Observation of the Υ''' at the Cornell Electron Storage Ring

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During an energy scan at the Cornell Electron Storage Ring, with use of the Columbia University–Stony Brook NaI detector, an enhancement in $\sigma(e^+e^- \to \text{hadrons})$ is observed at center-of-mass energy ~10.55 GeV. The mass and leptonic width of this state (Υ''') suggest that it is the 4^3S_1 bound state of the b quark and its antiquark. After applying to the data a cut in a (pseudo) thrust variable, the natural width is measured to be $\Gamma = 12.6 \pm 6.0$ MeV, indicating that the Υ''' is above the threshold for $B\bar{B}$ production.

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In the quarkonium model,[1] vector mesons are considered to be triplet S states of a quark-antiquark system in a "Coulombic-plus-confining" potential, with the number of quasistable radial excited states increasing with the mass of the quark. In particular, for the b quark ($M \sim 5$ GeV) the 1^3S_1, 2^3S_1, and 3^3S_1 states (Υ, Υ', and Υ'') have been observed as narrow enhancements in $\sigma(e^+e^- \to \text{hadrons})$,[2-4] as well as in proton-nucleon scattering.[5] A 4^3S_1 state should also exist, with an excitation energy of ~1.15 GeV. The 4^3S_1 state is expected to be close to the threshold for $B\bar{B}$ production,[6] where B is a pseudoscalar bound system of b and $\bar{u}$ or $\bar{d}$ quarks. If the 4^3S_1 state lies below the $B\bar{B}$ threshold, its natural width would be well below 1 whereas if it lies above the $B\bar{B}$ threshold, the opening up of decay channels would result in a natural width which increases rapidly with $M(4^3S_1) - 2M(B)$.[7]

We report here on the production of a new state in the Υ family, the Υ''', which we identify, from a measurement of its leptonic width Γ_{ee}, with the 4^3S_1 $b\bar{b}$ state. In addition, we observe a total width $\Gamma_{\text{obs}}(4^3S_1) \sim 19$ MeV; unfolding the contribution ($\Gamma \sim 10.8$ MeV) due to the Cornell Electron Storage Ring (CESR) beam-energy spread gives a natural width $\Gamma \sim 12.6$ MeV. This suggests that this state is above the $B\bar{B}$ threshold. We also obtain the (pseudo) thrust distribution for this new state and compare it with the corresponding distribution obtained for the continuum and for the $\Upsilon(1^3S_1)$.

These results were obtained in a twenty-day run covering the energy range 10.46 to 10.60 GeV, with an integrated luminosity of 1100 nb^{-1}. We had seen preliminary evidence for the new state during a run covering 10.55 to 10.80 GeV with a total integrated luminosity of 400 nb^{-1}. During the present run, we also collected data at the $1^3S_1(\Upsilon)$ with 300 nb^{-1} and at the $3^3S_1(\Upsilon'')$ with 150 nb^{-1}.

The principle of the Columbia University–Stony Brook layered NaI detector has been described in our previous Letter,[4] in which we reported the first measurements of the Υ, Υ', and Υ'' at CESR. For the present run, the complete NaI array was available, and for half of the run, in three of the four quadrants, drift chambers between the beam pipe and the NaI array were in operation. The NaI array consists of five radial layers, each subdivided into two polar halves and 32 azimuthal sectors (see Fig. 1). In contrast to its earlier configuration, our detector now covers the polar angle range $45° < \theta < 135°$ and a solid angle of approximately two-thirds of 4π, with each of the 64 sectors covering ~1% of 4π. In the following, we consider the detector as being composed of eight octants, four with $90° < \theta < 135°$ (West) and four with $45° < \theta < 90°$ (East), each spanning $\Delta\varphi$ intervals of 90°.

The operation of the detector was also described in Ref. 4. All NaI signals are integrated every

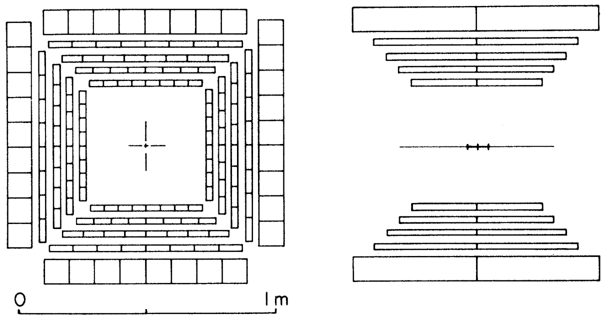

FIG. 1. A front view and a cut-away side view of the NaI array. An error bar shows the length of the interaction region.

machine cycle (2.56 μs) but are digitized only if a trigger is present. Only a single total-energy trigger is used, requiring $\geq$ 700 MeV to be deposited in the outer three layers of the NaI array. Hadronic and large-angle Bhabha-scattering yields in the detector are monitored on line by counting on scalers events satisfying appropriate criteria. The hadronic criterion requires that the total energy deposited in the outer three NaI layers, $E_{\rm NaI}$, be in the range 1.2 GeV$<E_{\rm NaI}<$3.6 GeV, that two or more octants in each half have $\geq$ 100 MeV deposited in the outer four layers, and that two such octants be collinear with the interaction point. The hadron monitor sensitivity is such that the Υ and Υ'' signals are clearly visible in a few hours' run ($\sim$15 nb^{-1}); this monitor also provided an on-line indication of the Υ'''. The Bhabha-scattering criterion requires that $E_{\rm NaI}>5.4$ GeV, and that two collinear octants each have $\geq$ 100 MeV in the outer four layers. These on-line "Bhabhas" comprise approximately 80% of those found later in off-line analysis and serve as an on-line consistency check of the beam luminosity measurement obtained from the luminosity counters (which detect small-angle Bhabha scatterings). Additional electronic criteria were used to monitor and veto poor beam conditions. Typically we write 150 events on tape per inverse nanobarn of integrated luminosity, of which, at the Υ, about 15% are hadronic events and 10% are large-angle Bhabha scattering events. The live time of our detection system is 99.0%.

"$e^+e^- \rightarrow$ hadrons" events are recognized clearly in our detector. Photons from π^0 and η decay are detected as electromagnetic showers. Charged particles which do not shower electromagnetically nevertheless leave a clear signature since the five layers of NaI give five independent measurements of dE/dx. Recognition of "tracks" left in the NaI by minimum-ionizing particles is central to our hadronic-event-selection algorithms. Events containing at least one "track" pointing towards the beam and some additional energy deposition are hadronic candidates. Additional criteria imposed at succeeding levels of analysis include requirements that additional "tracks" or showers be present, and that energy be deposited in both the East and West halves of the detector.

Several independent hadronic-event-selection computer algorithms were developed. To guide us in this process, one or more physicists have examined over 95% of the hadronic-event candidates in the Υ''' energy scan. The various algorithms have efficiencies for continuum events of from 60 to 75% and background contaminations between 1 and 5%. The inefficiencies include loss of events due to detector solid angle. The background estimates are obtained from single-beam runs, and from reconstructed vertex position for those events having drift-chamber information. While the numbers of events found by the various algorithms and the on-line hadron monitor differ, the determinations of masses, widths, and relative cross sections of the resonances are in good agreement.

The present run yielded 5000 hadronic events at the Υ, 450 at the Υ'', and 3000 in the region around the Υ''', for a total 1550 nb^{-1} of integrated luminosity. The data are shown in Fig. 2(a). They have been normalized with use of the measured small-angle and large-angle Bhabha yields. Comparison of our observed cross sections with those measured at DORIS[2] and by CLEO[3] indicates that the product of acceptance by efficiency for our detector is approximately 73% for the continuum and 82% for the Υ.

A peak in the cross section is visible at a mass of 10.55 GeV. As has been shown in the DORIS experiments,[8] the spatial distributions of the continuum and Υ decay events are different. We choose here to test this difference using a simplified thrust variable, T', defined as the maximum of $\sum|\vec{E}_{\rm NaI}\cdot\hat{n}|/\sum E_{\rm NaI}$ over all possible $\hat{n}$ perpendicular to the beam axis. The distributions of T' for Υ and continuum events are given in Fig. 3. The difference between the two cases is quite evident and agrees with the conjecture that continuum events have a two-jet-like structure while resonance decays have a more spherical distribution. A cut at $T'<0.85$ has been made for all the data and the result is shown in Fig. 2(b).

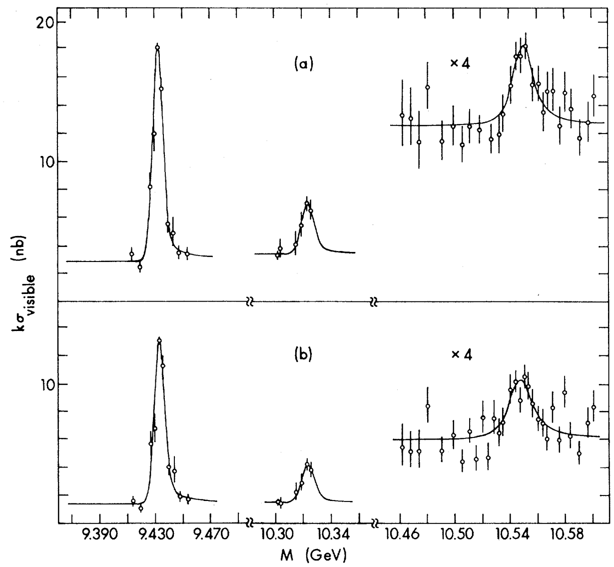

FIG. 2. (a) The observed cross section for e^+e^- →hadrons multiplied by $k = (M/M_\Upsilon)^2$. M is the e^+e^- invariant mass. (b) The same cross section after removing events with $T \geq 0.85$. The lines are fitted to the data including machine energy spread and radiative corrections. See text for explanation.

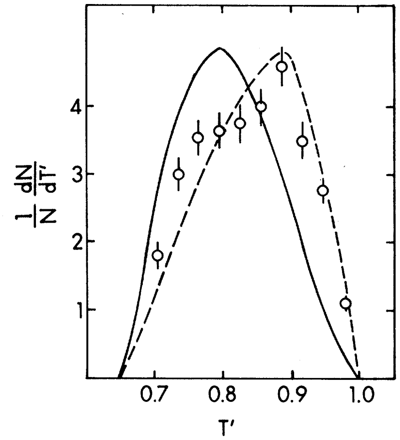

FIG. 3. Solid line, pseudothrust (see text) distribution for events in the Υ region; dashed line, distribution for continuum events. Data points are for events from the Υ''' region, showing contributions from both distributions.

The cut removes 52% of the continuum events but only 26% of resonance events.

We determine the parameters of the Υ''' by fitting the data sample with $T' < 0.85$; the uncut data give similar results but with less statistical significance. A fit to a constant continuum plus a Gaussian with radiative corrections gives an apparent machine energy spread of $\Gamma = 19 \pm 4$ MeV. We have also fitted the parameters of the Υ using our data from this running period, cut on $T' < 0.85$. This gives a full width at half maximum (FWHM) machine energy spread at the Υ of 8.7 ± 0.7 MeV. Scaling this by the expected $(E_{beam})^2$ dependence yields a FWHM at the Υ''' of $\Gamma = 10.8 \pm 0.9$ MeV. This is inconsistent with the observed result by 2 standard deviations. We therefore assume a Breit-Wigner, rather than Gaussian, resonance shape for the enhancement, fold in the machine energy spread and radiative corrections, and fit the Υ''' data with the resulting curve. The mass values are calculated from the CESR energy calibration, which gives a mass for the Υ 0.3% below the DORIS values.[2-4] The mass difference is $M(\Upsilon''') - M(\Upsilon) = 1114 \pm 2$ MeV with systematic uncertainty of 5 MeV. The ratio of leptonic widths calculated from the fitted areas is $\Gamma_{ee}(\Upsilon''')/\Gamma_{ee}(\Upsilon) = 0.25 \pm 0.07$. Both the mass difference and the ratio of leptonic widths are in excellent agreement with many phenomenological calculations for the 4^3S_1 state of $b\bar{b}$.[1,6,9] Therefore, we conclude that the enhancement observed at $M = 10.547$ GeV is most likely that state.

The natural width of the enhancement is also of great interest. Our fit gives a natural width $\Gamma = 12.6 \pm 6.0$ MeV. If we constrain the natural width to be much smaller than the machine energy spread, χ^2 increased by 8.3, from 40.3 for thirty degrees of freedom to 48.6 for 29 degrees of freedom. Thus, our value for the natural width is inconsistent with the expected width of less than 1 MeV for a resonance below $B\bar{B}$ threshold. A similar result has been obtained by the CLEO collaboration at CESR.[10] This implies that Υ''' is above threshold and that the mass of the B is less than 5.275 GeV. It also implies a production rate for B mesons which is greatly enhanced above the level in the neighboring continuum. If this is confirmed, the study of the Υ''' events should contribute enormously toward our understanding of the B meson.

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CP Nonconservation without Elementary Scalar Fields

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Dynamically broken gauge theories of electroweak interactions provide a natural mechanism for generating *CP* nonconservation. Even if all vacuum angles are unobservable, strong *CP* nonconservation is not automatically avoided. In the absence of strong *CP* nonconservation, the neutron electric dipole moment is expected to be of order 10^{-24} $e\cdot$cm.

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In this Letter, we show that there is a natural mechanism for generating *CP* nonconservation in dynamically broken electroweak gauge theories. Our proposal requires no new gauge interactions beyond those discussed previously.[1-4] Spontaneous *CP* nonconservation can appear when we carry out Dashen's[5] procedure to identify the correct chiral vacuum. Whether *CP* nonconservation occurs is determined in principal by *only* the gauge group and the fermion representation content of the theory.

These theories have no elementary scalar fields and no fermion bare masses. Even though there are no observable vacuum angles,[6] strong *CP* nonconservation[7] is not automatically avoided.[8] We state a criterion for the absence of strong *CP* nonconservation; if it is satisfied, *CP*-nonconserving phases in the quark mass matrix are naturally suppressed by a factor of order 10^{-9}. Additional *CP* nonconservation appears in the electroweak interaction and in the gauge interaction responsible for chiral symmetry breaking. We predict that the electric dipole moment of the neutron is of order 10^{-24} $e\cdot$cm.

In a theory of weak interactions without elementary scalar fields, a new gauge interaction[1,2] ("hypercolor," with gauge group G_H) is required, in addition to the familiar color [G_C =SU(3)] and electroweak [G_W =SU(2) $\otimes$ U(1)] interactions. Hypercolor becomes a strong interaction at mass scale $m_H \simeq 1$ TeV, and drives the breaking of G_W down to $U(1)_{EM}$.

A theory with gauge group $G_H \otimes G_C \otimes G_W$ alone cannot be realistic. A "sideways" interaction[3,4] (with group G_S) is needed to break explicitly all chiral symmetries not gauged by G_W. G_S is dynamically broken to a subgroup containing $G_H \otimes G_C$ at a mass scale $m_S \simeq 100$ TeV. (We need not speculate here on the origin of the G_S breakdown.)[4,9,10]

All fermions are in at most four irreducible representations of G_S.[3] In the effective gauge theory which describes physics below 100 TeV, each of these representations transforms reducibly under $G_H \otimes G_C$. If we neglect the broken sideways interactions and the weak interactions, the $G_H \otimes G_C$-invariant effective Hamiltonian $\mathcal{H}_0$ respects a global (chiral) flavor-symmetry group G_f. G_W is a subgroup of G_f.

When hypercolor and color become strong, G_f is dynamically broken to a subgroup S_f. Many Goldstone bosons result. Three of these are absorbed by the weak $W^\pm$ and Z^0 bosons.[1,2] The remaining Goldstone bosons acquire mass from the chiral-symmetry-breaking perturbation $\mathcal{H}'$ generated by the weak and sideways interactions.

The ground state of $\mathcal{H}_0$ is highly degenerate; the vacua are parametrized by the coset space

