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CURRENT PROBLEMS IN NEW FLAVOURS*

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ABSTRACT

In this summary talk I collect a number of current problems in the investigation of new flavours which were discussed at the 1982 Moriond Workshop.

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I. INTRODUCTION

In this summary, I have decided to depart from the perhaps more traditional role of dealing with general issues (the "big picture" approach), and instead have picked out some of the more specific problems in new flavours which were discussed at this Workshop. Thus, I hope to provide a list of reasonably well-defined problems with adequate references (usually to other talks at this Workshop) so that a reader whose interest is aroused by some puzzle can then consult a more detailed and expert discussion. As an experimentalist, I naturally tend to concentrate on issues of current experimental significance, and will avoid purely theoretical issues beyond my competence. This bias, plus the fact that almost 60 talks were given at this Workshop, implies that I must neglect many very interesting and valuable contributions.[1] For this I can only apologize and urge the reader to look at the other talks for a more complete picture.

The natural organization for this talk appears to be to break the physics up into three major subareas:[2] First, I will discuss the spectroscopy of heavy $Q\bar{Q}$ (Q stands for a heavy quark) states, turning second to the decays of particles manifesting heavy flavour. Finally, I will touch on some of the issues concerning the production of heavy-quark states in experiments with hadronic targets (and photon, lepton, or hadron beams).

II. HEAVY $Q\bar{Q}$ SPECTROSCOPY

The study of the spectroscopy of heavy quark-antiquark ($Q\bar{Q}$) systems has proved to be an enormously fruitful area of research ever since the discovery of the J/ψ in 1974. It is a field which is both experimentally and theoretically accessible. The theoretical accessibility is based largely on the ideas that the heavy $Q\bar{Q}$ states can be modeled as nonrelativistic systems and with distance scales often sufficiently small that perturbative strong interaction techniques may be employed. These assumptions should be even more justified for the $b\bar{b}$ system than for charmonium, and a comparison of the two systems is especially interesting for what we can learn about the nature of the relativistic and perturbative corrections in various processes, and the nature of the quark-antiquark interaction (potential - see Fig. 1). We eagerly await the discovery of toponium (if it exists!) for the potential wealth of new information at a substantially higher mass scale. At the other end, it appears that even the $s\bar{s}$ system can in some respects be treated as a "heavy" $Q\bar{Q}$ system.[5] The general picture of the charmonium spectroscopy (Fig. 2) is now fairly complete, and in agreement with the early predictions for the level scheme. It is amusing to note that we now have evidence for seven of the eight expected states of charmonium below $D\bar{D}$ threshold, so the experimental picture is, in a sense, more complete than that for the

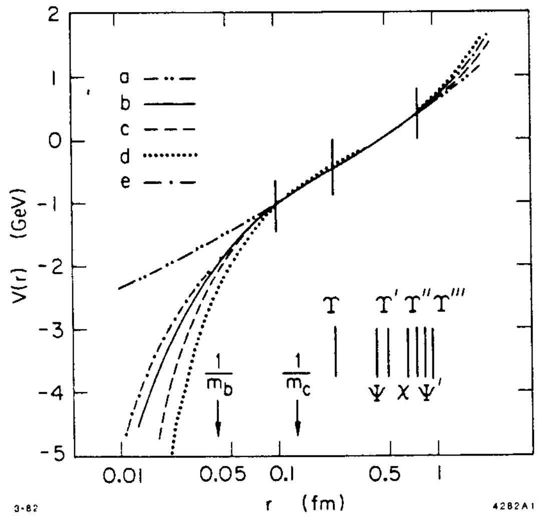

Fig. 1. A comparison of several potentials which have been used to fit the $c\bar{c}$ and $b\bar{b}$ systems:[3] (a) $A+Br^{\alpha}$ potential ($\alpha \approx 0.1$, i.e., nearly logarithmic;[5] (b) Buchmuller, Grunberg, and Tye QCD (empirical) potential;[6] (c) Coulomb plus linear plus logarithmic interpolation;[7] (d) Coulomb plus linear;[8] (e) as (c), but incorporating asymptotic freedom.[9] The normalization is free to the extent indicated by the vertical error bars.

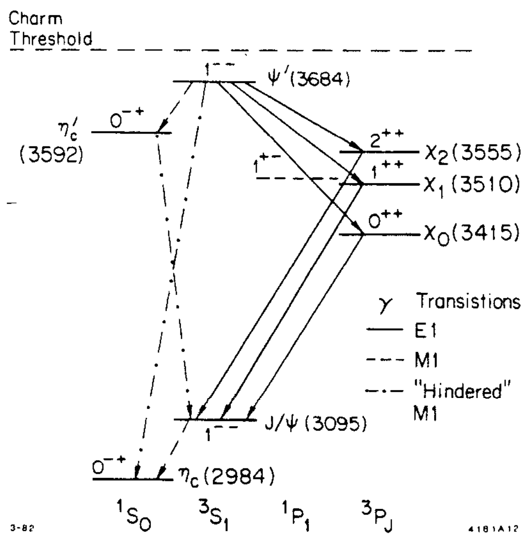

Fig. 2. The level scheme for bound state charmonium (scale approximate only). Some (but not all!) of the expected radiative transitions between states are indicated.

positronium system[10] which serves as a guide to our understanding of heavy $Q\bar{Q}$ spectroscopy.

The $b\bar{b}$ system (Fig. 3) should have an even richer spectroscopy than charmonium, but the experimental investigation is more difficult (many rates scale as $1/M^2$, and many important processes are electromagnetic, involving rates proportional to the square of the quark charge). Thus, much less is known about this system, but progress is nonetheless rapidly being made.

I now turn to a sequence of several current issues in heavy $Q\bar{Q}$ spectroscopy, as discussed at this Workshop.

II.1. Electric Dipole Transitions

One of the long-standing problems in charmonium spectroscopy has been the low observed $\psi' \to \gamma\chi_J$ rates compared with simple electric dipole predictions. A new measurement of these rates has been made by the Crystal Ball experiment

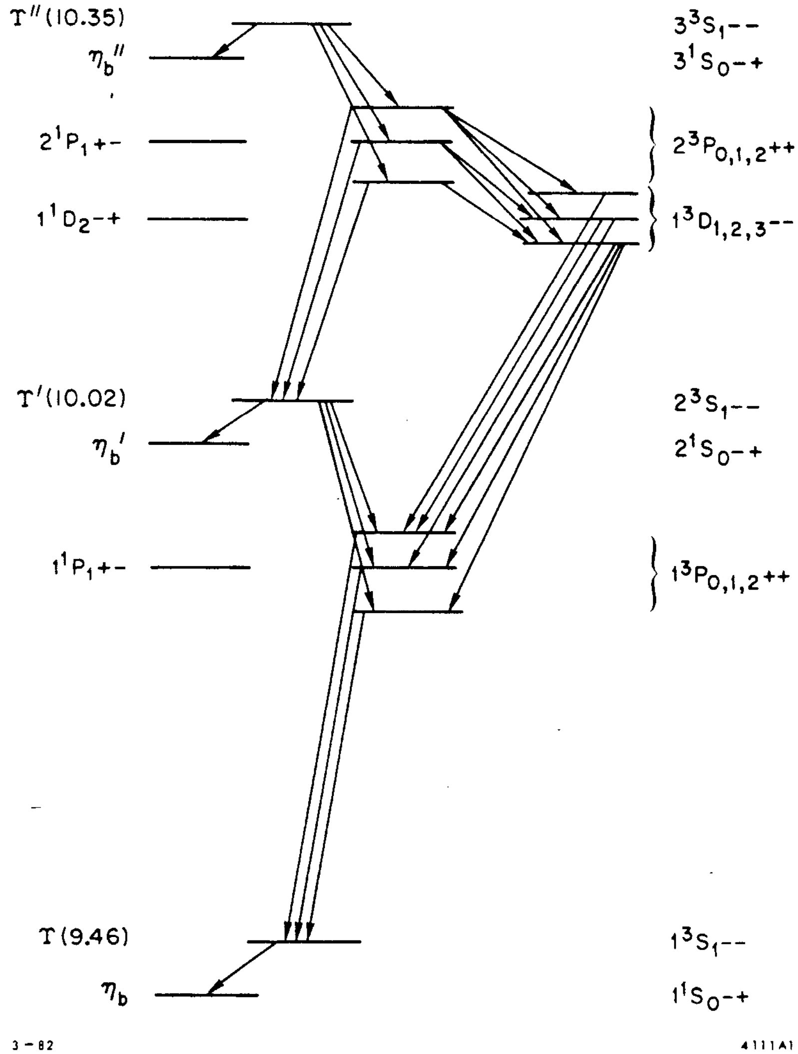

Fig. 3. The expected level scheme for $b\bar{b}$ spectroscopy below the Υ(3S). Some (but not all!) of the expected radiative transitions are indicated by the arrows.

(Table I), with slightly higher (but not inconsistent) results than the earlier numbers. In the meantime, theorists have estimated the effects of relativistic

TABLE I. Branching Ratios for $\psi' \to \gamma\chi$ [a)]

	BR($\psi' \to \gamma\chi_J$)		
	χ_0	χ_1	χ_2
Crystal Ball	0.097 ± 0.006 ± 0.016	0.088 ± 0.005 ± 0.014	0.077 ± 0.005 ± 0.012
SP-27	0.072 ± 0.023	0.071 ± 0.019	0.070 ± 0.020
Theory			
"Nonrelativistic Linear + Coulomb"	0.23 ± 0.04	0.21 ± 0.04	0.13 ± 0.03
"Nonrelativistic Coupled Channel"	0.20 ± 0.04	0.16 ± 0.03	0.11 ± 0.02
"Breit-Fermi Linear + Coulomb"	0.088 ± 0.016	0.130 ± 0.024	0.126 ± 0.023

a) For more detail, references, and a more thorough comparison with theory, see Ref. 11.

and other corrections on these rates, and it now appears that the observed numbers may be understood.

A cross check on this understanding of the E1 transition rates is the corresponding rates in the $b\bar{b}$ system, where relativistic effects should not be as important. The CUSB experiment is making progress toward measuring these rates in the inclusive photon spectrum at the $\Upsilon(3S)$.[12] In the meantime, they have obtained radiative rates for $\Upsilon(3S) \rightarrow 2^3P_{0,2}$ and $\Upsilon(2S) \rightarrow 1^3P_{0,2}$ by inference from the distribution of a thrust-like variable:

$$T' = \mathrm{Max}\left(\sum E_i |\cos \phi_i| / \sum E_i\right) \quad , \qquad (1)$$

where ϕ_i is the angle between particle i and the "thrust" axis (defined as the axis for which the maximum is obtained), and E_i is the observed energy for particle i. The idea of the measurement is that the $^3S_1$ and $^3P_1$ states decay in lowest order via annihilation to three gluons, whereas the $^3P_0$ and $^3P_2$ states can annihilate to two gluons. Thus, the processes $^3S_1 \rightarrow$ hadrons and $^3S_1 \rightarrow \gamma^3P_1 \rightarrow \gamma$ + hadrons should tend to result in 3-jet-like events, while the $^3S_1 \rightarrow \gamma^3P_{0,2} \rightarrow \gamma$ + hadrons decays should give 2-jet event shapes. A fit to the T' event shape distribution, Fig. 4, can then be used to extract the fraction of two-jet like events [compared with the "pure" 3-jet sample at the $\Upsilon(1S)$], and hence, the branching fraction for $^3S_1 \rightarrow \gamma^3P_{0,2}$ radiative transitions.

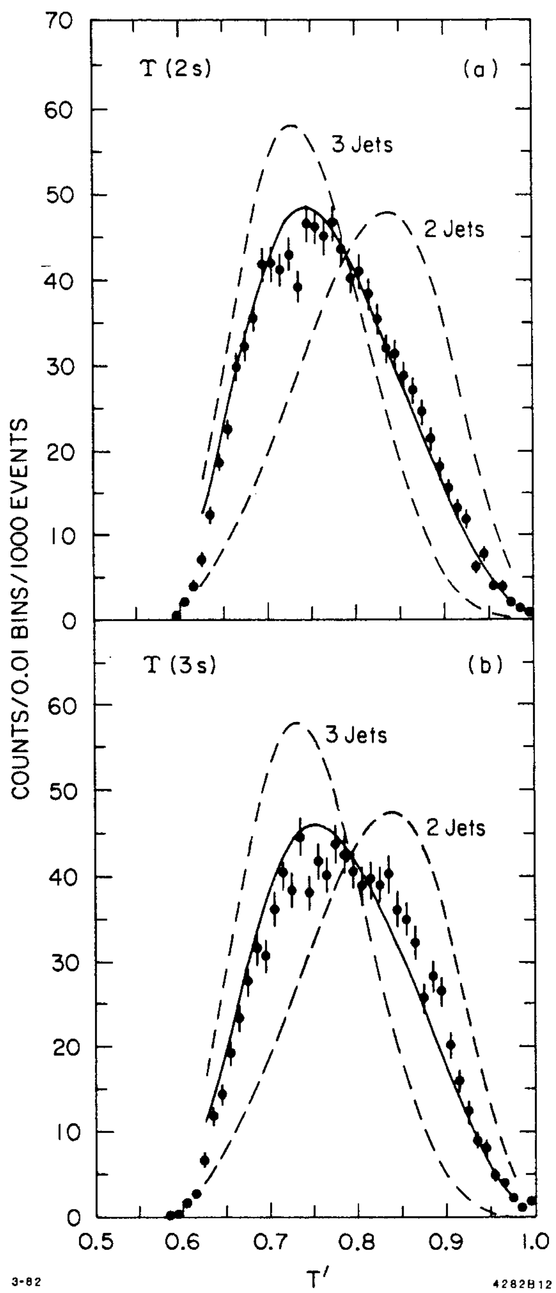

Fig. 4. The event shape distribution (in T', a thrust-like variable) as measured by CUSB for: (a) $\Upsilon(2S)$, (b) $\Upsilon(3S)$. The dashed curves indicate expected distributions for 2- or 3-jet events, and the solid curves are a result of fits to the data including both 2- and 3-jet contributions.

The results,[12] $BR(2S \to 1P_0) + BR(2S \to 1P_2) = 8 \pm 2\%$ and $BR(3S \to 2P_0) + BR(3S \to 2P_2) = 20 \pm 3\%$ may be compared with a prediction made at this Workshop of 14% and 25%, respectively.[4] We find that the $3S \to 2P$ prediction is reasonably compatible with the measurement, but the $2S \to 1P$ prediction is too high by three standard deviations. It is premature, however, to conclude that there is a problem here similar to that in charmonium, partly because of the indirectness of the measurement, and also because the prediction depends on the prediction of other unknown quantities in addition to the simple electric dipole formula (there exists a range of predictions in the literature). In particular, the rates depend sensitively on the S-P splitting, and a determination of the ^3P masses will help to sort things out.

II.2. Fine Structure Theory

The spin-dependent part of the Hamiltonian for heavy $Q\bar{Q}$ systems may, in the context of a Coulomb plus linear potential model $[V = -(4/3)(\alpha_s/r) + kr)]$, be written in terms of a QED-like short-range part, plus a long-range QCD-inspired part:[4),13]

$$\begin{aligned} H_{spin} = &\pm \left(\frac{1}{2m_1^2} \vec{L}\cdot\vec{S}_1 + \frac{1}{2m_2^2} \vec{L}\cdot\vec{S}_2 \right) \frac{k}{r} \\ &+ \frac{4}{3} \left(\frac{1}{2m_1^2} \vec{L}\cdot\vec{S}_1 + \frac{1}{2m_2^2} \vec{L}\cdot\vec{S}_2 + \frac{1}{m_1 m_2} \vec{L}\cdot\vec{S} \right) \frac{\alpha_s}{r^2} \\ &+ \frac{4}{3} \frac{\alpha_s}{m_1 m_2} \frac{3(\vec{S}_1\cdot\hat{r})(\vec{S}_2\cdot\hat{r}) - \vec{S}_1\cdot\vec{S}_2}{r^3} \\ &+ \frac{32\pi}{9} \frac{\alpha_s}{m_1 m_2} \vec{S}_1\cdot\vec{S}_2 \, \delta^3(\vec{r}) \quad , \end{aligned} \tag{2}$$

where m_1, m_2 are the two constituent quark masses. The first three terms give the fine structure, while the last term yields the hyperfine structure. The first term is a long range spin-orbit interaction, and it is amusing that two (QCD-motivated) models exist which predict the same term with opposite signs!

In principle, an experimental test for this sign can be made by comparing the fine structure splitting between the $^3P_2$, $^3P_1$, and $^3P_0$ states:

$$r_n(p) \equiv \frac{M(n^3P_2) - M(n^3P_1)}{M(n^3P_1) - M(n^3P_0)} \quad . \tag{3}$$

For $n = 1$ in the charmonium system, measurement yields $r_1(P) = 0.48 \pm 0.03$, while the plus sign in Eq. (2) predicts[13] 0.97, and the minus sign gives[4] 0.61. Thus, it would appear that the negative sign is favored, but the advocates of the positive sign have pointed out that higher-order perturbative and relativistic corrections could be important. It would be useful to have a measurement in the $b\bar{b}$ system where such corrections should not be as important. It would also be nice to have a better understanding from "first principles."

II.3. Hyperfine Splitting

With the recent observation[14] of a candidate for the η_c', the first radial excitation of the η_c, a relatively model-independent test of the nature of the spin-spin force has become possible in the comparison of the hyperfine splittings for the ground state with the first radial excitation. The prediction of the short range spin-spin force [see Eq. (2)] is that the splitting should be proportional to the square of the wave function at the origin. Thus, the experimental ratio,

$$\frac{M(\psi') - M(\eta_c')}{M(J/\psi) - M(\eta_c)} = \frac{92 \pm 5}{111 \pm 5} = 0.83 \pm 0.06 \quad ,$$

may be compared with a (relatively) model-independent estimate of 0.73 ± 0.12 for the ratio of the wave functions squared at $r = 0$ based on the leptonic widths.

The above comparison yields agreement, within errors, but it has been remarked at this Workshop that the effect of coupling to open channels may not be negligible,[15] with an estimate that the effect of the coupling of the ψ' to the $D\bar{D}$ channel can induce a shift in the $\psi' - \eta_c'$ splitting of -20 MeV. It should be noted that this estimate may not be consistent with the results of calculations by the Cornell group (Ref. 8), so we must await a more definitive statement before getting too worried.[16] However, the issue stresses the desirability of checks in the $b\bar{b}$ system (η_b and η_b') and in states with higher orbital angular momentum (e.g., $^1P - {}^3P$ splitting). The latter is particularly interesting because it provides a sensitive probe for possible long range components to the spin-spin interaction [Eq. (2) only includes a short range part].

II.4. The $^1P_1$ State

As just noted, a measurement of the mass of the $^1P_1$ $Q\bar{Q}$ state can provide insight into possible long-range spin-spin components of the $Q\bar{Q}$ force. Furthermore, observation of the $c\bar{c}$ $^1P_1$ state would nicely complete the predicted charmonium bound state spectroscopy (Fig. 2). Unfortunately, the usual game of observing states via radiative transitions from the vector meson states produced in e^+e^- collisions is not possible because the $^3S_1 \rightarrow \gamma {}^1P_1$ decay violates C-parity.

The Crystal Ball experiment has attempted to find the $^1P_1$ bound state of charmonium by looking for the monochromatic π^0 in the isospin-violating decay $\psi' \rightarrow \pi^0 {}^1P_1$.[17] No evidence was found, but the limits were sufficiently low to contradict the naively expected rates. A less-naive prediction will be required to understand this result.

Other possibilities for observing ^1P states were mentioned at this Workshop. The CUSB experiment will look for the photon in the $1^1P_1 \to \gamma\eta_b$ transition, where the $^1P_1$ is produced in the (isospin-allowed) decay $\Upsilon(3S) \to \pi\pi + 1^1P_1$. An interesting proposed experiment[18] using the CERN ISR $\bar{p}$ beam and a hydrogen jet to obtain high luminosity might be capable of finding the $c\bar{c}$ $^1P_1$ state.

II.5. Total Widths of the ^3P States

We are finally getting a glimpse at the total widths of the ^3P_J states of charmonium (χ_J). Estimates from Crystal Ball measurements[11] are compared with theoretical expectations in Table II. While the ratios of the widths are consistent with the famous 15:1:4 ratios [for $\Gamma(\chi_0):\Gamma(\chi_1):\Gamma(\chi_2)$] predicted in lowest order ("gluon counting") QCD, the magnitudes are substantially larger than prediction. However, the uncertainties, both theoretical (higher order corrections are expected to be substantial) and experimental, are still rather large, so this is only a first hint of a problem. It should be an interesting area to watch.

TABLE II. Widths of the χ States of Charmonium [a]

	Total Widths Γ (MeV)		
	χ_0	χ_1	χ_2
Crystal Ball	16 ± 4	0.75 ± 0.30 [b]	3 ± 2
Theory			
"Gluon Counting" (lowest-order QCD)	~ 2.4	~ 0.14	~ 0.64
Sum Rules	4 – 5		1.6 – 2.2

a) For more discussion and references, see Ref. 11.
b) Assuming E1-dominance in χ radiative decays.

II.6. Vibrational Excitations

It has been suggested that, in addition to the $Q\bar{Q}$ states expected in potential models (e.g., Figs. 2 and 3), there should exist states corresponding to vibrational modes of the confining "string" joining the $Q\bar{Q}$ pair.[19] Two structures in the total cross section for $e^+e^- \to$ hadrons have been cited as candidates for the lowest 1^{--} vibrational excitation (ψ_V) in the charmonium system, one at 3.96 GeV, and the other at 4.03 GeV. Using one or the other of these states as input, predictions have been made for the lowest 1^{--} vibrational excitation (Υ_V) in the $b\bar{b}$ system.[20] These predictions are listed in Table III, where ranges are given for the predictions due to the theoretical uncertainties in the $Q\bar{Q}$ potential and possible mixing with other vector states.[20]

Recently, the CLEO[21] and CUSB[12] experiments at CESR have completed a fine energy scan in the region between the $\Upsilon(3S)$ and $\Upsilon(4S)$ states to search for such

TABLE III. Predictions for Lowest Vector-Vibrational $b\bar{b}$ State [a]

Input Assumption	$m(T_V)$ (GeV)	$\Gamma_{ee}(T_V)$ (KeV)
$m(\psi_V) = 3.96$ GeV $\Gamma_{ee} = 0.3$ KeV	10.33 - 10.38	0.05 - 0.10
$m(\psi_V) = 4.03$ GeV $\Gamma_{ee} = 0.7$ KeV	10.39 - 10.51	0.12 - 0.35

a) See Ref. 20. Masses are given relative to M(T) = 9.434 GeV (CESR scale).

a vibrational state (and also to search for a $^3D_1$ state, which could be observed if the S-D mixing is sufficiently large). No significant structure in the total hadronic cross section is observed, allowing limits to be set on the existence of a new vector resonance:

CLEO $\Gamma_{ee} < 0.08$ KeV (90% C.L.) for $E_{c.m.} = 10.36 - 10.51$ GeV

CUSB $\Gamma_{ee} < 0.04$ KeV (90% C.L.) for $E_{c.m.} = 10.34 - 10.52$ GeV .

Note that the energy intervals here and in Table III correspond to the CESR energy scale, in which M(T) ≈ 9.434 GeV. Comparison of these limits with the predictions indicates that the higher mass possibility is ruled out, which also implies that the peak at 4.03 GeV in charmonium is also not a vibrational state. The other possibility is squeezed fairly hard, but is not completely dead. It may be difficult to obtain the required sensitivity in the remaining interval because of the proximity to the T(3S) resonance (and its radiative tail).

If the upsilon vibrational state should turn out not to appear in the remaining allowed region, two possible implications immediately come to mind. The first is that the string model intuition may be basically all right, but that the interpretation of the charmonium vibrational state candidates must be reexamined. The second, of course, is the more fundamental possibility that there may be a problem with currently popular ideas about confinement.

II.7. Search for Top

According to the "standard" six-quark SU(2) ⊗ U(1) model for weak and electromagnetic interactions, there should exist another charge 2/3 quark, the t (top) quark, required to complete the weak left-handed isodoublet containing the b' (b' refers to the appropriate Kobayashi-Mashawa mixing of the d, s and b quarks - see Sect. III). Assuming the t quark exists, the big question at the moment is: what is its mass? Theoretically, the problem of quark masses is not well-understood. Those brave enough to make predictions for m_t have come up with a large range of values, typically between 15 and 40 GeV.[22]

Experimentally, the search for top has taken place at the e^+e^- storage ring PETRA at DESY, with the CELLO, JADE, MARK J, PLUTO and TASSO detectors. This search has employed two quite different techniques:[23)]

(i) The first technique involves the measurement of R, the ratio of the total $e^+e^- \rightarrow$ hadrons cross section (via one-photon annihilation) to the lowest-order $e^+e^- \rightarrow \mu^+\mu^-$ QED cross section. A course (as a function of $E_{c.m.}$) measurement of R can reveal the presence of new flavour in the form of a step in the value of R (by 4/3 or 1/3 for charged 2/3 or 1/3 quarks respectively) as one crosses the new flavour threshold. A fine scan in energy can be used to look for the presence of narrow vector meson states (as was done, e.g., for the J/ψ and Υ states). Results from PETRA[23)] exclude the presence of a new charge 2/3 quark in data taken up to $E_{c.m.}$ = 36.7 GeV. This technique is only marginally sensitive to a charge 1/3 quark however.

(ii) The second technique involves the measurement of event shape distributions (e.g., the sphericity tensor or thrust), and turns out to have adequate sensitivity even for a charge 1/3 quark. The point is that as one crosses the threshold for the production of new heavy particles, the events from the new processes will have a more isotropic pattern than the typical 2- or 3-jet structures than one encounters far above threshold. This technique is illustrated with the result from TASSO in Fig. 5, which indicates that no new charge 1/3 or 2/3 quark has been found in data with $E_{c.m.}$ up to 36.6 GeV.[23)]

The conclusion is that, if the top quark exists, its mass must be $\gtrsim$18 GeV. The program at PETRA will pursue the search to higher energies, probably reaching $E_{c.m.} \sim$ 45 GeV sometime in 1983. If top still is not found, they will presumably push to even higher energies (using superconducting rf cavities) after 1983.

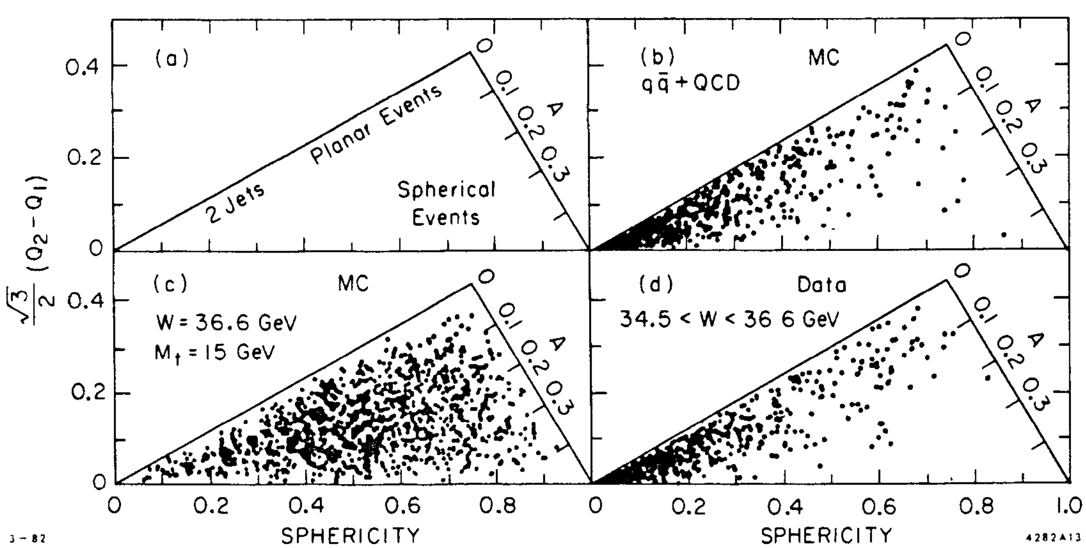

Fig. 5. Event shape (sphericity vs aplanarity) distribution for $e^+e^- \rightarrow$ hadrons: (b) top Monte Carlo; (c) 2-jet plus QCD ($q\bar{q}$ + $q\bar{q}g$) Monte Carlo; (d) TASSO data. See Ref. 23.

III. DECAY OF HEAVY FLAVOUR

The decay of heavy flavours is important in two rather different aspects. First, the weak decay of the quarks gives direct information concerning the fundamental parameters of the Kobayashi-Maskawa matrix[24)] (fundamental, at least until somebody finds a way to predict them, perhaps in a "grand unified" theory). Second, the weak decays of mesons and baryons containing heavy flavours are modified by the strong interaction, and hence provide insight into the nature of the strong interaction.

The charged weak current involving quarks in the "standard" $SU(2) \otimes U(1)$ model is given by:

$$J_\mu = (\bar{u}, \bar{c}, \bar{t})\ \gamma_\mu(1-\gamma_5)\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} , \tag{4}$$

where

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_1 & s_1c_3 & s_1s_3 \\ -s_1c_2 & c_1c_2c_3+s_2s_3e^{i\delta} & c_1c_2s_3-s_2c_3e^{i\delta} \\ -s_1s_2 & c_1s_2c_3-c_2s_3e^{i\delta} & c_1s_2s_3+c_2c_3e^{i\delta} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}. \tag{5}$$

The matrix in (5) is the Kobayashi-Maskawa mixing matrix (using the shorthand: $c_i \equiv \cos\theta_i$, $s_i \equiv \sin\theta_i$) which generalizes the Cabibbo rotation ($\theta_c = \theta_1$ if the other angles are 0) to the six-quark model. With this formalism, it is easy to obtain relative rates for the weak decays of quarks. For example, the $b \to u$ amplitude (Fig. 6) is simply proportional to s_1s_3.

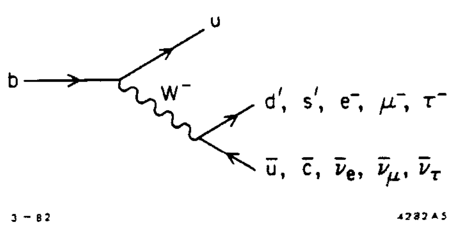

Fig. 6. Weak decay of the b quark into a u quark via emission of W^-.

This is all very nice, but it is not the end of the story because we live in a world with strong interactions. For example, such animals as "penguin" diagrams (Fig. 7) may be a significant contribution in processes which are otherwise "Cabibbo-suppressed." Furthermore, we do not have free quarks to play with, and the application of the simple KM formalism to the decay of a quark in a hadron is complicated by the uncertain role of the other quark(s) in the hadron.[25)] This issue is intimately tied to the problem of the D-meson lifetimes, which we discuss next.

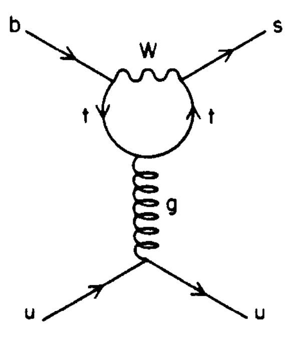

Fig. 7. A "penguin" diagram, which may contribute to the Cabibbo-suppressed $b \to u\bar{u}s$ decay.

III.1. Lifetime of the D-mesons

Early expectations for the decay of the charmed D-meson were that the "spectator" diagram [Fig. 8(a)] should dominate, where the light quark in the D is irrelevant to the decay of the charmed quark. Thus, it was expected that the lifetimes for the D^o and the D^+ (and the F^+) should be the same, up to minor differences in phase space. However, early experimental results indicated that the $D^\pm$ lifetime was actually substantially larger than the D^o lifetime. This suggested that non-spectator mechanisms, such as the "exchange" diagram in Fig. 8(b) are important, or perhaps that some mechanism is acting to suppress the D^+ rate (e.g., "sextet dominance").[25),26)]

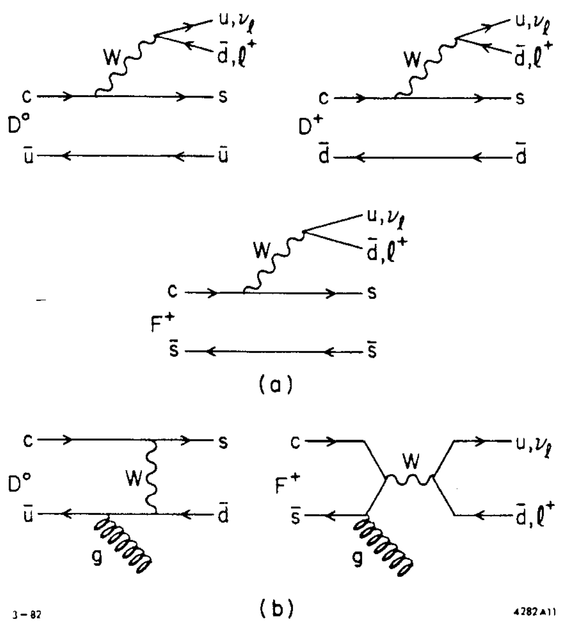

Fig. 8. Cabibbo-favored diagrams for the weak decays of charmed mesons: (a) spectator diagrams; (b) non-spectator ("exchange" and "annihilation") diagrams. A gluon is shown as the mechanism for eliminating helicity suppression; additional gluons are required to satisfy color conservation.

While the theoretical uncertainties have not been completely resolved, a more immediate difficulty is the experimental situation, which continues to be a controversial subject. An indirect measurement of the $\tau(D^+)/\tau(D^o)$ lifetime ratio is possible by measuring the semileptonic branching ratios, based on the assumption that the spectator process is the dominant process in such decays (see Ref. 26 for reservations, concerning the possible significance of Cabibbo-suppressed semileptonic decays of the D^+). Thus, we may infer the lifetime ratio according to:

$$\tau(D^+)/\tau(D^o) = BR(D^+ \to \ell^+ \nu_\ell h^o)/BR(D^o \to \ell^+ \nu_\ell h^-) \qquad (6)$$

where "h" stands for hadronic systems. Such measurements have been made in e^+e^- collisions (see Table IV).

Direct measurements of the D lifetimes are also possible by detection of the decay vertex in high-resolution targets. Results are now available from experiments using emulsions, high resolution bubble chamber techniques, and solid state

TABLE IV. Semileptonic Branching Ratios and Lifetime Ratio for D^o, $D^\pm$

EXPERIMENT	$BR(D^o \to e\nu X)$ (%)	$BR(D^\pm \to e\nu X)$ (%)	$\tau(D^\pm)/\tau(D^o)$
DELCO [a]	< 4.0 (95% C.L.)	$22.0^{+4.4}_{-2.2}$	> 4.3 (95% C.L.)
MARK II [a]	5.5 ± 3.7	16.8 ± 6.4	$3.1^{+4.6}_{-1.4}$

a) Ref. 27.

vertex detection. Current results from several such experiments were presented at this Workshop, as summarized in Table V.[28] The most recent subject of controversy has been the measurement of approximately equal lifetimes at the SLAC hybrid facility. However, as can be seen from the table, the lifetime ratio results of the direct measurements reported at this Workshop are not really in conflict, considering the still fairly large errors. All of these experiments are compatible with the $\tau(D^+)/\tau(D^o) = 2.4^{+0.8}_{-0.6}$ average value.

At the moment, the biggest problem with the lifetime ratio measurements seems to be the disagreement between the DELCO indirectly inferred limit and the direct measurements (especially the SLAC hybrid measurement). Whether this indicates an experimental problem, or an inadequacy in Eq. (6) is not clear. It should be noted that the direct experiments agree with each other on $\tau(D^+)$, but cover a fairly large range of values of $\tau(D^o)$.[29]

TABLE V. Direct Lifetime Measurements of D^o, $D^\pm$ [a]

Experiment	Beam	Number of Decays D^o	$D^\pm$	$\tau(D^o)$ (10^{-13}s)	$\tau(D^\pm)$ (10^{-13}s)	$\tau(D^\pm)/\tau(D^o)$
CERN						
NA1 - Solid state, Spectrometer	γ	-	98	--	$9.5^{+3.1}_{-1.9}$	--
NA16 - LEBC, European Hybrid Spectrometer	π^-,p	8	7	$2.1^{+1.3}_{-0.7}$	$6.5^{+4.7}_{-2.1}$	$3.1^{+2.9}_{-1.4}$
NA18 - BIBC (C_3F_8)	π^-	8	5	$3.8^{+2.4}_{-1.2}$	$6.3^{+6.0}_{-2.5}$	$1.7^{+1.9}_{-0.9}$
WA58 - Emulsion, Omega Spectrometer	γ	8	-	$1.34^{+1.0}_{-0.4}$	--	--
FERMILAB						
E531 - Emulsion, Spectrometer	ν	19	5	$2.3^{+0.8}_{-0.5}$	$10.3^{+10.3}_{-4.2}$	$4.5^{+4.7}_{-2.1}$
SLAC						
40" Hybrid Facility	γ	11	9	$6.7^{+3.5}_{-2.0}$	$8.2^{+4.5}_{-2.5}$	$1.2^{+0.9}_{-0.5}$
Moriond Workshop Average				$3.2^{+0.6}_{-0.5}$	$7.8^{+2.3}_{-1.5}$ [b]	$2.4^{+0.8}_{-0.6}$

a) Reported at Moriond Workshop. See Ref. 28.
b) Excluding NA1 measurement.

The consensus at this Workshop appears to be that the direct measurements of the lifetime ratio are not in serious disagreement at this point. More data will be available in the near future, so let us be patient for further information on this important measurement.

III.2. The F-meson

It has been pointed out that the lifetime and decay modes of the charmed-strange F-meson provide crucial assistance in untangling the various possible contributions to heavy flavour decays.[25] For example, if the spectator picture is dominant [Fig. 8(a)], then the F should decay into hadron systems with high $s\bar{s}$ content (e.g., ηX, $K\bar{K}X$), and should have a lifetime similar to the D lifetime. On the other hand, the annihilation diagram in Fig. 8(b) will not lead to any preference for strangeness-containing final states.

The problem with the F is that it has been so elusive. Several experiments have by now reported possible F signals, including the direct lifetime experiments. Taken together, the evidence for the F-meson is quite strong. However, no single analysis is entirely convincing by itself, and the natural worry arises that the results of the different experiments cannot be viewed as independent, i.e., that a "bandwagon" effect may be involved.

With the comparatively large amount of data that is becoming available from the direct lifetime experiments it may be possible to lay the existence question finally to rest with analyses relatively unbiased by preconceptions concerning the mass. Even when a decay vertex is observed, there are often ambiguities in interpretation (such as π-K ambiguities, and the contribution of neutral decay products), so it would be an interesting test to see how many different mass "particles" one can generate by making different assumptions for the ambiguities. If one mass is clearly favored, it would be strong evidence for the F, provided possible D backgrounds are understood. Conversely, one could make the test by a priori assuming that the F mass is some value (other than the currently popular one), and seeing whether as many events can be found which suit this hypothesis as for the popular mass value.

With large enough statistics, more traditional mass plots can be envisioned. Indeed, one direct lifetime experiment has shown such plots at this Workshop (Fig. 9).[30] There are even tantalizing high bins in these plots at the popular value for the F mass. One hopes that such efforts will soon pay off in establishing the F and we can go on with the important task of determining its properties.

III.3. Decay of the b-quark

With the discovery of the $\Upsilon(4S)$ resonance, above $B\bar{B}$ threshold, studies similar to those for the D meson at the ψ'' may be anticipated (although the

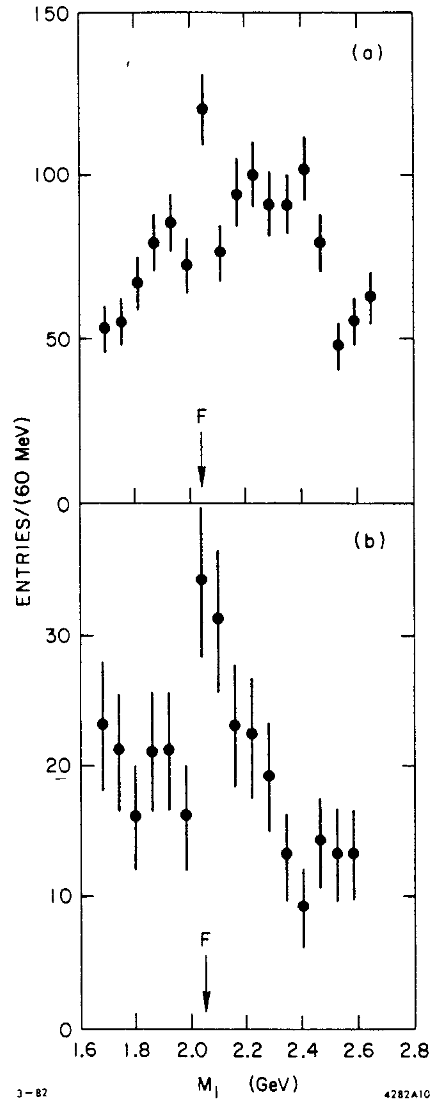

Fig. 9. Mass plots from exclusive channels in NA1 (coherent photoproduction) experiment: (a) $M(K^-K^+\pi^+\pi^o)$, recoiling against a system with mass $2.0 < M_2 < 2.1$ GeV; (b) $M(\eta\pi^+\pi^-\pi^+\pi^o)$, recoiling against $2.0 < M_2 < 2.1$ GeV.

experimental difficulties are greater). One of the fundamental issues which is already accessible to experiment is the determination of the relative $b \to u$ vs $b \to c$ decay amplitudes, which puts constraints on the Kobayashi-Maskawa parameters [Eq. (5)]:

$$\frac{A(b \to u)}{A(b \to c)} = \frac{s_1 s_3}{c_1 c_2 s_3 - s_2 c_3 e^{i\delta}} \quad . \qquad (7)$$

This has been accomplished by looking at inclusive kaon production on and off the $\Upsilon(4S)$. The idea is that for $b \to c$ decays, the $c \to s$ Cabibbo-favored decay tends to final states with kaons, while for $b \to u$ decays there is no enhanced kaon yield.

The two experiments at CESR have made measurements of the kaon yields on and off the $\Upsilon(4S)$, and compared the results with Monte Carlo calculations.[31] The CUSB experiment measures K^o_S production by reconstructing the $K^o_S \to \pi^+\pi^-$ decay vertex. Assuming equal K^o and $K^\pm$ contributions from B decays, they find 1.5 ± 0.3 K/B decay, to be compared with Monte Carlo calculations giving 0.47-0.66 expected for pure $b \to u$ and 1.25-1.67 for $b \to c$. The CLEO detector can measure both K^o_S and $K^\pm$ rates (Fig. 10), the latter using time-of-flight counters for $p_K \simeq 0.5$-1.0 GeV/c. They quote the result: 1.88 ± 0.28[K/Υ(4S) decay]/[K/continuum event], where the ratio to continuum events is used to reduce the sensitivity to possible normalization errors. This number may be compared with Monte Carlo calculations giving 0.95 ± 0.1 for $b \to u$ and 1.8 ± 0.1 for $b \to c$, yielding the following results:

$$\frac{\Gamma(b \to c)}{\Gamma(b \to all)} = 1.09 \pm 0.33 \pm 0.13$$

$$\frac{\Gamma(b \to u)}{\Gamma(b \to all)} < 0.6 \quad 90\% \text{ C.L.}$$

Thus, the data favor $b \to c$ over $b \to u$, which is what we would expect if the Kobayashi-Maskawa angles θ_1 and θ_3 are small.

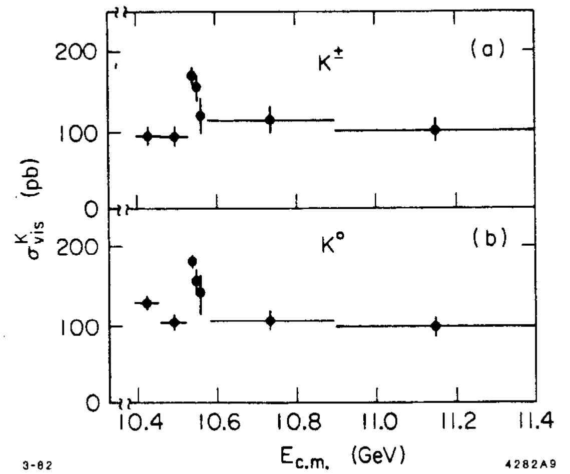

Fig. 10. Inclusive kaon production in e^+e^- collisions in the vicinity of the ϒ(4S) resonance (CLEO at CESR).

IV. HEAVY FLAVOUR PRODUCTION

Beginning with the discovery of the J/ψ, the study of heavy flavour production on hadronic targets has continued in photo-, lepto-, and hadro-production experiments. A fairly substantial body of data on both open[32)] and hidden[33)] charm production now exists, and continues to grow in quality and quantity. In this section, I briefly touch on a few of the issues which have been addressed with such data.

IV.1. Production Mechanisms

The primary thrust of the theoretical activity continues to be to understand the mechanisms responsible for the production of these heavy quark states. The ideas have evolved considerably since 1974, and further evolution can be anticipated. Both the theoretical and experimental status were discussed at this Workshop, and I shall attempt to summarize the current state here, at the same time giving references to the more learned presentations of the experts.

Figure 11 shows, very scehmatically, some of the popular pictures for the production of heavy quarks (Q) from hadronic targets. I will base my discussion around these diagrams, and some of their variants. I shall also couch the discussion in the context of QCD.

An important issue which is not represented by these diagrams is the question of what kind of hadrons the Q and $\bar{Q}$ end up belonging to. This issue has been

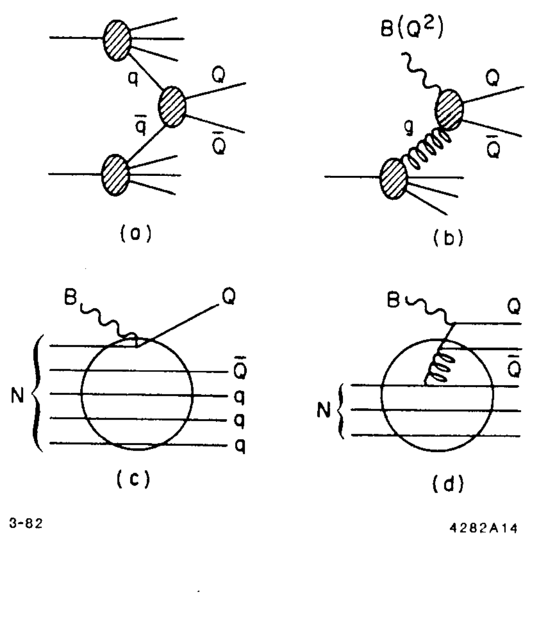

Fig. 11. Some examples of popular pictures for heavy quark (Q) production on hadronic targets. The "B" stands for vector boson and may be γ, Z^0, or gluon in these pictures, at some value of Q^2. (a) $q\bar{q}$ fusion; (b) Bg fusion; (c) intrinsic charm; (d) an example of excitation from the charmed sea. Other processes, not shown, but which may be important in appropriate circumstances, are flavour-changing (weak) currents, and vector meson dominance.

approached in two ways:[35] (i) One way depends on perturbation theory being valid, and treats the problem with due regard for quantum numbers (including color) and wave functions. Thus, the central "blobs" in Fig. 11(a) and (b) are resolved into the various possible low-order diagrams, and we must work in the short-distance regime. Where valid, this approach has the merit that rigorous predictions, including absolute rates, can in principle be made. (ii) Another approach uses the idea of duality to account for processes where soft gluon effects may be involved. The details of conservation laws and wave functions are ignored, being left to the soft gluons to take care of - the "blobs" in Fig. 11(a) and (b) remain "blobs". This approach has the advantage of applying in some nonperturbative regimes, but at the expense of rigorous predictability of rates. For example, one might assume that the total rate for bound state charmonium can be estimated by the total integrated cross section for $c\bar{c}$ production between an invariant mass at charmonium threshold and the threshold for associated production of open charm. The allocation of this cross section into individual states, however, requires additional assumptions beyond duality.

The first diagram in Fig. 11 is a Drell-Yan-like diagram, going under the general name of "$q\bar{q}$ fusion." It is known that this diagram cannot be the whole story, because (among other things) we would expect that the cross section for the production of, e.g., J/ψ would be at least an order of magnitude greater in $p\bar{p}$ than in pp collisions (at 40 GeV beam energy),[36] while the experimental ratio is roughly a factor of five.[34] On the other hand, the fact that the $\bar{p}$ rate is greater suggests that this diagram (and the valence quark composition) is important, as the other mechanism which is expected to contribute (gluon-gluon fusion, see below) predicts equal cross sections.

The second diagram in Fig. 11 has been generalized to apply to lepto-, photo- and hadro-production, and can be called "gluon-boson fusion," where the boson may be another gluon, a photon, or a weak boson. It appears that the production of $c\bar{c}$ bound states can be understood qualitatively in terms of Fig. 11(a) and (b),[35] but the question of absolute normalization is still unclear.

The production of open charm (e.g., D and Λ_c), however, is not so easily understood. The x_F distribution is flatter (more "diffractive") than the rather central production observed for J/ψ, and naively expected from the fusion diagrams. Furthermore, the charm production cross section (in pN collisions) at ISR energies ($\sqrt{s} \sim 60$ GeV) is some hundreds of μb [and tens of μb at Fermilab/SPS ($\sqrt{s} \sim 20$-30 GeV)],[32] too large to be understood in terms of the fusion diagrams.[37]

One mechanism that was proposed to explain these observations is the idea of "intrinsic charm" [Fig. 11(c)].[38] According to this idea, there is a long-lived $|uudc\bar{c}\rangle$ component in the proton wave function. Thus, the diffractive x_F distribution can be easily understood in this picture, since the charmed quarks will tend to carry most of the momentum of the proton. Also, the large cross section can be interpreted in terms of the size of the $|uudc\bar{c}\rangle$ component. A large cross section at the ISR for open beauty production (see next section) might also be understood by this mechanism. To understand the charm cross section at the ISR would require an intrinsic charm component of ~1-2%.

A major difficulty exists, however, for the intrinsic charm interpretation of the data. One expects the cross section to vary only slowly with energy in this picture. In fact, the cross section at Fermilab/SPS energies is substantially less than at the ISR. The CCFRS collaboration (350 GeV p+Fe, μ triggers) finds:[39]

$$\sigma_{tot}(c\bar{c}) = 22 \pm 9\ \mu b/\text{nucleon} \qquad (\sigma \propto A) \quad ,$$

and

$$\sigma_{\text{'diffractive'}}(c\bar{c}) = 3 \pm 1\ \mu b/\text{nucleon} \ (\sigma \propto A^{2/3}) \quad .$$

Thus, they can accommodate at most ~0.02% intrinsic charm component to the nucleon. Similarly, in deep inelastic muon scattering, the European Muon Collaboration experiment finds <0.59% (95% C.L.) intrinsic charm component.[40]

With this failure, we turn finally to the "excitation" picture [Fig. 11(d)], in which the $c\bar{c}$ pair comes from excitation of the charmed sea in the nucleon. This contribution has often been neglected because of the smallness of the charmed sea, but with the inadequacy of other mechanisms, it is being thoroughly reexamined.[37] One of the crucial (and largely unanswered) issues to the success of this idea is the question of how large Q^2 must be for the charmed sea to contribute. If this is small enough, then the subprocess scattering cross section in Fig. 11(d) can more than offset the smallness of the charmed sea (in comparison with the fusion diagrams). While we should be properly aware of this uncertainty, and of additiona uncertainties in the charmed sea, Monte Carlo calculations have given some encouraging results for the ability of this model to explain the data.[37]

IV.2. Has "Naked Beauty" Been Seen?

A good deal of excitement has been generated by the reported observation of a Λ_b candidate (exhibiting "naked beauty")[41] in an experiment using the split-field-magnet facility at the CERN ISR. The signal was seen in a search for the reaction:

$$pp \to \Lambda_b e^+ X, \quad \Lambda_b \to p D^o \pi^-, \quad D^o \to K^- \pi^+$$

where the e^+ trigger (p_T > 800 MeV) was used as a possible selection for semi-leptonic $\bar{b}$ decays. Motivated by the observed forward production for Λ_c baryons, a rapidity cut of $|y|_{pK^-\pi^+\pi^-} \geq 1.4$ was made, and x_F for the proton was required to be >0.32, to select for forward baryons.

The resulting $pK^-\pi^+\pi^-$ and $K^-\pi^+$ mass distributions show no significant structure, but the correlation plot has a peak in it with $m(K^-\pi^+)$ near the D mass. Making selections on the D mass region, they obtain the $pK^-\pi^+\pi^-$ mass distributions in Fig. 12, which have an enticing structure corresponding to a mass $M(pK^-\pi^+\pi^-) = 5425 {}^{+175}_{-75}$ MeV. The difference between the two parts of Fig. 12 is that part (a) has a $K^-\pi^+$ mass cut 300 MeV wide and centered at the known D^o mass, while part (b) has a narrower (150 MeV) cut centered at 1800 MeV, the difference from the known D^o mass being attributed to instrumental shift. One has to be a little nervous about this second spectrum, however, because the mass shift was determined using this signal, and not by an independent means. Thus, the effect of the procedure is to maximize the signal, tending to maximize also the statistical significance. Clearly, an independent mass calibration is important.

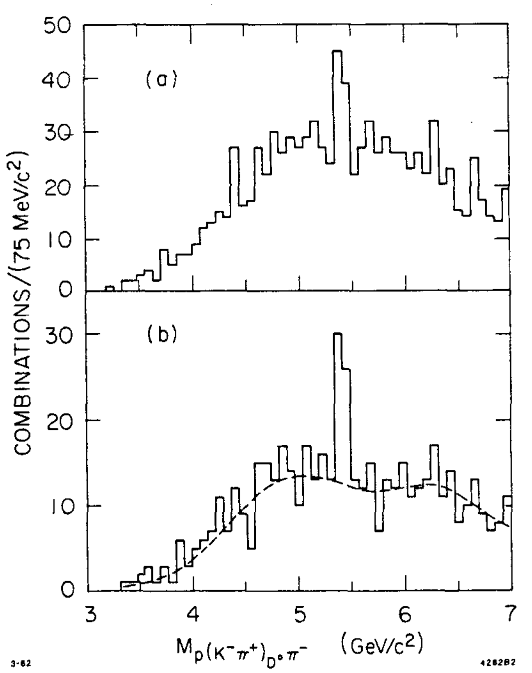

Fig. 12. $M(pK^-\pi^+\pi^-)$ mass distributions from a CERN-ISR-SFM experiment[41)] with an e^+ trigger and "leading" baryon selection, for two different cuts on $M(K^-\pi^+) \approx M(D)$; (a) $1.7 \leq M(K^-\pi^+) \leq 2.0$ GeV; (b) $1.725 \leq M(K^-\pi^+) \leq 1.875$ GeV.

This result has become the subject of substantial controversy because another experiment, also using the split-field-magnet, fails to observe significant structure with a sensitivity which is claimed to be ~7 times better.[42)] As both collaborations are sticking strongly by their results,[43)] we must await further confirmation or contradiction.

IV.3. Prompt Neutrinos

The measurement of prompt neutrino production in proton beam dump experiments has, in the past few years provided information on the production of charmed particles in p + nucleus interactions. The "prompt neutrinos" (as opposed to those from π and K decays) result from the semileptonic decays of charmed particles. Such decays should have almost identical rates into $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ (see Sect. III), so the prompt electron- and muon-neutrino fluxes from this source are expected to be equal. Thus, the comparison of prompt $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ fluxes provides a test of the charm production and decay origin, or, alternatively, can provide insight into the existence of such phenomena as neutrino oscillations.

At this Workshop, a new result on the ratio of prompt $\overset{(-)}{\nu}_e$ to prompt $\overset{(-)}{\nu}_\mu$ fluxes from an experiment at Fermilab was reported.[44] This result is compared with earlier results[45] from CERN in Fig. 13. All experiments use a beam energy of 400 GeV, with (typically) a copper target at CERN and a tungsten target at Fermilab. There are a number of differences among the various experiments, but the CERN experiments all use the same beam dump and vary only in detector and slightly in target-detector distance. Two differences between the Fermilab experiment and the CERN experiments are perhaps worthy of note: First, the target-detector distance is much different, ~60 meters at Fermilab, and ~800-900 meters at CERN. Second, the Fermilab experiment has a vertical bend in front of its target while the CERN beam dump does not. This suggests that any problems from beam loss upstream of the target (tending to produce an excess of $\overset{(-)}{\nu}_\mu$) will be different for the two beam dumps (all experiments claim that there is no problem by careful monitoring of the proton beam). The measurement of the prompt $\overset{(-)}{\nu}_e$ flux is made either by analysis of muonless-events (correcting for neutral current events), or by direct observation of the charged current $\overset{(-)}{\nu}_e$ interactions.

In Fig. 13 we see that all experiments find a greater prompt $\overset{(-)}{\nu}_\mu$ flux than prompt $\overset{(-)}{\nu}_e$. The statistical significance of the individual results is marginal, but taken together they are tantalizing (a simple weighted average yields 0.58 ± 0.11). Perhaps the biggest worry is whether the results may have some common systematic difficulty. Along with the several differences between experiments and analyses, some of which I have mentioned, there are certainly aspects in common as well. This could be an exciting area to watch as the data continues to accumulate and the analysis becomes more refined.

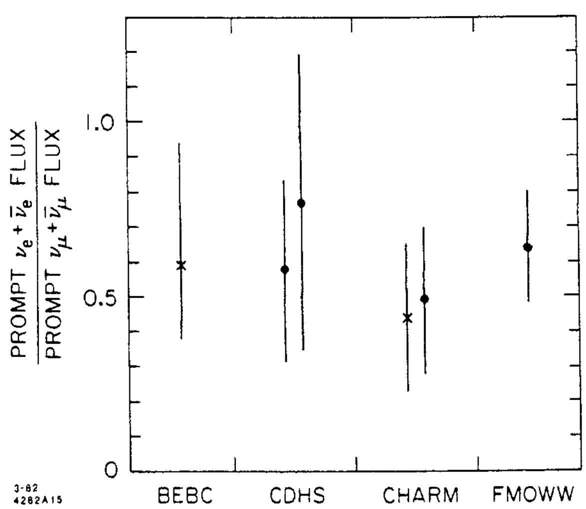

Fig. 13. The ratio of prompt $\overset{(-)}{\nu}_e$ to $\overset{(-)}{\nu}_\mu$ production in beam dump experiments.[44],[45] The crosses are measurements using direct electron identification in ν_e interactions; the dots are measurements inferring the ν_e rate from muonless interactions. The lower CDHS point obtains the prompt ν_μ flux by subtraction of nonprompt flux, the higher point by extrapolation to infinite target density. Note that multiple points for an experiment are not entirely independent measurements. The FMOWW errors are statistical only.

VI. CONCLUSIONS

Looking back over the previous three sections, one finds a somewhat different flavor to the problems in the different sections. In the spectroscopy of heavy $Q\bar{Q}$ bound states, we have a nearly complete experimental picture of one system (charmonium), and a steadily emerging picture of another (bottomonium), and our understanding of such systems is also qualitatively quite encouraging. The puzzles tend to be of a quantitative nature, probing the detailed nature of the strong force between heavy quarks. The quest for top continues to be suspensful - one hopes that it ceases to be frustrating.

The decay of heavy flavours is in principle understood at the rather fundamental level of the weak interaction, but the real-world effects of the strong interactions complicate this understanding. Compounding the theoretical problems is the unstable history of the D lifetimes - this may well be resolved very soon, but reliable measurements of the lifetimes (and decay modes) of other particles (such as the F) are also needed. In any event, the continued study of these weak decays, including the emerging study of b-flavour decays, will help to probe the strong interaction, as well as determine the fundamental parameters of the weak mixing matrix.

The mechanisms responsible for the production of heavy flavour with hadronic targets are not well-understood, in general, even qualitatively. A major difficulty is the nonperturbative nature of much of the process, with additional complications arising from the contributions of various possible decays. In spite of the difficulty, it is encouraging to see the substantial evolution in both the theoretical ideas, and in the experiments, and an understanding may be emerging.

Finally, I would like to express my appreciation for the efforts of Professor Tran Thanh Van, the organizing committee, and the conference secretaries. They have successfully labored to effect a most educational and enjoyable Workshop. In particular, I found the conducive atmosphere for informal communication between theorist and experimentalist to be a valuable and nearly unique feature of this meeting.

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2. In my talk, I actually included a fourth section on the glueball candidates (see D. Aschman, this Workshop). I have decided not to include this in the written version because it was not a central theme of the workshop, and hence, was not extensively discussed.

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MARK II: R. H. Schindler et al., Phys. Rev. D 24, 78 (1981).

28. I thank the experimenters at this Workshop for providing me with this compilation of their results, prepared in a reasonably consistent and conservative manner. For the individual experiments, see the talks by: L. Rolandi (NA1), S. Reucroft (NA16), E. Hugentobler (NA18), B. Conforto (WA58), K. Niu (E531), and G. Kalmus (SLAC 40").

29. This range is further enlarged if we include the indication of an earlier experiment (emulsion + BEBC) that $\tau(D^o) = (0.53 {}^{+0.57}_{-0.25}) \times 10^{-13}$s. However, they also found a relatively small value for $\tau(D^+) = (2.5 {}^{+2.2}_{-1.1}) \times 10^{-13}$s. D. Allasia et al., Nucl. Phys. B176, 13 (1980).

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