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POSTLUDE*

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ABSTRACT

A number of comments are made on issues raised by experimental results presented to the Conference. Prejudices and disconcertions are shared openly.

INTRODUCTION

Rather than attempt a summary of what we have heard or of where our field stands, I want to share with you my reactions to the findings reported here. These will include expressions of delight and of bewilderment, clarifications of folklore, and theoretical background comments. I have made little effort to achieve uniform coverage or to present all sides of every question. Indeed, what follows is simply my critical reading – here provocative, there didactic, elsewhere intemperate – of the papers delivered here.

HADRONIC PRODUCTION OF NEW PARTICLES

A number of searches for charmed or otherwise novel particles produced in hadron-hadron collisions have been carried out.[1-7] These have yielded a few curiosities but no one yet has a compelling candidate for the wallet cards. What is the interesting level of sensitivity for charm searches in hadron-hadron collisions? My viscera, and those of my colleagues[8,9] say that at Fermilab energies the total cross section for charm production is

$$\sigma(\text{charm}) \sim 1\ \mu\text{b} \quad .$$

If we divide this number by 3 for the distinct species of charmed pseudoscalars and multiply by 5% which appears to be a reasonable guess[10] for a typical nonleptonic branching fraction, we arrive at

$$\sigma \times \text{Branching ratio} \sim 1 \text{ to } 10 \text{ nb}$$

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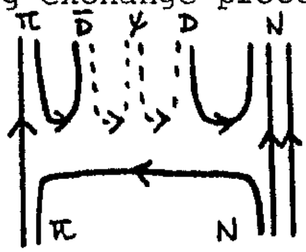
as the interesting level to penetrate. This is so small that the unsuccessful searches do not yet surprise or dismay the advocates of charm.

Special triggers have been employed to select events in which charmed particle production may be enhanced. If charmed particles have appreciable semileptonic decays, a (prompt) μ trigger might select events in which one charm has decayed semileptonically, leaving the other to be observed. The sensitivity required for this kind of search is no less demanding than in the untriggered case. With a semileptonic branching fraction of approximately 10%, we may expect to require

$$\sigma \times (\text{Semileptonic branching ratio}) \times (\text{Branching ratio for decay of second charm}) \lesssim 1 \text{ nb} \quad .$$

The use of a ψ trigger[11] to enhance the charm signal to background has also been attempted. Here it is assumed that ψ is a $(c\bar{c})$ bound state produced in an Okubo-Zweig-Iizuka rule[12] – respecting exchange process such as



where solid lines represent ordinary light quarks and broken lines represent charmed quarks. According to this line of reasoning, every ψ is accompanied by a pair of charmed particles. Likewise, the replacement of strange quarks for charmed quarks in the exchange diagram leads to the expectation that every produced ϕ should be accompanied by a pair of strange particles. A search[13] in low energy pp collisions has produced no evidence for a $\phi(K\bar{K})$ enhancement. What is wrong[14] with the argument? First, the OZI rule is unlikely to be exact; ϕ and ψ do decay into nonstrange and uncharmed hadrons, respectively. Second, it is not the only influence on production cross sections. For example, in 24 GeV/c pp collisions a final state like $pK\phi\Lambda$ is energetically far more costly than $p\phi p$. Finally, it may be that the dominant mechanism for ψ production is OZI-rule violating and has nothing to do with charmed particle exchange. In this event there is no reason to expect any $\psi(D\bar{D})$ correlation whatsoever.

We meet such a mechanism by asking whether ψ' is produced in hadron-hadron collisions. Data presented to this conference[15,16] indicate that in 300-400 GeV/c NN collisions

$$\sigma(\psi')/\sigma(\psi) \lesssim 1/10 \quad .$$

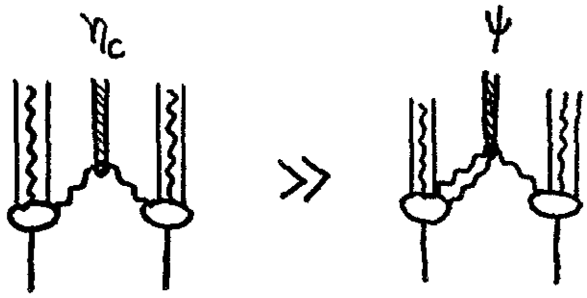
Earlier, the MIT-BNL group reported[17]

$$\sigma(\psi')/\sigma(\psi) < 1/100$$

in 28.5 GeV/c pBe collisions. Regardless of the numbers, no one has yet seen a clean ψ' peak in hadronic interactions.[18] Is this amazing? How might it be explained? Three possibilities leap instantly to mind. The first is a kinematical suppression.[19] I find this unappealing at several hundred GeV/c, but we may entertain a thermodynamic argument anyway. According to the usual lore[20] the ratio of production cross sections for particles whose masses differ by ΔM is, <u>ceteris paribus</u>, $\exp[-\Delta M/160 \text{ MeV}]$. For the case at hand, we have

$$\sigma[\psi'(3684)]/\sigma[\psi(3095)] = 0.025 \quad ,$$

which leaves us with nothing to explain. My only objection to arguments of this kind is that I do not understand them. A second coneivable explanation is that ψ and ψ' are not closely related objects. I dismiss this at once.[21] The third possibility is the one I find most interesting, if not entirely convincing: it is that the suppression has a specific dynamical origin[22] suggested by the charmonium picture of Appelquist and Politzer.[23] As Appelquist has reminded us in his talk,[24] the charmonium-positronium analogy explains the narrowness of ψ and ψ' by the requirement that these $C=-1$ $^3S_1$ states decay through 3-gluon intermediate states, whereas $C=+1$ psions (such as $^1S_0$ η_C and the χ or P_C states) can decay through 2-gluon intermediate states and should be broader. On this argument, the total width of the pseudoscalar η_C is expected to be about 5 MeV, 75 times the width of ψ. Let us now apply this reasoning to the OZI rule violating production mechanism posited by Einhorn and Ellis,[9] a Drell-Yan[25] process for gluons. Evidently



(the wavy lines represent gluons), so that

$$\sigma(\chi) \text{ or } \sigma(\eta_C) >> \sigma(\psi) \text{ or } \sigma(\psi') \quad .$$

Taking this line of reasoning too literally we arrive at the conclusion that <u>no ψs or ψ's are produced directly in hadron-hadron collisions</u>. All the ψs we see occur as decay products in reactions like

$$\pi N \rightarrow \chi + \text{anything}$$
$$\quad \hookrightarrow \psi + \gamma + \cdots$$

Notice that because $\chi(3500) \not\rightarrow \psi'(3684) + \cdots$, we require more massive C=+1 psions to feed ψ' production. If these lie below the putative charm threshold, E1 transitions to ψ should be favored over those to ψ' by the larger Q-value. If they lie above the threshold, they may not decay appreciably into either ψ or ψ'. In either instance we have reason to expect

$$\sigma(\psi) >> \sigma(\psi') \quad .$$

It is important to put this proposal to the test by searching for the decay photons accompanying ψs and by searching directly for χ production in reactions such as

$$\pi N \rightarrow \chi + \text{anything}$$
$$\quad \hookrightarrow \pi^+\pi^- \quad .$$

Unfortunately, the branching ratios I glean from Friedberg's report[26] do not encourage the hope that this will be easy.

HADRONIC PRODUCTION OF LEPTONS

One may ask whether ψ is produced strongly, or through the intermediary of a virtual photon. An old but good argument against the latter possibility is that a direct (i.e., nonelectromagnetic) coupling of ψ to hadrons is implied by the observation that

$$\Gamma(\psi\to\text{hadrons}) \gg \Gamma(\psi\to\ell^+\bar{\ell})\left.\frac{\sigma(e^+e^-\to\text{hadrons})}{\sigma(e^+e^-\to\mu^+\mu^-)}\right|_{\substack{\text{off}\\ \text{resonance}}} .$$

A less devious proof can be had by verifying that ψ production respects strong interaction symmetries such as isospin invariance. The ratio

$$\frac{\sigma(\pi^+C \to \psi + X)}{\sigma(\pi^-C \to \psi + X)} = 1$$

for strong production, including the cascade mechanism reviewed in the preceding section. I believe we know the outcome of this measurement before it is done: the ψ <u>is</u> produced strongly. However, for lepton pairs in general the origin and the production mechanism are quite uncertain. The same test applies.[27] We define

$$\rho = \frac{d\sigma}{dM^2}\,(\pi^+C \to \ell^+\ell^- + X)\Big/\frac{d\sigma}{dM^2}\,(\pi^-C \to \ell^+\ell^- + X) \quad ,$$

where M is the invariant mass of the $\ell^+\ell^-$ pair. If the pairs are produced through

$$\pi^{\pm}C \to \text{hadron} + X, \quad \text{hadron} \to \ell^+\ell^- \quad ,$$

$\rho=1$, but if they are produced through

$$\pi^{\pm}C \to \gamma_V + X, \quad \gamma_V \to \ell^+\ell^- \quad ,$$

$\rho\neq 1$ in general. An extreme example of the latter is Drell-Yan production by valence quark annihilation. For incident π^+ , the elementary process is $d\bar{d} \to \gamma_V$; for incident π^- it is $u\bar{u} \to \gamma_V$. The cross section is proportional to the square of the quark charge, so we find

$$\rho = \tfrac{1}{4} \quad .$$

In a less schematic Drell-Yan model, with valence and sea quarks, the value $\rho=\frac{1}{4}$ is attained only for rather large lepton pair masses. At very small masses, for which sea quark-sea quark annihilations are dominant, $\rho\to 1$. This is shown in Fig. 1 for two choices[28,29] of parton distributions.

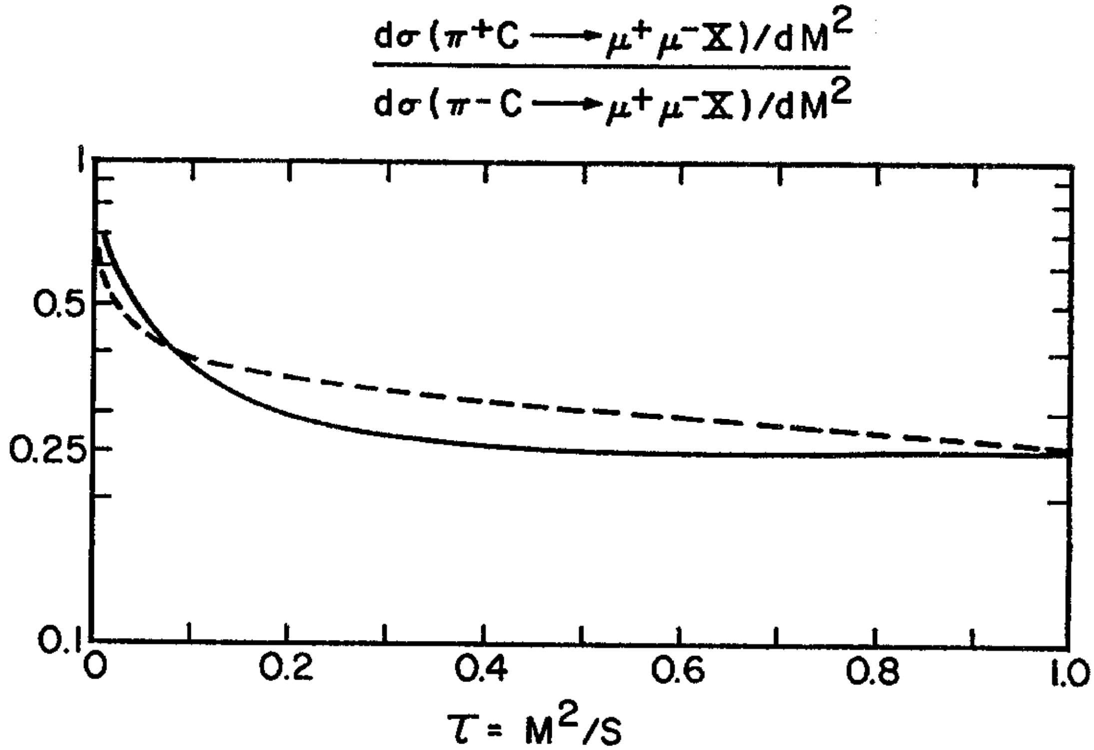


Fig. 1: Ratio of lepton-pair production in $\pi^{\pm}C$ collisions expected in the Drell-Yan model. The solid line is based on the parton distributions of Ref. 28; the dashed line on those of Ref. 29.

Is there indeed any lepton-pair continuum? Is it of Drell-Yan origin? Sanders,[30] reporting on a Chicago-Princeton experiment at Fermilab, has raised the possibility that there may be no continuum at all between ½ and 3 GeV/c^2 , that vector mesons ρ,ω,ϕ,ρ' might account for the entire observed signal. Increased resolution and the isospin test just discussed will help to clarify the situation. In his report on the Columbia-Fermilab-Stony Brook experiment, Appel[16] indicated that perhaps there is a continuum contribution above 5 GeV/c^2. If you believe Υ(5.97 GeV/c^2) is a resonance, the evidence for a continuum is very weak indeed. The extant data cannot sustain both a prominent resonance and a continuum. I cannot agree with Sullivan's conclusion[31] that the Drell-Yan mechanism is firmly established. We still require the convincing demonstration that $M^4 d\sigma/dM^2$ depends only upon M^2/s , that the pairs originate from virtual photons as distinct from vector mesons, and the observation of a credible continuum signal for values of M^2/s which are not tiny. Defensible estimates[32] of the Drell-Yan continuum lie at or below the levels reported by Appel[16] and by Sanders.[30] The identification of the Drell-Yan signal is of great importance for discussions of new accelerators intended as W boson factories.

At low lepton pair masses where we cannot expect Drell-Yan arguments to apply, the experimental situation is even more confusing — at least to me. There are backgrounds from η Dalitz pairs and from Bethe-Heitler conversion of the photons released in π^0 decay. Evidently both of these are imperfectly understood in practice. The rate for $\eta\to\mu^+\mu^-\gamma$ is only known theoretically, and different reasonable choices for the form factor lead to predictions[33] which differ by as much as 30%. Much more work, principally on low mass e^+e^- pairs, will be required to assess theoretical speculations[34] that copious radiation of nearly-real photons is responsible for the bulk of prompt lepton production.

The reports[15,16,35-39] on prompt production of leptons leave me terribly perplexed. I think this is not due entirely to my hebetude, but to contradictions among data sets. It appears to me that we speak with confidence about μ/e, μ/π, and e/π when in fact very little is known about the dependence of these ratios upon s, x, and $p_\perp$ beyond what was reported in 1974.[42] I simply don't know what to believe at small $p_\perp$ or at low energies. I should prefer to have the differences between experiments faced directly and not disregarded.

CHASING DOWN CHARM

Do charmed particles exist? Beyond reasonable doubt. Have they been discovered? Almost certainly. By whom? Ask me in a year.

I want to issue a warning about charmed particle mass formulas, which seem to be taken very seriously in some quarters. If you are told that someone can compute charmed particle masses to within a few MeV/c^2, my advice is to get a firm grip on your wallet. There are several ways of estimating these masses.[43] All are equally (in)credible. The situation is not closely analogous to the propitious days of the hunt for Ω^- , and experimental agreement with a theoretical mass is of far less consequence.

Although I am unprepared to state who has discovered charmed particles, we have been assured[44-46] that it isn't the e^+e^- annihilators. Why not? One possibility is that the quark of which psions are made is not the charmed quark. We lack any indication of a connection between the constituents of ψ and the weak interaction, but let us tentatively put aside this possibility in the interest of simplicity and because the charmed quark we believe we need[8] ought to lie in the explored mass region. More to the point is that we don't know how many new phenomena[47] are occurring in the range $3\ \mathrm{GeV} < s^{\frac{1}{2}} < 5\ \mathrm{GeV}$. As confidence grows[44,48] in the reality of the heavy leptons reported by Perl and coworkers at SPEAR,[49] the limits on charmed meson production recede from the threatening levels[50] of last summer.[51] Despite my faith in the reliability of these excuses, I shall feel more confortable when they no longer have to be made.

ISSUES IN NEUTRINO-INDUCED PRODUCTION OF CHARMS

In the Glashow-Iliopoulos-Maiani (GIM) scheme,[52] the hadronic weak current mediated by W^+ has the form

$$J^+ \sim \bar{u}(d \cos\theta_C + s \sin\theta_C) + \bar{c}(s \cos\theta_C - d \sin\theta_C) \quad .$$

The observation of $K_S e^+(\nu)\mu^-$ events in the 15' chamber at Fermilab[53] and in the Gargamelle chamber at CERN[54] hints that the GIM current may indeed by operating. It was anticipated[8] that of the charmed pseudoscalar mesons $D^+(=c\bar{d})$ would be most likely to have appreciable semileptonic decays. The simplest semileptonic decay mode is

$$D^+ \to \bar{K}^0 \ell^+ \nu \quad ,$$

which invites identification with the observed events. Two questions of vital importance are whether the $K_S e^+\mu^-$ events truly signal charm, and how the apparent new objects are produced. At the moment we can answer neither of these incontrovertibly. I shall therefore indicate some of the processes whereby charmed particles may be produced in $(\nu,\bar{\nu})N$ collisions.[55]

Let us first consider charged current interactions. The most reasonable possibilities for charm production in νN collisions are indicated in Fig. 2. The Cabibbo-favored diffractive process[56] $\nu N \to \mu^- + F^{*+}$ + anything likely results in the semileptonic decay

$$F^+ \to (\ell^+\nu)(s\bar{s}) \quad (s\bar{s}) \to \eta^0 \text{ or } K\bar{K} \quad .$$

It is a "delayed threshold" reaction in which the total hadronic energy must be large enough that the four-momentum transfer squared required to put the F^* on

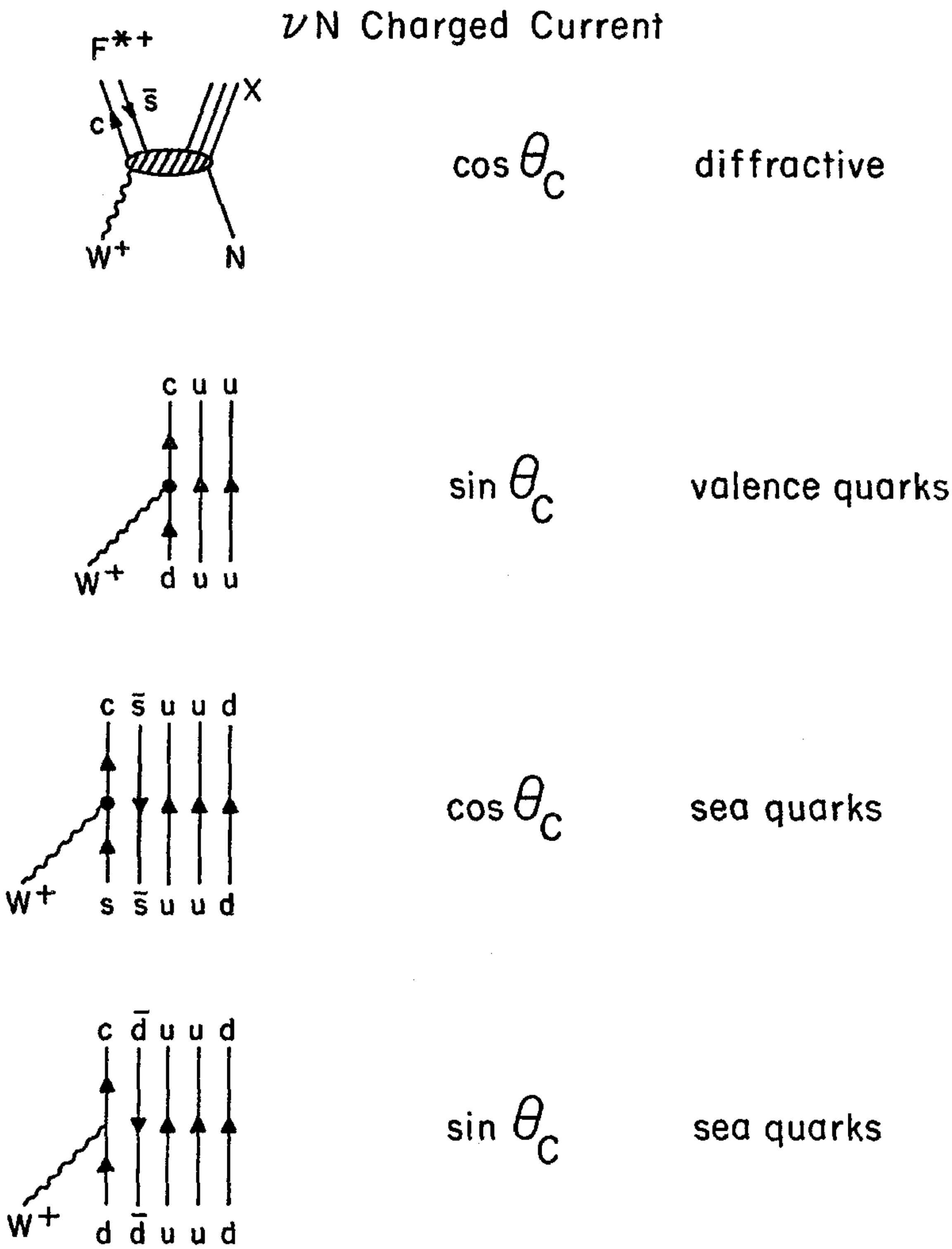


Fig. 2: Partial list of the charm-producing mechanisms which may operate in $(\nu,\bar{\nu})$-nucleon collisions. See Ref. 55 for additional discussion.

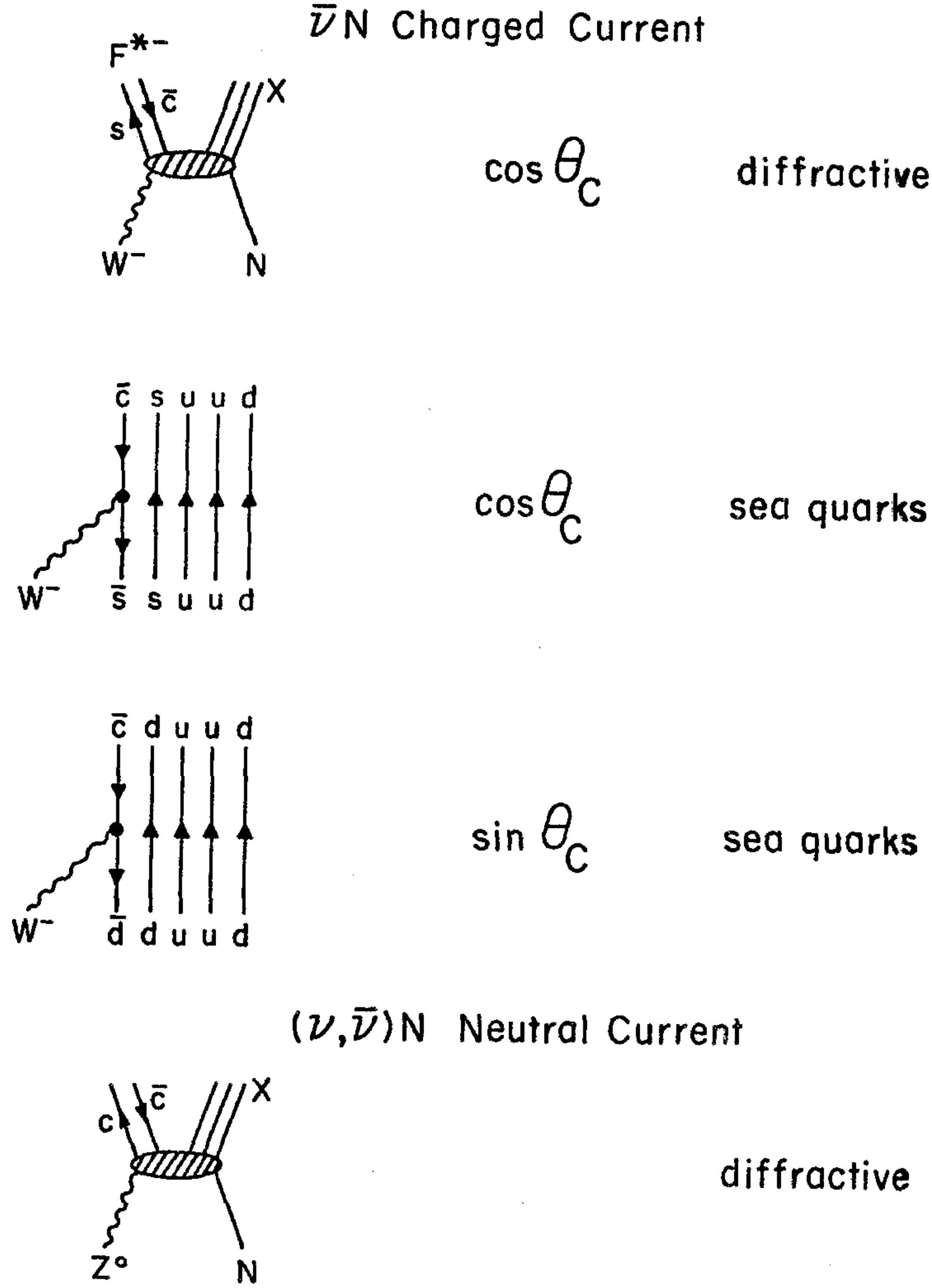


Fig. 2 (continued):

mass shell is small. The other reactions indicated lead to final states containing a single charmed meson or baryon, plus anything else. Some examples of expected semileptonic decays are[57]

$$D \to \bar{K}\ell^+\nu$$

$$C_1 \to \Sigma\ell^+\nu \quad .$$

Antineutrino-induced collisions are distinguished in two important ways from neutrino-induced collisions: No charm-changing interactions with valence quarks can take place, and no charmed baryons will be produced. The remaining mechanisms for the production of charmed particles, shown in Fig. 2, are counterparts of those we have already mentioned in the νN case.

Opportunities for charm production are more restricted in neutral current interactions. The neutral current can be represented schematically by

$$J^0 \sim u\bar{u} + c\bar{c} - d\bar{d} - s\bar{s} \quad ,$$

which gives rise to the diffractive production of charmed particle pairs by the last diagram in Fig. 2. Because two (heavy) charmed particles are produced by this process, I expect it to have an effective threshold energy about four times that required for diffractive F^* production. Following Einhorn and Lee[56] I estimate the needed beam energy at about 120 GeV.

PSION SPECTROSCOPY

The observation[26] of the transition

$$\psi' \to \gamma(260 \text{ MeV}) + X$$

at the 8-10% level removes a principal embarrassment for charmonium spectroscopists.[24,58] The remaining great problem is the mass of the apparent 0^{-+} state[44,45,59] $\eta_c(2800)$. With theoretical success comes theoretical hubris. Theoretical hubris wants the η_c mass to lie between 3000-3050 MeV/c^2. It would be delightsome if nature could be persuaded to cooperate.

We learned from Breidenbach[44] that the SLAC-LBL Group has failed to confirm the existence of Υ(5.97? GeV/c^2)[60] in the mass interval between 5.8 and 6.1 GeV/c^2. It is conceivable the Υ is produced copiously in pp collisions but not in e^+e^- annihilations if it is not a vector particle, or if its branching fraction into lepton pairs is tiny. To my mind it is too early to be very quantitative, but one should be prepared to be put off by the implication of a large production cross section (i.e., much greater than that of ψ) in hadronic interactions. Another argument discourages the belief that Υ represents the ψ-analog of yet another quark. If it were a bound state of a new heavy quark, we should expect a step in

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

within about 1 GeV. The step need not be as spectacular as the one near 4 GeV, where several new phenomena may coincide. For a quark of charge 1/3, the increment in R would be only 1/3, but there is no evidence[44] for even such a small change above $\sqrt{s}$ = 5 GeV. I have the same uneasiness about a heavy quark interpretation of the noname(4.8 GeV/c^2).[15]

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FOOTNOTES AND REFERENCES

1. Min Chen, These Proceedings.
2. E. Shibata, These Proceedings.
3. N. McCubbin, These Proceedings.
4. R. Harris, These Proceedings.
5. D. Ritson, These Proceedings.
6. H. Lubatti, These Proceedings.
7. J. Matthews, These Proceedings.
8. M.K. Gaillard, B.W. Lee, and J.L. Rosner, Rev. Mod. Phys. 47, 277 (1975).
9. M.B. Einhorn and S.D. Ellis, Phys. Rev. D12, 2007 (1975); Phys. Rev. Lett. 34, 1190 (1975).
10. M.B. Einhorn and C. Quigg, Phys. Rev. D12, 2015 (1975).
11. D. Sivers, Phys. Rev. D11, 3253 (1975).
12. S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, oral tradition (1964); J. Iizuka, Prog. Theor. Phys. Suppl. 37-38, 21 (1966).
13. V. Blobel, et al., Phys. Lett. 59B, 88 (1975).
14. H.J. Lipkin, Phys. Lett. 60B, 371 (1976).
15. I. Gaines, These Proceedings.
16. J. Appel, These Proceedings.
17. J. Leong, quoted in Ref. 8.
18. In a March 19, 1976 seminar at Fermilab, J. Weiss of the Columbia-Fermilab-Stony Brook Collaboration

showed a clear ψ' peak observed in $p\,Be \to e^+e^-X$ at 400 GeV/c, and inferred $\sigma(\psi')/\sigma(\psi) \sim 10\%$.

19. F. Halzen, Wisconsin preprint C00-501(1976).
20. See, for example, R. Hagedorn, in Atlas of Particle Production Spectra, by H.Grote, R. Hagedorn, and J. Ranft (CERN, Genève, 1970), p. 9.
21. A mountain of evidence appears in Proc. 1975 Int. Symposium on Lepton and Photon Interactions at High Energies, ed. W.T. Kirk (SLAC,Stanford, 1975).
22. This cascade mechanism has been considered by Gaillard, Lee, and Rosner, Ref. 8; implicitly by Einhorn and Ellis, Ref. 9; by F. Gilman, unpublished; and perhaps others. It is discussed at greater length by S.D. Ellis, M.B. Einhorn and C. Quigg, Fermilab-Pub-76/29-THY, and by C.E. Carlson and R. Suaya, William and Mary preprint WM-PP-10(1976).
23. T.W. Appelquist and H.D. Politzer, Phys. Rev. Lett. 34, 43 (1975).
24. T. Appelquist, These Proceedings.
25. S.D. Drell and T.-M. Yan, Phys. Rev. Lett. 25, 316 (1970).
26. C. Friedberg, These Proceedings.
27. P. Mockett, et al., Fermilab proposal P-332; J.Pilcher, et al., Fermilab experiment E-331.
28. R. Blankenbecler, et al., SLAC-PUB-1531 (1975, unpublished). An important misprint is corrected by Minh Duong-Van, Phys. Lett. 60B, 287(1976).
29. G. Altarelli, et al., Nucl. Phys. B92, 413 (1975).
30. G. Sanders, These Proceedings.
31. J.D.Sullivan, These Proceedings.
32. C. Quigg, unpublished calculations.
33. T. Miyazaki and E. Takasugi, Phys. Rev. D8, 2051 (1973); C. Quigg and J.D. Jackson, UCRL-18487, unpublished. The latter contains additional references to earlier estimates.
34. J.D. Bjorken and H. Weisberg, SLAC-PUB-1631; G. Farrar and S.C. Frautschi, CALT-68-518(Rev.).
35. J. Kirz, These Proceedings.
36. R. Johnson, These Proceedings.
37. S. Segler, These Proceedings.
38. L. Leipuner, These Proceedings.
39. R. Mischke, These Proceedings.
40. R. Ruchti, These Proceedings.
41. M. Mallary, These Proceedings.
42. See the talks by S. Segler, T. Yamanouchi, P.A. Piroué, R. Imlay, R. Cence, S. Nurushev, and L.M. Lederman in Proc. XVII Inst. Conf. on High Energy Physics, ed. J.R. Smith, (RHEL, Chilton, 1974), §V. More recent reviews are those by J.W. Cronin, "Review of Direct Lepton Production in Nucleon-Nucleon Collisions," 1975 Erice Lectures, and by L.M. Lederman, in Proc. 1975 Int. Symposium on Lepton and

Photon Interactions at High Energies, ed. W.T. Kirk (SLAC, Stanford, 1975), p. 265.

43. Gaillard, Lee, and Rosner, Ref. 8; A. de Rujula, H. Georgi, and S.L.Glashow, Phys. Rev. D12, 147 (1975); V.S. Mathur, S. Okubo, and S. Borchardt, Phys. Rev. D11, 2572 (1975).
44. M. Breidenbach, These Proceedings.
45. K. Pretzl, These Proceedings.
46. H. Rieseberg, These Proceedings.
47. E. Poggio, H.R. Quinn, and S. Weinberg, Phys. Rev. D (to be published).
48. B. Barnett, These Proceedings.
49. M.L. Perl, et al., Phys. Rev. Lett. 35, 1489 (1975).
50. M.B. Einhorn and C. Quigg, Phys. Rev. Lett. 35, 1114 (1975).
51. A.M. Boyarski, et al, Phys. Rev. Lett. 35, 196 (1975).
52. S.L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D2, 1285 (1970).
53. J. von Krogh, et al., to be published. J. Mapp, These Proceedings.
54. H. Deden, et al., Phys. Lett. 58B, 361 (1975); J. Blietschau, et al., Phys. Lett. 60B, 207 (1976).
55. A lengthier discussion may be found in B.W. Lee, "Dimuon Events," in Proc. of the Conf. on Gauge Theory and Modern Field Theory, 1975 (MIT Press, to be published).
56. M.B. Einhorn and B.W. Lee, Fermilab-Pub-75/56; M.K. Gaillard, S. Jackson, and D. Nanopoulos, CERN TH. 2049; V. Barger and T. Weiler, Wisconsin preprint C00-456.
57. See Gaillard, Lee, and Rosner, Ref. 8 for a more complete discussion.
58. E. Eichten, et al., Phys. Rev. Lett. 36, 500 (1976).
59. B. Wiik, in Proc. 1975 Int. Symposium on Lepton and Photon Interactions at High Energies, ed. W.T. Kirk (SLAC, Stanford, 1975), p. 69. J.Heintze, ibid., p. 97.
60. D.C. Hom, et al., Fermilab-Pub-76/19-EXP.