Some considerations on the production mechanisms for the J and ψ particles and charmed particles*

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The recent discovery of J and ψ particles with anomalous properties, together with the theoretical expectation of charm related particles with predicted mass values accessible to the Fermilab range of energy, suggests that a reasonably systematic discussion of production mechanisms for these particles might be appropriate. We discuss here (a) hadron-initiated, (b) photon-initiated, and (c) lepton-initiated ($l = e, \mu$) mechanisms for the production of these objects.

I. INTRODUCTION

Recently several theoretical studies have been carried out[1,2] in the framework of the Weinberg-Salam phenomenology[3] concerning the masses of the charmed hadrons needed to understand the absence of strangeness-changing neutral current effects in a unified gauge theory of weak and electromagnetic interactions. The constraint of K_L^0-K_S^0 mass difference taken together with the absence of suppression of the $K_L^0 \to 2\gamma$ mode among others have sharply delineated the mass range possible for charmed hadrons. Gaillard *et al.*[2] have suggested that the most reasonable range for the lowest pseudoscalar state in their notation is

$$1.4 \lesssim m_D \lesssim 5 \text{ GeV}, \tag{1}$$

and that for the lowest $J=\frac{1}{2}$ baryon state it is

$$2.4 \lesssim m_{C_0} \lesssim 19 \text{ GeV}. \tag{2}$$

Hence (1) and (2) are amenable to a search in the Fermilab range of energy.

Our appetite for exotic particles was much enhanced by the recent *experimental* discovery of the $J(3.105)$ and the $\psi(3.695)$ with anomalously long lifetimes.[4,5] The phenomenological properties of these states from e^+-e^- colliding beams (such as are known to date) have been discussed by a number of authors.[6,7] Theoretical explanations not including a conventional hadronic model of the new particles[8] can generally be categorized into three main theme directions:

(1) The exceedingly interesting suggestion of Nieh, Wu, and Yang[9] *that the $J^0(3.105)$ particle is part of an isotopic doublet set (J^+, J^0) and $(J^-, \bar{J}^0)$ with pairwise strong interactions with the usual hadrons (e.g., J^+J^-, $J^0\bar{J}^0 \to$ hadrons).* An additional additive t quantum number ($= \pm 1$) conserved in strong and electromagnetic interactions but violated in "weak" interactions (that governing the decays of the J and ψ particles) is suggested. In terms of this framework, the production characteristics of the J and ψ particles are especially interesting. For instance, it is known that whereas the J and ψ particles are both produced in the e^+-e^- colliding beam experiments,[4,5] the $\psi(3.695)$ is very little produced at Brookhaven National Laboratory in p + Be collisions.[10] This suggests the following options:

(a) Both J and ψ particles are to be understood in terms of pair production in strong interactions at BNL. The threshold production mechanisms for J and ψ (Refs. 9 and 11) could then be

$$pp \to Hp\bar{J}, \tag{3a}$$

$$pp \to Hp\bar{\psi}K, \tag{3b}$$

$$pp \to J\bar{J}pp, \tag{3c}$$

$$pp \to \psi\bar{\psi}pp, \tag{3d}$$

where H is a new baryon and (3b) has center-of-mass energy 1.1 GeV higher than for (3a) (assuming that $2.16 < m_H < 4.04$ GeV); likewise the c.m. energy for (3d) is about 1.2 GeV higher than (3c). Since the BNL energy is low and it requires the Fermi motion of the nucleons inside the Be target nucleus to make pair production possible, this could therefore be the reason for the lack of production of $\psi(3.695)$ at BNL. While this option is certainly a possibility, one feels a little uneasy about the size of the production cross section for $J(3.105)$ in beryllium (of the order 10^{-34} cm^2/nucleon) since it does not fit readily into the presently known mechanisms for generating pairs in strong interactions as discussed in Sec. II below.

(b) The $J(3.105)$ is produced singly at BNL through its medium weak coupling with the usual hadrons. Model calculations for either a vector or axial-vector J produced singly in $p + p$ or

p + nucleus collisions with medium weak coupling to hadrons do indeed reproduce the required cross section up to a factor of 3 to 5 or so—as discussed in Sec. II. The same calculations would be somewhat strained to understand the very little amount of $\psi(3.695)$ produced (with a typical cross section[10] $< 10^{-36}$ cm^2 already) if the ψ has roughly comparable medium weak strength to the usual hadrons and charged leptons [note though that the discrepancy is removed if the leptonic branching ratio is smaller for $\psi(3.695)$ than $J(3.105)$ as may well be the case] and has $J^P = 1^+$ or 1^-. This suggests that the $\psi(3.695)$ and the $J(3.105)$ may have different spin-parity quantum numbers. For instance, the assignment $(1^+, 0^-)$ for J and ψ both with $t=1$ and $S=0$ would stabilize the decay of ψ into pseudoscalar meson $+J$ (e.g., $\psi^0 \not\rightarrow J^0 + \pi^0$, $\psi^0 \not\rightarrow J^0 + \eta^0$) while allowing the seen decay mode $\psi^0 \rightarrow J^0 + (\pi\pi)$, which is possibly a strong decay. One would have to arrange for the single production of a pseudoscalar ψ to be suitably small at BNL energy at least via the medium-weak interaction.[12] One must stress again[9] that a spinless $\psi(3.695)$, say, can be coupled to $(e\bar{e})$ and $(\mu\bar{\mu})$ without difficulty. It is a new type of coupling, but the strength of the medium-weak interaction already makes it different any way from any previous couplings.

Finally we show that at Fermilab and CERN-ISR energies, pair production of $J\bar{J}$, $\psi\bar{\psi}$, etc. via, say, the diffraction dissociation mechanism can give not only a large production cross section but also a qualitative understanding of the yield and charge symmetry for $(e^\pm/\pi^0)$ $(\mu^\pm/\pi^0)$ at Serpukhov[13] and Fermilab/CERN-ISR energies.[14] These considerations together with other strong production mechanisms are discussed in Sec. II.

(2) The weak boson hypothesis.[15] Here the J or ψ is "semiweakly" produced singly in p + nucleus collision, and as we have remarked earlier, the production characteristics of $J(3.105)$ can be understood on this basis, though that for $\psi(3.695)$ (Ref. 10) quite possibly could not, should the weak boson have spin 1. We can include in this category the model of Schwinger[16] in which the particle is very weakly coupled to hadrons, though, strictly speaking, the model does allow for paired couplings with normal hadrons but with much attenuated strength.[17] A key signal for this class of models is that the $J(3.105) \rightarrow \nu\bar{\nu}$ mode should be present at a comparable rate[15] to $(e\bar{e})$ and $(\mu\bar{\mu})$ or at the 10% level in the Schwinger model.[16]

(3) The charmonium model.[18] Here the J and ψ are identified as the $^3S_1$ ground and radially excited state[19] ϕ_c of the $c\bar{c}$ system. In terms of production mechanism, the ϕ_c is expected to be *singly* produced in strong interactions in the BNL experiment. De Rújula and Glashow[18] point out that the Hagedorn thermodynamic model[20] gives the correct cross section for $\sigma(pp \rightarrow M_J + \cdots)$. However, the same argument applied to $\psi(3.695)$ would lead to a cross section of 5×10^{-34} cm^2 (see Sec. II below)—hence consistency with the characteristics of the little-produced $\psi(3.695)$ at BNL[10] is generally possible only by assuming a branching ratio $B(\psi\rightarrow e^+e^-/\psi\rightarrow \text{all}) < 0.2\%$. In Sec. III we show that diffractively produced orthocharmonium in an energetic photon beam can be a good test for the charmonium idea since a purely diffractive photoinduced process is unlikely to produce a weak boson[15] or a singly produced J^0 with $t \neq 0$ ($t=0$ for the photon) under categories (2) and (1) above. Of course it must also be understood that there is not yet a completely convincing explanation of the small hadronic width of $J(3.105)$.[7,19]

In Sec. II we discuss production cross sections for various mechanisms that take advantage of hadron-initiated states. Photon-initiated production is considered in Sec. III, while Sec. IV considers the possible cross sections in lepton-hadron ($l=e, \mu$) processes. Both the J and ψ and (where relevant) the charmed hadrons [e.g., the charged partners of the bound charm $\phi_c = J(3.105)$?] are considered. We have not studied neutrino-induced processes here because they have been adequately covered by existing literature for the case of charm[1,2] and weak boson.[15] For the new t-quantum number interpretation,[9] the $(\nu\bar{\nu}J)$ and $(\bar{\nu}lJ^\pm)$ couplings are expected to be small—perhaps vanishing.[21] Finally, in what follows we shall often use the generic symbol X to denote these new classes of particles (be it J, ψ, Z^0, ϕ_c, etc.) for convenience and generality.

II. HADRON-INITIATED PRODUCTION PROCESSES

We begin the discussion here by analyzing first the purely strong processes of production, starting from the pessimistic end. Easily the most pessimistic is the thermodynamics model[20] with its essentially energy-independent prediction of exponential damping arising from a universal temperature T of the order of 160 MeV.[22] Following De Rújula and Glashow,[18] the single production of a massive particle M is given by

$$\sigma(pp\rightarrow M+\cdots)/40 \text{ mb} \cong (M/m_\pi)^{3/2}e^{-M/T} = H(M)\,. \tag{4}$$

For *pair* production of particles of masses M_1 and M_2, the order-of-magnitude estimate for production can be obtained by replacing the right-hand side of (4) by

$$H(M_1)H(M_2)\,. \qquad (5)$$

For orthocharmonium, (4) yields a cross section $\sim 10^{-33}$ cm^2 or 10^{-34} cm^2 for e^+e^- production via the $J(3.105)$ resonance, agreeing with experiment.[4] However, Eq. (4) applied to a singly produced $\psi(3.695)$ as appropriate to the charmonium case would give a cross section of order 5×10^{-34} cm^2; hence consistency with the upper limit set by Aubert *et al.*[10] would require that branching ratio $B(\psi\to e^+e^-/\psi\to \text{all})$ satisfy

$$\sigma(pp\to M_{\psi}\,(\to e^+e^-) + \cdots) = 5\times 10^{-34}B < 10^{-36}\ \text{cm}^2 \qquad (6)$$

or $B< 0.2\%$. Associated production of a pair of charmed 2.2-GeV hadrons [e.g., the D pseudoscalar pair given by Eq. (1) or perhaps a 1^- D^* of Gaillard *et al.*[2]] would give via (4) and (5) a cross section of 10^{-34} cm^2 which is a disappointingly small result.[23] Pair or associated production via Eq. (3) of the J and ψ particles yield an upper limit of about 10^{-38} cm^2 for detecting either particle through the e^+e^- leptonic mode.

A more optimistic estimate of pair production of massive states has been proposed by Dorfan *et al.*[24] in connection with their pair search in strong interactions for heavy massive triplets and the antideuteron at BNL energy. The estimate is[25]

$$\sigma(pp\to M+\overline{M}+\text{anything}) \sim f(m_p/M)^4\sigma(pp\to p+\overline{p}+\text{anything})\,, \qquad (7)$$

where $\sigma(pp\to p+\overline{p}+\text{anything})$ is the cross section for $\overline{p}$ production in p-p interaction and f is a coupling to reflect the possibly attenuated strength of $(M\overline{M})$ strong coupling with the usual hadrons from the canonical value $f=1$. The production cross section for $\overline{p}$ rises to a value near 1 mb at laboratory proton energies near 25 GeV, approximately four times the threshold energy.[26] It is less easy to assess a precise value for f; however, experience with possible suppression due to the production of a new quantum number (charm or t in our case) in the case of hyperon-antihyperon production (S quantum number)[27] at least at moderate energies, together with the requirements of specific models,[28] do suggest that f might lie in the range 1 to 10^{-2}. A charmed particle [e.g., an m_D or m_D^* (Ref. 29)] or a $t\neq 0$ particle[9] (e.g., $t=1$ or -1, $S=1$ or -1, $B=0$) with mass, say, 2.2 GeV might well be produced with a cross section $>10^{-31}$ cm^2 according to this picture for incident lab energy of 30 GeV, say. Depending on the branching ratio B for the (πK) mode,[30] a search for (πK) peak in this mass range in $p+\text{Be}\to(\pi K)+\text{anything}$ with a sensitivity in cross section $\lesssim 10^{-31}B$ cm^2 might be of some interest. Application of Eq. (7) (even with $f\sim 10^{-2}$) for production of $\psi(3.695)$ would lead, however, to too large a cross section[10] unless $B(\psi\to e^+e^-/\psi\to\text{all}) < 2.5\times 10^{-5}$.

The production of X pairs via X exchange in the peripheral model[31] has also been estimated some time ago.[32] A cross section of a fraction of a mb can be obtained only if it is assumed that all momentum transfers $\Delta^2 \lesssim M_X{}^2$ are effective, without significant damping by form factors at the vertices. If this process is interpreted in terms of groups of states (with X quantum number) exchanged, this estimate may not be totally unreasonable.

Finally, the empirical suggestion[26] that the relative production of pions and $\overline{p}$ (at least at lab energies 4 times threshold energy) do follow roughly the proportionality rule $m_\pi{}^{-2}:m_p{}^{-2}$ has given impetus to the study of what constitutes the *maximal* cross section for production of heavy particles in strong interactions. The consensus seems to converge on a mechanism for production akin to diffraction dissociation.[33] Here we have chosen to visualize the production at energies much greater than threshold. In this region, diffraction dissociation, Pomeranchuk-trajectory exchange would seem to be the most reasonable hypothesis. In Fig. 1, M^* is supposed to carry a major fraction of the incident energy and to represent a group of intermediate states, which decay into X_1 and $\overline{X}_2$ (and very likely, some associated π's). Such a mechanism, when summed over all channels containing $X_1\overline{X}_2$ pairs, is expected to lead to a cross section roughly constant with energy.[34] As the energy is decreased toward threshold, the minimum momentum transfer Δ^2 increases; at energies $\gtrsim$ 3 to 4 times the threshold $\Delta^2 > 0.1$ GeV^2, so that suppression of the diffractive process can be expected. To wit, if X_1,

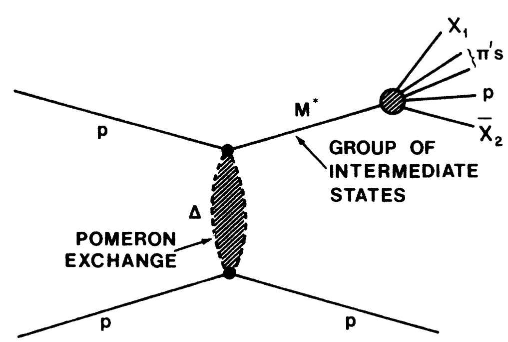

FIG. 1. Diffraction-dissociation model for X production in strong interactions.

$\overline{X}_2$ are produced in the forward direction in the center-of-mass system, then the minimum momentum transfer to the target nucleon is

$$\Delta_{\min} \approx m_p E_0^{\text{lab}}/E^{\text{lab}}, \tag{8}$$

where E_0^{lab} is the threshold for production of X. For

$$E^{\text{lab}} \gtrsim 4E_0^{\text{lab}} \text{ and } \Delta_{\min}{}^2 < 0.1 \text{ GeV}^2 \tag{9}$$

we can expect "diffraction dissociation" to dominate as a possible efficient production mechanism.

The nova model of diffractive production[35] provides a particularly convenient method for calculating an upper limit to the production cross sections for J and ψ and charmed particles. In this model, either the target or projectile proton is diffractively excited to a higher mass "resonance" M^*, which then decays (cf. Fig. 1). The total diffraction cross section upon summing over all M^* channels possible is

$$\sigma = \int \rho(M^*) dM^* . \tag{10}$$

$\rho(M)$ is called "the excitation spectrum." For this calculation, $\rho(M)$ is assumed to be independent of s [(c.m. energy)^2 for pp] and of the form

$$\rho(M) = \frac{c \exp[-\beta/(M-m_p)]}{(M-m_p)^2}, \tag{11}$$

where β is chosen so that $\rho(M)$ peaks at $M=1.9$ GeV (Ref. 35) and c is chosen so that as s increases, the single nova excitation mechanism accounts for all of the inelastic cross section ($\beta = 1.8$ GeV, $c = 60.5$ mb GeV). Threshold effects have been ignored although one might expect these to distort the spectrum at higher values of the momentum transfer Δ^2.

To produce various decay particles of interest, a minimum M^* is needed. Total diffractive cross sections are calculated for a range of M^* from 4 to 24 GeV [as is appropriate for pair production of the lowest charmed states; cf. Eq. (1) and Eq. (2)] and are plotted in Fig. 2 for useful values of s covering the BNL, Fermilab, and CERN-ISR ranges from

$$\sigma = (c/\beta)\{\exp[-\beta/(\sqrt{s} - 2m_p)] - \exp[-\beta/(M^*_{\min} - m_p)]\}. \tag{12}$$

Using for $M^*_{\min}$ $M_J + m_p \approx 4.1$ GeV, $M_\psi + m_p \approx 4.7$ GeV, $M_J + M_{\bar{J}} + m_p \approx 7.2$ GeV, and $M_\psi + M_{\bar{\psi}} + m_p \approx 8.3$ GeV, for single and pair production of J and ψ, we show in Table I the values for σ (in mb).

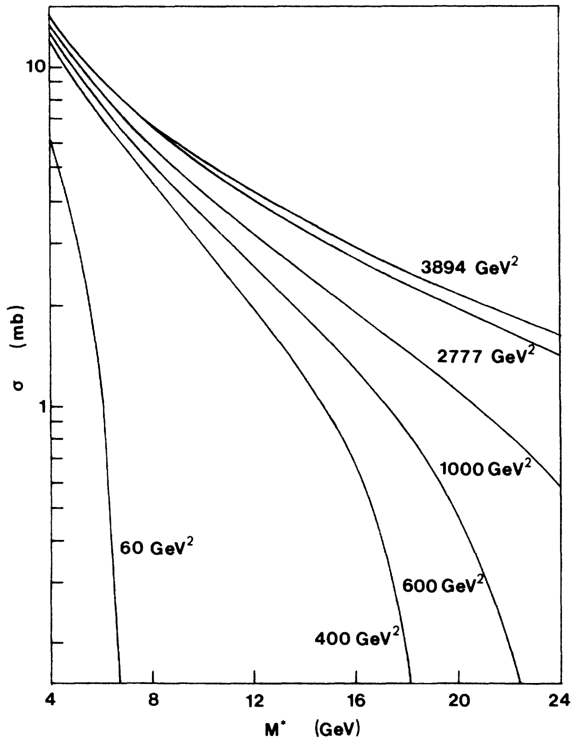

FIG. 2. Maximal cross sections σ (mb) as a function of the minimum M^* (in GeV) appropriate to the production of the particles of interest (charmed hadrons, J, ψ, etc.) at BNL ($s = 60$ GeV^2), Fermilab ($s = 400$, 600, 1000 GeV^2) and CERN ISR ($s = 2777$, 3894 GeV^2).

Remarks

(i) The production cross sections σ shown in Fig. 2 and in Table I are *emphatically* upper limits to a possible strong interaction production cross section. Though the integration in Eq. (10) is carried out from the kinematic threshold for possible production of X or X pair consistent with selection rules, it is certainly reasonable that the M^* range would include channels in which X is not present. It is expected, however, that X_1 and $\overline{X}_2$, which carry t or C quantum number

TABLE I. σ (in mb) at various energies with $M^*_{\min}$ corresponding to the threshold for single and pair production of J and ψ particles from pp initial states.

$M^*_{\min}$ (GeV) \ s (GeV^2)	60	400	600	1000	2777	3894
4.1	5.88	11.84	12.48	13.11	13.95	14.15
4.7	4.04	9.99	10.62	11.25	12.09	12.29
7.2	···	5.45	6.09	6.72	7.56	7.76
8.3	···	4.31	4.94	5.57	6.41	6.60

akin to B or Y, should emerge with a sizable finite fraction of the incident energy with good probability; this seems to be the case for baryon number (protons) and hypercharge (K and Y) at Fermilab energies.[36] Introducing as in (7) a parameter f to reflect the various possible suppressions, we guess that $f \sim 10^{-2}$ as suggested by some models[28] and hence

$$\sigma(pp \to X_1 + \bar{X}_2 + \cdots) = f\sigma \cong 10^{-2}\sigma \text{ mb}. \quad (13)$$

Such an estimate implies an X-pair production between one and two orders of magnitude smaller than the associated YK production cross section[36] which seems eminently reasonable. We wish to point out that more drastic suppressions, e.g., $f \sim (M_\rho/M_J)(\Gamma_J/\Gamma_\rho)$ [ratio of couplings $(g^2/4\pi)$ to normal hadrons] have also been suggested in connection with spin-1 J and ψ particles.

(ii) The diffractive mechanism for production is valid only at energies substantially above threshold. Hence use of (13) should be made only in conjunction with (8) and (9). For a charmed pair $m_D + m_{C^0}$ at the upper end of range given by (1) and (2) (e.g., for $M^* = 24$ GeV), the kinematic threshold $E_0^{\text{lab}} = 312$ GeV; hence the full force of a diffractively produced charmed pair of this mass would not be evident until the highest Fermilab ($s = 1000$ GeV^2) and CERN-ISR ($s = 2777$ GeV^2, 3894 GeV^2) energies are deployed. Here a production cross section of order 10^{-29} cm^2 may not be unreasonable as seen from Fig. 2 and Eq. (13). For an $m_D + m_{\bar{D}}$ at the lower end of the range ($M^* = 4$ GeV), even the lowest Fermilab energy ($s = 400$ GeV^2) should be able fully to explore such pair production at the level of 10^{-28} cm^2. For the J and ψ particles, it is difficult to understand the production of $J(3.105)$ as a singly produced charmonium ϕ_c via diffraction dissociation since the expected cross section would be about 6×10^{-29} cm^2 [though perhaps the BNL energy is not high enough for diffraction production of $\phi_c(3.105)$ to set in]. The t-quantum number model,[9] on the other hand, looks quite attractive. According to Table I, the basic production mechanism $pp \to X\bar{X} + \cdots$ does not allow kinematically for production of $J + \bar{J}$ or $\psi + \bar{\psi}$ ($E_0^{\text{lab}} > 32$ GeV) at $s = 60$ GeV^2; however, a fully allowed diffractive production cross section can be expected for $E^{\text{lab}} \gtrsim 120$ GeV [according to (8) and (9)]. Hence, throughout the range of Fermilab energies one could expect production of J and ψ pairs at the level of 10^{-29} cm^2. The probability of "direct" charged lepton events[37] with large $p_\perp$ relative to collision axis is crudely

$$P \sim \frac{f\sigma}{\sigma_{\text{tot}}} B((X^0, \bar{X}^0) \to l^+ l^- / (X^0, \bar{X}^0) \to \text{all}), \quad (14)$$

while the J/π and/or ψ/π ratio can go as high as 10^{-3}. Such a high ratio can explain the unexpectedly large lepton yield at high transverse momenta in pp at Fermilab/CERN-ISR energies,[14] viz.

$$e^\pm/\pi^0 \simeq \mu^\pm/\pi^0 \sim 10^{-4}, \quad (15)$$

with no significant charge asymmetry nor asymmetry between μ and e *and* a ratio remarkably constant. The lower yield $\sim 0.25\times 10^{-4}$ reported by Serpukhov[13] can perhaps be explained by the fact that at 76-GeV E^{lab} we have not yet reached "saturation" cross section for diffractively produced $J\bar{J}$ and/or $\psi\bar{\psi}$ pairs according to (8) and (9). Note that for a singly produced charmonium $\phi_c(3.105)$ [and/or $\phi_c(3.695)$], one might have expected diffractive production to be fully operative at Serpukhov energies and hence the yield should be comparable to (15); for charmed particles a +/− charge asymmetry may be present.

In concluding this section it is perhaps appropriate to consider some model calculations of "weak" single production of X^0 in hadron-initiated collisions. They are relevant to the class (2) models[15] of weak bosons which attempt to relate the J and ψ particles also with the evidence for neutral currents in neutrino experiments. In discussing neutrino experiments, one appeals often to the parton model which has been found to work very well in accounting for leptoproduction data. Experimental support for or against its applicability for timelike momentum transfer is clouded precisely by the appearance of new J and ψ particles. Nevertheless, if the Drell-Yan picture is valid for hadronic production of virtual timelike photons in the 3-GeV mass region, it would also be expected to be valid for the production of an X^0 in the same mass region. It is possible to relate the production for $p + p \to X^0(\to l^+ l^+) + \text{anything}$ with $p + p \to (\gamma \to l^+ l^-) + \text{anything}$ as follows[38]:

$$\sigma(p + p \to X^0 + \cdots)\Big|_{X^0 \to l^+ l^-} = \frac{3g^2}{8\alpha^2}\left(\frac{\sigma_\mu}{\sigma_h}\right)\frac{r'}{r} M_{X^0} \frac{d\sigma}{dq}(p + p \to \gamma + \cdots)\Big|_{\gamma \to l^+ l^-}\Big|_{q = M_X} \quad (16)$$

Here $g^2 \sim 4\times10^{-6}(M_X/m_p)^2$, $\sigma_h/\sigma_\mu \sim 2.5$ to 3 is taken from the observed (background) cross-section ratio for e^+e^- annihilation in the 3- to 4-GeV region, while $d\sigma/dq|_{q=M_X}$ is calculated from the Drell-Yan picture.[39] Specific models are needed to estimate (r, r'). For instance if X^0 is coupled to a "weak isospin" current, $X^0[g_h(\bar{p}p-\bar{n}n)+g(\bar{\nu}_L\nu_L-\bar{l}l)]$, where $\nu_L=\frac{1}{2}(1-\gamma_5)\nu$ (and γ_μ or $\gamma_\mu\gamma_5$ is understood), we obtain [38] $(r,r')=(3,3)$ and $g_h/g \gtrsim 1.5$. If it couples to Sakurai's baryonic and leptonic currents,[15] $X^0[g_h/3(\bar{p}p+\bar{n}n+\bar{\lambda}\lambda)+g(\bar{l}l+\bar{\nu}_L\nu_L)]$, we obtain $(r,r')=(\frac{1}{2},\frac{1}{3})$ and $g_h/g \gtrsim 4$.

Tables II and III tabulate $\sigma(p+p\to X^0(\to l^+l^-)$ + anything) for J^0 and ψ^0 as a function of s in the two models, respectively. It is seen that one could understand the BNL- ($s=60$ GeV^2) cross section for producing $J^0(3.105)$, at least up to a factor of 3 to 5 or so. One would be somewhat more hard pressed to understand the *lack* of production of $\psi(3.695)$ at BNL (if substantially below 10^{-36} cm^2) should the latter also have spin and parity $J^P=1^\pm$. However, even here one should exercise caution about excessive alarm since the assumption that the ψ has roughly comparable medium-weak strength to the usual hadrons and charged leptons as the J^0 is implicit in our calculations. A smaller leptonic branching ratio for $\psi^0(3.695)$ than $J^0(3.105)$ can enable us to readily understand the present level of absence of ψ^0 production in hadron collisions at BNL energy.[10] Note that our cross sections at $s=60$ GeV^2 for J^0 production are approximately an order of magnitude larger than those of the CERN Theory Boson Workshop.[38] This is because we have used the quark-parton distributions of the modified Kuti-Weisskopf model[39] successful in understanding both eN, νN data and a reanalysis of the earlier Columbia dimuon experiment $pU\to\mu^+\mu^-+X$. These distributions do not include, however, the $c\bar{c}$ annihilation mode (should J and ψ be related to the charmonium picture) in order to preserve our present discussion on as general a level as possible. It has been suggested by Gaillard[1] that the charm distribution in the nucleon is small; hence the charmonium interpretation for $J^0(3.105)$ might well lead to the expectation of a *small* J^0 production cross-section contribution via the Drell-Yan mechanism in nucleon-initiated collisions.

III. PHOTON-INITIATED PRODUCTION PROCESSES

Photoproduction of a pair of charmed particles directly via the thermodynamic model is of order $10^{-28}[H(M_c)]^2$ cm^2. Hence for $M_c>2$ GeV, the cross section is $<4\times10^{-36}$ cm^2. On the other hand, photoproduction in the nuclear Coulomb field [Fig. 3(a)] is suppressed by just a nominal α^2, and can be as large as $\alpha^2 10^{-30}$ cm^2, and hence is a good prospect for an energetic photon beam.

The orthocharmonium model for $X(3.105)$ and/or $X(3.695)$ can be best tested by studying the diffractive forward production process

$$\gamma+N\to\phi_c+N', \quad \gamma+\text{nucleus}\to\phi_c+\text{anything}, \tag{17}$$

as indicated in Fig. 3(b). Note that diffractive forward photoproduction is not possible in the weak boson model[15] nor in the t-quantum number model of Yang *et al.*[9] since the $\gamma\leftrightarrow X$ transition violates t conservation in electromagnetism. Typically the estimates[2,18] for

$$\left.\frac{d\sigma(\gamma N\to\phi_c+N)}{dt}\right|_{t=0}$$

range from 6 to 40 μb/GeV^2 for p_γ from 100 to 200 GeV. Characteristic features of diffractive

TABLE II. Cross sections of J and ψ particles according to the "weak" isospin current model. Colored quarks suppress these cross sections by another factor of 3. The parameter $r'=\frac{36}{11}$ instead of 3 for proton-heavy nucleus scattering.

s (GeV^2)	$\sigma(pp\to X^0(3.105)+\cdots)$, $X^0\to l^+l^-$ (cm^2)	$\sigma(pp\to X^0(3.695)+\cdots)$, $X^0\to l^+l^-$ (cm^2)
60	0.33×10^{-34}	0.42×10^{-35}
400	0.45×10^{-33}	0.28×10^{-33}
600	0.75×10^{-33}	0.39×10^{-33}
1000	1.38×10^{-33}	0.50×10^{-33}
2777.3	0.17×10^{-32}	1.08×10^{-33}
3893.8	0.18×10^{-32}	1.28×10^{-33}

TABLE III. Cross sections for production of J and ψ particles according to the baryonic- and leptonic-currents model. Colored quarks suppress these cross sections by another factor of 3. The parameter $r'=\frac{4}{11}$ instead of $\frac{1}{3}$ for proton–heavy nucleus scattering.

s (GeV^2)	$\sigma(pp\to X^0(3.105)+\cdots)$, $X^0\to l^+l^-$ (cm^2)	$\sigma(pp\to X^0(3.695)+\cdots)$, $X^0\to l^+l^-$ (cm^2)
60	0.22×10^{-34}	0.28×10^{-35}
400	0.29×10^{-33}	0.19×10^{-33}
600	0.49×10^{-33}	0.26×10^{-33}
1000	0.91×10^{-33}	0.33×10^{-33}
2777.3	0.11×10^{-32}	0.71×10^{-33}
3893.8	0.12×10^{-32}	0.84×10^{-33}

production are, of course, a sharp peak in the forward t direction and a cross section relatively independent of beam energy (up to log terms) once the diffractive process has truly set in.

Photoproduction of weak bosons[15] via the hadronic electromagnetic current [Fig. 3(c)] is possible, though the typical production cross section $\sigma(\gamma N \to X^0(3.105) + \text{anything})$ identified via the e^+e^- mode, say, is not higher than about $\beta_{ee}\alpha\sigma_{st}(pp \to X^0 + \text{anything}) < \beta_{ee}10^{-30}$ cm^2 [where $\beta_{ee} = g_{ee}{}^2/4\pi = 2\times 10^{-6}$ or thereabout from the phenomenological medium-weak properties[9] of $X^0(3.105)$]. This is in reasonable agreement with theoretical estimates[40] using a simple quark-parton model for a 20-GeV photon beam. Of course, singly produced charmonium ϕ_c could also occur via Fig. 3(c); however, the signature would not be so readily identified as that of diffractive production [Fig. 3(b)].

A possible mechanism for generating photoproduced (J^+, J^0) or $(J^-, \bar{J}^0)$ sets that have pairwise strong interactions[9] with the normal hadrons $(N, N'$, nucleus, etc.) is shown in Fig. 3(d). This is of course not a diffractive process but rather a "peripheral"-type mechanism such as has already been discussed for strong interactions in Sec. II. The production cross section suppressed by fine structure constant α can be of order of magnitude $\alpha\sigma_{st} \sim 10^{-30}$ to 10^{-32} cm^2. This is admittedly a guess which ignores the $(1/M_{X^\pm}{}^2)^2$ of the $X^\pm$ propagator (a factor of order 10^{-1}–10^{-2}). A more precise treatment needs to include phase space and spin factors which compensate the propagator in a not too simple way. Though the cross section due to Fig. 3(d) can be comparable to that characteristic of diffractive photoproduction [Fig. 3(b)], the mechanism here can allow the relatively heavy $X^\pm$ exchanged state to kick the N(nucleus) hard in strong vertex $X^\pm N \to (X^0, \bar{X}^0)N'$, so production of X^0 or $\bar{X}^0$ does *not* depend so sensitively on momentum transfer to (N, N'). In particular, there is no reason to expect peaking specific to the forward direction. For instance in γ + nucleus $\to (l^+l^-)$ + anything, one might expect the 3.1-GeV/c^2 state to undergo large transverse-momentum elastic or quasielastic scattering much more frequently than other hadrons (at least if these latter are diffractively produced). Since a pair of X in the final state is involved, one would not expect to produce them via photoproduction at SLAC energy (peak photon energy of 18.2 GeV) as is consistent with available data.[41] The decay of $X^\pm \to (\text{hadrons})^\pm e^+e^-$ might exist with comparable strength to $X^0 \to e^+e^-$ (Ref. 42) after phase-space adjustments have been made.[9] However, from a purely observational viewpoint, the signal to $X^0 \to l^+l^-$ is likely to be the dominant one.

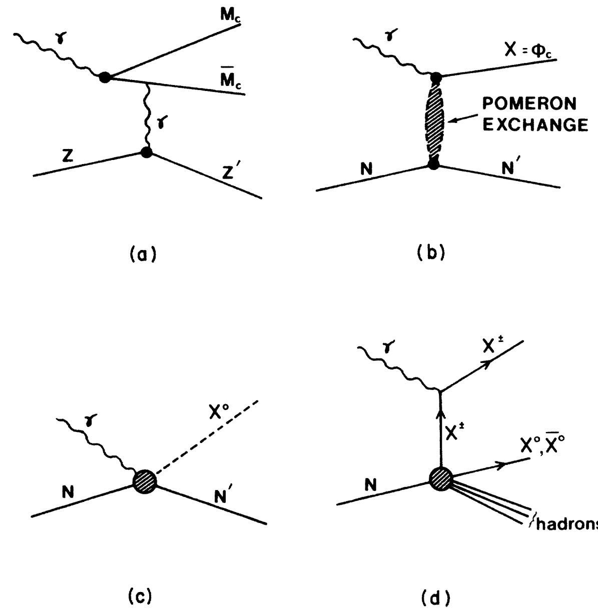

FIG. 3. (a) Photoproduction of charmed meson pair M_c in the Coulomb field of the nucleus. (b) Diffractive photoproduction of X [e.g., $X = \phi_c$ (3.105)]. (c) Photoproduction of X^0 via the hadronic electromagnetic current. (d) Mechanism for photoproduction of X pairs that have pairwise strong interactions with the usual hadrons.

IV. LEPTON-INITIATED PRODUCTION PROCESSES

Let us consider first the weak boson interpretation[15] for J and ψ. The diagrams for production of X^0 are shown in Figs. 4(a), 4(b), and 4(c) and have been generally studied by Brown *et al.*[43] Applied to $X^0(3.105)$,[40] the total electroproduction cross sections $e + N \to e + X^0 + N'$ from Figs. 4(a) and 4(b) are 1.3×10^{-39} cm^2 and 4.3×10^{-38} cm^2 at beam energies of 22.5 GeV and 200 GeV, respectively. As discussed by Brown *et al.*,[43] one must also add to the diagrams 4(a) and 4(b) the virtual photoproduction amplitude [Fig. 4(c)] which may increase these numbers substantially (?) if the coupling of X^0 to hadrons is enhanced relative to its coupling to leptons. This hadronic amplitude is of course model-dependent: A crude estimate would be to multiply the above cross sections by $\Gamma_{\text{hadronic}}/\Gamma_{\text{leptonic}} \sim 10$ for $X^0(3.105)$. Hence

$$\sigma(e^- + p \to e^- + X^0 + N) = \begin{cases} 1.3\times 10^{-38}\ \text{cm}^2 \text{ at } E_e = 22.5\ \text{GeV}, \\ 4.3\times 10^{-37}\ \text{cm}^2 \text{ at } E_e = 200\ \text{GeV}. \end{cases} \qquad (18)$$

If we assume that the cross section for $e(\mu) + p \to \text{all} \sim \alpha\sigma(\gamma p \to \text{all}) \sim 10^{-30}$ cm^2, then the weak X^0

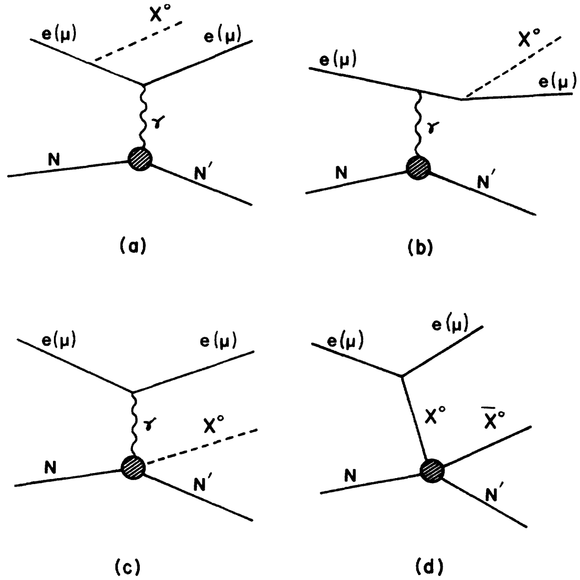

FIG. 4. Feynman diagrams for the production of X^0 by leptons in the electromagnetic field of some nucleus [diagrams (a) to (c)]. Diagram (d) illustrates a possible mechanism for generating X pairs from electroproduction.

boson electroproduction, identified via $(l\bar{l})$ mode at the X^0 mass, yields the branching ratios

$$\frac{e+p\to e+(l\bar{l})+\text{hadrons}}{e+p\to \text{all}} \sim \begin{cases} 1.3\times10^{-9} & (E_e=22.5\text{ GeV}),\\ 4.3\times10^{-8} & (E_e=200\text{ GeV}). \end{cases} \qquad (19)$$

Since the principle of $(\mu$-$e)$ universality is probably not violated in their interactions with the J particle,[40] Eqs. (19) likely give the correct order of magnitude also for $e\to\mu$.

If one assumes pairwise strong interactions[9] for the J and ψ particles, then one can produce J's and ψ's through the reactions [depicted in Fig. 4(d)]

$$e(\mu)+p\to e(\mu)+X+\text{hadrons}. \qquad (20)$$

An approximate production cross section for spin-1 $X\equiv J$ or ψ can be calculated, using the formalism of Kogut,[44] if the $(l\bar{l})X$ vertex interaction is represented by the effective Hamiltonian[9]

$$H=ig_{ee}[\bar{e}e]X+ig_{\mu\mu}[\bar{\mu}\mu]X+H_{\text{other}} \qquad (21)$$

(γ_λ or $\gamma_\lambda\gamma_5$ is understood). Assuming that the virtual X interacts with the hadrons only if it is transversely polarized and that the interaction is independent of the four-momentum and energy of the virtual X,[44] the results in Table IV are obtained in terms of g^2 and σ_t (cross section for transverse X on proton). Phenomenologically the value of g^2 for $J(3.105)$ is about[9] 5×10^{-5}, while the "geometric"-type cross section for σ_t can be between 2 to 20 mb. At SLAC energy of 20 GeV, the predicted cross section for $J(3.1)$ detected via its leptonic mode $(l\bar{l})$ is between $1.1\times10^{-34}B(J\to l\bar{l})$ cm^2 and $1.1\times10^{-33}B(J\to l\bar{l})$ cm^2. This is somewhat smaller than the conjecture of Yang *et al.*,[9] if one assumes that B is about $\frac{1}{10}$ to $\frac{1}{20}$ (as is consistent with data) and $e+p\to$ all has cross section of $\lesssim10^{-30}$ cm^2. Nevertheless, it would be of great interest to measure the cross section for $\mu+p\to\mu+l\bar{l}+$hadrons (where $l\bar{l}$ stands for $e\bar{e}$ or $\mu\bar{\mu}$ at the J mass) at the Fermilab energy $E_\mu=150$ GeV.[45] This cross section, according to the present premise, should not be much smaller than $0.25\times10^{-32}B$ cm^2.

TABLE IV. The total production cross sections for spin-1 X particles in lepton-nucleon processes $e(\mu)+N\to e(\mu)+X^0+$hadrons assuming that these particles have pair-wise strong interactions with the usual hadrons according to Fig. 4(d). Here E is the lab energy of incident lepton and M is the mass of the produced X-particle.

M (GeV) \ E (GeV)	20	56	150
3	$1.3\times10^{-3}g^2\sigma_t$	$9.4\times10^{-3}g^2\sigma_t$	$2.6\times10^{-2}g^2\sigma_t$
3.1	$1.1\times10^{-3}g^2\sigma_t$	$8.7\times10^{-3}g^2\sigma_t$	$2.5\times10^{-2}g^2\sigma_t$
3.7	$3.5\times10^{-4}g^2\sigma_t$	$5.4\times10^{-3}g^2\sigma_t$	$1.8\times10^{-2}g^2\sigma_t$
4.0	$1.7\times10^{-4}g^2\sigma_t$	$4.2\times10^{-3}g^2\sigma_t$	$1.6\times10^{-2}g^2\sigma_t$
4.2	$9.8\times10^{-5}g^2\sigma_t$	$3.6\times10^{-3}g^2\sigma_t$	$1.4\times10^{-2}g^2\sigma_t$
5.0	$1.2\times10^{-6}g^2\sigma_t$	$1.8\times10^{-3}g^2\sigma_t$	$9.8\times10^{-3}g^2\sigma_t$

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[11]After completion of our work, we received a report from T. K. Gaisser and F. Halzen [Report No. COO-435 (unpublished)] which overlaps in part some of the discussion in Sec. II here.

[12]Soft-pion arguments have sometimes given suppressed decays and couplings (cf. Ref. 2). However, the $\psi(3.695)$ cannot be really regarded as "soft."

[13]Reported by the Serpukhov group at the XVII International Conference on High Energy Physics, London, 1974 (unpublished). See also Ref. 2.

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