Critical temperature effect in K^0 production by ep collision at DESY HERA

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(Received 6 November 1995)

An analysis of a DESY HERA experiment $ep \to K^0$ with large rapidity gap indicates that the large forward-backward ratio $F/B \approx 15.0$ is due to the recoil proton to balance the c.m.s. momentum, that the particle densities at the peak of the forward and backward $dn/d\eta$ distributions are about the same as those of e^+e^- and $pp \to K^0$ at $\sqrt{s} \approx 29$ GeV, and that the suppression of K^0 at HERA, compared to the e^+e^- data, is a critical temperature effect on the specific heat: $T_K \gg T_c \approx 0.220$ GeV for ep and $e^+e^- \to K^0$, respectively; so that fewer but more energetic K^0 mesons are produced at HERA, although the available energy for K^0 production is about the same in both cases. [S0556-2821(96)02411-3]

PACS number(s): 13.85.Rm

I. INTRODUCTION

The strange particle production at high temperature is of great interest, especially from the point of view of the quark-gluon plasma, as an enhancement of strange matter production is expected when the temperature exceeds some critical point [1]. Recently, in a nondiffractive inelastic scattering with large rapidity gap for $e+p \to K^0 + \cdots$ at HERA, the Zeus Collaboration has observed a suppression of K^0 production compared to the e^+e^- data [2(a)].

The pseudorapidity η distribution of K^0, as is measured by the Zeus Collaboration for large rapidity gap events, Fig. 1, shows two outstanding and disparate peaks separated by a deep valley near the c.m.s. of collision, reflecting the behavior of limiting fragmentation [3(a)]. The forward to backward asymmetry is extremely large ~ 15.0, characteristic of the fragmentation of a virtual photon hitting a proton [2(b)].

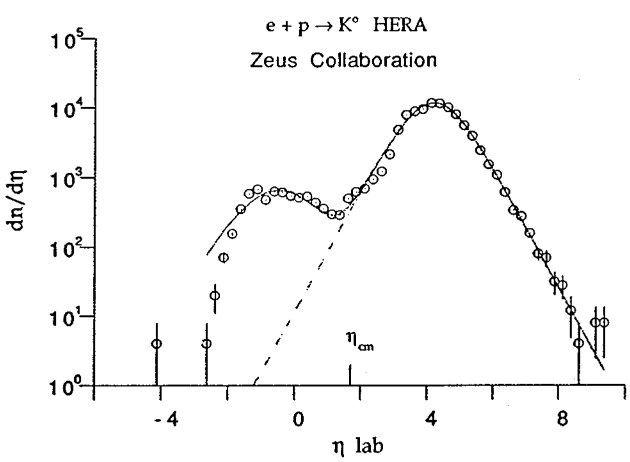

FIG. 1. The lab pseudorapidity distribution of K^0 with large rapidity gap $\eta_{\max} < 1.5$ from the deep-inelastic ep scattering at HERA, data from the Zeus Collaboration [2(a)]. The c.m.s. of collision is indicated by a vertical bar at $\eta_{\text{c.m.}} = 1.712$. The solid curve represents an overall fit to the forward (F) and the backward (B) parts of the η distribution according to the partition temperature model Eq. (1). The parameters are listed in Table I. The dotted line represents a separate fit to the F distribution $\eta > \eta_{\text{c.m.}}$, for the subtraction of the background in the B distribution, due to the overlapping with the F distribution. Parameters are in Table I.

The average transverse momentum of K^0 is ~ 0.971 GeV/c leading to a temperature $T_K \approx 0.369$ GeV$\gg T_c \approx 0.220$ GeV of the critical temperature for π^- and K^0 production by inclusive pp and $\overline{pp}$ collisions [4(a)]. The question arises: What is the cause of the suppression of K^0 production at very high temperature observed at HERA?

An attempt is made to understand these peculiar features of K^0 production with $T_K > T_c$ observed for the first time at HERA, in the context of critical phenomena, using the partition temperature model of Chou, Yang, and Yen [5] to analyze the properties of the η distribution (Sec. II). We will see that the large forward/backward F/B ratio of K^0 is mainly due to the recoil proton to balance the momenta of particles in the c.m.s. of ep collision (Sec. III) and that the specific particle density in the restframe of secondary K^0 mesons is the same as those of K^0 production by e^+e^- annihilation and pp collision at $\sqrt{s} \approx 29$ GeV, respectively (Sec. IV). It is found that the suppression factor of K^0 observed by the Zeus experiment [2] may be attributed to a critical temperature effect on the specific heat, which is smaller in the HERA experiment, as $T_K \gg T_c$, than that of e^+e^- annihilation at $\sqrt{s} \approx 29$ GeV, its temperature being 0.197 GeV$< T_c$ (Sec. V). Therefore, fewer but much hotter, i.e., more energetic K^0 mesons are produced in the HERA experiment compared to the e^+e^- data, notwithstanding the fact that the total energy of K^0 in the c.m.s. of collision is about the same in both cases.

II. THE PSEUDORAPIDITY DISTRIBUTION

Consider the pseudorapidity η distribution of $e+p \to K^0 + \cdots$ at HERA, measured in the lab system for large rapidity gap events by the Zeus Collaboration [2(a)], as reproduced in Fig. 1, the c.m.s. of the two colliding beams with $E_e = 26.7$ GeV and $E_p = 820$ GeV being at $\eta_{\text{c.m.}} = (1/2)\ln(E_p/E_e) = 1.712$, as is indicated by a vertical bar in the figure. We fit the forward (F) and the backward (B) data using the partition temperature model [5], generalized to account for the peak shift

$$\frac{dn}{d\eta} = \frac{A}{[\alpha + (1/T_p)\cosh(\eta - \eta^*)]^2}, \tag{1}$$

where η^* is the peak-shift parameter, T_p is the partition temperature, α is a known parameter corresponding to an exponential cutoff on the transverse momentum: $\alpha=2/\langle P_\perp\rangle$ and A is a normalization coefficient. Note that the fit determines αT_p, namely the width of the distribution, rather than T_p independently and that from the $P_\perp$ distribution of K^0, see Fig. 3, we get

$$\langle P_\perp\rangle=0.971\pm0.050\ \text{GeV}/c,$$

$$\alpha=2.060\pm0.106\ (\text{GeV}/c)^{-1}. \qquad (2)$$

indicating a very large momentum transfer in the K^0 production by ep at HERA, so that we are actually dealing with a hard process.

We have tried an overall fit to the η distribution in Fig. 1 by superposing the F and the B distributions corresponding to $\eta\gtrless\eta_{\text{c.m.}}=1.712$, respectively, according to (1), while leaving aside the end point at $\eta=-4.325$. The result is shown by the solid curve in the figure.

The parameters are listed in Table I. A comparison of the fit with the data indicates that the fit is rather good, especially for the F distribution. But in the case of the B distribution, the errors are rather large, mostly due to the background arising from the overlapping with the F distribution.

As a check of the parameters thus estimated, other trials are made to fit individually the F and the B distributions. First, consider the F data alone, we find exactly the same parameters as before, only the errors are slightly larger, see Table I. The fit is shown by the dotted line in Fig. 1. Next, we extrapolate this fit to the region $\eta<\eta_{\text{c.m.}}$ in order to subtract the background inherent in the B distribution and refit the corrected data with (1). The parameters thus obtained are listed in Table I. They are consistent with those of the overall fit, but the errors are more realistic, which will be used later for computations.

Finally, we note that if we fit the uncorrected data of the B direction, we get $\eta^*=-0.338\pm0.095$, whereas $\alpha T_p=1.488\pm0.592$ is much larger than the value of the overall fit, indicating that the width of the raw data is considerably broadened by overlapping from the F distribution as shown by the dotted line in the figure.

TABLE I. Parameters of the partition temperature model fits to the lab pseudorapidity distributions in the lab system for $e+p\to K^0$ for large rapidity gap events at HERA by the Zeus Collaboration, $\alpha=2/\langle P_\perp\rangle=2.060$ and $\eta_{\text{c.m.}}=1.712$. ρ^* is the specific particle density, Eq. (13).

	Forward $\eta>\eta_{\text{c.m.}}$	Backward $\eta<\eta_{\text{c.m.}}$
Overall η^*	4.204 ± 0.014	-0.486 ± 0.290
αT_p	0.050 ± 0.058	0.755 ± 1.350
$T_p^2A\times10^{-3}$	12.91 ± 1.05	1.99 ± 2.70
Separate η^*	4.203 ± 0.017	-0.467 ± 0.085
αT_p	0.053 ± 0.058	0.888 ± 0.407
$T_p^2A\times10^{-3}$	12.98 ± 1.27	2.27 ± 1.88
ρ^*	2.43 ± 0.06	2.04 ± 0.01

III. THE FORWARD-BACKWARD ASYMMETRY

From these considerations, we may use the overall fit to estimate the F-B asymmetry of the K^0 meson production. We find

$$\frac{F}{B}=\frac{23\,915\pm155}{1598\pm40}=14.97\pm0.39. \qquad (3)$$

The striking asymmetry manifests also in the ratio of partition temperatures of the F and B distributions. Indeed, from the estimates of αT_p in Table I, we find it, as $\alpha=2/\langle P_\perp\rangle$ is the same for both the F and the B directions, about 15.1, so that if n denotes the average multiplicity, we may write

$$(nT_p)_F\approx(nT_p)_B \qquad (4)$$

as expected from the principle of energy equipartition of the model.

From the average multiplicity of K^0 reported by the Zeus Collaboration [2(a)], namely, $n_K=0.289\pm0.021$, we deduce

$$n_F=0.27\pm0.02,\quad n_B=0.02\pm0.01. \qquad (5)$$

We will see that this large asymmetry reflects a kinematic effect, due to the recoil proton to balance the total momentum in the c.m.s. of collision.

Indeed, the average energy of a K^0 meson in the restframe of secondaries, specified by an asterisk, is

$$E_K^*=3T_K+m_KK_1(m_K/T_K)/K_2(m_K/T_K), \qquad (6)$$

where K_n is the modified Bessel function of the second kind of order n. From $\langle P_\perp\rangle$ of K^0, (2), we deduce the Boltzmann temperature

$$T_K=0.369\pm0.025\ \text{GeV}, \qquad (7)$$

leading to

$$E_K^*=1.330\pm0.048\ \text{GeV}. \qquad (8)$$

We now pass to the c.m.s. of ep collision. Recalling that the velocity β^* of the restframe of secondaries is determined by $\tanh(\eta^*-\eta_{\text{c.m.}})$, where η^* is the shift parameter and $\eta_{\text{c.m.}}=1.712$ with respect to the lab system, we get for the Lorentz factor for the F direction

$$\beta_F^*=0.986\pm0.001,\quad \gamma_F^*=5.997\pm0.225. \qquad (9a)$$

As $\beta_F^*\gamma_F^*\gg P_K^*/m_K$, the K^0 mesons are collimated in a narrow cone. The total momentum of F K^0 in the c.m.s. is

$$P_F\approx E_F\approx\gamma_F^*(1+\beta_F^*)2n_FE_F^*=8.55\pm0.78\ \text{GeV}, \qquad (10a)$$

where the factor 2 is to account for the pair production of $K^0\overline{K^0}$ as is required by the strangeness conservation.

Likewise, for the backward direction, dropping the minus sign for simplicity,

$$\beta_B^*=0.976\pm0.003,\quad \gamma_B^*=4.592\pm0.313. \qquad (9b)$$

As the average transverse momentum of the recoil proton, on average, amounts to zero, therefore $E_p^*=m_p$, and

$$P_B \approx E_B \approx \gamma_B^*(1+\beta_B^*)(2n_B E_B^* + m_p) = 8.99 \pm 0.67 \text{ GeV}. \tag{10b}$$

We find

$$P_F \approx P_B \tag{11}$$

within about half a standard deviation.

We note that the velocity β_B^* (9b) is consistent with that of the inclusive $p+p \rightarrow \pi^-$ at the same $\sqrt{s}=296$ GeV, namely, according to the scaling [4(d)]

$$\beta^* = 1 - \frac{4m_p}{\sqrt{s}} = 0.987. \tag{12}$$

The agreement is within about one standard deviation. This confirms that the limiting fragmentation [6] holds in the deep-inelastic ep scattering experiment at HERA, as has already been observed in the SLAC experiments by the SLAC-MIT Collaboration at a lower energy [7].

Finally, we note that from a similar distribution with large rapidity gap events for clusters, which are mostly pions, by another experiment of the Zeus Collaboration [2(c)], we find $F/B = 13.3 \pm 1.9$, almost the same as the K^0.

IV. THE INVARIANCE PROPERTY OF THE SPECIFIC PARTICLE DENSITY

The disparity shown by the F and the B η distributions of the K^0 mesons emitted by the electron and the proton in the ep collision at HERA, Fig. 1, is very striking, and yet they have this property in common, namely, their specific particle density measured in the restframe, i.e., at the peak η^*,

$$\rho^* = (dn/d\eta)_{\eta^*} \bigg/ \int (dn/d\eta) d\eta, \tag{13}$$

depends only on the energy. The values ρ^* for the F and the B η distributions in Fig. 1, according to the fits (1) are listed in Table I. They are practically equal, as should, in view of the invariant property of ρ^*, namely, it depends only on the c.m.s. energy of the collision.

We now proceed to investigate this important property using currently available data of π^- and K^0 production by pp and $\overline{p}p$ collisions [8] as well as by e^+e^- annihilations [9]. Consider first the case of π production, we present in Fig. 2(a) the log plot of $1/\rho^*$ vs $\sqrt{s}$, solid circles for e^+e^- and open circles for pp and $\overline{p}p$. The straight line represents a fit for

$$\frac{1}{\rho^*} = cs^{\alpha/2} \tag{14}$$

with

$$\alpha = 0.21 \pm 0.01, \quad c = 1.11 \pm 0.06. \tag{15}$$

Next, as for the K^0 production, in order to avoid systematic errors, we consider rather the ratio of $\rho^*{}_\pi$ to $\rho^*{}_K$ of the same experiment vs $\sqrt{s}$ as shown in Fig. 2(b). If we assume a power law like (14), we get $\alpha' = -0.0002 \pm 0.025$, consistent with zero, indicating that the energy dependence of $\rho^*{}_K$ is the same as $\rho^*{}_\pi$. The average of the ratio is shown by the straight line

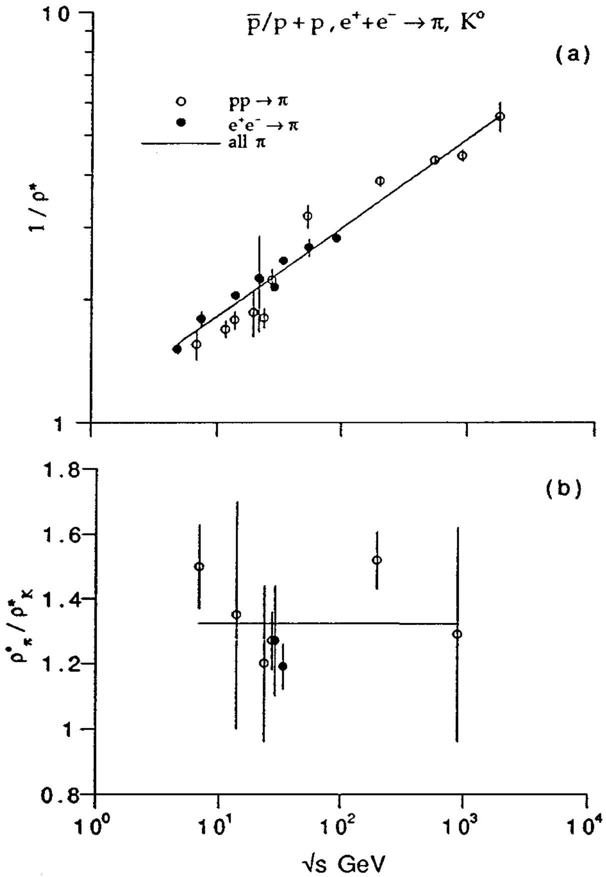

FIG. 2. (a) The energy dependence of the specific particle density $\rho^* = (dn/d\eta)\eta^*/\int(dn/d\eta)d\eta$ in the restframe of secondary pions from pp and $\overline{pp}$ collisions (open circles) and e^+e^- annihilations (solid circles). The solid curve is a least-squares fit: $1/\rho^* = c.s^{\alpha/2}(\sqrt{s}$ in GeV), with $\alpha = 0.21 \pm 0.01$ and $c = 1.11 \pm 0.06$. (b) The plot of $\rho^*{}_\pi/\rho^*{}_K$ against $\sqrt{s}$ (GeV) for pp and $\overline{pp}$ collisions (open triangles) and e^+e^- annihilations (solid triangles). A power-law dependence $s^{\alpha'/2}$ yields $\alpha' = -0.0002 \pm 0.0025$ consistent with zero, the horizontal line represents the average value of the ratios; $1.32 \pm 0.13 \approx 4/3$, ratio of statistical weights of isotopic spins of K and π.

$$\rho^*{}_\pi/\rho^*{}_K = 1.32 \pm 0.13 \approx 4/3, \tag{16}$$

comparable to the statistical weights of their isotropic spins, indicating that the specific particle density of π and K are related by

$$\frac{\rho^*{}_\pi}{\rho^*{}_K} = \frac{2(2I_K+1)}{2I_\pi+1}, \tag{17}$$

so that ρ^* is independent of the nature of secondaries.

In view of this invariant property, we may take the average of the estimates of $1/\rho^*$ in Table I for the $e+p \rightarrow K^0$ at HERA and find

$$1/\rho_K^* = 2.24 \pm 0.20. \tag{18}$$

Here also, this ratio is comparable to that of the cluster data with large rapidity gap [2(c)], namely $1/\rho^*_{\pi} = 2.26 \pm 0.11$.

We now use the value (18) to estimate the energy $\sqrt{s}$ of the collision between the virtual photon and the proton. We find by (16) and (13)

$$E_{\gamma^* p} \approx 31.4 \text{ GeV}. \tag{19a}$$

We note that this estimate is quite reasonable. Indeed, if we assume the energy spectrum of the virtual photon in the deep-inelastic ep scattering to behave like dk/k, we find for the HERA experiment

$$E_{\gamma^* p} = \frac{\sqrt{s}/2 - 2m_K}{\ln(\sqrt{s}/4m_K)} = 29.4 \text{ GeV}, \tag{19b}$$

in agreement with the previous estimate.

In the preceding section, we have estimated the total energy of $K^0\overline{K^0}$ in the c.m.s. amounting to 17.55 ± 1.01 GeV. Therefore the inelasticity of the HERA experiment $e+p \rightarrow K^0$ is $\sim 59 \pm 5\,\%$, comparable to that of meson production by hadron-proton collisions in general.

The K^0 multiplicity of e^+e^- at $\sqrt{s} = 29$ GeV is 1.36 ± 0.15 according to the SLAC experiments by TPC, Mark II, and HRS Collaborations [9]. Therefore for the HERA experiment, there is a suppression amounting to

$$\frac{(n_F)_{ep}}{n_{ee}/2} = 0.40 \pm 0.06. \tag{20}$$

We will discuss this point in the next section.

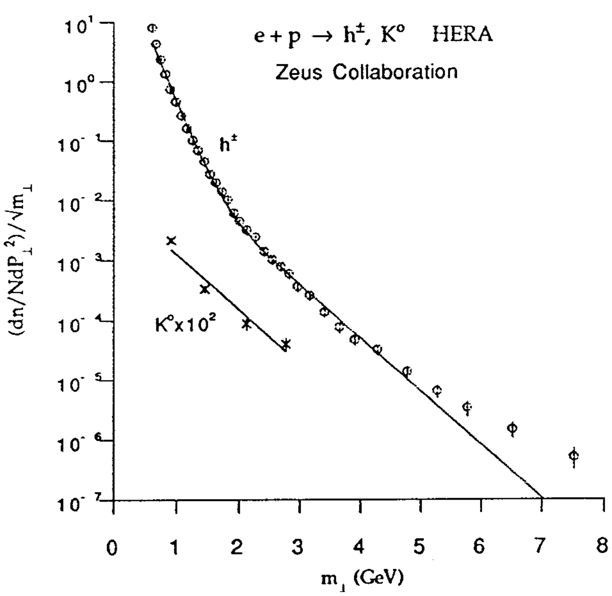

FIG. 3. Plots of the transverse momentum distributions of $e+p \rightarrow K^0$ and $h^{\pm}$ against $m_{\perp} = \sqrt{P_{\perp}^2 + m^2}$, HERA experiment by the Zeus Collaboration [2]. (1) K^0 mesons (crosses), the solid line represents the average of $P_{\perp}$. (2) Charged secondaries of nondiffractive photoproduction at $\langle W \rangle = 180$ GeV (open circles), the curve is a fit using the two-temperature model, Eq. (21), see text.

V. THE CRITICAL TEMPERATURE EFFECT ON $ep \rightarrow K^0$ AT HERA

The suppression of K^0 production by the deep-inelastic scattering at HERA indicates that we are not dealing with a soft process like the π production. Here, the average transverse momentum of K^0 is ~ 0.971 GeV/c (2), much higher than that of charged particles, i.e., pions, from the nondiffractive process at $\langle W \rangle = 180$ GeV measured by the Zeus Collaboration [2(b)], as shown in Fig. 3, together with the case of K^0 mentioned before. From the semilog plots of $(dn/NdP_{\perp}^2)/\sqrt{m_{\perp}}$ vs $m_{\perp}$, Fig. 3, we see that their slopes, i.e., $1/T$, are quite different, so that they are produced by different processes.

As the π data cover a wide range of large $P_{\perp}$, we fit with a two-temperature model:

$$\frac{dn}{NdP_{\perp}{}^2} = A\sqrt{m_{\perp}}e^{-m_{\perp}/T} + A'\sqrt{m_{\perp}}e^{-m_{\perp}/T'}, \tag{21}$$

where $m_{\perp} = \sqrt{P_{\perp}^2 + m^2}$ and $T < T'$. A least-squares fit is shown by the solid curve in the figure. The parameters (T in GeV) are

$$T = 0.167 \pm 0.005, \quad A = 177.5 \pm 34.7$$

for the first term and for the second term

$$T' = 0.489 \pm 0.016, \quad A' = 0.182 \pm 0.041. \tag{22}$$

As the contribution of the second term is rather small $\lesssim 2\%$, we may take the temperature of π production at HERA by limiting to $P_{\perp} \leqslant 1.5$ GeV/c. We thus find

$$T_{\pi} = 0.197 \pm 0.005 \text{ GeV} \tag{23}$$

in good agreement with the equilibrium temperature 0.196 ± 0.007 GeV of $e^+ + e^- \rightarrow \pi$, K^0, and other hadrons of the SLAC experiment at $\sqrt{s} = 29$ GeV [4(b)], the velocity of the restframe of secondaries in the latter case being $\beta^* = 0.850 \pm 0.020$, as reported elsewhere [4(a),4(b)]. We find the energy of forward K^0 in the c.m.s. $E_K = 3.95 \pm 0.59$ GeV. Comparing to the HERA data, (10a), we find

$$\frac{E_K(FDee)}{E_K(FD\gamma^* p)} = 0.46 \pm 0.08 \tag{24}$$

comparable to the suppression factor (20), indicating that the total energy of forward K^0 mesons in the c.m.s. of collision is inversely proportional to the multiplicity. Therefore we find about the same available energy for K^0 production in both HERA and SLAC experiments.

Consider next the Λ temperature of the HERA experiment. From the $P_{\perp}$ distribution measured by the Zeus Collaboration [2(a)], we deduce $\langle P_{\perp} \rangle_{\Lambda} = 0.747 \pm 0.127$ GeV/c, leading to

$$T_{\Lambda} = 0.210 \pm 0.055 \text{ GeV}. \tag{25}$$

We therefore find T_{Λ} slightly higher than T_{π}, a well-known property for hadron production by pp and $\overline{p}p$ collisions, namely $T_m \approx T_{\pi} + (m - m_{\pi})\Delta T/\Delta m$ with $\Delta T/\Delta m \approx 0.032$. However, here, for the HERA experiment,

$T_K \gg T_\Lambda$, this is rather unexpected. It indicates that in the deep-inelastic scattering at HERA, the K^0 mesons are not in the same phase as the π's and the Λ's, because its temperature is above T_c.

Indeed, we recall that the specific heats C of π and K^0 from pp and $\overline{p}p$ collisions follows approximately a Curie-Weiss-type law, with $C_\pi \approx 2C_K$, the critical temperature being $T_c \approx 0.220$ GeV. Therefore for the HERA experiment, we get

$$T_\pi < T_\Lambda < T_c, \quad T_K \gg T_c. \tag{26}$$

As the rate $\Delta C/\Delta T$ changes sign across the critical point, therefore the specific heat of K^0 in the HERA experiment is deemed to be less than that in the case of e^+e^- production at the same c.m.s. energy, as its temperature is below T_c. It follows that in the HERA experiment, the available energy is used to produce fewer, but much hotter, i.e., more energetic, K^0 mesons. Consequently, a suppression instead of an enhancement of the number of K^0 mesons is observed, in spite of the fact that the temperature is actually very high, well above T_c.

VI. CONCLUDING REMARKS

We have analyzed the hard process of K^0 production by ep scattering at HERA of the Zeus Collaboration [2(a)] and found that the salient features of the η distribution of large rapidity gap events and the K^0 suppression can be understood in terms of statistical physics.

The very large forward to backward asymmetry, $\sim$14.9, is due to the recoil proton to balance the total c.m.s. momentum in the final state, a kinematic property characteristic of large rapidity gap events. The invariance property of the specific particle density, (13), holds for large rapidity gap events.

The K^0 production is distinguished from π and Λ production by its large average transverse momentum, $\sim$0.971 GeV/c much higher than those of π and Λ, indicating that $e+p \to K^0$ at HERA proceeds via a hard process.

The K^0 temperature, quite different from those of π and Λ: $T_K \approx 0.369$ GeV, is well above the critical temperature $T_c \approx 0.220$ GeV, compared to 0.196 GeV and 0.210 GeV for π and Λ production, respectively, which are below T_c. As this temperature of K^0 at HERA is about twice higher than the equilibrium temperature 0.197 ± 0.007 GeV for $e^+e^- \to K^0$ at about the same energy, namely $\sqrt{s} \approx 29$ GeV, and the specific heat of K^0 at HERA is smaller [10], therefore fewer but hotter K^0 mesons are produced. Therefore a suppression is found by comparing their multiplicities. However, the available energy for the forward K^0 production is the same in both ep and e^+e^- cases.

Finally, it is to be noted that this property of producing fewer and more energetic particles when $T > T_c$, as has been observed in the HERA experiment of $ep \to K^0$, [2] is quite general. It is a consequence of energy conservation in the c.m.s. of collision, reflecting an effect of the critical temperature on the specific heat of secondaries. Further investigation with other particles associated with K^0 production will shed more insight into the property of phase transition, especially quark-gluon plasma. In this regard, it is interesting to know whether the specific heat above the critical temperature follows also a Curie-Weiss law, just like the paramagnetism [10]. If in the affirmative, then the ratio of specific heats for the forward K^0 production of HERA and SLAC experiments may be simply related without free parameters as follows: $C_K(ep)/C_K(e^+e^-) = [T_c - T_K(e^+e^-)]/2[T_K(ep) - T_c]$. Thus, assuming this ratio to be the same as the suppression factor for K^0 given by (20), we get $T_c \approx 0.273 \pm 0.032$ GeV according to the T_K values of HERA and SLAC, comparable to $\sim$0.220 GeV estimated from $\overline{p}/p + p \to \pi^-$, K^0 collisions [4(a)], within about one and a half standard deviations.

ACKNOWLEDGMENTS

The author wishes to thank G. Gidal and I. Hinchliffe for discussions, H. J. Crawford for the hospitality at LBNL, and the Tsi Jung Fund for the support.

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Nucl. Phys. **B129**, 365 (1977); 27.4 GeV, NA27 Collaboration, M. Anguilar-Benitez *et al.*, Z. Phys. C **40**, 321 (1988); 23.8 GeV, V. V. Ammosov *et al.*, Nucl. Phys. **B115**, 269 (1988); 21.7 GeV, B. Y. Oh *et al.*, Nucl. Phys. **B116**, 13 (1976); 21.7 GeV, NA22 Collaboration, M. Adamus *et al.*, Z. Phys. C **39**, 301 (1988); I. V. Ajimento *et al.*, *ibid.* **46**, 525 (1990); 19.4 GeV, K. Jaeger *et al.*, Phys. Rev. D **11**, 2405 (1975); T. Kafka *et al.*, *ibid.* **16**, 1261 (1977); 16.7 GeV, D. Brick *et al.*, Nucl. Phys. **B164**, 1 (1980); J. W. Champman *et al.*, Phys. Lett. **47B**, 465 (1973); 13.90 GeV, A. K. Naudi *et al.*, Nucl. Phys. **B169**, 20 (1980); C. M. Bromberg *et al.*, Phys. Rev. D **9**, 1864 (1974); 11.9 GeV, V. V. Ammosov *et al.*, Nucl. Phys. **B115**, 269 (1976); Nuovo Cimento A **40**, 237 (1977); 6.8 GeV, V. Blobel *et al.*, Nucl. Phys. B **69**, 454 (1976); **B147**, 317 (1979).

[10] See, e.g., L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon Press, Oxford, 1960), p. 146.