Probe the QCD phase diagram with $\phi$-mesons in high energy nuclear collisions

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Abstract.

High-energy nuclear collision provide a unique tool to study the strongly interacting medium. Recent results from the Relativistic Heavy Ion Collider (RHIC) on $\phi$-meson production has revealed the formation of a dense partonic medium. The medium constituents are found to exhibit collective behaviour initiated due to partonic interactions in the medium. We present a brief review of the recent results on $\phi$ production in heavy-ion collisions at RHIC. One crucial question is where, in the phase diagram, does the transition happen for the matter changing from hadronic to partonic degrees of freedom. We discuss how $\phi$-meson elliptic flow in heavy-ion collisions can be used for the search of the QCD phase boundary.

1. Introduction

$\phi$-mesons were first observed in bubble chamber experiments at Brookhaven National Laboratory (BNL) in the year 1962 through the reaction $K^-+p \rightarrow \Lambda+K+\bar{K}$. Results on $\phi$-meson production at the Relativistic Heavy Ion Collider (RHIC) at BNL has so far provided deep insight on the nature of the medium formed in heavy ion collisions at high energies [1, 2]. The $\phi$-meson has several interesting features and each of these features are capable of providing valuable information about the medium properties in high energy heavy-ion collisions. Some of these features and possible information they provide are tabulated in Table 1. Hence $\phi$-mesons can be termed as a golden tool (term borrowed from golden ratio used in Mathematics and Art [3]) to address various aspects of heavy-ion collisions.

In this paper we first review the existing results on $\phi$ production at RHIC. These will be presented with a motivation of establishing observations regarding $\phi$ production (through rapidity, transverse momentum and azimuthal distribution) as a clear indication of dense partonic medium formation at RHIC energies. The results presented are mostly from the hadronic decay mode $\phi \rightarrow K^+K^-$ in Au+Au and Cu+Cu collisions at midrapidity [1, 2]. We will first discuss three physics issues: (a) strangeness enhancement, (b) partonic recombination and hints of thermalization at RHIC and (c)
partonic collectivity using $\phi$ production. These will provide the basis for our proposal of using the $\phi$-meson elliptic flow ($v_2$) as a probe of QCD phase boundary, which will be discussed next in the paper. Finally we will conclude by summarizing the observation on $\phi$ production at RHIC and possibilities it offers for the future high energy heavy-ion collision program.

Table 1. Various features of $\phi$-meson and possible information they may provide about the medium formed in high energy heavy-ion collisions

| Feature                      | Information                                                                 |
|------------------------------|----------------------------------------------------------------------------|
| Quark content: $s\bar{s}$    | Strangeness enhancement; net strangeness $\Delta S = 0$ Canonical suppression not applicable. |
| Meson, Mass = 1.019 GeV/$c^2$ | Differentiates Mass and Number of constitutent quark (NQ) effects; Mass $\sim$ baryons ($p$ and $\Lambda$) Experimentally clean signal; Change in width reflects medium effects |
| Width = 4.43 MeV/$c^2$       |                                                                              |
| Decay modes                  | Both Hadronic and Leptonic; Leptons do not interact strongly with the medium. $\sim$ 100%; not affected by resonance decays |
| Primodial fraction           |                                                                              |
| Small interaction with nucleons | Early freeze-out; Information of partonic stage                               |
| Life time $\sim$ 45 fm/$c$  | With $K^*$ (lifetime $\sim$ 4 fm/$c$) ideal to understand rescattering and regeneration effects for resonances |

2. $\phi$-meson yields - strangeness enhancement

The large abundances of $s$ and $\bar{s}$ quarks in the Quark Gluon Plasma (QGP), may lead to a dramatic increase in the production of $\phi$-mesons and other strange hadrons relative to non-QGP $p+p$ collisions [4]. Alternative ideas of canonical suppression of strangeness in small systems as a source of strangeness enhancement in high energy heavy-ion collisions have been proposed for other strange hadrons (e.g $\Lambda$, $\Xi$ and $\Omega$) [5]. According to these models, strangeness enhancement in nucleus-nucleus collisions, relative to $p+p$ collisions, should increase with the strange quark content of the hadrons. This enhancement is predicted to decrease with increasing beam energy [5]. So far, discriminating between the two scenarios (strange hadron enhancement being due to dense partonic medium formed in heavy-ion collisions or due to canonical suppression of their production in $p+p$ collisions) using the available experimental data has been, to some extent, ambiguous. $\phi$-mesons due to its zero net strangeness is not subjected to Canonical suppression effects. Enhancement of $\phi(s\bar{s})$ production in Cu+Cu and Au+Au relative to $p+p$ collisions would clearly indicate the formation of a dense partonic medium in these collisions. This would then rule out canonical suppression effects being the most likely cause for the observed enhancement in other strange hadrons in high energy heavy-ion collisions.
Figure 1. (color online) Top Left: Upper panel: The ratio of the yields of $K^-$, $\phi$, $\Lambda$ and $\Xi + \bar{\Xi}$ normalized to $\langle N_{\text{part}} \rangle$ in nucleus-nucleus collisions to corresponding yields in inelastic $p+p$ collisions as a function of $\langle N_{\text{part}} \rangle$ at 200 GeV. Lower panel: Same as above for $\phi$-mesons in Cu+Cu collisions at 200 and 62.4 GeV. Top Right: Average transverse momentum ($\langle p_T \rangle$) for produced hadrons in Au+Au and p+p collisions as function of collision centrality at 200 GeV and as a function of beam energy. $N(\phi)/N(K^-)$ ratio and $N(\phi)/N(h^-)$ as a function of collision centrality in high energy collisions. Bottom Left: Ratio of slope of transverse momentum distribution of $\phi$-mesons to $K^-$ as a function of beam energy in heavy-ion collisions. Bottom Right: $N(\phi)/N(\omega)$ ratio as function of beam energy in $p+p$ collisions. The line shows the expectation due to OZI rule [6].

Figure 1 shows the ratio of strange hadron production normalized to $\langle N_{\text{part}} \rangle$ in nucleus-nucleus collisions relative to corresponding results from $p+p$ collisions at 200 GeV. The results are plotted as a function of $\langle N_{\text{part}} \rangle$. $K^-$, $\Lambda$ and $\Xi + \bar{\Xi}$ [1] are seen to show an enhancement (value $>1$) that increases with the number of strange valence quarks. However, the enhancement of $\phi$-meson production from Cu+Cu and Au+Au collisions shows a deviation in ordering in terms of the number of strange constituent quarks [7]. Enhancement is larger than for $K^-$ and $\Lambda$, at the same time being smaller than in case of $\Xi + \bar{\Xi}$. So the $\phi$-mesons do not follow the strange quark ordering as expected in the canonical picture for the production of other strange hadrons. The observed enhancement in $\phi$-meson production being related to medium density is further...
supported by the energy dependence shown in the lower panel and top-left plot of Fig. 1. The \( \phi \)-meson production relative to \( p+p \) collisions is larger at higher beam energy, a trend opposite to that predicted in canonical models for other strange hadrons.

To establish that the observed enhancement of \( \phi \)-meson production is a clear indication of the formation of a dense partonic medium in \( Au+Au \) collisions at 200 GeV we need to establish the following: (a) \( \phi \) production is not from \( K\bar{K} \) coalescence (as Kaons could be subjected to canonical suppression effects) and (b) \( \phi \) production is not OZI suppressed in \( p+p \) collisions. There are several experimental observations which shows that at RHIC energies \( \phi \) production is not dominantly from \( K\bar{K} \) coalescence. These include: (i) \( N(\phi)/N(K^-) \) ratio is observed to be independent of colliding beam energy and at a given beam energy independent of collision centrality (Fig. 1 top right) [1]. Naive expectation from \( K\bar{K} \) coalescence models is a linear increase of the \( N(\phi)/N(K^-) \) ratio with increase in collision centrality [8]; (ii) If \( \phi \) production is dominantly from \( K\bar{K} \) coalescence, one expects the ratio of inverse slope of transverse momentum distribution of \( \phi \) to those of \( K^- \sim 2 \). This is not observed from the available experimental data (Fig 1 bottom left); (iii) If \( \phi \) production is dominantly from \( K\bar{K} \) coalescence, one expects the width of the rapidity distribution of \( \phi \)-mesons to be related to those for charged Kaons as \( 1/\sigma_{\phi}^2 = 1/\sigma_{K^-}^2 + 1/\sigma_{K^+}^2 \). Measurements at SPS energies show a clear deviation of the data from the above expectation [9]; (iv) Finally, if \( \phi \) production is dominantly from \( K\bar{K} \) coalescence it would be reflected in elliptic flow \( (v_2) \) measurements. We observe at intermediate \( p_T \), the \( v_2 \) of \( \phi \)-mesons and Kaons are comparable (discussed later in Fig. 3) [1, 2]. Now about OZI suppression of \( \phi \) production in \( p+p \) collisions. These effects are experimentally observed by measuring the ratio of \( \phi \) to \( \omega \) production. This ratio takes up a value of \( 4.2 \times 10^{-3} \) for validity of OZI rules. Violations of OZI rule [6] has been observed in \( p+p \) collisions at higher energies as shown in Fig. 1 (bottom right) [10]. Due to the high gluon density created in high energy collisions, the OZI suppression does not play a role in \( p+p \) collisions at RHIC. So it is very unlikely that \( \phi \) enhancement observed in \( Au+Au \) collisions is due to OZI suppression of its production in \( p+p \) collisions. Thus with both the physics points discussed in (a) and (b) above established, the observed enhancement of \( \phi \)-meson production then is a clear indication that the strangeness enhancement in \( Au+Au \) collisions at 200 GeV is due to the formation of a dense partonic medium.

3. \( \phi \)-meson production - quark recombination and thermalization

Figure 2 (left) shows the \( p_T \) distributions of \( \phi \)-mesons as a function of centrality. Each \( p_T \) spectrum in Fig. 2 has been fitted using both an exponential function (dashed lines) in \( m_T \) and a Levy function (dotted lines) which has an exponential-like shape at low \( p_T \) and is power-law-like at higher \( p_T \). While the central data are fitted equally well by both functions the more peripheral spectra are better fitted by the Levy function indicating less thermal contributions in peripheral collisions. In Fig. 2 (right), the ratios of \( N(\Omega)/N(\phi) \) vs. \( p_T \) are presented as a function of centrality. Also shown in the
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Figure 2. (color online) Left: $p_T$ distributions of φ-mesons from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Right: The $N(\Omega)/N(\phi)$ ratio vs. $p_T$ for three centrality bins in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. The solid and dashed lines represent recombination model predictions for central collisions [11] for total and thermal contributions, respectively.

figure are recombination model expectations for central collisions [11] based on φ and Ω production from coalescence of thermal and shower s quarks in the medium. The model describes the trend of the data up to $p_T \sim 4$ GeV/c but fails at higher $p_T$. With decreasing centrality, the observed $N(\Omega)/N(\phi)$ ratios seem to turn over at successively lower values of $p_T$ indicating a smaller contribution from thermal quark coalescence in more peripheral collisions. This is also reflected in the smooth evolution of the spectra shapes from the thermal-like exponential to power-law shapes shown in Fig. 2. These results indicates that the bulk of the φ-mesons are made via coalescence of seemingly thermalized s quarks in central Au+Au collisions.

4. φ-meson anisotropy - partonic collectivity

The top panel of Fig. 3 (left) shows the $v_2(p_T)$ of the φ-meson from Au+Au collisions for four centrality bins. The lower panel of Fig. 3 (left) shows the minimum bias (0-80%) result compared to parameterizations for number-of-quark scaling for mesons (NQ=2) and baryons (NQ=3) whose free parameters have been fixed by fitting to the Λ and $K^0_S$ results simultaneously [1]. In this case, for $p_T < 2$ GeV/c, the φ $v_2$ follows a mass-ordered hierarchy where the values of $v_2$, within errors, fall between those of the heavier Λ and lighter $K^0_S$. However, at intermediate $p_T$, between 2-5 GeV/c, the φ $v_2$ appears to follow the same trend as $K^0_S$. When we fit the $v_2(p_T)$ of φ-mesons with the quark number scaling ansatz [1], the resulting fit parameter NQ = 2.3 ± 0.4. The fact that the φ $v_2(p_T)$ is the same as that of other mesons indicates that the heavier s quarks flow as strongly as the lighter u and d quarks.

In order to show that φ $v_2$ reflects partonic collectivity we have to demonstrate that (a) φ-mesons are not formed through kaon coalescence and (b) φ-mesons do not participate strongly in hadronic interactions and freezes out early from the system. As
previously discussed, $\phi$-mesons are not formed through kaon coalescence [1]. In support for (b) we discuss the following observations from both experiments and theoretical models. The general trend for $\bar{p}$, $K^-$ and $\pi^-$ is an increase in $\langle p_T \rangle$ as a function of centrality, which is indicative of an increased transverse radial flow velocity component to these particles’ momentum distributions (Fig. 1 top right) [1]. The $\phi$ $\langle p_T \rangle$, however, shows no significant centrality dependence. This indicates that the $\phi$ do not participate in the later hadronic rescatterings as that of $\bar{p}$, $K^-$ and $\pi^-$. This is expected if the $\phi$ decouples early on in the collision before transverse radial flow is completely built up. If the $\phi$ hadronic scattering cross section is much smaller than that of other particles, one would not expect the $\phi$ $\langle p_T \rangle$ distribution to be appreciably affected by any final state hadronic rescatterings. In contrast to these observations, the RQMD predictions of $\langle p_T \rangle$ for kaon, proton and $\phi$ all increase as functions of centrality [8, 1]. Phenomenological analysis [4] has suggested a relatively small hadronic interaction cross section for $\phi$-mesons. Further the data on coherent $\phi$ photoproduction shows that $\sigma_{\phi N} \sim 10 \text{ mb}$ [12]. This is about a factor of 3 times lower than $\sigma_{\rho N}$ and $\sigma_{\pi N}$; about a factor 4 times lower than $\sigma_{\Lambda N}$ and $\sigma_{NN}$ and about a factor 2 times lower than $\sigma_{KN}$. A hydrodynamical (and
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hydro motivated blast wave) description of the \( \phi \)-meson spectra clearly indicates that the freeze-out temperature of \( \phi \)-mesons (Fig. 3 right, 160-190 MeV) at RHIC energies is close to the critical temperature \( T_C \) for quark-hadron phase transition predicted by Lattice QCD calculations [13]. All these indicate that \( \phi \)-mesons decouple early from the system and do not participate strongly in hadronic interactions. In addition discussion in previous section indicates that \( \phi \)-mesons are produced from seemingly thermalized \( s \)-quarks. Therefore the \( \phi \)-meson \( v_2 \) results demonstrate partonic collectivity.

5. **\( \phi \)-meson anisotropy - probe the QCD phase diagram**

In the previous sections we discussed the following features for \( \phi \)-mesons at RHIC: (a) primordial contribution close to 100\%, (b) decouples early from the system and close to \( T_C \), (c) at higher energies not formed from \( K \bar{K} \) coalescence, (d) enhancement reflects dense partonic medium formation, (e) formed by coalescence of seemingly thermalized \( s \bar{s} \) quarks and (f) substantial collectivity which at intermediate \( p_T \) exhibits NQ scaling. All these indicate the large \( \phi \) \( v_2 \) is developed due to partonic interactions in the medium. Based on these observations we propose that, absence and reduction of \( \phi \) \( v_2 \) compared to other hadrons and absence of NQ scaling for \( \phi \) \( v_2 \) (note \( \phi \)-mesons so far is the only hadron that can differentiate between mass and NQ effects upto RHIC energies) indicate during the evolution the system remains in the hadronic phase. Since the number of quark scaling requires the deconfinement to take place. Therefore one does not expect such a scaling in a pure hadronic system. More supporting arguments that substantial \( \phi \) \( v_2 \) can only arise from partonic interactions comes from the transport model calculations. Both RQMD and UrQMD calculations failed to explain the substantial \( v_2 \) for charged hadrons measured as a function of collision centrality in Au+Au collisions at 200 GeV in RHIC [8]. Thereby leaving for a substantial scope for partonic interactions to generate the remaining \( v_2 \).

In Fig. 4 we show \( \phi \) \( v_2 \) from A Multi Phase Transport Model (AMPT) [14] as a function of difference in average transverse mass \( \langle m_T \rangle \) and hadron mass \( m \) both normalized by the number of constituent quarks (along with other hadrons: \( \pi, K, p, \Lambda \)) for two cases (a) right plot shows the results with default setting and (b) left plot shows the results with string melting scenario, which incorporates partonic coalescence mechanism. All results are for Au+Au collisions at \( \sqrt{s_{NN}} = 9.2 \) GeV, for \(-1.0 < \eta < 1.0 \) and impact parameter less than 14 fm. Clearly one observes breaking of NQ scaling for the results in the default case and excellent NQ scaling for the string melting case. This indicates the \( \phi \) \( v_2 \) can be used to probe if the relevant degrees of freedom for the medium formed in heavy ion collisions is partonic or hadronic. One may question the high values of \( \phi \) \( v_2 \) in this model for default case. This could be because of other mechanism of \( \phi \) production incorporated in the model, like from example \( K \bar{K} \) coalescence. However results from RHIC data has indicated that such mechanisms are not dominant. Those processes if taken out could possibly lead to small \( \phi \) \( v_2 \) in the default case. In short, two predictions from the model analysis: without the formation of partonic matter we
expect to observe (i) the absence of the $v_2$ NQ scaling for all hadrons; (ii) small or zero $v_2$ for the $\phi$-mesons.

\[ (m_T - \text{mass})/n_q \text{ (GeV)} \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{(color online) Elliptic flow ($v_2$) of $\phi$, $\pi$, $K$, $p$, $\Lambda$ normalized by NQ from Au+Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV at midrapidity for impact parameter less than 14 fm. The results from AMPT model [14] are plotted as a function of $(m_T - m)/n_q$ normalized by NQ. Left-plot: String melting scenario where partonic interactions were mimicked via breaking a string into quarks and the hadronization is achieved by quark recombination. Right-plot: Default case where only hadronic interactions were employed. This is the case most close to the low energy collisions below the possible phase diagram.}
\end{figure}

6. Summary

Several interesting features of $\phi$-mesons are observed to provide important information about the medium formed in heavy ion collisions. These are summarized in Table 1. $\phi$-meson production in Au+Au and Cu+Cu collisions relative to $p+p$ collisions has shown that the strangeness enhancement in heavy-ion collisions at RHIC is due to formation of a dense partonic medium and not due to Canonical suppression effects. Results on $\phi$-meson elliptic flow provides a clear evidence that the collectivity observed in heavy-ion collisions at RHIC is developed at the partonic stage. The results from the $N(\Omega)/N(\phi)$ ratios and comparison to model calculations indicate the $\phi$-mesons are produced via coalescence of seemingly thermalized $s$-quarks. Based on the several interesting observation connected to $\phi$-meson production it is possible to use the observation of large collectivity and number of constituent quark scaling of $\phi$-meson elliptic flow as an indication that matter went through partonic phase. Hence $\phi$ $v_2$ can be used as a probe for locating the QCD phase boundary. This can be explored in future RHIC beam energy scan program and at the compressed baryonic matter experiment at GSI.
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