EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE EXPERIMENTAL SEARCH FOR CHARMED HADRONS

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Abstract : We give a review of the motivation, scope, methodology, and promise of experimental projects that look for the postulated new additive quantum number, charm.

Résumé : Nous discutons les investigations expérimentales à la poursuite du nouveau nombre quantique postulé pour les hadrons: le charme, sa motivation, son étendue, les méthodes employées et l'information à obtenir.

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For a number of years, the existence of a new, simply additive, quantum number has been postulated for the hadrons[1]. This postulate was motivated originally by the observation of relatively subtle phenomena in the weak interaction of hadrons: the $K_L - K_S$ mass difference, the small decay mode $K_L \to 2\mu$, the recent observation of neutral $\Delta S = 0$ weak currents; and by a desire to put leptons and hadrons on a similar logical level by juxtaposing *four* basic hadronic building blocks (e.g. quarks) to the four leptons μ, ν_μ, e, ν_e. The fourth (new) quark would carry the new quantum number; all previously known hadrons would carry a zero eigenvalue of the new charge, the new quark would have an eigenvalue of one.

Only recently has this new quantum number been called upon to do the yeoman's work usually assigned the hadronic "charges" B, Q, (or I_3), S (or Y): to help explain the gross features of the observed hadron spectrum. The emergence of narrow mesonic states with masses much superior to those of all previously known hadronic states, and widths considerably inferior to those of all well-established strongly decaying hadrons, gives a new impetus to ask whether a law implying the conservation of a new charge, CHARM, can be established to be at the basis of these phenomena.

Charm has to date not been explicitly observed. If the narrow heavy meson states are due to bound pairs of quarks and antiquarks carrying the charm quantum number, we may find ourselves in the position of the experimenter who knows all about positronium but is in search of electric charge; or of the observer of ϕ mesons who is not sure whether there is such a thing as strangeness. Is this a likely conjecture? Theories abound, and will permit any variation of the basic charm theme to be considered. We will here avoid all prejudice in this matter and simply review the experimental evidence.

I will quickly focus on some utilitarian topics that will later on permit me to discuss the most incisive experimental efforts that have been undertaken or, at last, are close to yielding data. These topics are:

1) Summary of parameters: *What,* if any, observables do we look for?

2) Production mechanisms: *Where* do we look?

3) Detection strategy and techniques: What experimental effects do we expect, and *how* do we isolate a signal?

We will then discuss individual efforts chosen both for the promise they offer, and for representative illustration of the various approaches. Finally, a *status quo* of our knowledge as to the existence or non-existence of charmed hadrons will be given, with an outlook on the foreseeable future.

1. SUMMARY OF PARAMETERS

What hadronic states are expected? For each quark in the qqq baryon and $q\bar{q}$ meson states, we now have four possible choices. Using the properties of the new quark, p′ (or c)

$$\begin{aligned} I &= 0 \qquad Q = {}^{2}\!/_{3} \\ S &= 0 \qquad B = {}^{1}\!/_{3} \end{aligned} \qquad (1)$$

we span a three-dimensional lattice for the spectroscopy of hadrons. Figure 1a shows the fundamental quartet. The weak interaction connects states of different eigenvalues of C (as of S) according to the favoured mode (by $\cos\,\theta_c$) C

$$\Delta S = \Delta C \; , \qquad (2)$$

and we assume that all the known selection rules of the weak interaction remain valid. This simple picture then gives charm-changing interactions which (Fig. 1b) predominantly change strangeness simultaneously according to (2), with $\Delta S/\Delta Q = 1$. We will be looking for the weak decays of the lowest-mass charmed hadrons, whose *narrow width* and *largely strange* final-state will be the most telling features.

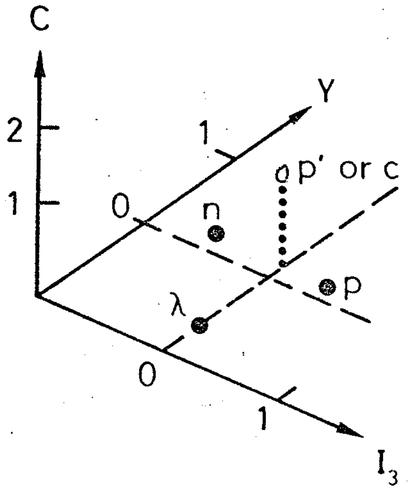


Fig. 1a

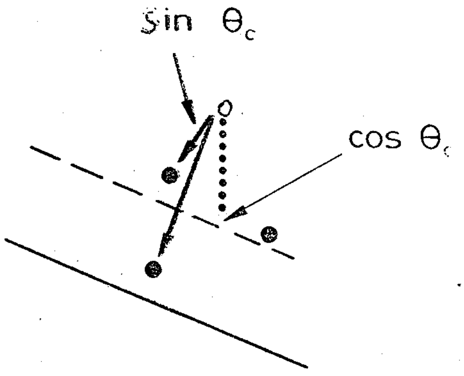
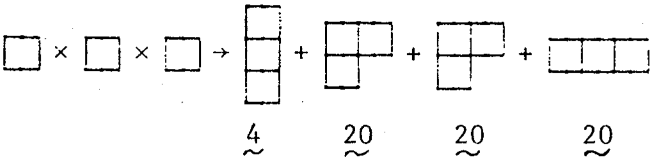


Fig. 1b

What are the lowest-mass charmed hadrons? For baryons, we have the qqq states

$$\underset{\sim}{4} \times \underset{\sim}{4} \times \underset{\sim}{4}$$



The symmetric $\underset{\sim}{20}$  is identified as

$$\underset{\sim}{20}\ (J^P = 3/2^+) = \underset{\sim}{10} + \underset{\sim}{6} + \underset{\sim}{3} + \underset{\sim}{1}$$

(with charm 0 1 2 3) .

$\underset{\sim}{10}$ contains the Δ's and their strange partners, the $\underset{\sim}{6}$ gives charm-one Δ-type states. For mixed-symmetry, we have

$$\underset{\sim}{20}\ (J^P = 1/2^+) = \underset{\sim}{8} + \underset{\sim}{6} + \underset{\sim}{\bar{3}} + \underset{\sim}{3}$$

(with charm 0 1 1 2) .

$\underset{\sim}{8}$ is the usual nucleon octet; we have a $\underset{\sim}{6}$ and $\underset{\sim}{\bar{3}}$ of singly charmed $\frac{1}{2}^+$ states, the non-strange members of which would decay principally (by $\Delta I = 0$) into $\Sigma^{\pm 0}$ and Λ^0. If we make the reasonable assumption that the S = 0, C = 1 baryons are the charmed baryon "ground states" that can decay only weakly, there should be sharply defined narrow states decaying into Σ + pions from an I = 1 multiplet containing a *doubly charged* state, and into Λ + pions from a singlet that has Q = 1.

For the mesons, we have the basic

$$\underset{\sim}{4} \times \underset{\sim}{\bar{4}} \rightarrow \underset{\sim}{15} + \underset{\sim}{1} ,$$

where

$$\underset{\sim}{15}\ (J^P = 0^-, 1^-) = \underset{\sim}{8} + \underset{\sim}{3} + \underset{\sim}{\bar{3}} + \underset{\sim}{1}$$

(with charm 0 -1 +1 0)

yields back the pseudoscalar and vector octets, plus positively and negatively charmed triplets that decay characteristically into K and π combinations.

The current structure of the weak interaction imposes certain selection rules on these decays, as has been worked out in detail in Ref. 2; most noticeably, the lowest-mass pseudoscalar meson would not decay into $K\pi$ in its charged state, which couples to $K\pi\pi$, but its neutral partner would decay into $K^{\mp}\pi^{\pm}$.

So, we will be looking for narrow $K\pi$, $K\pi\pi$, $\Lambda\pi\ldots$, $\Sigma\pi\ldots$ peaks, including a $\Sigma^+\pi^+$ state; but at what masses and lifetimes?

The range of possible masses for the charmed "ground states" is highly model-dependent, but the analogy between c and p quarks which effects the cancellation of the $\Delta S = 1$ weak neutral currents sets limits. A reasonable range might be for baryons, B^c, and mesons, M^c,

$$2.5 \lesssim m(B^c) \lesssim 5 \quad \text{GeV}$$

$$1.5 \lesssim m(M^c) \lesssim 3.5 \text{ GeV} .$$

If, however, we assume that the observed narrow mesonic state at 3.1 GeV is to be interpreted as a bound $(c\bar{c})$ state ϕ^c, a mass scale gets established that allows us to narrow our range of interest. This could lead, for the mesons, to masses of order

$$m(M^c) \simeq \frac{1}{\sqrt{2}}\, m(\phi^c) \simeq 2.2 \text{ GeV}$$

for the 0^-, 1^- triplets of $C = \pm 1$. If the $\psi(3.1)$ is the charm analogy to the $\phi = (\lambda\bar{\lambda})$, we also expect an η analogy,

$$\eta^c = (p\bar{p} + n\bar{n} + \lambda\bar{\lambda} - 3c\bar{c})\,\frac{1}{\sqrt{12}}$$

where the mass is

$$m(\eta^c) \simeq \frac{\sqrt{3}}{2}\, m(\phi^c) \simeq 2.7 .$$

For the baryons, masses depend on our choice as to the use of a linear or quadratic mass formula. If we choose the linear formula, the $J^P = \frac{1}{2}^+$ states will have masses

$$m(\underset{\sim}{\bar{3}}) \simeq 4.5 \text{ GeV} ,$$

$$m(\underset{\sim}{6}) \simeq 6 \quad \text{GeV} .$$

With the use of a quadratic mass formula, we find

$$m(\underset{\sim}{\bar{3}}) \simeq 2.7 \text{ GeV} ,$$

$$m(\underset{\sim}{6}) \simeq 3.3 \text{ GeV} .$$

These numbers will set an approximate scale for minimum total-energy requirements in charm search experiments.

The lifetimes follow from simple dimensional considerations in a strangeness charm analogy. They yield[2)]

$$\tau \lesssim 10^{-13} \text{ sec}$$

$$c\tau \lesssim 10^{-3} \text{ cm} \quad .$$

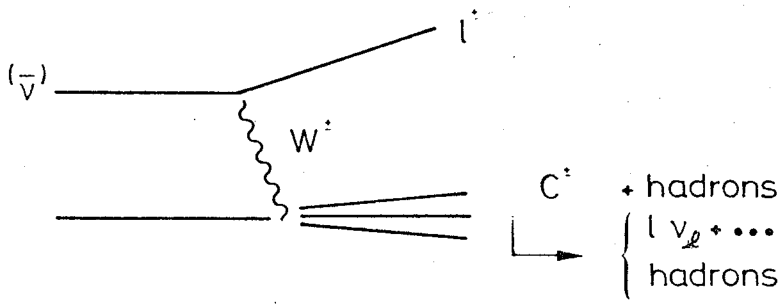
2. PRODUCTION MECHANISMS

2.1 Weak production

This will be principally observable from

$$\nu N \text{ (or } \nu A) \to C^{\pm} + \ldots + \text{lepton}$$

according to



The principal difficulties are these: the small cross-section of the weak production process; the suppression of the production of $(c\bar{n}, c\bar{p})$ states from non-strange nucleon constituents, by $\sin^2 \theta_c$ ($\sim 1/20$); the small amount of $\lambda\bar{\lambda}$ pairs inside the nucleon, to make $\Delta C = \Delta S$ transition to $(c\bar{p}, c\bar{n})$ states without suppression.

2.2 Electromagnetic production

This can occur from lepton or photon beams: first, in electron-positron collisions

$$e^+e^- \to \gamma \to C^+C^- + \ldots \quad .$$

Below threshold for $C^+ + C^-$ production, there may be the production of the "hidden-charm" bound state analogous to the hidden-strangeness $\phi = (\lambda\bar{\lambda})$:

$$e^+e^- \to \gamma \to (c\bar{c}) \qquad (\psi,\ \psi',\ \ldots\ ?) \quad .$$

If this were the correct interpretation of ψ, ψ' production, then we would almost certainly have to see

$$(c\bar{c})_{\text{ortho}} \rightarrow (c\bar{c})_{\text{para}} + \gamma ,$$

with $(c\bar{c})_{\text{ortho}}$ to be identified with either $\psi(3.1)$ or $\psi'(3.7)$, and the monoenergetic photon giving the process away.

For the production of meson pairs $C^+ + C^-$, all the characteristics of the weak C decays would be useful. There should be an enhancement in the K/π ratio, the reconstructibility of sharp mass peaks, semi-leptonic decays giving direct leptons, and more.

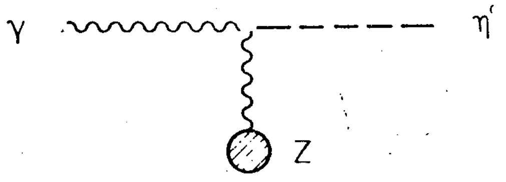
Furthermore, a promising route of investigation would be the photoproduction or electroproduction processes

$$\begin{aligned} \gamma p \text{ (or } \gamma A) &\rightarrow C^+C^- + \ldots \\ &\rightarrow (c\bar{c}) + \ldots \end{aligned}$$

If, again, we believe the $(c\bar{c})$ interpretation of $\psi(3.1)$, then the ψ photoproduction cross-section observed at FNAL$^{3)}$ can give a rough idea of what C^+C^- cross-section to expect:

$$\frac{\sigma(C^+C^-)}{\sigma_{\text{tot}}(\gamma p)} \lesssim 10^{-3} .$$

A particularly telling experiment may be feasible at high energies, using the Primakoff production graph to observe the pseudoscalar η^c state,



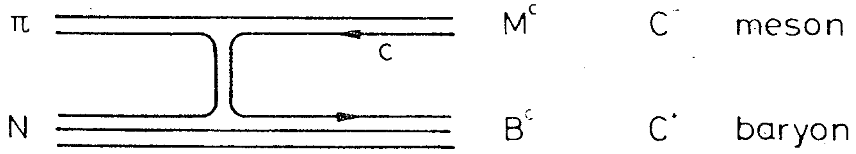
and its expected subsequent 2γ decay mode. The characteristic energy and Z-dependence of this sharply forward-peaked process open it up to very selective observation; note, however, that this meson still has no *manifest* charm even if its quark composition is correctly estimated.

2.3 Production by strong interaction processes

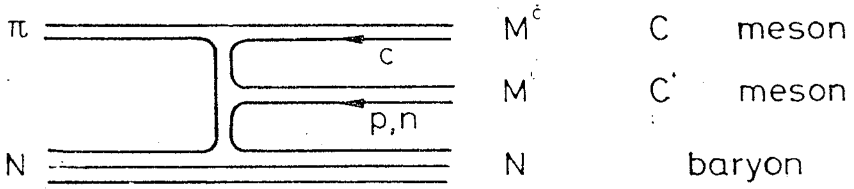
This will proceed largely in analogy with the strong production of strange hadrons: charm conservation leads to "associated production":

$$NN \text{ (or } \pi N) \rightarrow C^+C^- + \ldots ,$$

where C^+ and C^- are baryons or mesons carrying opposite charm number. What hadron states will be visible? Close to threshold, the most economical quark graphs in πN interactions will be

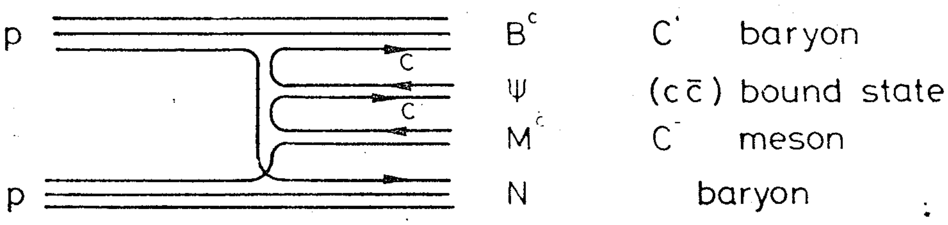


and, if $M^{\bar{c}}$ and B^c are the charmed "ground states", their characteristic weak decay properties should be noticeable. Alternatively,



will lead to the observation of two mesonic "ground states". If $m(B^c) > m(N) + m(M^c)$, these two graphs may not be experimentally distinguishable. As the available energy increases, more channels open up, but most likely there will be strong cascading to C^-, C^+ ground states, so that the basic observation of narrow states of relatively low mass remains a promising tactic.

One specific stratagem that, if valid, would lead to a particularly telling signature for associated charmed hadron production is predicated on the assumption that $\psi(3.1) = (c\bar{c})$, and on the empirical rule that will not permit quark lines to meet inside a bound system (= hadron)[4]: if, in a high-energy pp collision, a $\psi(3.1)$ can be identified, say, by its $\mu^+\mu^-$ decay mode, C^+C^- production is indicated by means of diagrams of the type



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Since the $\psi \to \mu\mu$ events should stand out clearly, these assumptions and an acceptable cross-section for ψ production would lead to the clearest C^+C^- trigger imaginable. Unfortunately, it is not quite clear whether in the parallel case of $pp \to \phi\ (= \lambda\bar{\lambda}) + S^+S^-$, such a mechanism is manifest. Irrespective of the precise process occurring, strong production should ultimately yield, by SU(4) symmetry, plentiful C^+C^- events.

3. DETECTION STRATEGIES

In the above-discussed production processes, what will be the most promising stratagems for detecting the charmed states? We will quickly pass review, then go over to the experimental methods by which we can most profitably follow these courses of attack.

3.1 Weak interaction

The production of *single* charmed states according to

$$\overset{(-)}{\nu}N \to C^{\pm} + \ell + \ldots$$

(with ℓ the appropriate final-state lepton) is most easily indicated by a "dilepton signature": *if* $C^{\pm}$ has an appreciable (semi-)leptonic decay mode, then lepton pairs $\ell^+\ell^-$ (with $\ell = \mu$ or e) would be a telling feature. Thus neutrino interactions yielding lepton pairs of *opposite charge* should be closely studied. While the interpretation of dilepton signals⁵⁾, in the absence of detailed additional information, remains an open question, their charm connotation is certainly a probability.

If detailed observation of a neutrino event is possible, there is also the observation of an apparent violation of the $\Delta S = \Delta Q$ rule, as in an event recently reported by a BNL group⁶⁾. However, precise reconstruction of kinematics and correct particle identification, with satisfactory statistics, are hard tasks in neutrino interactions (see below).

Other, less direct, implications of charmed hadron production would reflect in inclusive features of neutrino interactions⁷⁾: the kinematical distributions (in the y variable) would change; sum rules would change their saturation values; apparent charge asymmetries may show up in the final state; and the scaling of the structure functions describing neutrino-nucleon scattering would exhibit a new threshold. None of these features, while indicative, will give information sufficiently concise to establish or rule out any specific type of charm scheme.

3.2 Electromagnetic interaction

The production processes discussed under Section 2.2 are open to a variety of conclusive experimental checks: $e^+e^- \to C^+C^-$ will most clearly give rise to observables: there should be a discernible threshold in $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$; mass reconstruction should be possible for C^+,C^- decaying into charged hadrons; a threshold should show up for lepton yields from the weak C^+,C^- decays; the mean charged multiplicity should change abruptly at C^+C^- threshold, as should the ratio of neutral to charged particle energy, owing to the sudden occurrence of neutrinos.

Many of these features should equally be observable in photoproduction and in electroproduction. There, the use of higher-Z targets may also allow the coherent diffractive production of $J^P = 1^-$ systems, with characteristic angular dependence. The same holds for the process $\gamma Z \to \eta_c Z + \ldots$, as mentioned before.

3.3 Strong interaction

We start from the basic scheme

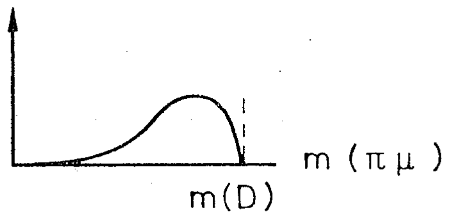
$$h + h \to C^+C^- + \ldots$$

$$\hookrightarrow \begin{cases} \ell\bar{\nu}_\ell \text{ (+ hadrons)} \\ \text{hadrons} \end{cases}$$

We assume C^+,C^- to be "ground states" that decay weakly and have a sharply defined mass. The principal stratagems then are the following:

i) C^+ and/or $C^- \to$ charged hadrons: look for any sharp mass peak among final-state hadron combinations, particularly those involving strange particles (favoured by $\sim \cos\theta_c$).

ii) $C^+ \to \ell\nu + \ldots$, $C^- \to \ell\nu + \ldots$: look for dileptons of opposite charge, in particular for $\mu^\mp e^\pm$. Also, invariant mass distributions of lepton + + hadron(s) should exhibit limiting values:



iii) $C^{\pm} \rightarrow K$ (or π) $\ell\nu$, $C^{\mp} \rightarrow$ hadrons: use "direct" lepton ℓ for trigger; then reconstruct invariant masses of hadron combinations, $\pi\mu$, πK, as above.

iv) $C^{\pm} \rightarrow K\pi$, $C^{\mp} \rightarrow K\pi\pi$: trigger on large p_T kaon, use fully reconstructed 4C events to determine invariant masses of $K\pi$, $K\pi\pi$ systems. Plot $m(K\pi)$ versus $m(K\pi\pi)$: an enrichment along the bisector $m_1 = m_2$ would indicate pair production C^+C^-.

3.4 All interactions

Direct observation of a charged-particle track of very short range, with characteristic subsequent decay, will be an extremely potent indicator. However, the expected short lifetimes of $\tau \lesssim 10^{-13}$ make this method suitable only for techniques resolving on the 10^{-4} cm level.

4. DETECTION TECHNIQUES

In order to make use of the stratagems reviewed above, what are the most appropriate detection methods in the particle physicist's arsenal?

4.1 Visual techniques

For the reconstruction of charged-particle decays, all visual techniques, depending on their time and space resolution, are useful.

Nuclear emulsions have by far the most precise spatial resolution, to a level of ∿ 1 micron. Disadvantages are obvious: the recording of an event cannot be triggered; the emulsion contains high-Z nuclei rather than free nucleons; feedback to the experimenter is extremely slow.

Bubble chambers: reconstruction is good for all charged tracks; selective triggering of the camera system permits the experimenter to use hybrid systems for, say, muon identification outside the chamber. Disadvantages are its virtual lack of particle identification, its limited total mass for neutrino exposures, and its slow thermodynamics, which combine to disallow searches for very small cross-section processes.

Streamer chambers do not share these disadvantages: selective triggering of chamber and recording gear allow small cross-sections to be tackled. The low-density gas volume permits accurate kinematical reconstruction. High-intensity beams (up to several hundred particles per chamber memory time) can be tolerated, liquid or heavy targets can be inserted. On the negative side, particle identification remains a problem, and the interaction vertex is not directly visible in most cases.

4.2 Electronic techniques

In addition to the visual techniques, which allow for a full reconstruction of multiparticle final states, as well as visualization of decay vertices, all electronic detection techniques come into the game: precision spectrometers have the advantage of separating charged-particle rest masses as well as their momenta and charges. Double-arm or wide-acceptance spectrometers are able to give a fairly precise determination of two-particle masses at high counting rates. Large solid-angle devices such as the Omega spectrometer at CERN or LASS at SLAC are capable of combining many of the useful features of visual and electronic techniques, although their performance still has to be established in rigorous tests.

5. SOME CHARM SEARCHES DONE OR IN PROGRESS

I will now mention a number of experimental projects that have been undertaken or, at least, started charm searches. Before the unexpected discovery of the ψ (or J) particles[8] last fall, only one such experiment was completed[9]. Subsequently, a flood of projects has been entered upon; some have published results. While a connection between ψ's and the charm quantum number may or may not turn out to be existent, the current vogue of charm searches has certainly been largely motivated by their advent on the scene of particle physics.

Since completeness is not a meaningful criterion under the circumstances, I have chosen projects that best illustrate the stratagems and techniques described in the previous sections, and that show the highest promise of yielding telling results, confirming or refuting the charm hypothesis (in the simple form assumed in Section 1).

5.1 Neutrino experiments

Exposures of hydrogen bubble chambers have looked for narrow peaks involving many-particle mass combinations. No sharp peaks have emerged. Direct charmed-particle tracks do not appear, even at FNAL energies, just as expected from the lifetime estimates. One event has been reported from BNL$^{6)}$, with an apparent $\Delta S = -\Delta Q$ implication in the fit

$$\nu_\mu p \to \mu^- \Lambda^0 \pi^+ \pi^+ \pi^+ \pi^- \ .$$

A charm interpretation would imply the existence of a fairly low-mass (2.4 GeV) $C = 1$ baryon. We would hope to see more results from that (low-energy) experiment before forming an opinion in this connection.

The counter experiments in the FNAL Neutrino Laboratory have produced suggestive results on dimuon production$^{10)}$: experiment 1A sees some 30 $\mu^+\mu^-$ pairs, with reconstructed masses between 2 and 4 GeV. There is no dimuon signal of equal sign. A charm connection is possible, but can hardly be expanded upon in the absence of all detailed information on vertex, full final-state, precise momenta, etc.

An interesting project has just moved past the approval stage$^{11)}$: Some of the calorimeter and muon identification apparatus of the FNAL neutrino counter experiments will be used to give fast external information on where a vertex may be found inside a set of 5.6 cm thick emulsion stacks. Direct charmed-particle tracks can be resolved for lifetimes of $\gamma^{-1} \times 3 \times 10^{-15}$ sec. The idea is simply to let the external muon track guide the experimenter to a νZ vertex inside the stack; then follow the hadron tracks from this vertex to see whether there is a charmed-particle decay vertex at a distance of more than 1 μm (Fig. 2). For all its statistical limitation, we believe this to be a very promising effort.

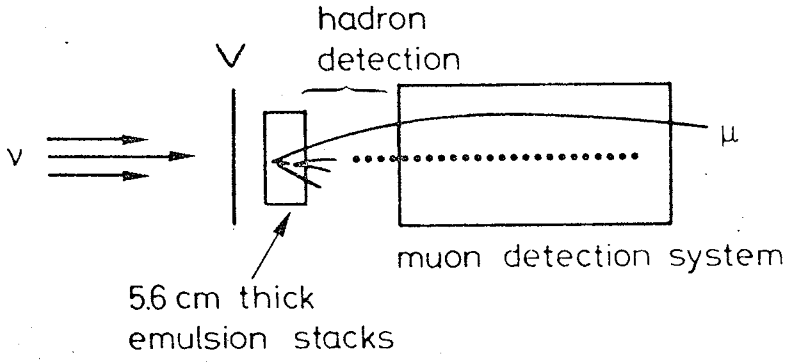


Fig. 2

5.2 Electromagnetic interaction experiments

The well-known experimental set-ups at SPEAR (Stanford) and DORIS (Hamburg) are training their sights on all possible signals for charmed-particle production. While both magnetic detection systems can tell charges and momenta of particles emerging from e^+e^- collisions, there are the problems of incomplete solid-angle coverage; of limited π/K separation, and of electron, photon, and muon detection and identification. Still, within these limitations, some very important features have emerged.

Suppose that $\psi(3.1)$ is the $(c\bar{c})$ state analogous to the $(\lambda\bar{\lambda})$ state $\phi(1.02)$. Then the naïve charm picture demands that there be charmed 0^- mesons of masses not much above 2.2 GeV each; in other words, at a total energy of 4.8 GeV (2.4 GeV per beam), SPEAR should find itself above the threshold for charmed meson pair production. We might also identify the reported broader "resonance" $\psi''(4.15)$ and the accompanying increase in $R \equiv \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$ as denoting the onset of C^+C^- production. Then the strategies discussed under Section 3.2 above should apply.

In fact, data collected at those energies give no indication that any of the criteria discussed would indicate C^+C^- emergence[12]. The K/π ratio does not increase within errors, the ratio of neutral to charged energy has no noticeable step, neither does the charged hadron multiplicity. A reconstruction of invariant masses for various mesonic systems shows no sign of a meaningful enhancement[13], to a level of cross-section X branching ratio of nanobarn order. These observations, if anything, *rule out the simple charm scheme with* *the mass scale set by the ($c\bar{c}$) identification of $\psi(3.1)$.* Improved and more detailed results may have to await another generation of detectors to become really restrictive.

In photoproduction, the recent commissioning of the FNAL Tagged Photon Laboratory should allow an early result on the conjectured production of η^c and its 2γ decay. Approved experiments$^{14)}$ should set clean limits within a year's time.

5.3 Strong interaction experiments

A number of experiments have been performed; we will mention them according to the stratagems discussed in Section 3.3.

i) Looking for mass peaks (inclusively)

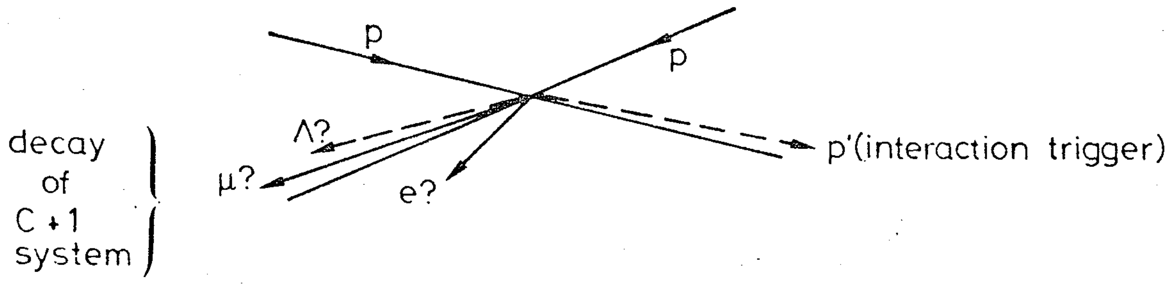
The MIT-BNL experiment that discovered the $\psi(3.1)$ in $pp \to e^+e^- + \ldots$ $^{8)}$, can use its precise double spectrometer to look for properly defined and identified *pairs* of charged hadrons. In a recent six-week run, no meaningful signal was found in the $K^\pm\pi^\mp$, $\pi^\pm\overset{(-)}{p}$, $K^\pm p^\mp$, $\pi^+\pi^-$ or K^+K^- channels in the mass range expected by the simple charm scheme$^{15)}$; this experiment was performed at BNL, where the total hadronic energy available is of order 8 GeV. Note that this project is limited to all-charged, all-hadronic two-body decays.

ii) Looking for dileptons from C^+C^- decays

At the CERN Intersecting Storage Rings, an experiment is in progress$^{16)}$ to study (semi-)leptonic decays of charmed hadron pairs by means of precisely identifying leptons in the final state. The experiment banks on a diffractive production process

$$
\begin{array}{l}
pp \to pp^{*} \\
\qquad \hookrightarrow B^c + \bar{M}^c \;(\text{or } p + M^c + \bar{M}^c) \to \left\lbrace \begin{array}{l} \ell^\pm\mu^\mp + \ldots \\ \ell^\pm + \ldots \\ \mu^\pm + \ldots \end{array} \right.
\end{array}
$$

where both the charmed meson and the charmed baryon will essentially follow the excited proton:



A very efficient electron spectrometer (Fig. 3) is seen to be set at ∿ 30° to the beam; a forward large-aperture spectrometer incorporating Čerenkov counters and large wire-chamber planes as well as a steel shield for muon identification should make it possible to probe for B^c, $\bar{M}^c$ decays into leptons and (strange) hadrons, with the $e^\pm$ arm giving a precisely defined trigger. The high centre-of-mass energy of the ISR should make this project definitive in the framework of the production model employed. It is at present in the running stage. A result on $\mu - e$ coincidences should soon be emerging.

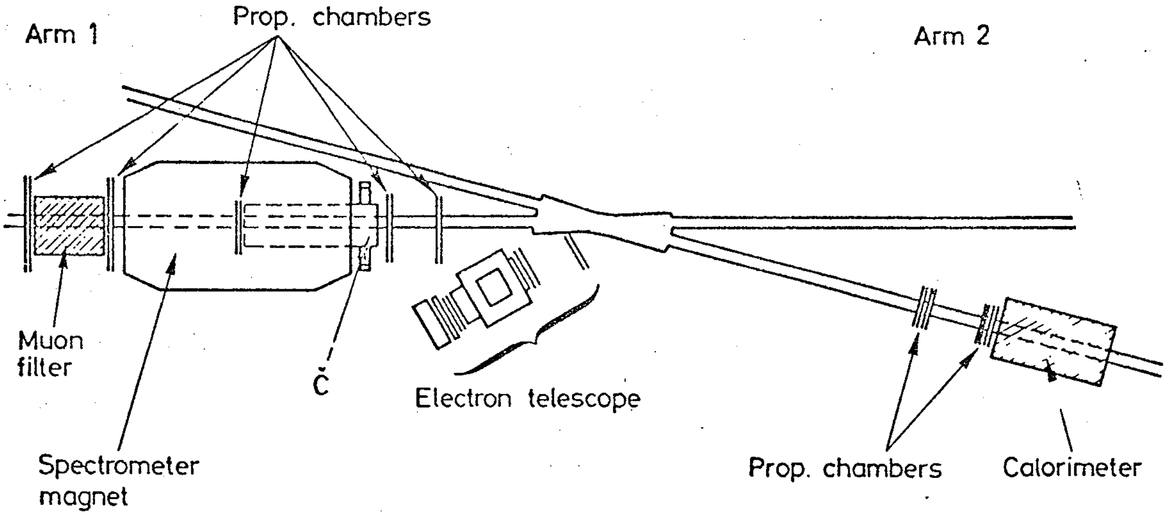


Fig. 3

iii) <u>$C^\pm \to \ell\nu_e + \ldots$ *yields trigger,* $C^\mp$ *gives (strange) hadrons for sharp mass reconstruction*</u>

One such project is in final preparation at the ISR$^{17)}$. While the previous experiment assumed peripheral C^+C^- production, this one starts from the notion that a *central* collision is most likely to give rise to the production of new particle types. In terms of quark diagrams, Figs. 4a and 4b show the approach of the R-605 experiment versus that of the R-702 ISR experiment in

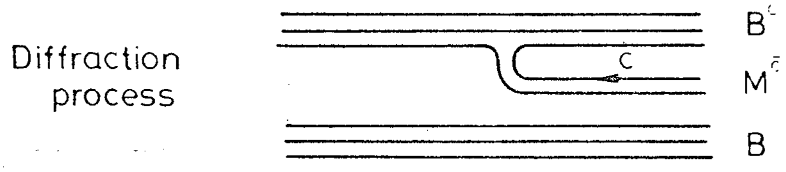


Fig. 4a

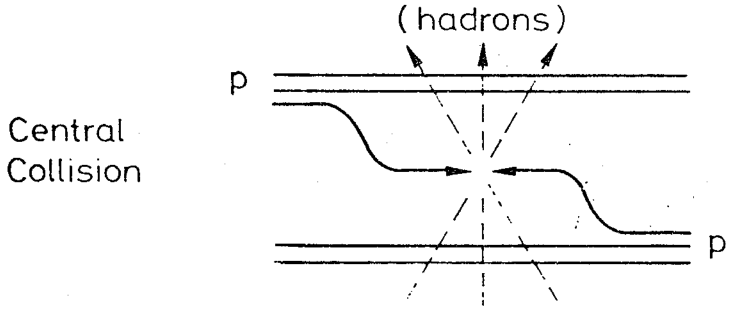


Fig. 4b

preparation by the CERN-Saclay Collaboration. Their method is illustrated in Fig. 5: since a central collision leads to isotropic emission of secondaries, large-angle detection of leptons and (strange) hadrons will be most clearly promising. Two large solid-angle magnets combined with hodoscopes and wire chambers, with Čerenkov counters inserted in their aperture, determine production and decay vertices of processes "tagged" by the emission of a large p_T electron. These electrons are momentum-analysed in the magnets *and* energy-analysed in a bank of lead-glass total absorption counters that provide the trigger for event read-out. Detection of γ and π^0 will therefore also be possible over a limited solid angle.

One lower-energy experiment using this same stratagem -- trigger on direct lepton, reconstruct hadron masses -- was completed in June of last year at SLAC by a Santa Cruz-SLAC Collaboration$^{9)}$. It made use largely of detection apparatus that had been tuned for a very selective muon trigger from muon inelastic scattering. The apparatus is schematically shown in Fig. 6. A 15 GeV pion beam of small phase space interacts with nucleons in a number of discretely positioned polyethylene targets inside a 2 m long streamer chamber. All charged particles emerging from the interaction are momentum-analysed in the chamber. If there is a muon from $C^{\pm} \to \mu + \nu + \ldots$, it will, over a large solid angle, be identified by penetration of a 1.5 cm Pb wall. The trigger for streamer chamber firing and event read-out is thus simply a muon of energy $\gtrsim$ 2 GeV in the final state.

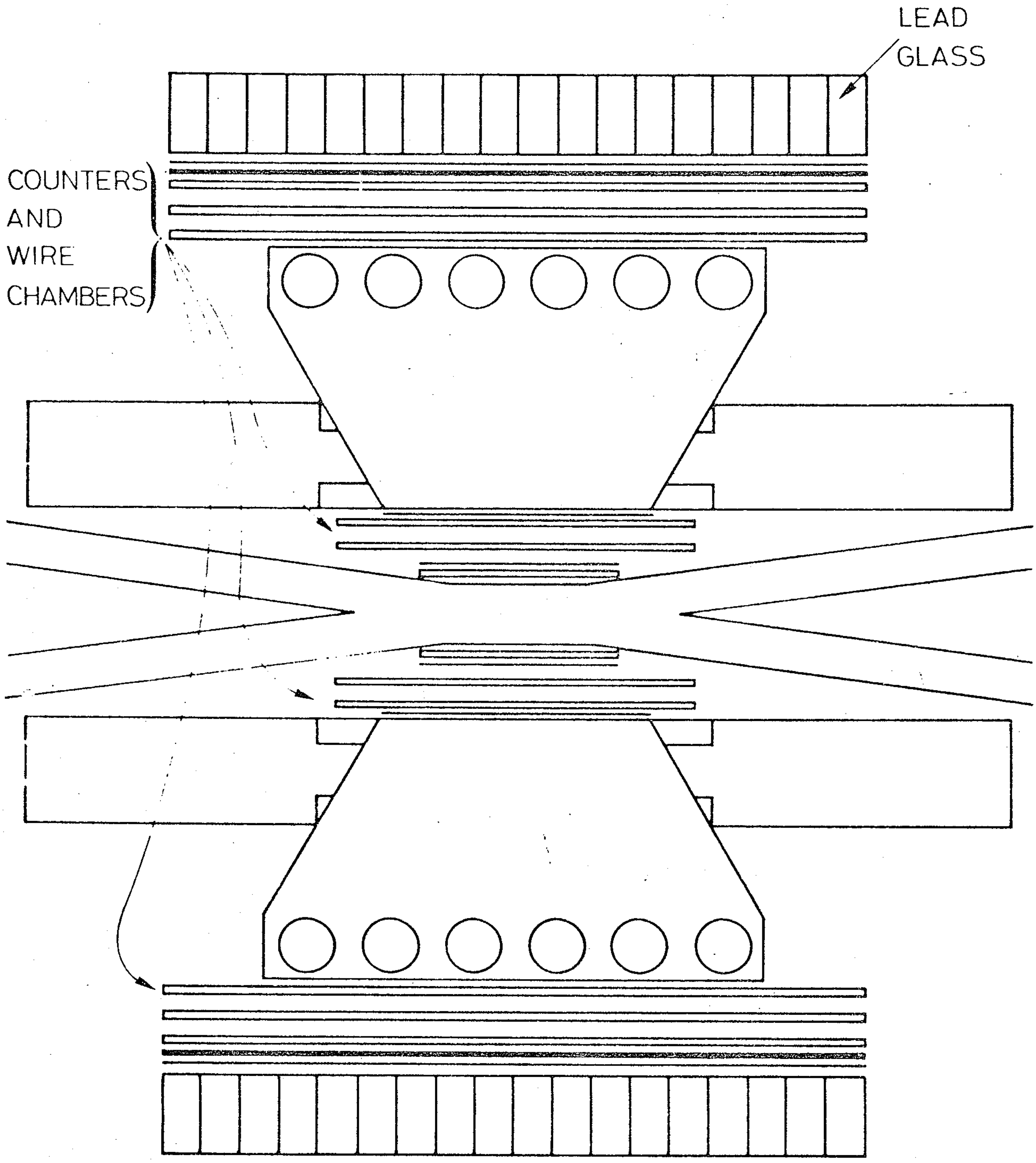


Fig. 5

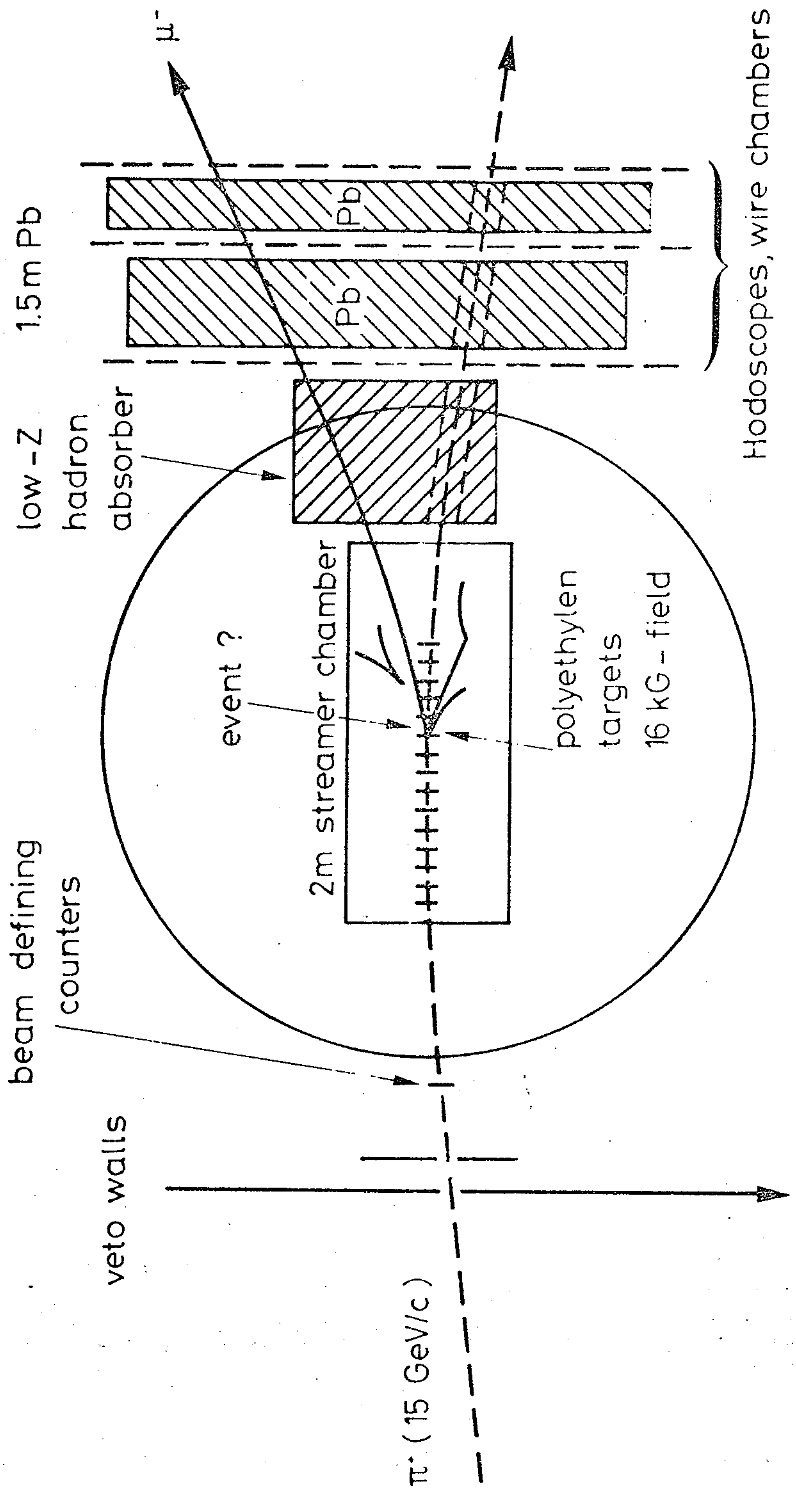

μ⁻
1.5 m Pb
Pb
Pb
Hodoscopes, wire chambers
low-Z
hadron
absorber
2m streamer chamber
event ?
polyethylen
targets
16 kG-field
beam defining
counters
veto walls
π⁺ (15 GeV/c)

Fig. 6

The strategy for first analysis was straightforward: look for obvious strange-particle events (vees from Λ^0, K^0 decay in the chamber) triggered by the "prompt" muon. Then reconstruct hadron tracks, calculate invariant masses of all charged-particle combinations as well as K^0, Λ^0 plus charged particles. A total of 16,000 pictures were taken: it became immediately obvious that a first look at these data did *not* show a strange-particle yield much superior to that seen in normal hadron-hadron collisions. A much more sophisticated analysis then became necessary: measure all events; calculate all invariant mass distributions ($K\pi$ ..., $\Lambda\pi$ ..., KK, Kp, $\pi\pi$ ...) for any 2, 3, 4 ... charged tracks and K^0's, Λ^0's. Cuts can then be introduced to clean up the sample, which will have a considerable combinational background: on the p_T of trigger muon or (strange) hadron, on location of the vertex in the chamber (the further downstream the event occurred, the less the chance that a secondary π decayed before hitting the absorbers, thus simulating a "direct" muon), and others. The Collaboration has to date not seen any conclusive evidence for a narrow peak; bear in mind, however, that the hadronic mass W in that experiment is about 5.6 GeV, just enough to make a pair of charmed mesons in addition to the proton, according to our above mass estimates, or possibly a $B^c M^{\bar{c}}$ pair. One would have to bank on a threshold enhancement to expect a large yield.

The sensitivity of the experiment is defined by its $\sim$ 1000 events/μb exposure, but may be heavily modified by systematic effects.

iv) $C^+, C^- \rightarrow$ *hadrons: try for charmed meson-antimeson production*

A Collaboration[18)] using the Omega Spectrometer Facility at CERN has proposed to use full kinematic reconstruction of an all-charged final state in the reaction

$$\pi^- p \rightarrow M^c \, M^{\bar{c}} \, p \; (+ \ldots)$$
$$\left.\begin{array}{l} M^{\bar{c}} \rightarrow K\pi\pi \\ M^c \rightarrow K\pi \end{array}\right\} \text{all charged}$$

to search for the occurrence of sharp mass peaks associated with kaons, for *two* simultaneously occurring particle combinations. The set-up is sketched in Fig. 7: salient points are the K^- trigger at high p_T, the requirement of $\gtrsim 5$

charged particles in the final state, identification of K versus π and p by a large-aperture Čerenkov counter, and the capability of multiparticle momentum analysis.

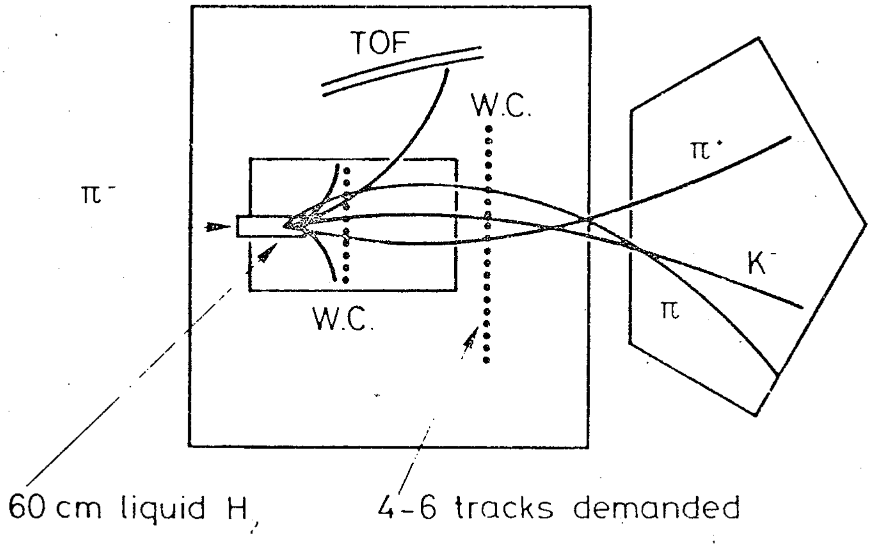
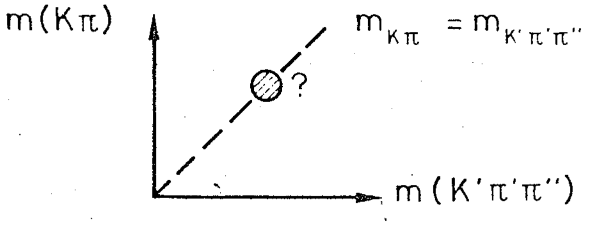


Fig. 7

The experiment is quoted to be sensitive to $M^cM^{\bar{c}}$ pair production on the 50 - 100 nb level; preliminary results looking for an event enrichment along the m(Kπ) = m(Kππ) (where K's and π's are all different particles) line



have not produced any suggestive evidence[19].

v) <u>$pp \to \psi(3.1) + B^c + (\ldots)^{\bar{c}}$: *use $\psi \to 2\mu$ decay to tag an event containing charmed hadrons*</u>

This scheme, highly model-dependent though it is, is sufficiently attractive to motivate serious efforts at the ISR. Appropriate detection apparatus will consist of a large magnetic detector including a muon identifier -- with reconstruction power sufficient to pin down narrow states such as ψ(3.1). A dimuon experiment performed recently in the Split-Field Magnet[20] using the iron of that structure for hadron/muon rejection, may be able to give first limits. There is another approved project looking for dimuons, together with hadron track reconstruction close to the vertex, that will do the same thing in a much more ambitious way[21)].

6. SUMMARY AND OUTLOOK

Throughout this discussion, we have centred our attention on the observation of clear signals for the existence of charmed hadrons in the framework of the straightforward SU(4) charm scheme as suggested by the non-observation of $\Delta S = 1$ neutral weak currents. We have discussed the nature of the observables that we might hope to experimentally detect, specifically leaving out estimates of production cross-sections, which are of necessity based on assumed, un-understood dynamical models, and therefore vary by large amounts.

Next, we reviewed the most promising ways in which the experimenter may be able to convince himself of the existence of these observables. We then followed active (or, in some cases, merely approved) experimental efforts at various accelerator laboratories, trying to illustrate the different lines of attack by our choice. There are many efforts, particularly approved FNAL experiments, that we left out since they either follow similar lines, or, as in the case of the various hh → dimuon experiments, will not lead to results that are restrictive enough to decide between C^+C^- or other mechanisms.

At the time of the writing of this lecture (May 1975), there are these inferences outstanding:

- the simple charm scheme with its scale set by the subsidiary assumption that $\psi(3.1) = \phi^c(c\bar{c})$ does not work;
- no statistically meaningful indication has been seen of sharp mass peaks, implying the existence of weakly decaying charmed hadron "ground states", either mesonic or baryonic.
- sufficiently many experimental efforts are presently active that, within the foreseeable future, the framework of this review should be experimentally exhausted.

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