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**SUPPRESSION OF HIGH p_T NUCLEONS - A SIGNATURE OF
DECONFINEMENT IN HEAVY ION COLLISIONS?**

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ABSTRACT

Protons with large transverse momenta are produced in proton-proton collisions primarily by hard scattering of diquarks. If the diquark radius were close to the Debye screening length, yields of protons, neutrons and lambdas with large transverse momenta would be suppressed in a deconfined quark-gluon plasma. It will be argued that this effect is not likely to be generated by dense hadronic matter.

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1. INTRODUCTION

The phase transition of hadronic matter to a deconfined quark-gluon plasma (QGP) has become an object of experimental efforts with the availability of ion beams at BNL and CERN. Due to the intricate space-time history of ultrarelativistic nuclear collisions [1] the traces of a QGP may not be recognizable easily. The most direct consequence of deconfinement was, until recently, supposed to be the suppression of J/ψ production. Bound states cease to exist in a QGP if their radii are larger than a Debye screening radius ξ . For temperatures T just above the deconfinement temperature T_C one finds $\xi \approx 0.2 \div 0.3$ fm, which tends to be smaller than the J/ψ radius ($0.2 \div 0.5$ fm) [2]. The level of suppression depends also on the formation time of the resonance and on the momentum of the quark-antiquark pair [3], i.e. on the time it stays in the QGP. It was, however, argued [4] that dense hadronic matter may also suppress J/ψ production rather efficiently.

A less ambiguous signal of deconfinement would, therefore, be provided by a correlated two-quark object ('diquark') of sufficiently large radius, which is not absorbed more strongly in nuclear reactions than in nucleon-nucleon collisions. There is accumulating experimental evidence that such diquarks exist. Recent data suggest, for example, that hard scattering of diquarks dominates high transverse momentum (p_T) proton production in pp collisions [5]. Hence a reduction of, e.g., proton yields at high p_T in nuclear collisions should be directly related to a screening of correlations between the two quarks in a QGP.

2. DIQUARKS

The concept of a proton wave function containing diquark components, e.g.

$$p = \lambda_1 |u, u, d\rangle + \lambda_2 |(ud), u\rangle + \lambda_3 |(uu), d\rangle, \lambda_1^2 + \lambda_2^2 + \lambda_3^2 = 1,$$

turns out to be very successful in a phenomenological description of inclusive features of hadron-proton collisions [6]. In particular, scalar (ud)-diquarks (denoted by D) seem to be tightly bound in contrast to uu-systems [6e,7]. In such a scheme the problem of formation time does not exist.

Data from deep-inelastic lepton-nucleon scattering do not seem to be in disagreement with a diquark picture [7]. Also analyses of hadron production in e^+e^- collisions [8], of the neutron charge radius [9a], of large angle pp elastic scattering [9b] and of other exclusive processes [9c] are based upon schemes of bound diquarks.

From (anti-) baryon production in e^+e^- collisions a (current-) diquark mass $m_D \approx 200-300$ MeV was determined [8a,b]. In an instanton vacuum model $m_D \approx 330$ MeV was obtained [10] for the current mass. Alternatively, m_D can be estimated in a constituent picture [11] using a quark mass m_q derived from the Δ^{++} resonance which does not contain scalar diquarks:

$$m_D \approx m(\text{proton}) - m_q \approx 500 \text{ MeV}, \quad \text{with } m_q = 1/3 m(\Delta^{++}).$$

This is compatible with ref. [8c]; the differences between estimated constituent and bare quark masses are on the expected level [10]. In such a scheme the diquark has a binding energy $BE = 2m_q - m_D \approx 300$ MeV.

The radius r_D of a strongly bound diquark can be calculated from the relation $r_D = (2 m_q)^{-1}$ [12] yielding $r_D \approx 0.25$ fm for $m_q \approx 0.4$ GeV in rather good agreement with $r_D \approx 0.3$ fm in the instanton model [10]. One concludes that r_D is probably larger than ξ for $T/T_c > 1.1$.

3. PROTONS AT HIGH p_T

There is further strong evidence that bound diquarks exist inside protons. It was demonstrated for pp collisions that, so far, only the hypothesis of hard diquark scattering in a QCD framework (Fig. 1a) accounts fully for the measured inclusive proton yields, which depend on cms energy $\sqrt{s}$, cms scattering angle θ and p_T [5b,e,f,g,h], as well as for the phase space density and quantum number composition of associated hadrons [5a].

In pp collisions, high p_T protons at $\theta \gg 0^\circ$ are leading fragments of jets [5a] which are produced in association with jets (at $\theta \approx 0^\circ$) with the quantum numbers of single valence quarks [5a] as expected from diquark scattering (Fig. 1a). It is very unlikely that high p_T protons originate frequently from final state recombination of two quarks scattered simultaneously (Fig. 1b). The latter process would generally give rise to two recoiling jets with non-vanishing relative opening angle and with $p_T(\text{jet}) \approx p_T(\text{proton})/2$. None of the observed features supports this scheme [5a].

For both experimental and theoretical reasons inclusive yields are often given as ratios since systematic uncertainties tend to cancel in this way. For pp interactions inclusive proton cross sections are displayed in Fig. 2 [13] relative to those for π^+ which come primarily from u-quark

scattering (Fig. 1c, [5i]). With the exception of the data at 70 GeV/c, the ratios decrease with increasing transverse momentum; they also decrease with increasing energy. These features are well reproduced by diquark models in a QCD framework (not shown, [5e,f,h]) containing a diquark form factor $F(Q^2) = 1/(1+Q^2/M^2)$ as an essential ingredient; $\sqrt{Q^2}$ is a typical 4-momentum transfer on the parton level and M a mass parameter. A mean radius $\sqrt{\langle r_D^2 \rangle}$ can be calculated from $F(Q^2)$ assuming spherical diquarks:

$$\langle r_D^2 \rangle = -6 \partial F / \partial Q^2 \big|_{Q^2=0} = 6/M^2 \text{ GeV}^{-2}$$

The data were reproduced with $M^2 \approx 9 \div 20 \text{ GeV}^2$ corresponding to $\sqrt{\langle r_D^2 \rangle} \approx 0.10 \div 0.16 \text{ fm}$ [5e,f,h]; this is not too different from previous estimates. However, the values used for M are affected by various other assumptions entering the model, as mentioned in ref. [5f]. In particular, there is a dependence on the definition of Q^2 , a quantity which is not directly accessible experimentally. Analyses of deep-inelastic lepton-nucleon interactions tend to favor $M \approx 1 \div 2 \text{ GeV}$ [7c,d], i.e. larger values of $\sqrt{\langle r_D^2 \rangle}$.

A comparison of the data with a QCD prediction excluding diquarks in Fig.2 [5f,h] suggests now that provided all diquarks were melted in the QGP, the inclusive proton yield should decrease by about a factor $f \geq 10 \cdot f'(3 \cdot f')$ §) at $p_T \approx 3(6) \text{ GeV/c}$ in nuclear collisions at a beam momentum of 200 GeV/c nucleon. The effect would be nearly one order of magnitude larger at 70 GeV/c. Suppression of nucleons $N(p,n)$ and $\Lambda (=uds)$ in the range $p_T=3 \div 6$

§) Note that the π^+ yield is smaller in the case of (nearly) isoscalar beams and targets [13b] such that another factor $f' \approx 1(2)$ is gained at $p_T \approx 3(6) \text{ GeV/c}$.

GeV/c is therefore the proposed potential signature of deconfinement. While measurements are also worthwhile at lower transverse momenta, the interpretation in a QCD framework becomes less reliable for $p_T \leq 3$ GeV/c. At larger p_T the effect is weaker since protons are already strongly suppressed by the diquark form factor.

High p_T antiprotons are expected to be produced mainly by quark and gluon scattering (Fig. 1d) in nucleon-nucleon collisions. If diquarks were deconfined in the QGP, also protons would be dominated by these mechanisms. In this case, one would therefore predict an inclusive proton-to-antiproton ratio

$$R_A^{\text{QGP}}(p/\bar{p}) = \frac{\sigma(AA \rightarrow p+X)}{\sigma(AA \rightarrow \bar{p}+X)} \approx 1$$

at $p_T \approx 2$ GeV/c in collisions of nuclei with atomic mass A . This results from a dominance of gluons and sea (anti-) quarks [5c], both of which do not carry baryon number on the average. At $p_T \approx 6$ GeV/c, $R_A^{\text{QGP}}(p/\bar{p}) \approx 2$ follows from ref. [5f], if diquarks do not contribute. This deviation from unity reflects the fact that fast protons are favored over fast antiprotons in the fragmentation of scattered quarks (Fig. 1d), which manifests itself more markedly at very high p_T .

Measurements of $R_{pW}(p/\bar{p})$ and $R_{pp}(p/\bar{p})$ from pW and pp collisions [13b,c, 5g] are reproduced in Fig. 3 as functions of $x_T = 2 p_T / \sqrt{s}$; the ratios rise from 4 at $x_T \approx 0.1$, exceeding a value of 15 at $x_T \approx 0.35$. If all diquarks were to disappear in the QGP one would observe $R_A^{\text{QGP}}(p/\bar{p}) \leq 2$ corresponding to suppression factors $f > 7$ (depending on p_T) in good agreement with the

previous estimate. Note that this estimate of f should be less model dependent than the one obtained from Fig. 2 where uncertainties of fragmentation models enter more directly.

Experimental systematic uncertainties depend generally on the charge of a particle; hence they tend to affect $R(p/\bar{p})$ more strongly than $R(p/\pi^+)$.

4. DIQUARKS IN HADRONIC MATTER

It was shown experimentally that nuclei are more efficient in producing e.g. hadrons $h = \pi^+, p, \bar{p}$ at $\theta \approx 10^\circ + 90^\circ$ than single nucleons:

$$\sigma(pA \rightarrow h + X) = K_0 \sigma(pp \rightarrow h + X) A^{\alpha_h(p_T)},$$

where K_0 is a constant and $\alpha_h(p_T) > 1$ for $p_T \geq 2$ GeV/c [13b,14]. This probably reflects the fact that multiple hard scattering of the relevant constituents in the target nuclei is more economic than a single large angle deflection in the case of amplitudes (and form factors) which decrease strongly with increasing scattering angle [15].

More recently it was established in $\alpha\alpha$ collisions at the ISR [16] that $\sigma(\alpha\alpha \rightarrow \pi^0 + X) = K_1 \sigma(pp \rightarrow \pi^0 + X) A^{2\alpha_\pi(p_T)}$, with $K_0 \approx K_1$, in agreement with multiple scattering models [15]. It is therefore plausible to expect for dense hadronic matter (HM) produced in nuclear collisions that $R_{NN}(p/h) : R_{NA}(p/h) : R_A^{HM}(p/h) \approx 1 : A^{\Delta\alpha} : A^{2\Delta\alpha} \approx 1 : 1 : 1$, since $\Delta\alpha = \alpha_p - \alpha_h \approx 0$ (Fig. 3), [13b]. In a QGP, however, protons should be suppressed by a factor f :

$$R_A^{QGP}(p/h) = \frac{1}{f} R_A^{HM}(p/h).$$

5. DISCUSSION

In order to justify the use of arguments presented above, the shapes of inclusive spectra at high p_T have to be measured in heavy ion collisions; they must deviate from thermal distributions.

The level of suppression of baryons at high p_T depends on the fraction of diquarks traversing the QGP, which is formed at a time t_i , and on the time diquarks stay in the QGP.

The fraction ε of all diquarks entering the QGP can be estimated as follows. In a central collision two Lorentz contracted nuclei of radius r_A/γ overlap completely at a time $t = 0$ and at a longitudinal coordinate $z = 0$ in the overall center-of-mass system. A thermalized QGP at $z = 0$ exists at t_i ; at that time the nuclei have moved a distance $t_i \cdot c$ ($c=1$) along the beam direction. Therefore the fraction of diquarks entering the QGP at $z = 0$ is given by $\varepsilon \approx (r_A/\gamma - t_i) \cdot \gamma / 2r_A = (1 - \gamma r_A^{-1} \cdot t_i) / 2$. Using $t_i = 0.27 \cdot A^{-1/6}$ fm/c from ref. [17] one arrives at $\varepsilon \approx (1 - 0.32 \cdot \gamma \cdot A^{-1/2}) / 2$. For Pb-Pb collisions at 200 GeV/c/N $\varepsilon \approx 0.4$ is obtained. Clearly, conditions are less favorable for lighter nuclei and higher energies (see also fig. 2).

After scattering at $\theta_D \approx 90^\circ$ the transverse distance r_T in the cm system traversed by a diquark during a time t in its rest frame is given by $r_T = \beta_D \gamma_D t = (p_T(D) / m_D) \cdot t$, where $p_T(D) \approx 1.3 p_T(\text{baryon})$ [5f]. This limits the useful range of $p_T(\text{baryon})$ once the time t_D available for dissociation in the QGP is known, since r_T must be smaller than the radius

of the QGP, i.e. r_A . Typically $t_D \approx \xi/v$, which is the time needed by a bound quark of velocity v to reach the screening radius. From the uncertainty relation the quark momentum $|\vec{p}|$ inside a diquark is : $|\vec{p}| > 1/r_D$, which corresponds to $\beta_D > 0.9$ for $m_q \approx 400$ MeV. From the estimated values of ξ and β_D one obtains $t_D \approx 0.2$ fm/c. Hence there is a good chance to reach efficient suppression even for rather light nuclei for the transverse momentum range $p_T = 3\div 5$ GeV/c where it is supposed to be strongest.

Due to "Brownian" motion in the QGP, the diquark may spend more time in the QGP than assumed above. Related effects of energy loss tend to cancel when considering ratios of cross sections since the interactions are determined mainly by color factors which are the same for quarks (triplets) and diquarks (antitriplets).

A problem to address again is that of multiple scattering in hadronic matter formulated on the basis of data from nuclear targets. Dense hadronic matter may be composed mainly of meson resonances with an average number probably proportional to A . Thus all arguments should still hold even if the effective parton-parton collision energy is slightly larger in case of meson "targets" at given beam momentum.

On theoretical grounds, one expects stronger suppression for increasing rapidity density dn/dy . In scaling hydrodynamics dn/dy is a measure of the initial temperature T [18] which affects the value of the screening radius. Similar arguments hold for atomic number A , since $T \propto A^{1/6}$ [17]. On the other hand, transverse collective motion tends to increase the ratio $R_A^{QGP}(p/\pi^+)$ over the value 0.05 (fig. 2), which may be more pronounced at larger dn/dy [19]; it should not affect $R_A^{QGP}(p/\bar{p})$.

A further interesting feature to study is the dependence, e.g. of $R_A(p/\pi^+)$ on θ at fixed p_T . For decreasing values of θ the diquark spends less time in the QGP, hence the suppression should cease at some point beyond which the strong angular dependence known from pp collisions [13a] should be recovered.

Δ^{++} resonances at high p_T are believed to result from hard scattering of uu-diquarks in pp collisions [5a]. If these diquark systems were as tightly bound as ud-diquarks, all reasoning presented so far should also apply to Δ^{++} production. If uu-diquarks are basically unbound, as anticipated [6e,7], they may not even survive multiple scattering in NA collisions.

Finally, it should be mentioned that for deuteron production $R_{pW}(d/\bar{d}) \approx 60$ was measured at $p_T = 3\div 4$ GeV/c [14]. There is no detailed model for deuteron production in pp collisions so far; possibly, deuterons originate from recombination of high p_T nucleons [14,20] which may be due to simultaneous scattering of two diquarks. In this framework deuteron production should be even more sensitive to deconfinement than single nucleons. An experimental challenge is the fact that $R_{pW}(\bar{d}/\pi^-) \approx 10^{-4}$ for $p_T = 3\div 4$ GeV/c and $\sqrt{s} = 27$ GeV [14].

6. SUMMARY

Strong suppression of inclusive nucleon and lambda yields at $p_T = 3\div 5$ GeV/c and $\theta \approx 90^\circ$ is expected as a consequence of a deconfining phase transition in high energy nuclear collisions at SPS energies. The

suppression should be caused by the 'melting' in the QGP of correlated ud-diquarks, which are at the origin of high p_T protons in pp collisions. The actual level of suppression depends e.g., on the Debye screening radius (especially in baryon rich plasmas) relative to the radius of diquarks as well as on the space-time development of the QGP. The most effective suppression may be found for heavy nuclei and at beam momenta below a few hundred GeV/c/N. A suppression of this type is not likely to occur in dense hadronic matter. For more practical purposes one may add that i) one can, of course, trigger on high p_T nucleons and that ii) the events selected in this way are very useful for studying acoplanarities of jets [21]. A more detailed theoretical treatment of diquark properties, of multiple scattering in hadronic matter, and of QGP properties is needed.

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Figure 1

Figure 3