CHARMED QUARK COMPOSITION OF THE NUCLEON AND ψ PHOTOPRODUCTION

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We present here the calculations on the ψ(3.1) photoproduction cross section, $\sigma(\gamma N \to \psi(3.1) + \text{anything})$, within the framework of Drell–Yan mechanism using the modified Kuti–Weisskopf quark parton distributions with a view to assessing the charmed quark contents of the nucleon. Our results show that the charmed quarks in the nucleon must be rarer than the strange quarks by about 50%.

One of the most plausible interpretations of the narrow resonances ψ(3.1) and ψ'(3.7) is that they are bound states of quark and antiquark ($c\bar{c}$) pairs, with the quarks carrying a new additive quantum number called charm. Based on this identification a class of models has been proposed to predict the properties of charmed quarks and hence those of the charmed hadrons [1].

The purpose of the present work is to make some speculations on the charmed quark contents of the nucleons by performing a Drell–Yan calculation of the ψ(3.1) photoproduction cross section. The main motivation has been derived from plausible arguments [1] to the effect that the charmed quarks are likely to be present at a lower level than the strange quarks in a nucleon. The essential ingredients of the Drell–Yan mechanism [2] are provided by the annihilation of the charmed quark (c) and its charge conjugate ($\bar{c}$) into the ψ resonance which subsequently decays into a massive lepton pair of mass-squared Q^2. Our calculations are based on the reasonable assumption that the ψ(3.1) is an SU(3) singlet, neutral vector particle with $I(J^{PC}) = 0(1^{--})$.

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Following Blankenbecler et al. [3] the general expression for the photoproduction differential cross section, $d\sigma/dQ^2$ ($\gamma N \to \psi(\to l\bar{l})X$), to form a massive lepton pair ($l\bar{l}$) in the mass region of the ψ can be written in the form

$$\frac{d\sigma}{dQ^2} = \frac{g^2_{\psi c\bar{c}} g^2_{\psi l\bar{l}} \int_0^1 dx \int_0^1 dy\, \delta(xy-\tau)\, [xyG(x, y)]}{12\pi[(Q^2-m^2_\psi)^2 - m^2_\psi \Gamma^2_{\psi\,\mathrm{tot}}]}, \tag{1}$$

where $\tau = Q^2/s$ and $G(x, y) = c_N(x)\bar{c}_\gamma(y) + \bar{c}_N(x)c_\gamma(y)$. Here $c_N(x)$ ($\bar{c}_N(x)$) represents the probability of finding a charmed quark (antiquark) in the nucleon with momentum fraction x.

In what follows we use the modified Kuti–Weisskopf (MKW) model [4] prescriptions to obtain the explicit forms of the quark parton distributions. It may be pointed out that the recent high energy experiments on the production of dilepton ($l\bar{l}$) continuum in pp collisions and the dip for small x in the νW_2 function per nucleon (assuming scaling) in μ–d deep inelastic scattering severely limit the options on various possible quark parton distributions. The MKW distributions appear unique in surviving these tests reasonably well. One of the distinctive features of this parametrization is that the antiquark distribution behaves like $(1-x)^{7/2}$ as was originally proposed by Kuti and Weisskopf which is in contrast, for instance, to the distributions of Chu and Gunion [3] or to those of Barger and Phillips [3] as discussed by Okada, Pakvasa and Tuan [4]. In addition, this particular choice is known to maximize the lepton pair cross sections and gives best agreement with the data, particularly in the region of large τ. We are, therefore, motivated to use the MKW distributions, in preference to others, in the calculations of the photoproduction cross sections.

The relative magnitude of the charmed quarks in the nucleons as compared with the corresponding amount of strange quarks can be assessed quantitatively if we assume that the distribution of charmed quark in the nucleon is given in terms of a simple multiple (charm parameter η) of that of the strange quarks. The explicit form of the distribution is then written as

$$c_N(x) = \eta s_N(x), \quad s_N(x) = 0.1x^{-1}(1-x)^{7/2}, \quad c_N(x) = \bar{c}_N(x). \tag{2}$$

The corresponding charmed quark distribution in the photon is given by the expression [5]

$$c_\gamma(y) = \frac{\alpha e_c^2}{2\pi} \ln(s/m_c^2)\, [y^2 + (1-y)^2], \quad c_\gamma(y) = \bar{c}_\gamma(y), \tag{3}$$

where $e_c(=2/3)$ and $m_c(\sim 1.6$ GeV) refer to the charge and mass of the charmed quark, respectively.

The cross section $d\sigma/dQ^2$ can now be integrated over Q^2 in the region $Q^2 \sim m^2_\psi$ by making use of the fact that the ψ has an extremely small width ($\Gamma_\psi \ll m_\psi$). In this narrow width approximation we can write

$$[(Q^2-m^2_\psi)^2 + m^2_\psi \Gamma^2_{\psi\,\mathrm{tot}}]^{-1} \to \frac{\pi}{m_\psi \Gamma_{\psi\,\mathrm{tot}}}\, \delta(Q^2-m^2_\psi). \tag{4}$$

With this prescription the integrated cross section acquires the form

$$\sigma(\gamma N \to \psi(\to l\bar{l})X) = \frac{g^2_{\psi c\bar{c}} g^2_{\psi l\bar{l}}}{6 m_\psi \Gamma_{\psi\,\mathrm{tot}}} \int_\tau^1 dx \frac{\tau}{x} \left[c_N(x) c_\gamma(\tau/x)\right]. \tag{5}$$

The cross section $\sigma(\gamma N \to \psi X)$ can be readily obtained from the above expression (5) on dividing $\sigma(\gamma N \to \psi(\to l\bar{l})X)$ by the branching ratio $\Gamma_{\psi l\bar{l}}/\Gamma_{\psi\,\mathrm{tot}} \approx 0.67$. In Fig. 1 we plot

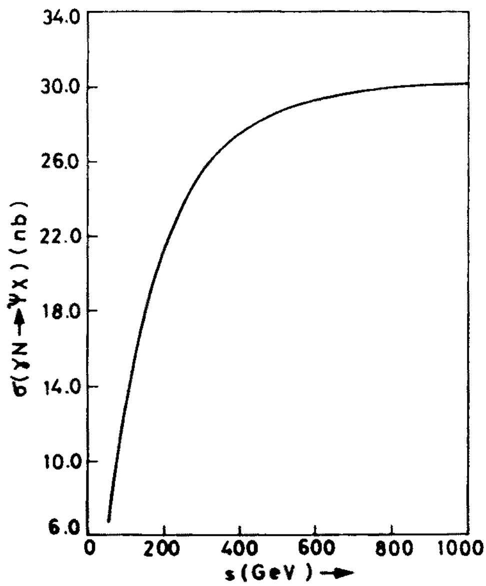

Fig. 1. Plot of the total photoproduction cross section, $\sigma(\gamma N \to \psi X)$ (in nb) as a function of the squared center-of-mass energy s (in GeV^2). The charm parameter η is taken to be 1

the integrated cross section $\sigma(\gamma N \to \psi X)$ as a function of the various squared center-of--mass energies (s) accessible at Fermilab.

For the sake of completeness we also calculate the longitudinal distribution of ψ production. The relevant expression for $d\sigma/d\xi$, where $\xi = 2Q_L/s^{\frac{1}{2}}$ and Q_L is the longitudinal momentum of the observed lepton pair, can be written as [2, 3]

$$\frac{d\sigma}{d\xi} = \frac{g^2_{\psi c\bar{c}} g^2_{\psi l\bar{l}}}{6 m_\psi \Gamma_{\psi\,\mathrm{tot}}} \frac{\tau}{(\xi^2+4\tau)^{\frac{1}{2}}} c_N(\xi_1) c_\gamma(\xi_2), \tag{6}$$

where $\xi_1 = \frac{1}{2}[(\xi^2+4\tau)^{\frac{1}{2}}+\xi]$ and $\xi_2 = \frac{1}{2}[(\xi^2+4\tau)^{\frac{1}{2}}-\xi]$. In Fig. 2 we plot $d\sigma/d\xi$ as a function of ξ $(-1 \leqslant \xi \leqslant 1)$ for different values of s. For the purposes of computing expressions (5) and (6) the $\psi c\bar{c}$ coupling is assumed to be of the order of typical strong interaction so that we set $g^2_{\psi c\bar{c}}/4\pi = 1$, whereas the $\psi l\bar{l}$ coupling is adjusted from the known width ($\sim$ 4.8 keV) of the ψ into a pair of leptons ($l\bar{l}$) which, in the limit of point coupling, is given by the expression $m_\psi g_{\psi l\bar{l}}^2/4\pi = (2J+1)\,\Gamma_{\psi l\bar{l}}$.

The curves depicted in Fig. 1 and Fig. 2 have been plotted with the charm parameter $\eta = 1$. This particular choice of the charm parameter clearly corresponds to the case where the charmed quarks in the nucleon are present at the same level as the strange quarks.

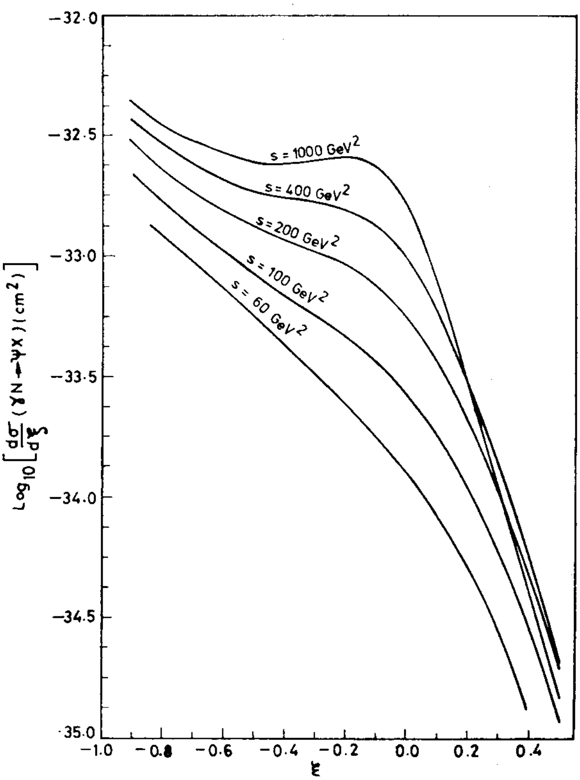

Fig. 2. Plot of Log $[d\sigma/d\xi(\gamma N \to \psi X)]$ as a function of the longitudinal momentum fraction (ξ) at s = (60, 100, 200, 400, 1000) GeV^2. The charm parameter is taken as $\eta = 1$

Based on this identification we find from an examination of Fig. 1 that the calculated photoproduction cross section for the process $\gamma N \to \psi(3.1)X$ is predicted in the range 15–28 nb for the squared c. m. energies $s \sim$ (100–200) GeV^2. This value is about a factor $\sim$ 1.5 larger than the corresponding yield of (10–20) nb in the same energy range, estimated from VMD arguments. Agreement of our results can be obtained by suppressing the calculated cross section by $\sim$ 1.5, which essentially amounts to reducing the charm parameter η by this factor. This is done by setting $\eta = 1/1.5$ giving rise to $\eta^2 \approx 0.5$, which represents precisely the probability of finding a charmed quark relative to a strange one within the nucleon. From this analysis it immediately follows that the amount of charmed quarks in the nucleon is about half as much as that of the strange ones. This observation lends additional support that the ψ shares the same common features with the ordinary vector mesons in the spirit of VMD [6]. Furthermore, if the experimental evidence on ψ photoproduction happens to support the VMD estimates we are led to the conclusion that the charmed quarks in the nucleon must exist at a level lower than the strange quarks by about 50%.

Conclusions arrived at in the present work are in conformity with other approaches, viz., Regge–Pomeron or asymptotic freedom suggesting weaker $c\bar{c}$–Pomeron coupling than $q\bar{q}$–Pomeron coupling. This is further confirmed from ψ-p total cross section inferred from $\gamma p \to \psi p$ experiments via vector dominance that $\sigma(\psi p) < \sigma(\phi p) < \sigma(\varrho p)$, implying thereby that the pomeron couples more weakly to charmed quarks than to strange quarks. Hence the concentration of charmed quarks in the sea is less than that of strange quarks. It is also worth noting that the maximum contribution to the cross section comes from the wee partons (carrying small momentum fraction x) in the nucleons [7].

Finally, the results presented in this note admit of modifications. For instance, a non-local vertex for the $\psi c\bar{c}$ coupling need to be used since the ψ is considered as a bound state $(c\bar{c})$ hadron. This modification, however, is expected to be small enough not to affect our results significantly.

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