Charm production in the valon model

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The valon model for hadron structure is extended to include charm quarks in the sea. The resultant charm distribution is then used in the recombination model to determine the inclusive distributions of charm particles produced in hadronic collisions at low p_T. Predictions agree well with experiment.

A point of view about hadron-hadron collisions has recently been expressed suggesting that low-p_T reactions provide a good means for learning about the structure of hadrons, in many respects much better than high-p_T processes.[1] The formalism used to carry out the analysis is decribed in the framework of the valon model.[2] While applications have been made to demonstrate the feasibility of the procedure to extract phenomenologically hadron structures such as that of a kaon,[3] there is a need to turn the attention to "new" physics to show that massive-particle production can also be understood in the same formalism. Indeed, the production of charm particles has raised questions about the charm-quark content of a proton.[4] The problem is generally regarded as being highly topical, but in our view is just an example of the relevance of low-p_T processes to the question of hadron structure. The "old" physics of pion production is less topical, but not less relevant. Our aim in this paper is to show that by a simple extension of the valon model to include charm quarks in the sea we can easily explain the observed spectra of charm particles produced in pp collisions.

The central part of the valon model is that sea quarks are partitioned into clusters, each belonging to one of the valence quarks. A valence quark together with its associated sea quarks and gluons is collectively called a valon.[5] The quark distribution in a hadron is therefore a convolution

$$q_i(x)=\sum_v \int_x^1 \frac{dy}{y} G_v^h(y) P_i^v\left(\frac{x}{y}\right) , \tag{1}$$

where $G_v^h(y)$ is the valon distribution in hadron h and $P_i^v(z)$ the cluster distribution of quark i in valon v. The large-x behavior of $q_i(x)$ is clearly governed by the large-y behavior of $G_v^h(y)$ and the large-z behavior of $P_i^v(z)$. It has previously been shown[2,6] that in a proton the dominant valon distribution at large y is

$$G_U^p(y) \propto (1-y)^2 . \tag{2}$$

Thus if $P_i^v(z)$ behaves as $(1-z)^c$ as $z \to 1$, then (1) implies

$$q(x) \propto (1-x)^{3+c} \tag{3}$$

for large x.

In the hypothetical situation where a valon is to be identified with a valence current quark (i.e., no sea quarks or gluons in the hadron) then $P_i^v(z) = \delta(1-z)$ and $q(x)$ would behave as $G(y)|_{y=x}$, as it should by assumption. More realistically, a valence quark loses some of its momentum to the sea quarks and gluons in forming the cluster that is the valon. The valence-quark distributions in the cluster, $P_{\rm val}^v(z)$, would still be peaked at $z=1$, but not as sharply as a δ function. For low-p_T reactions it has been found[3] that $zP_{\rm val}^v(z)$ (denoted by $K_{\rm NS}$ in Refs. 1–3) behaves as $(1-z)^{-0.4}$. In leptoproduction at moderate to high Q^2 there is more Altarelli-Parisi evolution in a valon and $P_{\rm val}^v(z)$ becomes finite as $z \to 1$.[1] It then follows from (3) that $q_{\rm val}(x) \propto (1-x)^3$, which is the commonly accepted behavior as determined in deep-inelastic scattering. On the other hand, for sea-quark distribution the value of c in (3) has been found to be 2.7 for soft hadronic processes[3] and 3.5 for leptoproduction processes,[2] so $q_{\rm sea}(x)$ behaves as $(1-x)^{6-7}$.

The key question now is what can be said about the charm-quark distribution. In the valon model all sea quarks reside in one valon or another. Consider a virtual $c\bar{c}$ pair in a valon. Although we have no reliable way to calculate the overall probability of its occurrence, we do nave a reasonable estimate of its momentum distribution in a valon.

As an introduction, consider first the deuteron problem. Since it is a very loosely bound system ($m_d \simeq m_p + m_n$), the constituents (proton and neutron) do not exchange very much momentum; consequently, the momentum distribution of the nucleons is sharply peaked at $x=\frac{1}{2}$, where x is the fraction of deuteron momentum. Consider next the pion. It is a bound state of two valons which, in the static problem, can be identified with the constituent quarks. Since the constituent quark mass is ~350 MeV, the pion is a tightly bound state. Thus the valons can readily exchange momentum, resulting in a valon wave function that is very spread out in momentum space. Indeed, we have obtained $G^{\pi}(y) \simeq 1$ from the structure function of the pion as inferred from lepton-pair production.[2]

In both examples above, the momentum distributions of the constituents are symmetrical about the value $\frac{1}{2}$ for the momentum fraction. The spread of the distribution about the average is consistent with $1/RM$ suggested by a physically reasonable bound-state model,[7] where R estimates the size of the composite system and M its mass. The deuteron form factor is known to have an anomalous threshold, so R is anomalously large. In the case of the pion, it is M that is anomalously small.

We now consider the charm-quark distribution $P_c^v(z)$ in a valon along the same line of reasoning as above. The charm-quark mass is $\sim$1.5 GeV so a $c\bar{c}$ pair would be a tightly bound subsystem in a U or D valon. Since the valence-quark mass is negligible compared to m_c, the distribution $P_c^v(z)$ should be symmetrical about $z=\frac{1}{2}$. A deeply bound state in a potential generated by gluon exchange corresponds to very-short-range interaction because such a potential behaves as $-1/r$ at small r. Thus the separation between the c and $\bar{c}$ quarks is very small. In other words, a highly virtual state has a small uncertainty in coordinate spread. By the argument of the preceding paragraph the spread of the z distribution in $P_c^v(z)$ must be very large. Furthermore, M (here the valon mass) is very small relative to $2m_c$, so again $P_c^v(z)$ is expected to be flat. To be definite we set

$$P_c^v(z)=a \quad , \tag{4}$$

where a is a constant much smaller than one, signifying the low probability of finding a $c\bar{c}$ pair in a valon.

It should be stressed that, despite (4), the light-quark distribution in a valon is not flat because none of the arguments used above apply. The dominant situation is that a $c\bar{c}$ pair is not created virtually in a valon so the valence quark is peaked at $z=1$ while the sea quarks are peaked at $z=0$. But in the rare situation when a $c\bar{c}$ pair is created, then the average momentum of a charm quark, not weighted by the probability of its occurrence, i.e., $\int Pz\,dz/\int P\,dz$, is $\frac{1}{2}$ according to (4). Thus the $c\bar{c}$ pair, once created, carries all the momentum of the valon reflecting the massiveness of the $c\bar{c}$ state. The same is true with b- and t-quark distributions except that the normalization would be even lower.

The special characteristics of the valon model are that all sea quarks (massive or not) are associated with one valon or another and that they have various momentum distributions (depending on their flavors) in a valon independent of the valon momenta themselves. Since nonperturbative effects are important in the confinement problem, it is not useful to speculate on the nature of the lifetime of the $c\bar{c}$ state in a valon on the basis of perturbative arguments. The model we discuss asserts that (a) a proton is made up of three valons only (based on the phenomenological success of baryon spectroscopy in terms of three constituent quarks) and (b) the interaction between the valons is through soft gluons which do not affect the quark distributions at large momentum fractions. Thus if quark distribution in a valon, such as (4), is obtained on rather general grounds, it enables us to give, through (1), a reliable description of the quark distribution in any hadron for which $G_v^h(y)$ is known. For charm quarks in a proton we therefore have, by virtue of (3),

$$xc^p(x) \propto (1-x)^3 \quad . \tag{5}$$

Without changing the large-x behavior we have attached a factor x to $c^p(x)$ to render the distribution invariant. Since the valon distribution in a pion is constant, we also have

$$xc^{\pi}(x) \propto (1-x) \quad . \tag{6}$$

Like most quark distributions, (5) and (6) are probably roughly valid for $x > 0.2$.

Note that $xc^p(x)$ and $xc^{\pi}(x)$ are much more slowly falling than the usual sea-quark distributions. In fact, they are very similar to the u-quark distribution in p and π^+, respectively. This similarity is the key to our understanding and prediction of charm-particle production in hadronic collisions.

For the production of particles at low p_T, the recombination model[8] has been shown to be highly successful as a mechanism for hadronization of quarks. For charm-particle production an elaborate calculational scheme can be developed in the valon model along the lines of Ref. 2, but the computation has not yet been carried out. In view of the large errors of the charm-production data available now, it is useful for us to give here a quick and easy way of obtaining a qualitative result that is adequate for comparison with the present data.

Protons are produced via the recombination of uud quarks. Charm baryons Λ_c^+ are formed from cud quarks. Since the c-quark distribution in a proton, according to (5), is essentially the same as the u-quark distribution, we immediately expect the longitudinal-momentum distribution of Λ_c^+ produced in the proton fragmentation region to be very similar to that of the proton. The difference in the recombination functions for the two particles would not introduce significant discrepancy. The major difference is in the large-x region where a proton can recoil against a diffractive excitation; contributions of that kind to the proton spectrum should be excluded when comparison is made between the p and Λ_c^+ spectra. The corresponding data[9,10] are shown in Fig. 1 where normalizations are adjusted to fit. The data

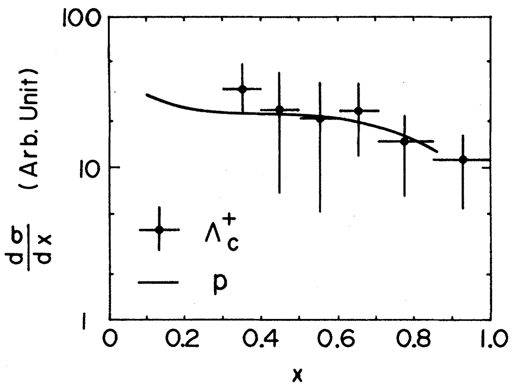

FIG. 1. Comparison of inclusive distributions of Λ_c^+ and p production in pp collision. Data points are from Ref. 9 and solid curve is determined from data in Ref. 10.

for proton are represented by a curve which is determined from Ref. 10 by an average over the data points for $p_T = 0.5$ and 0.75 GeV/c. The agreement is evidently very good.

It should be noted that although each quark distribution falls off in x at least as rapidly as $(1-x)^3$, the baryon distribution is rather flat, something like $(1-x)^{0.4}$, as suggested in Ref. 9. That is due to the three-quark recombination for which, at large x of the baryon, there is larger phase space for the three constituent quarks to recombine, since the baryon recombination functions are not sharply peaked. Though Λ_c^+ may be produced diffractively in conjunction with $\bar{D}^0$, there is no need in the quark-recombination model to address the problem of diffraction. The reasoning is based mainly on the recognition that fast quarks in the incident proton pass through the interaction region with minimal disturbance on account of short-range correlation in rapidity, and that the momenta of the three quarks add up to be the momentum of the produced baryon. In that picture there is very little differenc betwen producing a proton and producing a Λ_c^+.

The total cross section for Λ_c^+ production at CERN ISR is 250–750 μb.[11] This is at the 1–2% level of the inelastic pp cross section. Thus (5) should have a normalization that is of the same level compared to the u-quark distribution. Since the u-quark distribution in a valon, $P_u^v(z)$, is of order 1, it implies that the parameter a in (4) is roughly 0.01 to 0.02. In the intrinsic-charm model,[12] the intrinsic-charm state $|uudc\bar{c}\rangle$ in a proton is postulated to exist also at the 1% level.

For D-meson production we have $c\bar{u}$ and $c\bar{d}$ recombination for D^0 and D^+, respectively. In proton fragmentation, $\bar{u}$ and $\bar{d}$ are sea quarks with distribution peaked at small x. Hence the inclusive cross sections for D^0 and D^+ should have the same x dependence as $xc(x)$ which is $\sim(1-x)^3$. This behavior is indeed what has been observed.[11] For the production of $\bar{D}^0$ and D^- the recombining quarks are $u\bar{c}$ and $d\bar{c}$, respectively; all those quarks have x distributions behaving as $(1-x)^{3-4}$. Thus $\bar{D}^0$ and D^- should be more forwardly produced than D^0 and D^+, but not as much as Λ_c^+ since the latter has a momentum that is the sum of the momenta of three quarks with the same distribution. It is reasonable then for us to suggest that the inclusive cross sections for $\bar{D}^0$ and D^- should behave as $(1-x)^n$, with n around 2. There is, at present, no data on their production.

Since the valon model provides us with the charm-quark distribution in a pion also, as indicated in (6), we are able to make certain predictions about charm-particle production in pion-initiated reactions. Again, not having carried out detailed calculations on the subject, the predictions will be qualitative estimates which should be adequate for now since no (accurate) data are available at present. From (6) we see that $c(x)$ is very similar to the valence-quark distribution in a pion. An immediate consequence in the recombination model is that in the π^+ fragmentation region the x dependences of the inclusive production of π^0, D^0, D^- should all be similar since in all three cases a sea quark at low x is picked up. On the other hand, the formation of $\bar{D}^0$ and D^+ involves the recombination of two quarks both of which are distributed according to $\sim(1-x)$, so their production would be even more favored in the forward direction. Furthermore, their inclusive distributions should be similar to that of Λ_c^+ which involves one sea quark at low x.

More precise predictions will have to await the results from an elaborate calculation yet to be performed. In that calculation consideration will be given to all possible ways that the recombining quarks can come from the initial valons. It will also need some reasonable input on the recombination functions for the charmed particles. Indeed, when the data become sufficiently accurate, we can reverse the procedure and use the inclusive distributions as inputs for the phenomenological determination of the wave functions of Λ_c^+ and D mesons, a possibility which illustrates the usefulness of low-p_T reactions. For now, our crude estimates are sufficient to demonstrate that the valon model is quite compatible with existing data on charm production and has predictive power to suggest the nature of inclusive distributions of charm particles in reactions not yet observed.

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