Psi production through three-gluon fusion

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We consider a mechanism for psi hadroproduction involving the fusion of a gluon from the beam hadron with two gluons from the target or vice versa. The matrix element is obtained by crossing from the charmonium decay amplitude. A model for the joint distribution function of two gluons in a hadron is constructed based on the counting-rule form for the single-gluon distribution function. Particularly strong effects are found in psi production from heavy nuclei, in agreement with recent experimental results.

I. INTRODUCTION

In recent years, the dominant model[1] for psi hadroproduction has been based on the parton subprocess

$$G+G \rightarrow \psi + G \; . \tag{1}$$

The matrix element for this process is obtained by crossing from the ψ decay amplitude into three gluons and is fixed in normalization by the ψ wave function at the origin as determined by the leptonic decay rate. The present experimental result for this parameter including leading-order QCD corrections is

$$|\Psi(0)|^2=(5.5\pm0.5\times10^{-3}\text{ GeV})M_\psi^{\,2} \; . \tag{2}$$

The suggested scaling as M^2 seems to holds also for the ϕ and Υ wave functions. Process (1) partially explains the longitudinal-momentum distribution and the relatively large observed transverse momentum of the typical hadroproduced ψ. Unfortunately the magnitude of the observed ψ production cross sections are considerably larger than expected on the basis of process (1) with reasonable values of the strong coupling constant. For example, using the standard gluon distribution function in a proton,

$$G(x)=(N+1)(1-x)^N/2x \; , \tag{3}$$

with $N=5$ (the counting-rule value) and with $\alpha(s)=0.22$ (the value suggested[2] at the scale of the ψ mass by charmonium decay rates and jet physics), the theoretical result for the ψ production cross section from process (1) falls short of the experimental values[3] by a factor of 20 at a c.m. energy of 19.4 GeV. If one uses an effective value of $\alpha(s)=0.37$, in anticipation of some "K factor" from higher-order QCD corrections, the theoretical cross section [proportional to $\alpha(s)^3$] is still significantly below the experimental values, as shown in the dashed curve of Fig. 1. The experimental fit of Ref. 3, shown by the solid curve in Fig. 1, is

$$\sigma_{\text{expt}}(pN\rightarrow\psi X)=(1700\text{ nb})e^{-17\sqrt{\tau}} \; , \tag{4}$$

where

$$\tau\equiv M_\psi^{\,2}/s \; .$$

One would, of course, expect the experimental values at higher energies than presently measured to rise above the fit of Eq. (4) since it seems unlikely that the inclusive ψ production cross section will be less than a constant fraction of the logarithmically rising total cross section. The asymptotic theoretical cross section from process (1) is

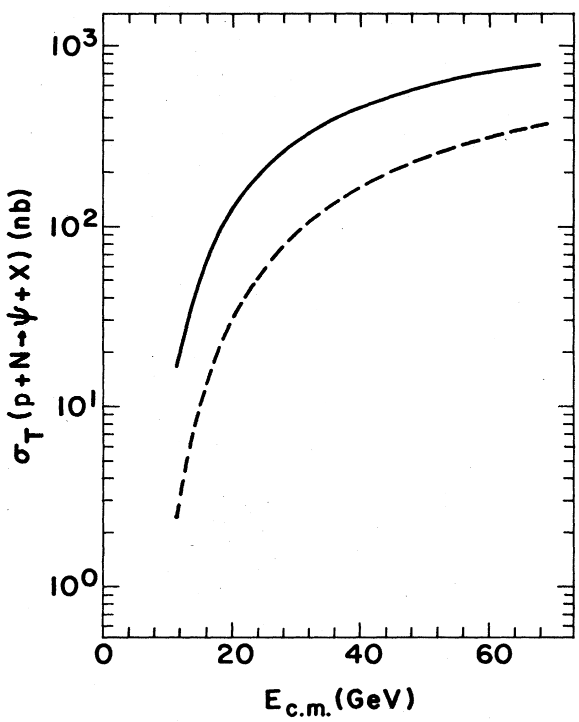

FIG. 1. Fit of Ref. 3 to the experimental total cross section in pN collisions (solid curve) as a function of the hadronic center-of-mass energy compared to the theoretical contribution from $GG\rightarrow\psi G$ (dashed curve) using $\alpha(s)=0.37$ (see text).

$$\sigma_{\text{theor}}(pN\to\psi X)$$
$$=\tfrac{20}{3}\pi^2\alpha(s)^3\frac{\Psi(0)^2}{M_\psi{}^5}(5\pi^2-48)\left[\frac{N+1}{6}\right]^2\ln(\tau^{-1})\ . \tag{5}$$

At sufficiently high energies the contribution from process (1) will rise above the extrapolated Eq. (4), and may, therefore, meet the data. Part of the excess cross section (30 to 40% of the experimental σ_{tot}) at present energies is understood as coming from ψ's occurring as decay products of a primarily produced higher charmonium state through processes such as

$$G+G\to{}^3P_J\ , \tag{6}$$

with the P-wave state decaying into $\psi\gamma$. This process is a model for the three-gluon fusion mechanism we wish to discuss in the present paper. Although large effective values of $\alpha(s)$, such as the 0.37 used in the dashed curve of Fig. 1, are usually justified in terms of expected higher-order effects, no large higher-order contributions to ψ hadroproduction have as yet been established.[4] The contribution from quark-gluon scattering, in fact, decreases the theoretical cross section by about 5% after the leading-mass singularity is absorbed into the scaling violations in the gluon distribution.[5]

In addition there are now experimental indications[6] that, at least in nuclei, effects beyond process (1) and its QCD radiative corrections are important. One of the most interesting of these effects involves the function

$$R(x_F)=\frac{A\,d\sigma(H)/dx_F}{d\sigma(A)/dx_F}\ . \tag{7}$$

The denominator here is the differential ψ production cross section on a heavy nucleus of atomic number A while the numerator is A times the corresponding cross section on hydrogen. In Eq. (7), x_F is the momentum component of the produced ψ in the beam direction divided by its kinematic maximum. The NA3 collaboration[6] has investigated $R(x_F)$ in their 150-to-280-GeV data on platinum ($A=195.09$). Experiments show a value $R(0)$ about 1.2 increasing to about 3 at $x_F=0.8$. The effect is even more pronounced if one restricts one's attention to the ψ's produced at low transverse momentum. Their results have been confirmed by the CERN Omega Spectrometer's data[7] on tungsten ($A=185$) at 39.5 GeV/c, although other groups[8] seem not to see a similar effect.

In this paper, we propose a model for these nuclear effects as well as for the "missing" production cross section on hydrogen based on the fusion of two gluons from the beam with one from the target and vice versa. We attribute the x_F dependence of R to the increased probability of obtaining two gluons from a heavy nucleus.

The necessity for three interacting gluons to produce a ψ due to color and spin-parity conservation makes ψ production a perhaps ideal experiment for studying correlated gluon distributions in hadrons.

In Sec. II, we discuss the formalism for a process with three partons in the initial state. Unlike the familiar case of a two-particle-initiated cross section, the present calculation involves an explicit volume dependence. We assume that this volume of quantization can be identified with the interaction volume. Although, at this point, this is basically a free parameter, we propose a model-dependent geometric estimate of the interaction volume. In Sec. III, we propose a simple extension of the single-gluon distribution function in a hadron to the probability to find two gluons with given fractions of the beam momentum. It is assumed that the effective value of the strong coupling constant is the same (0.37) for the three-gluon fusion as for the reaction of Eq. (1). We discuss numerical results including the A dependence of the ψ production cross section, the variation of the R parameter of Eq. (7) as a function of x_F and P_T, a prediction of the behavior of R for negative x_F, and the contribution of three-gluon fusion to the total ψ production cross section. In the concluding section we summarize our results and discuss the implications of the present model for photoproduction and for the production of excited charmonium states.

II. THREE-GLUON FUSION IN Ψ HADROPRODUCTION

For the sake of clarity in our further treatment, we can review the formalism including normalization factors in the case of the $2\to n$ cross section defined as the transition probability per unit time per target particle per unit incident flux:

$$d\sigma(2\to n)=\frac{|S(f,i)|^2}{T}\prod_f\frac{V\,d^3p_f}{(2\pi)^3}\frac{V}{|\mathbf{v}_1-\mathbf{v}_2|}\ . \tag{8}$$

The S-matrix element $S(f,i)$ is given in terms of the invariant matrix element, M, by

$$S(f,i)=\frac{(2\pi)^4\delta^4(\sum p_i-\sum p_f)M}{\left[\prod_i(2E_iV)\prod_f(2E_fV)\right]^{1/2}}\ . \tag{9}$$

The square of the δ function, as usually understood, brings in a factor of VT,

$$\left[(2\pi)^4\delta^4\left[\sum p_i-\sum p_f\right]\right]^2$$
$$=(2\pi)^4\delta^4\left[\sum p_i-\sum p_f\right]VT\ . \tag{10}$$

In the case of $GG\to\psi G$, the squared matrix element, including factors from spin and color averaging in the initial state, is

$$|M(GG\to\psi G)|^2=\tfrac{5}{9}[4\pi\alpha(s)]^3\Psi(0)^2M_\psi M_0(s,t)\ , \tag{11}$$

where

$$M_0(s,t)=\left[\frac{t^2}{D_s{}^2D_u{}^2}+\frac{u^2}{D_t{}^2D_s{}^2}+\frac{s^2}{D_t{}^2D_u{}^2}\right] \tag{12}$$

with $D_s=s-M_\psi{}^2$, $D_t=t-M_\psi{}^2$, and $D_u=u-M_\psi{}^2$. Putting together Eqs. (8)–(12) gives us the standard $2\to n$ cross section in which explicit reference to the interaction volume, V, cancels out:

$$d\sigma(2\to n)=|M|^2d\Omega/(2s)\ . \tag{13}$$

Here, the invariant phase space is

$$d\Omega=(2\pi)^4\delta^4\left[\sum p_i-\sum p_f\right]\prod_f \frac{d^3p_f}{2E_f(2\pi)^3} \tag{14}$$

and the flux factor has become

$$4E_1E_2\,|\mathbf{v}_1-\mathbf{v}_2|=2s\ . \tag{15}$$

To get the hadroproduction cross section for process (1) we integrate Eq. (13) over gluon distribution functions:

$$d\sigma(A+B\to\psi X)=\int dx_1dx_2G(x_1)G(x_2)d\sigma(GG\to\psi G)\ . \tag{16}$$

Note that $s=x_1x_2s_T$ where the hadron-hadron c.m. energy is $\sqrt{s_T}$. $2s_T$ represents the flux of hadrons, and therefore $G(x)/x$ is a measure of the probability to find a gluon carrying a fraction x of the momentum of the parent hadron.

We would now like to consider the direct fusion of three gluons into a ψ. The matrix element squared will still be given by Eqs. (11) and (12) divided, however, by an extra factor of 16 for spin and color averaging of the third initial-state gluon and taken in the appropriate region of s, t, and u. We will find, however, that in this case explicit reference to the interaction volume V does not cancel out and in fact is required on dimensional grounds. We have a lightlike gluon with energy E_1 from one hadron colliding with a collinear pair of gluons with energies E_2 and E_3 from the opposing hadron. In addition to a model-dependent single-gluon distribution $G(x_1)$, given, for example, by Eq. (3), we will later need to make a model for the joint-gluon distribution function $G(x_2,x_3)$. Proceeding as before, with all due attention to normalization factors, the cross section for hadrons A and B to emit three gluons which subsequently fuse into a ψ is

$$\begin{aligned}d\sigma(A+B\to GGG\to\psi X)&=\frac{V}{|\mathbf{v}_1-\mathbf{v}_2|}\,\frac{(2\pi)^4\delta^4(p_1+p_2+p_3-p_\psi)VT\,|M|^2}{T\prod_i(2E_iV)}\\&\quad\times\frac{d^3p_\psi V}{2E_\psi V(2\pi)^3}dx_1dx_2dx_3[G_A(x_1)G_B(x_2,x_3)\\&\qquad+G_B(x_1)G_A(x_2,x_3)]\ .\end{aligned} \tag{17}$$

Here the gluon energies are $E_i=(x_i\sqrt{s_T})/2$. The matrix element squared is obtained from Eqs. (11) and (12) by going to the case of three collinear gluons:

$$|M|^2=\tfrac{5}{72}[4\pi\alpha(s)]^3\Psi(0)^2/M_\psi^{\,3}\ . \tag{18}$$

Thus,

$$\begin{aligned}d\sigma(A+B\to GGG\to\psi X)&=\frac{5\pi[4\pi\alpha(s)]^3}{72Vs_T^{3/2}}\,\frac{\Psi(0)^2}{M_\psi^{\,3}}\delta(x_1(x_2+x_3)s_T-M_\psi^{\,2})\\&\quad\times\frac{dx_1dx_2dx_3}{x_1x_2x_3}[G_A(x_1)G_B(x_2,x_3)\\&\qquad+G_B(x_1)G_A(x_2,x_3)]\ .\end{aligned} \tag{19}$$

Instead of treating the interaction volume V as a free normalization parameter, we tentatively propose the following model.

(1) We assume that a gluon from the beam has a hard collision with a gluon from a heavy nucleus at a random location in the nucleus.

(2) The resultant color octet $c\bar{c}$ system propagates forward toward the outer edge of the nucleus. This path length, in the rest frame of the nucleus is on the average $3R/4$, R being the nuclear radius, $1.4A^{1/3}$ fm. In this distance, it must absorb a second gluon from the beam or target if a ψ is to be produced through gluon fusion. Of course, the system could in this time, or after leaving the nucleus, emit a gluon to produce a ψ by the mechanism of Eq. (1).

(3) In the rest frame of the colliding hadrons, this interaction length is Lorentz contracted by a factor $2M_N/\sqrt{s_T}$.

(4) The interaction volume is this distance multiplied by a base area of about 0.33 fm^2 from which gluons can be drawn. This number is chosen to fit the present nuclear effect. *A priori*, any figure up to about 1 fm^2 would be equally reasonable. Thus, as a reasonable estimate of the interaction volume to be used in Eq. (19), we propose

$$V=0.35A^{1/3}(2M_N/\sqrt{s_T})\ \text{fm}^3\ . \tag{20}$$

This expression is clearly only a model. It is meant only to show that the volume required to fit the present data is not unreasonable from a physical point of view. The important thing to our further considerations is that the interaction volume is characteristic of the collision as a whole and does not depend on whether the particle beam or nuclear target emits the third gluon.

III. JOINT GLUON DISTRIBUTION IN A NUCLEON

Correlated parton distributions in a hadron have been discussed by previous authors.[9] Consistent with these considerations, we assume that the double-gluon distribution function $G(x_1x_2)$ (1) is symmetric in the two momentum fractions x_1,x_2, (2) vanishes when the two gluons carry the total hadron momentum, $G(x,1-x)=0$, and (3) is related to the single-gluon distribution function by integration over one of the gluon momenta. This last requirement is

$$\int_0^{1-x_2}dx_3\frac{G(x_2,x_3)}{x_2x_3}=\frac{G(x_2)}{x_2}\ . \tag{21}$$

The solution we adopt is

$$G(x_2,x_3)=x_2x_3\left[-\frac{d}{dz}\frac{G(z)}{z}\bigg|_{z=x_2+x_3}\right]. \tag{22}$$

Here $G(z)$ is the single-gluon distribution function given by a form such as Eq. (3). The double distribution, like the single distribution is model dependent, but the relation between the two [Eq. (22)] is probably unique in the small-z limit which governs the asymptotic behavior.

The single-gluon distribution function $G(x)$ is expected to vary linearly with atomic number since hard collisions, due to asymptotic freedom, are expected to sample the nucleus uniformly. The correlated double-gluon distribution would also behave as A if both gluons originated from the same nucleon. However, as a first approximation to the full double-gluon distribution in a nucleus, we take $G(x_2,x_3)$ to vary as $A^{4/3}$ since the first collision is randomly located but the second gluon must come from those nucleons in the interaction path discussed above. As we shall see, this is adequate for our present considerations although a more refined treatment may be required as parton correlations in nuclei come to be better understood.

Then, if V is the interaction volume discussed in the previous section, the probability to fuse one gluon from a particle beam with two from a nuclear target is proportional to $A^{4/3}/V \propto A$. On the other hand, the probability to fuse two gluons from a particle beam with one gluon from a target nucleus is proportional to $A/V \propto A^{2/3}$. This leads to a forward-backward asymmetry in ψ production on nuclear targets and a coupling of the A dependence with that of x_F.

We now substitute this model for the double-gluon distribution into Eq. (19) and perform the trivial x_1 and x_3 integrals, adopting the case of proton-nucleus collision for definiteness:

$$\begin{aligned}d\sigma(p+A\to GGG\to\psi X)&\\ =\frac{5\pi[4\pi\alpha(s)]^3\Psi(0)^2}{(s_T^{1/2}M_\psi^{2}V)72M_\psi^{5}}&\\ \times\tau z\,dz\Bigg[G_p(x_1)\left[-\frac{d}{dz}G_A(z)/z\right]&\\ +G_A(x_1)\left[-\frac{d}{dz}G_p(z)/z\right]\Bigg]&\end{aligned} \tag{23}$$

with x_1 evaluated at τ/z. Our previous model for the interaction volume leads to the dimensionless number

$$s_T^{1/2}M_\psi^{2}V=820A^{1/3}. \tag{24}$$

This implies the differential cross section in x_F from three-gluon fusion:

$$\begin{aligned}&d\sigma(p+A\to GGG\to\psi X)/dx_F\\ &\quad=(1.93\text{ nb})[\alpha(s)/0.37]^3A[f(z_+)+A^{-1/3}f(z_-)],\end{aligned} \tag{25}$$

where

$$z_\pm=\mp x_F(1-\tau)/2+[x_F^{2}(1-\tau)^2+4\tau]^{1/2}/2 \tag{26}$$

and

$$f(z)=\frac{9z}{\tau+z^2}(1-\tau/z)^5(1-z)^4(2+3z). \tag{27}$$

The contribution to the total cross section is

$$\begin{aligned}\sigma_T=&34.7\text{ nb}[\alpha(s)/0.37]^3A(1+A^{-1/3})\\ &\times\int_\tau^1 dz(1-\tau/z)^5(1-z)^4(1+3z/2)/z.\end{aligned} \tag{28}$$

Asymptotically this behaves like

$$\sigma_T=(34.7\text{ nb})[\alpha(s)/0.37]^3A(1+A^{-1/3})\ln\tau^{-1}. \tag{29}$$

Comparing with Eq. (5), one sees that three-gluon fusion contributes asymptotically an amount equal to about 20% of the $GG\to\psi G$ cross section, but it is relatively more important at lower energies, the two processes being about equal on hydrogen at 19.4 GeV c.m. energy. Formulas (5) and (29) are in fact ultra-asymptotic approximations approaching the full result only in the TeV-energy range.

In Fig. 2 we show the predicted x_F distribution for the case of proton platinum collisions at 200 GeV/c. The dashed curve represents the $GG\to\psi G$ component using Eq. (5) for the gluon distribution. The dotted curve shows the contribution of three-gluon fusion according to Eq. (25). The latter is seen to be dominant at large x_F. This will remain true even if the data eventually require that one harden the single-gluon distribution, as long as one maintains the relation Eq. (22). The three-gluon fusion result is seen to be asymmetric in x_F, being much more important at negative x_F than for forward production. This leads to the results shown in Fig. 3 for the $R(x_F)$ of

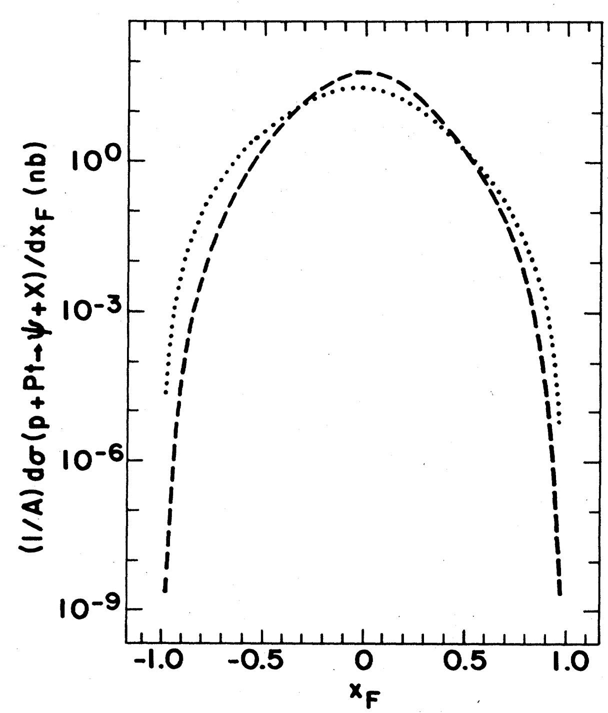

FIG. 2. Theoretical x_F dependence of ψ production in 200-GeV/c p-Pt collisions from $GG\to\psi G$ (dashed curve) and $GGG\to\psi$ (dotted curve).

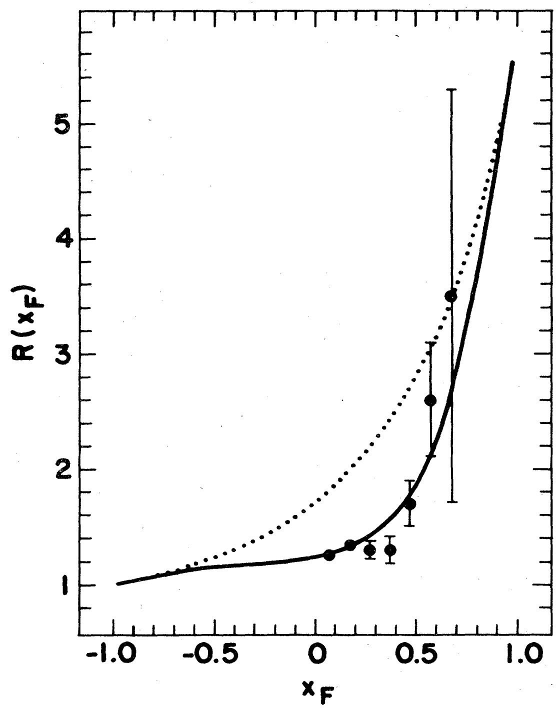

FIG 3. Behavior of $R(x_F)$ in proton collisions for three-gluon fusion alone (dotted curve) and including $GG \rightarrow \psi G$ "background" (solid curve). Data are from NA3 (Ref. 6).

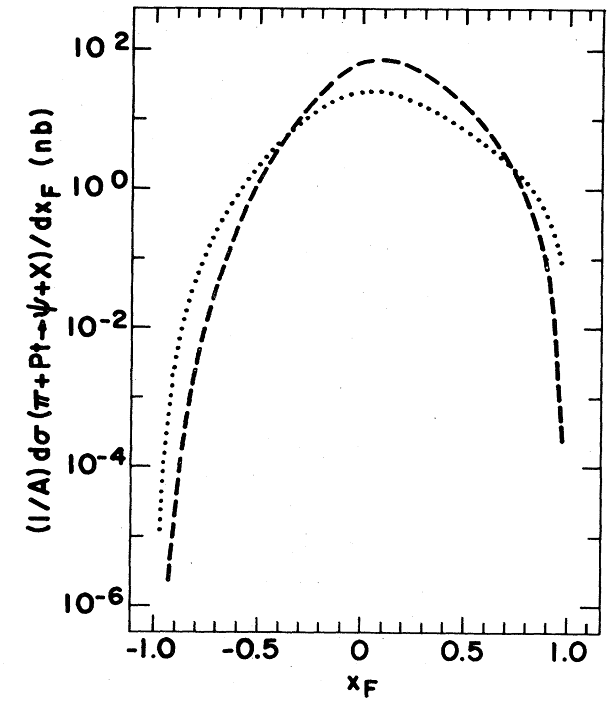

FIG. 4. Theoretical x_F dependence of ψ production in 200-GeV/c π^--Pt collisions from $GG \rightarrow \psi G$ (dashed curve) and $GGG \rightarrow \psi$ (dotted curve).

Eq. (7). The dotted curve shows the result for the three-gluon fusion only, while the solid curve gives the net effect for $GG \rightarrow \psi G$ and $GGG \rightarrow \psi$ together. The 200-GeV/c p-Pt data of NA3 (Ref. 6) are shown for comparison. In Figs. 4 and 5 we show the corresponding results for π^--Pt collisions using, for the gluon distribution function of the pion, Eq. (5) with $N=2$. In cases of both proton- and pion-initiated ψ production, the three-gluon fusion by itself would predict [from Eq. (25)]

$$R(0)=2/(1+A^{-1/3}) \sim 1.7 \ . \tag{30}$$

The background from $GG \rightarrow \psi G$ or other processes depresses this value somewhat. This background is characterized by a relatively large average transverse momentum of the produced ψ, whereas the $GGG \rightarrow \psi$ mechanism takes place at $P_T=0$ (neglecting intrinsic transverse momentum of the gluons). It is therefore encouraging for the picture proposed here that, when one cuts on ψ's produced with low transverse momentum, the resultant $R(0)$ rises[6] toward the prediction of Eq. (30). Conversely, since the present picture corresponds to a contribution at $P_T=0$ varying as $A^{2/3}$ plus a contribution with a large P_T tail varying as A, the α parameter in A^α rises as a function of P_T. This is clearly seen in the data of Refs. 6–8.

The A dependence of the forward cross section is obtained by integrating Eq. (25) over the region of $x_F>0$ and adding this to the corresponding contribution from process 1 which is taken linear in A. In Figs. 6 and 7, we show the results for 200 GeV/c π^- and proton collisions to compare with the A^α dependence found by NA3,

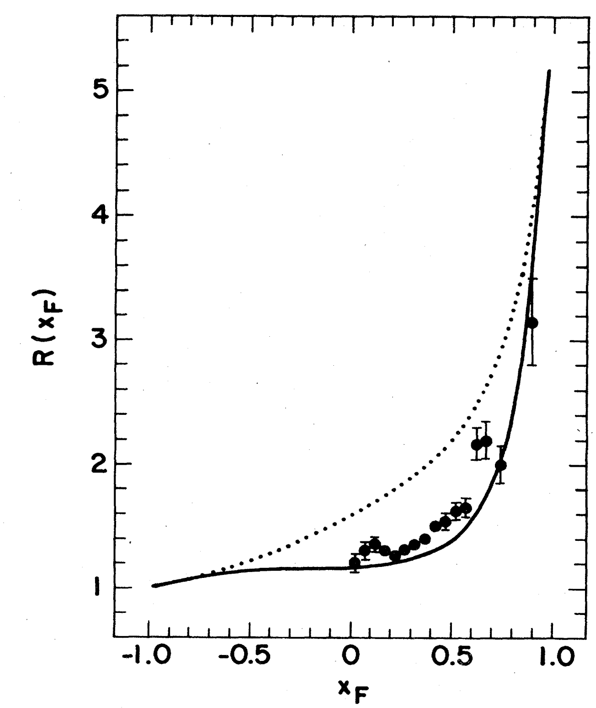

FIG. 5. Behavior of $R(x_F)$ in π^- collisions for three-gluon fusion alone (dotted curve) and including $GG \rightarrow \psi G$ background (solid curve). Data are from NA3.

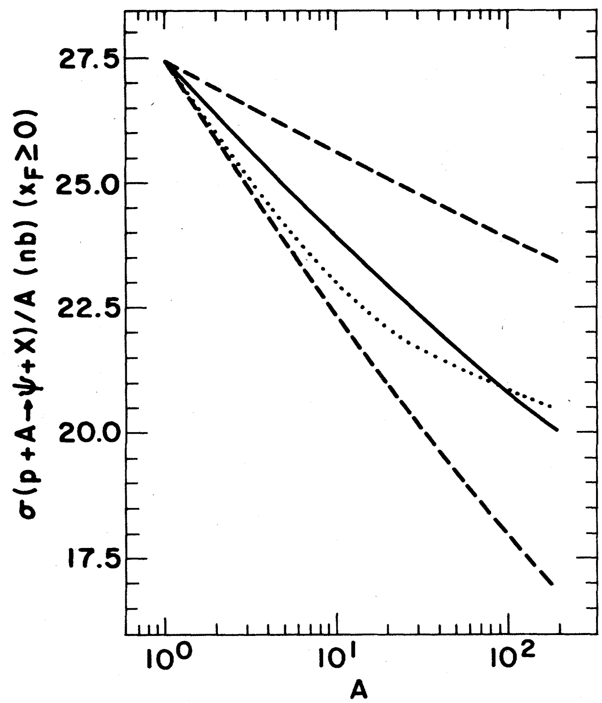

FIG. 6. Atomic-number dependence of the forward ($x_F > 0$) ψ production cross section by protons (dotted curve). The experimental NA3 fit is indicated by the solid curve with errors indicated by the dashed curves (see text).

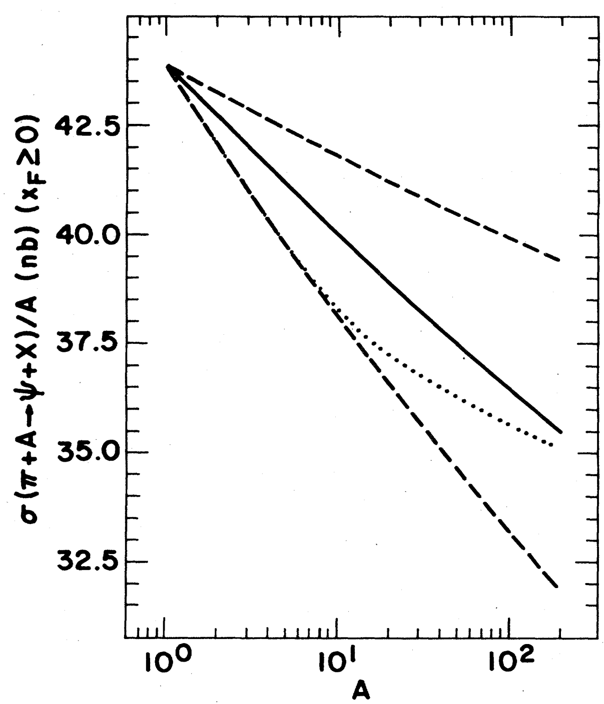

FIG. 7. Atomic-number dependence of the forward ψ production cross section by pions, theory (dotted curve), and experiment (solid and dashed curves) as in Fig. 6.

namely, $\alpha=0.96\pm0.02$ for π^- and $\alpha=0.94\pm0.03$ for proton. The experimental results are normalized to the theoretical cross sections on hydrogen. Satisfactory agreement is found for both cross sections. This agreement is only slightly sensitive to the implicit assumption that other contributions to ψ hadroproduction have approximately the same ratio of A and $A^{2/3}$ dependences since these other contributions should be relatively small.

IV. CONCLUSION

We have proposed a model for the nuclear effects seen in ψ hadroproduction by NA3 and the Omega Spectrometer groups. The mechanism is based on a direct fusion of three gluons into the ψ analogous to the well known direct fusion of two gluons into the P-wave charmonium states. The model exhibits a suppression of extreme forward ψ production in heavy nuclei as compared to production in hydrogen. The effect is restricted to the low-transverse-momentum sample in agreement with experimental indications. The overall atomic-number dependence of the forward ψ production is also satisfactorily accounted for.

In addition to the predictions given in Figs. 4 and 5 for backward ψ production, we might mention the following consequences of the presently proposed picture.

Recently it has been observed that the production cross section of the $^3P_1$ charmonium state is about equal to that of the $^3P_2$ state.[10] This is important since the $^3P_1$ has a large branching ratio into $\psi\gamma$, but it poses a problem for the theory since the tensor state has the low-order production mechanism of Eq. (6) whereas the axial vector does not. The $^3P_1$ state, however, does have a strong coupling to three gluons. We speculate, therefore, that the resolution of this puzzle lies in a large production cross section of the $^3P_1$ through three-gluon fusion leading to the prediction of a strongly enhanced $^3P_1/^3P_2$ ratio at high x_F and to a strong atomic-number dependence. Further calculations are required in order to quantify this expectation.

In ψ photo- (or muo-) production we would expect a contribution from the usual $\gamma G\to\psi G$ to be supplemented by a direct fusion mechanism

$$\gamma GG\to\psi\ . \tag{31}$$

This would, however, not lead to an x_F dependence of the α parameter since the two gluons could only come from the nuclear target so that the extra $A^{1/3}$ dependence of the double-gluon distribution is always canceled by the same dependence of the interaction volume. The presence of a large contribution from the double-gluon distribution function as suggested here, implies, however, that the extraction of the single-gluon distribution function from ψ muoproduction will not be as straightforward as was hitherto thought.

As a further result, we would not expect a strong A-dependent x_F effect in continuum lepton-pair production or open-charm production, since, in contrast to ψ production, multiple-parton effects are always higher-order processes for these reactions. There is some experimental evidence supporting this prediction.[6]

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