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Quark fragmentation into vector and pseudoscalar mesons at LEP

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Abstract:

Some data on the ratio of vector to vector + pseudoscalar mesons, $V/(V+P)$, and the probability of helicity zero vector states, $\rho_{00}(V)$, are now available from LEP. A possible relation between these two quantities and their interpretation in terms of polarized fragmentation functions are discussed; numerical estimates are given for the relative occupancies of K and K*, D and D*, B and B* states.

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1 - Introduction

The inclusive production of hadrons in e^+e^- annihilations at LEP, $e^+e^- \to h + X$, allows the fragmentation properties of quarks to be studied; this fragmentation process has recently received much attention both theoretically [1]– [4] and experimentally [5], [6]. It yields information on basic non-perturbative aspects of strong interactions or, in the case of heavy quarks, may test existing perturbative computations of fragmentation functions.

We consider here some spin dependence of particular fragmentation processes, namely the production of vector and pseudoscalar mesons, their relative abundance and the probability for the vector meson to be in a zero helicity state. These quantities can be related to polarized and unpolarized quark fragmentation functions and their measurement supplies basic information on the hadronization process of a quark; simple statistical models for such a process are discussed.

The quarks produced in e^+e^- annihilation at LEP are longitudinally polarized with a probability $\rho_{\pm\pm}(\mathrm{q})$ of being in a $\pm$ helicity state; the off-diagonal elements of the quark helicity density matrix $\rho_{\pm\mp}(\mathrm{q})$ can be neglected. The probability for a hadron h produced in the fragmentation of such a quark q to be in a helicity λ_h state is then given by

$$\rho_{\lambda_\mathrm{h}\lambda_\mathrm{h}}(\mathrm{h}) = \frac{1}{\sum_\mathrm{q} D_\mathrm{q}^\mathrm{h}} \sum_\mathrm{q} \left[D_{\mathrm{q},+}^{\mathrm{h},\lambda_\mathrm{h}}\, \rho_{++}(\mathrm{q}) + D_{\mathrm{q},-}^{\mathrm{h},\lambda_\mathrm{h}}\, \rho_{--}(\mathrm{q}) \right] , \tag{1}$$

where $D_{\mathrm{q},\lambda_\mathrm{q}}^{\mathrm{h},\lambda_\mathrm{h}}$ is the polarized fragmentation function of a quark q with helicity λ_q into a hadron h with helicity λ_h. The unpolarized fragmentation function is

$$D_\mathrm{q}^\mathrm{h} = \frac{1}{2} \sum_{\lambda_\mathrm{h},\lambda_\mathrm{q}} D_{\mathrm{q},\lambda_\mathrm{q}}^{\mathrm{h},\lambda_\mathrm{h}} = \sum_{\lambda_\mathrm{h}} D_\mathrm{q}^{\mathrm{h},\lambda_\mathrm{h}} . \tag{2}$$

Equation (1) holds in a probabilistic scheme, with a single-quark independent fragmentation. In Refs. [7] and [8] it has been shown that for diagonal matrix elements this is a good approximation and that the coherent fragmentation of the quark, which takes into account its interaction with the $\bar{\mathrm{q}}$, only induces corrections of $\mathrm{O}(p_\mathrm{t}/(x\sqrt{s}))^2$, where p_t is the transverse momentum of the hadron relative to the jet axis and x is the fraction of the quark energy carried by the hadron.

Let us first consider final hadrons which predominantly originate from the fragmentation of only one type of quark, like mesons containing one heavy flavour, D, D^*, B, B^* and possibly K, K^* at large x. In such a case one obtains

$$\begin{aligned} \rho_{11} &= \frac{1}{D_\mathrm{q}^V} \left[D_{\mathrm{q},+}^{V,1}\, \rho_{++}(\mathrm{q}) + D_{\mathrm{q},-}^{V,1}\, \rho_{--}(\mathrm{q}) \right] , \\ \rho_{00} &= \frac{1}{D_\mathrm{q}^V}\, D_\mathrm{q}^{V,0} , \\ \rho_{-1-1} &= \frac{1}{D_\mathrm{q}^V} \left[D_{\mathrm{q},+}^{V,-1}\, \rho_{++}(\mathrm{q}) + D_{\mathrm{q},-}^{V,-1}\, \rho_{--}(\mathrm{q}) \right] \end{aligned} \tag{3}$$

and

$$P_V \equiv \frac{V}{V+P} = \frac{D_\mathrm{q}^V}{D_\mathrm{q}^V + D_\mathrm{q}^P} , \tag{4}$$

where V stands for vector and P for pseudoscalar mesons. Both above and in the following we exploit the parity invariance of the fragmentation process, i.e.

$$\begin{aligned} D_{\mathrm{q},+}^{V,0} &= D_{\mathrm{q},-}^{V,0} = D_{\mathrm{q}}^{V,0}, \\ D_{\mathrm{q},+}^{V,1} + D_{\mathrm{q},+}^{V,-1} &= D_{\mathrm{q},-}^{V,1} + D_{\mathrm{q},-}^{V,-1} = D_{\mathrm{q}}^{V,1} + D_{\mathrm{q}}^{V,-1}. \end{aligned} \tag{5}$$

Note that for valence quarks and meson wave functions with zero orbital angular momentum one expects

$$D_{\mathrm{q},-}^{V,1} = D_{\mathrm{q},+}^{V,-1} = 0\,. \tag{6}$$

Experimentally, only $\rho_{00}(V)$ — via observation of the angular distribution of the vector meson two-body decays — and the ratio $V/(P+V)$ can be determined; let us discuss what can be learnt about the quark hadronization process from such measurements. These two observables do not depend on the quark polarization state, but only on the spin and helicity of the final meson.

We define

$$\frac{D_{\mathrm{q}}^{V,1} + D_{\mathrm{q}}^{V,-1}}{D_{\mathrm{q}}^{V,0}} \equiv \gamma_{\mathrm{q}}^{V}\,; \qquad \frac{D_{\mathrm{q}}^{P}}{D_{\mathrm{q}}^{V,0}} \equiv \beta_{\mathrm{q}}^{V}\,. \tag{7}$$

Such quantities might depend on x. From equations (2)–(5) we obtain

$$\rho_{00}(V) = \frac{1}{1+\gamma_{\mathrm{q}}^{V}} \tag{8}$$

and

$$P_V = \frac{1+\gamma_{\mathrm{q}}^{V}}{1+\gamma_{\mathrm{q}}^{V}+\beta_{\mathrm{q}}^{V}}\,, \tag{9}$$

which implies

$$P_V = \frac{1}{1+\beta_{\mathrm{q}}^{V}\,\rho_{00}}\,. \tag{10}$$

Note that in pure statistical spin counting one finds

$$\gamma_{\mathrm{q}}^{V} = 2\,, \qquad \beta_{\mathrm{q}}^{V} = 1\,, \tag{11}$$

so that

$$\rho_{00} = \frac{1}{3}\,, \qquad P_V = \frac{3}{4}\,, \tag{12}$$

and the vector meson alignment

$$A = \frac{1}{2}\,(3\rho_{00}-1) \tag{13}$$

is zero.

Equations (8) and (9) show the relation between the measurable quantities $\rho_{00}(V)$ and P_V and the parameters γ_{q}^{V} and β_{q}^{V}, whose physical meaning is clear through the definitions (7). Equation (10) gives a relation, in terms of the parameter β_{q}^{V}, between the probability for a quark to fragment into a vector meson and the probability for the vector meson to have zero helicity. Note that an increase of ρ_{00} implies a decrease of P_V and vice versa for a fixed value of β_{q}^{V}.

There are some models in the literature which predict a definite relation between P_V and ρ_{00}. In Ref. [9] one assumes $\beta = 1$ so that $P_V = 1/(1+\rho_{00})$, while in Ref. [10] one assumes $\gamma = 1+\beta$ and $P_V = 1/(2-2\rho_{00})$.

In case of more than one flavour contributing to the final mesons, as for π, ρ, the expressions of ρ_{00} and P_V become

$$\rho_{00}(V) = \frac{\sum_q D_q^{V,0}}{\sum_q D_q^{V,0}\,(1+\gamma_q^V)} \tag{14}$$

and

$$P_V = \frac{\sum_q D_q^{V,0}\,(1+\gamma_q^V)}{\sum_q D_q^{V,0}\,(1+\gamma_q^V+\beta_q^V)}\,, \tag{15}$$

while equation (10) changes to

$$P_V = \frac{\sum_q D_q^{V,0}}{\sum_q D_q^{V,0}\,(1+\beta_q^V\,\rho_{00})}\,. \tag{16}$$

This reduces to the simple results (8)–(10) not only in the case of a single flavour contributing, but also when γ_q^V and β_q^V do not depend on the flavour q. This might be the case for valence quarks.

2 - Numerical values and their interpretation

To estimate the numerical values of the parameters γ and β we use data on K, K^*, D, D^* and B, B^* production obtained by the OPAL Collaboration [6].

$$\begin{aligned}
\rho_{00}(\mathrm{K}^*) &= 0.550 \pm 0.050, \quad P_V(\mathrm{K}) = 0.750 \pm 0.102, \quad for\ \ x > 0.5 && (17)\\
\rho_{00}(\mathrm{D}^*) &= 0.400 \pm 0.020, \quad P_V(\mathrm{D}) = 0.570 \pm 0.060, \quad for\ \ x > 0.2 && (18)\\
\rho_{00}(\mathrm{B}^*) &= 0.360 \pm 0.092, \quad P_V(\mathrm{B}) = 0.760 \pm 0.090, \quad for\ \ x > 0.33 && (19)
\end{aligned}$$

where x is the energy fraction of the mesons. The contributions from weak decays were subtracted, where appropriate [1]. This, via equations (8)–(10), yields

$$\begin{aligned}
\gamma_s^{\mathrm{K}^*} &= 0.82 \pm 0.17\,, \qquad \beta_s^{\mathrm{K}^*} = 0.61 \pm 0.33\,. && (20)\\
\gamma_c^{\mathrm{D}^*} &= 1.50 \pm 0.12\,, \qquad \beta_c^{\mathrm{D}^*} = 1.89 \pm 0.47\,. && (21)\\
\gamma_b^{\mathrm{B}^*} &= 1.78 \pm 0.71\,, \qquad \beta_b^{\mathrm{B}^*} = 0.88 \pm 0.49\,. && (22)
\end{aligned}$$

The parameters γ and β have a natural definition in terms of fragmentation functions, but the experimental results can also be interpreted in terms of the relative occupancies of all vector and pseudovector states [5]: let us denote by P_S^λ the probability that the fragmenting quark produces a meson with spin S and helicity λ and let us consider only the production of vector and pseudovector mesons. Then we obtain

$$\rho_{00}(V) = \frac{P_1^0}{P_1^{\pm 1} + P_1^0} \tag{23}$$

and

$$P_V = P_1^{\pm 1} + P_1^0 \tag{24}$$

with

$$P_1^{\pm 1} = P_1^1 + P_1^{-1}\,, \qquad P_1^{\pm 1} + P_1^0 + P_0^0 = 1\,. \tag{25}$$

[1] We have interpolated the charged kaon rates to $x > 0.5$ using a fit to the differential cross-section listed in Ref. [6]. We subtracted the contributions from charm and bottom events to the production of strange mesons using the JETSET [11] model, assigning systematic errors to this subtraction as determined in Ref. [12].

In terms of previous parameters

$$P_1^{\pm 1} = \frac{\gamma}{1+\gamma+\beta}\,, \qquad P_1^0 = \frac{1}{1+\gamma+\beta}\,, \qquad P_0^0 = \frac{\beta}{1+\gamma+\beta}\,\cdot \tag{26}$$

The data (17)–(19) give

$$P_1^{\pm 1}(\mathrm{K}^*) = 0.34 \pm 0.06 \qquad P_1^0(\mathrm{K}^*) = 0.41 \pm 0.07 \qquad P_0^0(K) = 0.25 \pm 0.10 \tag{27}$$

$$P_1^{\pm 1}(\mathrm{D}^*) = 0.34 \pm 0.04 \qquad P_1^0(\mathrm{D}^*) = 0.23 \pm 0.03 \qquad P_0^0(\mathrm{D}) = 0.43 \pm 0.06 \tag{28}$$

$$P_1^{\pm 1}(\mathrm{B}^*) = 0.49 \pm 0.09 \qquad P_1^0(\mathrm{B}^*) = 0.27 \pm 0.08 \qquad P_0^0(\mathrm{B}) = 0.24 \pm 0.09 \tag{29}$$

in agreement with equations (20)–(22) and (26). Simple spin counting would give $P_1^{\pm 1} = 0.5$ and $P_1^0 = P_0^0 = 0.25$.

3 - Comments and conclusions

We have shown how the simultaneous measurements of the ratio of vector to vector + pseudovector mesons and $\rho_{00}(V)$ supply basic information on the fragmentation of quarks; such information does not depend on the helicity of the quark, but on the spin and helicity of the final meson. Some data are available for K, D and B mesons and in some cases show clear deviations from simple statistical spin counting and predictions of other models. Such information could be of crucial importance for the correct formulation of quark fragmentation Monte Carlo programs, which at the moment widely assume simple relative statistical probabilities.

Let us consider our results, equations (20)–(22) and (27)–(29). For strange mesons the data agree with spin counting in the amount of K versus K*. However, among vector mesons, helicity zero states seem to be favoured; in absolute terms, these are the most abundantly produced, $P_1^0(\mathrm{K}^*) = 0.41$. For charmed mesons both values of $\gamma_c^{\mathrm{D}^*}$ and $\beta_c^{\mathrm{D}^*}$ differ from the spin counting values (11), suggesting a prevalence of pseudoscalar states, $P_0^0(\mathrm{D}) = 0.43$, and, among vector mesons, of helicity zero states. They also disagree with the models of Refs. [9] and [10], which, respectively, predict $\beta = 1$ and $\gamma = 1 + \beta$. The heavy b-mesons, instead, are produced in good agreement with statistical spin counting rules, as one expects.

Data from LEP1 are still being analysed. For this kind of study it is important that the production rates for the scalar and vector mesons and the results on spin alignment are presented on the same footing, i.e. with the same cuts on the scaled energies and a consistent subtraction of the contributions from weak decays. It will be interesting to determine the parameters γ and β and the relative spin state occupancies P_S^λ for other mesons, like π and ρ. There might be some common features to all light quark fragmentation processes, leading to the same vector and pseudovector state occupancy probabilities for π, ρ and K, K^*.

It would also be worthwhile to study the dependence of these probabilties on the scaled energy of the mesons. Also, the degree of universality of quark fragmentation could be tested by studying the same quantities discussed here in other processes, like meson production in lepton–hadron or photon–hadron interactions; or in γ–γ and hadron–hadron collisions. It would also be interesting to compare data on the production of spin 1/2 and spin 3/2 baryons. Some non perturbative aspects of strong interactions can only be tackled by gathering experimental information and looking for patterns and regularities which might allow the formulation of correct phenomenological models.

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