Big Bang Nucleosynthesis with Matter/Antimatter Domains

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We investigate Big Bang nucleosynthesis (hereafter, BBN) in a cosmic environment characterized by a distribution of small-scale matter/antimatter domains. Production of antimatter domains in a baryo-asymmetric universe is predicted in some electroweak baryogenesis scenarios. We find that cosmic antimatter domains of size exceeding the neutron-diffusion length at temperature $T \sim 1$ MeV significantly affect the light-element production. Annihilation of antimatter preferentially occurs on neutrons such that antimatter domains may yield a reduction of the ^{4}He abundance relative to a standard BBN scenario. In the limiting case, all neutrons will be removed before the onset of light-element production, and a universe with net baryon number but without production of light elements results. In general, antimatter domains spoil agreement between BBN abundance yields and observationally inferred primordial abundances limits which allows us to derive limits on their presence in the early universe. However, if only small amounts of antimatter are present, BBN with low deuterium *and* low ^{4}He, as seemingly favored by current observational data, is possible.

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Big Bang Nucleosynthesis is one of the furthest back–reaching cosmological probes available. By means of comparing the predicted and observationally inferred light element abundances the cosmic conditions as early as a few seconds after the Big Bang may be scrutinized. Nucleosynthesis has thus been used to constrain, for example, inhomogeneities in the baryon-to-photon ratio or abundances and properties of decaying particles during the BBN era (for reviews on non-standard BBN see [1]).

In this Letter we examine the BBN process in a universe where matter and antimatter are segregated. A segregation of matter and antimatter may affect BBN abundance yields even if the average segregation scale is very small in terms of characteristic astrophysical scales. Such small scales imply annihilation of antimatter well before the present epoch. We are therefore particularly interested in the case where the universe contains net baryon number, as for example, through an excess of matter domains over antimatter domains. A baryo-asymmetric universe filled with a distribution of small-scale matter/antimatter domains may arise during an epoch of baryogenesis at the electroweak scale. It has been shown within the minimal supersymmetric standard model, and under the assumption of explicit as well as spontaneous CP violation, that during a first-order electroweak phase transition the baryogenesis process may result in individual bubbles containing either net baryon number, or net anti-baryon number [2]. Recently, it has been argued that pre-existing stochastic (hyper)magnetic fields in the early universe, in conjunction with an era of electroweak baryogenesis, may cause the production of regions containing either matter or antimatter [3]. In general, any segregation of matter and antimatter either produced on subhorizon scales at cosmic temperatures below $T \lesssim 1$ TeV [4] or produced on superhorizon scales during earlier inflationary epochs may be subject to constraint by BBN.

Nevertheless, the study of matter/antimatter domains present during the BBN era has to our knowledge not received any prior attention. The influence of antimatter on the light-element production has only been examined with respect to a homogeneous injection of antiprotons into the primordial plasma after the completion of a conventional BBN era ($T \lesssim 10$ keV) [5]. The conclusion of such studies is that only a small fraction of about $\sim 10^{-3}$ antiprotons per proton may be injected after the BBN epoch. Larger fractions lead to overproduction of deuterium and ^{3}He via $\bar{p}^4$He annihilation reactions. A further trend in such scenarios is that $\bar{p}^4$He reactions tend to overproduce ^{3}He relative to deuterium.

Annihilation of antimatter before, or during, the BBN era may be an astonishingly quiescent process. For local net antibaryon-to-photon ratios of the order, or less, than the net cosmic average baryon-to-photon ratio, η, the entropy release associated with annihilation is only a minute fraction of the entropy in the photon-pair plasma. Heating of the plasma is therefore unimportant. In the absence of turbulent fluid motions and convective processes mixing of matter and antimatter should mainly proceed via (anti) baryon diffusion. Neutrons diffuse most easily through the plasma and their diffusion length d_n at the epoch of weak freeze-out ($T_{\rm W} \approx 1$ MeV) is approximately $d_n(T_{\rm W}) \approx 0.1$ cm. Throughout the paper we give length scales comoving to temperature $T \approx 100$ GeV [6].

We distinguish three different limiting cases of the influence of antimatter domains on BBN, according to the segregation scale of matter and antimatter, or equivalently, the approximate matter-antimatter annihilation time: (a) Annihilations before weak freeze–out: No effect on the light–element abundances because the n/p–ratio, which is important for the determination of light-element abundances, is reset to the equilibrium value by the fast weak interactions. (b) Annihilations between weak freeze–out ($T \approx 1$ MeV) and the onset of significant ^{4}He synthesis ($T \approx 0.08$ MeV): The n/p–ratio is strongly affected and a highly non–standard BBN scenario results. For reference, the neutron diffusion length scale at $T \approx 0.08$ MeV is roughly $d_n \approx 10$ cm in comoving units. (c) Annihilations well after BBN: Such a scenario may be approximated by a homogeneous injection of antiprotons, towards the end, or after the epoch of BBN, as discussed above. Via only a few $\bar{p}^4$He annihilation reactions the (^{2}H+^{3}He)/H ratio, as well as the ^{3}He/^{2}H ratio easily exceed their observationally allowed limits. We are here most interested in the non-standard BBN scenario of case (b).

Annihilation of an antinucleon on a nucleon typically results in the production of a few pions and photons, i.e. $\bar{N}N \mapsto$ a few $\pi^{\pm}, \pi^0, \gamma' s$. Pions may subsequently decay via $\pi^- \mapsto \mu^- + \bar{\nu}_\mu \mapsto e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$ and $\pi^0 \mapsto 2\gamma$. It is of interest if these pions or their decay products may alter the abundance yields, either through their effect on weak freeze-out or by, for example, the photodisintegration of nuclei. We assume that the number of annihilations per photon is not much larger than a few $\times 10^{-10}$. In this case, annihilation generated ν_e's have negligible effect on the n/p-ratio since their number density is more than nine orders of magnitude smaller than the thermal ν_e's, which govern the weak equilibrium. The same holds for electrons and positrons produced in μ-decay which are quickly thermalized by their electromagnetic interactions. Annihilation-generated γ-rays cascade on the background photons via pair production and inverse Compton scattering, on a time scale rapid compared to the time scale for photodisintegration of nuclei [7]. This cascade only terminates when individual photons do not have enough energy to further pair-produce on background photons. For temperatures $T \gtrsim 3$ keV, the energy of γ-rays below the threshold for $e^{\pm}$-production does not suffice for the photodisintegration of nuclei. Pions may perturb the n/p-ratio via charge exchange reactions, $\pi^+ + n \mapsto \pi^0 + p$ and $\pi^- + p \mapsto \pi^0 + n$ with rate $(1/n_\pi)dn_\pi/dt \approx 4.8 \times 10^5\,(\eta/3 \times 10^{-10})\,(T/\mathrm{MeV})^3\,\mathrm{s}^{-1}$, where η is an appropriate local (anti-) baryon-to-photon ratio [8]. This rate should be compared to the typical decay rate of charged pions, $\Gamma_{\pi^\pm} \approx 3.8 \times 10^7 \mathrm{s}^{-1}$ which indicates that only at high temperatures, and for large local η pions participate in charge exchange before decaying. We conclude that pions may have some effect on the n/p-ratio around the time of weak freeze-out only if produced in abundance. For small amounts of antimatter the effect of annihilation-generated pions should be negligible.

The main effect of the presence of antimatter on BBN yields for annihilation between $1\,\mathrm{MeV} \gtrsim T \gtrsim 0.08$ MeV is through a preferential annihilation of antimatter on neutrons. This is because neutrons diffuse out into the antimatter regions and annihilate there, whereas protons are confined to the matter regions. Antineutrons which diffuse into the matter regions and annihilate on neutrons, as well as protons, have a comparatively weaker effect if one assumes the density of antineutrons to be smaller than the density of neutrons. If annihilation occurs below temperature $T \lesssim 1$ MeV, weak interactions are nearly frozen out and the residual interactions cannot compensate for an annihilation-generated n/p-ratio reduction. Since the final ^{4}He mass fraction Y_{p} strongly depends on the n/p-ratio at $T \approx 80$ keV, in particular, $Y_{\mathrm{p}} \approx 2(n/p)/(n/p+1)$, less ^{4}He than in standard BBN is produced in scenarios with antimatter. Abundance yields of other light isotopes are affected comparatively weaker.

We have performed numerical simulations of the light-element nucleosynthesis in a universe with matter and antimatter domains. We have incorporated antinucleons and their weak interactions into the inhomogeneous nucleosynthesis code of [9]. This code solves the BBN network coupled to all relevant hydrodynamic processes, such as diffusion of baryons, photon diffusive heat transport, neutrino heat transport and late–time hydrodynamic expansion of high-density regions. The nuclear reaction network and the thermodynamics are treated as in the Kawano-code [10].

Initial conditions for the determination of abundance yields are chosen to approximate a distribution of small, spherical antimatter domains immersed within ordinary matter regions. This is accomplished by performing simulations with radial symmetry of antimatter bubbles surrounded by a comparatively larger matter shell. We have found that due to the large annihilation rates most annihilation takes place at the boundary between matter and antimatter domains [11]. In order to minimize inevitable effects of an inhomogeneous distribution of matter, and isolate the effects of antimatter during the BBN era, we have chosen constant baryon-to-photon ratios in the spherical shells of $\eta_b = 1.3\langle\eta\rangle$, irrespective of amount of antimatter present and the radius of the antimatter bubble. Here $\langle\eta\rangle = (1 - f_V)\eta_b - f_V\eta_{\bar{b}}$ is the cosmic spatial average net baryon-to-photon ratio, with f_V the fraction of space in antimatter bubbles, and $\eta_{b(\bar{b})}$ the assumed constant (anti-)baryon-to-photon ratios in the matter shells (antimatter bubbles). Simulations are distinguished by the cosmic average ratio of antinucleons to nucleons, $R = f_V\eta_{\bar{b}}/(1 - f_V)\eta_b$, where it is understood that this quantity is taken well after the QCD-transition so that there is no thermally produced baryon number, in particular, the η's reflect net (anti-) baryon-to-photon ratios.

In Figure 1 we show the abundance yields of such matter/antimatter BBN scenarios as a function of the radius of the antimatter domains, r_A, and for various antimatter fractions, R. Figure 2 shows contours of predicted ^{4}He mass fraction in our simulations in the R-r_A plane. All calculations are performed for average net $\langle\eta\rangle = 3.316 \times 10^{-10}$, corresponding to a fractional contribution of baryons to the critical density of $\Omega_b = 0.0125h^{-2}$, with h the Hubble constant in units of $100\mathrm{km\ s^{-1}\ Mpc^{-1}}$.

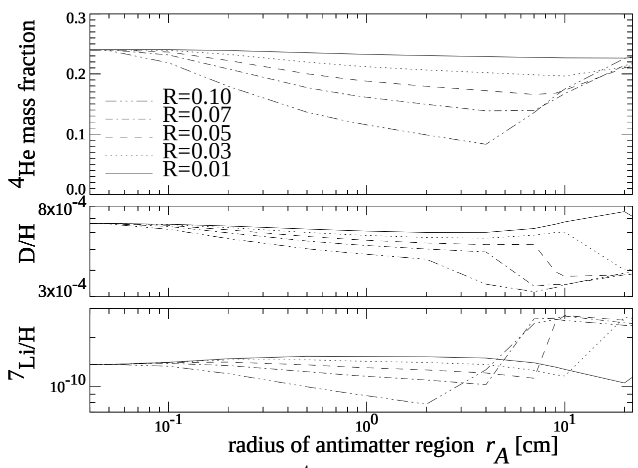

FIG. 1. Mass fraction of ^{4}He and number densities of deuterium and ^{7}Li relative to hydrogen as a function of the radius of the antimatter region $r_{\rm A}$ in comoving units [6]. Results are shown for different antimatter fractions R.

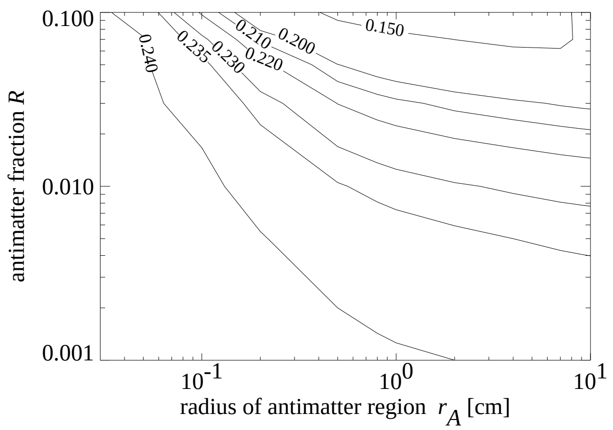

FIG. 2. Contours of constant ^{4}He mass fractions in the R-$r_{\rm A}$ plane

It is evident from the top panel of Figure 1 and from Figure 2 that the presence of antimatter during BBN results in a reduction of the ^{4}He abundance compared to the abundance in a standard BBN scenario (the values at the far left of Figure 1). The effect of ^{4}He-reduction is more pronounced for larger matter/antimatter separation length scales. Interconversion of neutrons into protons through residual weak interactions after the approximate weak freeze-out ($T_{\rm W}$) and neutron decay still reduce somewhat the n/p-ratio between weak freeze-out and synthesis of ^{4}He. The rates for these processes are proportional to the neutron density. One may approximately assume that a fixed number of neutrons are removed through annihilation on antimatter for models with the same R. Early annihilation then weakens the post-weak freeze-out reduction of neutron density compared to annihilation taking place late. When segregation length scales become too large some annihilation of antimatter occurs after the binding of neutrons into ^{4}He. This is evident in the figure by the rising ^{4}He mass fractions. In this regime, annihilations of antiprotons on ^{4}He, which are not included in our simulations, would have by far the most dominant effect on the BBN abundance yields such that all the shown models would be excluded by ^{3}He and deuterium overproduction.

Within observational primordial abundance determination uncertainties the abundances of the other light isotopes are only significantly modified with respect to standard BBN for large antimatter fractions. Nevertheless, such large antimatter fractions produce observationally disallowed low ^{4}He mass fractions. It is interesting to note that there is no limit to the amount of ^{4}He reduction possible. In particular, we have found scenarios with large antimatter fractions where *all* neutrons will be removed at temperatures above $T \approx 80$ keV. In such scenarios there is also negligible production of other light elements. These would result in universes, or local regions of the universe, where *no* light-element production in the early universe occurs, but which, nevertheless, have net baryon number.

Models for the segregation of matter and antimatter in the early universe with comparatively large mean separation lengths $\langle l \rangle$ between domains and large antimatter fractions R are, generically, in conflict with observationally inferred primordial abundance limits. The approximate constraints on antimatter domains which may thus be derived from BBN are shown in Figure 3. Whereas for $\langle l \rangle$ between the neutron diffusion length at weak freeze-out and onset of ^{4}He synthesis the most stringent constraints derive from an underabundant production of ^{4}He, for larger $\langle l \rangle$ limits are due to ^{3}He and ^{2}H overproduction. It is interesting to note that similar limits derived from distortions of the blackbody distribution of the cosmic microwave background radiation (CMBR) are comparatively weaker. These limits are also shown in Figure 3 where the amount of nonthermal energy allowed to be released into the CMBR without producing observable distortions in the blackbody has been convolved with annihilation -time and -energy in antimatter scenarios. The calculation assumes that mixing of matter and antimatter after the BBN epoch mainly proceeds via proton diffusion.

The BBN constraints on antimatter may be used, in turn, to constrain processes occurring in the early universe before the BBN epoch. In the electroweak baryogenesis scenario by [2] individual bubbles of broken phase during a first-order electroweak transition create either net baryon or antibaryon number. Segregation of matter and antimatter is expected on the electroweak bubbles scale, $l_{\rm N}^{\rm EW}$, which has been estimated to fall in the range $l_{\rm N}^{\rm EW} \sim (10^{-5} - 10^{-1}) l_{\rm H}^{\rm EW}$ with $l_{\rm H}^{\rm EW}$ the electroweak horizon scale $l_{\rm H}^{\rm EW} \approx 2\,{\rm cm}(T/100\,{\rm GeV})^{-2}$ [13]. Observable signatures in the BBN yields for such segregation scales are not anticipated. Nevertheless, some scenarios of [2] envision only a slight excess in the number of bubbles, N_b, over the number of antibubbles, $\bar{N}_b$, i.e. $(N_b - \bar{N}_b)/(N_b + \bar{N}_b) \sim 10^{-3}$. In this case the effective segregation scale of a realistic distribution may well exceed the bubble scale. Meaningful limits on the models by [3] from BBN are more probable. Here stochastic matter/antimatter distributions are produced by pre-existing (hyper) magnetic fields. Segregation scales are not related to $l_{\rm N}^{\rm EW}$ but to the coherence scale of the magnetic fields. Assuming equipartition between the energy in the magnetic fields and radiation, a scale-invariant magnetic field distribution, for example, may yield average (anti-) baryon-to-photon ratios as large as $|\eta| \sim 10^{-5}$ on the scale $d_n(T_{\rm W})$. Even though scale-invariance may be unrealistic, a similar scenario with a factor 10^5 smaller fluctuation amplitude already leaves an imprint on the BBN abundances. In any case, fluctuation amplitudes as large as $|\eta| \sim 10^{-5}$ have not been properly investigated in this Letter due to the influence of pions. It is further difficult to assess and model a realistic three-dimensional matter/antimatter distribution and its BBN yields.

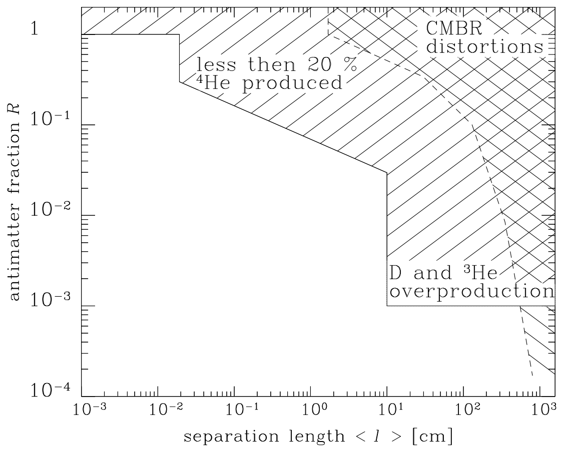

FIG. 3. Limits from BBN and CMBR distortions on the fraction of antimatter allowed to be present in the early universe. In this figure $\langle l \rangle$ denotes the mean segregation scale of matter and antimatter in comoving units [6]. For separation lengths as large as $\lesssim 5 \times 10^2$ cm, which correspond to annihilation at redshifts of $z \gtrsim 10^3$, limits from BBN are more stringent then those from CMBR distortions.

It is tempting to speculate about BBN yields from stochastic distributions with net cosmic η larger than that inferred from standard BBN. Local regions with large R do not contribute to the light element nucleosynthesis but contribute to Ω_b. If the protons of such regions are mixed with the yields of regions at low R and low as well as high η, some relaxation of the bound on Ω_b inferred from standard BBN may result. It seems, however, not easy to satisfy simultaneously observational constraints on all the light-element abundances at much larger Ω_b. It is also not clear if such scenarios would require extreme fine-tuning of fluctuation parameters.

In summary, we have investigated BBN in the presence of matter/antimatter domains. We have concentrated on the study of BBN with small antimatter fractions at the canonical cosmic net baryon-to-photon ratio $\sim 3\times 10^{-10}$. Surprisingly, antimatter fractions of the order $R \lesssim 1\%$ surviving to the epoch of weak freeze-out may considerably alleviate the decade old tension between the primordial ^{4}He and ^{2}H abundances in standard BBN and their observationally inferred limits [14]. Even though other modifications of BBN have been proposed which also yield low ^{4}He and ^{2}H [15], our model may have some motivation from electroweak baryogenesis scenarios which may generate antimatter domains.

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