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Hadron production by ep collisions at HERA

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The $P_{\perp}$ distribution of hadrons from deep-inelastic ep collisions of the H1 experiment determines for the hadrons in the final state, a temperature 277 ± 14 MeV $\gg$ 220 MeV of the critical temperature predicted by QCD, suggesting the formation of quark-gluon plasma (QGP). From their forward to backward ratio, it is found an excess of hadrons arising from the deconfinement of quarks inside the proton.

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1. Introduction

The hadrons in the final state of deep-inelastic scattering experiment at HERA have been investigated by the H1 Collaboration [1]. They have found a striking forward to backward asymmetry, reflecting the difference in nature of the colliding electron and proton. whereas their $P_{\perp}$ and $x_F = 2P_{\parallel}/\sqrt{s}$ distributions agree in general with what expected from the quark model.

We note that the temperature deduced from their $P_{\perp}$ distribution amounts to 277 MeV. On the other hand, their x_F distribution follows well from that of the covariant Boltzmann factor, indicating that the Feynman-Yang scaling holds also in the case of deep inelastic ep scattering.

As the hadronic temperature at HERA experiments exceeds by far the critical temperature ~ 220 MeV predicted by QCD [2], which is also found experimentally using the π and K data of pp and $\bar{p}p$ collisions [3a], therefore quark-gluon plasma formation is expected to take place in these deep-inelastic scattering with production of strange matter [4]. We will investigate this situation using the measurements of the H1 Collaboration [1].

A comparison of the forward to backward ratio of their $dE_T/d\eta$ distribution with that computed for π 's from the fragmentation of the proton and the electron indicates an excess of π production by the proton, arising from the deconfinement of quarks inside the proton, due to an overheating of the hadronic matter to a temperature above the critical temperature by π 's from the electron fragmentation.

2. The forward to backward ratio of $ep \rightarrow$ hadrons at HERA

Consider first the pseudo-rapidity η distribution of the transverse energy E_T flow in the final state as is measured by the H1 Collaboration [1], reproduced in Fig. 1. The asymmetry of the forward (full circles) to backward

(open circles) ratio is very striking indeed. In order to estimate this ratio, we use the Gaussian distribution of the Landau model [5].

$$\frac{dE_T}{d\eta} = N \cdot e^{-(\eta - \eta^*)^2 / 2L} \quad (1)$$

where η^* is the peak-shift and L the width of the distribution. The parameters of least-squares fits to the forward and the backward data are listed in Table I. The fits are shown in Fig. 1.

We now use these fits to estimate the phase covered by the forward ($\eta > 0$) hadrons

$$\phi_{\eta > 0} = \int_0^{2.8} \left(\frac{dE_T}{d\eta} \right) d\eta \quad (2)$$

and likewise for the backward hadrons. The values thus obtained are listed in Table I. We find for the forward to backward ratio of the H1 experiment [1]:

$$F/B = 2.02 \pm 0.13.$$

Next, we consider the specific particle density in the central region, namely

$$h_{1/2} = \left(\frac{dE_T}{d\eta} \right)_{\eta=0} / \phi \quad (3)$$

the subscript 1/2 is to remind that, contrary to the case of hadrons from pp and e^+e^- collisions [3b]; here, the phase space we are dealing with ep collisions is limited only to one hemisphere. The values for the forward and the backward hadrons thus computed are listed in Table I.

It is interesting to compare these $h_{1/2}$ with those of pp and e^+e^- collisions [3b]. We recall that in these cases, $h = C \cdot E_{cm}^{-\alpha}$, with $\alpha = 0.31 \pm 0.05$, the coefficients are $C_{pp} = 1.37 \pm 0.07$ and $C_{ee} = 2.17 \pm 0.07$. For E_{cm} corresponding to the HERA energy, i. e. $\sqrt{s}/2 = 148$ GeV, we find $h_{pp} = 0.295 \pm 0.015$, so that

$$h_{1/2}(\eta < 0) \approx 2.h_{pp} \quad (4)$$

indicating that the hadrons in the $\eta < 0$ direction behave just like those from pp collisions.

As for the hadrons in the forward direction, we expect from e^+e^- : $h_{ee} = 0.461 \pm 0.015$ and find that

$$h_{1/2}(\eta > 0) \ll 2.h_{ee} \quad (5)$$

indicating more hadrons produced than normally produced in the e^+e^- collision. We will discuss this excess of hadrons in Sec. 4.

3. The $P_\perp$ and the x_F distributions

We now analyze the $P_\perp$ and the $x_F = 2P_\parallel / \sqrt{s}$ distributions of the hadrons in the final state of the deep-inelastic ep scattering of the H1 experiment [1] in terms of the covariant Boltzmann factor:

$$f \sim e^{-(E - \beta^* P_\parallel)/T} \quad (6)$$

where E and $P_\parallel$ are the total energy and the longitudinal momentum of a secondary in the cms of ep collision. The two parameters are the temperature T and the velocity β^* of the rest-frame of the secondaries in one hemisphere with respect to the cms of collision.

The $P_\perp$ distribution according to (6) is

$$\frac{dn}{dP_\perp^2} \sim \sqrt{m_\perp} \cdot e^{-m_\perp/T} \quad (7)$$

where $m_\perp = \sqrt{P_\perp^2 + m^2}$. In Fig. 2 we have plotted $(1/\sqrt{m_\perp})(dn/dP_\perp^2)$ of the H1 measurements against $m_\perp$, assuming $m = m_\pi$. The dotted line represents the least-squares fit with (7), leaving aside the end point at $m_\perp = 4$. We find

$$T = 0.277 \pm 0.014 \text{ GeV}. \quad (8)$$

which exceeds by far the critical temperature $\sim 220 \text{ MeV}$ predicted by QCD.

Next, consider the x_F distribution of the H1 experiment. Their data are reproduced in Fig. 3. According to (6), we expect

$$\frac{dn}{dx_F} \sim e^{-ax_F} \quad (9)$$

with

$$a = \frac{(1 - \beta^*) \sqrt{s}}{2T} \quad (10)$$

The fit is shown by the solid line with

$$a = 10.18 \pm 2.55. \quad (11)$$

Noting that here, $\sqrt{s}$ is equal to one half of the E_{cm} of the HERA energy, i.e. 148 GeV, we find

$$\beta^* = 0.962 \pm 0.004. \quad (12)$$

We now compare this velocity of the rest-frame of secondaries with that expected from the scaling of $p + p \rightarrow m + \dots$ at the same $\sqrt{s} = 148$ GeV, namely $\beta^* = 1 - 2/\gamma_{cm}$, $\gamma_{cm} = \sqrt{s}/2m_p$ being the Lorentz contraction factor of the pp collision [3c]; we get $\beta^* = 0.975$, indicating that the scaling property holds for hadrons production in the HERA experiments.

4. The hadron multiplicity

The kinematic properties of hadrons from the H1 experiment enable us to estimate the multiplicities of various secondaries produced by ep collisions at HERA, leaving aside the possible formation of quark-gluon plasma to be discussed later on.

We assume the limiting fragmentation and write the multiplicity for ep collision as follows:

$$n_{ep} = n_e + n_p \quad (13)$$

where n_e and n_p denote the multiplicities corresponding to e^+e^- and pp collisions at $\sqrt{s} = 296/2 = 148$ GeV.

As regards the proton fragmentation, we recall that the process proceeds like bremsstrahlung [3c], namely

$$n_p(m\bar{m}) = 2\alpha_o \left(\frac{m\pi}{m}\right)^2 \left[\sqrt{s}/\gamma^* - 2m_p - \Delta m\right] \quad (14)$$

where γ^* is the Lorentz contraction factor of the rest-frame of secondaries of mass m and $\Delta m = 2m$ the threshold energy for particle-antiparticle pair production. We know β^* from the scaling, i.e. the x_F distribution of the H1 experiment [Sec. 2]: so that $\gamma^* = 4.500$ and from the pp and $\bar{p}p$ data the coefficient

$$2\alpha_o = 0.51 \pm 0.04.$$

As for the hadrons from the electron fragmentation, we recall that in view of thermal equilibrium, characteristic of $e^+e^- \rightarrow m\bar{m} + \dots$ reported before [3b]. We express n_e in terms of a semi-empirical formula derived from the Boltzmann factor (1), namely

$$n_e(m\bar{m}) = \frac{C}{(1+\delta)(2I+1)(2J+1)} T^3 \left(\frac{m}{T}\right)^2 K_2\left(\frac{m}{T}\right) u^i s^j \quad (15)$$

where I and J are the statistical weights and δ is the Kronecker symbol:

$\delta = 0$ for particle-antiparticle pair production,

1 for self charge conjugate particles such as $\phi(s\bar{s})$ and $K\bar{K}$ production.

T is the temperature, $K_2(x)$ is the modified Bessel function of the second kind and u and s are the fugacities of light u and s quarks, whereas i and j are the quark contents of the secondary under consideration.

We use a previous analysis of $Z^0 \rightarrow h\bar{h}$ [3b] to determine the constants needed for the HERA experiment at $T = 0.277$ GeV, namely,

$$CT^3 = 73.07 \pm 2.2, \quad u \approx 0.74 \quad \text{and} \quad s \approx 0.20.$$

These formulae (14) and (15) are used to estimate the production of π , K , ϕ and $\bar{\Lambda}$. The results are summarized in Table II.

We note that for π 's, the ratio $n_e/n_p = 3.13 \pm 0.26$ is much larger than the forward to backward ratio $F/B = 2.02 \pm 0.13$ of the H1 experiment [1] as mentioned above. This suggests that more π 's are actually produced by the proton fragmentation in the deep inelastic scattering experiment at HERA, an excess which may arise from the deconfinement of quarks inside the collided proton, deconfinement due to very high temperature in the final state, 277 MeV, far above the critical temperature ~ 220 MeV.

However, on the other hand, we find the K/π ratio $\sim 11\%$ is about the same as in the general case of pp , $\bar{p}p$ and e^+e^- collisions. Thus the K/π ratio may serve as a criteria to test further if there is formation of quark-gluon plasma in the HERA experiments, although the signal is rather small. In this regard, we note that the F/B ratio of $\phi(ss)$, which, without QGP, is ~ 1.13 [see Table II], drops to ~ 0.74 if strange quarks are produced in the same proportion as u/d quarks by the deconfinement of the quarks inside the proton, and it drops still more if strange matter is also produced

5. Remarks

In an analysis of the $P_\perp$, x_F and η distributions of hadrons in the final state from ep collisions at HERA by the H1 Collaboration [1], we find the temperature of hadrons to be 277 ± 14 MeV, much higher than ~ 220 MeV of the critical temperature predicted by QCD [2], indicating that quark-gluon plasma may be formed during the deep inelastic ep scattering at HERA.

However, at HERA energy, the difference between the initial temperatures of π 's from the fragmentation of the electron and the proton is

very large, $\sim 174 \text{ MeV} \gtrsim m_\pi$. As the number of π 's from the electron is ~ 3 times larger [see Table II] than that of the proton, the radius of the fireball of π 's from the electron is $\sim 3^{1/3} \approx 1.44$ times larger, so that it envelopes for thermalization not only the π 's of the proton, but also the proton itself and proceeds to reach thermal equilibrium in the final state. Thus the temperature of the proton and its π 's is raised from $\sim 159 \text{ MeV}$ [6] to that of hadrons in the final state, namely $\sim 277 \text{ MeV}$. This temperature, which exceeds by far the critical temperature $\sim 220 \text{ MeV}$, allows the deconfinement of quarks inside the proton and consequently the formation of quark-gluon plasma.

The forward to backward ratio 2.02 ± 0.13 measured by the H1 experiment [1] is significantly less than 3.13 ± 0.26 computed according to the semi-empirical formulae for π production by the fragmentation of the proton and the electron, corresponding to the HERA energy [Table II]. This suggests that an additional $\sim 56 \%$ π 's which are unaccounted for by (14) and which are actually produced by quark-gluon plasma.

It would be very interesting to investigate the strange particle production to detect if strange matter has actually been produced also [4], when more HERA data will become available.

Needles to say, en passant, that such a high hadron temperature above the critical temperature can not be reached by the present $\bar{p}p$ colliders and that HERA open up a new chapter for experimental investigation of this problem of quark-gluon plasma, which is of fundamental importance not only for the particle physics, but also for the cosmology.

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Table I - Parameters of Gaussian fits to the pseudo-rapidity η distributions $dE_T/d\eta$ in the forward and the backward directions of the H1 Collaboration [1]

	Backward ($\eta < 0$)	Forward ($\eta > 0$)
η^*	-0.41 ± 0.06	2.65 ± 1.39
L	0.74 ± 0.10	12.59 ± 13.95
N(GeV)	2.32 ± 0.07	2.48 ± 0.14
$\int \frac{dE_T}{d\eta} d\eta$	3.51 ± 0.11	6.59 ± 0.40
$h_{1/2}$	0.59 ± 0.02	0.30 ± 0.02

Table - II Estimates of multiplicities of π , K, ϕ and $\bar{\Lambda}$ from the fragmentations of the electron and the proton in the deep-inelastic ep scattering at HERA, in terms of the semi-empirical formulae, Eqs. (14) and (15)

	n_e	n_p	Total
$\pi^+\pi^-$	25.5 ± 0.8	8.05 ± 0.62	33.3 ± 1.0
$K\bar{K}$	3.06 ± 0.09	0.62 ± 0.05	3.68 ± 0.10
ϕ	0.17 ± 0.01	0.15 ± 0.02	0.32 ± 0.02
$\Lambda\bar{\Lambda}$	0.73 ± 0.02	0.19 ± 0.01	0.92 ± 0.02

Figure Captions

1. Pseudo rapidity distributions of E_T measured by the H1 Collaboration [1]. The curves are Gaussian fits using the Landau model. The parameters are in Table I.
2. The $P_\perp$ distribution of hadrons in the final state of the deep inelastic scattering measured by the H1 Collaboration [1]. The dotted line represents the fit with Eq. (7). The Boltzmann temperature of hadrons is 0.277 ± 0.014 GeV.
3. The x_F distribution of hadrons in the final state of the deep inelastic scattering measured by the H1 Collaboration [1]. The line shows the fit according to the covariant Boltzmann factor Eq. (9). The velocity of the rest-frame of secondaries with respect to the cms is $\beta^* = 0.962 \pm 0.004$ consistent with 0.975 expected from the the scaling.

Fig. 1

Fig. 2

Fig. 3