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MULTIPLICITY DEPENDENCE OF p_t SPECTRUM AS A POSSIBLE SIGNAL
FOR A PHASE TRANSITION IN HADRONIC COLLISIONS

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A B S T R A C T

It is argued that the flattening of the transverse momentum (p_t) spectrum for increasing multiplicity n , observed at the CERN proton antiproton collider for charged particles in the central rapidity region I), may serve as a probe for the equation of state of hot hadronic matter. We discuss the possibility that this p_t vs n correlation could provide a signal for the deconfinement transition of hadronic matter.

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1. - Experiments at the CERN $p\bar{p}$ collider (c.m. energy $\sqrt{s} = 540$ GeV) have shown that the charged particles produced in the central region of rapidity ($|y| \leq y_0 = 2.5$) have the following properties.

- a) - The multiplicity per unit of rapidity, dn/dy , continues to grow above ISR energies ($\sqrt{s} = 30-60$ GeV) ^{2),3)}.
- b) - There is a clear dependence of the p_t spectrum on the central multiplicity

$$n = \int_{-y_0}^{y_0} (dn/dy) dy \quad (1)$$

When plotted for successive intervals of n , the p_t spectrum (in the interval $0.3 \text{ GeV/c} < p_t < 6 \text{ GeV/c}$) becomes flatter as n increases ¹⁾. This flattening corresponds to an increase of the mean $\langle p_t \rangle$ at constant shape of the spectrum. The flattening slows down around $dn/dy \sim 8$ ($n \sim 40$) and seems to stop around $dn/dy \sim 15$; this could be a kinematic effect due to lack of available energy ¹⁾. The increase of $\langle p_t \rangle$ is from ~ 0.33 to $\sim 0.5 \text{ GeV/c}$.

Property b) is a p_t vs n correlation which is not found at the ISR, neither in pp nor in $\alpha\alpha$ collisions ⁴⁾, but it is in line with crude indications from cosmic ray data ⁵⁾.

2. - Whereas the growth of dn/dy with $\sqrt{s}$ can be accounted for in a natural way by the additive quark or dual parton models ⁶⁾, this is not so for result b). Its most natural interpretation is in thermodynamic terms applied to the excited blob of hadronic matter out of which the central region secondaries emerge, to be called the central blob (it contains by definition the matter with bulk motion obeying $|y| < y_0$, e.g., $y_0 = 2.5$ as above). Following the general concepts of Landau's hydrodynamical model ⁷⁾, dn/dy reflects the entropy, whereas the p_t spectrum reflects the combined effects of temperature and transverse expansion of the central blob ^{8),9)}. Most of the entropy is presumably created early in the collision when thermalization takes place, mainly through interactions of the sea gluons of the incident hadrons ¹⁰⁾, and this is followed by expansion and hadronization of the blob with approximate conservation of entropy. The use of thermodynamics to analyze these phenomena does not preclude the existence of a dynamical description in terms of quantum chromodynamics (non-perturbative QCD methods would of course be required). It only takes advantage of the fact that if the actual

physical states of the central blob are close to a microcanonical distribution as far as the relevant variables are concerned, thermodynamics is a simple and powerful method to analyze the measurements and to relate them to the bulk properties of hot hadronic matter.

3. - The central multiplicity n , Eq. (1), is approximately proportional to σV , the entropy contents of the blob ⁷⁾, where V is the volume of the blob and σ its average entropy density (during the expansion of the blob, σ decreases and V increases with σV approximately constant). Larger n means larger σ and/or V at some fixed reference time, e.g., the beginning of the expansion. Except at a phase transition (see below), larger σ means higher temperature T , leading to a flatter p_t spectrum; the transverse expansion should be less affected because it depends on $p/(T\sigma)$ [see Eq. (2) of Ref. 9]. In contrast, larger V at constant σ is expected to increase n without modifying the p_t spectrum; the n vs V dependence should be about the same at all high $\sqrt{s}$, since the variation of V from collision to collision is essentially geometric (being dominated by the variation of the impact parameter). What is of interest in the p_t vs n correlation found at the $p\bar{p}$ collider is that higher n indicates (after averaging over V) hotter hadronic matter in the central blob. This opens the possibility of using the correlation to draw conclusions on the σ vs T relation, i.e., on the equation of state of hadronic matter. Our aim is to show how the correlation may be qualitatively affected by the deconfinement phase transition from hadron gas to quark gluon plasma which hadronic matter is believed to undergo when the density of quarks plus antiquarks reaches a value of order $2-4 \text{ fm}^{-3}$ ¹¹⁾. We shall argue that the occurrence of the transition in the central blob could be signalled by an anomaly in the variation of $\langle p_t \rangle$ with n , a possible indicator which would be simpler to search for experimentally than the signals usually proposed for quark gluon plasma formation (directly produced dileptons and photons, strange particles).

4. - In the central region, the net baryon number is small, so that the thermodynamic relations relevant to the central blob are those for hadronic matter at zero chemical potential. From numerous investigations of both phases (gas of hadrons and resonances at low temperature, QCD lattice calculations for transition and plasma phase), one can now guess the qualitative temperature dependence of the entropy density σ , the pressure p and the energy density $\epsilon = T\sigma - p$. For QCD with two species of light quarks, they are illustrated in Fig. 1, the transition

temperature T_c being of order 200 MeV ; the quantities plotted are σ/T^3 , p/T^4 , ϵ/T^4 which approach their (constant) ideal gas values at $T \gtrsim 3T_c$:

$$\sigma/T^3 = 4p/T^4 = 4\epsilon/3T^4 = 74\pi^2/45 \quad (2)$$

The nature of the transition is not known, but the lattice calculation predicts that it is sharp and has a large latent heat, corresponding to an increase of ϵ by perhaps a factor $\gtrsim 2$ from below to above T_c . Since p is always small ($p \leq \epsilon/3$), σ increases by about the same factor at the transition. As for p , the thermodynamic relation $\sigma = dp/dT$ implies that it behaves smoothly through the transition. The curves of Fig. 2 are chosen among those of Dixit et al.¹²⁾, where one also finds a list of references.

5. - We assume the σ vs T dependence to be of the type shown in Fig. 1 and we consider first the simplified case where, at the reference time, the central blob volume V (sec par. 3) is the same in all collisions, giving $n = a\sigma$, $a \approx$ constant. If the flattening of the p_t spectrum for increasing n starts well before the transition is reached (i.e., when the maximum temperature T in the central blob is well below T_c), it will continue until n grows enough for T to reach T_c . Further growth of n then corresponds to σ increasing through the transition (see Fig. 1), without appreciable change of T and p . The temperature contribution to the p_t spectrum therefore remains constant, and the transverse expansion effect may even decrease because $p/(T\sigma)$ decreases as one goes through the transition. Above the transition, T again increases for growing n [and so does $p/(T\sigma)$ for a short while], but these variations should now have at most a weak flattening effect on the p_t spectrum because most hadrons emerging from the central blob will do so when the quark-gluon plasma is cool enough to hadronize, i.e., at $T \approx T_c$. The qualitative shape expected for the p_t vs n correlation from these considerations is sketched as the dashed line of Fig. 2, where the flattening of the p_t spectrum is expressed as growth of the mean $\langle p_t \rangle$ above the standard value $\langle p_t \rangle_0 \approx 350$ MeV/c found at lower energies. The solid line suggests what might be qualitatively expected in the real case where the blob volume V at the fixed reference time varies from collision to collision and is averaged over, corresponding to a spreading of values of $a = n/\sigma$ and therefore of the horizontal scale in Fig. 2. We have drawn the dashed line for the mean value of V , hence the equality of slopes at small multiplicity. We do not attempt here to estimate the coefficient a as a function of V , nor $\langle p_t \rangle$ as a function of T . Consequently, we do not predict the numerical scales of Fig. 2.

6. - Figure 2 suggests how the correlation between $\langle p_t \rangle$ and dn/dy , two of the simplest quantities measurable in hadronic collisions, may probe the existence of a hadronic phase transition. In fact, the data of Ref. 1) are compatible with the behaviour of the solid line in the Figure in as far as they show a slowing down in the increase of $\langle p_t \rangle$ at $dn/dy \gtrsim 8$. Whether this effect is kinematic (lack of available energy) should be easily tested by changing the incident energy. If the curve does not change, the deconfinement transition may be the correct explanation. One should note that in Fig. 1, the increase of σ at $T \sim T_c$ may be smaller than indicated. This would shrink or even suppress the shoulder in the curves of Fig. 2, leaving only a decrease of their slope for increasing dn/dy as a sign of the transition. Also this behaviour is compatible with present collider data. If the observed slowdown in the increase of $\langle p_t \rangle$ with dn/dy is kinematic, conclusions are harder to draw. The transition may still occur but take place at too low values of dn/dy to give an anomaly in the p_t vs n correlation (remember that the flattening of the p_t spectrum only shows up above ISR energies), or at too high values to be accessible at the collider. Furthermore, our basic assumptions may go wrong in various ways ; the central blob perhaps never thermalizes, or its expansion and hadronization may be quite different from what one suspects them to be, or the QCD lattice calculations may be wrong and hadronic matter has perhaps no deconfinement transition of the type depicted in Fig. 1.

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FIGURE CAPTIONS

Figure 1 An example of the expected qualitative dependence on temperature T of entropy density σ , energy density ϵ and pressure p for hadronic matter at zero chemical potential.

Figure 2 Expected structure in the $\langle p_t \rangle$ vs dn/dy correlation resulting from the phase transition in Fig. 1 (solid line), and sharper structure expected for a given impact parameter (dashed line).

Fig. 1

Fig. 2