SLAC-PUB-1662 October 1975 (T/E)

#### NEW PARTICLE SEARCHES AND DISCOVERIES AT SPEAR\*

# G. J. Feldman

# Stanford Linear Accelerator Center Stanford University, Stanford, California, USA

# I. INTRODUCTION

This morning Roy Schwitters reported several indications that new particles are being produced at center-of-mass energies ( $E_{c.m.}$ ) above 4 GeV.<sup>1</sup> Then Gerry Abrams told us that a large fraction of  $\psi$ ' decays are unaccounted for.<sup>2</sup> Now we will attempt to tie together a few of these loose ends and conclude this trilogy with a report on searches for and discoveries of new particles. Due to limitations of time the emphasis will have to be on the discoveries.

The four topics to be covered are

a. the search for nonleptonic decays of charmed particles,

b. a study of radiative  $\psi'$  decays to new states,  $\psi' \rightarrow \gamma \chi$ , where the  $\chi$ 's are observed to decay into hadrons and into  $\gamma \psi$ ,

c. evidence for anomalous lepton production, and

d. limits on inclusive muon production.

# II. SEARCH FOR NONLEPTONIC DECAYS OF CHARMED MESONS

A few months ago we published a search for nonleptonic decays of charmed mesons.<sup>3</sup> The search was conducted by looking for narrow peaks in inclusive two- and three-body invariant mass distributions in eight different decay modes. The data sample was about 10,000 hadronic events at  $E_{c.m.} = 4.8$  GeV. This was the largest data sample available at that time.

Figure 1 shows the data for this search. There are no narrow peaks which we consider significant and we have accordingly set upper limits which correspond to several percent branching fractions for each of these modes.

We have continued this search by looking at other energies and other modes and by using a variety of techniques to try to enhance the signal. -All of the results so far have been negative. We are, however, continuing this search.

#### III. NEW STATES IN $\psi^{\dagger}$ RADIATIVE DECAYS

### A. Introduction

In models in which the  $\psi$  and  $\psi'$  are bound states of a new quark and the  $\psi'$  is a radial excitation of the  $\psi$ , other states should exist which could be reached by radiative transitions from the  $\psi'$ .<sup>4</sup> Figure 2 shows the most likely scheme. The new states could be either pseudoscalar states or P-wave states, and they could decay into the  $\psi$  by a radiative transition or could decay directly to ordinary hadrons. We will use  $\chi$  as a generic name for all of these new C-even states.

\* Work supported by the U.S. Energy Research and Development Administration.



-2-



Fig. 2--The most likely  $\gamma$ -ray transitions in the charm model.

 $\psi'$  and  $\psi$ . In the case of the  $\psi$  (Fig. 4b) the  $m_X^2$  distribution is consistent with a missing  $\pi^0$ , but inconsistent with a missing  $\gamma$ . In the  $\psi'$  decays (Fig. 4a) the exact opposite is true – the missing neutral is consistent with being a  $\gamma$  and is not consistent with being a  $\pi^0$ . Thus, we have the exceptional circumstance that in this  $p_X$  range we are observing a  $4\pi\gamma$  final state. (Fig. 4c shows additional evidence that  $\psi' \to 4\pi^{\pm}\pi^0$  is not a major decay.)

We now select those events near  $m_x^2 = 0$  (-0.03  $\leq m_x^2 \leq 0.03 \text{ GeV/c}^2$ ), make a one-constraint fit, and plot the resulting  $4\pi$  mass in Fig. 5a. Events with masses above 3.60 GeV/c<sup>2</sup> are consistent with the second order electromagnetic decay  $\psi' \rightarrow 4\pi$ . The background from  $\psi' \rightarrow 4\pi^{\pm}\pi^0$  is indicated by a dashed line and is small. There are two structures left – a narrow peak at 3.41 ± 0.01 GeV/c<sup>2</sup>, whose width is in agreement with our calculated mass resolution, and a broader structure centered at 3.53 ± 0.02 GeV/c<sup>2</sup>. Based on this mass spectrum we conclude that there are at least two  $\chi$  states present, one at 3410 MeV/c<sup>2</sup> and the other at around 3530 MeV/c<sup>2</sup>. However, the latter state is either broad or, more likely, is composed of two or more unresolved states.

We can go through the same procedure with six pion decays. Again there is a cluster of events near  $m_x^2 = 0$  and with  $p_x$  between 100 and 300 MeV/c. And again the missing mass recoiling against these

B.  $\chi$  Decays to Hadrons

The search for  $\chi \to 4\pi^{\pm}$  begins in Fig. 3, which contains scatter plots of missing mass squared  $(m_{\chi}^2)$  versus missing momentum  $(p_{\chi})$ for four-prong events from  $\psi$  and  $\psi'$  decays.<sup>5</sup> In the  $\psi$  case (Fig. 3b) a dense band of events exists near  $m_{\chi}^2 = 0$  extending across the entire  $p_{\chi}$  range. These events correspond to the five-pion decay of the  $\psi$ , one of its major decay modes. The  $\psi'$  decays, shown in Fig. 3a after subtraction of  $\psi' \to \pi^+\pi^-\psi$  decays, appear quite different. The band is absent, but instead there is a cluster of events in the  $p_{\chi}$  region between 100 and 300 MeV/c.

To investigate this further, we select the events in this region  $(100 \le p_x \le 300 \text{ MeV/c})$  and plot the projection of these data on the  $m_x^2$  axis. The results are shown in Fig. 4 for the







Fig. 4--The square of the missing mass for four-prong events. (a)  $\psi^{\circ}$  decays with 0.1 <  $p_X < 0.3$  GeV/c. (b)  $\psi$  decays with 0.1 <  $p_X < 0.3$  GeV/c. (c)  $\psi^{\circ}$  decays with  $p_X > 0.3$  GeV/c. The solid and dashed lines give the predicted resolution functions for a missing  $\pi^{\circ}$  and  $\gamma$ , respectively.



Fig. 5--Invariant mass distributions after applying the constraint  $m_X^2 = 0$  for the modes (a)  $4\pi^{\pm}$ , (b)  $6\pi^{\pm}$ , (c)  $\pi^+\pi^-K^+K^-$ , and (d) the sum of  $\pi^+\pi^-$  and  $K^+K^-$ . No missing momentum cut has been made. Events above 3.60 GeV/c<sup>2</sup> in (a) - (c) are mainly events having no missing-neutral and thus were fitted to the wrong hypothesis. The dashed line is the estimated background from (a)  $4\pi^{\pm}\pi^{0}$  and (b)  $6\pi^{\pm}\pi^{0}$ .

events is consistent with that of a  $\gamma$  and is inconsistent with that of a  $\pi^0$  (see Fig. 6). When we make a one-constraint fit, we obtain the distribution shown in Fig. 5b. Here the number of events is too low to establish the existence of discrete states, but it is clear that the states which decay to four pions also decay to six pions.

The situation is similar with decays to  $\pi^+\pi^-K^+K^-$ . Both time-of-flight information and kinematic fitting are used to isolate this channel. Figure 5c shows the results, which are suggestive of what was seen in the multipion decays.



Fig. 6--Missing mass squared for six-prong events. (a)  $\psi$ (3684) decays with 0.1 <  $p_x < 0.3$  GeV/c. (b)  $\psi$ (3095) decays with 0.1 <  $p_x < 0.3$  GeV/c. (c)  $\psi$ (3684) decays with  $p_x > 0.3$  GeV/c.

The decay into two pseudoscalars is particularly interesting since only  $\chi$  states with both even spin and parity can decay to this mode.<sup>6</sup> The shower counters and muon chambers are used to eliminate the enormous potential background from radiative electron and muon pairs. Figure 7 shows a scatter plot of  $p_X$  versus  $m_X^2$  for all events satisfying either the hypothesis  $\psi^{\dagger} \rightarrow \pi^+\pi^-\gamma$  or  $\psi^{\dagger} \rightarrow K^+K^-\gamma$ . The value of  $m_X^2$  is shown for both



Fig. 7--Scatter plot of missing momentum versus missing mass squared for two-prong events calculated for both the  $\pi\pi$  and KK hypothesis. Events with a dashed line (including both events which are off the right side of the graph) contain evidence of two missing photons.

hypotheses. With an rms  $m_x^2$  resolution of 0.04  $(GeV/c^2)^2$  it is not possible to distinguish event by event which is the proper hypothesis (as was possible in the four-prong case). However, the most likely hypothesis for each event is about equally

divided between the two possibilities and it is quite improbable that they are all pion pairs or all kaon pairs.

There are two important observations to be made from Fig. 7. First, the absence of events near  $p_x = 0$  means that the background from lepton pairs has been completely eliminated and that there is no measurable rate from  $\psi! \rightarrow \pi^+\pi^-$  or  $\psi! \rightarrow K^+K^-$ . 7 Second, almost all of the events cluster around  $p_x = 300 \text{ MeV/c}$  which implies that there is no appreciable background from  $\psi! \rightarrow \pi^+\pi^-\pi^0$  or  $\psi! \rightarrow K^+K^-\pi^0$ .

Figure 5d shows the two-particle mass spectrum after a one-constraint fit to the most likely hypothesis for each event. Remarkably, all eleven events cluster around a mass of  $3400 \pm 10 \text{ MeV/c}^2$  with an rms width of 22 MeV/c<sup>2</sup>. These values are in good agreement with the narrow peak seen in the  $4\pi$  spectrum. From these events we conclude that the  $\chi$  (3410) has  $J^{PC} = (\text{even})^{++}$ . We have no information on the spin or parity of the other state (or states) around 3530 MeV/c<sup>2</sup> where no two-prong decays are observed.

-5-



Fig. 8--Square of the missing mass recoiling against the  $\psi$  and converted photon.



Fig. 9--Scatter plot of the two solutions for the mass of intermediate states in  $\psi^{\dagger} \rightarrow \psi \gamma \gamma$  events with a converted photon.

# C. $\chi$ Decays to $\gamma\psi$

The  $\chi$  particles can also decay to  $\gamma\psi$ .<sup>8</sup> We have two methods of detecting these decays. In both methods the  $\psi$  is observed in its muon pair decay, so that we have a final state corresponding to  $\psi^{*} \rightarrow \gamma\gamma\mu^{+}\mu^{-}$ .

In the first method we detect  $\mu^+\mu^-$  and observe a conversion of one of the photons in the 0.05 radiation lengths of material surrounding the beam pipe. Figure 8 shows the  $m_X^2$  of the particle recoiling against the  $\gamma\psi$  state. Most of the events cluster around  $m_X^2 = 0$ . This is, in fact, the most convincing evidence that we are observing the decay  $\psi^{\dagger} \rightarrow \gamma\gamma\psi$ .

The primary background is expected to be from the decay  $\psi' \rightarrow \pi^0 \pi^0 \psi$ , where a  $\gamma$  from one of the  $\pi^0$ 's converts. For such events  $m_X^2 > 0.02$  (GeV/c<sup>2</sup>)<sup>2</sup>. There is one such event in Fig. 8 which we discard. In the range 0.01 <  $m_X^2 < 0.02$  there are three events which we keep although it is probable that one or two of them are background events.<sup>9</sup>

Of the eight remaining events, one is consistent with  $\psi' \rightarrow \eta \psi$  We eliminate it and in Fig. 9 plot the  $\gamma \psi$  mass obtained after a oneconstraint fit. There are two solutions for each event since we do not know a priori which  $\gamma$  was emitted first. Six of the seven events cluster together at either a mass of  $3500 \pm 10$  or  $3280 \pm 10 \text{ MeV/c}^2$ . The seventh event is possibly background. If we had accepted only events with  $m_x^2 < 0.0175$  instead of  $m_x^2 < 0.020 (\text{GeV/c}^2)^2$ , it would have been eliminated.

In the second method we detect  $\mu^+\mu^-$  and both photons in the shower counters. Only the  $\gamma$  angles are used; the azimuthal angle is determined by which shower counter is hit and the polar angle is determined by the relative pulse height at the two ends of the counter. A twoconstraint fit is possible in this situation. We do not actually make such a fit, but we use a

procedure which is equivalent. After rejecting  $\psi' \rightarrow \pi^0 \pi^0 \psi$  background by requiring a good fit, we obtain the  $\gamma \psi$  mass spectrum shown in Fig. 10. Events that are consistent with  $\psi' \rightarrow \eta \psi$  (m<sup>2</sup><sub> $\gamma\gamma$ </sub> > 0.27) have been omitted. Again there are two solutions for each event. The data do not resemble the phase space distribution indicated by a dashed line, but form two distinct peaks. The solid line indicates the distribution we would expect from background plus a single narrow state at either 3500 or 3270 MeV/c<sup>2</sup>. It matches the data quite well. The background, which is indicated separately by a dotted line, was calculated from the data in which three or four photons are detected. It is not being

underestimated since there are fewer events where the background peaks than predicted by the Monte Carlo simulation.

Thus both methods yield data which are consistent with a single state with mass of either  $3500 \pm 10$  or  $3270 \pm 10$  MeV/c<sup>2</sup>.

The two methods are complementary. The first method has limited statistics but good mass resolution (about 7 MeV/c<sup>2</sup> rms). With additional data it should be able to resolve the twofold mass ambiguity by observing the Doppler broadening. It will also be the method to use to search for other states which decay to  $\gamma\psi$ . The strength of the second method is that it has higher statistics. Thus it will be used to try to determine the spin of the state from the angular correlations.

#### D. The $\chi$ Spectroscopy

In the  $4\pi$  spectrum we have observed a narrow state at 3410 MeV/c<sup>2</sup> and either a broad state or two or more narrow states centered around 3530 MeV/c<sup>2</sup>. In addition, we have observed a narrow state which decays to  $\gamma\psi$  at either 3500 or 3270 MeV/c. We will use the name suggested by the DASP Collaboration, <sup>10</sup> P<sub>c</sub>, to distinguish this latter state from the ones which have been identified by their hadronic decays. Fig. 11 shows five possible solutions for the  $\chi$  mass spectrum, all of which are consistent with the present data. The multiplicity of solutions arises first from the ambiguity in the P<sub>c</sub> mass, second from whether the  $\chi$  (3530) is split, and third from whether the



Fig. 10--The reconstructed mass of intermediate states in  $\psi' \rightarrow \psi \gamma \gamma$  for events in which both photons are detected in shower counters. Both solutions are plotted. The dashed curve represents phase space and the solid curve represents the expected distribution from a narrow state at either 3.50 or 3.27 GeV/c<sup>2</sup>. Expected backgrounds from  $\psi' \rightarrow \pi^0 \pi^0 \psi$  are included in the solid curve and also shown separately by the dotted curve.

 $P_c$  is identical to one of the splittings of the  $\chi$  (3530). All of the solutions have at least three  $\chi$  states. The only way to construct a solution with only two  $\chi$  states is to identify the  $P_c$  with a single broad state at 3530 MeV/c<sup>2</sup>. But this is unacceptable for two reasons: one state is broad and the other is narrow, and the difference in their central masses is beyond the experimental error.

#### E. Branching Fractions

Table I gives the branching fractions for the combined decay  $\psi' \rightarrow \gamma \chi$ ,  $\chi \rightarrow f$ , for each  $\chi$  state and each final state f. The question marks in the table arise from the ambiguities illustrated in Fig. 11. The upper limit on  $\chi(3410) \rightarrow \gamma \psi$  is derived from the data in Fig. 10. The branching fraction for  $\psi' \rightarrow \gamma P_{c} \rightarrow \gamma \gamma \psi$  is about 4% and the branching fractions for  $\psi' \rightarrow \gamma \chi$  are around  $10^{-3}$  for each identified hadronic decay mode. We have not measured the total branching fractions for  $\psi' \rightarrow \gamma \chi$ , but we can hazard a rough guess. Based on our experience with  $\psi$  decays, we would guess that  $\chi$  branching fractions into particular hadronic modes would be of the order of 5% or less. This would correspond to  $\psi' \rightarrow \gamma \chi$  branching fractions of 2 to 5% for each  $\chi$  state.



Fig. 11--Possible solutions for the number and masses of  $\chi$  states. P is used as the name of the state which has been observed to decay to  $\gamma\psi$ .

## TABLE I

Branching fractions in percent for the combined decay  $\psi' \rightarrow \gamma \chi$ ,  $\chi \rightarrow f$ . The question marks arise from the ambiguities illustrated in Fig. 11. The "~" indicates that the branching fraction has been determined only to a factor of 2 or 3. Upper limits are given at the 90% confidence level.

| mode f/state                        | <b>χ (</b> 3410) | χ (3530)        | P <sub>c</sub> |
|-------------------------------------|------------------|-----------------|----------------|
| $4\pi^{\pm}$                        | $0.14 \pm 0.07$  | $0.20 \pm 0.10$ | ?              |
| $6\pi^{\pm}$                        | ~ 0.1            | ~ 0.2           | ?              |
| $\pi^+\pi^-K^+K^-$                  | ~ 0.07           | ~ 0.05          | ?              |
| sum of $\pi^+\pi^-$<br>and $K^+K^-$ | $0.13 \pm 0.05$  | < 0.027         | < 0.027        |
| γψ                                  | < 0.5            | ?               | $3.6 \pm 0.7$  |

What do we have left to learn? Almost everything? The number of  $\chi$  states, their masses, their decay modes, and their spins and parities. These studies will be an important part of our SPEAR program this fall.

#### IV. ANOMALOUS LEPTON PRODUCTION

## A. Existence of Anomalous Events

We now come to a potentially even more interesting subject – anomalous lepton production.  $^{11}\,$ 

We have observed events which contain a muon and an electron and no other detected charged or neutral particle. And we know of no conventional process which can account for these events.

Events of this type were first observed in SPEAR I data at  $E_{c.m.} = 4.8 \text{ GeV}$ . Twenty-four events were observed with an estimated background of five events from misidentifications, leaving a signal of 19 events. I won't have time in this talk to discuss the background calculations for these events. However, there is a detailed discussion in Martin Perl's lectures at the McGill Summer School<sup>12</sup> which I recommend you read.

We have now looked for these events at other energies in the SPEAR I data (up to July 1974) and in the more extensive SPEAR II data (from January 1975). Doing a similar analysis, we find now a total of 86 e- $\mu$  events with an estimated background of 22 events, leaving a signal of 64 events. The odds against seeing 86 events when you expect 22 are astronomical, so the only valid question concerning these events is whether the background has been calculated correctly.

For this reason it is worthwhile to look at a subset of the data in which the backgrounds due to misidentifications will be smaller. This is possible because for SPEAR II we built an additional muon identifier (called the muon tower) on top of the magnetic detector. The SPEAR I and II configurations are illustrated in Fig. 12. We will refer to muons being identified at three levels. Level 1 corresponds to particles which penetrate the shower counters, the coil, and the flux return, the equivalent of about 30 cm of iron. All of the analysis which I've mentioned so far has been done at level 1,





ignoring the higher levels. Level 2 or 3 corresponds to particles which penetrate level 1 and one or two barite-loaded concrete absorbers, each of which corresponds to about 30 cm of iron.

We take all SPEAR II data with  $E_{c.m.}$  ranging from 3.9 to 7.8 GeV and require that

- a. two and only two oppositely charged tracks be visible in the detector, and no photons be visible in the shower counters,
- b. both momenta be over 650 MeV/c,
- c. one particle be a muon candidate at level 2 or 3 and the other particle be a muon candidate at level 1,
- d. the two particles be acoplanar by at least  $20^{\circ}$ ,
- e. the square of the missing mass recoiling against the two particles be greater than 1.5  $(\text{GeV}/\text{c}^2)^2$ .

A muon candidate is defined as a particle which has sufficient momentum and is heading in the right direction to be seen in a muon spark chamber if it were a muon. The last two requirements are included to reduce the number of radiative  $e^+e^-$  and  $\mu^+\mu^-$  pairs.

A total of 58 events satisfied these criteria. Ten events were identified as  $e^+e^-$ , eleven events were identified as  $\mu^+\mu^-$ , and the other 37 events were identified as other combinations of e's,  $\mu$ 's, and hadrons, including five events which appear to be an  $e\mu$  pair with the  $\mu$  identified at level 2 or 3.

We now want to calculate the number of  $e\mu$  events which would be expected to occur from misidentifications of known processes. We determine the probability that an electron is identified as a muon or vice versa by studying collinear lepton pairs. The probability that an electron gives a small pulse height in a shower counter and also gives a signal at levels 1 and 2 in the muon tower is less than  $2 \times 10^{-3}$ . And the probability that a muon both gives a large pulse height in the shower counter and fails to fire a muon chamber is less than  $3 \times 10^{-3}$ . The probabilities for a hadron to be identified as a lepton can be determined from data in which three or more charged particles are detected. There is approximately a 20% probability for a hadron to be misidentified as an electron and about a 7% probability for a hadron to be misidentified as a muon at level 2.

### TABLE II

Calculation of expected backgrounds from misidentifications to the five  $e\mu$  events observed in the muon tower.

| mode     | events | misidentification<br>probability | expected<br>background |
|----------|--------|----------------------------------|------------------------|
| ee       | 10     | 0.002                            | 0.02                   |
| $\mu\mu$ | 11     | 0.003                            | 0.03                   |
| hh       | 37     | $0.2 \times 0.07$                | 0.52                   |
| total    | 58     |                                  | 0.57                   |

We take the number of ee and  $\mu\mu$  events detected as the number of true ee and  $\mu\mu$  events and make the conservative assumption that the other 37 events come from multihadronic events in which all but two charged hadrons were undetected. The arithmetic is summarized in Table II. The expected number of background events in the five  $e\mu$  events is 0.57. Thus the statistical probability of backgrounds accounting for all five events is only about  $3 \times 10^{-4}$ . It is even possible to eliminate from the calculation the 20% probability of a hadron being misidentified as an electron. Instead of considering all 37 hadron-hadron events, we can calculate the background from events in which the particle which is not heading toward the muon tower has been identified as an electron. There are only twelve such events including the five  $e\mu$  events. Multiplying by 0.07 (the probability that a hadron is misidentified as a muon at level 2) we obtain 0.84 background events if we include the  $e\mu$ events in the sample, or 0.49 background events if we exclude them.

Figure 13 shows a computer reconstruction of an  $e\mu$  event. The event occurred at  $E_{c.m.} = 6.6$ GeV. The positively charged particle heading into the muon tower is clearly identified as a muon. It has a momentum of 1.6 GeV/c. The other particle has a negative charge and a momentum of 1.0 GeV/c and is identified as an electron by the large pulse height (113 units) in the shower counter. On the average, a 1.0 GeV electron typically gives a pulse height of 100 in a shower counter.

# B. <u>Hypotheses for the Origin of the Anomalous</u> Events

These events do not appear to be caused by any conventional process such as radiative electron or muon pair production, multihadron production, or two-photon processes.<sup>13</sup> We can, however, imagine several hypothetical new processes which could account for these events. One possibility is a two-body decay of a charged (and presumably vector) meson,





Fig. 13--Computer reconstruction of an  $e\mu$  event. The numbers indicate shower counter pulse heights.

(2)

A second possibility is that these events result from the leptonic decays of a heavy sequential lepton,



And a third possibility is that these events arise from semileptonic decays of charmed mesons, for example



or



However, semileptonic decays such as these cannot account for all of the anomalous  $e\mu$  events since there would also have to be a large number of events with two leptons plus hadrons, and such events are not observed. More work is needed to set limits on the possible contribution of semileptonic decays to the anomalous  $e\mu$  signal.

#### C. Properties of the Anomalous Events

We have not yet studied the properties of these  $e\mu$  events in sufficient detail to conclusively determine their origin. But we do have some important indications. Fig. 14 shows the observed cross sections for anomalous  $e\mu$  production in the magnetic detector as a function of  $E_{c.m.}$ . These cross sections have not been corrected for geometrical acceptance, or for momentum and angle cuts, since these corrections depend in detail on the origin of the events. The true cross sections may be factors of 2 to 10 higher.

Due to the large statistical errors, the cross sections themselves do not distinguish between the production of lepton and meson pairs. The data can be fit adequately by either cross sections which are proportional to  $\beta/s$ , which would be expected for lepton pairs, or  $\beta^{3}/s^{3}$ , which would be typical for meson pairs.

The momentum spectrum offers more information. We construct a variable  $\rho$ ,

-12-



Fig. 14--The observed cross section for observing an e and a  $\mu$  and no other particles as a function of  $E_{c.m.}$ . These data have not been corrected for momentum and angle cuts and for the geometry of the detector.

$$p = \frac{p - 0.65 \text{ GeV/c}}{p_{max} - 0.65 \text{ GeV/c}}$$

so that all of the data can be displayed from 0 to 1 independent of  $E_{c.m.}$ . This is shown in Fig. 15 along with several theoretical curves. The solid line represents a heavy lepton decay with a V-A interaction and is a good fit to the data with a  $\chi^2$  per degree of freedom of about one. The dotted curve represents an isotropic two-body decay. It is a poor fit with a  $\chi^2$  per degree of freedom of about four. Furthermore, it does not give a particularly good description of the distribution of collinearity angles. If the experimental angular distribution is imposed, then the two-body decay is an even worse fit to the data, as indicated by the dashed line. From these data we can conclude that two-body decays cannot account for all of the anomalous eµ events, although such decays could be present at some level.

Finally, Fig. 16 shows the distribution of angles between the e and  $\mu$  direction for three  $E_{c.m.}$  ranges. The three-body decays again fit the data better than two-body decays. However, the striking feature of these graphs

(3b)



Fig. 15--The distribution in  $\rho = (p-0.65)/(p_{max}-0.65)$  for all  $E_{c.m.}$ . The solid curve represents the expected distribution for the decay of heavy leptons of mass 1.8 GeV/c<sup>2</sup>. The dotted curve represents two-body isotropic decays of a boson of mass 1.9 GeV/c<sup>2</sup>. The dashed curve is the same as the dotted curve except that the distribution in collinearity angle has been set to fit the data.



Fig. 16--The distribution in the cosine of the collinearity angle for three different  $E_{c.m.}$  intervals. The curves are explained in the caption to Fig. 15.

is the energy dependence of the distributions. At low  $E_{c.m}$  the distribution tends to be much more isotropic than at high  $E_{c.m.}$ . This is, of course, characteristic of the production of a pair of particles of fixed mass. As the energy increases, the decay products are swept more and more back to back by the Lorentz transformation. It is significant that the backgrounds from multihadronic production do not exhibit this behavior.

# D. Current Status of Anomalous Events

We can summarize the current status of our knowledge of these events as follows:

- a: Anomalous eµ events exist.
- b. Semileptonic decays cannot account for all the anomalous events.
- c. Two-body decays cannot account for all the anomalous events.
- d. We know of nothing which is inconsistent with the hypothesis that the anomalous events come from the production and decay of sequential heavy leptons.

There are, however, several important questions still to be answered:

- a. Is the heavy lepton hypothesis completely consistent with the data? We have not yet explored all of the consequences of this hypothesis.
- b. Is any other hypothesis consistent with the data?
- c. Is more than one thing going on?

# V. INCLUSIVE MUON PRODUCTION

The muon tower provides rejection against hadrons at the few percent level, so we can try to use it to study "direct" muon production in multiparticle events. There will be two major sources of backgrounds: pion and kaon decay and hadron penetration. The major difficulty in calculating decays is knowing how the complicated magnetic detector tracking and vertex finding computer programs react to a particle which decays in the region of the spark chambers. This has not yet been simulated. Pion and kaon penetration through the muon tower has been estimated by Monte Carlo cascade calculations.<sup>14</sup> We also have an experimental measure of backgrounds from the comparison of the apparent muon to hadron ratio at levels 2 and 3 of the muon tower for particles of the same momentum. The difference between these two ratios must be caused entirely by backgrounds.

The raw  $\mu$  to all charged particle ratios for events in which three or more charged particles are detected are shown in Fig. 17. The data come from the energy range  $6.2 \le E_{c.m.} \le 7.8$  GeV with the average  $E_{c.m.} = 7.0$  GeV. The pos-sible range of backgrounds is indicated by the shaded region.<sup>15</sup> There are suggestions of an inclusive direct muon signal, but at the present level of statistics and background calculations they are certainly not conclusive. We can, however, set upper limits on inclusive muon production and this is done in Table III. The limit at the highest momentum is the most significant, corresponding to just about what one would expect from the decay of a heavy lepton.

#### TABLE III

90% confidence level upper limits for inclusive  $\mu$  production at  $\langle E_{c.m.} \rangle = 7$  GeV for events with more than 2 produced charged particles.

| Momentum range<br>(GeV/c) | Upper limit (pb) |  |
|---------------------------|------------------|--|
| 0.9 to 1.2                | <170             |  |
| 1.2 to 1.5                | < 80             |  |
| 1.5 to 2.0                | < 74             |  |
| > 2.0                     | < 44             |  |



Fig. 17--The raw  $\mu$ /charged particle ratio as a function of momentum at levels 2 and 3 of the muon tower for events with three or more detected charged particles. The shaded region represents the possible background levels from hadron penetration and decay.

#### VI. CONCLUSION

Two years ago at the Bonn conference our knowledge of  $e^+e^-$  annihilation above 3 GeV was limited to 196 very significant events from the CEA.<sup>16</sup> I do not think that anyone at that conference – even Bjorken, who gave an incisive and farsighted talk<sup>17</sup> – could imagine what would be uncovered between then and now. At the start of this talk I said that we would attempt to tie together the loose ends. But some are still dangling: additional structure in the total cross section, deviations from scaling at 4 GeV, the dynamics of  $\psi$  decays, the unaccounted for  $\psi^{\circ}$  decays, the non-observation of charmed particles, the  $\chi$  spectroscopy, and the origin of the anomalous e $\mu$  events. We look forward to the next two years.

## REFERENCES AND FOOTNOTES

- 1. R. F. Schwitters, invited paper presented at this Symposium.
- 2. G. S. Abrams, invited paper presented at this Symposium.
- 3. A. M. Boyarski et al., Phys. Rev. Letters 35, 196 (1975).
- 4. C. G. Callan et al., Phys. Rev. Letters <u>34</u>, 52 (1975); T. Appelquist et al., Phys. Rev. Letters <u>34</u>, 365 (1975); E. Eichten et al., Phys. Rev. Letters <u>34</u>, 369 (1975); B. J. Harrington et al., Phys. Rev. Letters <u>34</u>, 706 (1975). Also see H. Harari, invited paper presented at this Symposium.
- 5. G. J. Feldman, B. Jean-Marie, B. Sadoulet, F. Vannucci, et al., Phys. Rev. Letters 35, 821 (1975).
- 6. Two pseudoscalars have  $J^{PC} = 0^{++}$ ,  $1^{--}$ ,  $2^{++}$ ,  $3^{--}$ ... for L = 0, 1, 2, 3.... But the  $\chi$  states must have C = +1 since they are produced in the radiative decay of

the  $\psi'$ , which has C = -1. Therefore the allowed J<sup>PC</sup> values are 0<sup>++</sup>, 2<sup>++</sup>, 4<sup>++</sup>, etc.

- 7. The 90% confidence level upper limits on the branching fractions for  $\psi' \rightarrow \pi^+ \pi^$ and  $\psi' \rightarrow K^+ K^-$  are  $1.9 \times 10^{-4}$  and  $2.3 \times 10^{-4}$ , respectively.
- 8. W. Tanenbaum, J. S. Whitaker, et al., SLAC Report No. SLAC-PUB-1644 (1975), submitted to Phys. Rev. Letters.
- 9. The background from  $\psi' \to \pi^0 \pi^0 \psi$  is small because  $\gamma$ 's from  $\pi^0$  decay tend to have too low an energy for us to detect the converted  $e^+e^-$  pair.
- 10. W. Braunschweig et al., Phys. Letters 57B, 407 (1975).
- 11. M. L. Perl et al., SLAC Report No. SLAC-PUB-1626 (1975), submitted to Phys. Rev. Letters.
- 12. M. L. Perl, SLAC Report No. SLAC-PUB-1592 (1975), to be published in Proc. Canadian Institute of Particle Physics Int. Summer School, McGill University, Montreal, Canada, June 16-21, 1975.
- 13. The two-photon process  $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$  could produce  $e\mu$  events without any particles being misidentified if one of the e's and one of the  $\mu$ 's escaped detection in the detector. However, we can experimentally rule out the possibility of this process contributing a major fraction of the anomalous events. The joint probability of an e and a  $\mu$  being detected should be independent of the signs of their charges. Thus, we would expect an equal number of events in which the particles had the same charge and in which the particles had the opposite charge. But we observe 86 events in which the particles have opposite charges and only three events in which they have the same charges. These three events are compatible with what we expect from backgrounds.
- 14. We are indebted to T. A. Gabriel of Oak Ridge National Laboratory for these calculations.
- 15. To calculate backgrounds we use the  $\pi/K$  ratio of 0.27 ± 0.08 determined by the MP<sup>2</sup> experiment at  $E_{c.m.} = 4.8$  GeV for momenta above 1.1 GeV/c. [T. L. Atwood et al., Phys. Rev. Letters 35, 704 (1975).]
- 16. K. Strauch, <u>Proc. VI Int. Symposium on Electron and Photon Interactions at High</u> <u>Energies</u>, <u>Bonn</u>, <u>1973</u> (North-Holland Publishing Company, Amsterdam, 1974), p. 1.
- 17. J. D. Bjorken, ibid., p. 25.

#### DISCUSSION

Note: Much of the discussion of  $e^+e^-$  experimental results from SPEAR and DORIS occurred after all the papers had been presented. See the separate section of these Proceedings called "SPEAR-DORIS DISCUSSION" for a report of these discussions.