Absence of particle creation in a hot Friedmann universe

A. D. Linde
P. N. Lebedev Physical Institute, Academy of Sciences of the USSR

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It is shown that taking into account the temperature dependence of particle masses in an expanding Friedmann universe leads to nearly complete suppression of the creation of particles with masses $m \lesssim 10^{17}$ GeV.

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1. One of the most interesting problems lying at the boundary between cosmology and the theory of elementary particles is the problem of particle creation in an expanding universe. In the 15 years after the problem was first stated,[1] many brilliant and impressive results have been obtained in this area (see Ref. 2 along these lines). However, virtually all of these results concerned a model of the universe which initially did not contain matter, rather than the currently accepted model of a hot universe.[3] As will be shown in what follows, taking into account the corresponding high-temperature effects greatly changes the existing picture of particle creation in the early universe.

2. As an example, we shall examine the theory of a scalar field with mass m_0 with the Lagrangian

$$L = \frac{1}{2}(\phi_{;\mu})^2 - \frac{1}{2}\left(m_0^2 + \frac{R}{6}\right)\phi^2 - \frac{\lambda}{4}\phi^4 \qquad (1)$$

in a flat Friedmann universe with metric

$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2 + dz^2).$$

In order to study the creation of particles belonging to the field ϕ, it is convenient to

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make a conformal transformation to the metric

$$ds^2 = a^2(\eta)\,(d\eta^2 - dx^2 - dy^2 - dz^2), \tag{2}$$

where

$$\eta = \int a^{-1}(t)\,dt,$$

and to the transformed field

$$\psi = a(\eta)\phi.$$

The equation of motion for the field ψ in the metric (2)

$$\frac{d^2\psi}{d\eta^2} - \Delta\psi + a^2(\eta)m_0^2\,\psi + \lambda\psi^3 = 0 \tag{3}$$

describes the field with variable "mass'

$$M(\eta) = m_0 a(\eta).$$

The nonadiabaticity of the change in the quantity $M(\eta)$ with increasing η leads to creation of particles of the field ψ and, therefore, to particles of the field ϕ^2. The nonadiabaticity is characterized by the quantity

$$\delta = M^{-2}(\eta)\frac{dM}{d\eta} = m_0^{-1}a^{-1}(\eta)\frac{da}{dt}, \tag{4}$$

and, in addition, for small values of δ, the probability for creation of particles is decreased by a factor $\exp-(1/\delta)^2$.

With the universe expanding according to the law

$$a(t) = a_0 t^q, \qquad 0 < q < 1,$$

where t is the time from the beginning of expansion, the nonadiabaticity parameter (4) is

$$\delta = q/m_0 t. \tag{5}$$

Hence, it follows that in the early universe particles with any nonzero mass m_0 must have been created and, in addition, the creation process occurred for $t \lesssim m_0^{-1}$, while for $t \gg m_0^{-1}$, particle creation was exponentially suppressed.[2]

3. We shall now take into account the fact that the effective mass of particles of the field ϕ is modified in matter whose temperature is $T \gg m_0$:

$$m^2(T) = m_0^2 + \frac{\lambda}{4}T^2, \tag{6}$$

and Eq. (3) takes the form

$$\frac{d^2\psi}{d\eta^2} - \Delta\psi + a^2(\eta)\left(m_0^2 + \frac{\lambda}{4}T^2\right)\psi + \lambda\psi^3 = 0. \tag{7}$$

We also note that according to the standard representations of the theory of a hot universe,[3] the quantity aT at the time of expansion of the universe remains nearly constant, $aT \approx a_0 T_0$. In this case, for $\lambda T^2 \gg m_0^2$,

$$M(\eta) \approx \frac{\sqrt{\lambda}}{2} T_0 a_0 + \frac{m_0^2 a^2}{\sqrt{\lambda}\, T_0 a_0}, \tag{8}$$

and, in addition, the first term on the right side of (8) is much greater than the second term and does not depend on η. The adiabaticity parameter δ, in this case, is

$$\delta = M^{-2}(\eta)\frac{dM}{d\eta} \approx \frac{m_0^2}{\left(\frac{\sqrt{\lambda}}{2} T\right)^3} a^{-1}\frac{da}{dt}. \tag{9}$$

It is not difficult to see that the quantity δ (9) for $\lambda T^2 \gg m_0^2$ is much less than the quantity δ in (4) and (5), calculated without using the temperature dependence of the particle masses (12).

4. In order to estimate the role of the decrease in nonadiabaticity due to the temperature dependence of the particle masses, we recall that the expansion of the early universe, filled with particles interacting according to the modern theories of weak, strong, and electromagnetic interactions, is described by the equation

$$a^{-1}\frac{da}{dt} = \sqrt{\frac{4\pi^3 N}{45}}\frac{T^2}{M_p}, \tag{10}$$

where $M_p \approx 1.2 \times 10^{19}$ GeV is the Planck mass, N is the effective number of degrees of freedom (species of particles), and $N \sim 200$ in the simplest theories.[3,5] Taking into account also the fact that in these theories the coefficient $\lambda/4$ in front of T^2 in (6) is replaced by some coefficient $c \sim 1$ due to the interaction of the field ϕ with a large number of fields of other types.[6] In this case, it follows from (15) and (16) that for $T \gtrsim m_0$

$$\delta \approx \frac{20\, m_0^2}{c^3 T M_p}. \tag{11}$$

It follows from (17) for $c \approx 1$ that the scalar particles are created in a hot Friedmann universe only if

$$m_0 \gtrsim 5 \cdot 10^{17}\,\text{GeV}. \tag{12}$$

It may be shown that an analogous conclusion is also valid for vector and spin particles. At the same time, scalar particles without the conformal increment $\frac{1}{6}R$ to the square of the mass (1) are created with arbitrary value of m_0 (if $R \neq 0$), but in any case, it turns out that particle creation ceases at $T \lesssim 5 \times 10^{17}$ GeV.

The results obtained here differ considerably from those of preceding investigations, carried out without regard for the high-temperature effects.[2] It would be interesting to clarify the possible value of these effects for the theory of particle creation in an anisotropic universe.

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