Production Dynamics of the Υ in Proton-Nucleon Interactions

S. Childress,[a] P. M. Mockett, J. P. Rutherfoord, and S. R. Smith[b]
University of Washington, Seattle, Washington 98195

H. R. Gustafson, L. W. Jones, M. J. Longo, T. J. Roberts,[c] and M. R. Whalley[d]
University of Michigan, Ann Arbor, Michigan 48109

and

D. A. Garelick, P. S. Gauthier,[e] M. L. Mallary,[f] M. J. Glaubman, and H. Johnstad[a]
Northeastern University, Boston, Massachusetts 02115
(Received 5 August 1985)

We present new data on the Feynman-x dependence of Υ production in proton-tungsten collisions at a proton-beam momentum of 400 GeV/c. Comparing these data with the well-understood Drell-Yan dimuon continuum, we conclude that the Υ production mechanism must be qualitatively different.

PACS numbers: 13.85.Ni, 14.40.Gx

In a large-acceptance dimuon-production experiment at Fermilab we have measured $p+W \rightarrow \Upsilon + X$ at a proton-beam momentum of 400 GeV/c. We present data on the sum of the Υ states[1] since the experimental mass resolution of our solid-iron magnetic spectrometer of $\sim 7.5\%$ is not sufficient to resolve the three individually. These data cover both the previously explored range near $x_F = 0$ and also virgin territory out to large positive x_F. By comparing the magnitude and kinematic dependence of Υ production with the well-parametrized Drell-Yan dimuon continuum,[2] we show that the Υ production mechanism is certainly not electromagnetic and probably not due to a quark-antiquark annihilation process alone.

The apparatus and much of the data analysis have been described previously.[2,3] Figure 1 shows our dimuon mass spectra in intervals of x'_F.[4] The dimuon continuum part of these data outside of the resonance region are presented in Ref. 2 but binned differently. Here we include the dimuon data in the Υ mass region which were excluded in Ref. 2. All of these mass spectra have been corrected as detailed in Ref. 2 under the assumption that the yield is from the Drell-Yan continuum only. This assumption somewhat distorts the resonance signal. The Υ signal was extracted from the dimuon mass spectrum by interpolation of our dimuon continuum parametrization[2] through the Υ mass region. The excess signal (totaling $\sim 15\,000$ events) above the continuum was fitted with a form which assumed three Υ's with masses and production ratios as given by Ueno *et al.*[5] and smeared by experimental resolution effects[2] and radiative corrections[6] as determined by Monte Carlo simulation. The small distortion of the resonance signal due to the continuum corrections was also simulated and accounted for in the fitting function. The overall magnitude was the only free parameter in the fit. In determining the experimental acceptance, we assumed that the angular distribution in the Collins-Soper frame[7] is proportional to $1+\cos^2\theta$ for the continuum and isotropic for the Υ resonances. The protons incident on our thick tungsten target produced pions and other secondaries

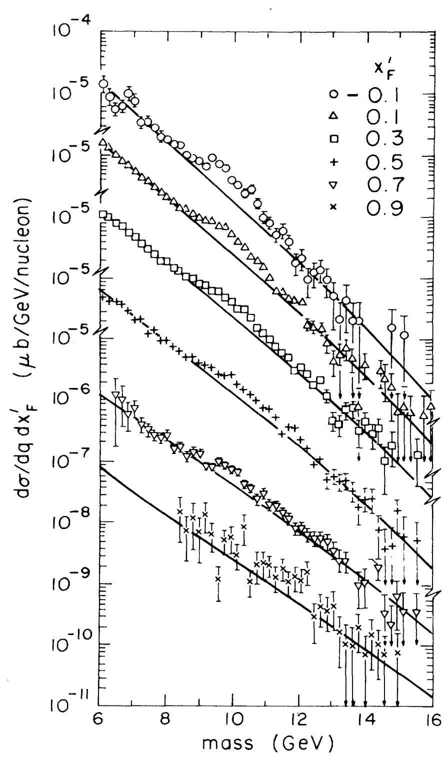

FIG. 1. Dimuon-production cross sections as a function of dimuon invariant mass, q, at fixed values of x'_F and at $\sqrt{s} = 27.4$ GeV. The curves are from fits to the data. Although the fits included the Υ resonances, the curves displayed here show only that part of the fit representing the continuum. An overall systematic error of 11% is not shown.

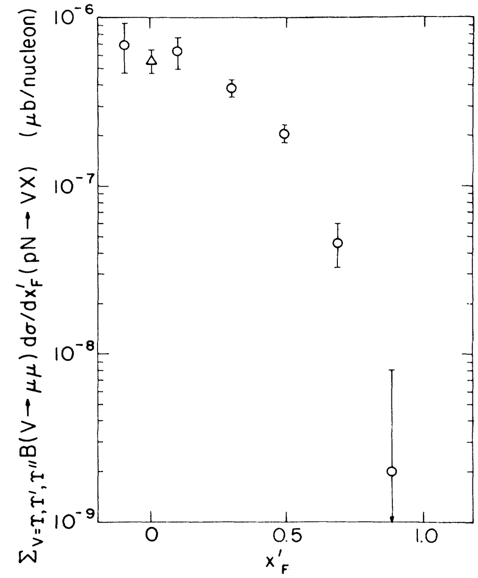

FIG. 2. Sum of the cross sections for the production of the three Υ states in proton-nucleon collisions at $\sqrt{s}=27.4$ GeV times the branching ratio to dimuons as a function of x'_F. The circles are data from this experiment. An overall systematic error of 11% is not shown. The triangle is from Ref. 5.

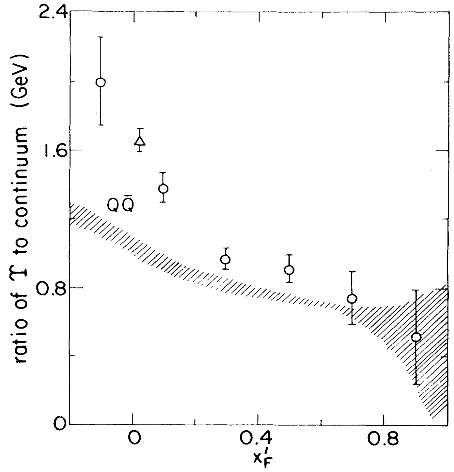

FIG. 3. The ratio R defined in the text as a function of x'_F at $\sqrt{s}=27.4$ GeV. The circles are data from this experiment. The triangle is from Ref. 5. The shaded region shows a range of shapes for R with the assumption of a variety of production mechanisms via quark-antiquark ($Q\bar{Q}$) annihilation.

which interacted later in the target and could also produce dimuons. The calculated correction for this effect is different for the Υ than for the continuum by at most 7%. An uncertainty in this correction equal to 50% of the correction has been assigned. We have assumed that any atomic-weight (A) dependence for the Υ is the same as for the continuum.[8]

We analyze our data in terms of R, the ratio of the resonance production cross section to the Drell-Yan dimuon continuum cross section,

$$R=\frac{\sum_v B(V\rightarrow\mu\mu)\,d\sigma(pN\rightarrow VX)/dx_F}{d\sigma(pN\rightarrow\mu\mu X)/dq\,dx_F|_{q=9.46\ \mathrm{GeV}}},$$

where $V=\Upsilon,\Upsilon',\Upsilon''$. The study of R introduces the smallest systematic errors and provides the most incisive phenomenological interpretation. However, we have also extracted just the numerator of the above expression, making the further assumption that the Υ-production cross section goes as $A^{1.0}$. These results are presented in Fig. 2 along with the data point from Ueno *et al.*[5] at $x_F=0$. As explained in footnote 25 of Ref. 8, these authors had chosen an older calibration constant for normalizing their incident-beam flux. Use of constants consistent with ours would raise the cross section of Ueno *et al.*[5] by 9%. The ratio data are displayed in Fig. 3. The errors in Fig. 3 include the statistics of the fit plus uncertainties in the corrections to the ratio discussed above. The errors in Fig. 2 include these plus all additional uncertainties discussed in Ref. 2. An overall systematic uncertainty of 11% is not shown.

Figure 4 shows the results of this and other experiments[5,9–13] near $x_F=0$ graphed versus $\sqrt{\tau}\equiv m_\Upsilon\sqrt{s}$.

Notice that within errors the data of Fig. 2 appear to be symmetric about $x'_F=0$ as expected of a flavor-independent strong-interaction process and in sharp contrast to the behavior of the Drell-Yan continuum.[2,5,8,9] This explains the lack of symmetry about $x'_F=0$ displayed by the ratio data in Fig. 3.

If the production mechanism of the Υ's were electromagnetic as it is in e^+e^- collisions, then it is

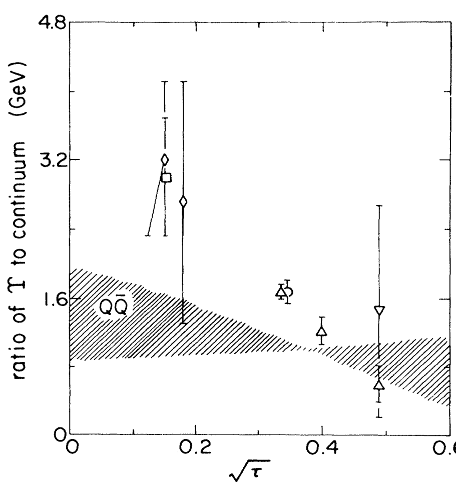

FIG. 4. The ratio R defined in the text as a function of $\sqrt{\tau}$ near $x_F=0$. The triangles are from Refs. 5, 9, and 10, the inverted triangle from Ref. 11, the diamonds from Ref. 12, the square from Ref. 13, and the circle from this experiment. The shaded region has the same meaning as in Fig. 3.

straightforward to show[14] that

$$R = \frac{9\pi\Gamma^2(\Upsilon \rightarrow \mu\bar{\mu})}{2\alpha^2\Gamma(\Upsilon \rightarrow \text{all})} \sim 10^{-2}\ \text{GeV}.$$

Our results are approximately two orders of magnitude larger than this prediction.

The (electromagnetic) Drell-Yan continuum production is due to a particular combination of quark-antiquark annihilation processes. If the Υ production mechanism were also due to some combination of quark-antiquark annihilation processes (not the same combination as for the continuum since the couplings are not electromagnetic), then we would expect the kinematic dependence of R to be relatively flat in Figs. 3 and 4. Guided by previous phenomenological studies[15,16] of vector-meson production, we have calculated a range of shapes for the expected kinematic dependence of R. These are summarized by the shaded regions in Figs. 3 and 4. It can be seen that it is not easy to accommodate our results with a quark-antiquark annihilation mechanism alone. Another process (with a very different kinematic dependence from quark-antiquark annihilation), such as glue-glue amalgamation,[16-18] must also be contributing to Υ production.

This work was supported by the National Science Foundation. Illuminating discussions with S. D. Ellis, N. Fleishon, W. J. Stirling, and J. Rosner are gratefully acknowledged.

(a)Present address: Fermilab, Batavia, Ill. 60510.

(b)Present address: Columbia University, New York, N.Y. 10027.

(c)Present address: Bell Laboratories, Naperville, Ill. 60566.

(d)Present address: Department of Physics, University of Durham, Durham City DH1 3LE, England.

(e)Present address: American Science and Engineering, Cambridge, Mass. 02139.

(f)Present address: Digital Equipment Corporation, 146 Main Street, Maynard, Mass. 01754.

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4We use standard definitions of kinematic variables: q is the invariant mass of the μ pair, p_L is the longitudinal momentum of the μ pair in the hadronic center-of-mass system, and s is the square of the hadronic center-of-mass energy. From these are defined $x_F \equiv 2p_L/\sqrt{s}$ and $\tau \equiv q^2/s$. For the binning of data, it is more appropriate to use $x_F' \equiv x_F/(1-\tau)$.

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