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FRAGMENTATION OF HADRONS FROM HEAVY QUARK PARTONS

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A B S T R A C T

A model is presented to describe hadron fragmentation off light and heavy partons. Fragmentation functions are parametrized by one variable. When a heavy parton of a new flavour fragments, a heavy hadron tends to carry away most of the parton momentum, leaving light hadron (π and K) spectra softer than those from light partons.

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Dimuon production by neutrinos has aroused much interest in the dynamical mechanism for fragmentation of hadrons from a heavy quark carrying a new flavour. A wide variety of fragmentation functions have been suggested to fit the dimuon data ¹⁾⁻⁸⁾. In this paper, we construct a dynamical model of fragmentation on the basis of our current knowledge of hadron physics and propose a unified form of fragmentation functions which involves one parameter aside from a quark mass.

To discuss fragmentation functions, we work in the parton model with no scaling violation as the zeroth approximation to reality. To be definite, we consider the inclusive hadron production in e^+e^- annihilation

$$e^+ + e^- \longrightarrow \bar{q} + q \longrightarrow h + X \quad (1)$$

in the energy region, where the centre-of-mass energy $\sqrt{s} = 2E$ is much larger than any quark or hadron masses involved. Our results are equally applicable to hadron production by neutrinos. Our model is as follows: After energetic q and $\bar{q}$ are produced by a virtual photon, they polarize the vacuum by emitting gluons, decelerate by converting their own kinetic energies into physical hadron energies, and become two fireballs, each of which contains q or $\bar{q}$, surrounded by a cloud of physical hadrons. The invariant masses of the fireballs are larger than that of the naked q and $\bar{q}$ by the amount attributable to hadrons dressed around q and $\bar{q}$. We will treat each of the two fireballs separately by ignoring a small quantum number compensating interaction between them. Our first quantitative assumption comes in here:

1) the invariant masses of the fireballs containing q and $\bar{q}$ are given by

$$M_q = m_q + Q, \quad (2)$$

where m_q is the mass of quark q and parameter Q is assumed to be independent of the flavour of q . Validity of this assumption will be discussed later in this paper. Next, we specify how physical hadrons dissociate from the fireballs.

2) the energy distribution of physical hadrons obeys the Boltzmann distribution in the rest frame of each fireball,

$$\omega^* dn/d^3p^* = C \exp(-\kappa \omega^*), \quad (3)$$

where (ω^*, p^*) is the four-momentum of a final hadron ($\omega^{*2} - p^{*2} = m_h^2$) and C is a normalization constant. The temperature, κ , is taken to be m_π or a little larger, as is deduced from various lepton-hadron and hadron-hadron collisions. Once the Boltzmann distribution is assumed, we disregard kinematical constraints that should be imposed near kinematical boundaries. They may be introduced, if we wish, by hand in an ad hoc manner. Because of the statistical nature of our model, we do not distinguish among different charge states of hadrons. Before proceeding to kinematics, we would like to remark on a qualitative difference between production of light hadrons and production of heavy hadrons. If the parton model is valid for light quarks, starting from $\sqrt{s} \sim 4$ to 5 GeV in e^+e^- annihilation, which seems to be the case experimentally^{9),10)}, Q introduced in Eq. 2 can not be much larger than 1 GeV. It does not allow creation of a heavy quark pair in a fireball so there is only one heavy hadron in each fireball, which is kicked around by pions and kaons in thermal equilibrium. In contrast, pions are easily created by vacuum polarization.

The fireballs are moving with $\gamma = E/M_q$. In the limit of $\gamma \rightarrow \infty$, distribution of hadrons with mass m_h is given in the laboratory frame by

$$\omega dn/d^3p = C \exp[-\kappa \omega^*(p)] ,$$

$$\omega^*(p) = \frac{1}{2} M_q \left(x + \frac{m_{hT}^2}{M_q^2} \cdot \frac{1}{x} \right) + O\left(\frac{1}{\gamma^2}\right), \quad (4)$$

where $m_{hT}^2 = m_h^2 + p_T^2$ with p_T being the component of momentum transverse to the fireball momentum and x is defined by ω/E . Integrating over $\vec{p}_T$, we obtain in terms of x

$$dn/dx = C' \exp \left[-\frac{1}{2} \kappa M_q \left(x + \frac{m_h^2}{M_q^2} \cdot \frac{1}{x} \right) \right] . \quad (5)$$

This is identified with the fragmentation function commonly denoted by $D(x)$. This distribution has a peak at $x = m_h/M_q$, falling rapidly for $m_h^2/M_q^2 \ll 1$ as $x \rightarrow 0$ and 1. Choosing a value for the parameter arbitrarily as $Q \simeq 1$ GeV, the scale of hadron physics, we have drawn the fragmentation functions for π and K in Fig. 1. They agree well with the inclusive hadron production data in e^+e^- annihilation at $\sqrt{s} = 3$ GeV except near $x = 0$ where we expect finite energy effects for the data. Our curve for pions fits well the inclusive $\bar{\nu} + p \rightarrow \mu^+ + \pi^- + X$ data above $x = 0.1$, as shown in Fig. 2¹¹⁾. There is a significant discrepancy between the data and the curve below $x = 0.1$, which can probably be attributed largely to fragmentation of pions from spectator partons. It agrees reasonably for $x \gtrsim 0.2$ with the charge-averaged fragmentation function extracted by Sehgal from electroproduction data, too¹²⁾.

Our main interest is in applying Eq.(5) to the charmed and heavier quarks. For the charmed meson D, the distribution is less sharply peaked and the location of the broad peak is at

$$x_{peak} = m_D / (m_c + Q) . \quad (6)$$

The right-hand side is equal to 0.75 numerically for $Q = 1$ GeV and $m_c = 1.5$ GeV. Because of the finite value of Q independent of $\sqrt{s}$, the range of values allowed for x is limited kinematically to

$$x > x_{min} = (x_{peak})^2 , \quad (7)$$

which is equal to 0.56 for $Q = 1$ GeV and $m_c = 1.5$ GeV (see Fig. 2). As long as the energy release Q is limited, it is a simple kinematical consequence that the peak of distribution shifts to higher values as the quark mass increases. In qualitative arguments one may approximate the distribution in Eq. (5) by

$$dn/dx = \delta \left(x - \frac{m_D}{m_c + Q} \right) \quad (8)$$

for the charmed meson D (8). This is even a better approximation for heavier partons. Another interesting observation is on the fragmentation of π and K from heavy partons. Because the value of M_q for c is larger than that for u , d , and s , the distribution (5) shrinks considerably towards $x = 0$; the peak is at 0.06 and the slope on the right side of the peak is roughly twice as sharp for π from the charmed quark as for π from the (u, d) quarks (see Fig. 3).

We conclude with a few critical remarks on our model. We have treated fragmentation as disintegration of the two fireballs with fixed mass in the thermal equilibrium. Our crucial assumption is that Q is independent of m_q . There is no convincing argument for it. But, the experimental observation that there is no sudden discontinuous behaviour in final hadron multiplicity $\langle n \rangle$ across the charm threshold gives us some comfort. Theoretically, the polarization of vacuum is caused by the gluons that are flavour blind. An alternative model orthogonal to ours is to assume that partons fragment physical hadrons one after another without reaching thermal equilibrium. One will need to specify dynamics more in detail in order to deduce heavy hadron fragmentation in such a model. In either models, as long as they predict an exact scaling, light hadron multiplicity

$\langle n \rangle$ stays constant as $\sqrt{s}$ increases. Experimentally, $\langle n \rangle$ shows a small but definite rise in $\log s$ in the range of $\sqrt{s} \sim 3$ to 7 GeV. The small energy dependence of $\langle n \rangle$ will be included in our case by taking into account a quantum-number compensating interaction linking the two fireballs, namely, the pionization between the two fragmentation regions. Because of its universal nature, the pionization contribution can be estimated, without contamination due to decay products of charmed hadrons, from the central plateau in rapidity plot of inclusive hadron-hadron collisions. We find a flat distribution between the two fireballs

$$dn/dx = a \ln(s/s_0) \quad \text{for } x < m_h/M_q, \quad (9)$$

where $a \simeq 1.3$ ¹³⁾ and $s_0 = 4 M_q^2$ with $M_q = Q + m_q$. The observed rise of $sd\sigma/dx$ near $x = 0$ above the charm threshold in e^+e^- annihilation ⁹⁾ which is clearly beyond what Eq. (9) indicates, might be regarded as supporting the shrunk distribution of pions from the charmed quark that we have obtained. To draw a definite conclusion on this aspect, however, we need more detailed knowledge of weak decay properties of the charmed hadrons. The shape of the heavy parton fragmentation functions, particularly for partons heavier than the charmed parton, will be best studied through inclusive lepton spectra in e^+e^- annihilation and dimuon production by neutrinos.

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FIGURE CAPTIONS

- Fig. 1 : Fragmentation functions of π and K compared with inclusive annihilation. $x' \equiv \beta x$. They are plotted in the logarithmic scale in an arbitrary unit.
- Fig. 2 : Fragmentation function of π compared with the inclusive anti-neutrino reaction and with a theoretical curve extracted from inclusive electroproduction in Ref. 12).
- Fig. 3 : Fragmentation functions of D and π from the charmed quark compared with that of π from the u and d quarks.

FIG. 1

FIG. 2

FIG.3