[8]Units are $\hbar = c = 1$. The metric is $(+---)$. The four-vector n is null: $n = (1, \vec{n})$, with $\vec{n}^2 = 1$. The four-potential of the plane wave is $A(\tau) = (0, \vec{A})$, where $\vec{n} \cdot \vec{A} = 0$ and $\tau = n \cdot r = t - \vec{n} \cdot \vec{r}$. $\vec{E}(\tau)$ and $\vec{H}(\tau) = \vec{n} \times \vec{E}$ are the electric and magnetic fields of the plane wave. The γ matrices are chosen in the standard representation.

[9]J. Kupersztych, Phys. Rev. D 17, 629 (1978).

[10]P. Avan, C. Cohen-Tannoudji, J. Dupont-Roc, and C. Fabre, J. Phys. (Paris) 37, 993 (1976); F. Ehlotzky, Opt. Commun. 25, 221 (1978).

Evidence for the Υ″ and a Search for New Narrow Resonances

K. Ueno, B. C. Brown, C. N. Brown, W. R. Innes, R. D. Kephart, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

S. W. Herb, D. C. Hom,[(a)] L. M. Lederman, H. D. Snyder,[(b)] and J. K. Yoh
Columbia University, New York, New York 10027

and

R. J. Fisk,[(c)] A. S. Ito, H. Jöstlein, and D. M. Kaplan[(d)]
State University of New York, Stony Brook, New York 11794
(Received 11 December 1978)

The production of the Υ family in proton-nucleus collisions is clarified by a sixfold increase in statistics. Constraining Υ,Υ′ masses to those observed at DORIS we find the statistical significance of the Υ″ to be 11 standard deviations. The dependence of Υ production on p_t, y, and s is presented. Limits for other resonance production in the mass range 4–18 GeV are determined.

We report on further details of upsilon[1,2] production in proton-nucleus collisions at Fermilab. In addition to data published previously,[1-4] we present here results from data taken in 1978. Our entire data sample can be divided into four subsets: (I) published data with 400-GeV incident proton energy and 1200 Υ (or Υ′) events, mass resolution ($\Delta M/M$) of 2.2% (rms)[1,2]; (II) 200/300 GeV, 500 Υ's, $\Delta M/M = 2.2\%$; (III) 400 GeV, 7000 Υ's, $\Delta M/M = 2.2\%$; (IV) 400 GeV, 500 Υ's, $\Delta M/M = 1.7\%$. Except where noted all results hereafter are from the 400-GeV data. The resolution improvement in data set IV was achieved by lowering the intensity of protons so that a multiwire proportional chamber could be installed and operated halfway between the target and the analysis magnet.

All the data from sets I, III, and IV between masses of 7.3 and 12.9 GeV were fitted simultaneously. Cross sections per Pt nucleus were converted to cross section per nucleon by dividing by $A_{\rm Pt} = 195$. An isotropic decay-angle distribution was assumed for resonances while $1 + \cos^2\theta$ (Gottfried-Jackson frame) was assumed for the continuum. A linear exponential form was assumed for the continuum. This form fits the continuum well in this mass range.

The continuum shape, resonance mass separations, and relative cross sections were the same for all data sets but mass resolution,[5] acceptance, normalization,[5] and mass scale were particular to each set. Assuming three resonances and letting all parameters vary we obtain the first column in Table I.[6] This fit yields the spacing $m_{\Upsilon'} - m_{\Upsilon} = 0.57 \pm 0.03$ GeV. If we constrain $m_{\Upsilon'} - m_{\Upsilon}$ to the value of 0.555 ± 0.011 GeV measured at DORIS[7] we obtain the result in the second column of Table I. In this case assuming two resonances instead of three increases χ^2 by 125 indicating a statistical significance of 11 standard deviations for the Υ″. We consider this convincing evidence for a third resonance. Data set III with continuum subtracted is plotted in Fig. 1 and compared with the fit constrained by the DORIS measurements.

These results combined with the observation of Υ and Υ′ at DORIS[7,8] strongly support the interpretation that the Υ, Υ′, and Υ″ are the $n^3S_1Q\bar{Q}$ states ($n = 1,2,3$) of a new heavy quark with charge $\frac{1}{3}$ ("bottom"). Successful fitting of both J/ψ and Υ families with a common potential,[9,10] successful prediction of ≥ 3 states,[11] $m_{\Upsilon''} - m_{\Upsilon}$,[9,10] Γ_{ee} (Υ and Υ′),[7,8,11] and $B(\Upsilon \to \mu\mu)$,[12] all reinforce this interpretation.

In Fig. 2 we show the energy dependence of Υ

TABLE I. Resonance fits.[a]

Parameter	($m_{\Upsilon'}-m_{\Upsilon}$ Free)	$m_{\Upsilon'}-m_{\Upsilon}$=.555±.011
Continuum Parameters ($d^2\sigma/dmdy\|_{y=0} = Ae^{-b(m-m_{\Upsilon})}$)		
A_I (pb/GeV)	0.262±.004(±.04)	0.262±.004(±.04)
A_{III} (pb/GeV)	±.003 (b)	±.003 (b)
A_{IV} (pb/GeV)	±.004 (b)	±.004 (b)
b (GeV^{-1})	0.954±.006(.015)	0.953±.006(±.015)
Resonance Parameters		
m_{Υ} (GeV)	9.46 (fixed)	9.46 (fixed)
R/C$^{(c)}$ (GeV)	1.15 ±.03	1.14 ±.03
$Bd\sigma/dy\|_{y=0}$ Υ (pb)	0.30 ±.01(±.05)	0.30 ±.01(±.05)
$m_{\Upsilon'}-m_{\Upsilon}$ (GeV)	0.574±.027	0.558±.011
$Bd\sigma/dy\|_{y=0}$ Υ'/Υ	0.32 ±.03	0.31 ±.03
$m_{\Upsilon''}-m_{\Upsilon}$ (GeV)	0.97 ±.05	0.95 ±.03
$Bd\sigma/dy\|_{y=0}$ Υ"/Υ	0.13 ±.029	0.15 ±.017
Common Parameters		
Δm/m (rms) I	0.022 fixed	0.022 fixed
Δm/m (rms) III	0.022 fixed	0.022 fixed
Δm/m (rms) IV	0.020±.002	0.020±.002
m factor I	0.998±.002	0.997±.002
m factor III	1.001±.001	1.001±.001
m factor IV	1.000±.002	1.000±.002
χ^2/DF	163/155	163/156

[a]Where significant, systematic errors are given in parentheses.

[b]Since data sets III and IV have not been carefully normalized, the precise values of these parameters are irrelevant.

[c]This parameter is $B_{\mu\mu}\, d\sigma/dy|_{y=0}$ for Υ production divided by $d^2\sigma/dmdy|_{y=0,\, m=m_{\Upsilon}}$ for the continuum.

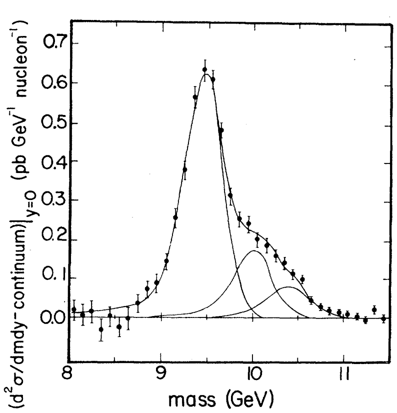

FIG. 1. Mass spectrum in the Υ region with continuum subtracted (from data set III). The curve is the fit described in the second column of Table I.

production[13] and compare it to that for ψ production.[14] We see that they are similar.

Figure 3(a) shows the P_t dependence of the Υ cross section (continuum subtracted). The curve shows a fit to the continuum in adjacent mass bins. We see a significant difference particularlyat the highest values of p_t. $\langle p_t\rangle_{\Upsilon}$ is 1.48 ± 0.04 GeV, while $\langle P_t\rangle$ of the continuum is 1.20 ± 0.02 GeV (assuming $1+\cos^2\theta$ decay instead of flat decay yields $\langle p_t\rangle_{\Upsilon}$ of 1.44 ± 0.04). Figure 3(b) shows the y dependence of the Υ (also continuum subtracted) and a curve showing the expected continuum behavior based on interpolation from the surrounding continuum via the parton annihilation model. We see that in contrast to the continuum distribution the Υ distribution is symmetric about $y=0$. $[d\ln(d^2\sigma/dm\,dy)/dy]_{y=0}$ is 0.1 ± 0.2 for the Υ vs 0.5 ± 0.1 for the continuum. This, together with the p_t dependence, the small ratio of Υ to continuum seen in our 200-GeV data (at $y=0.4$),[4] and the large ratio of Υ to continuum seen at the CERN intersecting storage rings[13] ($\sqrt{s}=60$ GeV), suggests that the Υ production mechanism differs from that of the continuum.

The observed mass spectrum [Fig. 4(a)], combined with knowledge of the mass resolution (confirmed by the observed resolution of J/ψ, ψ', and Υ) allows us to determine upper limits for $B_{\mu\mu} \times d\sigma/dy$ for narrow resonances (independent of origin) in the mass range 4–18 GeV in proton-nucleus collisions. These are presented in Fig. 4(b). To set limits on the masses of new quarkon-

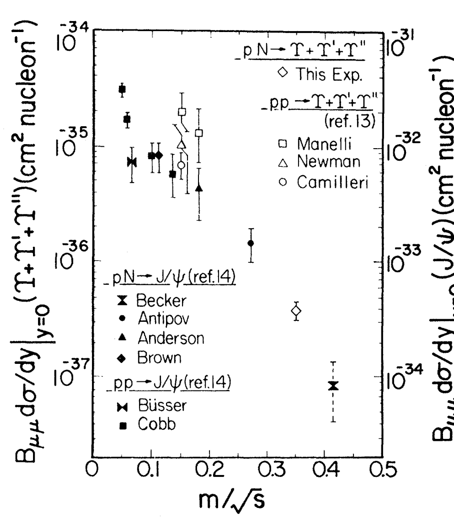

FIG. 2. s dependence of Υ and ψ production. The Υ data are from this experiment and Ref. 13. The J/ψ data are from Ref. 14.

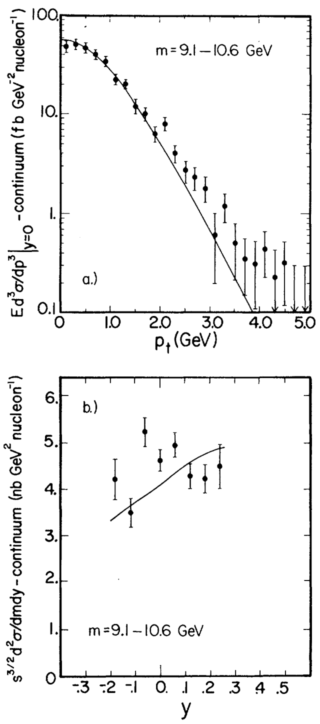

FIG. 3. (a) p_t dependence of Υ production (continuum subtracted). The curve shows the p_t dependence of the adjacent continuum (the continuum p_t spectrum is independent of mass in this mass range). (b) y dependence of Υ production (continuum subtracted). The curve shows the continuum y dependence based on interpolation from the adjacent continuum with a parton annihilation model.

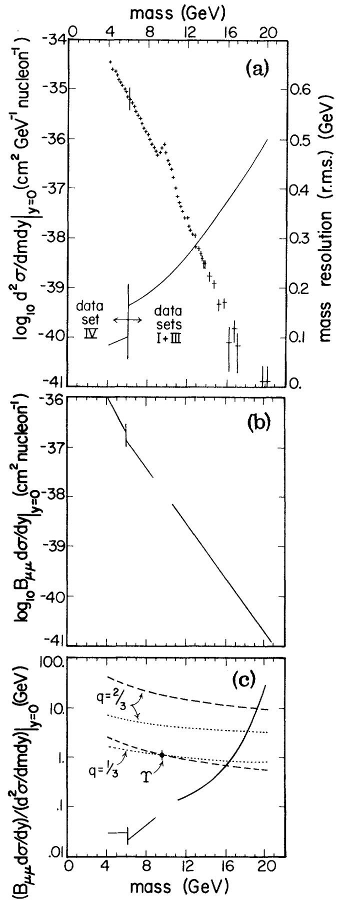

FIG. 4. (a) Mass spectrum. The 4–6-GeV region is from data set IV. The 6–20-GeV region is from data sets I and III. The curve shows the mass resolution. (b) Upper limits (at 95% confidence level) on $B_{\mu\mu}\, d\sigma/dy|_{y=0}$ for new resonance production. (c) Upper limits (at 95% confidence level) on the ratio of resonance to continuum production. The dotted curves are the predictions calculated with the model of Ellis *et al.* (Ref. 15). The dashed curves are the predictions calculated with the model of Cahn and Ellis (Ref. 12).

ium systems, we must make some assumptions. Since no resonance production data are available for $\sqrt{\tau}$ greater than 0.5, we assume the resonance excitation curve falls no faster with $\sqrt{\tau}$ than that of the continuum (the two curves are tangent between 0.3 and 0.4). We must also assume a production model. Figure 4(b) compares the 95%-confidence-level upper limit for $[(B_{\mu\mu}d\sigma/dy)(\text{resonance})]/[(d^2\sigma/dm\,dy)(\text{continuum})]$ with the predictions of two production models.[12,15] Following Ellis *et al.*,[15] we find $m_{1/3} > 15$ GeV and $m_{2/3} > 16.5$ GeV for charge-$\frac{1}{3}$ and charge-$\frac{2}{3}$ quarks, respectively. Following Cahn and Ellis[12] we find $m_{1/3} > 15$ GeV and $m_{2/3} > 17.5$ GeV.

In summary, further data on Υ production in proton-nucleus collisions and the observation of Υ' at DORIS have increased the statistical significance of the Υ'' to 11 standard deviations and supplied more evidence for the quarkonium interpretation of the Υ family. Assuming that only one additional narrow resonance above the Υ' contributes to our mass spectrum, we determine the Υ'' mass to be 10.41 ± 0.05 GeV. Differences in the dynamics of Υ and continuum production point to differing production mechanisms. Other quarkonium families with comparable resonance/continuum signals are unlikely in the mass range 4–14 GeV. A quarkonium family based on a charge-$\frac{2}{3}$ quark is unlikely below 16.5 GeV.

We wish to thank the staffs of our respective institutions, particularly the accelerator staff at Fermilab. This work was funded in part by grants from the National Science Foundation and the U. S. Department of Energy.

[(a)] Present address: Riverside Research, 80 West 3rd Ave., New York, N. Y.

[(b)] Present address: Gallaudet College, Washington, D. C. 20002.

[(c)] Present address: Fermi National Accelerator Laboratory, Batavia, Ill. 60510.

[(d)] Present address: Nevis Laboratories, Columbia University, Irvington, N. Y. 10533.

[1]S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977).

[2]W. R. Innes *et al.*, Phys. Rev. Lett. 39, 1240, 1640(E) (1977).

[3]D. M. Kaplan *et al.*, Phys. Rev. Lett. 40, 435 (1978).

[4]J. K. Yoh *et al.*, Phys. Rev. Lett. 41, 684 (1978); D. M. Kaplan, thesis, State University of New York, Stony Brook, 1979 (unpublished); A. S. Ito *et al.*, to be published.

[5]The resolution function was obtained by Monte Carlo techniques and by studying the measured shape of the ψ and Υ peaks. The agreement was very good, the only non-Gaussian effect detected (arising from the low-mass radiative tail) was specifically included. The normalization of the data presented here differs from that of our previous publications. The primary cause of this change was the discovery that the Pt target used in data set I had partially melted. Other causes are changes in the decay-angle and p_t distributions assumed in calculating the acceptance and the inclusion of nucleon-motion and radiative corrections.

[6]The mass scales in these fits were adjusted to yield the DORIS result $m = 9.46$ GeV. If this is not done, our result is $m_\Upsilon = 9.45 \pm 0.05$ GeV. The error is entirely systematic and arises from uncertainties in the magnetic field measurement and in knowledge of the energy loss in the hadron absorber.

[7]C. W. Darden *et al.*, Phys. Lett. 78B, 364 (1978); J. K. Bienlein *et al.*, Phys. Lett. 78B, 360 (1978).

[8]C. W. Darden *et al.*, Phys. Lett. 76B, 246 (1978); C. Berger *et al.*, Phys. Lett. 76B, 243 (1978).

[9]C. Quigg and J. L. Rosner, Phys. Lett. 71B, 153 (1977).

[10]H. Thacker, C. Quigg, and J. L. Rosner, Phys. Rev. D 18, 287 (1978).

[11]E. K. Eichten and K. Gottfried, Phys. Lett. 66B, 286 (1977).

[12]R. N. Cahn and S. D. Ellis, Phys. Rev. D 16, 1484 (1977).

[13]L. Camilleri, J. Manelli, and H. Newman, private communication.

[14]B. C. Brown *et al.*, Fermilab Report No. Pub-77/54-Exp, 1977 (unpublished); K. J. Anderson *et al.*, Phys. Rev. Lett. 36, 237 (1976); Yu. M. Antipov *et al.*, Phys. Lett. 60B, 309 (1976); U. Becker *et al.*, private communication as reported by Anderson *et al.*; J. H. Cobb *et al.*, Phys. Lett. 68B, 101 (1977); F. W. Büsser *et al.*, Phys. Lett. 56B, 482 (1975).

[15]J. Ellis *et al.*, Nucl. Phys. B131, 285 (1977).