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Hadronic nature of the early universe

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A model for particle structure is used to describe the "hadron era" of a charge-symmetric model for the early universe. A value of $s \gtrsim 10^7 k$ is obtained at $t \sim 10^{-7}$ sec for the fundamental quantity s, the entropy per baryon. This value for s/k is directly related to the magic number of cosmology 10^{40}.

I. INTRODUCTION

The early stages of a hot universe should be described by a strongly interacting system of highly localized particles at very high temperatures and densities.[1] At these early moments of an expanding universe the description must be based on a knowledge of both cosmology and high-energy physics.[2-6] A very fundamental problem in particle physics is the internal structure and constituents of the nucleon and of other hadrons, particles interacting via strong or nuclear forces. One may ask if knowledge of the structure of hadrons is sufficient to give a description of the early universe. It is suggested in this work that the description of the internal structure of hadrons can be taken over for the description of the different stages the universe goes through at its earliest moments.

A distinctive feature of high-energy physics is the existence of massive resonances and the realization that more massive states will emerge at still higher energies. In this respect the work of Hagedorn[7] has furthered our understanding of the high-mass end of the hadron spectrum. Hagedorn finds that the density $\rho(m)$ of hadronic states increases exponentially with hadron mass m. This result has received much attention[4,5] since it was taken to imply that hadronic matter has a maximum limiting temperature of $T \sim m_\pi c^2/k \sim 10^{12}$ °K. Thus, there exists a maximum temperature for any system in thermal equilibrium, e.g., the "hadron era" of the big bang.

Recently, Harrison[3,8] has challenged the existence of a maximum temperature for hadronic matter on the grounds of a model for particle structure which also leads to an exponentially rising hadron spectrum.[9,10] This model describes a physical particle as a spatially localized gas of virtual particles, hence, taking the size as the main property of a physical particle. This is accomplished by introducing distinguishable quasiparticles as constituents of a hadron. One obtains an exponentially rising hadron spectrum $\rho(m) \to am^b e^{m\beta}$ as $m \to \infty$ with $b \geq -\frac{5}{2}$, with the added feature that the volume V_0 of a hadron is determined by the relation

$$1 = \frac{4\pi V_0}{(hc)^3}(m_0 c^2)^2 \frac{K_2(m_0 c^2 \beta)}{\beta}, \tag{1}$$

with m_0 representing the lowest mass of the system and K_2 the modified Bessel function of the second kind. Harrison[3,8] assumes that all hadrons of size $\hbar/mc \geq ct$ cannot exist at time t measured from zero at the singular point $R=0$, $\rho \to \infty$. Hence, $m_0 c^2 \sim \hbar/t$, which gives from Eq. (1), with $V_0 \sim (\hbar/m_0 c)^3$, that $kT_0 \equiv \beta^{-1} \sim \hbar/t$ in the "early hadronic era" ($10^{-43} \leq t \leq 10^{-23}$ sec). The time $t \sim 10^{-43}$ sec corresponds to the "primordial chaos barrier" of Wheeler.[11] Consequently, in the "early hadronic era" of the big bang the temperature rises above the maximum temperature suggested by Hagedorn.

II. HADRONIC MATTER IN THE EARLY UNIVERSE

In the early universe there must be an interplay between the forces which determine the structure of a particle and the gravitational force which determines the global development of the universe. The structure of a hadron is determined by its constituents, which we assume to be distinguishable quasiparticles with masses equal to the masses of existing physical particles and energy-momentum relationship given by that of free relativistic particles, $\epsilon(\vec{p}) = (c^2\vec{p}^2 + c^4 m^2)^{1/2}$. This gives a description of a localized system without specifying the dynamical forces which hold together the constituents of a hadron. The experimentally determined hadron mass spectrum (with $\beta^{-1} \approx 160$ MeV and the pion mass as the lowest hadron state) gives, together with result (1), the correct size of free hadrons 10^{-13} cm. The inclusion of electromagnetic and weak forces should have the effect of changing the mass and decay properties of the physical particles and, thus, the masses of the quasiparticles. However, these added forces will have a negligible effect on the size of a hadron as determined by Eq. (1) with $m_0 = 0$.

We shall consider the simple case of a universe with zero net quantum numbers, e.g., zero net electric charge, zero net baryon number, etc. The global aspect of the universe will be assumed to be determined by the Robertson-Walker line element and Einstein's field equations[12] with constant gravitational coupling G. In the big-bang theories, the scale factor $R(t)$ becomes zero in the finite past and one has for $R(t) \sim t^{\delta}$, as $t \to 0$, with $0 < \delta \leqslant \frac{2}{3}$, that

$$\rho(t) = 3\delta^2/8\pi G t^2$$

and (2)

$$p(t) = (2 - 3\delta)\, c^2\, \rho(t)/3\delta$$

as $t \to 0$ for the material density $\rho(t)$ and an isotropic pressure $p(t)$. Behavior (2) is independent of the values of the cosmological and spatial curvature constants. Singularities in cosmology exist under more general conditions than those given by the isotropic and homogeneous general-relativistic models considered here.[13]

Throughout the "hadron era" of the universe we shall suppose that the assembly of hadrons is a relatively close-packed configuration. Hence, the "hadron era" ends at $t \sim 10^{-4}$ sec, when the overwhelming majority of particles are pions and $\rho \sim m_\pi/\lambda\!\!\!^-{}_\pi^3$ with $\lambda\!\!\!^-{}_\pi = \hbar/m_\pi c$. Owing to the close-packed nature of hadronic matter, the temperature and pressure of the quasiparticles inside a hadron are also the temperature and pressure of the universe. Therefore, inside the hadron one has a miniature replica of the very early universe.

The distribution of quasiparticles[9, 10] with momentum $\vec{p}$ and mass m is given by

$$n(\vec{p}) = \frac{\exp[-(c^2\vec{p}^2 + c^4 m^2)^{1/2}/kT]}{1 - [4\pi/(hc)^3]\, V_0 (mc^2)^2\, kT\, K_2(mc^2/kT)}\,, \tag{3}$$

with $kT_0 \equiv \beta^{-1} \geqslant kT$. Note that the distinguishability of the quasiparticles gives a classical form for the single-particle distribution function. Nevertheless, the quasiparticles are governed by relativistic kinematical laws. From (2) and (3), the experimentally determined parameters for the hadron mass spectrum[4] ($a = 2.6 \times 10^4$ MeV$^{3/2}$ and $kT_0 = 160$ MeV), and $b = -\frac{5}{2}$ one determines at what time the maximum temperature T_0 is attained. One obtains for $T \to T_0$ that

$$\begin{aligned} kT &= kT_0 - \frac{3a(kT_0)^{7/2}\, G t^2}{\sqrt{2\pi}\, c^2 (\hbar c)^3} \\ &= kT_0 - 1.6 \times 10^{10} (t/\mathrm{sec})^2 \ \mathrm{MeV}\,. \end{aligned} \tag{4}$$

Therefore, for $t \lesssim 10^{-5}$ sec, $T = T_0$.

A. Equation of state

One calculates the equation of state in the "hadron era" by first obtaining the entropy. The entropy of a particle is given by $S_p \equiv k \ln \omega(E_p)$, where $\omega(E_p)$ denotes the density of states. One obtains[10] as $E_p \to \infty$, that is, $T \to T_0$, that $\omega(E_p) \to g(E_p) e^{\beta E_p}$ with $g(x) = o(e^{\epsilon x})$ as $x \to \infty$ with $\epsilon > 0$. Therefore,

$$S_p = E_p/T_0 \text{ for } E_p \gg T_0\,. \tag{5}$$

In the "hadronic era" ($10^{-23} \leqslant t \lesssim 10^{-7}$ sec) the effect of gravitational collapse is to create massive hadrons from lighter ones always in our supposed close-packed configuration. Since hadrons have the same size, then by Eq. (1) the maximum temperature T_0 does not change. Therefore, $S = E/T_0$ where S and E are the total entropy and energy, respectively. Hence, by Einstein's equations $S = \text{const}$ implies $E = \text{const}$, which means, by relation (2), that the number of hadrons is changing with time as t^2 and the pressure is zero. Therefore, in the "hadronic era" the universe is matter-like. The time 10^{-23} sec plays a unique role within the "hadron era." At times earlier than 10^{-23} sec, the fundamental volume $4\pi\lambda\!\!\!^-{}_\pi^3/3$ can no longer represent a particle, since the Hubble distance ct is smaller than $\lambda\!\!\!^-{}_\pi$ and, hence, parts of the same object would be causally unconnected. For this reason Bahcall and Frautschi[6] have chosen this time to represent a "hadron barrier."

We have seen that the particle description breaks down at the "hadron barrier" when the overwhelming majority of hadrons have mass $M \sim c^2 \lambda\!\!\!^-{}_\pi/G$, which represents the mass for which the strong and gravitational forces are of equal strength since $Mc^2 \sim GM^2/\lambda\!\!\!^-{}_\pi$. Therefore, the "hadron barrier" also represents the time when the effect of the gravitational collapse wins over the forces, keeping inviolate the fundamental size of a particle.

At times earlier than the "hadron barrier," the universe may be viewed as subdivided into a fixed number of self-bound cells of comoving volume V_c. The same description by means of quasiparticles applies, and, because of the uniformity and isotropy assumptions, the cells are completely independent.[1] Since the comoving volume V_c is reducing in size as $R^3(t)$, hence, by Eq. (1), the maximum temperature T_0 is increasing. This increase will take place up to the "primordial chaos barrier" at which time effects of space quantization may become necessary.[11]

In the "early hadronic era" one obtains the equation of state with the aid of the entropy per cell, which is given by $S_c = E_c/T_0$, where the subscript c denotes the cell of comoving volume V_c. Using Eq. (1) with $m_0 = 0$ we have

$$dS_c = (1/T_0)\, dE_c - (E_c/T_0^2)\, dT_0$$
$$= (1/T_0)\, dE_c + (E_c/3V_cT_0)\, dV_c$$
$$= 0\ . \qquad (6)$$

The last equality follows from Einstein's field equations, since the total entropy $S = N_c S_c$ is a constant. The pressure can be identified from Eq. (6) and is $p = E_c/3V_c$. This result also follows directly from the definition of pressure $p \equiv -(\partial E/\partial V)_S = -S_c\, \partial T_0/\partial V_c = E_c/3V_c$, where the last equality follows from Eq. (1) with $m_0 = 0$. Since $E = N_c E_c$ and $V = N_c V_c$, then $p = E/3V$. Hence, in the "early hadronic era" the universe is radiationlike. Since the total entropy and the number of cells of volume V_c are constants, we have that the entropy per cell S_c is also a constant. From relation (2) one has $E_c/V_c = 3c^2/32\pi G t^2$. Also, $E_c = T_0 S_c$, and for $m_0 = 0$ Eq. (1) becomes $V_c T_0^3 = \pi^2(\hbar c/k)^3$. Therefore, the constant value for S_c can be determined by the boundary condition $kT_0 = m_\pi c^2$ at $ct = \lambda\!\!\!^{-}_\pi$, and one obtains

$$S_c = 3\pi\hbar c k/32 G m_\pi^2 = 2.3\times 10^{39} k\ . \qquad (7)$$

For times later than the "hadron barrier," the cells are identified with hadrons. Thus, we have the rather interesting result that at the "hadron barrier," the entropy per particle is $2.3\times 10^{39}k$.

B. Entropy per baryon

One may also calculate the entropy per particle S_p in the "hadronic era" and, in particular, at $t \sim 10^{-7}$ sec, the time for which the universe is still at its maximum temperature T_0. As we have seen in the "hadronic era," the mass of the overwhelming majority of hadrons at time t is $m_h = V_0\rho(t) = \pi\hbar^3/6c^3 m_\pi^3 G t^2$, and, hence, the entropy per particle, $S_p = E_p/T_0$, is

$$S_p = \pi\hbar^3 k/6 m_\pi^4 c^3 G t^2 \quad \text{for } 10^{-23} \leqslant t \lesssim 10^{-7} \text{ sec.} \qquad (8)$$

[The minor difference of a factor of $\frac{9}{16}$ between Eq. (8) evaluated at $t = \lambda\!\!\!^{-}_\pi/c$ and result (7) is due to our abrupt change at $t = \lambda\!\!\!^{-}_\pi/c$ from radiationlike to matterlike behavior. Of course, this transition can be made smooth.]

Evaluating result (8) for $t \sim 10^{-7}$ sec one obtains an entropy per particle $S_p \sim 10^7 k$. At $t\sim 10^{-7}$ sec baryons separate spatially from antibaryons (see below). We assume that only hadrons with baryon number ± 1 or 0 have the basic volume V_0 given by Eq. (1). The expansion of the universe up to $t \sim 10^{-7}$ sec is thermodynamically reversible—entropy remains constant. At $t\sim 10^{-7}$ sec the baryon-antibaryon phase separation may be brought about by irreversible processes with a consequent increase in entropy. Hence,

$$S_+ + S_- + \Delta S \geqslant S\ ,$$

where S is the total entropy for times slightly earlier than 10^{-7} sec. And, S_+ (S_-) is the total entropy of the regions containing baryons (antibaryons), and ΔS is the entropy of the interface, with zero net baryon number, between baryon and antibaryon regions for times slightly later than 10^{-7} sec. We shall suppose that $\Delta S/S_+$ is small—of the order of a surface-to-volume ratio. For times later than 10^{-7} sec the expansion of the universe is again assumed to be thermodynamically reversible and, hence, with entropy conservation. The total number of particles N is $N = N_+ + N_- + N_0$, where N_+ (N_-) is the total number of particles with baryon number $+1$ (-1), and N_0 is the total number of particles with baryon number zero.

Since our universe has zero net baryon number it follows that $N_+ = N_-$. Also, from the fundamental symmetry between matter and antimatter one must have that $S_+ = S_-$. Therefore, the entropy per baryon number s at $t\sim 10^{-7}$ sec satisfies

$$S_p = \frac{S}{N} \leqslant \frac{S_+ + S_-}{N} \leqslant \frac{S_+ + S_-}{N_+ + N_-} = \frac{S_+}{N_+} = s\ . \qquad (9)$$

That is, $s \geqslant 10^7 k$ at $t\sim 10^{-7}$ sec. Although this result is somewhat low compared to the present value[12] of $\sim 10^8 k$, it is interesting to obtain theoretically a rather large value for s from a simple model of the very early universe. It is interesting to note that our result for the entropy per baryon s follows from the value of S_p at the "hadron barrier" given by result (7) and which is of the order of the magic number of cosmology $e^2/G m_e m_p \sim 10^{40}$.

Actually our result for S_p for $t\sim 10^{-7}$ sec represents a lower bound. The asymptotic expression for the entropy per particle, $S_p = E_p/T_0$, holds for $t \lesssim 10^{-5}$ sec and E_p large. The next correction[10] to this expression for the entropy per particle is a positive term of the form $(E_p^\gamma - 1)/\gamma$, where $\gamma \equiv (\frac{5}{2}+b)/(\frac{7}{2}+b)$ and, hence, $0 \leqslant \gamma < 1$. Therefore, the value of S_p is rather sensitive to the asymptotic form of the hadron mass spectrum and the added positive correction makes our value for S_p a lower bound. If γ is rather close to its maximum value of one, our result for s at $t\sim 10^{-7}$ sec may increase somewhat.

C. Temperature

In our model the temperature is $T_0 = (\hbar m_\pi c^2/k^2 t)^{1/2} = 3.5\ ^\circ\text{K}\ (\text{sec}/t)^{1/2}$ in the "early hadronic era" and has a constant value $T_0 \approx m_\pi c^2/k \approx 10^{12}\ ^\circ\text{K}$ in the "hadronic era." For $t \gtrsim 10^{-5}$ sec our model must include corrections to the leading terms of $\rho(m)$ and $\omega(E_p)$. However, the low-mass region of the particle spectrum cannot be obtained from the statistical model for particle structure considered here—this region of the spectrum must be added to the theory. At $t \gtrsim 10^{-5}$ sec the low-mass particles, e.g., lighter hadrons, leptons, zero-mass particles, etc., form the overwhelming majority of particles. Therefore, the subsequent eras are radiation-dominated, with the entropy per baryon remaining almost constant, the pressure developing a nonzero value, and the temperature falling as $t^{-1/2}$. Consequently, our model may provide the initial conditions assumed in big-bang cosmology with charge symmetry for describing initial nucleosynthesis and galaxy formation[12] without giving rise to a radiation catastrophe.[14,15]

III. MATTER-ANTIMATTER SEPARATION

The charge symmetry of the model brings forth the question of matter-antimatter separation in order to explain observations around us. This question has been investigated by Omnès[16] who shows the existence of a spatial separation of nucleons and antinucleons for a temperature in the range $m_\pi c^2 < kT < m_n c^2$. The phase separation should occur in our model when the majority of particles are nucleons and antinucleons, that is, at $t \sim 10^{-5}$ sec. Omnès mentions the possibility that the separation could be the result of a thermodynamic phase transition. However, it is quite possible that the baryon-antibaryon phase separation takes place earlier than 10^{-5} sec when the baryons (and antibaryons) are much more massive than the nucleons. The entropy per baryon would have a higher value and if little baryon annihilation ensues, then the present value of s is almost entirely that which had existed at the time of the phase separation.

A. Baryon-antibaryon phase transition

For $kT_0 = m_{\pi^\pm} c^2$, one obtains—from (1) with $m_0 = 0$—a radius $r_0 = 1.87$ F for a hadron. Our model for bulk hadronic matter is essentially that of a dense hard-sphere classical gas—of a given radius r_0. Therefore, the total elastic cross section is $\sigma_{el} = \pi r_0^2$. Also, at extremely high energies, the collision between two hadrons gives rise to a single more massive hadron that subsequently breaks up. Hence, the asymptotic hadron-hadron collision is completely absorptive and one has $\sigma_{el}/\sigma_{tot} = \frac{1}{2}$. Therefore, at high energies the hadron-hadron total cross section is

$$\sigma_{tot} = 2\pi r_0^2 , \tag{10}$$

that gives, for $r_0 = 1.87$ F, a value $\sigma_{tot} = 220$ mb. This value for the hadron-hadron total scattering cross section is a limiting high-energy value. At higher densities, that is, higher energies, the radius r_0 does not change by virtue of the constancy of T_0. [At inaccessible energies, $s \gtrsim 10^{76}$ GeV^2, the hadron-hadron total cross section falls off as s^{-1} since $\sqrt{s}/V_0 = c^2/6\pi G t^2$ and $r_0 = 1.87(t/10^{-23}\ \text{sec})^{1/2}$ F for $t \leqslant 10^{-23}$ sec.] One determines at what energy we expect the leveling of the hadron-hadron total cross section to take place. For this estimate, we use the rising proton-proton total cross section based on cosmic-ray data[17]:

$$\sigma_{tot}(pp) = 38.8 + 0.4 \ln^2(s/131) , \tag{11}$$

where s is the square of the total center-of-mass energy in GeV^2. Therefore, for $\sigma_{tot} = 220$ mb, one obtains $s \sim 10^{11}$ GeV^2—a rather large value for the asymptotic region in high-energy physics.

With the aid of the relation between total center-of-mass energy $\sqrt{s}$ and mass density ρ, $\rho c^2 = \sqrt{s}/V_0$, one has for $s \sim 10^{11}$ GeV^2 that $\rho \sim 10^{19}$ g/cm^3. Since $\rho = 1/6\pi G t^2$, one gets that for $t \sim 10^{-7}$ sec the universe reaches its maximum limiting temperature $T_0 = m_{\pi^\pm} c^2$. Consequently, the value of the entropy per baryon of the universe must increase—since the baryon-antibaryon phase separation occurs at an earlier time—and one has for the entropy per baryon $s \gtrsim 10^7 k$ at $t \sim 10^{-7}$ sec.

From (1), with $m_0 = 0$, and (10) one has

$$kT_0 = \hbar c (9\pi^5/2)^{1/6} / \sigma_{tot}^{1/2} \quad \text{for } 10^{-7} \leqslant t \leqslant 10^{-5} \text{ sec.} \tag{12}$$

For $t \leqslant 10^{-7}$ sec all hadrons have the same size. Therefore, hadronic matter is described, as previously mentioned, by a dense hard-sphere classical gas of radius r_0. But, for $t \geqslant 10^{-7}$ sec ($s \leqslant 10^{11}$ GeV^2) the total cross section for different hadronic processes will differ. For instance,[18] the nucleon data for $\sigma_{tot}(pp)$ and $\sigma_{tot}(p\bar{p})$ indicate such a difference up to $s \sim 100$ GeV^2. Consequently, for $t \geqslant 10^{-7}$ sec our model for hadronic matter becomes one where the baryons and antibaryons have different radii owing to effects of charge-conjugation noninvariance. At near close-packed densities, a classical gas of hard spheres of two different radii has a phase transition.[19] Therefore, at $t \sim 10^{-7}$ sec we should have a baryon-antibaryon phase separation and a difference in temperatures in the separated regions for $t \geqslant 10^{-7}$ sec as given by (12). It is interesting that the low-energy data[18] may indicate a crossover of the cross sections for pp and $p\bar{p}$. Hence, the baryon-antibaryon total cross section may approach the asymptotic limit (220 mb) from below the baryon-baryon and the antibaryon-antibaryon total cross sections. This would imply from (12), that the annihilation regions are at a higher temperature than the separated baryon and antibaryon regions, thus providing an additional (thermal) stability which furthers and preserves the phase separation. However, local thermal instabilities certainly cannot rule out the baryon-antibaryon phase separation due to the phase transition.

If one supposes that during and after the phase separation there is at most a 90% baryon annihilation, then one has the attractive feature that the presently observed entropy per baryon is generated entirely in the course of the conventional "hadron era."

B. Metastable hadronic matter

The "hadron era" is based on a model of a hadron which is described by an equilibrium state. This state resembles a superheated liquid which is simultaneously a supercooled vapor.[9] (For ordinary fluids, the critical point is the only state with this property. Here, it occurs for the continuum of states with densities $\rho \gtrsim 10^{19}$ g/cm^3.) Superheated liquids and supercooled vapors are ordinarily associated with metastable states.[20] We shall see that, for $10^{-7} \leqslant t \leqslant 10^{-5}$ sec, the metastable state describing hadronic matter has negative pressure.[20] Therefore, in the latter part of the "hadron era," hadronic matter behaves as a superheated liquid vaporizing at $t \sim 10^{-5}$ sec.

The negative pressure is obtained as follows: Let N denote the total number of particles in the comoving volume V. One obtains

$$(E/3V-p)\,dV=(E/3N)\,dN\,, \tag{13}$$

with E and p the energy and pressure, respectively, in the comoving volume V. Einstein's field equations for a perfect fluid and the constancy of the entropy have been employed in obtaining (13). Note that if $dV>0$, then $dN>0$ implies $E/3V>p$, and, hence, $\delta>\frac{1}{2}$. For t small, $p=(2-3\delta)E/3\delta V$, and, hence, (13) may be integrated to give $V^{(4\delta-2)/\delta}\sim N$. Owing to the close-packed nature of hadronic matter $N/V=(9\pi/2)^{1/2}/\sigma_{\text{tot}}{}^{3/2}$, and, hence,

$$\sigma_{\text{tot}} \sim V^{4/3\delta-2} \sim t^{4-6\delta}\,. \tag{14}$$

For the overwhelming majority of hadrons, one has $m_h c^2=\rho c^2 V_0 \sim t^{-2}\sigma_{\text{tot}}{}^{3/2}$ and also $m_h c^2=\rho c^2 V_0 =\sqrt{s}$. Thus, $t^2 \sim s^{-1/2}\sigma_{\text{tot}}{}^{3/2}$. Combining this result with (14) one has

$$\sigma_{\text{tot}}(s) \sim s^{(3\delta-2)/(9\delta-4)}\,. \tag{15}$$

The total cross section increases with energy if $\delta>\frac{2}{3}$. (Recall that $\delta>\frac{1}{2}$.) Therefore, the pressure is negative and hadronic matter is a superheated liquid described by a metastable equilibrium state.

Experimental data on $\sigma_{\text{inel}}(pp)$ has been fitted[18] by an expression of the form of (15), $\sigma_{\text{inel}} \sim s^{+0.04}$, and gives $\delta=\frac{23}{33}$. Note that for δ very close to $\frac{2}{3}$, $\sigma_{\text{tot}}(s) \sim C_1+C_2 \ln s$ with C_1 and C_2 positive constants. This result has been considered also as a fit to the available data on the pp total cross section.

IV. COMMENTS

The baryon-antibaryon phase separation which results from the phase transition at $t\sim 10^{-7}$ sec gives rise to baryon and antibaryon regions with different temperatures, pressures, and particle densities. The determination of the sizes of these regions of matter and antimatter is a difficult problem of particle physics and, especially, statistical mechanics. These regions may be contained within the light horizon and, therefore, be as large as 30 m and as massive as $10^{-3}M_\odot$. It is clear that the sizes, together with the time development of these regions of matter and antimatter, will have a strong bearing on the question of galaxy formation.

The problem of galaxy formation has been investigated by others.[16,21] However, their physical assumptions differ considerably from ours. Carlitz, Frautschi, and Nahm consider the statistical-bootstrap model—with its associated exponentially rising hadron mass spectrum—with a longer "hadron era" and with matter out of equilibrium. The problem of the separation of baryons and antibaryons is avoided by considering a nonzero baryon number universe. This model demands the existence of superbaryons. Omnès considers a charge-symmetric universe of nucleons and antinucleons in thermodynamic equilibrium with temperature $T=1.52\times10^{10}\,{}^\circ\text{K}(t/\text{sec})^{-1/2}$ (no limiting maximum temperature). Omnès finds a nucleon-antinucleon phase separation at approximately 10^{-5} sec—when in our model the overwhelming majority of particles are nucleons and antinucleons. This phase separation occurs at the critical temperature $kT_c \approx 350$ MeV.

The phase separation in the present charge-symmetric model occurs at 10^{-7} sec at a temperature of 140 MeV. It involves baryons 10^5 times more massive than the nucleons. At times earlier, and perhaps much earlier than 10^{-5} sec, the phase separation should be complete. The baryon regions become nucleon regions via elementary particle processes.

If there is little baryon annihilation one would have the usual big-bang model of a radiation-dominated universe for $t \geqslant 10^{-5}$ sec with the correct matter-to-radiation content. The temperature can be obtained from (11) and must equal (12) at $t\sim 10^{-5}$ sec. This gives

$$T = 1.22\times 10^{10}\,{}^\circ\mathrm{K}(t/\mathrm{sec})^{-1/2} \text{ for } t \geq 10^{-5} \text{ sec.} \tag{16}$$

It is interesting that (16) is just what one obtains in a universe where radiation predominates even for earlier times.

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