WEAK PRODUCTION OF CHARMED BARYON RESONANCES

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We evaluate weak neutrino production cross sections for 7 conjectured charmed baryon resonances in the four flavour quark model. Effects resulting from the mass difference of uncharmed and charmed quarks are explicitly taken into account. The quark model results are only taken at $q^2 = 0$ to determine the $q^2 = 0$ values of the invariant transition form factors. These are then continued to $q^2 \neq 0$ by suitably chosen form factors. Our numerical results are compared with the results of other calculations of weak charm production.

Recently some evidence for the existence of charmed particle has been reported in e^+e^--experiments [1]. The dilepton events [2] in ν-reactions are also considered as strong evidence for the production of charmed particles. The production of the ground state charmed baryons has been evaluated by Lee Schrock [3] and Finjord and Ravndal [4]. In this paper we give calculations of the production corss section for several charmed baryons including *excited* states in the quark model. A characteristic point of our evaluation is the introduction of the quark masses. Since the mass difference of the normal quarks (p, n) and the charmed quark (c) may be quite large, the symmetry breaking which is induced by the quark mass difference will be large and must play an important role.

Model. The production of charmed baryons is represented as the quasi-elastic process [5, 6] $\nu N \to \mu^- C$ (C = charmed baryon). We treat the excitations to the $L = 0$ ground state charmed baryons with $J^P = \frac{1}{2}^+, \frac{3}{2}^+$ and to the excited states $\frac{3}{2}^-$ and $\frac{5}{2}^+$ in analogy to the D_{13} and F_{15} seen in electroproduction[‡1]:

$$L = 0: \quad C_0 \equiv (20; 0; \tfrac{1}{2}^+), \qquad C_1 \equiv (20; 1; \tfrac{1}{2}^+), \qquad C_1^* \equiv (20'; 1; \tfrac{3}{2}^+)$$

$$L = 1: \quad (20; 0; \tfrac{3}{2}^-), \qquad (20; 1; \tfrac{3}{2}^-)$$

$$L = 2: \quad (20; 0; \tfrac{5}{2}^+), \qquad (20; 1; \tfrac{5}{2}^+)$$

with the notation (SU (4) representation; $I; J^P$). The internal wave function of the ground state baryons composed of 3 quarks in momentum space is written as follows:

$$\Phi(\boldsymbol{p}) = \int \prod_{i=1}^{3} d^3k_i\, \delta^3\Big(\boldsymbol{p} - \sum_{i=1}^{3} \boldsymbol{k}_i\Big) \phi(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) \chi_{123}, \tag{1}$$

where ϕ and χ stand for the space and the spin-unitary spin wave functions, respectively. We shall evaluate the hadronic matrix elements of charmed particle production in the isobar rest frame. One obtains

$$\bar{\Phi}_f(\boldsymbol{p}_f)\Gamma_\mu^{V,A}(0)\Phi_i(\boldsymbol{p}_i) = \langle C.G.\rangle \int \prod_{j=1}^{3} d^3k_j\, \delta^3\Big(\boldsymbol{p}_i - \sum_{j=1}^{3} \boldsymbol{k}_j\Big) \phi_f^+(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3 + \boldsymbol{q}) \phi_i(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) \otimes \bar{u}_c(\boldsymbol{k}_3 + \boldsymbol{q}) \Gamma_\mu^{V,A} u_n(\boldsymbol{k}_3), \tag{2}$$

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[‡1] There are altogheter 25 charmed baryon states with $C = 1, S = 0$ and $L = 0, 1, 2$ in the lowest radial mode, of which 19 can be excited by neutrinos. We have checked by explicit calculation that the production cross sections for the above 7 states are the largest ones for the respective $L = 0, 1$ and 2 orbital modes.

where the relevant charm changing current operator is $\Gamma_\mu^V + \Gamma_\mu^A = \gamma_\mu(1 - i\gamma_5)\cos\theta_C$ with $\sin\theta_C = 0.235 \pm 0.005$. ⟨C.G.⟩ is a Clebsch-Gordan type coefficient.

In the non-relativistic model the $\boldsymbol{k}$-dependence of the Dirac spinor is neglected and instead the Pauli spinors are used. Such an approximation is reliable only if $|\boldsymbol{q}|$ and the cut-off momenta for the $\boldsymbol{k}$'s in Φ are small. But in the present case the mass difference between the n and c quarks is so large that $|\boldsymbol{q}|$ is very large even at $q^2 \approx 0$. Therefore we may neglect the $\boldsymbol{k}$-dependence of the Dirac spinors, but not their $\boldsymbol{q}$-dependence. In the above approximation we reduce eq. (2) as follows:

$$\langle \mathrm{C.G.}\rangle \bar{u}_c(\boldsymbol{q})\Gamma_\mu^{V,A}u_c(0)\int \prod_{j=1}^{3} d^3k_j\, \delta^3\Big(\boldsymbol{p}_i - \sum_{j=1}^{3}\boldsymbol{k}_j\Big)\phi_f^+(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3+q)\phi_i(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3). \tag{3}$$

The dependence of the current matrix elements on the quark masses m_n and m_c is explicitly contained in the Dirac spinors u_n and u_c. The overlap integral for the ground state in eq. (3) is a function of q^2 which is normalized to 1 at $q^2 = 0$. In the case of the production of excited states the overlap integral $\int\phi_f^+\phi_i$ is proportional to $|\boldsymbol{q}|^L$ which gives a very large cross section for large mass excited states even at $q^2 = 0$. Here we evaluate the following two cases for the excited states

$$\text{Model I:}\quad \phi_f^+\phi_i\Big|_{q^2=0} = \left(\sqrt{\frac{2}{\Omega}}|\boldsymbol{q}|\right)^L \exp\left[-\frac{m^2q_{0c}^2}{\Omega(m^2+M^2)}\right]\Bigg|_{q^2=0}$$
$$\text{Model II:}\quad \phi_f^+\phi_i\Big|_{q^2=0} = \left(\frac{|\boldsymbol{q}|}{M}\right)^L\Bigg|_{q^2=0}, \tag{4}$$

where $m(M)$ = mass of nucleon (resonance), $|\boldsymbol{q}|^2 \equiv q_c^2 = [(M+m)^2 - q^2]\,[(M-m)^2 - q^2]/4M^2$, $q_{0c} = (M^2 - m^2 + q^2)/2M$ and $\Omega = 1.05\ \mathrm{GeV}^2$. The above forms of the overlap integrals correspond to the model presented by Feynman-Kislinger-Ravndal [7] (model I) and a simple dimensional argument for the invariant coupling strengths (model II)[‡2].

In principle the quark model prediction for the q^2-dependence of the current matrix elements is contained in eq. (3) and the equivalent expressions for resonance excitation. However, besides the difficulty that the q^2-dependence of the overlap integral is model dependent, the q^2-structure of the remaining spin part tends to be unreliable. For example, for the electro-production of the $D_{13}(1520)$, the quark model prediction for the q^2-dependence of the ratio of the $\frac{1}{2}$ to $\frac{3}{2}$ helicity amplitudes does not agree with experiment. Thus we shall use the quark model results only at $q^2 = 0$ and continue to $q^2 < 0$ by continuing a suitable set of constraint free form factors via a generalized meson dominance q^2-dependence. In ref. [9] it was shown that resonance excitation in electro-production can be accounted for quite well using such a continuation procedure.

Cross section and form factors. If one neglects the lepton mass one obtains a very simple expression of the differential cross section $d\sigma/dq^2$ in terms of the isobar rest frame helicity amplitudes. One has [5]

$$\frac{d\sigma}{dq^2} = \frac{G_C^2}{4\pi}\left[2uv|f_0|^2 + \frac{-q^2}{q_c^2}(u^2|f_+|^2 + v^2|f_-|^2)\right],$$

where

$$2M^2|f_\pm|^2 = \frac{1}{2}\sum_\lambda |\langle C,\lambda\mp 1|J_\pm|N,\lambda\rangle|^2, \qquad 4M^2|f_0|^2 = \frac{1}{2}\sum_\lambda |\langle C,\lambda|J_0 + \frac{q_{0c}}{q_c}J_z|N,\lambda\rangle|^2, \tag{5}$$

and $J_\pm = \frac{1}{2}(J_x \pm iJ_y)$. The weak hadron current is $J_\mu = J_\mu^V + J_\mu^A$. The u and v are functions of q^2 and of E and E',

‡2 It should be noted that the quark model presented by Fujimura-Kobayashi-Namiki [8] gives a suppression form $\int\phi_f^+\phi_i \propto (|\boldsymbol{q}|/\gamma)^L$, where $\gamma = (M^2+m^2)/2Mm$ at $q^2 = 0$. That form is quite similar to that of the model II for an excited state with large mass.

the lab. energies of initial and final lepton: $2Eu = E + E' + (M/m)q_c$ and $2Ev = E + E' - (M/m)q_c$. For the weak coupling G_c one has $G_c = G \sin \theta_c$ for the weak charm production processes treated here.

The asymptotic q^2-dependence of the helicity form factors will be determined from the Drell-Yan threshold relation. If one has $\nu W_2 \sim (1-x)^{2c-1}$ ($c = 2$ corresponds to the canonical dipole case) and asymptotic suppression of the scalar cross section $\sigma_S \propto |f_0|^2$ relative to the transverse cross section $\sigma_T \propto |f_+|^2, |f_-|^2$ versus $\sigma_S/\sigma_T \sim q^{-2}$ one obtains

$$f_\pm \sim (q^2)^{-c+1/2}, \quad f_0 \sim (q^2)^{-c-1/2}. \tag{6}$$

In the case $\frac{1}{2}^+ \to \frac{1}{2}^+$ (unequal mass) this implies for the constraint free invariant form factors [9] $G_i^{\prime V,A} \sim (q^2)^{-1-c}$, where we define

$$\langle \tfrac{1}{2}^+ | J_\mu | \tfrac{1}{2}^+ \rangle = \bar{u}(p^*) \{ \gamma_\mu [G_0^{\prime V} - i\gamma_5 G_0^{\prime A}] + (i/2M)\, \sigma_{\mu\nu} q_\nu [G_1^{\prime V} - i\gamma_5 G_1^{\prime A}] + (1/M^2)(q^2\gamma_\mu - \not{q} q_\mu)[G_2^{\prime V} - i\gamma_5 G_2^{\prime A}] \}\, u(p). \tag{7}$$

For the $\frac{1}{2}^+ \to \frac{3}{2}^+$ transition one has $G_i^{V,A} \sim (q^2)^{-1-c}$ ($i = 0, 1, 2$) and $G_3^{V,A} \sim (q^2)^{-2-c}$, where we define

$$\langle \tfrac{3}{2}^+ | J_\mu | \tfrac{1}{2}^+ \rangle = \bar{u}_\beta(p^*) \Gamma_{\beta\mu}\, i\gamma_5\, u(p), \tag{8}$$

and where

$$\Gamma_{\beta\mu} = [G_0^V - i\gamma_5 G_0^A]\, g_{\beta\mu} + [G_1^V + i\gamma_5 G_1^A](q_\beta \gamma_\mu - \not{q} g_{\beta\mu})/M + (1/M^2)[G_2^V - i\gamma_5 G_2^A](q_\beta p^*_\mu - p^* q g_{\beta\mu}) + [G_3^V - i\gamma_5 G_3^A](q_\beta q_\mu - q^2 g_{\beta\mu})/M^2.$$

For the other cases treated in this paper constraint free invariant form factors can be defined in complete analogy to eq. (7) and (8).

For the invariant form factors we shall make a generalized meson dominance ansatz in the form of a product of meson poles as predicted by the dual current model [10] for leading baryon resonance excitation [11]. We write

$$F(q^2) = \prod_{n=0}^{N(c,J)-1} \left(1 - \frac{q^2}{m_M^2 + n\alpha'^{-1}}\right)^{-1}, \tag{9}$$

where m_M is the meson mass, α' the Regge slope and where the number of poles $N(c, J)$ is determined by the desired large q^2-behaviour as discussed before.

The form factors $G_i^{V,A}$ will in general obtain contributions from mesons with $J^{PC} = 1^{--}, 1^{++}, 1^{+-}, 0^{-+}$ and 0^{++}. In the case of charm production the mesons in (9) carry a charm unit. Since not much is known about the mass spectrum of charmed mesons yet, we shall be using one common set of mass values of the charmed mesons entering in eq. (9), namely the D* with mass 2.0 GeV [12]. For the Regge slope which determines the masses of the D*-recurrences we take $\alpha' = 0.5$ GeV^{-2}, a value that lies between the $\alpha' \approx 1$ GeV^{-2} of uncharmed vector mesons and the $\alpha' \approx 0.25$ GeV^{-2} of the ψ, ψ' sequence.

Results. The model is now completely specified: the quark model is used to calculate the $q^2 = 0$ helicity amplitudes which are then projected onto the invariant amplitudes at $q^2 = 0$. The invariant amplitudes are then continued to $q^2 \neq 0$ by the GMDM form factors as described before. Except for the transition $\frac{1}{2}^+ \to \frac{3}{2}^+$ we shall assume canonical behaviour ($c = 2$) for all form factors. For the former we take $c = 3$ corresponding to a faster fall-off of the N–Δ form factor as observed in electro-production experiments [13].

The model contains 4 parameters, namely the mass of the produced charmed baryon M, the mass of the charmed vector meson m_{D^*}, the slope of the D*-trajectory α'_{D^*} and the ratio of the masses of the n and c quarks. For these we use $m_n \approx (m/3) = 0.313$ GeV and $m_c \approx \frac{1}{2} m_\psi \approx 1.6$ GeV. The charmed baryon masses are estimated in a heuristic way by noting that every charmed baryon resonance ($C = +1$) has a strange baryon partner ($S = -1$) with the same values of I and J^P. We then estimate $M(C = +1) = M(S = -1) - m_\lambda + m_c$ with $m_\lambda \approx 0.466$ GeV. The results are not very sensitive to small variations in the masses M.

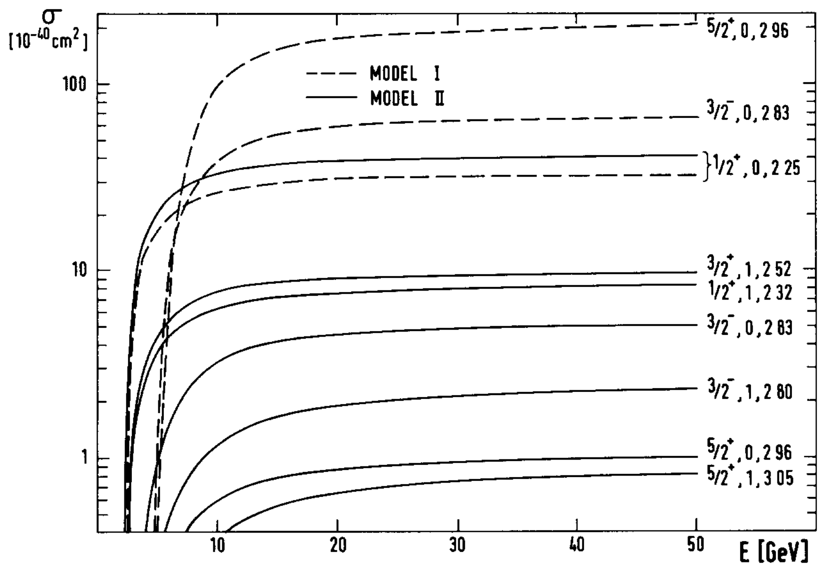

Fig. 1. Full line: Production cross sections for 7 prominent charmed baryons and resonances using model II. Dashed line: Production cross sections for $I = 0$ states with $J^P = \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+$ using model I.

The dependence on the form factor parameters α'_{D^*} and m_{D^*} is such that $\sigma(\text{small } \alpha'_{D^*}) > \sigma(\text{large } \alpha'_{D^*})$ and $\sigma(\text{small } M_{D^*}) < \sigma(\text{large } m_{D^*})$ which immediately follows from the form factors eq. (9). The variation for $0.25 < \alpha'_{D^*} < 1$ and $2.0\ m_D\ 2.2$ is not significant. Our subsequent discussion is based on the choice $\alpha'_{D^*} = 0.5\ \text{GeV}^2$ and $m_{D^*} = 2.0$ GeV [12].

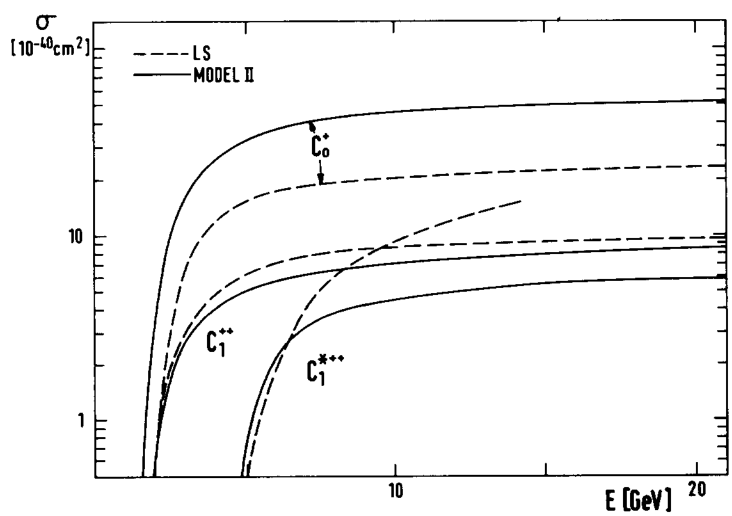

Fig. 2. Comparison of our results with results of LS. Mass parameters are $M_{C_0^+} = M_{C_1^{++}} = 2$ GeV and $M_{C_1^{*++}} = 3$ GeV, and, in the case of LS $m_{0^*} = 1.95$ GeV. For C_1^{*++} we take the LS tripole result.

An interesting point is the difference between the results of models I and II (fig. 1).

Model I has σ(ground state) $<$ σ(excited state), whereas model II gives σ(ground state) $>$ σ(excited state).

We believe therefore that the results of model II are more reliabel since the results of model I would lead to unreasonably large cross sections for high orbital excitations.

In fig. 1 we also present our predictions for the production cross sections of the remaining 4 $I = 1$ states using model II. The production cross section for C_0^+ off neutrons is large compared to the other cross sections. In fig. 2 we compare our results for the $L = 0$ states C_0^+, C_1^{++} and C_1^{*++} with those of Lee and Shrock (LS) [3] [‡3]. In order to facilitate the comparison with LS we use mass-parameters that differ from those of fig. 1. In the case of the C_1^{*++} we get similar results as LS. Our C_0^+ cross-section is ≈ 2 times larger than the result of LS. This discrepancy is not easily accounted for. The C_1^{++} cross section is smaller than the LS result for energies $E \gtrsim 7$ GeV. This is mostly accounted for by the fact that the q^2-dependence of their form factors is flatter than ours, since they are not imposing the asymptotic constraints eq. (6) on their form factors.

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‡3 The cross section estimates of ref. [4] are orders of magnitude lower. As remarked by LS, this is due to an imprudent choice of form factors.

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