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φ-Meson Production as a Probe of the Quark-Gluon Plasma

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Abstract

The formation of the quark-gluon plasma in relativistic nuclear collisions may be indicated by enhanced production of φ-mesons. This enhancement would result from a large abundance of strange quarks in the plasma and the absence of the OZI rule which suppresses φ production in ordinary p-p and π-p collisions. The φ will not rescatter significantly in the subsequent expanding hadronic phase and would thereby retain information on the conditions of the hot plasma.

In recent years it has become evident that quarks and gluons are the basic constituents of matter and that QCD describes their interactions.[1] These constituents are very strongly bound and apparently cannot be liberated from the perturbative vacuum in which they exist.[2] At sufficiently large energy densities, nuclear matter would dissolve into quarks and gluons in a phase in which the perturbative vacuum would exist over the nuclear volume.[3] In this phase, the quarks and gluons would no longer be confined to the individual hadrons. Detection of the quark-gluon plasma (QGP) would serve as a more direct evidence for the quarks and gluons.

Collisions of heavy nuclei at high energies appears to be the most promising method for creating and detecting the QGP.[4] The transient nature of the nuclear

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collisions forming the hot plasma, followed by the fast cooling and hadronization into conventional color singlet particles, makes the inference of the existence of the plasma and a study of its properties difficult and uncertain.[5] Rafelski and his collaborators[6,7] have shown that a plasma created in nuclear collisions would result in an enhanced production of strange quarks, possibly at a level 10-50 times that in ordinary hadronic collisions. The strange quarks produced in the plasma would retain their identity during the hadronization phase and result in an enhancement of strange and multiply strange particles such as $\Lambda, K, \bar{\Lambda}, \varphi, \Xi$, and Ω. Interactions and rescattering of these particles in the expanding hadronic phase would, however, rearrange strangeness among the mesons and baryons (anti-baryons) and would tend to wash out spectral information from the plasma.

In this letter, we point out two features of the φ-meson which would make it an excellent probe of the QGP. The φ is a vector meson similar to the ρ and ω, but is composed of a strange quark-antiquark pair. Its production in N-N and π-N collisions is suppressed by the Okubo-Zweig-Iizuko (OZI) rule which excludes graphs with unconnected quark lines.[8,9] In fact, in p-p collisions at 24 GeV/c, the ratio $\frac{\sigma(pp \rightarrow \varphi + X)}{\sigma(pp \rightarrow \rho + X)}$, which would otherwise be approximately unity, was measured to be 0.045 as a result of the OZI suppression.[10] The OZI rule would not apply in a QGP where the production of $s\bar{s}$ pairs would proceed mostly by g-g interactions.[6] This fact–in addition to a large abundance of strange quarks in the plasma–may provide for a dramatic enhancement in the production of the φ-meson following a formation of the QGP.

A second useful feature of the φ-meson is a small cross section for scattering with non-strange hadrons. Non absorptive processes involving the φ are suppressed by the OZI rule and proceed only by Pomeron exchange.[8] This means that following the decay of a QGP phase, φ-mesons produced by the plasma will not rescatter appreciably during the expanding hadronic phase. The φ will act as a penetrating probe in the sense that it will retain information on the conditions present during the hot plasma phase of the nuclear collision. Reliable information on intensive variables, for example the temperature of the plasma, can be extracted from a measurement of, say, the transverse momentum distribution of the φ.

The prediction of particle yields in nucleus-nucleus collisions is difficult and depends on the specific mechanism for equilibration and decomposition of the plasma.[11] We can assume that heavy mesons are produced by the coalescing of a quark and anti-quark from the decaying plasma. As a first approximation, the yields of heavy mesons should be proportional to the density in the plasma of the quarks which comprise these mesons. Thus for the φ-meson ($s\bar{s}$), K^+ ($u\bar{s}$), and K^- ($\bar{u}s$), we would expect

$$\frac{\langle\varphi\rangle}{\langle K^-\rangle} = \left(\frac{n_{\bar{s}}}{n_{\bar{u}}}\right) \qquad \frac{\langle\varphi\rangle}{\langle K^+\rangle} = \left(\frac{n_s}{n_u}\right)$$

where $\langle\,\rangle$ denotes the average particle multiplicity. This scheme is not applicable to pion production which can be copious due to radiation from the cooling plasma[12] and by mechanisms associated with entropy production.[13]

For a non-interacting QGP in thermal equilibrium, the density of quarks is readily calculable.[14,15] The density for the nonstrange light quarks and anti-quarks (assumed to be massless) are given by

$$n_q = S_q \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{p/T \mp \mu/T} + 1}$$

where the minus (plus) sign refers to quarks (anti-quarks). The chemical potential μ is a measure of the baryon density and is determined by

$$n_B = 3(n_q - n_{\bar{q}}) = \frac{2}{3\pi^2}\left(\mu^3 - \mu(\pi T)^2\right)$$

The number S represents the number of quantum states available (spin, isospin, color). The density for strange (anti-strange) quarks is given by

$$n_s = S_s \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{\sqrt{M_s^2 + p^2}/T} + 1}$$

where M_s is the mass of the strange quark. For the sake of illustration, we take the strange quark mass and the temperature of the plasma each to be equal to 200 MeV. For both cases, this value is within the range estimated for these quantities.[15,16]

Figure 1 shows the calculated ratios for the strange to non-strange quarks in the plasma. As indicated above, the ratio $<\varphi>/<K^->$ should be comparable to that of $(n_s/n_{\bar{u}})$, and $<\varphi>/<K^+>$ should be comparable to (n_s/n_u) for mesons created as a result of the coalescing of quarks from the plasma. The ratio $<\varphi>/<K^->$ would then increase with baryon density, from a value of 0.85 at $n_B = 0$ to a value of 5 at $n_B = 10 \times n_0$, while the ratio of $<\varphi>/<K^+>$ would decrease from 0.85 to 0.2 over this range of baryon density. These ratios calculated for plasma decay should be contrasted with those measured in hadronic interactions. For p-p collisions, the measured value for $<\varphi>/<K^->$ remains fairly constant at 0.13 over the energy range from $\sqrt{s}$ = 6.8 (E_p = 24 GeV) up to $\sqrt{s}$ = 52 GeV, whereas the measured value for $<\varphi>/<K^+>$ varies from 0.05 up to 0.085.[17]

The ratios for $<\varphi>/<K>$ for production from a decaying QGP, inferred from the calculated ratios for (n_s/n_u) in the plasma, are appreciably larger than the corresponding ratios observed in p-p interactions. Note that the kaon yields are themselves enhanced in the plasma.[18] The enhancement in the absolute cross section of φ-mesons from a QGP should therefore be even more pronounced than that for the $<\varphi>/<K>$ ratio or the absolute kaon cross sections. This would be important for detecting a plasma rarely produced or one due to only local fluctuations.It has been suggested that non-equilibrium conditions in a plasma may result in an $s\bar{s}$ pair staying close together to eventually coalesce and form a φ.[7] This effect would further increase the yield of φ-mesons. However, the φ could be absorbed in the hadronic phase by the processes $\varphi N \rightarrow YK (\sigma \approx 8\text{mb})$ and $\varphi\pi \rightarrow K\bar{K}$. These reactions would tend to diminish the yields of φ-mesons and increase the yields of kaons. The extent of these effects is very much dependent on the mechanism for the formation and decay of the plasma but should not significantly alter the conclusion of enhanced φ production and enhanced $< \varphi >/< K >$ ratios.

The φ-meson, once produced, has a small probability for further interaction. The φN cross section is extracted from data on photoproduction on proton and nuclear targets.[19] The vector dominance model relates photoproduction of the φ to φN scattering through the relation[20,21]

$$\sigma(\gamma + p \rightarrow \varphi + p) = \left[\frac{3\Gamma(\varphi \rightarrow e^+e^-)}{\alpha M_\varphi} \right] \sigma(\varphi + p \rightarrow \varphi + p)$$

For photon energies between 2 GeV and 10 GeV, the measured φN production cross section increases from about 0.3 μb to 0.55 μb.[22] Only about 15% of the photoproduction goes through inelastic channels at these energies.[23] Such a slow rise from near threshold is consistent with φN interaction mediated by Pomeron exchange.[19] The inferred φN rescattering cross sections are from 0.6 to 1.1 mb for φ energies from .4 to 8 GeV.[20] The total φN cross section is derived from photoproduction at 0° and is about 8 mb at these energies.[24] This cross section is predominantly due to absorption, i.e. $\varphi N \rightarrow YK$, which is OZI allowed. The systematics of φ scattering with pions should be similar--a small rescattering due to Pomeron exchange, and a total cross section dominated by $\varphi\pi \rightarrow KK$.

The small φ rescattering with nucleons and pions is an assurance that the energy distribution of the φ's created by the decaying plasma will not be significantly altered during the subsequent cooling hadronic phase. The absorption of the φ is somewhat more significant, but is not expected to be very drastic given the modest cross section of 8 mb. As an example, for φ-mesons uniformly distributed with random velocities in a nucleus at normal density with a radius of 7 fm, 30% of the φ's would be absorbed and only about 5% would be rescattered.

The φ-meson may have an advantage as a penetrating probe over electromagnetic probes. Photons and di-leptons are also produced by the direct n-n collisions during the pre-equilibrium stage of the nuclear reaction and it may be difficult to disentangle the contribution from the plasma.[25] The production of the φ from sources other than the plasma is expected to be small and should not confuse the signal from the plasma.

The above arguments should be applicable to other vector mesons such as the J/ψ and Υ. However, due to the small transition time for the colliding nuclei, the equilibration of the plasma will not be complete. The approximation of a Boltzman distribution will break down for states where $M/T >> 1$.[6] This will certainly be the case for heavy particles such as the J/ψ and Υ.[26]

We have pointed out that enhanced φ production in high energy nuclear collisions would be an excellent indicator for the formation of the QGP. H. Lipkin[27] has suggested in the past that φ-mesons could be used as a "low noise trigger" to study new states whose decay to the φ would not be OZI suppressed. This would certainly be the case for φ-mesons produced by the decay of the QGP. In addition, the rescattering of the φ in the expanding hadronic phase would be insignificant so the φ would retain information on the conditions of the plasma. The φ would be easy to measure since it decays to K^-K^+ with a 49% branching ratio with a sharp width and small Q value.

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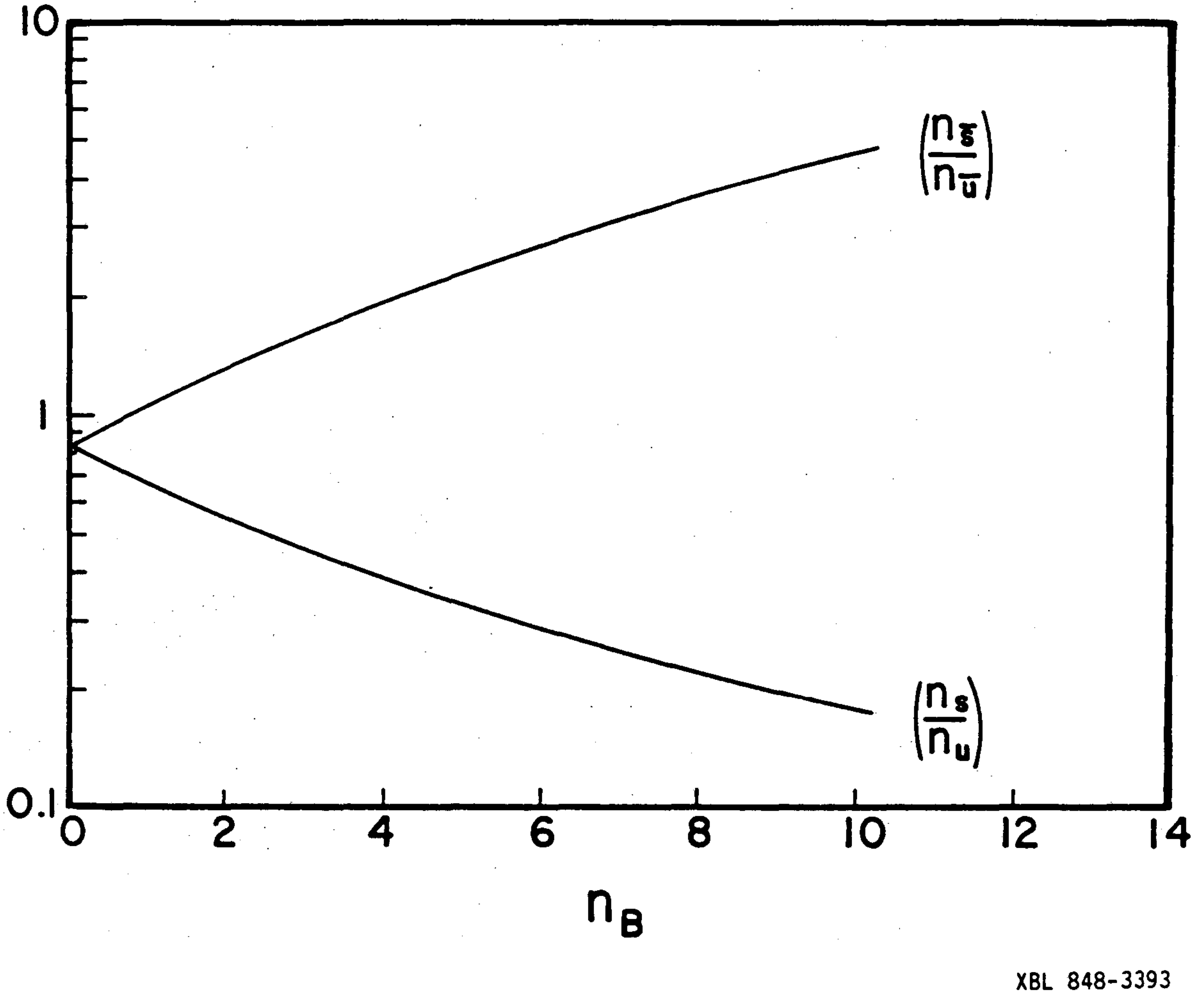
10
1
0.1
0
2
4
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8
10
12
14
n_B
$\left(\frac{n_{\bar{s}}}{n_{\bar{u}}}\right)$
$\left(\frac{n_s}{n_u}\right)$
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Fig. 1

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