Anomalously small baryon yield as signalling the formation of a quark-gluon plasma

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It is shown in the model of chromoelectric tubes that the ratio of the number of baryons emitted from a plasma to the number of π mesons emitted is depressed in comparison with the corresponding ratio in hadron reactions.

Experiments on the collisions of relativistic heavy nuclei have attracted increased interest to processes which might signal the formation of a quark-gluon plasma.[1] It appears that one such process might be the emission of hadrons from the plasma, but unfortunately the theory in its present state is incapable of calculating the characteristics of hadron spectra from first principles. As in hadron reactions, it is necessary to use a model regarding the nature of the hadronization of the quarks and gluons in the calculations. One the one hand, this circumstance slightly detracts from the predictive power of hadron signals in comparison with photon signals and lepton signals, but on the other it allows us to develop our understanding of confinement properties.

Let us examine the process by which hadrons are emitted from a plasma in the model of chromoelectric tubes, which is successful in describing experimental data on e^+e^- annihilation to hadrons.[2] This model was applied to a plasma by Banerjee,[3] who showed that the radiation pressure of mesons is low in comparison with that of quarks. This model is also capable of calculating some subtler characteristics of the emission process, namely the ratios of the numbers of π mesons, strange mesons, and baryons which are emitted.

The hadron emission process itself has the following form in the chromoelectric tube model.[3,4] When an energetic quark (or antiquark) intersects the plasma surface, a chromoelectric tube-string stretches out and connects the quark with the plasma. As the quark moves, its energy is converted into the energy of the color field of the tube. There is a certain probability that the tube will "rupture" through the creation of a quark-antiquark pair, with the result that a hadron system forms. This hadron system will escape from the plasma volume.

Since an increase in the mass of quarks is accompanied by decreases in both their flux out of the plasma volume and the probability for the creation of the corresponding pair, the dominant processes are those which involve the lightest quarks, i.e., the u and d quarks. As a result, it is primarily π mesons which are evaporated. The production of other hadrons requires either that a massive quark intersect the plasma surface or that a massive pair form in the field of the tube. We will discuss both of these possibilities here. We will write only the final results for estimating the number of hadrons produced in the process.

In the former case, the average number of hadron systems with an invariant mass $m_{\rm inv} \geqslant M$ which escape from the plasma per unit time from a unit area is

$$\frac{d^3N}{dSdt} \approx \frac{\gamma T^5}{(2\pi)^2 k_c^2}\left[3\frac{M}{T}K_1(M/T) - (M/T)^2 K_1'(M/T)\right]$$

$$\approx \frac{\gamma T^5}{(2\pi)^2 k_c^2} \times \begin{cases} 4 + O(M/T), & M \ll T, \\ \sqrt{\dfrac{\pi M}{2T}}\, e^{-M/T}\left[\dfrac{M}{T} + \dfrac{31}{8} + O(T/M)\right], & M \gg T, \end{cases} \qquad (1)$$

where K_1 and K_1' are the modified Bessel function and its derivative, respectively, T is the plasma temperature, and $\gamma = 2\times 2\times 3 = 12$ is the number of degrees of freedom of the massive quarks. The momentum k_c characterizes the confinement properties and is the only parameter in the model ($k_c = 1.45$–2.78 GeV; Refs. 3 and 4).

In the latter case, we find the following expression for the average number of hadron systems:

$$\frac{d^3N}{dSdt} \approx \frac{gT^5}{(2\pi)^2 \tilde{k}_c^2}\exp\left(-\frac{M+\mu}{T}\right)\left\{\left[4 + \frac{M+\mu}{T} + \frac{(M-\mu)^2}{2\mu T}\right]\exp\left[-\frac{(M-\mu)^2}{2\mu T}\right]\right.$$

$$\left. + \int_0^{(M^2-\mu^2)/2\mu T}\left[3 + \frac{\mu}{T} + \sqrt{y^2 + \frac{M^2}{T^2}}\right]\exp\left[\frac{M}{T} - \sqrt{y^2 + \frac{M^2}{T^2}}\right]\right\}, \qquad (2)$$

where $g = 2\gamma$ is the number of degrees of freedom of massless u and d quarks, and 2μ is the mass of a pair produced in the field of the tube.

It is important to note that different notation has been used in (2) for the characteristic momentum: $\tilde{k}_c$ in place of k_c. The reason is that the values of this momentum are different in the cases of the production of massive and massless pairs. By definition, we have[3]

$$k_c = (\sigma^2/pA)^{1/2},$$

where A is the cross-sectional area of the tube, which is related to the strong-binding constant α_s by $A = \pi\alpha_s/2\sigma$, where p is the probability for pair production in the field of the tube. The probability is determined by the parameter σ (the energy of the color field per unit length of the tube) and by the quark mass μ. The production of massive pairs is thus exponentially suppressed in comparison with the production of massless pairs[5]: $p_\mu/p_0 \sim \exp(-\pi\mu^2/\sigma)$. In certain phenomenological models the probability ratio p_μ/p_0 is an adjustable parameter, which is determined by the corresponding ratio found experimentally for the numbers of hadrons in the final state. In any case, the ratio $k_c^2/\tilde{k}_c^2$ can be taken to be a small parameter, which determines the suppression of the production of the heavier hadrons.

We turn now to the qualitative consequences of Eqs. (1) and (2) which might prove useful in identifying plasma events. In the first place, if we are interested in the production of fairly massive hadron systems ($M \gg T$), then in both the former and latter cases the requirement $m_{\rm inv} \geqslant M$ leads to an exponential suppression of the intensity of the emission of such systems in comparison with the emission of π mesons (for which the assumption $\mu = M = 0$ is very accurate). Furthermore, in the latter case there is an additional suppression due to the difference between the parameters k_c and $\tilde{k}_c$. As a result, the emission of strange mesons occurs primarily in the first channel, and the ratio of their number to the number of π mesons emitted is determined primarily by the exponential factor $\exp(-M_s/T)$, where $M_s \approx 500$ MeV.

For baryons, the situation is different. In the chromoelectric tube model,[2] baryons are produced when a massive entity—a diquark-antiquark—is produced in the tube. The explicit presence of bound states—diquarks—in a plasma is improbable, since otherwise we would be equally justified in suggesting that the plasma contains other bound states, e.g., colorless mesons. This circumstance means that in the picture we are looking at baryons can be produced only in the second channel. If the probability for the ratio of the production of a diquark pair to the probability for the production of u, d-quark pairs is fixed on the basis of the experimentally observed ratio of the number of baryons to the number of π mesons in hadron reactions,[2] $:k_c^2/\tilde{k}_c^2 \approx (N_{\rm bar}/N_\pi)_{\rm exptl}$, then the suppression stemming from the invariant mass of the hadron state which is formed serves an additional factor which reduces the probability for this process in comparison with those for hadron reactions. Because of the large mass of a proton, this suppression can be substantial: At $T \approx 200$ MeV, the value of $\exp(-M_p/T)$ is on the order of $e^{-5} \approx 1/150$. An anomalously small yield of baryons might thus constitute one signal of the production of a plasma.

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