International Journal of Theoretical Physics, Vol. 32, No. 9, 1993

Particle Masses in the Early Universe: Matter and Entropy Productions

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Received December 20, 1991

This article deals with the particle and entropy productions in the early universe, which is regarded as a thermodynamically open system in the sense of Prigogine, by incorporating the epoch dependence of elementary particle masses. The epoch dependence of particle masses for some of the Robertson–Walker (RW) universes appears as a consequence of previous considerations of the hadronic matter extension in the inner space-time regarded as anisotropic and Finslerian in character. The nature of the evolution of the early universe has been discussed in the framework of the modified thermodynamic energy conservation law and the new mass formula apart from the other Einstein equation. The trivial solution of these equations is the usual inflationary stage of the early universe, whereas the matter-dominated RW universe appears as the nontrivial solution. It is shown that at the "transition epoch" $t = 10^{-23}$ sec the creation phenomenon stops and the usual cosmology of the radiation era follows with Pascal's equation of state. This model can also account for the observed specific entropy per baryon of the present universe and the generation of the large value of K^{-1}, where $K = Gm_p^2/\hbar c$, m_p being the mass of the proton.

1. INTRODUCTION

In recent papers (De, 1986, 1989, 1990, 1991) it has been shown that the anisotropic Finslerian character of the inner space-time of hadronic matter extension can give rise to the "dynamics" of the subatomic particles as well as establish the evolution equation in curved space-time. Those considerations have also important cosmological consequences because the epoch dependence of the elementary particle masses appears as a result in some Robertson–Walker (RW) universes. Thus, it is necessary to look into the standard cosmology, particularly for the early stage of the universe. In fact, it is necessary to find a framework in this changed scenario which can account for the creation of matter constituents accompanied by large-

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scale entropy production as well as make it possible to avoid the initial singularity in the big-bang model. Prigogine (1989) proposed a phenomenological macroscopic approach toward such a direction by introducing thermodynamics of open system for the early stage of the universe. This consideration allows production of both the particles and entropy prevalent in our universe mostly in the form of blackbody radiation. Although several authors (Brout *et al.*, 1978, 1979a, b, 1980) considered earlier the particle production quantum mechanically in the framework of Einstein's equations, because of the adiabatic and reversible nature of these equations, a huge entropy production accompanying the production of matter is not possible. The quantum production of matter (particle-creation), particularly for the Friedmann metric, was considered long ago by, e.g., Parker (1968), Grib and Mamaev (1969), and Zel'dovich and Starobinsky (1971). Such considerations were also made by several other authors and the review by Gibbons (1979) gives a good account of these (see also Birrell and Davies, 1982). But the problem of large-scale entropy production persisted until the work of Prigogine, who considered particle production phenomenologically. Nardone (1989) has discussed the particle production quantum mechanically and by using a perturbation approach, he has shown that the Minkowski space-time is unstable with the created particles of masses 50 times the Planck mass m_{Pl}, which have been regarded as black holes. Gunzig *et al.* (1987) and Gunzig and Nardone (1989) proposed that due to the fluctuations of the conformal degrees of freedom of this initial Minkowski vacuum, de Sitter space-time might appear with the creation of matter. The black holes evaporate during this inflationary stage. The model can also account for the specific entropy per baryon of the present universe. This consideration, of course, is based on the production of massive particles (masses $50m_{\mathrm{Pl}}$) only in the early universe. Similar speculation regarding the existence of Planck-scale massive particles in the early universe was made by Parker (1989) and also by Bekenstein (1977) in his variable mass theory (VMT).

The present article deals with this situation of the early universe when the epoch dependence of the elementary particle masses, which appears as the consequence of the hadronic matter extension in the anisotropic Finslerian microdomain, as pointed out earlier, became predominant. It is indeed possible that the created massive particles in this framework might have masses several times larger than the Planck mass in the very early stage of the universe (at near the Planck time) and thus it is worthy studying their impact on the evolutionary character of the early universe regarded as a thermodynamically open system. The RW matter-dominated universe from the era of the Planck time appears in the picture as very natural and the creation of particles and entropy continued up to the transition epoch around $t = 10^{-23}$ sec. In fact, the creation phenomenon stopped at the onset of the radiation era in that epoch with the "usual" cosmology. For this early thermodynamically open universe, we have to modify, following Prigogine (1989), the thermodynamic energy conservation law for homogeneous and isotropic universes, which replaces the usual Einstein equation, and to incorporate the mass formula derived earlier (De, 1990, 1991). The quantum creation of matter constituents together with the avoidance of the initial singularity of the universe will be considered in a separate article.

In the following, the derivation of the basic equations for the early universe will be made first and in a subsequent section the consequences of the solutions of these equations will be discussed. There we shall also derive the specific entropy per baryon of the present universe, which will be found to be in good agreement with the observational data. We shall use units for which $\hbar = c = 8\pi G = k = 1$.

2. THE EQUATIONS FOR THE EARLY UNIVERSE

As pointed out earlier the present author (De, 1986, 1989, 1990, 1991) has recently considered the inner space-time of hadronic matter extension to be anisotropic in character. To be more specific, this anisotropy has been regarded as Finslerian; that is, the microdomain is considered as four-dimensional Finslerian space-time. From the general metric of this micro-space-time of subatomic particles, the RW background metric of the universe can be derived by some prescribed "averaging" procedure. This RW metric for the spatially homogeneous and isotropic universe is conformally related to the Minkowski metric. In particular, the open RW universe with flat Euclidean spacelike cross sections (i.e., $k = 0$ and deceleration parameter $q_0 = 1/2$), whose line element is given by

$$ds^2 = dt^2 - R^2(t)\, dl^2 \tag{1}$$

where dl^2 is the line element of the three-dimensional space, is related conformally to the Minkowski metric by

$$ds^2 = f(\eta)\, \eta_{\mu\nu}\, dx^\mu\, dx^\nu \tag{2}$$

The Minkowski metric is $\eta_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$ and $f(\eta)$ is a function of the conformal time $\eta = x^0$ only. Here $R(t)$ represents the scale factor of the RW universe and t is the cosmological proper time.

As pointed out earlier, the important consequence of the anisotropic microdomain of hadronic matter extension is the epoch dependence of the masses of the elementary particles in some of the RW universes. In fact, it has been found that the mass of the particle has contributions from two separate mass terms, one of which is independent of the epoch time and the other of which is epoch dependent; that is

$$m = \bar{m} + M\zeta(\eta)\, e(\eta) \tag{3}$$

Here $\bar{m}$ represents the present mass (we may call it the "inherent" mass of the particle) and M is the mass arising from the anisotropic nature of the space-time of hadronic matter extension. The functions $\zeta(\eta)$ and $e(\eta)$ are related to $f(\eta)$ by

$$\begin{aligned} \zeta(\eta) &= \frac{1}{2b_0} \frac{f'(\eta)}{f(\eta)} \\ e(\eta) &= [f(\eta)]^{-1/2} \end{aligned} \tag{4}$$

where $b_0 = 1/\tau$, $\tau/3$ being the present Hubble age of the universe.

In the RW-universe time, i.e., in the cosmological proper time t, the above mass relation (3) can be expressed as

$$m = \bar{m} + M\tau H(t) \tag{5}$$

where $H(t) = R'(t)/R(t)$ is the Hubble function. In fact, the present Hubble constant H_0 is related to τ by the relation

$$\tau = 2H_0^{-1} \tag{6}$$

We have set $M = \lambda\bar{m}$ for massive particles, where λ is a dimensionless constant. For massless particles such as neutrinos, $\bar{m} = 0$ and we may write $M = \lambda\hat{m}$, where $\hat{m}$ is the "assumed" mass at the very early epochs of the universe. [We have considered the value of λ to be 10^{-41} (De, 1990) and $\hat{m}$ is the "assumed" mass at the epoch time $t = 10^{-23}$ sec.] The mass $\hat{m}$, of course, may be zero for some of the massless particles. Thus, the mass relation (5) becomes

$$\begin{aligned} m &= \bar{m}[1 + \lambda\tau H(t)] \\ m &= \lambda\hat{m}\tau H(t) \end{aligned} \tag{7}$$

for massive and massless particles, respectively. It is to be noted that for the value of $\lambda = 10^{-41}$, the above mass relation, i.e., the epoch dependence of the masses of the particles, has relevance only in the very early epoch of the universe. Presently, we shall incorporate this epoch dependence of masses into the thermodynamics of open systems following the considerations of Prigogine (1989) on the particle and entropy productions in the early stages of the universe through the modification of the thermodynamic energy conservation laws for homogeneous and isotropic universes. For an adiabatic transformation this law is modified to be

$$d(\rho V)+p\,dV-\frac{h}{n}\,d(nV)=0 \tag{8}$$

where ρ and p are the density and the pressure (for the adiabatic perfect fluid model), respectively, and $h=\rho+p$ is the enthalpy per unit volume. Also, $n=N/V$, N being the number of particles in a given volume V [i.e., the comoving volume $R^3(t)$]. Equation (8) can be reduced to

$$\dot{\rho}=\frac{\dot{n}}{n}\,(p+\rho) \tag{9}$$

which replaces the usual Einstein equation (Bianchi identities for homogeneous and isotropic universe), i.e.,

$$\dot{\rho}=-3H(p+\rho) \tag{9a}$$

The other Einstein equation remains the same. For the zero-curvature three-dimensional space, this equation is

$$k\rho=3H^2 \tag{10}$$

In an alternative interpretation of the conservation equation (8) or (9), we may retain the usual conservation law (Bianchi identities) with the phenomenological pressure $\hat{p}$ instead of the above true thermodynamic pressure p. That is,

$$d(\rho V)=-\hat{p}\,dV \tag{11}$$

where these two pressures $\hat{p}$ and p are related by

$$\hat{p}=p+p_c \tag{12}$$

Here p_c represents a pressure, negative or zero, and corresponds to the creation of particles. In fact, when $p_c=0$, the creation of particles stops and in this case $\hat{p}=p$. Consequently, the usual conservation law holds, or, in other words, the usual general relativity with the usual Einstein equations holds. The expression for p_c is

$$p_c=-\frac{p+\rho}{3H}\frac{\dot{S}}{S} \tag{13}$$

where S is the entropy. Also, it can be shown that (Prigogine, 1989)

$$\frac{\dot{S}}{S}=\frac{\dot{N}}{N}=\frac{\dot{n}}{n}+3H \tag{14}$$

Let us now suppose that the equation of state is of the form

$$p=f(\rho) \tag{15}$$

Then, we have from equations (9), (12), and (13),

$$\dot{\rho}=\frac{\dot{n}}{n}[\rho+f(\rho)] \tag{16}$$

$$p_c=-\left[\rho+f(\rho)+\frac{\dot{\rho}}{3H}\right] \tag{17}$$

Using equation (10), we also have from equations (12) and (16),

$$p_c=-\left[\rho+f(\rho)+\frac{2\dot{H}\rho}{3H^2}\right] \tag{18}$$

$$\hat{p}=-\rho\left(1+\frac{2\dot{H}}{3H^2}\right) \tag{19}$$

Again, in the perfect fluid model, the phenomenological pressure $\hat{p}$ can be related to the density ρ by the relation

$$\hat{p}=\frac{1}{3}\rho\frac{\langle v^2\rangle}{c^2} \tag{20}$$

where c is the velocity of light and $\langle v^2\rangle$ is the mean square velocity of the particles. Thus, we can have, using equation (19),

$$\frac{\langle v^2\rangle}{c^2}=-3-\frac{2\dot{H}}{H^2} \tag{21}$$

In the particle-production era of the very early universe the energy density $\rho=\rho_m+\rho_\gamma$ should be dominated by the matter density $\rho_m=mn_m$, where n_m is the number density of particles and m is the particle mass at the epoch time that we are considering. The radiation density ρ_γ will dominate only after the particle production stops and, in fact, when the radiation era begins and $\rho_\gamma=(\gamma-1)mn_m+E_\gamma n_\gamma$, where E_γ and n_γ are the energy per photon and photon number density, respectively. Here, of course, we are assuming for simplicity that the created particles have the same masses. γ is related to the mean square velocity of the particles by

$$\gamma = \left(1 - \frac{\langle v^2 \rangle}{c^2}\right)^{-1/2} = \left(4 + \frac{2\dot{H}}{H^2}\right)^{-1/2} \tag{22}$$

Thus, for the radiation era to begin γ must be large and the matter density $\gamma m n_m$ contributes to the energy density

$$\rho = \rho_m + \rho_\gamma = \gamma m n_m + E_\gamma n_\gamma \tag{23}$$

But when the particle production occurs γ is nearly equal to one and $\rho \simeq m n_m$. In the following we shall consider the particle production in the early stages of the universe from the Planck time $t_{\text{Pl}} = 5.4 \times 10^{-44}$ sec to the time $t = 10^{-23}$ sec when the particle production stops and subsequently the radiation era begins. For this particle and entropy-production era, the equations that govern the cosmology of this era are given by [from equations (7), (9), (10), and (16)]

$$\frac{\dot{\rho}}{\rho} = \frac{2\dot{H}}{H} = \frac{\dot{n}}{n}\left(1 + \frac{f(\rho)}{\rho}\right) \tag{24}$$

$$\frac{\dot{m}}{m} = \frac{2\alpha \dot{H}}{1 + 2\alpha H} \tag{25}$$

where $\lambda\tau = 2\alpha$ and for the value of $\lambda = 10^{-41}$, as mentioned earlier, we find $\alpha \simeq 10^{-23}$ sec. Here, n represents the total particle number density, i.e., $n = n_m + n_\gamma$. Now, if we write for the radiation density $\rho_\gamma = 3\hat{p}$, we have from equations (20) and (22)

$$\frac{\rho_\gamma}{\rho_m} = \gamma^2 - 1 = -\frac{3 + 2\dot{H}/H^2}{2(2 + \dot{H}/H^2)} \tag{26}$$

This equation can also be achieved in the perfect fluid model by considering the RW universe as the conformal Minkowski space-time. Let us rewrite the line element (2) of the conformal Minkowski space-time related to that of RW universe given by (1), in the following form:

$$dS^2 = \Omega^2(\eta)\left[d\eta^2 - \sum_{i=1}^{3} (dx^i)^2\right] \tag{27}$$

where

$$d\eta = \frac{dt}{\Omega(\eta)} = \frac{dt}{R(t)} \tag{28a}$$

or

$$\eta = \int \frac{dt}{R(t)} \tag{28b}$$

The conformal Ricci scalar and tensor $\bar{R}$ and $\bar{R}^{\nu}_{\mu}$ can be computed to be

$$\begin{aligned} \bar{R} &= 6\Omega^{-3}\Omega_{;00} \\ \bar{R}^{\nu}_{\mu} &= -2\Omega^{-1}(\Omega^{-1})_{;\mu 0}\, g^{0\nu} + \tfrac{1}{2}\Omega^{-4}(\Omega^2)_{;00}\,\delta^{\nu}_{\mu} \end{aligned} \tag{29}$$

where $g^{\mu\nu}$ is the conformal metric.

In the perfect fluid model, we have

$$\begin{aligned} &-2\Omega^{-1}(\Omega^{-1})_{;\nu 0}\, g^{0\mu} + \delta^{\mu}_{\nu}[\tfrac{1}{2}\Omega^{-4}(\Omega^2)_{;00} - 3\Omega^{-3}\Omega_{;00}] \\ &\quad = -k[(\rho+\hat{p})u^{\mu}u_{\nu} - \hat{p}\,\delta^{\mu}_{\nu}] \end{aligned}$$

Here, $u^{\mu}u_{\nu} = 0$ for $\mu \neq \nu$,

$$u^0 u_0 = 1, \qquad u^1 u_1 = u^2 u_2 = u^3 u_3 = 0$$

Then we have the following expressions for the density and pressure:

$$\begin{aligned} k\rho &= 3\dot{\Omega}^2/\Omega^4 \\ k\hat{p} &= (\dot{\Omega}^2 - 2\Omega\ddot{\Omega})/\Omega^4 \end{aligned} \tag{30}$$

Here, the dot represents the differentiation with respect to the conformal time η. Writing $\rho_{\gamma} = 3\hat{p}$ again, we have

$$\begin{aligned} \frac{\rho_{\gamma}}{\rho} &= 1 - \frac{2\Omega\ddot{\Omega}}{\dot{\Omega}^2} \\ \frac{\rho_{\gamma}}{\rho_m} &= \frac{\dot{\Omega}^2}{2\Omega\ddot{\Omega}} - 1 = \frac{(dR/dt)^2}{2[(dR/dt)^2 + R\, d^2R/dt^2]} - 1 \end{aligned}$$

Since $H(t) = \dot{R}(t)/R(t)$, we get the same expression (26) for the ratio ρ_{γ}/ρ_m in terms of the Hubble function $H(t)$. The relation between γ and $H(t)$ follows from equation (22).

Now, using relations (23)–(26), we can deduce the following relations:

$$\begin{aligned} \frac{n_m}{n} &= \frac{E_{\gamma}}{E_{\gamma} + \gamma(\gamma-1)m} \\ \frac{n_{\gamma}}{n} &= \frac{\gamma(\gamma-1)m}{E_{\gamma} + \gamma(\gamma-1)m} \end{aligned} \tag{31}$$

$$\left(\frac{\dot{E}_\gamma}{E_\gamma}+\frac{\dot{n}_\gamma}{n_\gamma}\right)-\left(\frac{\dot{m}}{m}+\frac{\dot{n}_m}{n_m}\right)=\frac{\dot{\gamma}}{\gamma}\frac{2\gamma-1}{\gamma-1} \qquad \text{for} \quad \gamma\neq 1$$
$$\frac{\dot{E}_\gamma}{E_\gamma}+\frac{\dot{n}_\gamma}{n_\gamma}=0 \qquad \text{for} \quad \gamma=1 \tag{32}$$

and

$$\frac{2\dot{H}}{H}=\frac{\dot{\rho}}{\rho}=\frac{\dot{\gamma}}{\gamma^2}+\frac{1}{\gamma}\left(\frac{\dot{m}}{m}+\frac{\dot{n}_m}{n_m}\right)+\frac{\gamma-1}{\gamma}\left(\frac{\dot{E}_\gamma}{E_\gamma}+\frac{\dot{n}_\gamma}{n_\gamma}\right) \tag{33}$$

and finally we obtain the following governing equations that decide, together with equation (25), the "cosmology" of the creation era in the very early universe:

$$\frac{\dot{\rho}}{\rho}=\frac{2\dot{H}}{H}=\frac{\dot{n}}{n}\left(1+\frac{\dot{f}(\rho)}{\rho}\right)$$
$$=\frac{E_\gamma}{E_\gamma+\gamma(\gamma-1)m}\left[\frac{\dot{m}}{m}+\frac{\dot{E}_\gamma}{E_\gamma}(\gamma-1)\frac{\gamma m}{E_\gamma}+\frac{\dot{\gamma}}{\gamma}\left(2-\frac{\gamma m}{E_\gamma}\right)\right]\left(1+\frac{\rho}{f(\rho)}\right) \tag{34}$$

3. THE SOLUTIONS: CONSEQUENCES AND CONCLUDING REMARKS

It is apparent from equations (24) and (25) [also from the equations (31)–(34)] that they possess the trivial solution

$$\dot{\rho}=\dot{H}=\dot{n}=\dot{m}=0 \tag{35}$$

This solution corresponds to the inflationary stage of the very early universe. It should be noted that during this period the particle mass remains constant and after that period the mass decreases. The particle mass achieves a value of a few multiples of the present value as soon as the age of the universe is only $\alpha=10^{-23}$ sec. For the scale factor $R(t)\propto e^{Dt}$ in the inflationary stage of the universe, the mass of the particle is given by

$$m=\bar{m}(1+2\alpha D)\simeq 2\alpha\bar{m}D \tag{36}$$

since $\alpha D\gg 1$. In fact, for the typical inflationary parameter $D\sim 10^{34}\,\text{sec}^{-1}$ the value of αD is $10^{11}\gg 1$.

For the RW universe with $H=\beta/t$, the situation is quite different. In this case, the masses for the elementary particles might have been of the order of the Planck mass (or even more) around the Planck epoch so that they can achieve the present masses at the present epoch of the universe or be only a few multiples of the present values at the epoch time $t=\alpha=10^{-23}$ sec. Thus, the creation of such (Planck scale) massive particles in the very early universe (say, from the Planck epoch time) ensures that the energy density ρ must be dominated by the matter density and consequently the value of γ is almost one. In other words, these created massive particles of the "creation era" are nonrelativistic in nature and in the transition from the creation era to the radiation era around the epoch time $t=10^{-23}$ sec they become relativistic with large γ, the value which will be found later. Consequently, the energy density is dominated by the radiation density. It is to be noted that the pressure p_c which is responsible for the particle creation must be zero at this transition around 10^{-23} sec at which epoch time the masses of the elementary particles achieve the values of the order (only few multiples) of their present values. Around this epoch, therefore, we must have $\hat{p}=p=\rho/3$ and $\dot{N}/N=\dot{S}/S=0$, giving $\dot{n}/n=-3H$ [cf. equations (13) and (14)]. Thus the entropy production accompanying the particle creation stops and remains constant afterward. The modified Einstein equation (9) becomes the usual Einstein equation (9a) and the usual cosmology of the radiation era follows subsequently.

For $\gamma \simeq 1$, $\rho_\gamma \ll \rho_m$, we have from equation (34) or from (24) and (25) (noting that $\dot{\gamma}/\gamma \ll \dot{m}/m$)

$$\frac{\dot{\rho}}{\rho}=\frac{2\dot{H}}{H}=\frac{\dot{n}}{n}\left(1+\frac{f(\rho)}{\rho}\right)=\frac{\dot{m}}{m}\left(1+\frac{\rho}{f(\rho)}\right) \tag{37}$$

Apart from the trivial solution (35), the above equations possess the following nontrivial solution:

$$\begin{aligned} f(\rho)&=\frac{\alpha H\rho}{1+\alpha H} \\ n&=\frac{3H^2}{k\bar{m}(1+2\alpha H)} \end{aligned} \tag{38}$$

For the RW universe $H=\beta/t$, we have, therefore, $f(\rho)=\alpha\beta\rho/(t+\alpha\beta)$ and for $t\ll\alpha=10^{-23}$ sec this equation of state becomes $p=f(\rho)\simeq\rho$, which corresponds to the maximally stiff equation of state (Zel'dovich, 1962). The value of β in this case is 2/3. On the other hand, when the particle creation stops, then the value of β must be close to 1/2 (which corresponds to large γ; in fact, the relation between them is $1/\gamma^2=4-2/\beta+2\dot{\beta}t/\beta$). Therefore $f(\rho)=\rho/3$ at $t=\alpha=10^{-23}$ sec and $p_c=0$, as $\hat{p}=\rho/3$ for the radiation era.

When in the transition β changes from its value 2/3 to 1/2, then γ increases from its value one to a large value and we have the equation of state

$$\frac{f(\rho)}{\rho}=\left\{\frac{E_\gamma}{E_\gamma+\gamma(\gamma-1)m}\left[\frac{\dot{m}}{m}+\frac{(\gamma-1)\gamma m}{E_\gamma}\frac{\dot{E}_\gamma}{E_\gamma}+\frac{\dot{\gamma}}{\gamma}\left(2-\frac{\gamma m}{E_\gamma}\right)\right]\right\}$$

$$\times\left\{\frac{2\dot{H}}{H}-\frac{E_\gamma}{E_\gamma+\gamma(\gamma-1)m}\left[\frac{\dot{m}}{m}+\frac{(\gamma-1)\gamma m}{E_\gamma}\frac{\dot{E}_\gamma}{E_\gamma}+\frac{\dot{\gamma}}{\gamma}\left(2-\frac{\gamma m}{E_\gamma}\right)\right]\right\}^{-1} \quad (39)$$

The value of γ increases in the transition to the radiation era when the particles become relativistic. In fact, our conjecture is that the part of the energy density $\gamma m n_m$ due to the massive particles contributes to the radiation energy density ρ_γ and it is due to the fact that γm for large γ at the transition time around 10^{-23} sec becomes the relativistic mass-energy and increases to the order of E_γ at that epoch, i.e.,

$$E_\gamma \simeq \gamma_\alpha m \quad (40)$$

where γ_α is the value of γ at $t=\alpha=10^{-23}$ sec. The relation (40) determines the value of γ_α from the known values of the particle mass m and E_γ at the epoch $t=\alpha$, since the usual cosmology follows subsequently. In fact, the value of E_γ at $t=\alpha$ is 10^{22} cm^{-1} and $m\simeq 10^{13}$ cm^{-1} for muons (in the units $\hbar=c=k=8\pi G=1$), which are taken as the "representative" particles [and also the fundamental particles and the constituents of the hadrons (De, 1986, 1989)]. These values of mass and energy per photon at the transition epoch give $\gamma_\alpha=10^9$. Again, from the previous expressions of ρ_m and ρ_γ as well as from (26) we can derive that

$$\frac{E_\gamma n_\gamma}{m n_m}=\gamma(\gamma-1) \quad (41)$$

Now, we can also derive the ratio of the photon to particle (baryon) numbers at this transition epoch $t=\alpha$ by using equations (40) and (41). This ratio remains constant after this transition epoch from the creation to the radiation era because the particle creation has ceased afterward. This ratio is

$$\frac{n_\gamma}{n_m}=\gamma_\alpha-1\simeq 10^9 \quad (42)$$

which is in conformity with the observational data. The ratio of the photon to baryon number is, in fact, related to the present specific entropy S per baryon by the relation $S = 3.7\, n_\gamma/n_m$. This specific entropy per baryon can be easily found to be

$$S = 3.7 \frac{\rho_{\gamma 0}}{\rho_{m0}} \frac{m_b}{T_0} \tag{43}$$

where $\rho_{\gamma 0}$, p_{m0}, and T_0 refer to the present value of the corresponding quantities and m_b is the baryon mass. This specific entropy per baryon can also be directly computed from the quantities of the transition epoch $t = \alpha$ by using the relation (26) and the following adiabatic constant (since, after the epoch $t = \alpha$, the usual cosmology follows):

$$\frac{\rho_\gamma}{\rho_m T} = \text{constant} = \frac{\rho_{\gamma 0}}{\rho_{m0} T_0} \tag{44}$$

Therefore, at $t = \alpha$, $\rho_{\gamma 0} T/\rho_{m0} T_0 = \rho_\gamma/\rho_m = \gamma_\alpha^2 - 1 \simeq 10^{18}$. The temperature T at the epoch $t = \alpha$ can be computed using the Einstein equation (10) and the usual relation

$$\rho_\gamma = \frac{\pi^2}{30} N_{\text{eff}} T^4, \qquad \text{where} \quad N_{\text{eff}} = N_b + \frac{7}{8} N_f$$

(Blau and Guth, 1987). It can be found that $T \simeq 10^{22}\,\text{cm}^{-1}$ and therefore the present specific entropy per baryon can be easily found to be $S = 1.76 \times 10^{10}$, where we have used the proton mass as the representative mass for the baryons. This result is in good agreement with the observational facts.

We point out that in the transition epoch just before $t = \alpha = 10^{-23}$ sec, $\dot{\gamma}/\gamma$ begins to increase with increasing γ from its very small value (or from its value zero) of the pretransition creation era. Consequently, it is evident from equation (39) that $f(\rho)/\rho$ decreases from its value one and makes $p_c = 0$ just before $t = \alpha$ because $\hat{p}/p = 1/3(1 - 1/\gamma^2)$ [which follows from equations (20) and (22)] increases from its value zero to a positive value that is equal to $f(\rho)/\rho$ at some time α' (say, $\alpha' \lesssim \alpha$) just before $t = \alpha$. Thus, the matter creation stops and the usual cosmology follows with increasing γ, which culminates in the value 10^9 at $t = \alpha$. In this very small time interval between α' and α, $f(\rho)$ and $\hat{p}$ may become negative since $\dot{\gamma}/\gamma$ might become large compared to $\dot{m}/m$ and $\dot{E}_\gamma/E_\gamma$ in this period, stimulating creation of radiation within the framework of the usual cosmology. Of course, by the decays of particles or by the phase transitions the radiation energy might also increase in this transition era. But, at $t = \alpha$ as well as in subsequent epochs, $\dot{\gamma}/\gamma$ becomes small again compared to $\dot{E}_\gamma/E_\gamma$ and $\dot{m}/m$ and then we have from equation (34), since γ is very large,

$$\frac{\dot{\rho}}{\rho}=\frac{2\dot{H}}{H}=\frac{\dot{n}}{n}\left(1+\frac{f(\rho)}{\rho}\right)=\frac{\dot{E}_\gamma}{E_\gamma}\left(1+\frac{\rho}{f(\rho)}\right) \tag{45}$$

with $\hat{p}=p=f(\rho)=\rho/3$ for the radiation era. These equations give $n\propto t^{-3/2}$ and $E_\gamma \propto t^{1/2}$, which are the results of the usual cosmology. Thus, the equation of state (38) continues up to the epoch $t=\alpha$ except for the very short period of time between α' and α, which characterizes the "sharp" transition from the creation to the radiation era.

We have discussed the consequences of the epoch dependence of mass in the early universe, which is considered as a thermodynamically open system. Both the matter constituents and entropy production occur in this framework. Although inflationary evolution may occur in the early universe and this appears as a trivial solution of the equations of this model, the RW matter-dominated creation era is also found to be a natural possibility which appears as a nontrivial solution. At the Planck time t_{Pl} the epoch dependence of masses of subatomic particles is very dominant and in fact some of the elementary particles such as protons or neutrons might have masses several times (50–100 times) larger than the Planck mass. Such heavy massive particles can make the Minkowski space-time unstable and lead to the expanding phases of the universe (Nardone, 1989). Also, Parker (1989) pointed out the possible existence of particles of masses of the order of the Planck mass (masses $0.28\,m_{\mathrm{Pl}}$) in the very early universe (at the Planck time t_{Pl}) in his discussion of the possible anomalous decay of the neutral pion into gravitons. The GUT and SUSY theories also require such heavy massive particles (neutrinos) and the present consideration admits all such Planck-scale massive particles. Again, at the epoch time around $t=\alpha=10^{-23}$ sec the masses of these subatomic particles reduce to only a few multiples (approximately twice) their present values. This epoch is also the transition epoch from the creation to the radiation era and determines the maximum value of γ from the values of the universe temperature and mass of a fundamental particle at that epoch of the universe. This value of γ gives rise to a constant value of the specific entropy per baryon in good agreement with the present value from the observational data. The pressure p_c which is responsible for particle creation becomes zero at that epoch and the usual cosmology follows subsequently with Pascal's equation of state for the radiation era. Thus, the transition epoch, change in the equation of state, discontinuation of creation (of both the entropy and matter constituents) characterized by $p_c=0$, and the achievement of particle masses of the order of only a few multiples of their present values are all interrelated and manifested in observational facts such as the specific (constant) entropy per baryon.

This framework also seems to be very encouraging for the question raised by Dicke and Peebles (1979) with respect to the beginning of the universe as a "quantum fluctuation" with $K^{-1} \sim 1$ where $K = Gm_p^2/\hbar c$ (m_p being the mass of the proton). In fact, in our framework $K^{-1} \sim 1$ (in our unit $\hbar = c = k = 8\pi G = 1$, $Gm_{\rm Pl}^2 \sim 1$ and since at the Planck time $t_{\rm Pl}$, the proton mass $m_p \sim m_{\rm Pl}$ we find $K \sim 1$) and the generation of K^{-1} (to the present large value) is possible together with the generation of matter and entropy, since the proton mass decreases from its Planck-scale value to its present value.

Lastly, we point out that some of the shortcomings of the standard model, related to the overproduction of magnetic monopoles, flatness problems, etc., may be resolved in the present framework. These problems may be resolved as in the case of the inflationary scenario which appears here as a trivial possibility. Apart from this situation of trivial solution, these problems might be avoided for the nontrivial case, too. As an example, we might consider the flatness problem; the large value of the entropy S per comoving volume (i.e., $S > 10^{87}$) may be viewed as an alternative statement of this problem (Blau and Guth, 1987) and such an entropy production is quite possible in the present framework. Detailed discussion will be made in a subsequent paper in which we also show how the universe might have originated from the Minkowski space-time through an "instability" before the Planck time. In fact, we shall discuss how, by the quantum creation of matter in the perturbed "anisotropic" Minkowski space-time, the creation of matter constituents as well as the avoidance of the initial singularity are possible. More specifically, the "anisotropy" in the Minkowski space-time occurs in a very short period of time in comparison with the Planck scale time, which signifies the "origin" of the expanding universe without a singularity (initial). The universe, consequently, began to expand due to the instability engendered by the created Planck scale massive particles from that epoch just after the "anisotropy period" (stopped due to back reaction) around the Planck epoch of the universe.

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