Study of Primordial Deuterium Abundance in Big Bang Nucleosynthesis

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Abstract

Big Bang nucleosynthesis (BBN) theory predicts the primordial abundances of the light elements 2H (referred to as deuterium, or D for short), 3He, 4He, and 7Li produced in the early universe. Among these, deuterium, the first nuclide produced by BBN, is a key primordial material for subsequent reactions. To date, the uncertainty in predicted deuterium abundance (D/H) remains larger than the observational precision. In this study, the Monte Carlo simulation code PRIMAT was used to investigate the sensitivity of 11 important BBN reactions to deuterium abundance. We found that the reaction rate uncertainties of the four reactions d(d, n)3He, d(d, p)t, d(p, γ)3He, and p(n, γ)d had the largest influence on the calculated D/H uncertainty. Currently, the calculated D/H uncertainty cannot reach observational precision even with the recent LUNA precise d(p, γ)3He rate. From the nuclear physics aspect, there is still room to largely reduce the reaction-rate uncertainties; hence, further measurements of the important reactions involved in BBN are still necessary. A photodisintegration experiment will be conducted at the Shanghai Laser Electron Gamma Source (SLEGS) Facility to precisely study the deuterium production reaction of p(n, γ)d.

Full Text

Preamble

Study of Primordial Deuterium Abundance in Big Bang Nucleosynthesis

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Big Bang nucleosynthesis (BBN) theory predicts the primordial abundances of the light elements ^{2}H (referred to as deuterium, or D for short), ^{3}He, He, and Li produced in the early universe. Among these, deuterium—the first nuclide produced by BBN—serves as a key primordial material for subsequent reactions. To date, the uncertainty in predicted deuterium abundance (D/H) remains larger than observational precision.

In this study, we used the Monte Carlo simulation code PRIMAT to investigate the sensitivity of 11 important BBN reactions to deuterium abundance. We found that the reaction rate uncertainties of four reactions—d(d, n)^{3}He, d(d, p)t, d(p,)^{3}He, and p(n,)d—had the largest influence on the calculated D/H uncertainty. Currently, the calculated D/H uncertainty cannot reach observational precision even with the recent precise LUNA d(p,)^{3}He rate. From the nuclear physics perspective, there remains substantial room to reduce reaction-rate uncertainties; hence, further measurements of the important reactions involved in BBN are still necessary. A photodisintegration experiment will be conducted at the Shanghai Laser Electron Gamma Source (SLEGS) Facility to precisely study the deuterium production reaction p(n,)d.

Keywords: Big Bang Nucleosynthesis; Abundance of deuterium; Reaction cross section; Reaction rate; Monte Carlo method.

Introduction

The hot Big Bang theory, first proposed in 1946 by Gamow [?], is now the most widely accepted cosmological model of the universe, describing its expansion from a very high-density state dominated by radiation. This theory has been confirmed by observations of the cosmic microwave background \cite{2–4}, the expansion of the universe, and good global agreement between predictions and observations of the primordial abundances of the lightest elements in nature: hydrogen, helium, and lithium. According to the Big Bang theory, the universe began as a fireball approximately 13.8 billion years ago. Following inflation and cooling, primordial big-bang nucleosynthesis (BBN) commenced when the universe was approximately 3 minutes old (when the temperature dropped to approximately 1 GK, i.e., particle energy $E \approx kT \approx 0.1$ MeV) and ended less than half an hour later when nuclear reactions were quenched by low temperature and density conditions in the expanding universe. Only the lightest nuclides were synthesized in appreciable quantities through BBN: approximately 75% ^{1}H and 25% He, with small amounts of ^{2}H, ^{3}He, and Li. These relics provide a unique window into the early universe. More comprehensive reviews on BBN can be found in the literature \cite{5–7}.

In general, the primordial abundances of ^{2}H (referred to as D) and He inferred from observational data agree with predictions, except for the lithium problem [?, ?]. Deuterium, a fragile isotope, was destroyed after BBN. Its most primitive abundance was determined from observing cosmological clouds at high redshift on the line of sight of distant quasars. Recently, the precision of deuterium observations in cosmological clouds has dramatically improved, reaching an accuracy of 1.19% for primordial deuterium abundance (D/H), specifically D/H $= (2.527 \pm 0.030) \times 10^{-5}$ [**?**]. Therefore, nuclear cross-section data relevant to deuterium in the BBN network must be known with similar precision to further constrain cosmological parameters, particularly the cosmic baryon density.

In this study, we focused on BBN deuterium abundance. In BBN, deuterium synthesis occurs first, and the accumulation of primitive deuterium significantly affects the rates of subsequent reactions. Therefore, accurate determination of deuterium abundance in BBN calculations is crucial. While extensive studies relevant to BBN deuterium abundance have been conducted \cite{11–13}, few have examined the impact of uncertainties in the relevant reaction rates on D/H uncertainty. We used the Monte Carlo simulation code PRIMAT [**?**] to study D/H uncertainty within BBN reaction networks and demonstrated the reaction rate sensitivity for major reactions. Additionally, we examined the uncertainties of both nuclear physics inputs and cosmological parameters needed to satisfy the accuracy of observed deuterium abundance.

II. BBN Model & Monte Carlo Method

For a standard BBN model, the evolution of nucleosynthetic abundance can be obtained by solving the following system of differential equations [**?**]:

$$\sum_{j,k,l} \left(\Gamma_{kl\to ij} \frac{Y_k Y_l}{N_k! N_l!} - \Gamma_{ij\to kl} \frac{Y_i Y_j}{N_i! N_j!} \right)$$

where N_i represents the mass number of the corresponding nuclide, Y_i is the abundance of the corresponding nuclide, and Γ denotes the reaction rate, which is usually obtained using the following formula [**?**, **?**, **?**]:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} (kT)^{-3/2} \int \sigma(E) E e^{-E/kT} dE$$

The standard Big Bang model is also a single-parameter model, using only the parameter η—the ratio of the number of baryons to the number of photons—where different η values correspond to different nuclide abundance evolution curves or frozen abundances. In BBN studies, we typically obtain the corresponding abundance value by entering the observed η into the model as a parameter and then comparing it with observed abundances. Such calculations require input parameters including nuclear reaction rates, element abundances, and baryon density.

However, because reaction network models incorporate an increasing number of nuclides, conventional numerical calculations have become increasingly computationally expensive when computing uncertainties. Furthermore, according to research by Longland et al. [**?**], the traditional method of error propagation fails to incorporate the statistical significance of errors. In this study, we adopted the Monte Carlo sampling technique to calculate the abundance of targeted nuclides. The abundance uncertainty can be directly determined by generating a data distribution through the sampling process.

The Monte Carlo method is a statistical approach based on the law of large numbers. Converting the solutions of mathematical problems into random samples can significantly reduce the difficulty in solving complex models. Because specific physical quantities are sampled following certain distributions (such as Poisson, Gaussian, and log-normal distributions), this approach preserves the statistical significance of the physical quantities and their associated uncertainties and applies them realistically in the calculation results.

In this study, we used the PRIMAT code [**?**] for BBN calculations. PRIMAT consists of several main components: first, it determines cosmological parameters such as the parameter $a(t)$ of the Friedman-Lemaitre (FL) spacetime, which in the code is obtained from plasma thermodynamics through numerical inversion; second, it calculates the effects of weak interactions and stores their relationship with temperature on a hard disk; finally, it establishes a reaction network model to calculate nuclear reaction processes for temperatures $\geq$ 10 GK, 10–1.25 GK, and $\leq$ 1.25 GK according to temperature changes. Throughout the process, the code uses random sampling of the distribution of relevant parameters to obtain the abundance distribution function and then determines abundance uncertainties.

The primary focus of BBN is nuclear physics input quantities, specifically the reaction rates of relevant reactions. The PRIMAT code assumes that reaction rates follow a lognormal distribution [**?**]:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$$

where x denotes the reaction rate, i.e., $x = N_A \langle \sigma v \rangle$, and μ and σ are parameters of the lognormal distribution. For this distribution, the corresponding low, median, and high rates are $x_{\mathrm{low}} = e^{\mu-\sigma}$, $x_{\mathrm{med}} = e^{\mu}$, and $x_{\mathrm{high}} = e^{\mu+\sigma}$, where x_{low}, x_{med}, and x_{high} represent the reaction rates with probabilities of 16%, 50%, and 84%.

III. Model Parameters & Simulation

The main adjustable parameters in the PRIMAT code are the reaction rates and associated uncertainties of the 11 reactions of primary importance [**?**] involved in the BBN network, which we evaluated for their impact on deuterium abundance. The reaction rates were adopted from the default rates used in the PRIMAT code, with data sources listed in Table 1 . Additionally, we adopted the default values set in the PRIMAT code: the cosmological parameter $\Omega_b h^2 = (0.02225 \pm 0.00016)$ [**?**] for the baryon-to-photon ratio, and the neutron lifetime $\tau_n = (879.5 \pm 0.8)$ s [?]. Notably, in the original PRIMAT calculations [?], a D/H uncertainty of 1.46% was obtained using default reaction rates and their uncertainties without considering the uncertainties of the cosmological parameter $\Omega_b h^2$. Under the same conditions, we obtained a similar D/H uncertainty of 1.47%, confirming the correctness of our calculations.

First, we studied the effect of uncertainties in the 11 reaction rates, $\Omega_b h^2$, and τ_n on the calculated D/H uncertainties, with results listed in Table 2 . This shows that the uncertainty in neutron lifetime $\Delta\tau_n$ negligibly impacts D/H uncertainty, whereas uncertainties in reaction rates and $\Omega_b h^2$ have much larger effects. Conversely, $\Delta\tau_n$ significantly impacts ^{4}He abundance. The impact of neutron lifetime on Big Bang nucleosynthesis was studied in Ref. [?] and is not discussed here.

We then investigated the sensitivity of reaction-rate uncertainties to primordial deuterium abundance (D/H) uncertainties by simultaneously considering the uncertainties of $\Omega_b h^2$ and τ_n. The default reaction rate uncertainties adopted in PRIMAT for the four most important reactions are presented in Table 3 .

To examine sensitivity, we multiplied the default uncertainty of just one reaction rate by arbitrary factors of M.F. = 0.1, 0.8, 0.9, 1, 2, 4, and 6, respectively, while setting the remaining 10 reactions to their default rate uncertainties. We found that the d(p,)^{3}He, d(d, n)^{3}He, d(d, p)t, and p(n,)d reactions are the four major reactions with the largest influence on D/H uncertainty. The calculated results are listed in Table 4 and shown in Fig. 1 [Figure 1: see original paper].

For multiplying factors less than one (i.e., reducing current rate uncertainty), the decreasing trend for the four reactions of interest is shown in the inset of Fig. 1. This demonstrates that calculated D/H uncertainties can reach 1.41%, 1.76%, 1.77%, and 1.82% when the reaction rate uncertainties of d(p,)^{3}He, d(d, n)^{3}He, d(d, p)t, and p(n,)d are reduced by a factor of 10 (i.e., M.F. = 0.1, nearly no rate uncertainty). In general, the current default d(p,)^{3}He rate uncertainty (3.7%) dominates the calculated D/H uncertainty because the default rate uncertainties for the latter three reactions are already quite small (see Table 3). Thus, reducing their uncertainties further would not significantly affect the calculated D/H uncertainty. Therefore, the main source of D/H uncertainty originates from the d(p,)^{3}He reaction rate, a conclusion consistent with recent LUNA studies [?]. The "Original" line (i.e., M.F. = 1 case) indicates results calculated with default rates and uncertainties from the original PRIMAT code [?], corresponding to a D/H uncertainty value of 1.83%.

Additionally, we found that changing the uncertainty of the reaction rate also affected the central value of deuterium abundance. This occurs because sampling of reaction rates in the code follows a log-normal distribution, which is a typical skewed distribution where larger parameter σ values cause the most likely position to shift leftward. The change in the central value of deuterium abundance caused by increasing uncertainty is equivalent to the change caused by the shift in the most likely position associated with uncertainty.

IV. Access to the Observational Precision

Recent astronomical observations [?] recommend a deuterium abundance of D/H = $(2.527 \pm 0.030) \times 10^{-5}$ with approximately 1.19% accuracy, which is better than the PRIMAT calculated accuracy of 1.83%, i.e., $(2.459 \pm 0.045) \times 10^{-5}$. Therefore, we focus on the four reactions with the largest influence on D/H uncertainty and use a binary search to determine whether reducing their rate uncertainties can improve BBN calculated accuracy to observational levels.

However, we found that current deuterium abundance observation accuracy cannot be achieved by reducing only reaction rate uncertainties; the uncertainty of $\Omega_b h^2$ must also be reduced. Note that the d(p,)^{3}He reaction rate for all above calculations was adopted from Ref. [?]. Recently, Mossa et al. [?, ?] measured the d(p,)^{3}He cross section in the $E_{c.m.}$ = 33–263 keV energy region using the LUNA 400 kV accelerator to unprecedented precision better than 3% by exploiting the million-fold reduction in cosmic-ray muons at Gran Sasso. Their new astrophysical S factor remarkably improved evaluation of the present-day baryon density, $\Omega_b h^2$, using the standard BBN model alone. In this study, we utilized the updated d(p,)^{3}He reaction rate from LUNA [?] to calculate abundances and uncertainties of these primordial light nuclides. Results are listed in Table 5 , where He abundance is expressed using its mass fraction Y_p, while other nuclide abundances are expressed as the ratio of their number density to that of ^{1}H. We find that utilizing the LUNA d(p,)^{3}He reaction rate reduces the calculated D/H uncertainty from 1.83% to 1.56%, but does not reach observational precision. This goal can be achieved by reducing the current uncertainty in $\Omega_b h^2$ by approximately 50%.

V. Conclusion & Outlook

In this study, we investigated primordial deuterium abundance and its uncertainty using the BBN code PRIMAT. We found that predicted deuterium abundance uncertainties were dominated by reaction rate uncertainties in the four most important reactions—d(p,)^{3}He, d(d, n)^{3}He, d(d, p)t, and p(n,)d—as well as by uncertainty in $\Omega_b h^2$. Although current BBN calculations can achieve 1.56% deuterium abundance precision with the recent precise LUNA d(p,)^{3}He rate, a 0.4% gap remains relative to observational precision. We found this gap cannot be substantially reduced by decreasing reaction rate uncertainties alone; the uncertainty of $\Omega_b h^2$ must also be reduced. If the uncertainty of $\Omega_b h^2$ adopted from the Planck 2015 results [?] is reduced by approximately 50%, the calculated D/H uncertainty can reach observational levels.

In nuclear physics, reaction rate uncertainties for the remaining three reactions must be significantly reduced beyond the d(p,)^{3}He reaction. A photodisintegration experiment will be conducted at the Shanghai Laser Electron Gamma Source (SLEGS) Facility to precisely study the deuterium production reaction p(n,)d. This experiment will provide crucial data to further reduce uncertainty in primordial deuterium abundance predictions and help constrain cosmological parameters with greater precision.

Note: Figure translations are in progress. See original paper for figures.

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