Multiple production of particles in models with spontaneous symmetry breaking

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It is shown that the existence of temperature phase transition in strong-interaction models with spontaneous breaking of chiral symmetry can lead to observable consequences in processes of multiple production of particles.

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It is known that the behavior of matter, within the framework of field models with spontaneous symmetry breaking, has interesting singularities. The large values of the temperature, of the charge densities can lead to restoration of spontaneously broken symmetry (relativistic phase transition[1]).

Do any observable consequences of such transitions exist?

For the unified models of electromagnetic and weak interactions, the crystal temperature is of the order of 10^2 GeV.[1] It appears that such high temperatures are meaningful only when one speaks of astrophysical objects.[2]

In the strong-interaction model the temperature of the relativistic phase transition can be of the order of several GeV. Such temperatures are encountered in connection with the static approach to multiple production of particles at energies $E > 10^3$ GeV (see, e.g., [3]). In this approach it is assumed that during the initial stage of the process of multiple production there is produced a hot hadron cloud that is in thermodynamic equilibrium.

As a theory describing strong interactions of nucleons and mesons, we consider the simplest SU(2)⊗SU(2) variant of the σ model[4] with a Lagrangian

$$L = \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec{\pi})^2 + \frac{1}{2}\mu_0^2(\sigma^2 + \vec{\pi}^2) - \frac{\lambda}{4!}(\sigma^2 + \vec{\pi}^2)^2 + \bar{\psi}\left\{(i\gamma_\mu \partial_\mu - g(\sigma - i\gamma_5 \vec{\tau}\vec{\pi})\right\}\psi , \tag{1}$$

where σ is the scalar field, $\vec{\pi}$ is an isotriplet of pseudoscalar fields, and ψ is the spinor field of the nucleons. The ground state in the σ model is characterized by an anomalous vacuum mean value $\sigma_0 = \sqrt{6/\lambda}\mu_0$, corresponding to spontaneous breaking of the chiral symmetry of the Lagrangian (1).

A calculation of the temperature dependence of the average scalar field $\langle\sigma\rangle_T$ reduces to a determination of the minimum of the thermodynamic potential $\Omega(\langle\sigma\rangle_T)$ of the hadronic matter. Calculations analogous to those performed in[5] for the Higgs model show that a realistic relation between the constants $g^4 \gg \lambda (\mu_0 \sim \text{GeV})$ in the σ model, a first-order phase transition takes place, in which $\langle\sigma\rangle_T$ vanishes jumpwise:

$$\langle\sigma\rangle_T \approx \begin{cases} \sigma_0, & T < T_c \\ 0, & T > T_c \end{cases} \qquad T_c \sim \mu_0/\sqrt{g} \tag{2}$$

(for the strong constants g and λ these formulas can be valid only in order of magnitude). We then have for the effective masses of the pions and nucleons

$$m_\pi \approx \begin{cases} 0, & T < T_c \\ gT, & T > T_c \end{cases}, \qquad m_N \approx \begin{cases} g\sigma_0, & T < T_c \\ 0, & T > T_c \end{cases} \tag{3}$$

(at $T > T_c$ the chiral symmetry is restored, $m_\sigma = m_\pi$).

The use of the statistical formulas is justified in this case if the particle mean free path in the hadron matter $l \sim (\Sigma n)^{-1}$ (where Σ is the cross section for the scattering of particles by each other, $\Sigma \sim m_\pi^{-2}$, and n is the density of the particles) is small in comparison with the dimension of the system. The smallness of l at $T < T_c$ is due to the smallness of the pion rest mass μ_π. In spontaneous breaking of the chiral symmetry, the pion appears as a massless Goldstone boson. Above the phase-transition temperature T_c, when the chiral symmetry of the ground state is restored, the pion becomes a heavy particle. This leads to a sharp screening of the effective radius of the strong interaction and, consequently, to a sharp increase in the particle mean free path at $T > T_c$.

In the high-temperature phase ($T > T_c$), the hadronic matter in the σ model consists mainly of massless nucleons and antinucleons, the total density of which is $n \sim T^3$ [the presence of the remaining particles is suppressed by the exponential factor $\exp(-g)$]. According to (3), the mean free path is

$$l \sim g^2/T . \tag{4}$$

Using (4), we can easily show that for $g > 1$ establishment of thermodynamic equilibrium in the high-temperature phase is impossible in the characteristic small collision volume.

The low-temperature phase ($T < T_c$) can be described by the ordinary Landau hydrodynamic model, in which the thermodynamic equilibrium takes place at $T > \mu_\pi$.

We see that in strong-interaction models with spontaneous breaking of chiral symmetry the statistical description of the process of multiple production is possible only in the temperature interval $\mu_\pi < T < T_c$. In other words, the applicability of the ordinary hydrodynamic theory for the considered models is limited to the energy region $E < E_c$, for which the temperature of the hadronic matter does not exceed T_c. For an equation of state in the form $P = c_0^2\epsilon$ (where P and ϵ are the pressure and density of the energies of the hadronic matter) we have

$$E_c \sim \mu_\pi \left(\frac{T_c}{\mu_\pi} \right)^{\frac{1 + c_0^2}{c_0^2}} \tag{5}$$

in the laboratory frame. In the case $c_0^2 = 1/3$ and $T_c \sim 1$ GeV we have $E_c \sim 10^3$ GeV.

The presence of a non-hydrodynamic stage in the process of multiple production for $E > E_c$ can lead to a change in the multiplicity and the angular distribution of the secondary particles in comparison with the predictions of the hydrodynamic model.

The most sensitive to the existence of a phase transition can be the distribution of secondary particles with respect to their transverse momenta. At the present time it is likely[6] that for large $p_\perp$ this distribution is connected with emission of particles during early stages of the hydrodynamic process, and is given by the expression

$$f(p_\perp) \sim \exp\left\{ - \frac{p_\perp}{T_{in}} \right\} , \tag{6}$$

where $T_{in}(E)$ is the initial temperature of the hadronic matter. Our analysis shows that no temperature $T_{in} > T_c$ can be established in models with phase transition. Therefore $f(p_\perp)$ ceases to depend on the primary-particle energy at $E > E_c$ [Eq. (5)].[1)]

We note in conclusion that strong-interaction models with spontaneous breaking of chiral symmetry, for which $T_c < 1$ GeV, apparently contradict the existing experimental data.

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