A STUDY OF HIDDEN AND UNVEILED BEAUTY WITH THE CUSB DETECTOR

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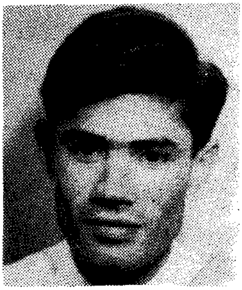

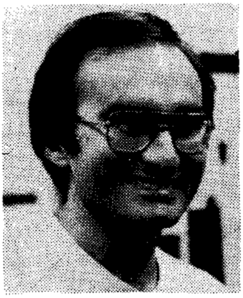

ABSTRACT

Results on the spectroscopy of bound $b\bar{b}$ states, the properties of the B meson and the weak interaction of the b quark are reported.

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1. INTRODUCTION

The CUSB detector,[1] operated at CESR by the CUSB collaboration,[2] has been described in many publications. The detector is essentially an electromagnetic calorimeter, complemented by good tracking in the central region. A unique feature of our detector is the radial segmentation of the active converter material (NaI, Pb-glass) which provides excellent identification of electromagnetic showers by allowing observation of their longitudinal development. In general, photons, electrons, and hadrons can be clearly identified allowing us to measure with good accuracy the hadronic annihilation cross section, the inclusive photon spectra, and the beta decays of new heavy particles. Most of our results have been already reported at the XVII Rencontre de Moriond,[3,4] and we will therefore concentrate in the following on our most recent results.

2. SEARCH FOR NEW RESONANCES, R BELOW AND ABOVE THE NEW FLAVOR THRESHOLD

All the data collected with the CUSB detector, since its completion in early 1981 up to the end of February 1982, are shown in the form of $R = \sigma(e^+e^- \rightarrow had)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ in Fig. 1. Some 120,000 hadronic annihilations events were collected for a total delivered luminosity of 35,000 nb^{-1}. The striking appearance of three resonances with observed widths identical to the machine energy spread plus a fourth resonance of significantly larger width is now history. The four resonances, the Υ, Υ', Υ'', and Υ''', are bound and quasi-bound triplet s-wave states of the new heavy b quark of mass $\sim$ 5 GeV. The levels spacing and the leptonic widths of these four states have given new impetus to the study of heavy 'quarkonia' and in particular have allowed to prove that it is possible to construct potentials which reproduce both the ψ and Υ levels in a flavor independent way,[5,6] a fundamental result if QCD is to be a valid theory of strong interactions. An expanded view of the cross section measured with CUSB around the Υ'' and the Υ''' is shown in Fig. 2. We would like to draw attention to the higher value of R observed above the fourth resonance where we expect production of $b\bar{b}$ pairs to contribute to σ (hadron). The values of R measured in our experiment are $R(10.2 < W < 10.5 \text{ GeV}) = 3.54 \pm 0.04$ and $R(10.6 < W < 11.6 \text{ GeV}) = 3.85 \pm 0.05$, where W is the total c.m.

energy.[7] Systematic uncertainties, due to the calculation of the detector efficiency, luminosity measurement, and radiative corrections, are estimated to be 10%. Of particular interest is the observation that R changes by 0.31 $\pm$ 0.05 across the new flavor threshold. To zero order in QCD, the quark-parton model predicts an increase in R of $3x(Q_b)^2 = 0.33$ for Q_b, the charge of the b quark equal to 1/3 e. Thus the prediction is well confirmed and the charge of the b quark is again proved to be 1/3 e. The values of R given above are in good agreement with the values from DORIS and PETRA. The same data have been used to search for the production of additional narrow resonances with a sensitivity of 2 to 3% of the Υ cross section. For $10.25 < W < 10.30$ and $10.35 < W < 10.52$ GeV, no resonance was found and we can put an upper limit of $\Gamma_{ee} < 20$-30 eV for any resonance in the above mass ranges.[7] String vibrational states and d-wave states should have been observable in these energy ranges.[8,9]

3. HIDDEN BEAUTY SPECTROSCOPY

Figure 3 shows a level diagram for the first few $b\bar{b}$ bound states. Triplet s-wave bound states are the only ones produced in the e^+e^- annihilations. Many other states can be reached by hadronic cascades and electric dipole transitions as indicated. The $\Upsilon' \to \Upsilon\pi\pi$ transition was observed in early 1980,[10] and was an important result for proving that the Υ's are indeed bound states of the same quark. In addition, the result $\Gamma(\psi' \to \psi\pi\pi)/\Gamma(\Upsilon' \to \Upsilon\pi\pi) \sim 1/15$ is in good agreement with the simple picture that hadronic cascades of heavy vector mesons can be understood as two color electric dipole transitions.[11] For spin zero gluons the width for $N^3S(q\bar{q}) \to (N-1)^3S(q\bar{q}) + \pi\pi$ would be proportional to the color charge and the above ratio would be one. This is perhaps one of the most unambiguous proofs that color couples to a vector field. Very recent results from a large sample of data collected at the Υ'' are: a better measurement of the branching ratio for $\Upsilon'' \to \Upsilon\pi\pi$ (for earlier results see Ref. 12) and the first observation of $\Upsilon'' \to \Upsilon'\pi\pi$. The last reaction has a Q-value of $\sim$ 50 MeV and often pions will stop in the beam pipe. Four unambiguous events of the kind, $\Upsilon'' \to \Upsilon'\pi\pi$, $\Upsilon' \to e^+e^-$, were observed in CUSB with $M(ee) = M(\Upsilon')$ and both pions having only a few MeV energy, since they stop in the first NaI layer of the detector. The preliminary branching ratios for these decays, including charged and neutral pions, are $BR(\Upsilon'' \to \Upsilon\pi\pi) = 9 \pm 2\%$ and $BR(\Upsilon'' \to \Upsilon'\pi\pi) = 4.5 \pm 2\%$. Of considerable interest are the electric dipole transitions (E1) which allow us to reach the p-wave bound $b\bar{b}$ states thus providing additional experimental data (masses, transition rates, fine structure) against which potential models can be put to test and/or refined. One outstanding failure of the potential models is the prediction of the E1 rates for the ψ'.[13] This failure is usually blamed on the fact that charmonium is not sufficiently non-relativistic ($\langle v/c\rangle^2 \sim 0.2$) in order to allow reliable calculations of the wave functions of s-wave and p-wave states and in particular of $\langle\psi_f|\vec{r}|\psi_i\rangle$, the E1 matrix element. This problem should be greatly reduced for the upsilon family. The study of E1 transitions for the upsilon family presents formidable difficulties compared to the $\psi' \to \gamma\chi_c$ case. The b quark charge, the radius of the $b\bar{b}$ states and the increased multiplicity in the hadronic final state result in a E1 photon signal to background ratio approximately ten times smaller than for the ψ' case. At the same time, the 1/S factor in the one photon annihilation cross section, the quark charge again and the intrinsic scaling of the beam energy spread in a storage ring result in a production cross section which is about 100 times smaller. One therefore begins with a handicap of 10,000 to 1! One advantage of the Υ however is that the mass is high enough to make the jet structure of the various final states, $q\bar{q}$, two gluons and three gluons quite readily detectable using global energy flow parameter such as thrust. This point was first proved at DORIS,[14] where for the first time it was shown that a vector meson (the upsilon) decays by annihilation of the $q\bar{q}$ pair into three gluons. Earlier runs at CESR had resulted in CUSB accumulating some 10,000 Υ' and 6,000 Υ'' events. An analysis of the thrust distributions of their final states, using continuum events and Υ decay events to obtain the effective two jet ($q\bar{q}$) and three jet (three gluons) thrust distributions in our detector, allowed us to detect the presence of an excess two-jet fraction in the Υ' and Υ'' final states.[15] This excess can be explained as due to the presence of E1 transition to p-wave states. The triplet P_J states have $J^{PC} = 2^{++}, 1^{++}$, and 0^{++}. The $J = 2, 0$ states will therefore decay by annihilation of the $b\bar{b}$ pair into two gluons, the $J = 1$ state being forbidden to do so by a very well known argument (since however gluons carry color the J = 1 state decays into three gluons or a gluon and a quark pair). Analysis of DORIS and PETRA results have shown[16] that gluon jets and quark jets are very similar and therefore we conclude that the observed two jet excess is proof of production of p-wave states via E1 transitions. From the above analysis, we have computed the branching ratio for E1 transitions from triplet S to triplet P, J = 2, 0. We obtain $BR(\Upsilon' \rightarrow \gamma + 1\,^3P_{2,0}) = 6 \pm 3\%$ and $BR(\Upsilon'' \rightarrow \gamma + 2^3P_{2,0}) = 20 \pm 4\%$. These values times a factor 1.5 to account for the J = 1 state are in good agreement with potential model calculations.[17] The higher branching ratio for the Υ'' is easily understood. The r.m.s. radius of the Υ'' $(3\,^3S)$ is larger than that of the Υ' $(2\,^3S)$ resulting in both a larger E1 matrix element and a smaller annihilation rate. The competing hadronic decays for the Υ'' are also suppressed by the lack of phase space, for decays to Υ' and by $\Delta N = 2$, for decays to the ground state ; thus the result that $BR(\Upsilon'',E1) \sim 3\times BR(\Upsilon',E1)$.

While the above result is indirect evidence for E1 transition, it gives confidence that, as predicted by simple arguments, a sizable effect should be directly observable in the inclusive photon spectrum from Υ'' decays. During the period November 1981 through February 1982, CUSB ran mostly at the Υ''. For a total delivered luminosity of 19,000 nb^{-1}, we collected 64,000 hadronic events at the Υ'' peak of which 37,000 are resonance decays, 8,800 continuum events, and 16,000 events at the Υ peak of which 14,000 are Υ decays. A preliminary example of the observed inclusive photon spectrum from the 64,000 hadronic events at the Υ'' peak is shown in Fig. 4. A significant excess in a narrow energy range around 100 MeV is observed. The whole observed spectrum is mostly due to photons from π^o decays in the approximate ratio of 5 γ/event from π^o's to 0.1 γ/event from E1 transitions. The observed excess is consistent with these estimates. The actual shape of the expected photon spectrum from π^o's can be experimentally constructed by combining appropriate fractions of the inclusive photon spectra from Υ decays and continuum events. This is shown as a continuous line in Fig. 4, where the fractions of Υ and continuum data are determined by the previously discussed thrust analysis and the 'background spectrum' has been normalized by the number of hadronic events, not photons. In other words, the background is predicted in an absolute way without any freedom. The agreement between predicted background and observed spectrum is extremely good except for the excess around 100 MeV which we attribute to photon from E1 transitions. The statistical significance of the observed effect is between 12 and 14 σ's. The width of the enhancement, shown subtracted in Fig. 5, is approximately three times our energy resolution as determined by Monte Carlo calculation and the width of the reconstructed π^0 mass spectrum. The observed width is consistent with the superposition of three unresolved lines. These results are very preliminary at the moment and we prefer not to quote values for the center of mass of the 2P states, the fine structure splitting, and the total branching ratio. We have however used the observed enhancement to obtain a direct proof that the 2^{++} and 0^{++} states decay into two jets. By dividing our total sample into two classes, with thrust respectively greater and smaller than 0.8 and counting excess photon in each, we can extract the branching ratio for $\Upsilon'' \to \gamma + 2$ jets. The result is BR($\Upsilon'' \to \gamma + 2$ jets) ~ 0.2, in good agreement with the result obtained from our previous thrust analysis. This result is the first direct experimental proof that triplet p-wave $q\bar{q}$ pairs annihilate into two gluons.

4. PARTIAL AND TOTAL WIDTHS OF THE FIRST THREE UPSILON STATES

All the available information on leptonic widths and branching ratios for various decay channels can be combined to obtain the partial and total widths for the $b\bar{b}$ bound states below threshold. The lowest state, the Υ, can only decay through annihilation of the $b\bar{b}$ pair. Using the best value for $\Gamma_{ee} = 1.17 \pm 0.05$ keV,[12] and for $B_{\mu\mu} = \Gamma_{\mu\mu}/\Gamma_{tot} = 0.033 \pm 0.006$,[18] one obtains $\Gamma_{tot}(\Upsilon) = 35.5$ keV. For the next two states, both annihilations and transitions to other $b\bar{b}$ states contribute to the total width. If we write $\Gamma_{tot} = \Gamma_{annihil} + \Gamma_{other}$ and use the fact that the annihilation channels scale as Γ_{ee},[1] then we can write $\Gamma_{tot}(\Upsilon^i) = [\Gamma_{ee}(\Upsilon^i)/B_{\mu\mu}(\Upsilon)]/[1/(1-\mathrm{BR(other)})]$, where BR(other) is the sum of all branching ratios for decays to other $b\bar{b}$ states. From the results reported here and in Ref. 12, we obtain :

	Υ	Υ'	Υ''
Inputs			
Γ_{ee}, keV	1.17 ± 0.05	0.54	0.37
$B_{\mu\mu}$ %	3.3 ± 0.6	-	-
BR($\pi\pi$)%		28.7	13.5
BR(E1)%		9	30
Derived			
Γ_{tot} keV	35.5	26.3	19.8
$B_{\mu\mu}$ %	-	2	2
Γ(3g) keV	27.9	12.9	8.8
$\Gamma(\pi\pi)$ keV	-	7.5	2.7
Γ(E1) keV		2.4 ± 1.2	5.9 ± 1.2

Most errors are not given in the table. Typically the fractional errors on most entries are around 16%, due to the uncertainty in $B_{\mu\mu}$ plus a systematic uncertainty of 5 to 15% in leptonic widths and branching ratios.

5. AXION SEARCH

In the standard model the existence of a very light pseudoscalar particle with semi-weak coupling to quarks was postulated in 1978,[19] in order to avoid very large CP violation effects. Since the axion couples to the mass, it is possible to predict in an unambiguous way the width for the decay of a heavy vector meson into an axion and a photon with respect to the decay width into two leptons. The branching ratio for $V \to a + \gamma$ is given by: $BR(V\to\gamma+a)/B_{\mu\mu} = G_F m_q^2 x^2/(\pi \sqrt{2}\, \alpha)$, where x is $\langle\phi_1\rangle/\langle\phi_2\rangle$ for charge 2/3 quarks, and $\langle\phi_2\rangle/\langle\phi_1\rangle$ for charge 1/3 quarks, and $\langle\phi_1\rangle$, $\langle\phi_2\rangle$ are the vacuum expectation values of the Higgs field ϕ_1 and ϕ_2. Since the axion has semi-weak interaction, it can traverse undetected large amounts of matter. The decay $V \to a + \gamma$ where V is any Υ will therefore have the very characteristic signature in our detector of one single large angle photon of energy equal to the e^+ and e^- beam energies, ~ 5 GeV. We have searched in our detector for such events in a produced sample of 20,000 Υ and 60,000 Υ''. We compute our efficiency for detecting this type of event in our detector to be 0.32. This value is the product of an 82% identifying efficiency and a solid angle factor of 39%, using an angular distribution for the decay $\propto 1 + \cos^2\theta$, which we have computed.[20] No event was found in either sample, we thus obtain a 90% confidence level upper limit of 3.5×10^{-4} for $\Upsilon \to a + \gamma$ and of 1.2×10^{-4} for $\Upsilon'' \to a + \gamma$. A comparison of theory and experiment, independent of the value of the unknown parameter x, can be performed by noting that the product of the branching ratios for $\Upsilon \to \gamma + \gamma$ and for $J/\psi \to a + \gamma$ is independent of x and is given, according to the above formula, by 1.6×10^{-8}. First we combine our results for Υ and Υ'' by scaling down the number of produced Υ'' resonances by $B_{\mu\mu}(\Upsilon'')/B_{\mu\mu}(\Upsilon) = 2/3$ (see our table) and adding to the number of Υ's obtaining an upper limit of 1.09×10^{-4} for $\Upsilon \to a + \gamma$. This value combined with a recent result from the Crystal Ball,[21] which quotes an upper limit of 1.4×10^{-5} for $J/\psi \to a + \gamma$ at 90% c.l., results in an upper limit of 1.1×10^{-9} at 90% c.l. This result is more than a factor ten smaller than the theoretical prediction above. We therefore conclude that the "standard axion" does not exist. Our null result is valid for the decay of the Υ into a photon and a stable particle of up to 5 GeV mass. For a standard axion, the result is valid for masses less than 10 MeV, above which the axion would decay inside our detector into ee or $\gamma\gamma$.

6. B MESON RESULTS

We briefly recall that the fourth resonance discovered at CESR by CUSB,[22] and CLEO[23] in 1980 is observed to have a width of about 20 MeV, proving that it is above threshold and that it decays strongly into a pair of B mesons.[4] Direct evidence for this was also later obtained by CLEO and CUSB through the observation of the leptonic decay of the B meson.[24,25] CUSB has searched for the production of B^* meson in Υ''' decays.[26] The B^* meson is $\sim$ 50 MeV heavier than the B meson and therefore decays by emission of a 50 MeV photon. From the absence of such signal, we conclude that the Υ''' is only about 40 MeV above twice the mass of the B meson and therefore $M_B = 5256 \pm 7$ MeV.[4,26] This result is important in the study of the weak couplings of the b quark. CUSB has also measured the branching ratio for $B \to e\nu x$ obtaining the result BR = $13.6 \pm 2.5\%$.[25] This result is in good agreement with calculation in the standard model.[27] Similar results have been reported by CLEO. One very important question in the study of the weak interaction of the b quark is the determination of the relative strength of the (bc)W and (bu)W couplings. We shall return later to this point. We wish to present results of relevance to various "topless" schemes in which the b quark is assumed not to couple in the standard way to W's, quarks and leptons. In particular, it has been proposed that the b quark might have decays like i) $b \rightarrow q\ell\bar{\ell}$,[28] where $\ell\ell$ are lepton pairs ee, $\mu\mu$, $\tau\tau$, and $3\times\nu\nu$; and ii) $b \rightarrow q\bar{q}\ell$,[29] where ℓ again is a lepton. Both of these schemes imply that a considerable fraction of the total available energy would be carried away by neutrino. The CUSB detector is essentially a calorimeter with very good response to electromagnetic energy. In addition the detector responds to minimum ionizing hadrons with an average 350 MeV signal from dE/dx losses in NaI and Cerenkov light in the Pb glass blocks. Note that this value is very close to the average momentum of pions in hadronic final states. Finally all elements of our detector are continuously calibrated, when beams are stored in the accelerator, to a fraction of 1%. CUSB is therefore ideally suited to study processes which remove a fraction of the available energy. Figure 6 shows the average fraction of the total energy observed in CUSB at the Υ, Υ', Υ'', Υ''' and in the continuum. The first three values and the last are respectively 0.408 ± 0.001, 0.406 ± 0.002, 0.409 ± 0.001, 0.408 ± 0.001 and their average is 0.4082 ± 0.0006. For Υ''' events, correcting for the continuum, we measure in the detector in average 0.391 ± 0.005 of the total energy. The fractions measured for the continuum and the first three resonances agree very well with the estimated detector response of 40.5% and are remarkably constant in time and independent of beam energy. The slightly lower value observed for the Υ''' can be compared to what should be expected for the different decays of the b quark. In the standard model, using our value for $BR(B \rightarrow e\nu x) = 13.6\%$, we expect to detect 39% of the total energy in good agreement with observation. For models i) and ii) above respectively, we expect to detect in average 29.1% and 33.8% of the total energy. We therefore conclude that decay i) occurs less than 10% of the time and ii) less than 20%, both limits at 90% confidence level.

Coming back to the question of the b weak coupling in the standard model, we wish first to introduce some notation. Using

Maiani notation for the weak mixing matrix, the (bc)W and (bu)W vertex is described by an amplitude $\sin\beta (ub)_\alpha W_\alpha + \sin\gamma \cos\beta e^{i\delta} (cb)_\alpha W_\alpha$, where $(ub)_\alpha = \bar{u}_u \gamma_\alpha (1-\gamma_5) u_b$, etc. The advantage of Maiani's notation is that one immediately obtains from nuclear beta decay, muon decay, and Cabibbo angle that $\sin\beta < 5 \times 10^{-2}$ while for γ one has the weaker constraint $\sin\gamma < 0.5$.[31] Therefore $\Gamma(B \to \ell\nu x$, from $b \to u)/\Gamma(B \to \ell\nu x$, from $b \to c) \sim 10^{-2}$ which at present it is hopeless to verify. Nevertheless it is of great importance to experimentally determine the ratio of the (bc)W to (bu)W coupling since disagreement with the above bound would force us to abandon the present formulation of the standard model. A naive consequence of a dominant (bc)W coupling is that non-leptonic decays of the B meson lead to abundant production of K meson in the final state. Simple quark counting with phase space corrections leads to 1.25 K mesons per B decay for $b \to c$ versus 0.47 K's per B for $b \to u$. If $\Upsilon''' \to B\bar{B}$, we therefore expect 2.5 or 0.94 K's per event. Similar counting for continuum and bound $b\bar{b}$ states gives 1 K meson per continuum event and about 0.1 K meson per resonance event for the first three Υ's. Unfortunately these predictions are weakened by the effects of 'hadronization' which are at present rather poorly understood. In general $s\bar{s}$ pairs are expected to be created out of the vacuum increasing all the above numbers. In CUSB we have measured the K^0 yield for all resonances and the continuum.[4,32] The measured yield in the continuum is 0.81 ± 0.09 K^0/event. From the argument above, one expects 0.5 K^0's per event plus the vacuum pair contribution, in reasonable agreement with the measurement. However for the three bound upsilons, we measure 0.82 ± 0.11, 0.83 ± 0.09, and 0.83 ± 0.14 K^0's per event in strong disagreement with the naive prediction. At the fourth upsilon, we observe 1.58 ± 0.3 K^0's per event, corresponding to 1.58 K's/B, if here too we assume that half of the produced K mesons are neutral. These results certainly strongly support the dominance of the (bc)W coupling; it could however become meaningless if one were to assume for instance that K's from vacuum pairs are proportional to the observed multiplicities in the final state, an assumption incidentally which would help explain the observations for continuum and bound upsilons. Another method which can be used to determine the ratio of the b quark couplings is to study the electron spectrum. The end point of the spectrum, in the spectator model, is given by $(m_b^2 - m_{c,u}^2)/2m_b$ from which, using m_b = 5.2 GeV and m_c = 1.8 GeV,[6] E = 2.29 (b → c) and E = 2.6 GeV (b → u). The spectrum in addition is smeared out by the fermi motion of the quark inside the B meson and by the motion of the B in the laboratory frame. Figure 7 shows an example of such calculations similar to those of Ref. 3, without radiative corrections which tend to enhance the spectrum at the high energy end. Figure 8 shows the CUSB measurement of the electron spectrum from B decay,[25] compared with the calculation. Alternatively one can compute the electron spectrum for B → eνx, where x is a mixture of various final states as indicated in Fig. 9. Figure 10 shows the spectrum calculated in this way for M(x) = 2 GeV (b → c) and M(x) = 1 GeV (a larger mass than indicated in Fig. 9 for b → u) together with the CUSB measurement. A maximum likelihood calculation gives $|V_u|^2/|V_c|^2 < 0.1$, 90% c.l., where V_u and V_c are the elements of the mixing matrix as given before. We therefore conclude that at these levels of accuracy the (bc)W coupling is indeed dominant but we all are still a long way from being able to confirm or disprove the presently accepted limits on the angles β and γ.

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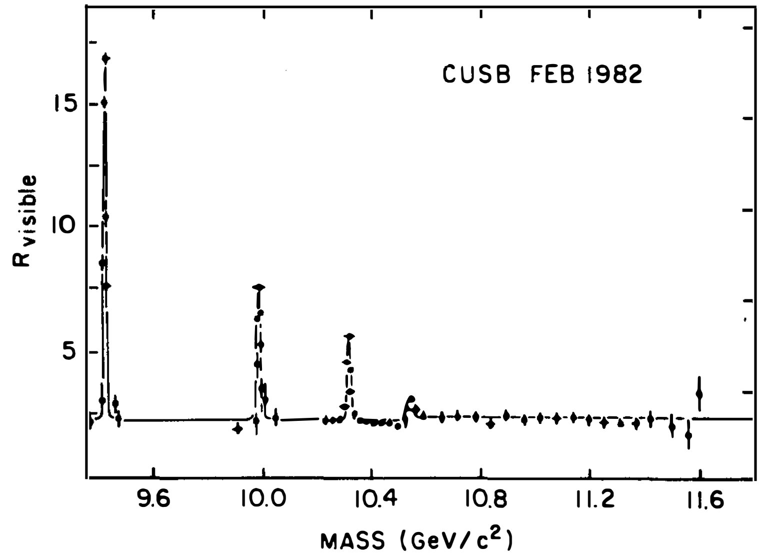

Fig. 1 The visible value of R, measured with CUSB at CESR, for an integrated luminosity of 34 pb^{-1} .

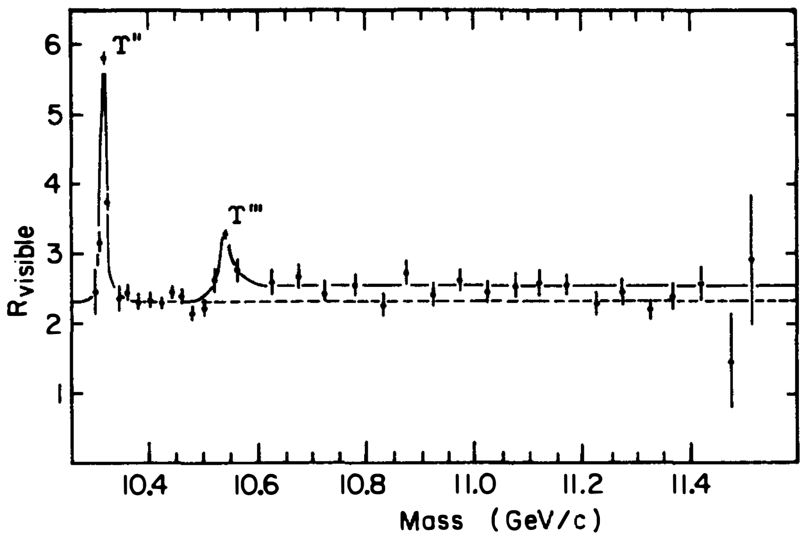

Fig. 2 The visible value of R, around T'' and T''' .

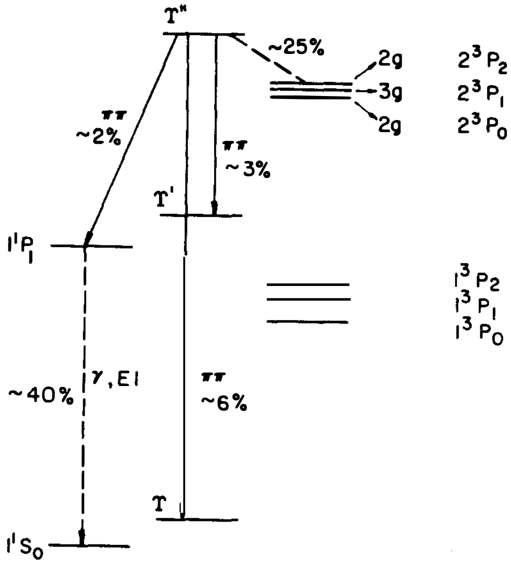

Fig. 3 Some bound $b\bar{b}$ levels and dominant transitions for Υ'' .

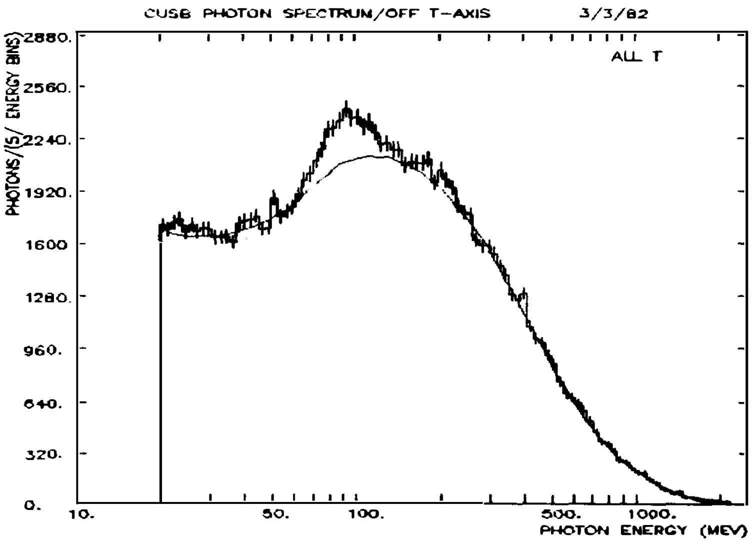

Fig. 4 The inclusive photon spectrum from ~ 37,000 Υ'' plus ~ 27,000 continuum events. The smooth curve is the contribution from all sources except for E1 transitions, see text.

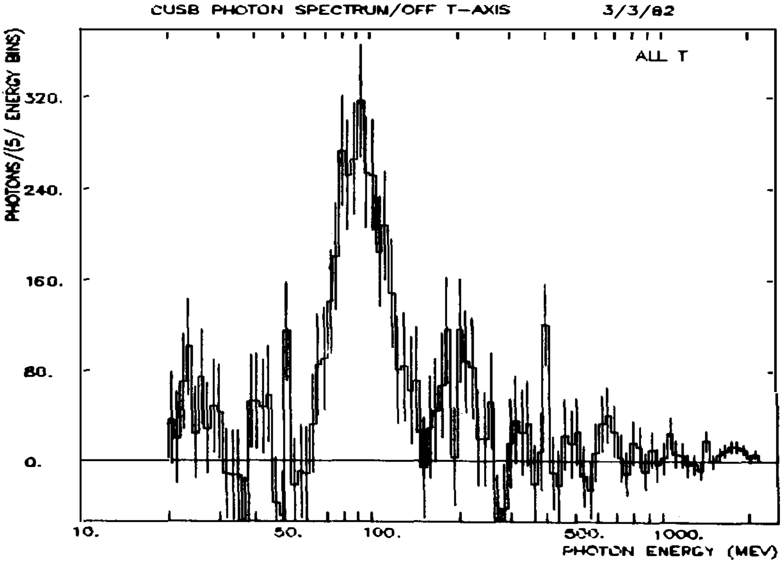

Fig. 5 The photon spectrum from ϒ'' after background subtraction.

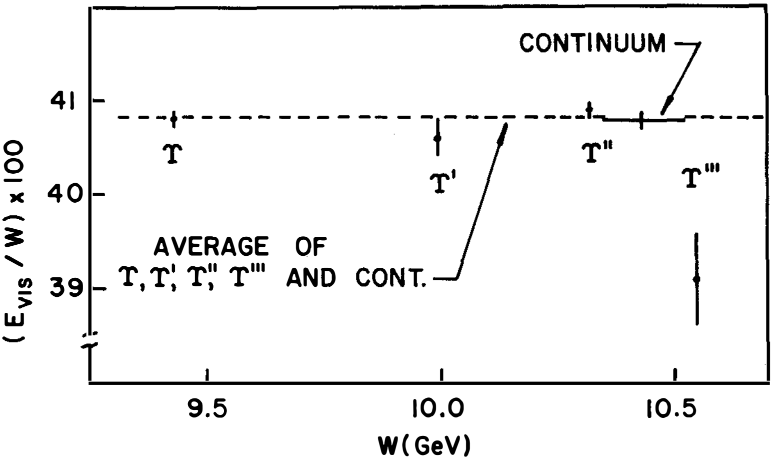

Fig. 6 Average energy fraction observed in CUSB vs. total energy. The values for resonances are corrected for continuum contributions.

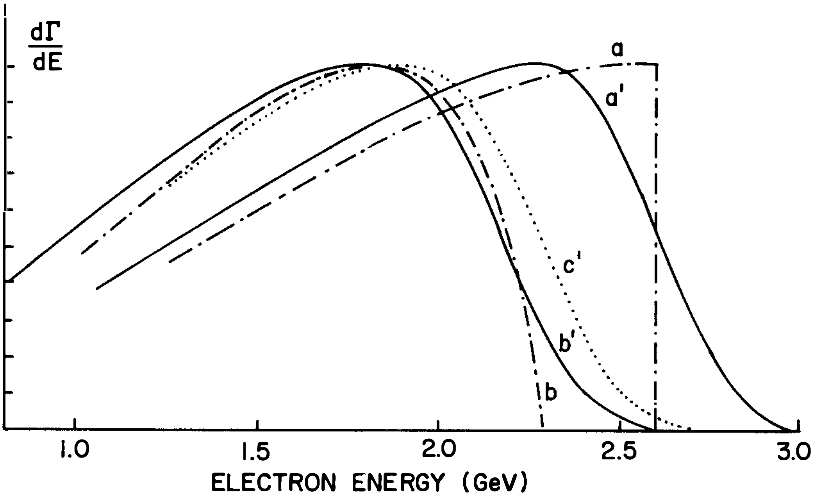

Fig. 7 Electron spectrum from $b \to e\nu q$. a) M_b = 5.2 GeV, M_q = 0, no motion. a') Same but smeared with Fermi motion and recoil. b) M_b = 5.2 GeV, M_q = 1.8 GeV, no motion. b') Same, but smeared as above. c') Same as b' but with M_q = 1.5 GeV .

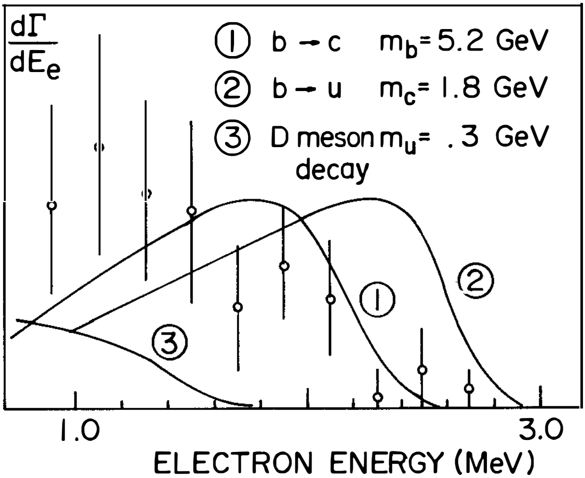

Fig. 8 The CUSB electron spectrum from B decay compared with calculations for the spectator model.

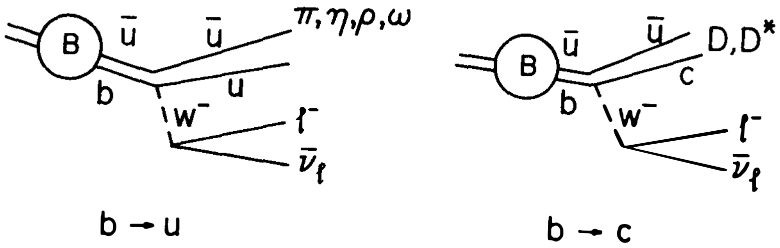

Fig. 9. Naive expectation for hadronic final states contributing to x in $B \to e\nu x$ for $b \to u$ and $b \to c$.

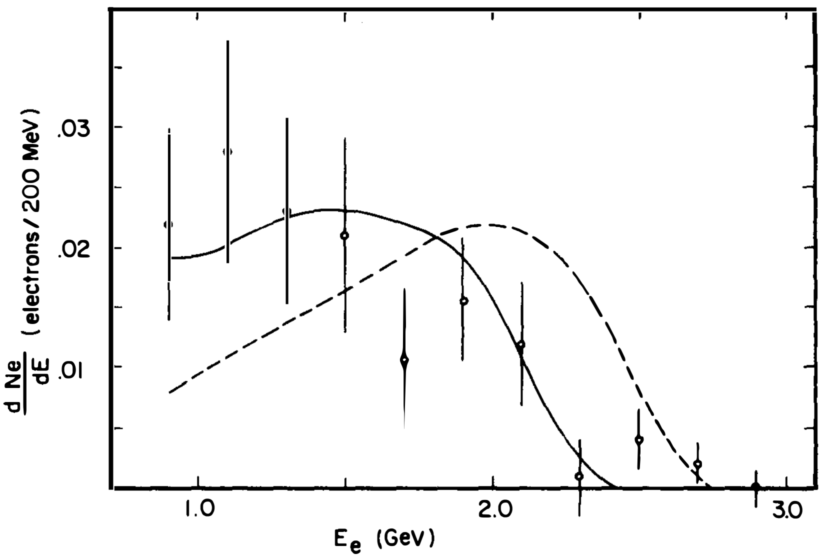

Fig. 10 The CUSB electron spectrum from B decay compared with the calculation for $B \to e\nu x$; M_x = 2 GeV solid line and M_x = 1 GeV dashed line.