Ref.TH.2520-CERN

GLUOPRODUCTION OF HEAVY QUARK FLAVOURS
IN HADRONIC SCATTERING

H. Fritzsch
University of Wuppertal
and
CERN - Geneva

and
K.H. Streng ^{*)}
University of Wuppertal

A B S T R A C T

Hadronic and photoproduction of heavy flavours are related to each other. QCD perturbation theory fails to describe the production of heavy flavours in hadronic scattering. The results for charm production are compared with the results of the recent CERN beam dump experiments. The possibility that b flavoured particles live longer than $10^{-7}s$ is ruled out.

^{*)} Supported by Deutsche Forschungsgemeinschaft.

Thus far the production of charmed particles in hadronic reactions has not been directly observed. However, three beam dump experiments ^{1,2,3)} performed recently at the CERN-SPS have shown that prompt neutrinos ($\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$) are produced in 400 GeV p-nucleus scattering. These neutrinos must originate from the production and subsequent decay of short-lived particles. The most conventional interpretation of the experimental results ^{1,2,3)} is to interpret them as due to the production of charmed particles. In this case one finds a surprisingly large cross section for the production of charmed particles in 400 GeV nucleon-nucleon scattering, which is of the order of 100 μb .

On the other hand there have been several attempts to estimate the production cross section of charmed particles using QCD perturbation theory. In lowest order QCD perturbation theory charmed particles can be produced in pairs by

- a) the annihilation of quarks and antiquarks into virtual gluons, ⁴⁾
producing a $c\bar{c}$ -pair
- b) the amalgamation of a pair of gluons (as constituents of the incoming hadrons) into a $c\bar{c}$ -pair. ^{5,6)}

Typically one estimates in these approaches (see especially ref.(6)) σ (charm) to be at most a few μb 's in p-p scattering at 400 GeV, i.e. the cross section turns out to be much smaller than the values quoted in refs. (1,2,3).

Thus the question arises how reliable the perturbative calculations to estimate the production of charm really are. In this paper we should like to present arguments which indicate strongly that the perturbative estimates are incorrect. Furthermore, we calculate the charm production cross section by comparing it with the cross section for the photoproduction of $\psi(J)$ mesons.

In ref.(7) we have estimated the photoproduction cross section of charmed particles by using lowest order QCD perturbation theory, where the production of charmed particles ($c\bar{c}$ pairs) proceeds via the amalgamation of the incoming photon and an incident gluon (as a constituent of the incident hadron). It has turned out that the asymptotic value of σ (γ +nucleon $\rightarrow$ charm pair + x) is well described by this prescription, if one compares it with the

estimate based on vectormeson dominance. However, the "observed" threshold behaviour of the charm production cross section is not reproduced. While the "observed" charm production cross section in photoproduction rises rather steeply after threshold (according to the estimate based on vectormeson dominance) the lowest order QCD calculation ⁷⁾ gives a rather smooth threshold dependence. This is a clear indication that the charm production near threshold cannot be described by QCD perturbation theory, and that nonperturbative effects ($c\bar{c}$ -bound states etc.) play an important rôle. Such effects are taken into account automatically by applying the vectormeson dominance hypothesis. Here the incident photon couples virtually to a bound $c\bar{c}$ -pair (in form of a $c\bar{c}$ vectormeson ($\psi, \psi', \dots$)), which subsequently scatters off the incoming hadron and desintegrates to produce a pair of charmed particles, among others.

In this note we suggest that similar nonperturbative effects play an important rôle in the hadroproduction of charmed pairs. In fact, within the QCD approach there exists a strong analogy between photons and gluons. Both couple to quarks with a γ_μ -coupling, the photon with strength $e_q \cdot e$ (e_q : quark charge in units of the positron charge), the gluon with strength g . Thus one may expect that photon-induced reactions and reactions, where gluons play an important rôle, are somewhat similar.

It is well known that gluons contribute about half to the proton momentum (in a rapidly moving frame). Therefore, as far as the production of charmed particles is concerned, an incident proton beam can be regarded as a beam of incident gluons, which (like photons) couple to $c\bar{c}$ -pairs and initiate in such a way the production of charmed pairs. This analogy between photoproduction and gluoproduction of charmed pairs is described in figs. (1) and (2). Averaging over the eight different colors, we obtain

$$\frac{\sigma(gN \rightarrow c\bar{c} + X)}{\sigma(\gamma N \rightarrow c\bar{c} + X)} = \rho \cdot \frac{\frac{1}{8} \sum_{A=1}^8 \text{tr} \left[\frac{\lambda_A}{2} \cdot \frac{\lambda_A}{2} \right]}{e_c^2} \cdot \frac{\kappa}{\alpha} = \frac{9}{8} \left(\frac{\kappa}{\alpha} \right) \rho, \quad (1)$$

where λ_A are the (SU(3)) color matrices (normalized such that $\text{tr}(\lambda_A \lambda_B) = 2 \delta_{AB}$), $\alpha = e^2/4\pi$, $\kappa = g^2/4\pi$, ρ is a factor of the order of 1, and e_c is the charge of the charmed quark taken to be 2/3.

Using eq.(1) we can calculate the production cross section for charmed pairs in proton-proton scattering. One finds (C: charmed hadron)

$$\sigma(pp \rightarrow C\bar{C} + x) \approx \rho \cdot 2 \cdot \left(\frac{9}{8}\right) \cdot \left(\frac{\kappa}{\alpha}\right) \int_{x_{\min}}^1 dx G(x) \sigma(\gamma p \rightarrow C\bar{C} + \dots, xE). \quad (2)$$

Here $G(x)$ denotes the gluon distribution function of the proton $x_{\min} = [(2M_D + M_p)^2 - M_p^2] / 2M_p E$ (threshold value of x), and $\sigma(\gamma p \rightarrow C\bar{C} + x, xE)$ denotes the photoproduction cross section of charmed particles at energy $x E$ (E : energy of incident proton in laboratory system).

In eqs.(1,2) we have averaged over the incoming colors of the gluons. However, it must be noted that a color octet gluon cannot couple, like a photon, directly to a physical $C\bar{C}$ meson, which constitutes a color singlet bound state. In order to do so, a color rearrangement must take place, e.g. by the emission or absorption of soft gluons (see also ref. (4)). To describe this effect, we have introduced in eq. (1,2) the parameter ρ . It is expected that the rearrangement of color takes place with unit probability, which implies $\rho = 1$.

Note however, that the emission or absorption of gluons changes the charge conjugation such that not only $J^{PC} = 1^{--}$ charmonium states can couple to the incoming gluon, but also η_C and η_C' as well as the χ -states.

In ref. (7) it was emphasized that the photoproduction of charm, according to the vectormeson dominance hypothesis, is rather well described by the empirical formula

$$\sigma(\gamma + \text{nucleon} \rightarrow C\bar{C} + x) \approx \left(1 - \frac{s_{th}}{s}\right) \sigma_0 \quad (3)$$

where $s = (p_\gamma + p_{\text{nucl.}})^2$, $s_{th} = (M_{\text{nucl.}} + 2 M_D)^2 = 21.7 \text{ GeV}^2$, and σ_0 is the asymptotic value, which comes out to be about $1.2 \mu\text{b}$, corresponding to $\sigma_{\text{tot}}[\psi(J) \text{ nucleon}] \approx 2 \text{ mb}$.

Inserting eq. (3) into eq.(2), one can calculate the charm production cross section as a function of the energy. For the gluon distribution we shall assume

$$G(x) = \frac{n+1}{2x} (1-x)^n. \quad (4)$$

Our results do not depend very much on the parameter n , if $4 < n < 8$. Various models (eq. ref. (5)) suggest $n \approx 5$ which we shall assume for our numerical calculations. The quark-gluon coupling constant relevant for our consideration should be the same as the one obtained by describing the hadronic decay of charmonium states via the gluon annihilation hypothesis (see e.g. ref. (8)). We shall take $\kappa = 0.2$ for estimating the charm production.

In fig. (3) we describe the charm production cross section as a function of the energy for $n = 5$ and $\rho = 1$. We find a very big cross section, about two orders of magnitudes larger than the one obtained by using QCD perturbation theory. This shows the importance of nonperturbative effects, and especially of threshold effects, in describing the production of charmed particles in hadronic scattering. Note that our findings are in good agreement with the new experimental results ^{1,2,3)}. Especially we should like to emphasize the very steep threshold dependence of the charm production cross section. While at $E = 400$ GeV one finds $\sigma(c\bar{c}) \approx 170 \mu\text{b}$ the cross section for $E = 30$ GeV is about $0.8 \mu\text{b}$. For $\sqrt{s} = 60$ GeV (CERN-ISR) we find $\sigma(c\bar{c}) \approx 440 \mu\text{b}$. The threshold dependence is especially shown in fig.(4). The charm production cross section rises logarithmically for large energies and passes 1 mb at $\sqrt{s} \approx 240$ GeV ($E = 3 \cdot 10^4$ GeV).

We should like to emphasize that these results are obtained for $\rho=1$. Due to the uncertainty about the factor ρ our estimates of cross sections can only be regarded as order of magnitude estimates (with an overall uncertainty of about a factor two.)

Finally we apply similar ideas to calculate the cross section for producing other heavy particles involving new heavy quarks. In this case we have to replace in eq.(1) e_c by the electric charge of the new quark, in eq.(2) the threshold value of x_{th} by the corresponding threshold value, and in eq.(3) σ_0 by the corresponding cross section for photoproduction. For example we may introduce a new quark b of charge $-1/3$, $m_b = 5$ GeV as the constituent of the $T(9.5)$ state.^{9,10,11)} In this case we find the cross section for the production of b -flavored particles shown in fig. (5). (We have used $\sigma_0(B) = 27$ nb, as estimated in ref.(7) and $\kappa = 0.15$).

The behaviour near threshold is especially shown in fig. (6).

The cross section for the production of b-flavored particles in proton-nucleon scattering at $E_{\text{lab}} = 400 \text{ GeV}$ is about $0.85 \text{ } \mu\text{b}$.

Recently some authors have discussed the possibility that b-flavored particles are stable or have a relatively large life-time ($> 10^{-7} \text{ sec}$) (see e.g. ref. (12)). We should like to mention that this possibility seems very unlikely if our estimate of the production cross section is correct. The best limit on the production cross section of neutral long-lived particles (e.g. $(\bar{b} d)$ mesons of mass 6 GeV) in 300 GeV proton-nucleon collisions comes from the experiment reported in ref. (13): $(\sigma(p N \rightarrow B^0 + x) < 5 \text{ nb})$. On the other hand we expect $\sigma(p N \rightarrow B^0 + x)$ to be of the order of 100 nb . We conclude that it is very unlikely that b-flavored particles have a life-time larger than 10^{-7} sec .

ACKNOWLEDGEMENT:

One of us (H.F.) is indebted to A. De Rújula, K. Kleinknecht and P. Musset for useful discussions.

REFERENCES

1. P.C. Bosetti et al., CERN-preprint EP 78-3 (1978), to appear in Phys.Lett.B.
2. P.Alibrán et al., CERN-preprint EP78-3 (1978), to appear in Phys.Lett.B.
3. T.Hansl et al., CERN-preprint(1978) ("Results of a Beam Dump Experiment at the CERN SPS").
4. H.Fritzsch, Phys.Lett. 67B (1977) 217; see also: F.Halzen and S.Matsuda, CERN-preprint TH 2354 (1977).
5. M.Glück, J.F.Owens, and E.Reya, Florida State University preprint (1977).
6. H.M.Georgi, S.L.Glashow, M.E.Machacek and D.V.Nanopoulos, Harvard University preprint HUTP - 78/Aoo8 (1978).
7. H.Fritzsch and K.Streng, Phys. Lett. 72B, 385 (1978), and references given there.
8. T. Appelquist and H.D.Politzer, Phys.Rev. D12 (1975) 14o4.
9. S.W.Herb et al., Phys.Rev.Lett. 39 (1977) 252.
10. Ch.Berger et al., DESY-preprint 78/21, to appear in Phys.Lett.
11. C.W.Darden et al., DESY-preprint 78/22, to appear in Phys.Lett.
12. R.N. Cahn, Phys.Rev.Lett. 4o (1978) 8o.
13. H.R.Gustafson et al., Phys.Rev.Lett. 37 (1978) 474.

FIGURE CAPTIONS

- Fig.(1) Photoproduction of charmed particles. The photon couples virtually to a bound $c\bar{c}$ -pair, which scatters off the incident nucleon to produce the final hadronic system including a pair of charmed particles.
- Fig.(2) Gluoproduction of charmed particles. The gluon couples virtually to a bound $c\bar{c}$ -pair, which scatters off the incident nucleon to produce the final hadronic system including a pair of charmed particles.
- Fig.(3) The charm production cross section in proton-nucleon-scattering as a function of $\sqrt{s}$ for $n = 5$ ($\kappa = 0.2$, $\rho = 1$).
- Fig.(4) The charm production cross section near threshold.
- Fig.(5) The cross section for the production of B-particles in proton-nucleon-scattering ($n = 5$, $\kappa = 0.15$, $\rho = 1$).
- Fig.(6) The B-production cross section near threshold.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6