In the standard big-bang model, the large primordial baryon and antibaryon abundance formed at hadronization of the deconfined quark-gluon plasma (QGP) disappears due to mutual annihilation, exposing a slight net baryon number observed today \( \mu \). Applying the knowledge of equations of state of hadronic matter derived from the study of high energy nuclear collisions, we consider quantitatively this evolution epoch of the early Universe.

Our objective is to quantify the values of the chemical potentials required to generate the observed matter-antimatter asymmetry, and to use this to quantify the magnitude of electrical charge distillation occurring during hadronization. While we do not enter here into the exploration of the consequences of these two findings, we note that the values of the chemical potentials allow detailed study of hadron and lepton abundances during the epoch the universe cools from the hadronization temperature to nucleosynthesis temperature. The dynamical process of distillation can at QGP hadronization enhance an initially small baryon-antibaryon asymmetry to the value we encounter in our region of the Universe.

The annihilation period began after the phase transformation from the QGP to a hot hadronic gas (HG), roughly 20–30\( \mu \)s after the big bang (when the Universe was at a temperature of \( \sim 170 \) MeV), and continued until the density had diminished to the level that a "nucleon freeze-out" occurred at approximately 1\( \mu \)s (\( T \approx 35 \) MeV). In this scenario, annihilation of antimatter was very complete, quantified by the result that the energy fraction in baryons and antibaryons in the Universe dropped from \( \sim 10\% \) when Universe was about 40\( \mu \)s old to \( \sim 10^{-7} \) when it was one second old.

The observational evidence about the antimatter non-abundance in the Universe is supported by the highly homogeneous cosmic microwave background derived from the period of photon decoupling. This has been used to argue that the matter-antimatter domains on a scale smaller than the observable Universe are unlikely; others see need for further experimental study to confirm this result.

The current small value of the baryon-to-photon ratio is the result of this near complete annihilation of the large matter-antimatter abundance. Other than a (relatively) small increase in photons during nucleosynthesis and electron-ion recombination, the baryon and photon numbers should be preserved back to the period of annihilation. Considering several observables, a range of \( \eta \) is established and we use here the latest WMAP result \( \eta \equiv n_B/n_\gamma = 6.1^{+0.3}_{-0.2} \times 10^{-10} \).

The importance of \( \eta \) is that it allows to determine the value of entropy per baryon \( S/B \) in the Universe, which is conserved in adiabatic evolution. At present the entropy is dominated by photons, and nearly massless (decoupled) neutrinos. It is straightforward to compute the entropy densities of these species from the partition function, and then to convert \( \eta \) to \( S/B \) using the photon number density. We obtain a value of \( S/B = 8.0/\eta = 1.3 \pm 0.1 \times 10^{10} \), assuming a lower neutrino than photon temperature (photons are reheated by \( e^+ e^- \) annihilation), and counting only left/right-handed neutrinos/antineutrinos.

Equations of State We argue that the Universe was in chemical and thermal equilibrium around the time of hadronization, i.e., when the quark-gluon Universe turned into a hadronic Universe. To compute the thermodynamic properties of the QGP and HG phases, we study the partition functions \( Z_{\text{QGP}} \) and \( Z_{\text{HG}} \) as described in Ref. 2: we employ latest QGP equations of state, which model in detail with properties of quantum chromodynamics (QCD) at finite temperature and finite baryon density obtained in lattice QCD. This approach involves quantum gases of quarks and effectively massive gluons with perturbative QCD corrections applied, and a confining vacuum energy-pressure component \( \mathcal{B} = 258 \) MeV fm\(^{-3} \). In the HG partition function, we sum partial gas contributions including all hadrons from Ref. 3 having mass less than 2 GeV, and apply finite volume corrections.

Our use of partition functions assumes that local thermodynamic equilibrium (LTE) exists. Considering the particle spectra and yields measured at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory (RHIC), it is observed that a thermalization timescale on the order of \( \tau_{\text{th}} \approx 10^{-23} \) s is present in the QGP at hadronization. The mechanisms for such a rapid thermalization are at present under investigation. We expect this result to be valid qualitatively in the primordial QGP phase of matter. This then assures us of LTE being present in the evolving Universe. The local chemical equilibrium (LCE) is also approached at RHIC, indicat-
ing that this condition also prevails in the early Universe.

To apply these experimental results, we recall that the size of a flat $k = 0$ Universe evolves as $R \propto t^{1/2}$, where $R$ is the size scale factor of the Universe. This scaling is valid if the energy and momentum are dominated by radiation. Furthermore, if the expansion is adiabatic and energy conserving, then $R \propto T^{-1}$. The thermalization timescale is roughly $\tau_{\text{th}} \approx 1/n \sigma v$, with $n$ the particle number density, $\sigma$ the cross section for (energy-exchanging) interactions, and $v$ the mean velocity. Allowing for the change in relative velocity and a reduction in density, we can expect an increase in $\tau_{\text{th}}$ as we cross from the relativistic QGP to the HG phase having strong non-relativistic components, such that $\tau_{\text{th}} \lesssim 10^{-22}$ s for the HG at $T = 170$ MeV. For a roughly constant value of $\sigma v$ during the expansion of the HG, the thermalization timescale increases to $\tau_{\text{th}} \lesssim 10^{-15}$ s at $T = 1$ MeV. At this point, the Universe is already one second old, so our assumption of LTE (and also of LCE) has a large margin of error and is in our opinion fully justified throughout the period of interest.

Chemical equilibrium timescales are significantly longer, due to smaller cross sections, than thermalization timescales. When chemical equilibrium cannot be maintained in an expanding Universe, we find particle yield freeze-out. Near the phase transformation from HG to QGP, chemical equilibrium for hadrons made of $u, d, s$ quarks is established. Hadron abundance evolution and deviations from the local equilibrium have not yet been studied in great detail in the early Universe. Our estimates suggest that the abundance of hadrons can be seen as being fixed by LCE down to a few MeV. Note that annihilation depletion of baryon density ceases around temperature $T \approx 35$ MeV.

In a system of non-interacting particles, the chemical potential $\mu_i$ of each species $i$ is independent of the chemical potentials of other species, resulting in a large number of free parameters. The many chemical particle interactions occurring in the QGP and HG phases, however, greatly reduce this number.

First, in thermal equilibrium, photons assume the Planck distribution, implying a zero photon chemical potential; i.e., $\mu_\gamma = 0$. Next, for any reaction $\nu_i A_i = 0$, where $\nu_i$ are the reaction equation coefficients of the chemical species $A_i$, chemical equilibrium occurs when $\nu_i \mu_i = 0$, which follows from a minimization of the Gibbs free energy. Because reactions such as $f + \bar{f} \rightarrow 2 \gamma$ are allowed, where $f$ and $\bar{f}$ are a fermion – antifermion pair, we immediately see that $\mu_f = -\mu_{\bar{f}}$ whenever chemical and thermal equilibrium have been attained.

Furthermore, when the system is chemically equilibrated with respect to weak interactions, we can write down the following relationships [11]:

$$\mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu} = \mu_\tau - \mu_{\nu_\tau} \equiv \Delta \mu_i, \quad (1)$$

$$\mu_n = \mu_d - \Delta \mu_i, \quad \mu_s = \mu_d, \quad (2)$$

with the chemical equilibrium of hadrons being equal to the sum of the chemical potentials of their constituent quarks; e.g. for $\Sigma^0 (uds)$: $\Sigma^0 = \mu_u + \mu_d + \mu_s = 3 \mu_d - \Delta \mu_l$, and the baryochemical potential is:

$$\mu_B = \frac{3}{2} (\mu_d + \mu_u) = 3 \mu_d - \frac{3}{2} \Delta \mu_l. \quad (3)$$

Finally, if the experimentally-favored “large mixing angle” solution [12] is correct, the neutrino oscillations $\nu_e = \nu_\mu = \nu_\tau$ imply that [12]: $\mu_{\nu_\mu} = \mu_{\nu_\mu} = \mu_\tau$, which reduces the number of independent chemical potentials to three. We choose these to be $\mu_d, \mu_\mu$, and $\mu_\tau$. We next seek to establish what values of our independent chemical potentials are required to generate the observed matter-antimatter asymmetry.

**Single Phase** In a homogeneous (i.e., single phase) Universe, we seek to satisfy the following three criteria:

$i)$ Charge neutrality ($Q = 0$) is required to eliminate Coulomb energy. This implies that:

$$n_Q = \sum_i Q_i n_i (\mu_i, T) = 0, \quad (4)$$

where $Q_i$ and $n_i$ are the charge and number density of species $i$, and the summation is carried out over all species present in the phase.

$ii)$ Net lepton number equals net baryon number ($L = B$) is required in many baryogenesis scenarios. This implies that:

$$n_L - n_B \equiv \sum_i (L_i - B_i) n_i (\mu_i, T) = 0, \quad (5)$$

where $L_i$ and $B_i$ are the lepton and baryon numbers of species $i$.

$iii)$ Constant entropy-per-baryon ($S/B$). This is the statement that the Universe evolves adiabatically, and is equivalent to:

$$\frac{s}{n_B} = \frac{\sum_i s_i (\mu_i, T)}{\sum_i B_i n_i (\mu_i, T)} = 1.3 \pm 0.1 \times 10^{10}, \quad (6)$$

where $s_i$ is the entropy density of species $i$.

Eqs. $(4) - (6)$ constitute a system of three coupled, nonlinear equations of three unknowns ($\mu_d, \mu_\mu$, and $\mu_\tau$) for a given temperature. These equations were solved numerically using the Levenberg-Marquardt method [14] to obtain Fig. [I] which shows the values of $\mu_d, \mu_\mu$, and $\mu_\tau$ as function of the age of the Universe (the top axis shows the corresponding temperature). As the temperature decreases, the value of $\mu_d$ approaches weighted one-third of the nucleon mass ($\langle 2m_n - m_p \rangle / 3 \approx 313$ MeV, see horizontal line in Fig. [I]). This follows because the baryon (proton and neutron) partition functions are in the classical Boltzmann regime at these temperatures.

The error bars arise from WMAP uncertainty in the value of $\eta$. The chemical potentials required to generate the current matter-antimatter asymmetry are smaller than 1 eV (horizontal line in Fig. [I]). Near the Universe
FIG. 1: Chemical potentials $\mu_d$, $\mu_e$, and $\mu_\nu$ around the time of the QGP-HG phase transformation. The error bars arise from the uncertainty in $\eta$. Insert — expanded view around the phase transformation. Horizontal and vertical lines inserted to guide the eye.

FIG. 2: The hadronic energy content of the luminous Universe as a function of temperature assuming a constant entropy-per-baryon number of $1.3 \times 10^{10}$.

hadronization temperature $T_h$ additional sensitivity in the value of chemical potentials arises due to the uncertainty in the value of hadronization temperature. With 6% uncertainty in $T_h = 170 \pm 10$ MeV we obtain 15% uncertainty in the minimal value of the d-quark chemical potential. This error is dominating the uncertainty of the minimal value of the baryochemical potential, and thus $\mu_{b|\text{min}} = 1.1 \pm 0.25$ eV.

Given the chemical potentials of all particles we can trace out all particle densities in the early Universe and can, for example, derive the hadronic energy content in the luminous Universe as a function of temperature, shown in Figure 2. The fraction of energy in baryons and antibaryons is roughly 10% at the QGP-HG phase transformation, but rapidly vanishes, becoming significant again only when the Universe has cooled, and enters nucleon rest mass matter-dominated era.

**Phase Transformation: QGP to HG** During the QGP to HG phase transformation, when both phases coexist, the macroscopic conditions i. – iii. above are no longer valid individually within either the QGP or HG phases, and that the correct expressions must contain combinations of the two phases. We therefore parameterize the partition function during the phase transformation as

$$\ln Z_{\text{tot}} = f_{\text{HG}} \ln Z_{\text{HG}} + (1 - f_{\text{HG}}) \ln Z_{\text{QGP}},$$

where the factor $f_{\text{HG}}$ represents the fraction of total phase space occupied by the HG phase. The correct expression analogous to Eq. (4) is:

$$Q = 0 = n_Q^{\text{QGP}} V_{\text{QGP}} + n_Q^{\text{HG}} V_{\text{HG}}.$$
\[ V_{\text{tot}} \left[ (1 - f_{HG}) n_{Q^G} + f_{HG} n_{Q^H} \right], \] (7)

where the total volume \( V_{\text{tot}} \) is irrelevant to the solution. Analogous expressions can be derived for Eqs. 5 and 6.

These expressions were used to obtain Fig. 4 which shows the fraction of the total baryon number in the QGP and HG phases as a function of \( f_{HG} \). We note that the QGP phase has a higher baryon number density than the HG phase throughout the transformation. This value is nearly constant, with \( n_{B^Q} / n_{B^H} \approx 3 \).

In Fig. 4 it was assumed that the value of \( f_{HG} \) evolved linearly in time and that the duration of the phase transformation was \( \tau_h = 10 \mu s \). In reality, these quantities are sensitive to the properties of the equations of state and the dynamics of the phase transformation. A more complete evaluation will require application of transport theory and is beyond the scope of the current work. Our value of \( \tau_h \) is an estimate discussed in [2].

Figure 4 shows the net charge per baryon in each phase as a function of \( f_{HG} \). At its onset the small region of HG phase takes on an initial positive charge density, which can be attributed to the proton-neutron bias toward positive charge. As a result, the QGP domain takes on a (initially tiny) negative charge density. Such distilled dynamical asymmetry in particle yields was previously explored for strangeness separation and associated strangelet formation [15, 16].

Since the sign of the effect seen in Figure 4 is the same across the entire hadronization region, the total charge of the remaining QGP domains is ever-increasingly negative and one would expect development of electromagnetic potential, which effectively alters the values of chemical potentials for charged species. It is evident that the process of charge distillation will have a feed-back effect on the QGP-HG transformation, and that flows of particles will occur that will alter the uniformly small net baryon density [17]. This can affect (during the phase transformation) any local initial baryon-antibaryon asymmetry, and may also serve as a mechanism for generating magnetic fields in the primordial Universe [18]. Quantitative evaluation of this baryon asymmetry enhancement effect entails methods of advanced transport theory beyond the scope of this work.

We have determined the chemical potentials required to describe the matter-antimatter asymmetry in the Early Universe. We have shown that the non-zero chemical potentials result in a charge distillation during the phase transformation, with the QGP and HG receiving negative and positive charge densities, respectively. We note that a separation of baryons and antibaryons into domains could maintain a homogeneous zero charge density Universe, a phenomenon which could, e.g., play a significant role in amplifying a pre-existent, much smaller net baryon yield, e.g. arising within the realm of the standard model. The evolution of the chemical potentials allows to trace out the particle abundance in the early universe prior to nucleosynthesis.

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