Observation of Structure in the Υ Region

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The properties of the dimuon enhancement seen in 400-GeV proton-nucleus collisions have been clarified by a threefold increase in data. We find two peaks whose widths are consistent with our resolution: $M_1 = 9.4$ GeV with $B\,d\sigma/dy|_{y=0} = 1.8\times10^{-37}$ cm^2/nucleon and $M_2 = 10.0$ GeV with $B\,d\sigma/dy|_{y=0} = 0.7\times10^{-37}$ cm^2/nucleon. Evidence for the possible existence of a third peak near 10.4 GeV is discussed as are the comparisons with the properties of a $q\bar{q}$ system, where q is a new heavy quark.

In a previous Letter[1] we presented evidence for a broad enhancement near 9.5 GeV in dimuon production in 400-GeV proton-nucleus collisions, based upon a study of 9000 muon pairs with invariant mass greater than 5 GeV. We present here conclusions based on 26 000 events above 5 GeV. The data were obtained with a fixed spectrometer setting (1500 A) and represent 2×10^{16} proton interactions in Pt and Cu targets. The mass spectrum is given in Fig. 1. The acceptance calculation has been improved by better knowledge of the p_T distribution of dileptons. Excluding the mass interval 8.8 to 11.0 GeV, we find a fit to the continuum of the form[2]

$$d^2\sigma/dm\,dy|_{y=0} = Ae^{-bm} \tag{1}$$

with

$$A = (1.26\pm0.02)\times10^{-33}\ \text{cm}^2/\text{GeV}\cdot\text{nucleon},$$

$$b = 0.953\pm0.01\ \text{GeV}^{-1}.$$

We stress that the errors are statistical only. We have, to date, studied the systematic errors only insofar as they affect the continuum subtraction process. An analysis of the continuum data will be published separately.

Figure 2 shows the excess of the data over the fit of Eq. (1). The enhancement represents ~1200 events, i.e., the continuum fit predicts 1300± 36 events and 2500 are observed. We note that the new picture which emerges from the improved statistics is in agreement with the earlier results but now clearly establishes the two (or more) narrow peak interpretation.

Table I presents the results of a fitting program under the hypotheses of two and three narrow peaks. "Narrow" here means a natural width less than one-half the resolution. These fits use the calculated resolution of 2.1% (rms). If the resolution is varied, the best-fit width is $2.1\pm0.14\%$.

It remains to discuss the systematic uncertainties. Clearly the relative intensities (although not the spacing of M_1 and M_2) depend on the pre-

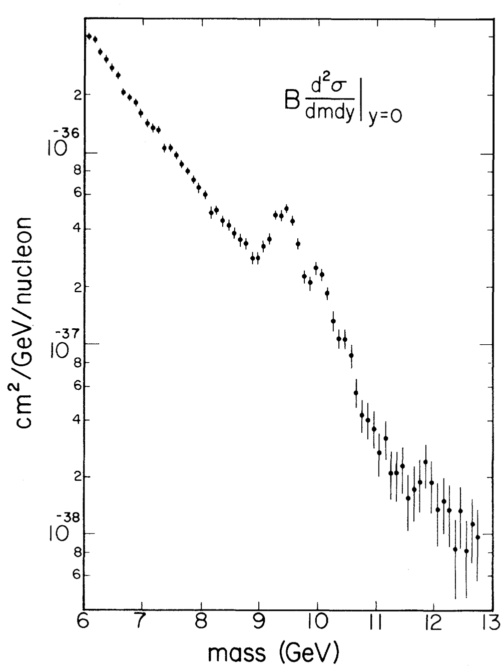

FIG. 1. Dimuon spectrum above 6 GeV.

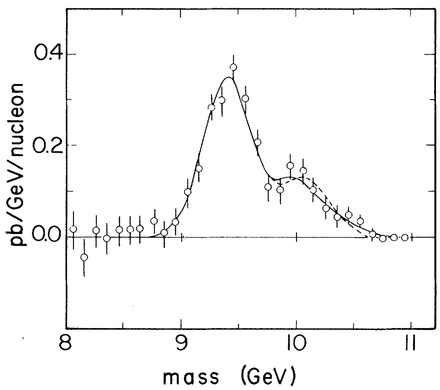

FIG. 2. Excess of the data over the continuum fit of Eq. (1). Errors shown are statistical only. The solid curve is the three-peak fit; the dashed curve is the two-peak fit.

cise form of the continuum. The first test is to vary the slope parameter, b, in Eq. (1). Variation each way by 2σ yields the results given in Table II. A detailed study has been made of the error matrix representing correlated uncertainties in the multiparameter fit. The correlations increase the uncertainties of Tables I and II by $\leq 15\%$.

Further uncertainties in the results presented above arise from the fact that the continnum fit is dominated by the data below 9 GeV. Nature could provide reasonable departures from Eq. (1) above this mass. These issues must wait for a large increase in the number of events, especially above ~11 GeV. However, the primary conclusions are independent of these uncertainties and may be summarized as follows: (i) The structure contains at least two narrow peaks: $\Upsilon(9.4)$ and $\Upsilon'(10.0)$. (ii) The cross section for $\Upsilon(9.4)$, $(B d\sigma/dy)|_{y=0}$, is[2] 0.18 ± 0.07 pb/nucleon. (The error includes our $\pm 25\%$ absolute normalization uncertainty and also the estimated uncertainty due to model dependence of the acceptance calculation.) (iii) There is evidence for a third peak $\Upsilon''(10.4)$ although this is by no means established.

TABLE I. Resonance fit parameters. Continuum subtraction is given by Eq. (1). Errors are statistical only.

		2 peak	3 peak
Υ	M_1 (GeV)	9.41 ± 0.013	9.40 ± 0.013
	$B\,d\sigma/dy\|_{y=0}$ (pb)	0.18 ± 0.01	0.18 ± 0.01
Υ'	M_2 (GeV)	10.06 ± 0.03	10.01 ± 0.04
	$B\,d\sigma/dy\|_{y=0}$ (pb)	0.069 ± 0.006	0.065 ± 0.007
Υ''	M_3 (GeV)	...	10.40 ± 0.12
	$B\,d\sigma/dy\|_{y=0}$ (pb)	...	0.011 ± 0.007
χ^2 per degree of freedom		19.3/18	14.2/16

TABLE II. Sensitivity of resonance parameters to continuum slope. Continuum subtraction of Eq. (1) but with b varied by $\pm 2\sigma$. Errors are statistical only.

		$b = 0.977$ GeV^{-1}	$b = 0.929$ GeV^{-1}
Υ	M_1 (GeV)	9.40 ± 0.013	9.40 ± 0.014
	$B\,d\sigma/dy\|_{y=0}$ (pb)	0.18 ± 0.01	0.17 ± 0.01
Υ'	M_2 (GeV)	10.00 ± 0.04	10.01 ± 0.04
	$B\,d\sigma/dy\|_{y=0}$ (pb)	0.068 ± 0.007	0.061 ± 0.007
Υ''	M_3 (GeV)	10.43 ± 0.12	10.38 ± 0.16
	$B\,d\sigma/dy\|_{y=0}$ (pb)	0.014 ± 0.006	0.008 ± 0.007
χ^2 per degree of freedom		14.1/16	15.4/16

Examination of the p_T and decay-angle distributions of these peaks fails to show any gross difference from adjoining continuum mass bins.

An interesting quantity is the ratio of $(B d\sigma/dy)|_{y=0}$ for $\Upsilon(9.4)$ to the continuum cross section $(d^2\sigma/dm\,dy)|_{y=0}$ at $M = 9.40$ GeV: This is 1.11 ± 0.06 GeV.

Table III presents mass splittings and cross sections (including systematic errors) under the two- and three-peak hypotheses and compares them with theoretical predictions to be discussed below.

There is a growing literature which relates the Υ to the bound state of a new quark (q) and its an antiquark ($\bar{q}$).[3-11] Eichten and Gottfried[3] have calculated the energy spacing to be expected from the potential model used in their accounting for the energy levels in charmonium. Their potential

$$V(r) = -\tfrac{4}{3}\alpha_s(m_q)/r + r/a^2 \qquad (2)$$

predicts line spacings and leptonic widths. The level spacings [Table III(a)] suggest that the shape of the potential may be oversimplified; we note that $M(\Upsilon') - M(\Upsilon)$ is remarkably close to $M(\psi') - M(\psi)$.[12]

Table III(b) summarizes estimates of $B d\sigma/dy|_{y=0}$ for $q\bar{q}$ states and ratios of the $n = 2, 3$ states to the ground state. Cascade models (Υ produced as the radiative decay of a heavier P state formed by gluon amalgamation) and direct production processes seem to prefer $Q = -\frac{1}{3}$ to $Q = \frac{2}{3}$. We note finally that the ratios in Table III may require modification due to the discrepancy between the observed spacing and the universally used

TABLE III. Comparison with predictions of some $q\bar{q}$ models.
(a) Mass splittings

		$\Delta m(\Upsilon'-\Upsilon)$ (MeV)	$\Delta m(\Upsilon''-\Upsilon)$ (MeV)
This experiment [a]	(two-peak fit)	650 ± 30	
	(three-peak fit)	610 ± 40	1000 ± 120
Eichten and Gottfried	(Ref. 3)	420	750

(b) Cross sections

		Q [b]	$\sum B \left.\frac{d\sigma}{dy}\right\|_{y=0}$ (pb) [c]	Υ'/Υ [d]	Υ''/Υ [d]
This experiment [a]	(two-peak fit)		0.25 ± 0.07	0.38 ± 0.04	
	(three-peak fit)		0.25 ± 0.07	0.37 ± 0.04	0.06 ± 0.04
Cahn and Ellis	(Ref. 4)	$-1/3$	~ 0.15		
		$2/3$	~ 2.4		
Ellis *et al.*	(Ref. 5)	$-1/3$	~ 1	0.3	0.15
		$2/3$	~ 4	0.12	0.05
Carlson *et al.* [e]	(Ref. 6)	$-1/3$	~ 0.5	0.3	0.08
		$2/3$	$\gtrsim 5$		
Hagiwara *et al.*	(Ref. 7)	$-1/3$	$\sim 30/N^2$ [f]		
		$2/3$	$\sim 120/N^2$		
Barnett	(Ref. 10)	$-1/3$	~ 0.4	~ 0.4	
		$2/3$	~ 1.6		

[a]Systematic errors have been included (except for the uncertainty of the extrapolation to cross section per nucleon).
[b]The assumed charge of the quark.
[c]This is the summed cross section for the three states Υ, Υ', and Υ''.
[d]These are ratios of $B\, d\sigma/dy|_{y=0}$.
[e]Gluon distribution taken as $(1-X)^N$ with $N = 4$.
[f]This is the cross section for the Υ only. N is the exponent of the gluon distribution as in preceding note (e).

Eichten and Gottfriend results.[3]

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