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

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(Received 24 August 1984)

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

PACS numbers: 25.70.Np, 12.35.Ht, 21.65.+f

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.

Collision 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 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.[5] Rafelski, and Muller[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 Λ, K, $\overline{\Lambda}$, ϕ, Ξ, and Ω. Interactions and rescattering of these particles in the expanding hadronic phase would, however, rearrange strangeness among the mesons and baryons (antibaryons) 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, composed of a strange and antistrange quark, is the lightest of the vector mesons with hidden flavor (i.e., $\phi, J/\psi, \Upsilon$). The systematics of the production and decay of these resonances are affected by the Okubo-Zweig-Iizuka (OZI) rule, which requires that transitions take place by means of connected quark diagrams.[8,9] OZI-violating transitions are suppressed by factors ranging from 10 (in the case of ϕ decay) to 1000 (in the case of J/ψ decay).[10] As an example, the exclusive reaction involving the production of a vector meson and charged pions in pp collisions at 24 GeV/c, while of almost equal magnitude for production of a ρ_0 or ω meson, is suppressed by a factor of 50 for ϕ production.[11] For inclusive ϕ production in pp and πp collisions, the OZI rule maintains that production of the ϕ should be suppressed unless accompanied by strange hadrons.[9,10,12] In fact, cojoint production of strange particles is not observed for ϕ production in pp collisions at 24 GeV/c,[11] and accounts for only a fraction of the total ϕ yield at higher bombarding energies.[13] An analogous situation is found for J/ψ production which occurs without cojoint production of charmed hadrons at Fermilab energies.[14] The suppression of the OZI-allowed reaction involves dynamical factors associated with the production of two additional strange hadrons.[9,10,12] The end result is that ϕ production in pp and πp collisions is at an appreciably lower level than production of other vector mesons of similar mass. For example, the ratio

$$\frac{\sigma(pp \to \phi + X)}{\sigma(pp \to \rho + X)}$$

has been measured as 0.045 ± 0.013 at 24 GeV/c, and remains at a level of $\sim \frac{1}{20}$ up to CERN intersecting storage rings (ISR) energies.[15]

Production of ϕ mesons in nuclear collisions would differ markedly were a QGP to be formed. In a plasma, strange and antistrange quarks would be produced primarily by gluon-gluon interactions.[6,7] These interactions would occur very rapidly, and the strange quark abundance would approach the equilibrium level. During the hadronization phase, s and $\bar{s}$ quarks from the plasma would be very likely to coalesce to form ϕ mesons. Production of ϕ's by this process would not be inhibited by the OZI rule. The lack of OZI suppression, in addition to the large abundance of strange quarks predicted to exist in the plasma,[7] may provide for a dramatic increase in the production of the ϕ meson following the formation of a QGP.

A second useful feature of the ϕ meson is a small cross section for scattering with nonstrange hadrons. Nonabsorptive processes involving the ϕ are suppressed by the OZI rule and proceed only by Pomeron exchange.[8] This means that following the QGP phase, ϕ mesons produced by the decaying 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 critical phase at which the plasma proceeds to hadronize. The spectra of the ϕ's produced during this phase will not be altered or distorted during the expanding hadronic phase. Reliable information on intensive variables, for example the critical temperature T_c, can be extracted from a measurement of, say, the transverse momentum distribution of the ϕ.

Vector-meson production in hadronic collisions has been a useful tool for extracting quark distributions in hadrons since most of these resonances are produced directly and not as by-products from the decay of heavier resonances.[16] The relative ratio for production of the ϕ and ω mesons would be especially useful in detecting plasma formation in high-energy nuclear collisions. The ϕ and ω are identical in their net quantum numbers and are comparable in their mass. They differ primarily in their quark content, the ϕ consisting of $s\bar{s}$ and the ω consisting of an isospin singlet combination of $u\bar{u}$ and $d\bar{d}$. The ratio for $\langle\phi\rangle/\langle\omega\rangle$ would then be very sensitive to a formation of a plasma rich in strangeness. (We note a previous mention of vector-meson production in high-energy nuclear collisions by Willis.[17])

We estimate the ratio $\langle\phi\rangle/\langle\omega\rangle$ for meson production from a decaying QGP. We can assume that production of colorless hadrons occurs when the plasma has cooled to the critical temperature T_c at which point the transition from a QGP to a hadronic phase occurs. Above this temperature, quarks and gluons occur as free particles and confined hadrons do not exist. In our model, heavy resonances (heavy relative to pions and kaons) are produced by the coalescing of a quark and an antiquark from the decaying plasma. The exact method for dressing the quark pair with gluons is not known. However, the ϕ and ω have the same net quantum numbers and nearly the same rest energies in excess of their valence quark masses.[18] Under these conditions, the ratio $\langle\phi\rangle/\langle\omega\rangle$ for production from a plasma will mostly depend on the abundances in the plasma of the quarks that comprise these mesons; i.e.

$$\frac{\langle\phi\rangle}{\langle\omega\rangle}=\left[\frac{n_s n_{\bar{s}}}{n_q n_{\bar{q}}}\right],$$

where the product $n_q n_{\bar{q}}$ refers to an isospin singlet combination of the nonstrange light quarks and antiquarks. The effects of the hadronization process are expected to approximately cancel out for this ratio.

For a noninteracting QGP in thermal equilibrium, the quark densities are readily calculable.[19,20] The densities for the nonstrange light quarks and antiquarks (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 (antiquarks) and the chemical potential μ is a measure of the net baryon density. The factor S represents the number of quantum states available (spin, isospin, and color). The density for the strange (or antistrange) quarks is given by

$$n_s=S_s\int\frac{d^3p}{(2\pi)^3}\frac{1}{\exp[(M_s^2+p^2)^{1/2}/T]+1}.$$

The value M_s for the strange quark mass in the perturbative vacuum is taken to be 150 MeV.[21]

Figure 1 shows the calculated values for the ratio $\langle\phi\rangle/\langle\omega\rangle$ as a function of plasma temperature for $\mu=0$ and for $\mu=300$ MeV. The dependence of this ratio on the chemical potential (baryon density) is weak. The values for the ratio $\langle\phi\rangle/\langle\omega\rangle$ for production from a QGP are to be contrasted with production in hadronic collisions. Although inclusive measurements of ω production are sparse, ample data for the ratio $\langle\phi\rangle/\langle\rho_0\rangle$ exist. In pp collisions, this ratio has been measured to be $\approx\frac{1}{20}$ for energies ranging from $\sqrt{s}=7$ GeV up to $\sqrt{s}=53$ GeV.[11,15] For π^+p at 16

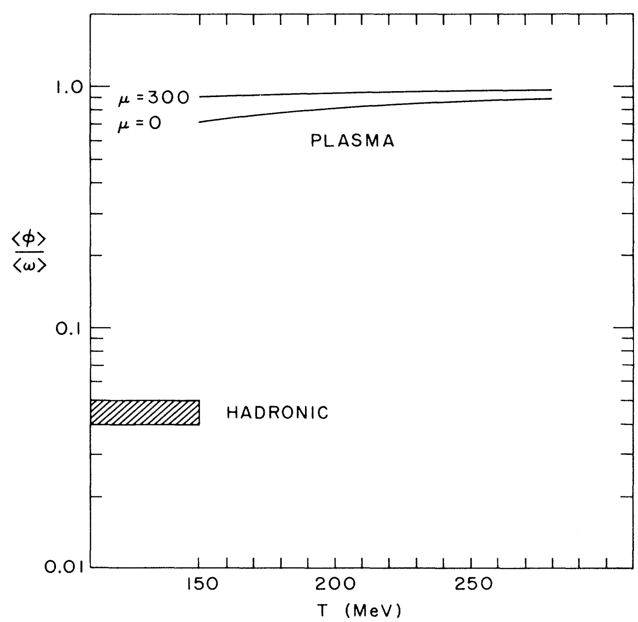

FIG. 1. $\langle\phi\rangle/\langle\omega\rangle$ ratio. Calculation for plasma production as a function of temperature is discussed in the text. The hadronic production is an estimate extracted from pp and πp interaction and is approximately independent of energy.

GeV/c, this ratio has been measured to be 0.028 ± 0.007.[22] The ratio of $\langle\omega\rangle/\langle\rho_0\rangle$ in pp collisions at $\sqrt{s}=53$ GeV has been determined by studies of $\pi^+\pi^-$ correlations which yield a ratio of 1.3 ± 0.3.[23] The observed linewidth of $\mu^+\mu^-$ pairs at the ρ,ω mass region in pN and πN collisions at 150 GeV/c was found to be consistent with the assumption of $\sigma_\omega \approx \sigma_{\rho_0}$.[24] We conclude that the ratio for $\langle\phi\rangle/\langle\omega\rangle$ in NN and πN collisions is at a level of $\frac{1}{20}$ or less. This value is smaller by more than an order of magnitude as compared to the $\langle\phi\rangle/\langle\omega\rangle$ ratios predicted for a QGP.

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.[25] The vector dominance model relates photoproduction of the ϕ and ϕN scattering through the relation[26,27]

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

For photon energies between 2 and 10 GeV, the measured ϕ production cross section increases from about 0.3 to 0.55 μb.[28] Only about 15% of the photoproduction goes through inelastic channels at these energies.[29] Such a slow rise from near threshold is consistent with ϕN interaction mediated by Pomeron exchange.[25] The inferred ϕN scattering cross sections are from 0.6 to 1.1 mb for ϕ energies from 0.4 to 8 GeV.[26] The total ϕN cross section is derived from photoproduction at 0° and is about 8 mb at these energies.[30] This cross section is predominantly due to absorption, i.e., $\phi N \to YK$, 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 $\phi\pi \to \bar{K}K$.

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 lifetime of the ϕ is about 50 fm/c so the ϕ will decay well outside of the nuclear environment.

The ϕ meson may have an advantage as a penetrating probe over electromagnetic probes. Photons and dileptons are also produced by direct N-N collisions and during the preequilibrium stage of the nuclear reaction and it may be difficult to disentangle the contribution from the plasma.[31] 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. It should be mentioned that the ϕ will only probe the critical phase, whereas electromagnetic probes will provide information on conditions present at temperatures above T_c.

The above arguments should be applicable to other vector mesons with hidden flavor such as the J/ψ and Υ. However, as a result of the small transit time for the colliding nuclei, the equilibration of the plasma will not be complete. States with a large mass, such that $M/T \gg 1$, are not expected to be much affected by plasma formation since there is not enough time to approach the equilibrium level. This will certainly be the case for heavy particles such as the J/ψ and Υ.[32]

We have pointed out that enhanced ϕ production in high-energy nuclear collisions would be an excellent indicator for the formation of the QGP. This effect will be most readily manifest in an increase of the $\langle\phi\rangle/\langle\omega\rangle$ ratio as compared to hadronic production. 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.

I gratefully acknowledge stimulating and informative discussions with U. Heinz, P. D. Bond, V. Perez-Mendez, J. Carroll, T. Mulera, I. Otterlund, and O. Hansen. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U. S. Department of Energy under Contracts No. DE-AC03-76SF00098 and No. DE-AC03-76SF00515.

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[18]If it is assumed that $m_s = 150$ MeV, then the energy needed to dress $s\bar{s}$ to form a ϕ would be $\approx \pi_\phi - 300$ MeV $= 720$ MeV, whereas for a $q\bar{q}$ to form an ω the required energy would be $\approx m_\omega = 783$ MeV if $m_q \approx 0$.

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