UCN bottle, and the number $n(t)$ of surviving UCN is measured after a certain time t. τ_n is obtained from the formula $\frac{n(t)}{n(t=0)} = \exp\left(-\frac{t}{\tau_n}\right)$. On the other hand, the decay method measures the decay rate R_n of a beam neutron by counting decay products and obtain τ_n using the formula $R_n = \frac{dn(t)}{dt} = -\frac{1}{\tau_n}\Phi_n$, where Φ_n is the incident neutron intensity. To solve the discrepancy between two methods, an independent measurement will be important. We are promoting an independent measurement with the decay method at the J-PARC materials and life-science experimental facility (MLF) [13]. Figure 3 shows a schematic view of the experimental setup [14].

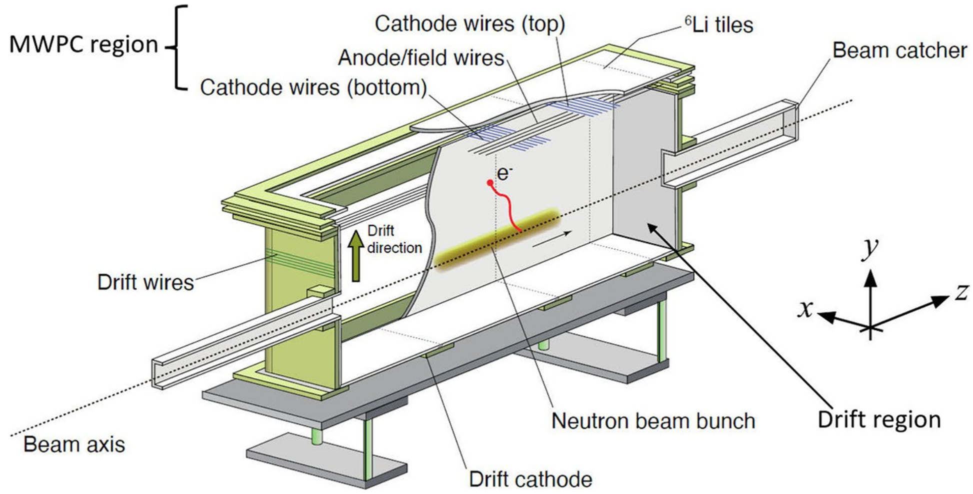

Fig. 3 Experimental setup of the neutron life-time measurement at J-PARC/MLF/BL05 [14]. The TPC consists of the MWPC region on the top and the drift region below

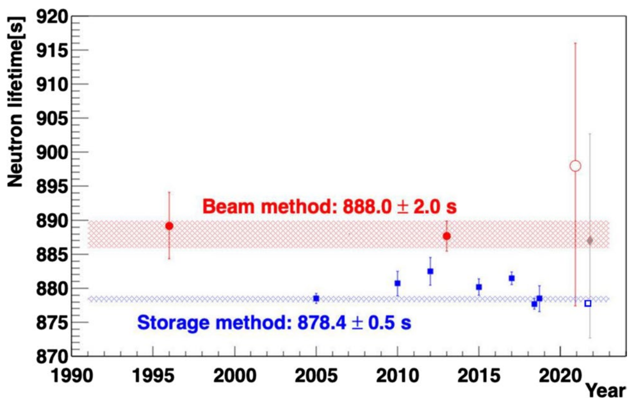

Fig. 4 Summary of the data of neutron lifetime η_n including our recent result (open circle, [14]). Open square shows the result with UCN stored in a magnetic trap [15]

We introduce a cold neutron beam provided at the BL05 beamline of MLF into a time-projection chamber (TPC). The unique point of our method is that the intensity of the incoming neutrons and their β-decay rate are simultaneously measured by counting the emitted particles from the ^{3}He(n,p)^{3}H reaction and the neutron β-rays, respectively, and therefore τ_n is determined with respect to the ^{3}He(n,p)^{3}H reaction cross section which is known with the accuracy of about 0.13%. This method has an advantage that the systematic errors such as the detection efficiencies and the solid angles are canceled at the lowest-order approximation between the measurements of the ^{3}He(n,p)^{3}H reaction and the neutron β-decay, which is essential for reliable determination of τ_n.

As shown in Fig. 4, our recent result [14] of $\tau_n = 898 \pm 10(\text{stat.})^{+15}{}_{-18}(\text{syst.})$ s seems consistent with the previous values. After the publication of Ref. [14], the measurement was continued, and the present statistical error in τ_n achieved 1.5 s according to the ongoing analysis. 11 s of the systematic error 15 s comes from the discrepancy between measured and simulated β-ray energy spectra due to the influence of the unknown background. Its origin is supposed to be the neutrons scattered by the gas, since the intensity of the background depends on the gas pressure in the TPC. From the energy distribution of the background, it is likely to be due to the γ-rays from (n,γ) reactions. At present the source materials of the capture γ-rays are under investigation.

Implications to elementary-particle physics

Discrepancy between the observed and calculated abundances of primordial elements might suggest some exotic physics beyond the standard model of elementary particles and fundamental interactions. As a possible new physics, the effect of the large-extra-dimension (LED) [16] was recently considered in the BBN calculation [17–19]. The LED model assumes that our world is ($N+1$) dimensional space–time (bulk), consisting of ordinary three-dimensional space (brane) and compact ($N-3$)-dimensional inner space, and only graviton can propagate both spaces, which is suitable to solve the "hierarchy" problem, i.e. extreme weakness of the gravitational interaction compared to the other fundamental interactions as the consequence of the leakage of the gravitational flux into the inner space. Because of the additional degree of freedom in the inner space, the expansion rate of the universe will be modified at the temperature above the characteristic energy M^* of the LED model of a few ~ a few ten TeV, affecting production yields of light elements in BBN. The effect of the extra dimensions to BBN has been studied in Refs. [17–19], and it was found that the dark radiation by the electric part of the five-dimensional Weyl tensor can reduce the abundance of ^{7}Li without affecting the abundances of ^{4}He and D. Those works considered the case of the number n of extra dimensions is equal to one, but unfortunately $n \leq 2$ scenarios with $M^* = a$ few ~ a few ten TeV have already been ruled out experimentally [20, 21]. Therefore, it is interesting to consider the BBN with $n \geq 3$ as well as to make the experimental verification of the case of $n \geq 3$. One of the predictions of the LED model is the deviation from the inverse-square law of the gravity (ISL) at the distance near the size of the inner space which corresponds to the Compton wavelength λ of the graviton in the inner space. The gravitational force $F(r)$ including the effect of LED is approximately given as Eq. (1);

$$F(r) = -G\frac{M \cdot m}{r^2} \cdot \left(1 + \alpha \exp\left(-\frac{r}{\lambda}\right)\right) \quad (1)$$

where r is the distance between two test objects with masses of M and m, G stands for the Newtonian constant of gravitation, and α is the relative coupling constant of the LED gravity with respect to G. Therefore, by experimentally searching for the exponential term in Eq. (1), it is possible to verify the LED model. So far ISL of the gravity has been tested via the experiments of Cavendish type, i.e. by precisely measuring the forces between two test objects with given separations in the region of the distance down to a few micrometers. The LED model suggests $\lambda < \sim 100$ nm in case of $n = 3$, At such a short distance, the previous experiments rapidly lose the sensitivity due to the huge background by the intermolecular force whose strength is inversely proportional to the sixth power of the distance [23]. Since the strength of the intermolecular force is proportional to the electric polarizabilities α of the test objects, it can be drastically suppressed by replacing one of the test objects with a neutron whose α is eighteen orders of magnitude smaller than those of ordinally atoms or molecules. The force between a neutron and another test object can be studied by measuring the differential cross section of the small-angle neutron scattering (SANS) [24]. For that purpose, we performed a precise measurement [25] of SANS at the J-PARC/MLF/BL05 with use of noble gases as the target whose form factors are well known.

Results and discussion

Figure 5 shows the summary of the upper limit to α obtained by various experiments.

In Fig. 5, the curves denoted with Refs. [25] and [26] are obtained using pulsed neutrons at J-PARC and continuous neutrons at the HANARO reactor, respectively, and due to the difference in the velocity distribution of the neutron beams, the obtained upper limits are different from each other. The result of Ref. [27] was obtained by means of the neutron interferometry, and thanks to its very high sensitivity, the upper limit better than [25] and [26] were obtained. Through those experimental efforts, the current upper limit on α obtained with the experiments using

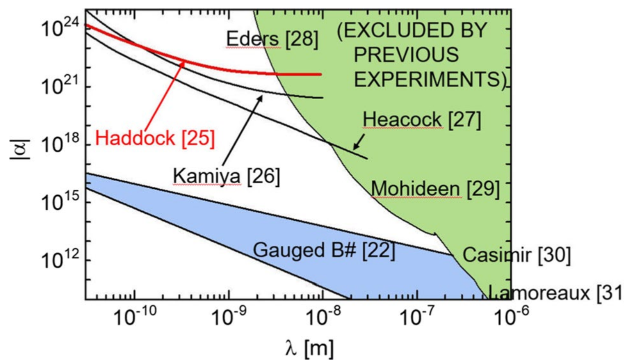

Fig. 5 Experimental constraint on the LED. Red curve (Haddock et al.) is the result of the experiment at the J-PARC [25]. Other results by Kamiya et al. [26] and Heacock et al. [27] are also shown. The green-filled and light-blue-filled areas indicate the regions excluded by previous experiments [28–31] and expected by the theory [22], respectively

neutrons is still 5–6 orders of magnitude higher than the theoretically expected region [22]. To improve the sensitivity of the SANS method, we are going to use a target made of nanoparticles in place of noble gas atoms. Since the mass of a nanoparticle is typically 10^6 times larger than that of a single atom, a large improvement in the sensitivity is expected. It should be noted that background due to the nuclear scattering is also enhanced with the same factor and should be suppressed. For that purpose, we are developing nanopowder made of null-matrix alloy [32] whose coherent scattering length is reduced by mixing two elements having opposite signs of the scattering lengths so as to cancel the total coherent nuclear scattering. To design such a material, accurate data of the scattering lengths of various isotopes are indispensable.

Conclusions

The BBN analysis provides a unique opportunity to investigate the origin of the universe and the fundamental laws in nature. Since the neutrons play critical roles in BBN, it is important to obtain accurate data of the fundamental properties of neutrons as well as of the neutron-induced nuclear reaction rates.

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Data availability Raw data that support the finding of this paper are available from the corresponding author upon request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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