Production of $\psi(3100)$ and $\psi'(3700)$ in p-Be Collisions at 400 GeV

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We report preliminary results on the production of electron-positron pairs in the mass range 2.5 to 4 GeV in 400-GeV p-Be interactions. Production cross sections of the $\psi(3100)$ near $x=0$ as a function of p_t, x, and the decay angle are presented and implications of these new data for single direct leptons are discussed. A $\psi'(3700)$ signal is observed at a level corresponding to $\sigma(\psi')/\sigma(\psi) = (10\pm 3)\%$.

We have reported the observation of high-mass (>5.5 GeV) e^+e^- pairs produced in 400-GeV proton-beryllium collisons.[1] In the same experiment we have observed a strong $J/\psi(3100)$ signal. This Letter presents the details of J/ψ production cross sections as a function of p_t, x, and the decay angle and reports the observation of $\psi'(3700)$.

The two-arm magnetic spectrometer used to make these measurements is described in detail in Ref. 1. The techniques described in Refs. 1 and by Appel *et al.*[2] of comparing the energy deposited in a lead-glass array with the measured momentum and the use of the longitudinal shower development in the lead-glass array permit rejection against hadrons of 4×10^{-4} per arm while retaining an efficiency for electrons of 0.80 ± 0.08.

The observed mass spectra for electron-positron pairs are presented in Fig. 1 for three different settings of the spectrometer. To obtain cross sections, $d\sigma/dm$, we assumed that the production at all masses is similar to that observed here for the $\psi(3100)$ and specified below in Eq. (3). Cross sections reported here have been corrected for trigger and reconstruction efficiencies which lead to a combined efficiency before electron cuts of 0.8 ± 0.1 for electron-pair events. Corrections have also been made for electron-cut inefficiency, target absorption of the proton beam, and for events lost as a result of bremsstrahlung of the electrons (estimated to be 0.075 ± 0.025 of the events at 3 GeV).

Figure 1(a) shows the data taken with spectrometer settings (600 and 800 A) optimized for the $m = 3$-GeV region. A strong $\psi(3100)$ signal is seen. The acceptance varies slowly over this mass interval and these data are used to study ψ produc-

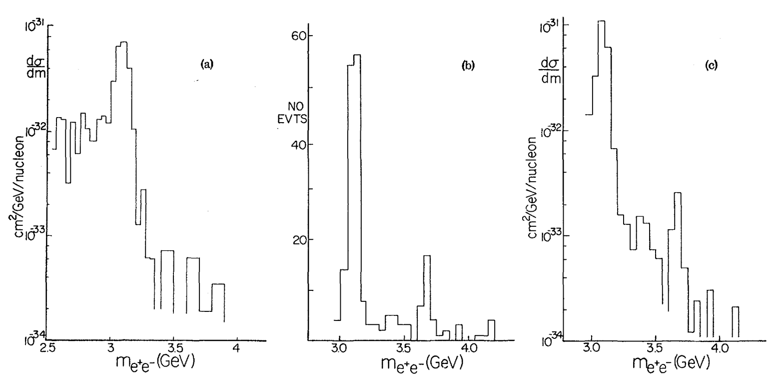

FIG. 1. Electron-positron mass spectra: (a) $d\sigma/dm$ per nucleon versus the effective mass. A linear A dependence is assumed. Spectrometer settings, 600 and 800 A. (b) Mass spectrum of observed events at 1100 A. (c) $d\sigma/dm$ per nucleon for data in (b).

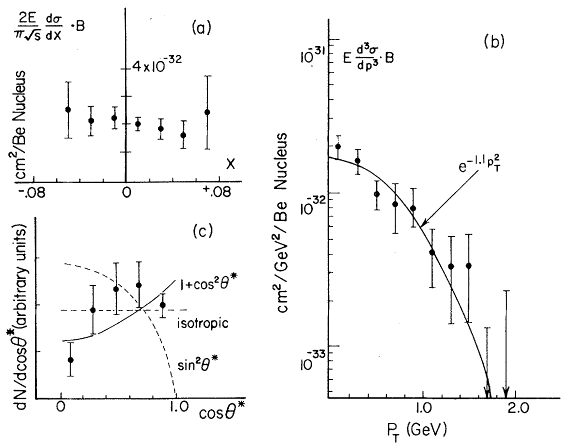

FIG. 2. ψ(3100) cross sections: (a) Invariant cross section versus $x \equiv p_{\parallel}^{\text{c.m.}}/p_{\max}^{\text{c.m.}}$ (integrated over p_t^2). (b) Invariant cross section versus p_t near $x=0$. (c) Decay-angle distribution in the helicity frame of the ψ. (Plotted errors are statistical only.)

tion. Figures 1(b) and 1(c) show data at 1100 A which is optimal for masses above 5 GeV. At 1100 A the acceptance is increasing rapidly for masses of 3.1 to 3.7 GeV. However, the integrated sensitivity at the ψ' mass is increased here by an order of magnitude over the data in Fig. 1(a). Both sets of data give consistent ψ(3100) cross sections. A ψ'(3700) peak is observed in the raw data in Fig. 1(b) and persists after correction for the acceptance as shown in Fig. 1(c).

The ψ(3100) resonance observed in Fig. 1(a) has a width of 40 MeV (rms) which is in good agreement with the calculated resolution of the apparatus. We measure a mass value of 3.096 ± 0.030 GeV. The cross sections for ψ production times its branching ratio to e^+e^- are shown in Figs. 2(a) and 2(b) plotted versus $x = p_{\parallel}^{\text{c.m.}}/p_{\max}^{\text{c.m.}}$ and p_t. No dip or significant variation in the invariant cross section is observed in our narrow range of x acceptance near $x=0$. The average invariant cross section on beryllium for x near 0 is found to be well described by a quadratic exponential in p_t:

$$E\frac{d^3\sigma}{dp^3}B = (1.7 \pm 0.4)\times 10^{-32}\exp(-ap_t^2) \quad (\text{cm}^2/\text{GeV}^2)/(\text{Be nucleus}) \qquad (1)$$

with $a = 1.1 \pm 0.35$ GeV^{-2}, where B is the branching ratio of ψ(3100) to e^+e^- and the p_t range measured is $0 < p_t < 2.0$ GeV. An equally valid description of our data is given by

$$E\frac{d^3\sigma}{dp^3}B = (2.5 \pm 0.6)\times 10^{-32}\exp(-bp_t) \quad (\text{cm}^2/\text{GeV}^2)/(\text{Be nucleus}) \qquad (2)$$

with $b = 1.6 \pm 0.35$ GeV^{-1}.

The errors on the cross sections presented here are dominated by the systematic uncertainty in the absolute normalization. The decay-angle distribution in the ψ rest system (helicity frame) is shown in Fig. 2(c) to favor $1+\cos^2\theta^*$ (confidence level 0.20).[3] The approximately 5% of background[1] under the ψ has not been subtracted in Fig. 2, but this does not significantly change any of these distributions.

The differential cross sections for the ψ(3100) are measured to be

$$(d\sigma/dx)_{x=0}B = (2.6 \pm 0.7)\times 10^{-31}\ \text{cm}^2/(\text{Be nucleus}), \quad -0.06 \le x \le 0.08,$$
$$(d\sigma/dy)_{y=0}B = (6.4 \pm 1.6)\times 10^{-32}\ \text{cm}^2/(\text{Be nucleus}), \quad -0.28 \le y \le 0.32,$$

where y is the center-of-mass rapidity. To obtain the total cross section, a distribution in x away from the $x=0$ region must be assumed. Using

$$E\,d^3\sigma/dp^3 \propto (1-|x|)^{4.3}\exp(-1.6p_t), \quad -1 \le x \le 1, \qquad (3)$$

which characterizes data from this and other experiments at high x,[4,5] we obtain a total cross section times branching ratio on beryllium of

$$\sigma B = (1.00 \pm 0.25)\times 10^{-31}\ \text{cm}^2/(\text{Be nucleus}).$$

Under the assumption of a linear A dependence, the total cross section per nucleon is

$$\sigma B = (1.1 \pm 0.3)\times 10^{-32}\ \text{cm}^2/\text{nucleon}.$$

For the ψ'(3700), the ratio of the differential cross section times branching ratio at $y=0$ to that of the ψ(3100) is

$$\left.\frac{(B\,d\sigma/dy)_{\psi'}}{(B\,d\sigma/dy)_{\psi}}\right|_{y=0} = (1.7 \pm 0.5)\%,$$

under the assumption of ψ' dynamics similar to ψ dynamics. This assumption is consistent with our data near $y=0$. The resulting ratio of production cross sections is $\sigma(\psi'(3700))/\sigma(\psi(3100))$

TABLE I. $\psi(3100)$: Comparison with other experiments.

Experiment	$\sqrt{s}$ (GeV)		Cross section	Additional assumptions necessary
This expt.	27.4	$B\,d\sigma/dy\|_{y=0}$	$(7.1\pm1.8)\times10^{-33}$ cm^2/nucleon	Linear A dependence
Büsser *et al.*	Mostly 52		$(7.5\pm2.5)\times10^{-33}$ cm^2/proton	...
This expt.	27.4	σB	$(1.1\pm0.3)\times10^{-32}$ cm^2/nucleon	
Knapp *et al.*	21.7		$\sim1.0\times10^{-32}$ cm^2/nucleon	Linear A, $(1-\|x\|)^{4.3}$
Blanar *et al.*	21.2		$(1.6\pm0.8)\times10^{-32}$ cm^2/nucleon	
This expt.	27.4	$B\,d\sigma/dy\|_{y=0}$	$(6.4\pm1.6)\times10^{-32}$ cm^2/(Be nucleus)	...
Anderson *et al.*	16.8		4.1×10^{-32} cm^2/(Be nucleus)	...
This expt.	27.4	σB	$(1.0\pm0.25)\times10^{-31}$ cm^2/(Be nucleus)	$(1-\|x\|)^{4.3}$
Antipov *et al.*	12.0		$(9.5\pm2.5)\times10^{-33}$ cm^2/Be nucleus)	...
This expt.	27.4	σB	1.1×10^{-32} cm^2/nucleon	$(1-\|x\|)^{4.3}$, linear A
Aubert *et al.*	5.1		$\sim10^{-34}$ cm^2/nucleon	$\exp(-6p_t)$, $p_\parallel$ independent

$=(10\pm3)\%$.

Table I shows a comparison of the results of this experiment with other measurements of $\psi(3100)$ production in hadron collisions.[5] Although some additional assumptions, indicated in the table, are necessary to compare these experiments, the agreement seems to be quite good with experiments with $\sqrt{s}>20$ GeV. Below that value, a substantial s dependence is apparent: There is a change of a factor of 10 between our results at 27.4 GeV and those of Antipov *et al.* at 12.0 GeV and a factor of 100 between our results and those of Aubert *et al.* at 5.1 GeV.

Finally, we calculate the yield of single direct leptons resulting from the $\psi(3100)$ production cross section measured here. Figure 3 shows a comparison of this yield, using Eqs. (1) and (2), with the long-dashed curve representing $\frac{1}{2}(\pi^++\pi^-)\times10^{-4}$ which is consistent with the direct lepton yield measured previously by this and other groups.[2,6] We find that for single-lepton p_t less than 2.0 GeV, the $\psi(3100)$ contributes less than 30% to the single-direct-lepton signal, in agreement with earlier results.[7]

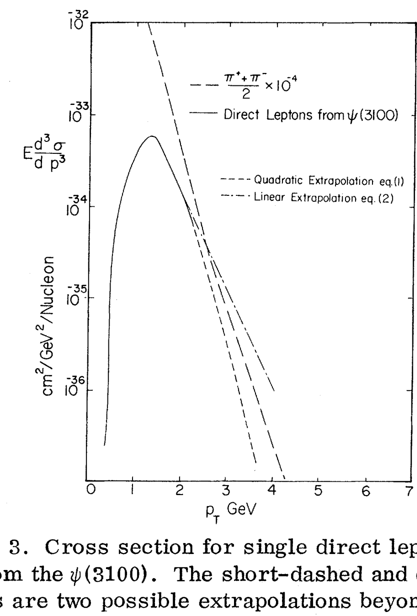

FIG. 3. Cross section for single direct leptons coming from the $\psi(3100)$. The short-dashed and dot-dashed curves are two possible extrapolations beyond p_t values for which this cross section is determined by this experiment.

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[1]D. C. Hom *et al.*, Phys. Rev. Lett. 36, 1236 (1976).

[2]J. A. Appel *et al.*, Phys. Rev. Lett. 33, 722 (1974).

[3]An isotropic distribution with confidence level 0.05 (probability of the fit) cannot be ruled out and would lead to an increase of 20% for all cross sections report-

ed here.

[4]An x distribution given by $E\,d^3\sigma/dp^3 \propto \exp(-6|x|) \times \exp(-1.6p_t)$ for $|x| > 0.2$ and flat in x for $|x| < 0.2$ also seems to describe the data in Ref. 5. Assuming such a distribution would increase the total cross sections quoted here by 60%. The differential cross sections, however, are not significantly affected.

[5]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974); B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975); Y. M. Antipov *et al.*, Phys. Lett. 60B, 309 (1976); F. W. Büsser *et al.*, Phys. Lett. 56B, 482 (1975); K. J. Anderson *et al.*, Phys. Rev. Lett. 36, 237 (1976); G. J. Blanar *et al.*, Phys. Rev. Lett. 35, 346 (1975), and private communication.

[6]J. P. Boymond *et al.*, Phys. Rev. Lett. 33, 112 (1974); F. W. Büsser *et al.*, Phys. Lett. 53B, 212 (1974); V. V. Abramov *et al.*, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1974*, edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975); D. Bintinger *et al.*, Phys. Rev. Lett. 35, 72 (1975).

[7]F. W. Büsser, in *Proceedings of the International Conference on Lepton and Photon Interactions, Stanford, California, 1975*, edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975).

Connection between Scale Breaking in Deep Inelastic Processes and Large-p_T Hadronic Reactions*

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Scaling violation in deep inelastic lepton-proton processes is shown to be related to the apparent p_T^{-8} behavior of the large-p_T pion inclusive distribution at $\sqrt{s} > 23.5$ GeV, within the framework of the quark-quark hard-collision model. Power-law scale-breaking fits of the structure functions as determined by the ep and μp data are used as inputs in our calculations. Excellent agreement with the high-energy data on large-p_T pions is obtained in both the energy and x_T dependences. No adjustable parameters are used except for one overall normalization.

The discovery of apparent scaling in deep inelastic scattering prompted the speculation that the production of particles with large transverse momenta in hadronic processes might proceed via the wide-angle scattering of pointlike constituents of the incident hadrons.[1] The prediction that at large p_T, inclusive cross sections should fall as $(1/p_T)^4$ was, however, contradicted by subsequent CERN intersecting-storage-rings (ISR) data[2] which suggested an exponent close to 8. Thus an alternative parton model,[3] in which the basic parton-parton interaction is discarded, leaving only those processes that can be pictured as involving the exchange of partons (rather than gluons), has been used to gain a phenomenological understanding of the existing data above 100 GeV.

The recent discoveries of scaling violation in lepton-induced processes imply that the hadronic constituents are probably not pointlike. This would, in turn, imply that in the Blankenbecler-Brodsky-Gunion (BBG) model[3] there is *no* subprocess that falls off slowly enough in p_T to account for the above-mentioned exponent of 8. If that is the case, the only way to rescue a constituent picture of high-p_T processes would be via the parton-parton subprocess, modified to include the effects of scale breaking. A previous attempt[4] has been made along these lines using the logarithmic violations of scaling that arise in asymptotically free theories. The results were negative. However, the observed pattern of scaling violation in no way demands asymptotic freedom; indeed, more conventional powerlike violations of scaling are equally consistent with the data.[5] It is this latter type of scale breaking which we shall investigate.

In this Letter we adopt the point of view that quarks are, in fact, not pointlike. Our aim is to relate the scaling violation in deep inelastic scattering to the large-p_T behavior in hadron-induced processes and to show that they are mutually consistent within the hard-collision model.

The differential probability $dP_{a/A}$ that a hadron A is seen by a probe with momentum transfer Q^2 to contain a constituent a with a fraction x_a of its longitudinal momentum is

$$dP_{a/A} \equiv f_{a/A}(x_a, Q^2)\,dx_a\,, \tag{1}$$

where $f_{a/A}$ can be inferred from the deep inelastic lepton scattering data. Similarly, the probability that a constituent c yields a hadron C carrying a fraction y of the constituent's momentum