

## $\phi$ MESON AS A PROBE OF QCD EQUATION OF STATE\*

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In this work, we extract the QCD Equation of State (EoS) using experimental results of the  $\phi$  meson produced in nuclear collisions at AGS, SPS and RHIC energies. The data are confronted to simple thermodynamic expectations and lattice results. The experimental data indicate a first order phase transition, with a mixed phase stretching energy density between  $\sim 1$  and  $3.2 \text{ GeV}/\text{fm}^3$ .

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### 1. Introduction

High energy heavy-ion collisions provide a unique opportunity to test the Quantum Chromodynamics (QCD) prediction of a phase transition from hadronic matter to a deconfined thermalised state of quarks and gluons called Quark Gluon Plasma (QGP). The value of the temperature,  $T_c$  for this transition is not settled yet — it varies from 192 MeV [1] to 151 MeV [2]. Current lattice QCD calculations indicate that the order of the transition depends on the quark masses, as well as on the baryochemical potential ( $\mu_B$ ). The magnitude of the baryochemical potential at the central rapidity region depends on the collision energy, it reduces with the increase in beam energy. Therefore, by changing the beam energy it is possible to study the change in the nature of QCD phase transition.

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In a first order phase transition scenario, the pressure increases with increasing temperature, until the transition temperature  $T_c$  is reached, then it remains constant during the mixed phase, and continues to increase after the end of the mixed phase. Related to this picture, Van Hove [3] suggested to identify the deconfinement transition in high energy  $p\bar{p}$  collisions, looking at the variation of average transverse momentum ( $\langle p_T \rangle$ ) of hadrons as a function of the hadron multiplicity at midrapidity ( $dN/dy$ ) and searching for an increase of  $\langle p_T \rangle$  followed by a plateau-like behavior and again a subsequent increase. The  $\langle p_T \rangle$  is expected to reflect the thermal freeze-out temperature ( $T_{\text{th}}$ ) and a flow component which can be related to the initial pressure, similarly the hadronic multiplicity reflects the entropy density of the system. While the purely thermal component of  $\langle p_T \rangle$  cannot be related to the initial temperature which remains unmeasurable above  $T_c$ , however the flow component in the inverse slope can reflect the plateau of the pressure during mixed phase.

It has been observed that in central heavy ion collisions, the  $\langle m_T \rangle (= \sqrt{p_T^2 + m^2})$  of pions, kaons and protons as a function of  $dN_{\text{ch}}/dy$  shows a Van-Hove-like behaviour as explained above for a wide range of collision energies [4, 5]. Hydrodynamic calculations assuming a first order transition could reproduce these data [4, 6]. In this work, we study for the first time the variation of the inverse slope,  $T_{\text{eff}}$  extracted from the  $p_T$  distribution of the  $\phi$ -meson as a function of the initial energy density,  $\varepsilon_{\text{Bj}}$  evaluated within the framework of Bjorken's hydrodynamical model [7] and  $\sqrt{s_{NN}}$  for energies spanning from AGS, SPS to RHIC [8]. This is an important new feature of such studies, because it connects the inverse slope with a parameter characterizing the initial state of the collision build up after  $\sim 1$  fm/c and which reflects at the same time the collision energy, the stopping and the impact parameter of the collision. For example, at a given  $\sqrt{s_{NN}}$ , different energy densities could be achieved by changing the colliding nuclei species or the impact parameter.  $\varepsilon_{\text{Bj}}$  can be directly compared to the critical energy density  $\varepsilon_c$  obtained in lattice QCD calculations-  $\varepsilon_c \sim 1$  GeV/fm<sup>3</sup>. In the following the  $\phi$  data will be analysed and confronted to simple thermodynamic expectations which relate to the Van Hove signature and to lattice QCD predictions. Due to its  $s\bar{s}$  valence quark content, the  $\phi$  meson is of special interest [9] to study strangeness enhancement, which is a potential probe of QGP formation. Because of its small hadronic rescattering cross section of  $\sigma(\phi N) = 10$  mb, it decouples earlier than other hadrons. Furthermore, due to its life time of  $\sim 45$  fm/c, its main decay product ( $K^+K^-$ ) suffer less rescattering. Experimental results from Au + Au collisions at RHIC energies indicate that  $\phi$  has a higher thermal freeze out temperature as compared to pions, kaons and protons. In particular, their thermal freeze out temperature is within errors compatible with the chemical freeze out temperature of

hadrons and the critical temperature. Therefore,  $\phi$  and its flow phenomena are particularly interesting probes for studying the EoS and the nature of the phase transition.

## 2. $\phi$ as a probe of the order of the phase transition

We have used the blast wave method [10] to study the experimental data on the  $p_T$  spectra of  $\phi$  measured at various collision energies [11–13]. The results obtained within the ambit of blast wave method is compared with the data in Fig. 1. The data for the energies under consideration are reproduced well with the values of the parameters *i.e.* the radial flow velocity,  $v_r$  and the ‘true’ freeze-out temperature,  $T_{th}$  of the blast wave approach are displayed in Table I. It has been found that  $T_{th} \sim 170$  MeV and  $v_r \sim 0.6$  and are independent of the center of mass energies beyond a threshold.  $T_{th}$  being close to  $T_c$  indicates that  $\phi$  meson freezes out near the phase boundary and could be used to extract the properties of QCD matter near the transition point. Moreover, the values of  $v_r$  indicate that QGP has undergone substantial radial flow. The values  $T_{th}$  and  $v_r$  can be used to reproduce the measured inverse slope parameter,  $T_{eff}$  by the formula:  $T_{eff} = T_{th} + \frac{1}{2}m \langle v_r \rangle^2$ .

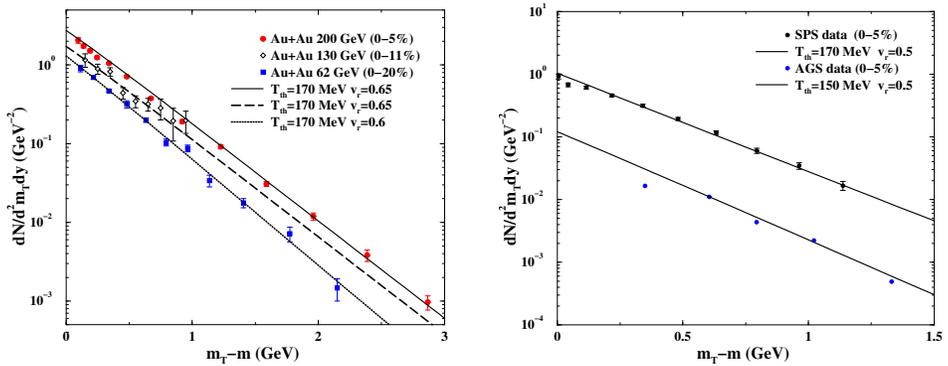


Fig. 1. Transverse mass distribution of  $\phi$  as a function of its kinetic energy at mid-rapidity for different colliding energies measured by the STAR Collaboration at RHIC (left) and for SPS and AGS energies (right). The theoretical curves are obtained within the framework of blast wave method.

In Fig. 2 the effective temperature of  $\phi$ ,  $T_{eff}^{\phi}$  (left) and the thermal component of the inverse slope  $T_{th}^{\phi}$  (right) are shown as a function of the collision energy  $\sqrt{s_{NN}}$ . We use the central collision data in almost the same  $p_T$  range, at mid-rapidity [11–17]. It is observed that from AGS to SPS energies these

TABLE I

Freeze-out temperature,  $T_{\text{th}}$  and the radial flow velocity,  $v_r$  for  $\phi$ -meson for various centre of mass energies,  $\sqrt{s_{NN}}$  extracted from the experimental data within the framework of blast wave method.

$\sqrt{s_{NN}}$ (GeV)	$T_{\text{th}}$ (MeV)	$v_r$
4.87	150	0.5
17.3	170	0.5
62.4	170	0.6
130	170	0.65
200	170	0.65

observables remain almost unchanged, showing a plateau-like structure. Going from SPS to RHIC energies, the inverse slope  $T_{\text{eff}}^{\phi}$  exhibits a sudden jump while an increase is still observed in the  $T_{\text{th}}^{\phi}$  component. This may be due to an imperfect transverse flow component subtraction at RHIC or other effects. It is observed that the  $T_{\text{th}}^{\phi}$  is reaching at RHIC values compatible within errors with  $T_C$ . The observed plateau of  $T_{\text{eff}}^{\phi}$  is a signature of a coexisting phase of quarks, gluons and hadrons for a first order phase transition, during which the initial pressure remains constant. The subsequent increase of  $T_{\text{eff}}^{\phi}$  with  $\sqrt{s_{NN}}$  at top RHIC energies indicates the end of the mixed phase and the entering into a pure QGP phase.

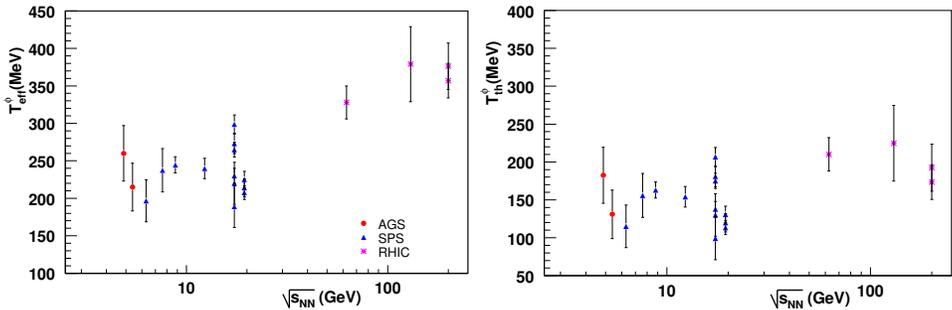


Fig. 2.  $T_{\text{eff}}^{\phi}$  (left) and  $T_{\text{th}}^{\phi}$  (right) as a function of  $\sqrt{s_{NN}}$  from AGS-SPS to RHIC.

Now we study the dependence of the inverse slope and its thermal component on the initial energy density,  $\varepsilon_{\text{Bj}}$ , estimated as  $\varepsilon_{\text{Bj}} = \left\langle \frac{dE_{\text{T}}}{dy} \right\rangle \frac{1}{\tau\pi R^2} = \left\langle \frac{dN}{dy} \right\rangle \langle m_{\text{T}} \rangle \frac{1}{\tau\pi R^2}$  where  $R = R_0 A^{1/3}$  and  $A \sim N_{\text{part}}/2$ . From the experimental measurements of  $dE_{\text{T}}/dy$  and  $dN/dy$  with  $\langle m_{\text{T}} \rangle$ , the observable  $\varepsilon_{\text{Bj}}$  could be estimated for all centralities and center of mass energies at mid-rapidity.

In Fig. 3  $T_{\text{eff}}^\phi$  (left) and  $T_{\text{th}}^\phi$  (right) are shown as a function of  $\varepsilon_{\text{Bj}} \tau$ . Note that the formation time,  $\tau$  is model-dependent and in general, in subsequent discussions we also assume  $\tau \sim 1 \text{ fm}/c$ . The above result reflects the properties of equation of state. We observe a plateau in  $T_{\text{eff}}^\phi$  stretching between  $\varepsilon_{\text{Bj}} \sim 1$  and  $3.2 \text{ GeV}/\text{fm}^3$ , and increasing suddenly above  $3.2 \text{ GeV}/\text{fm}^3$ . This behaviour as already discussed, suggests a first order transition, however from Fig. 3 we can now infer that the mixed phase is stretching between 1 and  $3.2 \text{ GeV}/\text{fm}^3$ . The use of the  $\varepsilon_{\text{Bj}}$  scale, allows us to establish here for the first time the  $\varepsilon_{\text{Bj}}$  range of the mixed phase. More data on the  $\phi$  at  $\varepsilon_{\text{Bj}}$  below  $1 \text{ GeV}/\text{fm}^3$  are needed to establish the increase of  $T_{\text{eff}}^\phi$  up to  $1 \text{ GeV}/\text{fm}^3$ , as seen in other hadrons. The increase of the inverse slope at RHIC energies again indicate a pure phase of QGP, as is expected from a first-order phase transition. The thermal component  $T_{\text{th}}^\phi$  shows also a plateau while a smaller increase is still observed at  $3.2 \text{ GeV}/\text{fm}^3$ . The step-like behavior in the excitation function of  $\langle m_{\text{T}} \rangle$  has also been explained by taking a first-order phase transition with a large latent heat or if the EoS is effectively softened due to non-equilibrium effects in the hadronic transport calculations [18].

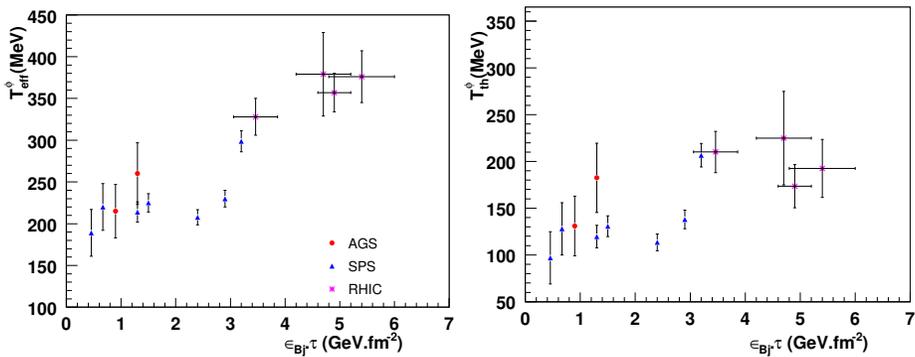


Fig. 3.  $T_{\text{eff}}^\phi$  and  $T_{\text{th}}^\phi$  as a function of  $\varepsilon_{\text{Bj}} \tau$  from AGS-SPS to RHIC.

The flow component of the inverse slope of the  $\phi$  reflecting the initial pressure, is of interest to look directly observables linked to this initial pressure like the transverse flow velocity,  $v_{\text{T}}$  for all hadrons and the elliptic flow  $v_2$  as a function of collision energy. The transverse flow velocity  $v_{\text{T}}$  shows exactly the same characteristic behaviour as the  $T_{\text{eff}}^\phi$  as a function of collision energy, namely increase, a plateau and subsequent increase at RHIC [19]. A similar pattern is suggested for the elliptic flow  $v_2$  as a function of collision energy [20]. The observation of a mixed phase goes in line with the fact that excitation function of various observables show anomalous behavior or saturation effects starting lower SPS energies [21, 22]. This could be related to the onset of deconfinement corresponding to this energy regime.

In addition, the fact that microscopic transport models, based on hadronic degrees of freedom failed to reproduce the observed behavior of kaon inverse slope [23, 24], also indirectly confirms the observation of a deconfinement transition.

### 3. Comparison of $\phi$ data with lattice predictions

In the following, we compare experimental data with lattice QCD predictions on energy density as a function of temperature as shown in Fig. 8 of [25]. In Fig. 4, the lattice prediction for the energy density as a function of the temperature is compared to  $\varepsilon_{Bj}$  as a function of  $T_{th}^\phi$  (left) and  $T_{eff}^\phi$  (right) extracted from the slopes of  $\phi$  spectra. First we discuss the left plot. The lattice prediction is for zero baryochemical potential, therefore, corresponds to the cross over region. The figure in the left is at non-zero  $\mu_B$  and shows the variation of the initial energy density with  $T_{th}^\phi$  temperature, which is measured at a later time than the energy density, namely at the thermal freeze out of the  $\phi$ . That is, the two variables in the data are a measure of the system at different times, while the lattice estimate is independent of time. This temperature is expected to be always below  $T_c$  and does not reflect the initial  $T$ , which may exceed  $T_c$  depending on the collision energy. This plot can be directly compared to figure 11 of [26], where the energy density from data has been studied as a function of  $T$ , while both  $x$  and  $y$  axis were estimated at the same time, namely at the hadronic chemical freeze out time and at  $\mu_B = 0$ . It is seen that the energy density increases approaching the  $T_c$  from below, from which both the  $T_c$  and critical exponents can be extracted [26].

If the transition occurs at  $T_c \sim 170$  MeV as expected, the temperature of  $\phi$  at the thermal freeze out should saturate below and near  $T_c$ , for all values of the initial density (up to infinity), as seen in Fig. 4 (left panel).

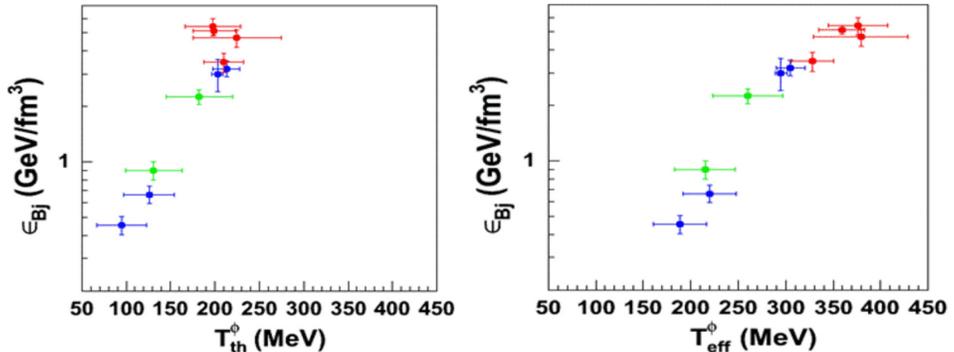


Fig. 4. Energy density as a function of  $T_{th}$  (left) and  $T_{eff}$  (right) for the  $\phi$  meson.

We observe a saturation in the value of  $T_{\text{th}}^\phi$  near  $T_c$ , because  $T_{\text{th}}^\phi \leq T_c$  as mentioned earlier. To measure temperatures above  $T_c$  photons and dileptons are useful probes.

We now discuss Fig. 4 (right panel), where the initial Bjorken energy density is shown as a function of the effective temperature of the  $\phi$  for collisions from AGS, SPS to RHIC. Now both the  $x$  and  $y$  axis are reflecting parameters at initial times, therefore, this plot is more appropriate to be compared to the lattice results. The effective temperature of the  $\phi$  here is a sum of a thermal freeze out temperature, which is expected to be always below  $T_c$ , and a non-thermal component due to transverse flow, which relates to the initial pressure and reflects the initial conditions above  $T_c$ . Therefore, the variables in the two plots compared here are not exactly the same but they are correlated. Further analysis is needed to compare the data to lattice *e.g.* using exactly the same variables in both estimates. A study can be also done involving the elliptic flow  $v_2$  and the transverse flow velocity  $v_t$  as a function of the initial energy density. Also a hydrodynamic calculation of the discussed variables is of interest.

#### 4. Summary

In summary, a first analysis of experimental data on the inverse slope parameter of  $\phi$  mesons as a function of  $\sqrt{s_{NN}}$  and energy density from AGS, SPS to RHIC, and their comparison to simple thermodynamic expectations, suggest a first order phase transition as predicted by lattice QCD at non-zero baryochemical potentials. The mixed phase of quarks, gluons and hadrons, is found to stretch between  $\varepsilon_{Bj}$  of  $\sim 1$  and  $3.2 \text{ GeV/fm}^3$ . The latent heat density in a first order phase transition is  $\varepsilon_Q(T_c) - \varepsilon_H(T_c) = 4B$ , where  $\varepsilon_Q(\varepsilon_H)$  is the energy density of QGP (hadrons) at  $T_c$  and  $B$  is bag constant. With  $\varepsilon_Q(T_c) \sim 3.2 \text{ GeV/fm}^3$  and  $\varepsilon_H(T_c) \sim 1 \text{ GeV/fm}^3$ , we get a reasonable value for  $B^{1/4} \sim 250 \text{ MeV}$ . If we ignore  $B$ , then  $\varepsilon_Q/\varepsilon_H \sim g_Q/g_H \sim 3.2$  also a reasonable number comparable to results from lattice QCD [27], here  $g_Q(g_H)$  is statistical degeneracy of QGP (hadrons). The plateau and subsequent increase of the inverse slope parameter of  $\phi$  above  $\varepsilon_{Bj} 3.2 \text{ GeV/fm}^3$  is in agreement with data from pions, kaons and protons, and is as well observed in the transverse flow velocity  $v_t$  reflecting the behaviour of the initial pressure. A first attempt to compare data to lattice QCD predictions is made.

The above results, while supporting the order of the transition predicted by lattice at large  $\mu_B$  up to  $\varepsilon_{Bj} \sim 3.2 \text{ GeV/fm}^3$ , they do not exclude a change of order of the transition at smaller baryochemical potentials. Which points to further work, towards mapping out the order of the QCD phase transition as a function of energy and baryochemical potential.

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