COO-1545-209 - "Lectures at McGill University, Montreal,
Quebec" - N. M. Reay

In the next series of talks I hope to motivate for you the search for charm and to discuss all the places where it may have been seen, and many of the places where it has not. Finally, I would like to indicate how many of the efforts could be extended in the future.) Since Professor Goldhaber talked on Monday of the recent SLAC resonance in the $K\pi$ and $K\pi\pi\pi$ states, you have had your dessert first, but perhaps there is enough substance in the remainder of the meal to satisfy your desire to bring the field as a whole into proper context.

In these exciting times, it almost seems as if physics is conducted within a shock wave. Near the front it is all sound and fury, intelligible perhaps to a few initiates. But stray as much as a year into the past and one is becalmed in the archives of ancient history. Please accept my apologies, for I plan to dust off those ancient Physical Review Letters of a year and a half ago, and start at the beginning.

Well, perhaps not quite at the beginning, for the charm search was first led by a small band of brave theorists. But experimentalists are a recalcitrant bunch, and despite the obvious aesthetic beauty of a renormalizable theory of weak interactions, most of us raised our heads from the sand only when confronted with the discovery of the $J-\psi$ particle at BNL and SLAC.

All of you are familiar with the beautiful semilog plot of this resonance shown in Figure 1.

Shortly thereafter, a number of resonances (both narrow and broad) were discovered at SLAC and DESY. In fact, as shown in Figure 2, the total of reasonably established new resonances now stands at 8. Immediately, everyone asked whether these particles were leptonic or hadronic, and if hadronic why were they so narrow? Quite soon, a substantial amount of evidence accumulated which indicated they were in fact hadronic.

MASTER

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First, some of the new resonances had normal wide hadronic widths. Second, the direct hadronic decays of the $\psi(3100)$ seemed to conserve isospin and G-parity, and this only occurs in strong interaction processes. Finally (and most convincing to me), photoproduction experiments indicated the ψP total cross-section to be comparable to that for other hadrons. Assuming vector dominance, one constructs the following diagram for photoproduction:

Adding a theoretical $\psi\gamma$ electromagnetic coupling (and assuming ψP scattering to be purely imaginary) it is possible to extrapolate to 0° , using the optical theorem to get the ψP total cross-section. Admittedly there are many assumptions, but it is hard to quibble with the derived cross-section of 1 to 3 millibarns.

Well, if these were hadrons, why were they so narrow? Perhaps they contained an unlocked quantum number. The evidence against this assumption accumulated rapidly. If indeed these particles had charm unequal to zero then direct hadronic decay would not be expected. Further, since the decay $\psi'(3700) \rightarrow \psi(3100) + 2\pi$ is allowed, unlocked charm would explain the narrowness of the ψ but not the ψ' . Finally, if the ψ possessed net charm, the higher mass resonances should decay copiously into the ψ , and this is just not the case.

But some new quantum number had to be floating around, so the Okubo-Zweig-Iizuka (OZI) rule was brought into play:

The diagram for e^+e^- production of ψ and subsequent decay into 3π was postulated to be as follows:

It is a fact that the few reactions characterized by a disconnected graph are suppressed; such an explanation accounts for the narrowness of the ϕ meson. However, as we shall see there are difficulties with this rule in certain reactions, and at best it is just good phenomenology.

Fortunately, the original band of theorists had already given the concept of charm much more respectable theoretical credentials. In the old V - A theory of weak interactions, there were two doublets of leptons,

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$$

but only a doublet and singlet of hadronic quarks

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} s' \end{pmatrix}$$

where $d' = d \cos\theta_c + s \sin\theta_c$

$$s' = -d \sin\theta_c + s \cos\theta_c$$

u and d are non-strange, and s is the strange quark. The lack of resemblance between leptons and quarks was indeed unaesthetic, but had further rather nasty implications. It was possible to have a $|\Delta S| = 1$ neutral weak isovector current $d' (1 + \gamma_5) \gamma_\mu d'$ with strength $\sim G \cos\phi_c \sin\phi_c$. This would give far too large a rate for the decay $K_L^0 \rightarrow 2\mu$, and a $K_L^0 - K_S^0$ mass difference of several electron volts.

One way out of these difficulties is to add an extra quark, a "charmed" quark:

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix}$$

Now the V - A neutral current is $d'\bar{d}' + s'\bar{s}' = d\bar{d} + s\bar{s}$, and is diagonal in quarks, hence conserving strangeness and charm. I.E. the $|\Delta S| = 1$ neutral currents vanish identically. Theorists tell me that the renormalization of weak

interactions demands strong interactions be invariant under the transformations $u \leftrightarrow d'$ and $c \leftrightarrow s'$. $SU(4)$ symmetry is thereby forced on the strong interactions, a symmetry badly broken by the lack of degeneracy of the masses. Unfortunately, this beautiful picture cannot explain all existing data, so in a later lecture we will touch briefly upon additional leptons, quarks, color, flavor and the like. However, at this time I would like to concentrate on the implications of the primitive (but perhaps more aesthetic) form of the theory, and to discuss some of the early experiments generated thereby.

Figure 3 shows the $SU(4)$ multiplets as presented in the classic phenomenological paper of Gaillard, Lee and Rosner.² Note that the old $SU(3)$ multiplets are preserved within horizontal planes in this figure, and that there are additional contributions with net charm equal to zero and new planes with charm equal to ± 1 . These latter states are the ones for which so many of us have searched in the past $1\frac{1}{2}$ years.

So how does one search for charm?

First, one considers the original qualitative argument arising from the form of the hadronic charged current:

$$J_{\mu}^C = \bar{u} (1 + \gamma_5) \gamma_{\mu} d' + \bar{c} (1 + \gamma_5) \gamma_{\mu} s'$$

Consider the $c \rightarrow s'$ transition component

$$\bar{c} (1 + \gamma_5) \gamma_{\mu} (-d \sin \theta_c + s \cos \theta_c)$$

Thus, the intensity of the $c \rightarrow s$ transition is weighted by $\cos^2 \theta_c \sim 1$, and the intensity of the $c \rightarrow d$ transition is suppressed by the factor $\sin^2 \theta_c \sim 0.05$. This is not an overwhelming argument, but it was quite sufficient to send myriad experimentalists (myself included) scurrying to search for high mass resonances such as $k\rho$, $k\pi$, $k(n\pi)$, and in fact any accessible strange final state.

Also, the lightest $C \neq 0$ particle would be stable under strong and electromagnetic interactions, and would be forced to decay weakly. Finding an unexpected final state lepton could then be an important factor in this search.

Where were these resonances expected? Using a lowest order quadratic form for SU(4) symmetry breaking, one derives

$$\begin{aligned} M_{D^*}^2 - M_\rho^2 &= M_{F^*}^2 - M_{K^*}^2 \\ &= \frac{1}{2} (M_\psi^2 - m_\rho^2) \end{aligned}$$

The mass of the D^* so derived is 2.24 GeV. More sophisticated variants of the theory suggested lightest masses as low as 1.6 GeV, which is particularly difficult for experiments using hadronic beams.³

The first wave of experiments in the Charm Search Derby showed unbridled optimism; old bubble chamber film was scanned for high mass and/or long lived states. A typical initial counter experiment was the Rochester-Rutgers collaboration,⁴ which used a single arm spectrometer viewing the Fermilab internal target, in an attempt to observe a jump in kaon production yield at charm threshold. These experiments which scanned at the microbarn level, were at least two orders of magnitude away from the sensitivity we now believe is needed in this business. There is an exception within this crude early wave. One of the first (if not the first) counter experiments to generate charm hadronically was also technologically the most solid. This experiment, shown in Figure 4, was the MIT-BNL experiment discussed Monday by Professor Ting.⁵ The concept is simple and beautiful. If a heavy particle produced near rest in the cms $\left[(x = p_{11}/p_{11\text{max}}) \sim 0 \right]$, decays into two much lighter particles, they will frequently proceed from the target at wide angles to the beam line. This permits the apparatus to reside wholly outside the beam and in a region where the single particle production yields are low. The particle momenta were measured by high rate magnetic spectrometers, and the particle type selected by a series of threshold Cerenkov counters. The results (partially shown in Figure 5) are disappointingly smooth. The table for KP , $K\pi$, $\pi\pi$, πP , $K\bar{P}$ and $P\bar{P}$ two body final states

is shown in Figure 6. Just for scale, the $\psi \rightarrow 2\mu$ cross-section times branching ratio is 0.1 nanobarn at 28 GeV.

Well, it is a fact that the production cross-section for the ψ rises by a factor of 100 in going from BNL to Fermilab energies, so Fermilab physicists felt that perhaps the yield for charm production with its higher mass threshold might increase even more. Let me discuss two typical second wave Fermilab counter experiments using hadronic beams. The first was a Michigan-Purdue-Fermilab collaboration⁶ which constructed a two arm spectrometer with the same modus operandi as the MIT-BNL effort. The layout is shown in Figure 7. An all drift chamber system permitted high data collection rates, and threshold Cerenkov vounters were used to tag the particle types. The system used up to 10^8 protons/pulse, and had a FWHM resolution of 15 MeV for the $\psi(3100)$, (as shown). Millions of events were collected for various two body states with masses between 1.7 and 4 GeV. Figure 8 exhibits the smooth mass spectra and the ratio limits for a four-standard deviation bound on narrow resonance production versus $\psi \rightarrow 2\mu$ production. They now have about three times the data and $\sqrt{3}$ times smaller ratios, but the curves are still smooth. Note the ratios are quite comparable to those of the technologically superior BNL experiment. This says something! It says we are not limited by statistics or technology, but rather by the size of the real two body non-resonant background.

However, the above experiments looked for production only at $x = 0$, and perhaps charmed meson could be produced diffractively. An Ohio State-Michigan State-Carleton collaboration (of which I was a member)⁷ addressed itself to the range $0.1 \leq x \leq 1.0$. The layout (shown in Figure 9) resembles a kaon spectrometer. If a particle decays near 90° in its cms into two light particles, each of the decay particles will have a $P_\perp$ of roughly $M/2$ in the lab. If the

magnet is set to give a sideward impulse of $M/2$, the in-bending decay particles will exit with parallel trajectories from the magnet, independent of the momentum of the original particle.

Events resulting from interaction of a 250 GeV neutron beam with a beryllium target resulted in a trigger if two parallel tracks exited the magnet on opposite sides of the beam line, and the system of two split threshold Cerenkov counters gave a selected topology of coincidences and anti-coincidences. The problems were simple: The mean multiplicity from the beryllium target was 8, and most of the events contained a kaon. Figure 10 shows the data. The sharp decrease at lighter masses was due to our apparatus, the high mass tail you may attribute to mother nature. Note that the legitimate non-resonant background rises close to 1 microbarn within a 20 MeV bin (our FWHM resolution) at 2.0 GeV. This gave rise to the ratio to $\psi \rightarrow 2\mu$ curves shown for a 4 standard deviation enhancement shown in Figure 11. Notice how rapidly the ratio rises at low masses. We observed a 5 standard deviation enhancement in the $K^-\pi^+$ mass spectrum at 2.3 GeV, and decided to take another look. The resolution was improved 30% and statistics increased by a factor of 4. Analysis is very preliminary, but a mass spectrum based on about 1/3 of the new data as shown in Figure 12 seems disappointingly smooth. It is now evident that brute force searches using hadronic beams are infeasible. Instead, one must incorporate additional theoretical prejudice into the trigger. Let us postpone the discussion of these new triggers until the final lecture, which is concerned with great expectations.

Let's now turn to the discussion of weak and electromagnetic production of charm, wherein positive signals have been observed.

Within the realm of high energy neutrino interactions, three interesting effects have been observed, two of which fit nicely into the picture of charm.

As mentioned by Perkins, there are now 4 events at CERN (Gargamelle),

and 16 Wisconsin-CERN-LBL-Hawaii (WCLH) Fermilab 15 foot bubble chamber events⁸ which have topology $\nu + N \rightarrow N + e^+ + \mu^- + nk^0$. In addition, the experiment of Columbia-BNL (Baltay)²² currently has 45 $\mu^- e^+$ events and a handful of $\mu^- e^-$ events, based on 1/5 of the final data sample. They are willing to state the background in the $\mu^- e^+$ sample is less than 10%, but have not progressed far enough in their analysis to quote backgrounds for the $\mu^- e^-$ sample or to state kaon multiplicity per event. However, the analysis for the 16 WCLH events is now more complete. The surprising fact is that while the events were selected solely on the basis of having a μ^- and an e^+ in the final state, Dave Cline has said the average number of K^0 mesons per event is 2.3 ± 0.7 . Of course the actual "seen" kaons is less than one per event, as in the main there is a factor of 3 correction for the ratio between $k \rightarrow$ anything and the visible reaction $k_S^0 \rightarrow \pi^+ \pi^-$. Any conclusion based on 14 events is somewhat premature, yet some members of this group have tentatively attempted to infer the total kaon yield per event as being as high as 4. However, Dave says this inference is not solid and that the average kaon yield per event is consistent with two. (Note added in press: The Columbia results have been reported at the February meeting of the APS, the $\pi^+ e^-$ yield is about 0.6% and there is a strong excess of kaons in these events as opposed to ordinary neutrino interactions. There is even the strong possibility of finding peaks in the non-leptonic decay mass spectra.)⁹ Two kaons per event may easily be explained within the framework of a charm theory using the following diagram:

$$\text{Or, } \nu + s \rightarrow \mu^- + c + X$$

$$(\bar{s}) \quad (\bar{s})$$

This reaction is suppressed due to the lack of $s \bar{s}$ quarks in a non-strange nucleon, but is enhanced because it is Cabbibo favored:

Remember the doublet

$$\begin{pmatrix} c \\ s' \end{pmatrix} \equiv \begin{pmatrix} c \\ -d \sin \theta_c + s \cos \theta_c \end{pmatrix}$$

The transition $d \rightarrow c$ is weighted by $\sin^2 \theta_c$, whereas the transition $s \rightarrow c$ is weighted by $\cos^2 \theta_c$, and may in fact be dominant. If it is, a leptonic decay of the charm quark gives rise two one kaon, and the $\bar{s}$ quark to the other. One is of course unable to see a peak in the effective mass due to the missing neutrino in the final state. We shall have more to say about the possibility of observing $K^0 \pi^0$ events in the last lecture.

A second exciting occurrence is the solid establishment of a dimuon signal both by the Caltech-Fermilab and by the Harvard-Pennsylvania-Wisconsin-Fermilab (HPWF) counter group collaborations at Fermilab. The HPWF apparatus is shown in Figure 13. Liquid scintillator tanks and steel slabs convert the neutrinos, and the muon is tagged by penetration of many absorption lengths of material. The momentum of the muon is measured to roughly 40% FWHM by a series of interspersed magnetized iron toroids and optical spark chambers, hadron energy is measured to $\frac{\delta E}{E} \sim \frac{2.5}{E}$ FWHM, where E is in GeV. It is possible for dimuon events to come from a normal charged current interaction with subsequent muonic decay of a pion or kaon. However, if the absorption length of the target is decreased, events from this source should be suppressed. As shown in Figure 14, such a test was made and indicates no

background, though a background of 30% would be compatible with the small statistics of the test. Experiments planned for operation early in 1977 both at the SPS at CERN and at Fermilab are shooting for 50 dimuons or more per day, and should give much information on the mode of production of dimuons.

Assuming the dimuon signal is solid, from where does it come? Both production of heavy leptons and a model based on charm have been conjectured. Suppose for the moment we too conjecture a heavy lepton, as below:

Since the $\mu^-\mu^+$ pair would then come from decay of the same lepton, theorists have bounded the ratio of μ^- to μ^+ momenta:

$$0.48 < \frac{p_{\mu^-}}{p_{\mu^+}} < 2.1$$

Experimentally the distribution of 61 dimuon momenta is shown in Figure 15. Note that the μ^- momenta show a large spread, while the μ^+ momenta are generally constrained to be small. In real life this ratio is determined to be 3.7 ± 0.65 . However, there is a caveat. Figure 16 shows a projection of the $\mu^-\mu^+$ mass spectrum. Note that there is a hump at low momenta, followed by a tail at larger momenta. I have taken the liberty of drawing solid and dashed curves which have no meaning whatsoever. These curves indicate to me that most of the high mass events (which are in the main highly asymmetric in momenta) could be faked with a 30% background from π decay. Also, events from the calorimeter with a higher contamination of pion decays might be expected to show a greater asymmetry in the muon momenta than the steel data. I have taken the liberty of analyzing some of their events and have found

this to be the case. The case against heavy leptons is then highly convincing, but not yet air-tight, particularly in view of Perl's results at SLAC. On the other hand, without any caveats, the data are consistent with the following charm model:

On the average, the μ^- absorbs roughly 1/2 the neutrino energy, while the μ^+ comes from a charmed meson which had to share the energy of the excited nucleon with a lot of other hadrons, and hence is not very energetic. Though one should never trust too much the relative normalization of different neutrino experiments, Figure 17 is indicative of a threshold for dimuon production at roughly 4 GeV above the nucleon mass in the cm system.¹⁰

Finally, devil's advocates point out that though the $\mu^- e^+ k$ and dimuon events are both consistent with the same charm model, on purely experimental grounds these two phenomena may have nothing to do one with another. To be visible in a bubble chamber, the e^+ must be relatively low energy, whereas in the case of dimuons, only fair energetic muons proceed at sufficiently small angles to make it through the entire apparatus. The two types of events in general do not come from the same kinematic range.

Both Fermilab neutrino counter groups now have convincing evidence for yet a third type of peculiarity in neutrino interactions, a high y contribution to anti-neutrino events present for high incident neutrino momenta but not for low incident momenta. To discuss this result we must first define variables:

Consider $\bar{\nu} N \rightarrow \mu^+ + \text{Anything}$:

The experimentally measured variables are

$$E_H \equiv \nu \quad (\text{Definition})$$

$$E_\nu = \nu + E_\mu$$

$$Q^2 = 2 E_\nu E_\mu (1 - \cos\theta_\mu)$$

In terms of scaling variables;

$$x = \frac{Q^2}{2m\nu}$$

$$y = \frac{\nu}{E_\nu}$$

Almost all experiments have a bias at large y , in that this kinematic region is populated with lower energy muons which depart at wide angles to the beam line and may escape undetected. In terms of these variables, the differential cross-sections are

$$\frac{d^2\sigma^{\nu N}}{dx dy} = \frac{G^2 m E_\nu}{\pi} \left[(1-y) F_2(x) + \frac{y^2}{2} 2xF_1(x) - y(1-\frac{y}{2}) xF_3(x) \right]$$

$$\frac{d^2\sigma^{\bar{\nu} N}}{dx dy} = \frac{G^2 m E_\nu}{\pi} \left[(1-y) \bar{F}_2(x) + \frac{y^2}{2} 2x\bar{F}_1(x) + y(1-\frac{y}{2}) x \bar{F}_3(x) \right]$$

If the target has net isospin equal to zero, charge symmetry invariance

implies $F_i(x) = \bar{F}_i(x) \quad i = 1, 3$

Experimentally, $2 x F_1(x) \sim F_2(x) \quad (\text{from e.m.})$

The final cross-sections used for fitting were then

$$\frac{d^2\sigma^{\nu N}}{dx dy} = \frac{G^2 m E \nu}{\pi} F_2(x) \left[1 - (1 - B)y + (1 - B)\frac{y^2}{2} \right]$$

$$\frac{d^2\sigma^{\bar{\nu} N}}{dx dy} = \frac{G^2 m E \bar{\nu}}{\pi} \bar{F}_2(x) \left[1 - (1 + \bar{B})y + (1 + \bar{B})\frac{y^2}{2} \right]$$

$$\text{where } B = - \frac{x F_3(x)}{F_2(x)} \quad \bar{B} = - \frac{x \bar{F}_3(x)}{\bar{F}_2(x)}$$

For pedagogical purposes, assume $B = \bar{B} = 1$, which for pure V-A is equivalent to assuming the absence of antipartons:

$$\frac{d^2\sigma}{dx dy} = \frac{G^2 m E \nu}{\pi} F_2(x)$$

$$\frac{d^2\sigma^{\bar{\nu}}}{dx dy} = \frac{G^2 m E \bar{\nu}}{\pi} \bar{F}_2(x) (1-y)^2$$

$$\text{Then, for an } I = 0 \text{ target } \frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} = \frac{\int_0^1 (1-y)^2 dy}{\int_0^1 dy} = \frac{1}{3}$$

The fact that the data go to zero is based on conservation of angular momentum if one assumes only left handed (V-A) currents, and no antipartons.

Experimentally, the HPWF experimental observations are shown in Figure 18. The line shown in the $\bar{\nu}$ data is an attempt to derive normalization of the $(1 - y)^2$ curve from the ν data, and is probably trustworthy only to $\pm 30\%$. It is therefore hard to pin down an exact number for the high y excess. Qualitatively, it is evident the excess grows with increasing $\bar{\nu}$ energy, and is large for $E_{\bar{\nu}} > 50$ GeV. Further, below 10 GeV, the ratio of $\sigma_{\bar{\nu}}$ to σ_{ν} is consistent with $1/3$, but the higher energy data show the onset of a new behavior. This could come from something as mundane as an anti-parton core in nucleon. On the other hand, opening of a threshold for production of (charmed?) mesons interacting via a (V+A) mechanism would give rise to a flat $\bar{\nu}$ y - distribution. However, many models may be invoked to explain this effect. For example, un-locked color models have gluons with both right and left handed helicity. Since both helicities are present, a high y excess could be explained even within the framework of a (V-A) theory. (I wish to thank Dr. Sidhu for his patient clarification of this point.)

Summarizing the current neutrino data, there are three interesting and indicative effects: $\mu^- e^+$ events at the 0.6% level which are associated with an excess of kaons, $\mu^+ \mu^-$ events at the same or greater level and in anti-neutrino interactions, an excess of events at high y for high $\bar{\nu}$ energies. Clearly, the body has not yet been found, but the circumstantial evidence is rapidly mounting. Second generation experiments at Fermilab and the SPS will detect hundreds of μe and thousands of $\mu\mu$ events, with much of the analysis in hand by the end of calendar 1977.

For completeness, let us now turn to the direct discovery of charm. Experiments involving real and virtual photons have small total cross sections and a relatively rich yield of charmed particles. Professor Goldhaber has

shown you unweighted graphs of his 4 GeV data in which k and π selections were made prior to plotting. The $k\pi$ and $k\pi\pi\pi$ peaks at 1.87 GeV are unmistakable, and there are hints of new effects in the recoil mass.

The SPEAR detector is shown in Figure 19. It is an array of conventional spark chambers tightly contained within a solenoidal field. Kaons are tagged in a crude fashion by time of flight in scintillation counters surrounding the apparatus. Clearly, it is a detector in which particle tagging and momentum resolution have been compromised in favor of large solid angle. This has proved to be a wise choice, as the resonance just discovered could have disappeared into statistical oblivion with appreciable reduction in rates. As you know, data were compiled for cms energies between 3.9 and 4.7 GeV. Searches were made in two through six prong final states, with a resolution of 60 MeV FWHM in the $K\pi\pi\pi$ state at 2 GeV. (the resolution in the two prong state was somewhat worse, the width derived in the paper is from the 4 prong state). Fits to the various momenta are made, then χ^2 cuts applied to the difference between the predicted and measured TOF to select kaons. This is difficult, as the average timing difference between π 's and kaons is 0.5 nanoseconds, while the FWHM resolution is about 1 nanosecond. The unweighted mass plots show a clear enhancement at 1.87 GeV as seen in Figure 20. For completeness, I show again the weighted mass distributions in Figure 21, which though more dangerous to interpret also show an even more pronounced enhancement at 1.87 GeV. A further indication that a new threshold has just opened is that the recoil mass appears to have one (or possibly two) unique values. That such a behavior is expected becomes obvious from the following diagram:

Of course, many other types of charmed particles may be produced by similar graphs, though charmed baryons will be suppressed.

The recoiling mass from the paper is shown from the weighted fits in Figure 22. There is no evidence of the split in recoil mass which becomes appreciable only if one forces a 1.87 GeV mass on the K system. The recoil mass under this constraint is shown in Figure 23. Another indicative piece of information is that the enhancements are produced perhaps 3 to 5 times more copiously at the 4.05 and 4.4 GeV ψ recurrence masses.¹¹ Finally, Figure 24 shows the dependence of $R = \left(\frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-} \right)$.¹² Clearly, there is a step in the yield near 3.9 GeV consistent with the opening of a new channel. The branching ratio for $\text{charm} \rightarrow K\pi$ is unknown, but if it is smaller than 3%, the production of this resonance could account for more than 1/3 of the decays at 4.05 and 4.4 GeV. There is a minute caveat, and that is the data of a BNL-CCNY group, (Figure 25), which shows a K^* recurrence with mass 1692 MeV and width less than 50 MeV.¹³ This says that conventional high mass resonances may have unexpectedly narrow widths.

Shortly after these lectures were presented the Columbia-Illinois-Fermilab group (Fermilab experiment E-87) found a $\bar{\Lambda}\pi\pi\pi$ resonance at 2.23 GeV from the reaction

$$\gamma + B_e \rightarrow (\bar{\Lambda}\pi\pi\pi) + X$$

shown in Figure 26.

The group has all the credentials, they have seen a substantial $\psi(3100)$ signal using both neutron and γ beams into their apparatus. The signal

appears to be real, though the lack of any signal in the $\Lambda\pi\pi$ channel is disturbing. In any case, we must wait until the spring of 1978 to find out for sure. They should have a much improved setup running in 1977, and analysis will just take that long. Even on paper this experiment is impressive, they plan to select Λ and K^0 vees in the trigger!

O.K., so what next? Let us move in the direction from least to most likely to yield new results.

In hadronic beams, assuming a (guessed) 1 microbarn charm production cross-section and a 3% branching ratio into $K\pi$, one must be able to discern cross-sections times branching ratios at least as small as 30 nanobarns. I for one believe the real figure of merit is the ability to discern effects at a level smaller than the $\psi \rightarrow 2\mu$ production cross section of 10 nanobarns. The problem is that within a 20 MeV wide bin at 1.87 GeV, the real non-resonant $K\pi$ background is roughly 1000 nanobarns or 1 microbarn. Unless this signal to noise ratio of one to 100 is reduced below 1 to 10, the experiments will come up empty. Currently, a 1 MeV mass resolution experiment does not appear feasible, though this obviously is the best way to reduce background. Thus, experimenters are forced to include additional theoretical prejudices in their triggers.

A cute experiment has been performed at Fermilab by the Michigan-Purdue-Fermilab group,¹⁵ in which they demand a decay downstream of the target.

A schematic of the target is shown below:

The scintillators anti tracks in one arm of their two arm spectrometer which come from the target. The placement of the anti counters subtends a very small

solid angle nowhere near the core of the interaction. They observe lifetimes as small as 5×10^{-13} seconds. Preliminary mass spectra are quite smooth, but the data are not sufficiently analyzed to show in public.

A second and more promising trick is being applied by several groups at several laboratories, and that is to demand a muon in the final state.¹⁶ The hope is that charm particles are produced in pairs, and that perhaps as much as 10% of the time one member will decay leptonically, giving rise to a muon. In this case, the real $K\pi$ background would be reduced considerably. The difficulties are twofold. First, some open space must be left near the target to permit the hadrons of interest to escape, giving rise to a muon background resulting from π and K decays. Second, many experiments are limited by junk background, and cannot raise the beam commensurate with the trigger rate reduction afforded by demanding a muon. If the leptonic branching ratio of charmed mesons is small statistics will be a problem. Still, there is room for some optimism. If one can avoid e^+ from conversion of γ 's, electrons may be better since many hadrons decay into muons.

Charm may also be expected to be produced coincidentally with the ψ . Groups such as the Saclay-Indiana group at super-CERN¹⁷ are pursuing this possibility, which is illustrated graphically below:

However, ϕ production is also modulated by a similar graph; just replace $\bar{D}$, D , ψ by $\bar{K}$, K , ϕ .

Production of every ϕ should be accompanied by production of two kaons, but the results of Blobel¹⁸ indicate the $\phi k k$ production mode is suppressed by at least an order of magnitude. However, the Saclay-Indiana group have come up with an argument which says that such a decay mode should be suppressed at low incident pion energies, and so are optimistic.

It may also be possible to increase the trigger bias. A Penn-BNL group plan to demand the $e\mu$ trigger found in the 15 foot chamber neutrino interactions.¹⁹ This means there would be a missing neutrino, but they hope to catch all particles but the neutrino in the BNL multiparticle spectrometer (MPS) and come up with a 1 C fit to possible leptonic decays of charmed particles. However, I feel they are overly enthusiastic and will miss by roughly two orders of magnitude in achieving the required ψ production yield level of 0.1 nanobarn.

Photon beams appear promising. At SLAC they are fortunate in having a virtual photon which is always massive if it interacts. At Fermilab the real photon spectrum would not be so constrained, but the total cross-section reduction in going from the 40 millibarn hadronic cross-section to the 0.1 millibarn photo cross-section may be evidenced in a drastic reduction of non-resonant K backgrounds. Since the coupling of the photon occurs via charge, once above threshold the production of charm should be copious.

One crude indication of this is that within a factor of three, ψ 's are produced with the same cross-section in photon and hadron beams at Fermilab.

Several groups are pursuing this possibility by building or using large spectrometers in photon beams at Fermilab and at the SPS.²⁰ The trick, of course, is to have both charged and neutral detection, $k\pi$ separation, have the ability to see vees in the trigger, and to push a thousand triggers per pulse in the data logging.

Turning now to neutrinos, it appears the massive counter experiments as presently designed²¹ point the way to new physics, but do not have the finesse to examine specific final states. However, the half kiloton setups presently coming into operation have the capability to detect millions of single muon and thousands of dimuon events. They will be able to pin down many features of the dimuon and high Y anomalies, such as their threshold onsets and the ratio of $\mu^-\mu^+$ to $\mu^-\mu^-$ events for neutrino beams, and similar ratios with μ^+ 's for E beams. Enough statistics will be gathered in various configurations to thoroughly understand background sources of dimuons. Only in this manner may one construct definite tests for heavy leptons.

Bubble chambers at Fermilab and the SPS will have the opportunity to reconstruct neutrino interactions,²² using visible vees as a try for strange particles. In the next five years, it may become possible to obtain several neutrino interactions per pulse in heavy liquid mixtures, permitting observation of statistically small mass peaks.

[Note added in press: Some of us do not believe bigger is always better and newest is always best. High energy physics is becoming a venerable science and there should be room for those who look to the past. A Kobe-Nagoya-Ohio State-Osaka-Quebec-Toronto collaboration²³ plans to place a tagged emulsion spectrometer in a neutrino beam; the emulsion target having a mass of 0.0001 kiloton. Just suppose, however, that several of the lightest charmed particles could only decay weakly, with lifetimes 10^{-13} sec., how would you produce them, and if produced, how could you see lifetimes this short? Of course, you would use ν beams, if the di-lepton production is over 1%, the charmed particle production including baryons must occur even more copiously. The older readers will remember emulsions were used to measure the π^0 lifetime, 0.8×10^{-16} seconds.

If emulsions are coupled to a spectrometer to minimize scanning and to reconstruct multiparticle events, it could be that a plethora of lifetimes (including those of heavy leptons?) will be found. "Visible" decay lengths would tag these particles and permit studying branching ratios without background. Our proposed setup is shown in Figure 27.)

Finally, we get to them that has! With new setups coming into being at SLAC and DESY, a new spectroscopy will be in full bloom by the end of the decade (though discovery of charmed baryons may be suppressed). The first PEP proposal decisions will be made in February 1977, ending titanic struggles between megagroups, and new physics may result even beyond charm. In fact, we have spent all our time discussing charm, but what about the top and bottom quarks and heavy leptons invoked by theorists to explain the jump in the R parameter at SLAC (shown in Figure 25)?

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

In terms of quarks $R = \sum Q_i^2$, where Q_i is the charge of the i th quark. If only 4 quarks and 3 colors are assumed, $R = 10/3$, significantly less than the experimentally determined value of 5.

I do not know what stock should be placed in these attempts, but evidence is coming from SPEAR that there is an excess of μe and $\mu\mu$ events, and even a step in $\mu\mu$ yields indicating a new threshold.²⁴

If this sort of evidence becomes solid, it will mean the birth of a varied spectroscopy quite as rich as was begun in the late 50's with the discovery of the ω meson.

Though science is unending, definitive experiments for charm are now surely at least on the drawing board, and it is just a matter of time until we decode nature's charming puzzle.

Le jeu sont fait!

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E-320 (Sciulli)
E-310, E-370 (Cline).
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E-380 (Baltay)
P-455 (Peterson)
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E-388 (Stevenson).
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FIGURE CAPTIONS

Figure 1. Cross-section versus energy for e^+e^- colliding beam interactions leading to a) multi-hadron final states
b) e^+e^- final states
c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states.
Taken from Ref. 1.

Figure 2. Status in 1975 of the ψ spectrum, taken from Ref. 12.

Figure 3. SU_4 weight diagrams for
a) the 4 quarks of SU_4
b) the three quark $\frac{1}{2}^+$ baryons
c) the vector and singlet pseudoscalars.
Taken from Ref. 2.

Figure 4. The layout for the charm search of Aubert, et al at BNL.

Figure 5. Various spectra from charm search of Aubert, et al.
a) pair vertex reconstruction at the target
b) time difference between the additional scintillation counters at the back ends of the right and left arms.
a) and b) indicate the high quality of the experiment.
Two body mass spectra are shown for the modes
c) $K^-\pi^+$
d) $\pi^+\pi^-$
e) π^+K^-
f) π^-P
g) K^+P
h) π^+P
i) K^+P
Taken from Ref. 5.

Figure 6. 5 standard deviation upper limits for two body narrow resonance production. For comparison, the cross-section for J/ψ production is about $\times 10^{-34} \text{ cm}^2$. Taken from Ref. 5.

Figure 7. The layout from the Fermilab two body charm search of Ref. 6. C's are Cerenkov counters, DC's are drift chambers, all other symbols refer to scintillator counters.

Figure 8. Effective mass spectra for
a) π^+K^- (47,000 events)
b) π^+K^- (26,000 events)
c) $\pi^+\pi^-$ (329,000 events)
d) the 4 standard deviation limits on narrow resonance production are shown as a ratio to the $\psi \rightarrow \mu^+\mu^-$ yield of about 10 nanobarns.
Taken from Ref. 6.

FIGURE CAPTIONS - continued

Figure 9. The layout for the forward produced two body narrow resonance search of Ref. 7.

Figure 10. Two body mass spectra for

- a) $\pi^+\pi^-$, low mass setting
- b) $\pi^+\pi^-$, higher mass settings
- c) $\bar{P}P$, low mass setting
- d) $\bar{P}P$, higher mass settings
- e) K^-P , low mass setting
- f) K^-P , higher mass settings
- g) $K^-\pi^+$, low mass setting
- h) $K^-\pi^+$, higher mass settings

Taken from Ref. 7.

Figure 11. 4 standard deviation upper limits for the inclusive production of narrow resonances in the channels $\mu^-\mu^+$, $K^-\mu^+$, $\bar{P}P$ and K^-P . For comparison, the cross-section times branching ratio for neutron production of $\psi \rightarrow 2\mu$ is 2 ± 1 nanobarn/nucleon. Taken from Ref. 7.

Figure 12. The experiment of Ref. 7 was improved and rerun due to the anomaly of Figure 11g marked by the arrow. Unfortunately, the anomaly disappeared with increased statistics. The data shown here are based on about 1/3 of the total sample for this new run.

Figure 13. The layout for the HPWF Fermilab neutrino experiment. A dimuon event is shown which resulted from a neutrino interaction in the steel target just downstream of the calorimeter. Figures 13 through 18 are private communications from T.Y. Ling.

Figure 14. This figure shows the primary argument for the existence of direct dimuons in the HPWF experiment. If the second muon were from π or K decay, the point with longer absorption length would be higher. Shorter absorption lengths occur from interactions in the steel target, longer ones from interaction in the calorimeter target (see Figure 13).

Figure 15. The momentum of each of the muons in a $\mu^-\mu^+$ event is represented by a point on this graph. There is a strong indication the leading muon (μ^- for neutrino and μ^+ for anti-neutrino interactions) usually has a higher momentum than the non-leading muon. Taken from the HPWF experiment.

Figure 16. The HPWF dimuon mass spectrum. The artist's additions were drawn by your lecturer and have no theoretical significance. They do show the possibility of a heavy lepton with mass of a few GeV riding on background from other sources.

FIGURE CAPTIONS - continued

Figure 17. Data from Serphukov and Fermilab are plotted to show the possibility of a sharp threshold for dimuon production.

Figure 18. HPWF experimental γ distributions for neutrino and anti-neutrino interactions in two ranges of incident energy

- a) neutrino beam $10 < E_\nu < 30$ GeV.
- b) anti-neutrino beam, $10 < E_{\bar{\nu}} < 30$ GeV.
- c) neutrino beam, $E_\nu > 70$ GeV.
- d) anti-neutrino beam, $E_{\bar{\nu}} > 70$ GeV.

Figure 19. The layout for the famous SPEAR apparatus.

Figure 20. The $K^-\pi^+$ mass plot from SPEAR communicated by G. Goldhaber. K^- and π^+ selection were made before plotting; this is an unweighted plot.

Figure 21. Two body mass plots from SPEAR taken from Ref. 11. Plots containing kaons are weighted according to the probability the particle selected as a kaon is selected correctly.

Figure 22. Recoil mass spectra for combinations in the $K\pi$ and $K3\pi$ peaks. Smooth curves are background estimates taken from either side of the mass peaks.

- a) $K^+\pi^-$, peak mass region 1.84 to 1.90 GeV/c^2
- b) $K^+\pi^-\pi^+\pi^-$, peak mass region 1.84 to 1.88 GeV/c^2 .

Taken from Ref. 11.

Figure 23. Recoil mass spectra taken from the $K\pi$ peak region and constraining the $K\pi$ mass to be 1.87 GeV/c^2 . Communicated by G. Goldhaber.

Figure 24. The $\bar{K}^0\pi^+\pi^-$ mass spectrum taken from Reference 13. It indicates that high mass conventional resonances may also be narrow.

Figure 25. $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ as a function of energy. Taken from Ref. 12.

Figure 26. Invariant-mass distributions for $\bar{\Lambda}3\pi$ combinations, separated by the total charge

- a) $\bar{\Lambda}^+\pi^+\pi^+\pi^-$ and
- b) $\bar{\Lambda}^+\pi^+\pi^-\pi^-$

There is a 7σ peak at 2.26 GeV/c^2 in the first distribution. Taken from Ref. 14.

FIGURE CAPTIONS - continued

Figure 27. The layout for Fermilab proposal P-531, in which a tagged emulsion spectrometer would be used to search for neutrino beam generated particles with lifetimes 2×10^{-15} to 3×10^{-12} seconds. The two cross-hatched planes are the emulsion stacks, the unmarked planes are drift chambers, and the SCM 104 is a wide aperture magnet. The existing γ detector is a $5\frac{1}{2}$ foot by $5\frac{1}{2}$ foot lead glass array.

Figure 1

Figure 3

Figure 4

Figure 2

Figure 5

Figure 5 (continued)

$\pi^+ \pi^-$	2.25 GeV	3.1 GeV	3.7 GeV
$\pi^+ K^-$	1×10^{-33}	4×10^{-35}	1×10^{-35}
$K^+ \pi^-$	4×10^{-33}	8×10^{-35}	4×10^{-35}
$p \bar{p}$	...	4×10^{-34}	2×10^{-35}
$K^+ K^-$	1×10^{-33}	5×10^{-35}	1×10^{-35}
$\pi^+ \pi^-$	8×10^{-33}	5×10^{-34}	3×10^{-35}
$p K^-$	7×10^{-33}	4×10^{-34}	3×10^{-35}
$K^+ p$	2×10^{-33}	4×10^{-35}	8×10^{-36}
$p \pi^-$	4×10^{-32}	4×10^{-33}	5×10^{-34}
$\pi^+ \bar{p}$	2×10^{-33}	4×10^{-35}	7×10^{-36}

Figure 6

Figure 9

Figure 10

Figure 7

Figure 11

Figure 8

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 22

Figure 21

Figure 23

Figure 24

Figure 25

Figure 26

Figure 27