

## NEW PARTICLE PRODUCTION BY $e^+e^-$ COLLIDING BEAMS\*

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There is much new information on the production of new particles in  $e^+e^-$  interactions available since the spring of 1975. Due to the constraint of time, it is possible to provide only a brief survey of the following topics: (1) the status of charmonium spectroscopy, (2) the question of a heavy lepton, and (3) charm particle production. More detailed information on these subjects can be found in the rapporteur talk at Tbilisi by Björn Wiik<sup>1</sup> and in the lectures of Feldman<sup>2</sup> and Hitlin<sup>3</sup> in the Proceedings of the 1976 SLAC Summer Institute.

### STATUS OF CHARMONIUM SPECTROSCOPY

One of the most interesting proposals put forward at the time of the discovery of the  $\psi$  particle was the proposal<sup>4</sup> that the  $\psi$  could be considered as the ground state of an atomic system formed from the charmed quark and its antiquark. This system has become known as charmonium. Additional excited levels related to the  $\psi$ , but involving states of different orbital angular momentum and spin configurations, were predicted by the charmonium idea; the predicted spectrum of charmonium states was expected to have the same qualitative features as that of positronium.

Since the initial discoveries of the  $\psi(3095)$  and  $\psi'(3684)$ , much experimental work has gone into the understanding of these possible additional charmonium levels. The experimental techniques employed can be summarized as follows:

The reaction

$$\begin{array}{l} \psi' \rightarrow \gamma\chi \\ \quad \quad \quad \searrow \\ \quad \quad \quad \gamma\psi \\ \quad \quad \quad \quad \quad \searrow \\ \quad \quad \quad \quad \quad e^+e^- \end{array} \quad (1)$$

has been studied by the DASP group<sup>5</sup> at DESY and the SLAC/LBL group<sup>6</sup> at SPEAR. In this reaction decays of the  $\psi'$  leading to  $\psi$  are identified by the characteristic two-lepton decay ( $e^+e^-$ ,  $\mu^+\mu^-$ ) of the  $\psi$ . Then the experimentalist can measure either the direction of both gamma rays or events where one of the gamma rays converts to an electron-positron pair. These two methods each overconstrain the kinematics for reaction (1) and they led to the initial discoveries of states intermediate in mass between  $\psi'$  and  $\psi$ , denoted here by  $\chi$ .

The second type of reaction that has been studied is

$$\psi' \rightarrow \chi\gamma \quad (2)$$

where the intermediate state  $\chi$  decays only to charged hadrons and the missing gamma ray can be inferred from energy-momentum balance. This reaction was studied by the SLAC/LBL collaboration.<sup>7,8</sup>

The most direct method to study gamma-ray transitions between charmonium levels is to measure the inclusive gamma-ray spectrum in reaction

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(2) and to look for monochromatic gamma rays. Experiments designed to study inclusive gamma-ray production have been performed by the Stanford/HEPL group,<sup>9</sup> SLAC/LBL group,<sup>6</sup> and a collaboration of physicists from the University of California at San Diego, the Maryland/Princeton/Pavia group, and SLAC.<sup>10</sup>

This last group has also studied inclusive gamma-ray spectra from the  $\psi$ . This measurement sought to establish the pseudoscalar partner of the  $\psi$  through the observation of monochromatic gamma rays from the reaction

$$\psi \rightarrow X\gamma \quad (3)$$

where X represents the expected pseudoscalar state. Other experiments searched for specific decay modes of the X. Two groups from DESY, the DASP group,<sup>11</sup> and a group from Heidelberg<sup>12</sup> studied three gamma final states looking for the decay of X into 2 gamma rays. The DASP group<sup>11</sup> and the SLAC/LBL group<sup>13</sup> have searched for decays of a state X leading to  $p\bar{p}$ .

Let us now examine the present status of the experimental data. The most recent results<sup>6</sup> from the SLAC/LBL collaboration studying reaction (1) are summarized in Fig. 1. In this experiment one of the gamma rays in the

cascade decay of the  $\psi'$  was observed to convert in the beam pipe to an electron-positron pair and the final state  $\psi$  was observed through its two-lepton decay.

Two values for the invariant mass of the gamma ray- $\psi$  system can be computed for each event.

This ambiguity corresponds to the two possible origins of the observed gamma ray, the  $\psi'$  decay or  $\chi$  decay, and can, in principal, be resolved with sufficient data.

The most significant cluster of events in Fig. 1 occurs at a mass of  $3504 \pm 7 \text{ MeV}/c^2$  and is designated  $\chi(3500)$  or  $P_c$  as first announced by the DASP group.<sup>5</sup>

There are two narrow clusters of four events each at  $3454 \pm 7 \text{ MeV}/c^2$  and  $3543 \pm 7 \text{ MeV}/c^2$ .

The DASP group<sup>1</sup> has reported one event near each of these clusters. The states at  $3504 \text{ MeV}/c^2$  and  $3543 \text{ MeV}/c^2$  ( $\chi(3550)$ ) are also seen to decay to charged hadrons; at present there are no other indications of the state at

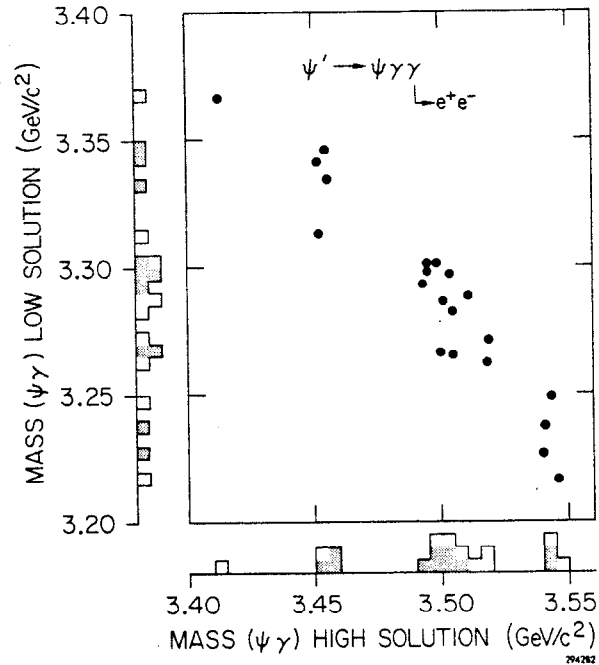


Fig. 1--Scatter plot of the two solutions for the  $\gamma\psi$  invariant mass in  $\psi' \rightarrow \gamma\gamma\psi$  decays.

$3454 \text{ MeV}/c^2$ . If one of the events in the  $3454 \text{ MeV}/c^2$  cluster is associated with the single background event expected in Fig. 1, then the remaining 3 events would share a common mass near  $3350 \text{ MeV}/c^2$ . When projected to the low-mass solution, the two higher mass clusters are broadened as expected from Doppler shifting and are inconsistent with a low-mass assignment. Finally, both SLAC/LBL and the DASP group observed one event near

3415  $\text{MeV}/c^2$ . As discussed below, there is a strong signal at this mass in various hadronic channels.

The branching ratio products for the decay sequence

$$\begin{array}{l} \psi' \rightarrow \gamma\chi \\ \quad \quad \quad \searrow \gamma\psi \end{array} \quad (4)$$

are  $0.2 \pm 0.2\%$ ,  $2.4 \pm 0.8\%$ , and  $1.0 \pm 0.6\%$  for the states  $\chi(3415)$ ,  $\chi(3500)$ , and  $\chi(3550)$ , respectively. The branching ratio product for the events near 3455  $\text{MeV}/c^2$  is  $0.8 \pm 0.4\%$ .

The SLAC/LBL collaboration<sup>8</sup> studied events of 2, 4, and 6 charged prongs with zero net charge in order to find examples of reaction (2) where the state  $\chi$  decays only to charged hadrons, all of which are detected. The existence of a single unobserved photon in these events is established by the match between missing momentum and missing energy. For example, in Fig. 2 the missing mass squared spectrum for 4-prong events recorded at the  $\psi'$  shows a peak having the position and width expected for a single missing gamma ray that is different from data obtained at the  $\psi$  where there is a strong  $\pi^0$  signal.<sup>14</sup> Events consistent with a single missing gamma ray were subjected to additional cuts in order to remove background from the cascade decay,  $\psi' \rightarrow \psi\pi^+\pi^-$ , to suppress electromagnetic backgrounds in the 2-prong events, and to isolate the various decay modes. One constraint kinematic fits were then applied to these events and the resulting invariant mass spectra are shown in Fig. 3. In all 4 spectra, there is a strong signal at  $3415 \pm 10 \text{ MeV}/c^2$  having a width consistent with experimental resolution alone. The 4-body spectra show, in addition, peaks at  $3500 \pm 10 \text{ MeV}/c^2$  and  $3550 \pm 10 \text{ MeV}/c^2$ . These modes also show a peak above 3600  $\text{MeV}/c^2$  that corresponds to nonradiative decays of the  $\psi'$ . The  $6\pi$  data have poorer mass resolution and the states at 3500 and 3550  $\text{MeV}/c^2$  are not resolved. The  $\pi^+\pi^-$  and  $K^+K^-$  spectrum shows a strong peak at 3415  $\text{MeV}/c^2$  and a fairly convincing peak at 3550  $\text{MeV}/c^2$ . These 2-body final states are significant because they imply that both the spin and parity of the two observed peaks must be even.

Angular distributions of the missing gamma ray in the SLAC/LBL analysis of 4-prong events are plotted in Fig. 4 for 3 ranges of invariant mass

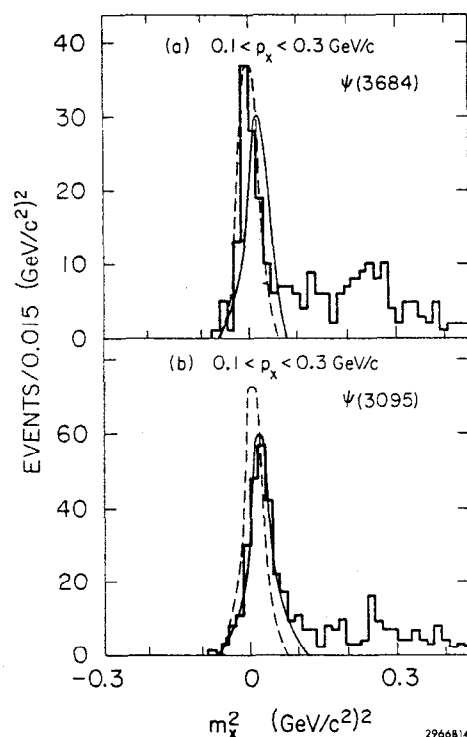


Fig. 2--(Missing Mass)<sup>2</sup> for 4-prong events having net momentum between 100 and 300  $\text{MeV}/c$ . (a)  $\psi'$  decays; (b)  $\psi$  decays. Dashed curve is expected shape for missing  $\gamma$  rays; solid curve is for missing  $\pi^0$ 's.

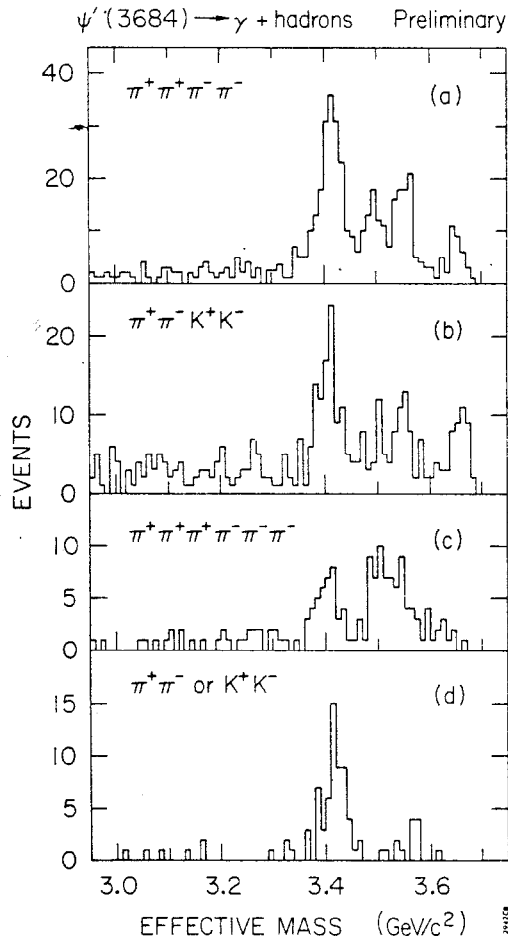


Fig. 3--Invariant mass plots for  $\chi$  states from  $\psi'$  decays. The different plots are for the indicated decay products of the  $\chi$ .

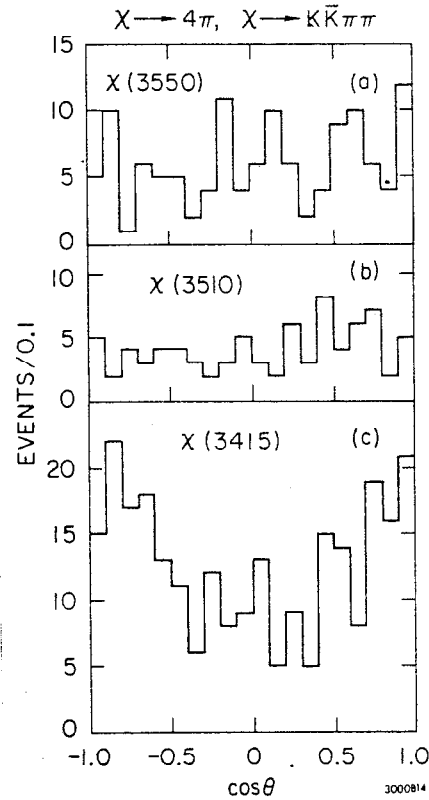


Fig. 4--Angular distribution of missing  $\gamma$  ray in the decays  $\psi' \rightarrow \gamma\chi$  where the  $\chi$  is observed to decay to 4 prongs.

corresponding to the 3 peaks in Fig. 3. The general form expected for this angular distribution is

$$1 + a \cos^2 \theta \quad (5)$$

where  $|a| < 1$ . The values for  $a$  determined from the data of Fig. 4 are presented in Table I. These data indicate that the spin of the  $\chi(3415)$  is 0, for

TABLE I

Coefficient  $a$  of Eq. (5) for angular distribution of gamma rays in the decays  $\psi' \rightarrow \gamma\chi$ .

| State        | $a$           |
|--------------|---------------|
| $\chi(3415)$ | $1.4 \pm 0.4$ |
| $\chi(3500)$ | $0.3 \pm 0.5$ |
| $\chi(3550)$ | $0.2 \pm 0.4$ |

which case there is the unambiguous prediction that  $a = +1$ . The value of  $a$  is not uniquely determined for higher spins. These data, however, indicate that the spins of the  $\chi(3500)$  and  $\chi(3550)$  differ from 0. Results from the DESY/Heidelberg group<sup>15</sup> find  $a = -1.1 \pm 0.3$  for the  $\chi(3500)$  region, also indicating that its spin is not zero.

The gamma-ray line spectrum of charmonium has finally been observed

directly through the inclusive gamma-ray spectrum from events taken at the  $\psi'$ . Initially, this line spectrum proved difficult to uncover, but the SLAC/LBL group<sup>6</sup> has reported the observation of a line near 270 MeV and, more recently, the University of California at San Diego, Maryland/Princeton/Pavia, SLAC collaboration<sup>10</sup> have presented a more complete spectrum displaying all of the features expected from previous information on intermediate states. The UCSDMPPS results are shown in Fig. 5. The three major low energy lines correspond exactly in position and width to the expected gamma ray transitions from the  $\psi'$  to the intermediate states  $\chi(3550)$ ,  $\chi(3500)$ ,  $\chi(3415)$ . The line near 400 MeV corresponds to the decay of the  $\chi(3415)$  back to the  $\psi$ . This line is Doppler broadened. There is no compelling evidence in this spectrum for the possible level at  $3454 \text{ MeV}/c^2$ . Branching ratios for the decay of the  $\psi'$  to the three  $\chi$  states are given in Table II.

In summary, there is now strong experimental evidence for the existence of three or four states with masses between those of the  $\psi'$  and  $\psi$  that are connected to the  $\psi'$  and  $\psi$  via gamma ray transitions. The best understood of these is the  $\chi(3415)$ . From the angular distribution of gamma rays it is known that this state has  $J=0$  and the observation of a strong  $\pi^+\pi^-$  or  $K^+K^-$  decay mode indicates that its parity is  $P=+$ . The state  $\chi(3550)$  is known to have  $J \neq 0$ . Again, a signal in the  $\pi^+\pi^-$  and  $K^+K^-$  channels indicates that its spin and parity are even. The  $P_c$  or  $\chi(3500)$  has been observed as a strong signal in the cascade decay of  $\psi'$  to  $\psi$ . Its spin cannot be zero. Finally, there exists weak evidence for a state at  $3454 \text{ MeV}/c^2$  seen only in the cascade decays of the  $\psi'$ .

It is standard to associate the three states,  $\chi(3415)$ ,  $P_c$ , and the  $\chi(3550)$  with the expected  $^3P$  states of charmonium. It is then natural to assign the possible state at  $3454 \text{ MeV}/c^2$  as

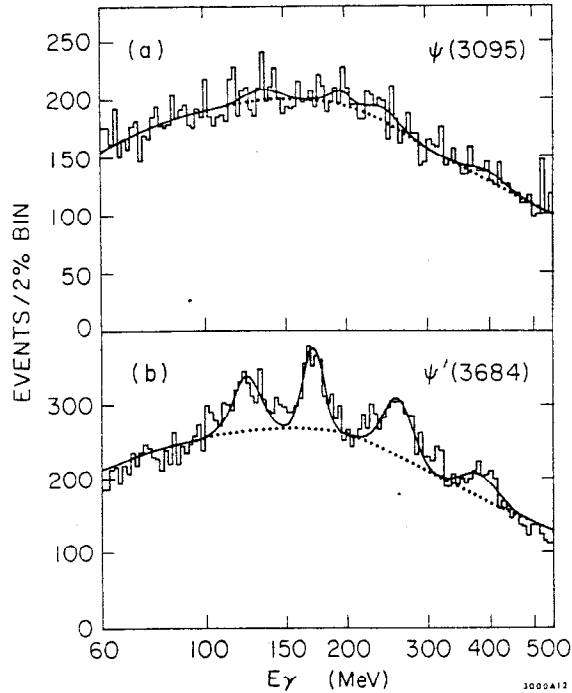


Fig. 5--Inclusive gamma ray energy spectrum from UCSDMPPS experiment. (a)  $\psi$  decays; (b)  $\psi'$  decays.

TABLE II

Branching ratios for the decays  $\psi' \rightarrow \gamma\chi$ .

| State        | BR $\frac{\psi' \rightarrow \gamma\chi}{\psi' \rightarrow \text{all}}$ | Ref. |
|--------------|--|------|
| $\chi(3550)$ | $0.08 \pm 0.03$  | 10   |
| $\chi(3500)$ | $0.09 \pm 0.03$  | 10   |
| $\chi(3415)$ | $0.10 \pm 0.04$  | 10   |
|              | $0.075 \pm 0.026$  | 6    |

the second excited state of the  $^1S_0$  charmonium state. There are problems with these assignments and there are other possible solutions; these will be discussed in the talk by Gilman.<sup>16</sup>

A most important problem in charmonium spectroscopy is the existence of the expected pseudoscalar state near the mass of the  $\psi$ . At the 1975 Lepton-Photon Symposium, two groups, the DESY/Heidelberg<sup>12</sup> and DASP<sup>11</sup> groups, reported on 3-gamma ray final states of the  $\psi$  and presented evidence for the existence of a state near  $2750 \text{ MeV}/c^2$  decaying into 2 gamma rays that has become known as X(2800). DASP group<sup>1</sup> revised upward its estimate of the mass of this state and presented a 3 to 4 standard deviation peak in the mass range  $2.8 \text{ GeV}/c^2$  to  $2.9 \text{ GeV}/c^2$ . Data from the original DASP and DESY/Heidelberg experiments are given in Fig. 6 in the form of

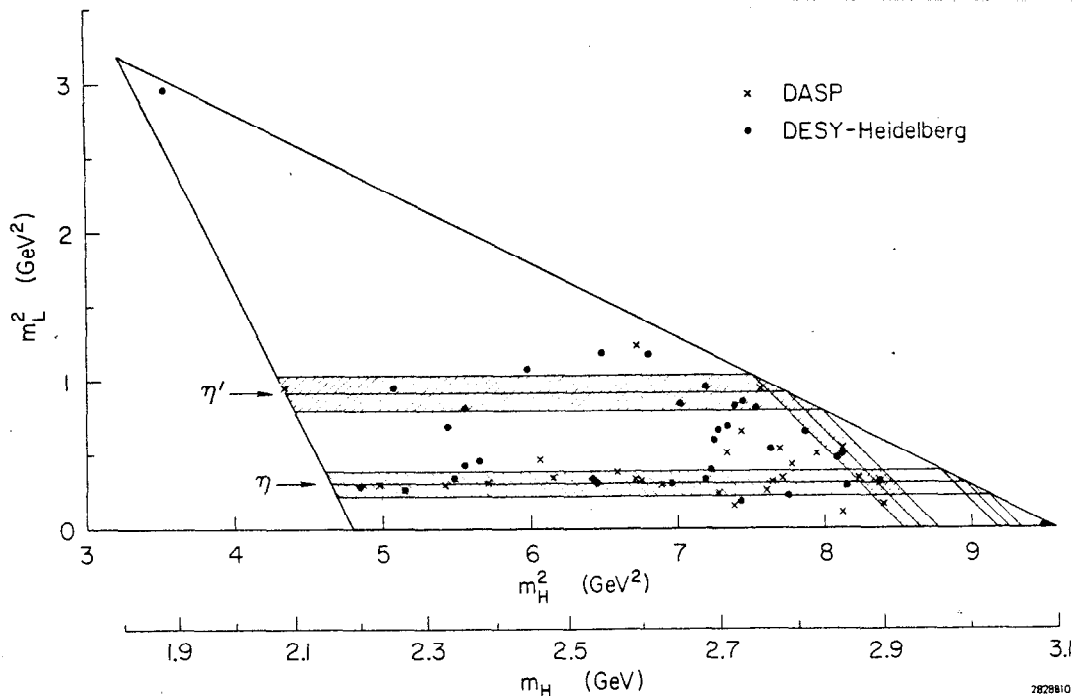


Fig. 6--Dalitz plot for 3- $\gamma$  final states of the  $\psi$  obtained by two DESY groups.<sup>11, 12</sup>

a Dalitz plot. It can be seen that the analysis of these 3 gamma ray final states is complicated by decays of the  $\psi$  to the  $\eta'$  and  $\eta$ . Nevertheless, both DESY groups claim a significant excess of events near  $2800 \text{ MeV}/c^2$ . The existence of the  $^1S_0$  state and the value of its mass are important ingredients in the charmonium picture and additional experiments confirming these results are necessary to establish firmly the existence of the pseudoscalar partner of the  $\psi$ .

Other decay modes of the X(2800) have been sought by the SLAC/LBL collaboration<sup>13</sup> who looked at pp events in the final states of the  $\psi$ . They set the limit on the product of branching ratios

$$\text{BR}(\psi \rightarrow \gamma X) \times \text{BR}(X \rightarrow p\bar{p}) < 4 \times 10^{-5} \text{ (90\% confidence level)} \quad (6)$$

The UCSDMPPS collaboration measured inclusive gamma ray spectra at the  $\psi$  and found no evidence for a monochromatic line corresponding to reaction (3). They set an upper limit on the branching ratio,

$$\text{BR}(\psi \rightarrow \gamma X) < 0.05 \text{ (90\% confidence level)} . \quad (7)$$

Our present knowledge of the charmonium spectroscopy is summarized in Fig. 7. The first levels to be discovered were the vector states  $\psi$ ,  $\psi'$ ;

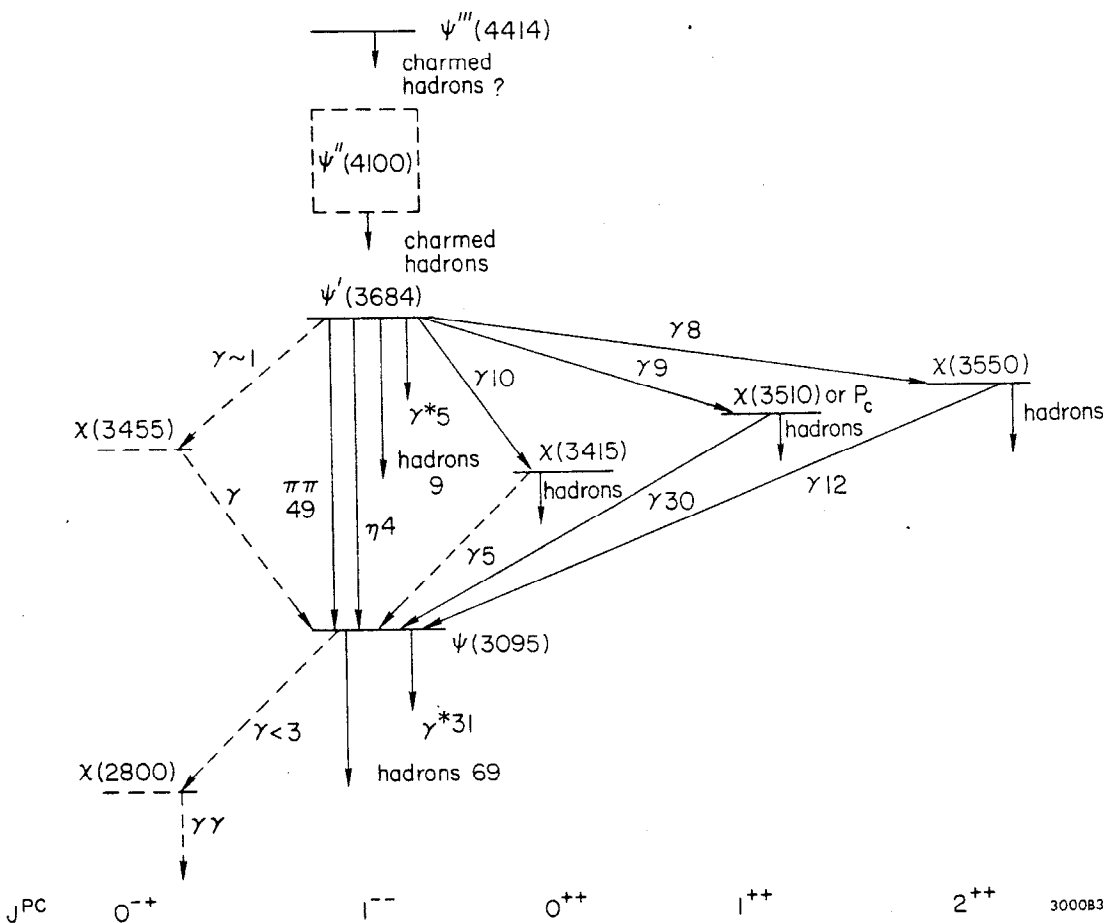


Fig. 7--Summary of charmonium spectroscopy. Uncertain states and transitions are indicated by dashed lines. Numbers indicate branching fractions in %.

there are now additional broad vector states,  $\psi''$ , with masses in the 4 GeV region. Many hadronic decay modes of the  $\psi$  have been studied<sup>1,2,17</sup> and they fit into the pattern expected for a state that is nearly a pure SU(3) singlet. There is now strong experimental evidence for 3 states intermediate in mass between the  $\psi'$  and the  $\psi$  which couple to these states via photon transitions. The quantum numbers of two of the states indicated in Fig. 7 are well established and the third is likely to be the third member of the expected  $^3P$  states of charmonium. Several hadronic decay modes of these states have also been studied. Finally, there exists much weaker evidence

for the pseudoscalar partners of the  $\psi$  and  $\psi'$ . Both of these states need experimental confirmation.

An early problem in the study of the  $\psi'$  was an apparent large number of decay modes that could not be accounted for either in terms of normal hadronic decays or cascade decays. However, with the new gamma ray transitions that have been established, one can account for the majority of  $\psi'$  decays.<sup>2</sup>

### A HEAVY LEPTON?

The proposition that a new lepton with a mass near 1.9 GeV is being produced in  $e^+e^-$  annihilation starts out with two strikes against it. First, if this proposition is true, then it is virtually impossible to prove conclusively because there will always be missing neutrinos in signal events and it is not possible to reconstruct a unique mass for the heavy lepton. Therefore, when dealing with experimental data one is always faced with the problem of checking the consistency of the data with the theoretical hypothesis. The second strike against this proposition is simply that it is too good to be true! It is difficult to believe that the heavy lepton mass could be so nearly the same as the mass of the lowest lying charmed particle. Nevertheless, a large body of data can be described by a heavy lepton; based on the work of Perl et al.,<sup>18</sup> the following consistency arguments can be made:

1. Events with an electron and muon in the final state and no other detectable particles have been observed.<sup>19,20</sup> The events selected by the SLAC/LBL group<sup>19</sup> had two charged tracks and no gamma rays observed in the detector. The two tracks were acoplanar with respect to the beam direction by at least  $20^\circ$  in order to reject electromagnetic backgrounds and the momentum of each track was greater than 650 MeV/c. The main experimental difficulty with these events is the rather large misidentification probabilities ( $\approx 20\%$ ) for hadrons to be called either electron or muon. To date, the SLAC/LBL group has published evidence for 139  $e\mu$  events where the estimated background is 34 events. The Pluto group<sup>20</sup> has announced between 4 and 6  $e\mu$  events taken at center-of-mass energies  $E_{c.m.}$  between 4.0 and 4.4 GeV. These are preliminary results, yet they appear to be consistent in character and cross section with the SLAC/LBL results. The SLAC/LBL group has also presented evidence<sup>18</sup> for the expected  $ee$  and  $\mu\mu$  final states that can arise from heavy lepton decays. Finally, the SLAC/LBL group<sup>21</sup> has installed, over a limited range of solid angle, an improved muon identification system and observe 13  $e\mu$  events with the  $\mu$  well identified. The expected background in this sample is less than 1 event. There is no conventional explanation for these events, but they are consistent with the hypothesis of the production of a pair of heavy leptons, one of which decays to a muon and two neutrinos, the other decaying to an electron and two neutrinos.
2. The energy dependence of the observed  $e\mu$  cross section from the SLAC/LBL experiment is shown in Fig. 8 and is consistent with that expected for heavy lepton pair production. The magnitude of the observed cross section and the assumption that the heavy lepton is produced with pointlike electromagnetic coupling



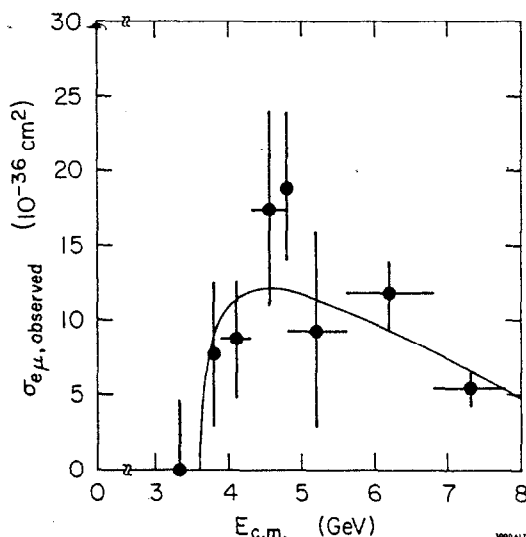
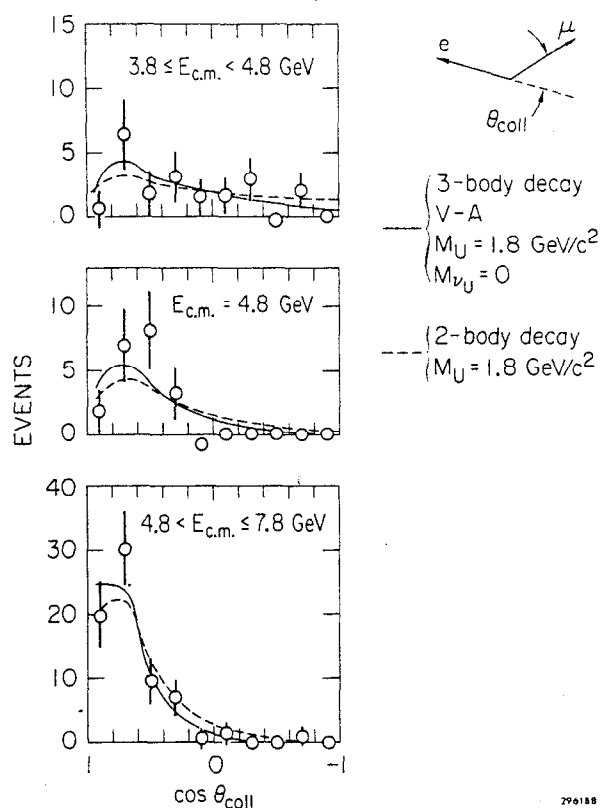


Fig. 8--Observed  $e\mu$  cross section corrected for background. The solid curve is the expected behavior for a heavy lepton of mass  $1.8 \text{ GeV}/c^2$ .



3. The kinematic behavior of  $e\mu$  events is consistent with heavy lepton production. In Fig. 9 the collinearity angle distributions for  $e\mu$  events are presented at various  $E_{c.m.}$ . As the  $E_{c.m.}$  increases, the  $e$  and  $\mu$  become more and more collinear, suggesting that they are decay products of particles originally produced in pairs. The distribution of charged tracks in  $e\mu$  events in the quantity  $\rho$  is presented in Fig. 10.  $\rho$  is related to the momentum  $p$  of the observed prong by:

$$\rho = \frac{p - 0.65 \text{ GeV}/c}{p_{\text{max}} - 0.65 \text{ GeV}/c} \quad (9)$$

where  $p_{\text{max}}$  is the maximum possible momentum of a particle at the particular  $E_{c.m.}$ . The data fall smoothly with increasing  $\rho$ ; this behavior is characteristic of 3-body decays of the  $U$  particle where the missing neutrals in these decays are rather light. Two-body decays of the  $U$

indicate that the leptonic branching ratio is:

$$\begin{aligned} \text{BR}(U \rightarrow \mu \nu \bar{\nu}) &= \text{BR}(U \rightarrow e \nu \bar{\nu}) \\ &= 0.17 \pm 0.06 \\ &\quad - 0.03 \end{aligned}$$

where  $U$  stands for the proposed lepton.

Fig. 9--Collinearity angle distribution for  $e\mu$  events in 3 regions of  $E_{c.m.}$ . Solid curves are for a  $1.8 \text{ GeV}/c^2$  heavy lepton; dashed curves are for 2-body decays of a boson with mass  $1.8 \text{ GeV}/c^2$ , produced in pairs.

particle would have a much flatter  $\rho$  distribution and seem to be ruled out by the data. Decay modes involving missing neutrals of mass greater than 1 GeV also appear to be ruled out by the data, although a missing neutral of mass 0.5 GeV is possible.

4. There is now information indicating that the majority of the missing neutral particles in decays of the U particle are neutrinos.<sup>18</sup> The basic philosophy behind these results is the fact that the probability of seeing something from decays of possible contaminating neutrals such as  $K^0$ ,  $\pi^0$ , gamma rays, etc., is rather large in the SLAC/LBL magnetic detector. Therefore, to explain all of the events of the type  $e\mu$  + nothing detected, there should be a large number of events of the form  $e\mu$  + something detected. Table III gives the number of events containing an e and a  $\mu$  as defined by the cuts outlined previously for various observed charged multiplicities and number of detected gamma rays. The most conspicuous entry in this table is the 2-prong zero-gamma ray entry where the number of observed events greatly exceeds the expected background; for the other entries, the background expected from particle misidentifications accounts for most, if not all, of the observed number of events. It is difficult to account for the large number of 2-prong zero-gamma ray events by more conventional sources of background without larger numbers of events in some of the other entries. As a specific example, the SLAC/LBL group has looked for events of the type  $e\mu \pi^+\pi^-$  where  $\pi^+\pi^-$  come from the decays of  $K^0$ . One event was observed with an expected background of 1 event. The probability of detecting a  $K^0$  (taking into account the half of  $K^0$ 's that decay via a  $K_S^0$ , the branching ratio of the  $K_S^0$  to  $\pi^+\pi^-$  and detection efficiencies) is 0.086; the probability of completely missing a  $K^0$  is approximately 0.55. Therefore, the SLAC/LBL group set an upper limit (90% confidence level) that less than 9% of U-particle decays which lead to the  $e\mu$  events contain a missing  $K^0$ . This kind of analysis has been carried on for other possible neutral particles in decay products of the U;

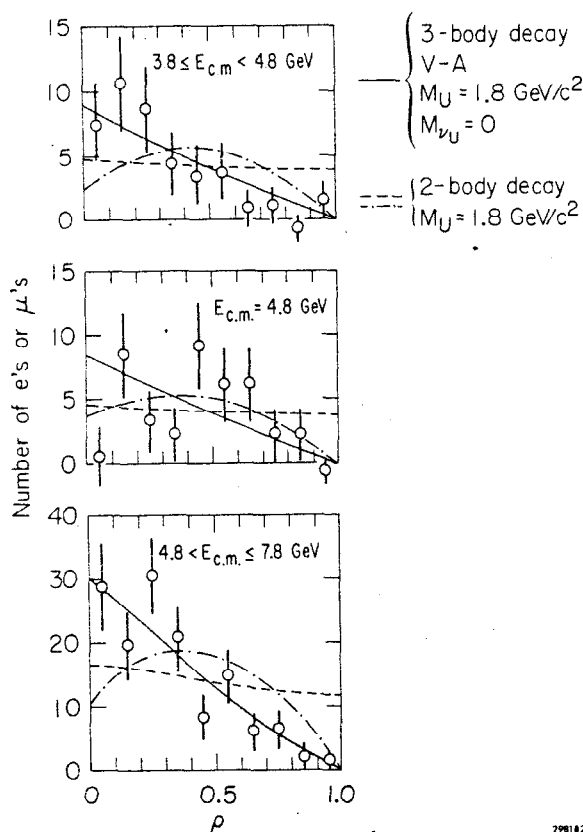


Fig. 10-- $\rho$  distribution of  $e\mu$  events. Solid and dashed curves are for the same models as used in Fig. 9. Dash-dot curve is for the 2-body decay of a pair of 1.8 GeV/c<sup>2</sup> vector bosons.

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TABLE III

The number of events containing an oppositely charged pair identified as  $e^\pm\mu^\mp$  categorized by total observed charged multiplicity and number of detected photons. Data are from Ref. 18. Numbers in parentheses are minimal and maximal background estimates.

| charged multiplicity | number of detected photons |                  |
|----------------------|----------------------------|------------------|
|                      | 0                          | $\geq 1$         |
| 2                    | 110<br>(14-28)             | 109<br>(51-104)  |
| 3                    | 67<br>(28-58)              | 198<br>(94-193)  |
| 4                    | 79<br>(37-76)              | 338<br>(180-356) |
| $\geq 5$             | 101<br>(56-109)            | 884<br>(506-971) |

TABLE IV

Upper limits on the fraction of U particle decays leading to events of the type  $e^\pm\mu^\mp$  + undetected neutrals that contain undetected particles that are not neutrinos.

| Undetected particle(s)                 | 90% confidence upper limit |
|--|----------------------------|
| $K^0$                                  | 0.09                       |
| $\pi^0$ or $\gamma$                    | 0.18                       |
| charged particle                       | 0.09                       |
| charged particle + $\pi^0$ or $\gamma$ | 0.11                       |
| Total                                  | 0.39                       |

cut on muon momentum, the second track in the event was required to be acoplanar with respect to the muon and beam direction by at least  $20^\circ$ , additional gamma rays are allowed in the events, and a missing mass cut of  $\geq 1.5 \text{ GeV}^2$  was imposed to reduce the background from purely electrodynamic events. As seen from the table, there exists a significant inclusive muon signal above the expected background. The

the limits established for these modes are given in Table IV.

While these results are consistent with the missing neutrals in  $e\mu$  events being only neutrinos, these limits are uncomfortably large.

5. The final argument in favor of the heavy lepton hypothesis is contained in new results on inclusive muon production from the SLAC/LBL collaboration.<sup>21</sup> As mentioned previously, an improved muon identification system, the muon tower, was added to the SLAC/LBL magnetic detector, reducing the probability

for hadron punch through to the order of 3 to 6 percent over 10% of  $4\pi$  solid angle. In order to penetrate the tower, the momentum of the muon must be greater than 900 MeV/c. Since there is wide theoretical consensus that a heavy lepton in the 2 GeV mass region should decay roughly 80% of the time to final states containing only 1 charged particle,<sup>22</sup> a measurement of the muon inclusive cross section in 2 charged-prong events can be used as a consistency check of the heavy lepton hypothesis. The recent SLAC/LBL results are presented in Table V. In addition to the

TABLE V

Inclusive muon + 1 charged particle results.

| $E_{c.m.}$ Range (GeV)                        | 3.9 - 4.3    | 4.3 - 4.8    | 5.8 - 7.8    |
|---|--------------|--------------|--------------|
| Average $E_{c.m.}$                            | 4.05         | 4.4          | 6.9          |
| $(\text{Missing Mass})^2 > 1.5 \text{ GeV}^2$ |              |              |              |
| Muon Candidates                               | 181          | 224          | 902          |
| Muons   | 24           | 29           | 177          |
| Estimated Background                          | 8.7          | 10.4         | 74           |
| $(\text{Missing Mass})^2 < 1.5 \text{ GeV}^2$ |              |              |              |
| Muons   | 24           | 17           | 53           |
| Estimated Background                          | 20.4         | 17.5         | 55.8         |
| Anomalous Muon Cross Section (pb)             | $200 \pm 70$ | $260 \pm 90$ | $220 \pm 50$ |
| Expected Heavy Lepton Cross Section (pb)      |              |              |              |
| $M_U = 1.8 \text{ GeV}/c^2$                   | 191          | 260          | 208          |
| $M_U = 2.0 \text{ GeV}/c^2$                   | 57           | 197          | 218          |

cross section at all three  $E_{c.m.}$  is roughly 200 picobarns. Events with small missing mass, which should be mainly background, agree with the background estimates. Finally, the cross sections expected for heavy lepton production with the branching ratio to muons given previously are also presented in the table. Two different masses for the heavy lepton have been assumed. These inclusive muon rates are consistent with the expectations of the heavy lepton. It is possible that there is an excess of muon production near 4.05 GeV beyond that expected for the heavy lepton.

The Maryland/Princeton/Pavia collaboration<sup>23</sup> has published results on anomalous muon production at the center-of-mass energy 4.8 GeV. They found 13 noncoplanar 2-prong events where the expected background was 3.9. This corresponds to a cross section of  $285 \pm 151 \text{ pb}$ . There are two criticisms of this result: (a) The  $\mu\mu\gamma$  background may be larger than was estimated in the published results. This would, of course, reduce the cross section for anomalous muon production. (b) The statistical accuracy of the measurement is very low. At the Tbilisi Conference the PLUTO group<sup>20</sup> reported on inclusive muon production at center-of-mass energies of 4.1 and 4.4 GeV. They observed 98 events with an estimated background of 91, setting an upper limit of 80 picobarns on the single muon inclusive cross section. At first sight, this is incompatible with both the SLAC/LBL and Maryland/Princeton/Pavia results. However, their 4  $e\mu$  events were not considered in the quoted cross section and it is possible that the background

from hadron punch-through was overestimated. The DASP group<sup>24</sup> has reported on inclusive lepton production in events with 4 or more tracks, but, as yet, has not commented on events of low multiplicity. Assuming that heavy leptons decay with low multiplicity, the present DASP results are not incompatible with existence of the heavy lepton.

In conclusion, the hypothesis of a heavy lepton of mass between 1.8 and 2 GeV is able to describe a large body of low multiplicity  $e^+e^-$  data involving leptons in the final state. At present there are no serious contradictions to this hypothesis, except possibly the PLUTO results, and no other simple hypothesis has been proposed to explain all of these data. However, before the hypothesis of the heavy lepton can be fully accepted, better experimental limits on the identity of the missing neutrals in the  $e\mu$  events, and the demonstration that these phenomena have pointlike electromagnetic couplings, are required.

### CHARMED PARTICLE PRODUCTION IN $e^+e^-$ COLLIDING BEAMS

That charmed particles are being produced in  $e^+e^-$  collisions is no longer a question. The initial evidence came from the observation by the SLAC/LBL group<sup>25</sup> of narrow peaks in the invariant mass spectra of  $K^\mp\pi^\pm$  and  $K^\mp\pi^\pm\pi^\mp\pi^\pm$  for data taken at center-of-mass energies between 3.9 and 4.6 GeV. These data showed peaks at a mass  $1865 \pm 15$  MeV/c<sup>2</sup> that were compatible with the long lifetime expected of charmed particles; the upper limit on the decay width was 40 MeV/c<sup>2</sup>. The new states were not produced at energies below the 4 GeV region and the recoil mass spectrum associated with the narrow peaks gave evidence for associated production. The next important piece of information came from the observation<sup>26</sup> of a narrow peak in the charged state  $K^\pm\pi^\mp\pi^\mp$ . This is an exotic combination of  $K\pi\pi$ ; all known  $K^*$  states exist in the nonexotic channel where the charge and strangeness are equal. There was no corresponding peak observed in nonexotic  $K\pi\pi$  combinations. The mass of the new charged state is  $1876 \pm 15$  MeV/c<sup>2</sup>; the upper limit on its decay width is 40 MeV/c<sup>2</sup>, and is set entirely by experimental resolution.

Taken together these results are strong evidence for the existence of the predicted doublet ( $D^0, D^\mp$ ) of charmed mesons.<sup>27</sup> Further evidence for the production of particles which decay weakly is available from DESY. The DASP collaboration<sup>24</sup> has presented evidence for a prompt electron signal with a threshold near 4 GeV. The PLUTO group<sup>28</sup> has presented evidence for an electron- $K^0$  correlation near 4 GeV.

Since the initial discoveries of charmed particles, the SLAC/LBL collaboration<sup>13</sup> has obtained additional data at the center-of-mass energy 4.028 GeV. As seen in Fig. 11 this energy corresponds to the top of a very sharp rise in  $R$ , the ratio of the total hadronic cross section to the muon pair-production cross section. These data have an unmistakable peak in the  $K^\mp\pi^\pm$  channel, as shown in Fig. 12.

Additional decay modes of the  $D^0$  are currently being studied. The preliminary invariant mass spectrum of the particles  $K_S^0\pi^+\pi^-$ , where the  $K_S^0$  is identified through its  $\pi^+\pi^-$  decay in the SLAC/LBL detector, is presented in Fig. 13. A strong signal near 1.87 GeV is evident. In addition to the  $D^0$  signal, there appears to be a significant excess of events in the region of the  $K^*(1420)$ . At present, the systematic uncertainties in cross section times branching ratio for these new states are very large. Roughly speaking, the

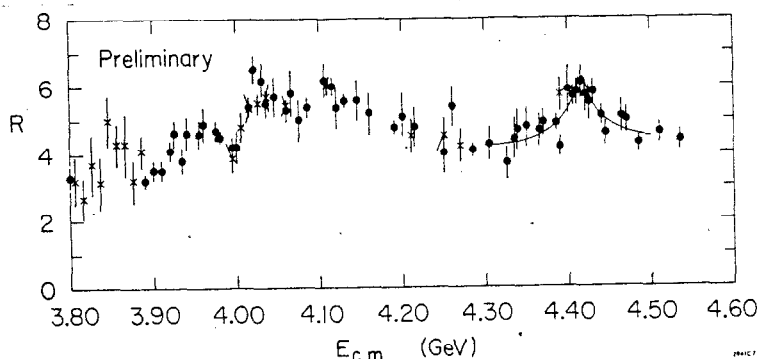


Fig. 11--Detailed plot of R in the 4 GeV region.

cross sections times branching ratio for the 3 established decay modes of the  $D^0$  and the only observed decay mode of the charged D all lie between  $\frac{1}{4}$  nb and 1 nb at  $E_{c.m.} = 4.028$  GeV, which are to be compared with the total hadronic cross section at this energy of  $33 \pm 5$  nb.

Evidence for parity violation in D decays has been obtained by the SLAC/LBL group<sup>29</sup> through a study of the Dalitz plot for  $K\pi\pi$  decays of  $D^\pm$ . The Dalitz plot is uniformly populated in contradiction to the boundary zeros expected<sup>30</sup> for decays that proceed through a state of natural spin-parity ( $P = (-1)^J$ ). Assuming the intrinsic parities of the  $D^0$  and  $D^\pm$  to be the same, parity violation in D decays follows because the  $K\pi$  decay mode of the  $D^0$  necessarily has natural spin-parity.

The final topic in this talk is a report on preliminary studies of  $D^0$  production at the fixed  $E_{c.m.} = 4.028$  GeV performed by the SLAC/LBL group.<sup>13</sup> In this analysis, a  $D^0$  is defined as any neutral 2-prong combination having time-of-flight information consistent with  $K\pi$  and invariant mass near  $1.87 \text{ GeV}/c^2$ . The spectrum of masses recoiling against  $D^0$ 's is given in Fig. 14. The spectrum is dominated by two large peaks, one centered near  $2.01 \text{ GeV}/c^2$ , the second at  $2.15 \text{ GeV}/c^2$ . There is only marginal evidence for a peak at  $1.87 \text{ GeV}/c^2$ , which would correspond to  $D^0$  pair production. It was immediately realized that the peak near  $2.01 \text{ GeV}/c^2$  could represent an excited  $D^0$  state which is designated  $D^{*0}$ . The interpretation of the higher recoil mass peak is ambiguous; it may represent an excited state near  $2.15$

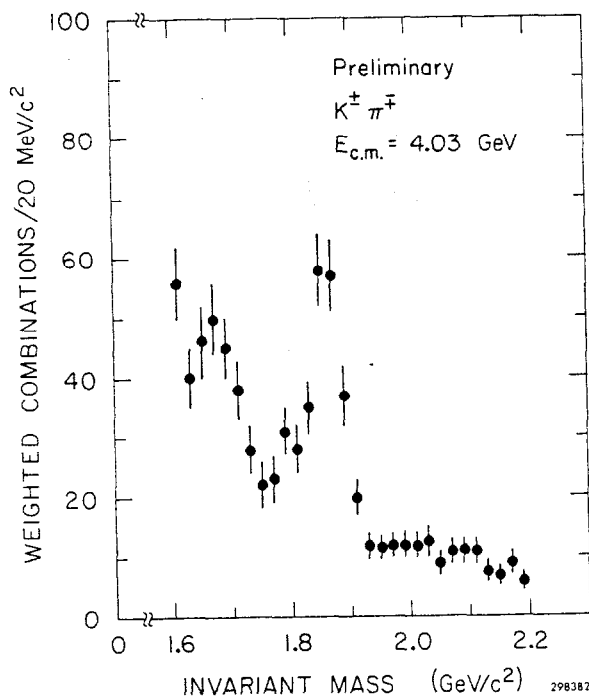


Fig. 12--Time-of-flight weighted invariant mass spectrum for  $K\pi$  combinations observed at  $E_{c.m.} = 4.028$  GeV.

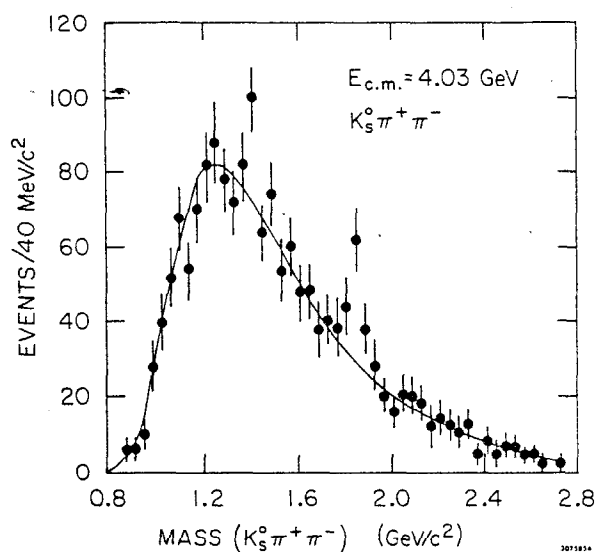


Fig. 13-- $K_S^0 \pi \pi$  invariant mass spectrum.

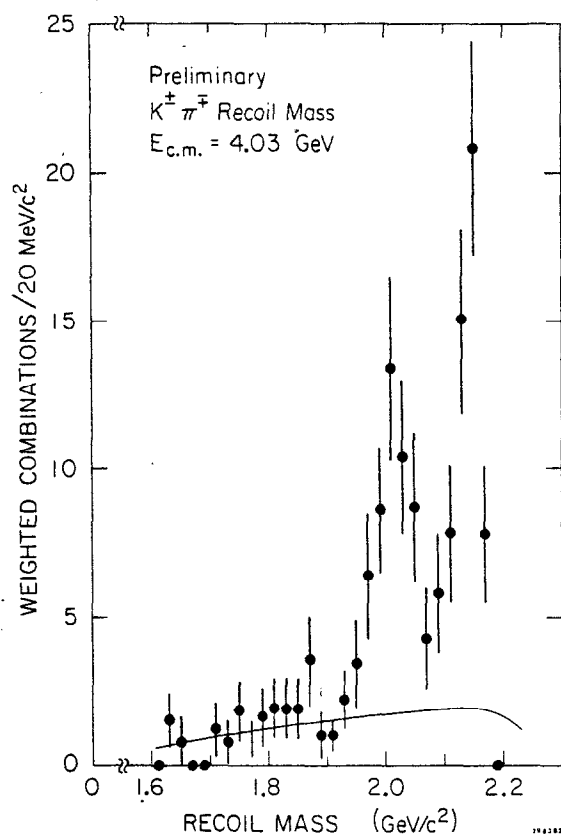


Fig. 14-- $D^0$  recoil mass spectrum at  $E_{c.m.} = 4.028$  GeV.

$\text{GeV}/c^2$  or, more likely, a kinematic reflection due to pair production of  $D^{*0}$  followed by the subsequent decay  $D^{*0} \rightarrow \pi^0 D^0$ . Data at higher  $E_{c.m.}$  can resolve this ambiguity, but for the present discussion the latter choice is taken.

In order to understand the  $D^0$  production mechanisms in more detail, it is convenient to consider the observed kinetic energy,  $T$ , spectrum of  $D^0$ 's, rather than recoil mass.  $T$  is computed from the net momentum of the 2-prong combination assuming a  $D^0$  mass of  $1.867 \text{ GeV}/c^2$ . The nonrelativistic nature of the kinematics and the use of only net momentum make  $T$  rather insensitive to the precise value of the  $D^0$  mass or to the  $\pi K$  mass assignments for the two detected prongs. If it is assumed that  $D^0$  production at  $E_{c.m.} = 4.028 \text{ GeV}$  arises only from 2-body production of  $D$  and  $D^*$ , then the possible sources of the observed  $D^0$ 's are:

$$e^+ e^- \rightarrow D^0 \bar{D}^0 + \text{c.c.} \quad (10)$$

$\downarrow$   
 $K\pi$

$$e^+ e^- \rightarrow D^0 \bar{D}^{*0} + \text{c.c.} \quad (11a)$$

$\downarrow$   
 $K\pi$

$$\rightarrow D^{*0} \bar{D}^0 + \text{c.c.} \quad (11b)$$

$\downarrow$   
 $\pi^0 D^0$   
 $\downarrow$   
 $K\pi$

$$\rightarrow D^{*0} \bar{D}^0 + \text{c.c.} \quad (11c)$$

$\downarrow$   
 $\gamma D^0$   
 $\downarrow$   
 $K\pi$

$$e^+ e^- \rightarrow D^{*0} \bar{D}^{*0} + \text{c.c.} \quad (12a)$$

$\downarrow$   
 $\pi^0 D^0$   
 $\downarrow$   
 $K\pi$

$$\rightarrow D^{*0} \bar{D}^{*0} + \text{c.c.} \quad (12b)$$

$\downarrow$   
 $\gamma D^0$   
 $\downarrow$   
 $K\pi$

$$e^+e^- \rightarrow D^{*+}D^{-} + \text{c.c.} \quad (13)$$

$$\quad \quad \quad \searrow \pi^+D^0$$

$$\quad \quad \quad \quad \quad \searrow K\pi$$

where c.c. refers to the charge conjugate reaction. Reaction (13) was suggested by De Rújula, Georgi, and Glashow,<sup>31</sup> who estimated that it might be the major contributor of detected  $D^0$  events if electromagnetic mass differences between  $D^0$ ,  $D^+$  were favorable.

The kinematics for all of these sources of  $D^0$ 's are slightly different, each giving a characteristic T or spread in T to the observed  $K\pi$  system.  $D^0$ 's produced in the original interaction have a unique T and are called direct  $D^0$ 's; combinations originating from decays of  $D^*$ 's have a spread in T and are called reflections. The width of the spread in T depends sensitively on the Q-value of the  $D^*$  decay. The various regions of T corresponding to reactions (10) - (13) are shown in Fig. 15.

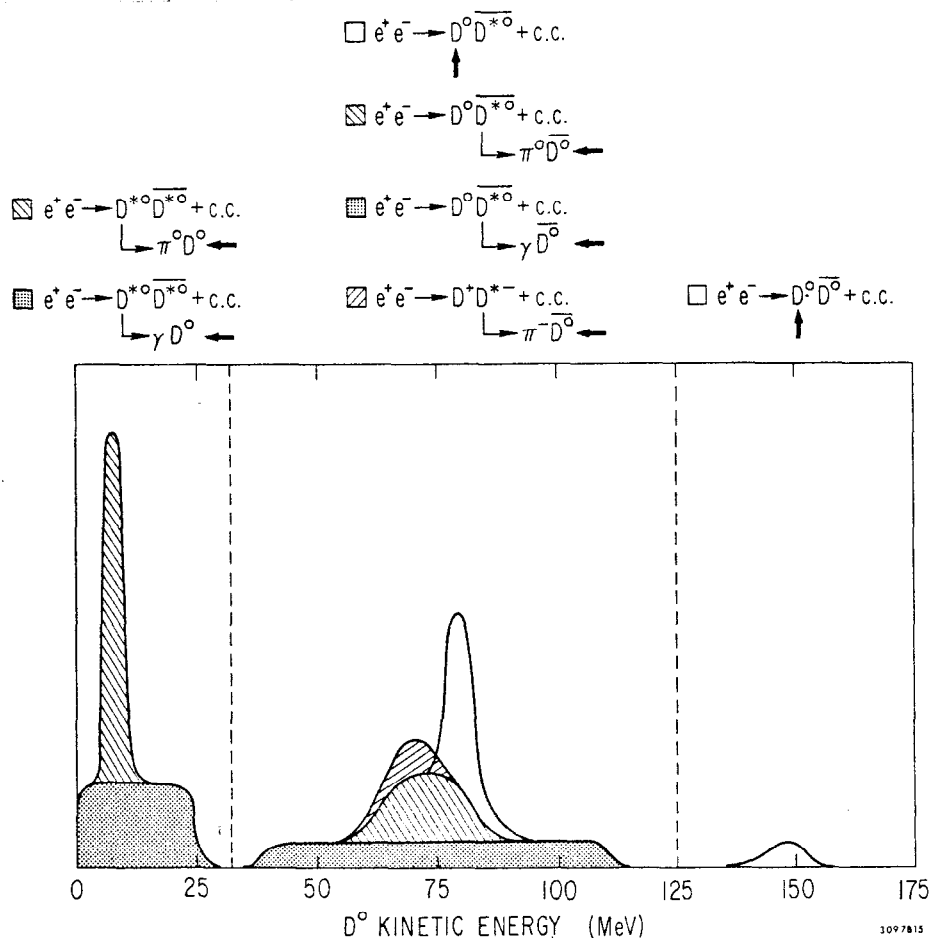


Fig. 15--Schematic representation of kinetic energy spectrum for  $D^0$ 's at  $E_{c.m.} = 4.028$  GeV for various production sources. Arrows indicate the observed  $D^0$ . c.c. refers to charge conjugate reaction.



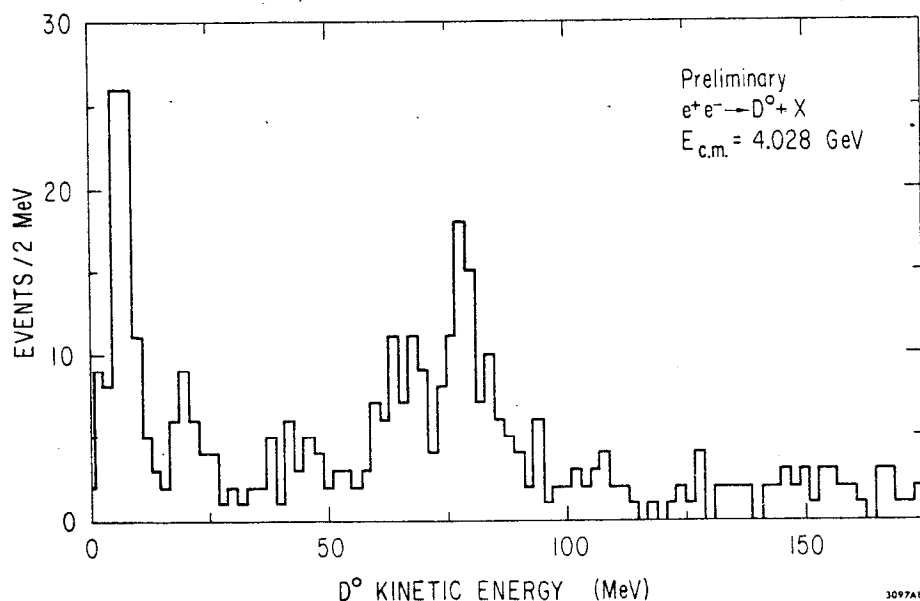


Fig. 16--Observed kinetic energy spectrum of  $D^0$ 's produced at  $E_{c.m.} = 4.028$  GeV.

The observed kinetic energy spectrum for  $D^0$ 's at  $E_{c.m.} = 4.028$  GeV is given in Fig. 16. The qualitative features of this spectrum agree remarkably well with the hypothetical spectrum of the preceding figure. The most striking feature is the very narrow peak near  $T = 12$  MeV, which corresponds to reaction (12a). The observed width sets an upper limit of 6 MeV on the  $Q$ -value in the decay  $D^{*0} \rightarrow \pi^0 D^0$  and the position implies the  $D^{*0}$  mass is  $2005.5 \pm 1.5$  MeV/ $c^2$ . Pair production of  $D^{*0}$  dominates the spectrum, yet is only 17 MeV above threshold! The structure near  $T = 75$  MeV corresponds to reactions (11) and (13). The detailed shape of this region indicates that reaction (13) is not a dominant contributor to observed  $D^0$ 's, but could be present at the 20% level or less. In both regions, there is a broad band of events indicating that the gamma ray decay rate of  $D^{*0}$  is comparable to the  $\pi^0$  rate. Finally, there is very little evidence for reaction (10), which should give  $D^0$ 's near  $T = 150$  MeV. A detailed fit of this  $T$  spectrum with a consistent set of masses,  $Q$ -values, and branching ratios is currently under way; it should yield precise values for these parameters.

In summary, we have seen a new world of charm particle spectroscopy open up during the past six months. The 4 GeV region of  $e^+e^-$  colliding beams has proved to be an exciting playground in which to find new particles being produced and there are still many charming things to do here. For example, the strange charmed relative of the  $D$ , the  $F$ , has yet to be uncovered. Charmed baryons, now seen in photoproduction,<sup>32</sup> should be produced in the 4 to 5 GeV region and can be studied in  $e^+e^-$  colliding beams. There should be additional excited states, P-wave states, etc., waiting to be

studied. One extremely interesting measurement that can be performed in the near future is to study the extent of  $D^0 - \bar{D}^0$  mixing by measuring the correlation in charge of the K mesons observed in  $D^0$  decays. The powerful constraints provided by the simple threshold kinematics will allow us to accurately determine masses of these new charmed particles. Finally, the quantitative study of decay modes, both hadronic and semileptonic, of these new states is a very rich field that is just beginning. The major question remains: Are we so lucky as to have also uncovered a heavy lepton in this rich 4 GeV region? For the future, one question is obvious: How many more such abundant thresholds await us as we go to higher and higher energies with  $e^+e^-$  colliding beams?

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